Low Level Measurements and Sourcing

LOW LEVEL MEASUREMENTS AND SOURCING

KEITHLEY

NUBICOM
키슬리 공식 채널파트너

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Technical Information

Low Voltage/Low Resistance Measurements

How to Select a Voltmeter

Many kinds of instruments can measure voltage, including digital multimeters (DMMs), electrometers, and nanovoltmeters. Making voltage measurements successfully requires a voltmeter with significantly higher input impedance than the internal impedance (source impedance) of the device under test (DUT). Without it, the voltmeter will measure less potential difference than existed before the voltmeter was connected. Electrometers have very high input impedance (typically in the order of 100TΩ [10^{14}Ω]), so they're the instrument of choice for high impedance voltage measurements. DMMs and nanovoltmeters can typically be used for measuring voltages from 10MΩ sources or lower. Nanovoltmeters are appropriate for measuring low voltages (microvolts or less) from low impedance sources.

Low Voltage Measurements

Significant errors may be introduced into low voltage measurements by offset voltage and noise sources that can normally be ignored when measuring higher signal levels. Steady offsets can generally be nulled out by shorting the ends of the test leads together, then enabling the instrument's zero (relative) feature. The following paragraphs discuss non-steady types of error sources that can affect low voltage measurement accuracy and how to minimize their impact on the measurements.

Thermoelectric EMFs

The most common sources of error in low voltage measurements are thermoelectric voltages (thermoelectric EMFs) generated by temperature differences between junctions of conductors (**Figure 1**).

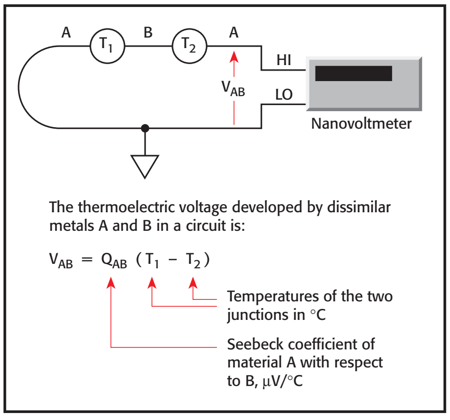


Figure 1. Thermoelectric EMFs

Constructing circuits using the same material for all conductors minimizes thermoelectric EMF generation. For example, connections made by crimping copper sleeves or lugs on copper wires results in cold-welded copper-to-copper junctions, which generate minimal thermoelectric EMFs. Also, connections must be kept clean and free of oxides.

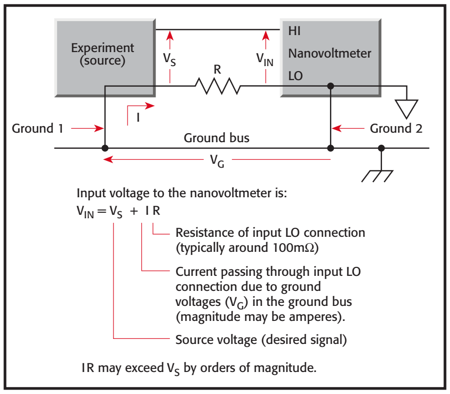


Figure 2a. Multiple grounds (ground loops)

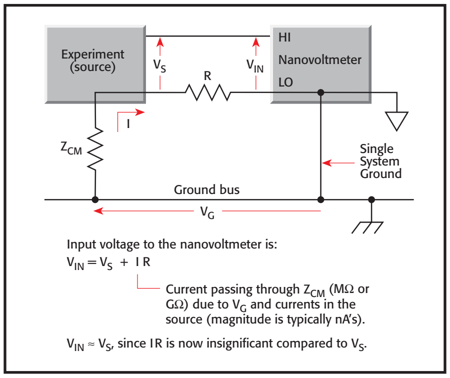


Figure 2b. Single system ground

Minimizing temperature gradients within the circuit also reduces thermoelectric EMFs. A way to minimize such gradients is to place all junctions in close proximity and provide good thermal coupling to a common, massive heat sink. If this is impractical, thermally couple *each pair* of corresponding junctions of dissimilar materials to minimize their temperature differentials which will also help minimize the thermoelectric EMFs.

Johnson Noise

The ultimate limit to how well the voltmeter can resolve a voltage is defined by Johnson (thermal) noise. This noise is the voltage associated with the motion of electrons due to their thermal energy. All sources of voltage will have internal resistance and thus produce Johnson noise. The noise voltage developed by any resistance can be calculated from the following equation:

$$V = \sqrt{4kTBR}$$

k = Boltzmann's constant (1.38×10^{-23} J/K)

T = absolute temperature of the source in Kelvin

B = noise bandwidth in Hz

R = resistance of the source in ohms

From this equation, it can be observed that Johnson noise may be reduced by lowering the temperature and by decreasing the bandwidth of the measurement. Decreasing the bandwidth of the measurement is equivalent to increasing the response time of the instrument; thus, *in addition to increasing filtering*, the bandwidth can be reduced by increasing instrument integration (typically in multiples of power line cycles).

Ground Loops

When both the signal source and the measurement instrument are connected to a common ground bus, a ground loop is created (**Figure 2a**). This is the case when, for instance, a number of instruments are plugged into power strips on different instrument racks. Frequently, there is a difference in potential between the ground points. This potential difference—even though it may be small—can cause large currents to circulate and create unexpected voltage drops. The cure for ground loops is to ground the entire measurement circuit at only one point. The easiest way to accomplish this is to isolate the DUT (source) and find a single, good earth-ground point for the measuring system, as shown in **Figure 2b**. Avoid grounding sensitive measurement circuits to the same ground system used by other instruments, machinery, or other high power equipment.

Magnetic Fields

Magnetic fields generate spurious voltages in two circumstances: 1) if the field is changing with time, and 2) if there is relative motion between the circuit and the field (**Figure 3a**). Changing magnetic fields can be generated from the motion of a conductor in a magnetic field, from local AC currents caused by components in the test system, or from the deliberate ramping of the magnetic field, such as for magnetoresistance measurements.

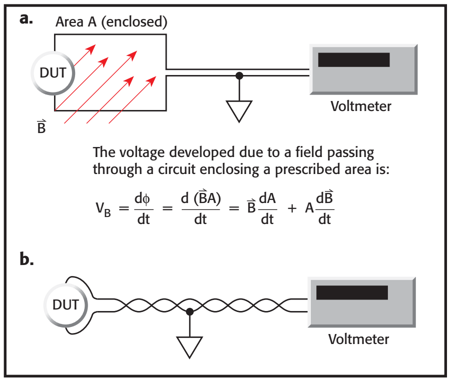


Figure 3. Minimizing interference from magnetic fields with twisted leads

To minimize induced magnetic voltages, leads must be run close together and should be tied down to minimize movement. Twisted pair cabling reduces the effects of magnetic fields in two ways: first, it reduces the loop area through which the magnetic field is interfering; second, a magnetic field will create voltages of opposite polarities for neighboring loops of the twisted pair that will cancel each other. (**Figure 3b**)

Low Resistance Measurements

Low resistances (<10Ω) are typically best measured by sourcing current and measuring voltage. For very low resistances (micro-ohms or less) or where there are power limitations involved, this method will require measuring very low voltages, often using a nanovoltmeter. Therefore, all the low voltage techniques and error sources described previously also apply here. Low resistance measurements are subject to additional error sources. The next sections describe methods to minimize some of these.

Lead Resistance and Four-Wire Method

Resistance measurements in the normal range (>10Ω) are generally made using the two-wire method shown in **Figure 4a**. The main problem with the two-wire method for low resistance measurements (<10Ω) is the error caused by lead resistance. The voltage measured by the meter will be the sum of the voltage directly across the test resistance

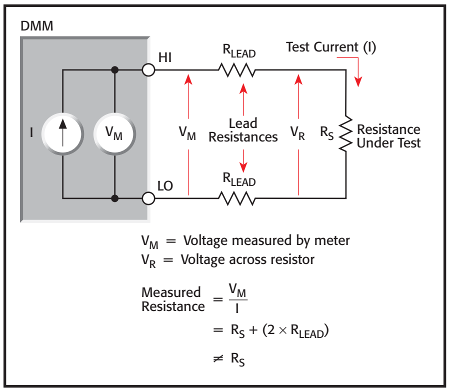


Figure 4a. Two-wire resistance measurement: Lead resistance error

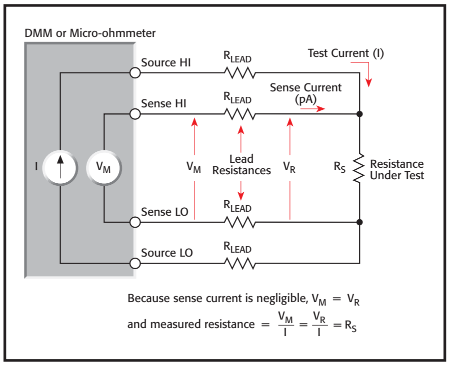


Figure 4b. Four-wire resistance measurement

and the voltage drop across the leads. Typical lead resistances lie in the range of 1mΩ to 100mΩ. Therefore, the four-wire (Kelvin) connection method shown in **Figure 4b** is preferred for low resistance measurements. In this configuration, the test current is forced through the DUT through one set of test leads while the voltage is measured using a second set of leads called the sense leads. There is very little current running through the sense leads, so the sense lead resistance has effectively been eliminated.

Thermoelectric EMFs

Thermoelectric voltages can seriously affect low resistance measurement accuracy. Given that resistance measurements involve *controlling* the current through the DUT, there are ways to overcome these unwanted offsets in addition to those mentioned in the low voltage measurement section, namely, the offset-compensated ohms method and the current-reversal method.

- **Offset Compensation Technique (Figure 5a)** applies a source current to the resistance being measured only for part of the measurement cycle. When the source current is on, the total voltage measured by the instrument is the sum of the voltage due to the test current and any thermoelectric EMFs present in the circuit. During the second half of the measurement cycle, the source current is turned off and the only voltage measured is that due to the thermoelectric EMF. This unwanted offset voltage can now be subtracted from the voltage measurement made during the first half of the delta mode cycle.

  With the Offset Compensation technique, the source current is decided by the instrument. To characterize at a specific current or a variety of currents, the Current Reversal technique/Two-step Delta technique (described below) will provide more flexibility.

- **Current Reversal Technique/Two-Step Delta Technique (Figure 5b)**

  Thermoelectric EMFs can also be cancelled by taking two voltages with test currents of opposite polarity. The voltage due to the test current can now be calculated using the formula shown in **Figure 5b**. This method provides 2× better signal-to-noise ratio and, therefore, better accuracy than the offset compensation technique. (*This is the method employed by the Model 2182A Nanovoltmeter/Model 622x Current Source combination.*)

For these methods to be effective, the consecutive measurements need to be made rapidly when compared with the thermal time constant of the circuit under test. If the instruments' response speed is too low, changes in the circuit temperature during the measurement cycle will cause changes in the thermoelectric EMFs, with the result that the thermoelectric EMFs are no longer fully cancelled.

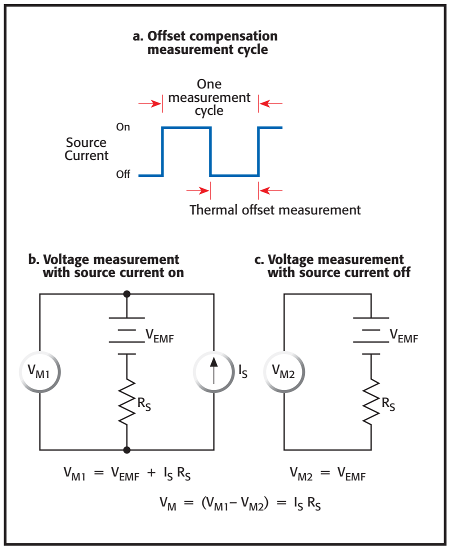


Figure 5a. Subtracting thermoelectric EMFs with Offset Compensation

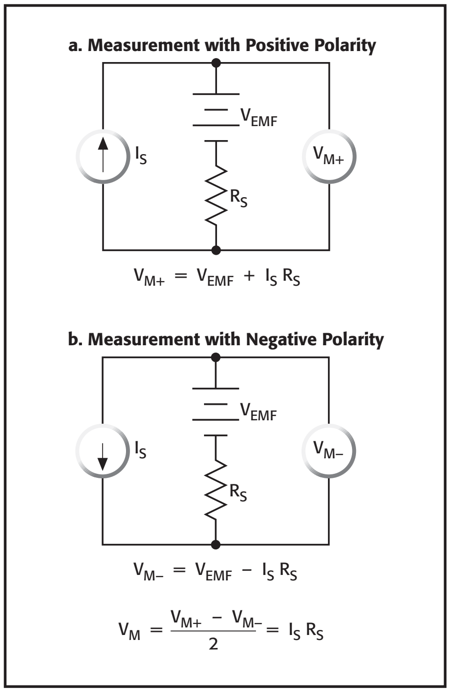


Figure 5b. Canceling thermoelectric EMFs with Current Reversal

Resistance Measurements on the Nanoscale

Three-Step Delta Technique

The three-step delta technique eliminates errors due to changing thermoelectric voltages (offsets and drifts) and significantly reduces white noise. This results in more accurate low resistance measurements (or more accurate resistance measurements of any type when it is necessary to apply very low power to DUTs that have limited power handling capability). This technique offers three advantages over the two-step delta technique.

A delta reading is a pair of voltage measurements made at a positive test current and a negative test current. Both the two-step and three-step delta techniques can cancel *constant* thermoelectric voltage by alternating the test current. The three-step technique can also cancel *changing* thermoelectric voltages by alternating the current source three times to make two delta measurements: one at a negative-going step and one at a positive going step. This eliminates errors caused by changing thermoelectric EMFs 10× better than the two-step technique (**Figure 6**).

The three-step technique provides accurate voltage readings of the intended signal unimpeded by thermoelectric offsets and drifts only if the current source alternates quickly and the voltmeter makes accurate voltage measurements within a short time interval. The Model 622x Current Source paired with the Model 2182A Nanovoltmeter is optimized for this application. These products implement the three-step technique in a way that offers better white noise immunity than the two-step technique by spending over 90% of its time performing measurements. In addition, the three-step technique is faster, providing 47 readings/second to support a wider variety of applications. Interestingly, the formula used for the three-step technique is identical to that used for differential conductance (**Figure 10**).

Pulsed, Low Voltage Measurements

Short test pulses are becoming increasingly important as modern electronics continue to shrink in size. Short pulses mean less power put into the DUT. In very small devices, sometimes even a small amount of power is enough to destroy them. In other devices, a small amount of power could raise the temperature significantly, causing the measurements to be invalid.

With superconducting devices, a small amount of heat introduced while making measurements can raise the device temperature and alter the results. When sourcing current and measuring voltage, the sourced current dissipates heat (I^2R) into the device and leads. With the lowest resistance devices (<10$\mu\Omega$), the power dissipated during the measurement may be primarily at contact points, etc., rather than in the device itself. It is important to complete the measurement before this heat can be conducted to the device itself, so fast pulsed measurements are critical even at these lowest resistances.

With higher resistance devices, significant power is dissipated within the device. Therefore, with these devices, it is even more important to reduce the measurement power by reducing the source current or the source pulse width. Many tests measure device properties across a range of currents, so reducing the current is not usually an option. Shorter pulses are the only solution.

The Model 6221 Current Source was designed with microsecond rise times on all ranges to enable short pulses. The Model 2182A Nanovoltmeter offers a low latency trigger, so that a measurement can begin as little as 10μs after the Model 6221 pulse has been applied. The entire pulse, including a complete nanovolt measurement, can be as short as 50μs. In addition, all pulsed measurements of the 6221/2182A are line synchronized. This line synchronization, combined with the three-step delta technique, causes all 50/60Hz noise to be rejected (**Figure 7**).

Dry Circuit Testing

Applications that involve measuring contact resistance may require that existing oxide layers remain unbroken during the measurement. This can be done by limiting the test current to less than 100mA and the voltage drop across the sample to no more than 20mV. Most low resistance meters have this "dry circuit" measurement technique built in.

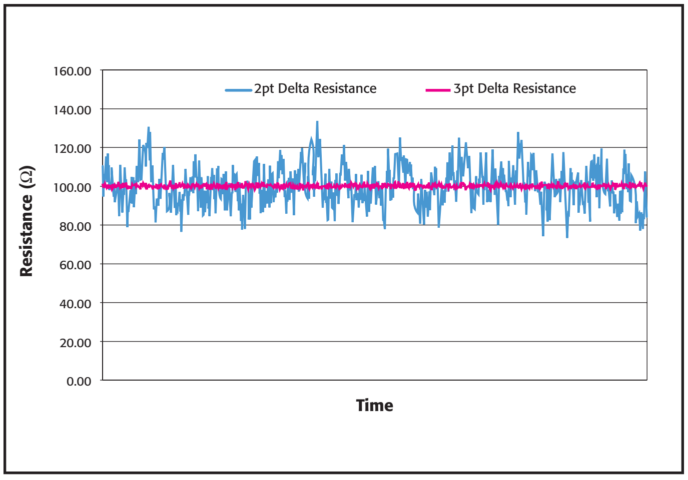


Figure 6. 1000 delta resistance readings using 100Ω resistor and 10nA source current.

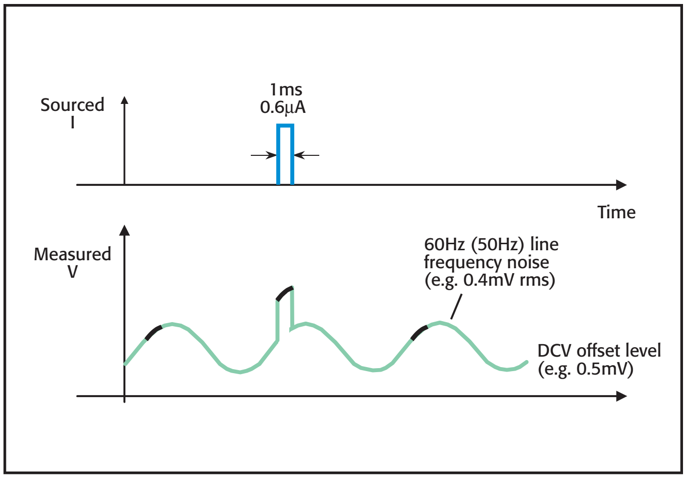


Figure 7. Operating at low voltage levels, measurements are susceptible to line frequency interference. Using line synchronization eliminates line frequency noise.

Resistance Measurements on the Nanoscale

Nanovolt Level Resistance Measurements

In the macroscopic world, conductors may have obeyed Ohm's Law (**Figure 8a**), but in the nanoscale, Ohm's definition of resistance is no longer relevant (**Figure 8b**). Because the slope of the I-V curve is no longer a fundamental constant of the material, a detailed measurement of the slope of that I-V curve at every point is needed to study nanodevices. This plot of differential conductance (dG = dI/dV) is the most important measurement made on small scale devices, but presents a unique set of challenges.

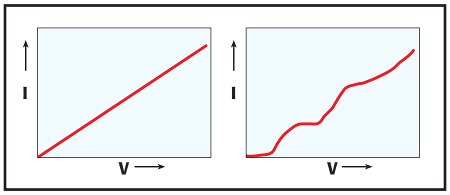


Figure 8a. Macroscopic scale (Classical)

Figure 8b. Nanoscale (Quantum)

Differential conductance measurements are performed in many areas of research, though sometimes under different names, such as: electron energy spectroscopy, tunneling spectroscopy, and density of states. The fundamental reason that differential conductance is interesting is that the conductance reaches a maximum at voltages (or more precisely, at electron energies in eV) at which the electrons are most active. This explains why dI/dV is directly proportional to the density of states and is the most direct way to measure it.

Existing Methods of Performing Differential Conductance

The I-V Technique:

The I-V technique performs a current-voltage sweep (I-V curve) and takes the mathematical derivative. This technique is simple, but noisy. It only requires one source and one measurement instrument, which makes it relatively easy to coordinate and control. The fundamental problem is that even a small amount of noise becomes a large noise when the measurements are differentiated (**Figure 9**). To reduce this noise, the I-V curve and its derivative must be measured repeatedly. Noise will be reduced by $\sqrt{N}$, where N is the number of times the curve is measured.

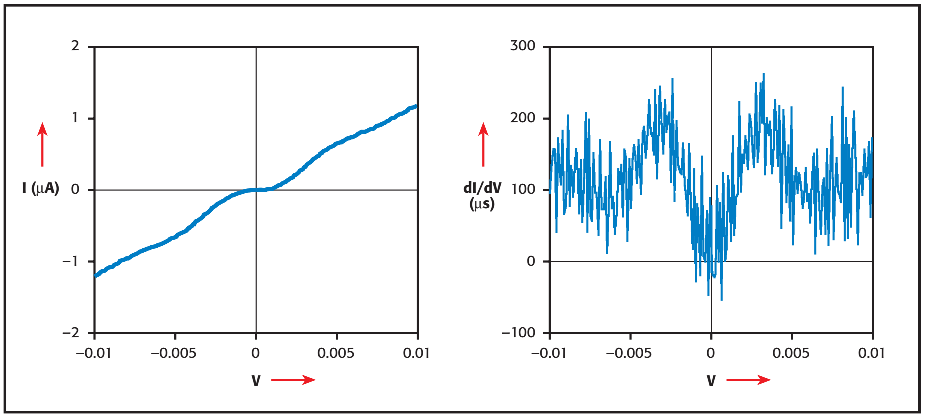


Figure 9a. I-V curve

Figure 9b. Differentiated I-V curve. True dI/dV curve obscured by noise.

The AC Technique:

The AC technique superimposes a low amplitude AC sine wave on a stepped DC bias to the sample. It then uses lock-in amplifiers to obtain the AC voltage across and AC current through the DUT. The problem with this method is that while it provides a small improvement in noise over the I-V curve technique, it imposes a large penalty in system complexity, which includes precise coordination and computer control of six to eight instruments. Other reasons for the complexity of the system include the challenges of mixing the AC signal and DC bias, of ground loops, and of common mode current noise.

Keithley has developed a new technique that is both simple and low noise: the four-wire, Source Current–Measure Voltage technique.

Four-Wire, Source Current – Measure Voltage Technique

Now there is another approach to differential conductance. This technique is performed by adding an alternating current to a linear staircase sweep. The amplitude of the alternating portion of the current is the differential current, dI (**Figure 10**). The differential current is constant throughout the test. After the voltage is measured at each current step, the delta voltage between consecutive steps is calculated. Each delta voltage is averaged with the previous delta voltage to calculate the differential voltage, dV. The differential conductance, dG, can now be derived using dI/dV. This technique requires only one measurement sweep when using the Model 2182A Nanovoltmeter and a Model 622x Current Source, so it is faster, quieter, and simpler than any previous method.

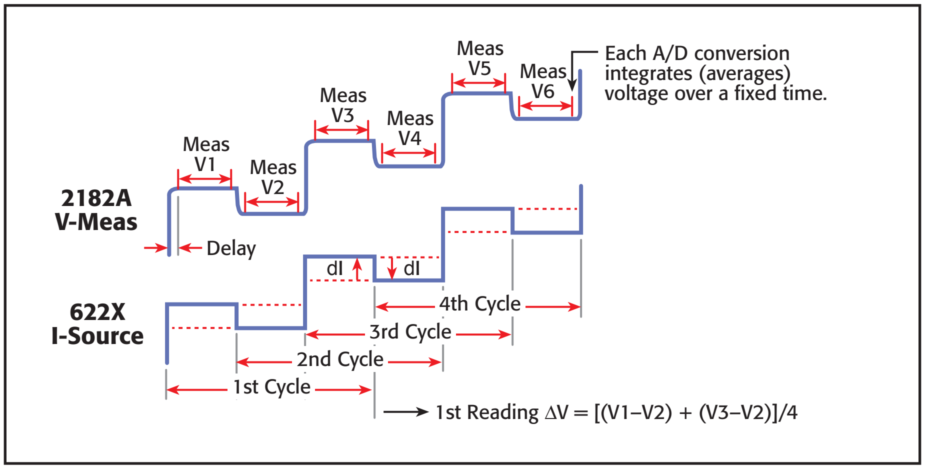


Figure 10. Detail of applied current and measured device voltage

Selector Guide Low Voltage/Low Resistance Meters

Model	2182A	6220/6221	3706A	2750	2010	2002
Page	91	97	102	248	237	231
VOLTAGE RANGE (Full Scale)						
From	10 mV	N/A	100 mV	100 mV	100 mV	200 mV
To	100 V	N/A	300 V	1000 V	1000 V	1000 V
Input Voltage Noise	1.2 nV rms	N/A	100 nV rms	<1.5 μV rms	100 nV rms	150 nV rms
CURRENT RANGE						
From	N/A	100 fA DC (also 2 pA peak AC, 6221 only)	N/A	N/A	N/A	N/A
To	N/A	±105 mA DC (also 100 mA peak AC, 6221 only)	N/A	N/A	N/A	N/A
RESISTANCE RANGE						
From[1]	10 nΩ[3]	10 nΩ (when used with 2182A)	0.9 mΩ	0.4 mΩ	0.9 mΩ	1.2 mΩ
To[2]	100 MΩ[3]	100 MΩ (when used with 2182A)	100 MΩ	100 MΩ	100 MΩ	1 GΩ
THERMOCOUPLE TEMPERATURE						
From	–200°C	N/A	–150°C	–200°C	–200°C	–200°C
To	1820°C	N/A	1820°C	1820°C	1372°C	1820°C
FEATURES						
IEEE-488	•	•	•	•	•	•
RS-232	•	•		•	•	•
CE	•	•	•	•	•	•
Input Connection	Special low thermoelectric w/copper pins. Optional 2187-4 Modular Probe Kit adds banana plugs, spring clips, needle probes, and alligator clips.	Trigger Link, Digital I/O, Ethernet	Rear panel 15 pin D-SUB. Optional accessories: 3706-BAN, 3706-BKPL, 3706-TLK	Banana jacks (4)	Banana jacks (4)	Banana jacks (4)
Special Features	Delta mode and differential conductance with Model 6220 or 6221. Pulsed I-V with Model 6221. Analog output. IEEE-488. RS-232.	Controls Model 2182A for low-power resistance and I-V measurements.	Dry circuit. Offset compensation. Plug-in switch/relay modules. USB. LXI Class B/Ethernet with IEEE-1588 protocol. Digital I/O.	Dry circuit. Offset compensation. DMM. IEEE-488. RS-232. Digital I/O. Plug-in modules.	Dry circuit. Offset compensation. DMM. IEEE-488. RS-232. Plug-in scanner cards.	8½ digits. DMM. Plug-in scanner cards.

NOTES

1. Lowest resistance measurable with better than 10% accuracy.
2. Highest resistance measurable with better than 1% accuracy.
3. Delta mode, offset voltage compensation with external current source. 10nΩ if used with 5A test current with Model 2440.

2182A

Nanovoltmeter

The two-channel Model 2182A Nanovoltmeter is optimized for making stable, low noise voltage measurements and for characterizing low resistance materials and devices reliably and repeatably. It provides higher measurement speed and significantly better noise performance than alternative low voltage measurement solutions.

The Model 2182A represents the next step forward in Keithley nanovoltmeter technology, replacing the original Model 2182 and offering enhanced capabilities including pulse capability, lower measurement noise, faster current reversals, and a simplified delta mode for making resistance measurements in combination with a reversing current source, such as the Model 6220 or 6221.

- **Make low noise measurements at high speeds, typically just 15nV p-p noise at 1s response time, 40–50nV p-p noise at 60ms**
- **Delta mode coordinates measurements with a reversing current source at up to 24Hz with 30nV p-p noise (typical) for one reading. Averages multiple readings for greater noise reduction**
- **Synchronization to line provides 110dB NMRR and minimizes the effect of AC common-mode currents**
- **Dual channels support measuring voltage, temperature, or the ratio of an unknown resistance to a reference resistor**
- **Built-in thermocouple linearization and cold junction compensation**

Flexible, Effective Speed/Noise Trade-offs

The Model 2182A makes it easy to choose the best speed/filter combination for a particular application's response time and noise level requirements. The ability to select from a wide range of response times allows optimizing speed/noise trade-offs. Low noise levels are assured over a wide range of useful response times, e.g., 15nV p-p noise at 1s and 40-50nV p-p noise at 60ms are typical. **Figure 1** illustrates the Model 2182A's noise performance.

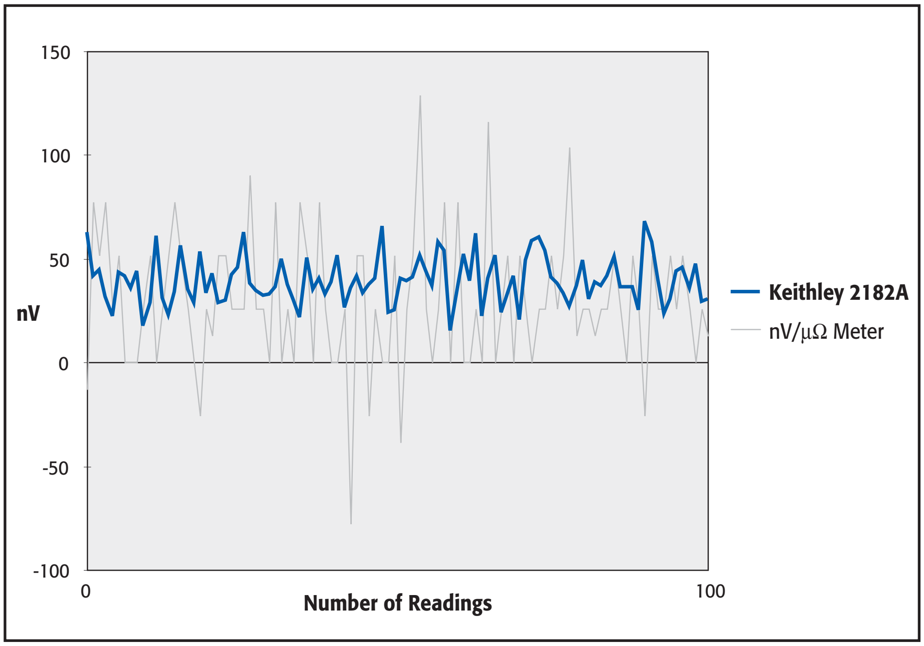


Figure 1. Compare the Model 2182A's DC noise performance with a nanovolt/micro-ohm-meter's. All the data shown was taken at 10 readings per second with a low thermal short applied to the input.

2182A Nanovoltmeter

Ordering Information

2182A Nanovoltmeter

Accessories Supplied

2107-4 Low Thermal Input Cable with spade lugs, 1.2m (4 ft).

User manual, service manual, contact cleaner, line cord, alligator clips.

ACCESSORIES AVAILABLE

2107-30	Low Thermal Input Cable with spade lugs, 9.1m (30 ft)
2182-KIT	Low Thermal Connector with strain relief
2187-4	Low Thermal Test Lead Kit
2188	Low Thermal Calibration Shorting Plug
4288-1	Single Fixed Rack Mount Kit
4288-2	Dual Fixed Rack Mount Kit
7007-1	Shielded GPIB Cable, 1m (3.2 ft)
7007-2	Shielded GPIB Cable, 2m (6.5 ft)
7009-5	Shielded RS-232 Cable, 1.5m (5 ft)
8501-1	Trigger Link Cable, 1m (3.2 ft)
8501-2	Trigger Link Cable, 2m (6.5 ft)
8502	Trigger Link Adapter to 6 female BNC connectors
8503	Trigger Link Cable to 2 male BNC connectors
KPCI-488LPA	IEEE-488 Interface/Controller for the PCI Bus
KUSB-488B	IEEE-488 USB-to-GPIB Interface Adapter

SERVICES AVAILABLE

2182A-3Y-EW	1-year factory warranty extended to 3 years from date of shipment
C/2182A-3Y-ISO	3 (ISO-17025 accredited) calibrations within 3 years of purchase*
TRN-LLM-1-C	Course: Making Accurate Low-Level Measurements

* Not available in all countries

APPLICATIONS

Research

- Determining the transition temperature of superconductive materials
- I-V characterization of a material at a specific temperature
- Calorimetry
- Differential thermometry
- Superconductivity
- Nanomaterials

Metrology

- Intercomparisons of standard cells
- Null meter for resistance bridge measurements

Reliable Results

Power line noise can compromise measurement accuracy significantly at the nanovolt level. The Model 2182A reduces this interference by synchronizing its measurement cycle to line, which minimizes variations due to readings that begin at different phases of the line cycle. The result is exceptionally high immunity to line interference with little or no shielding and filtering required.

Optimized for Use with Model 6220/6221 Current Sources

Device test and characterization for today's very small and power-efficient electronics requires sourcing low current levels, which demands the use of a precision, low current source. Lower stimulus currents produce lower—and harder to measure—voltages across the devices. Linking the Model 2182A Nanovoltmeter with a Model 6220 or 6221 Current Source makes it possible to address both of these challenges in one easy-to-use configuration.

When connected, the Model 2182A and Model 6220 or 6221 can be operated like a single instrument. Their simple connections eliminate the isolation and noise current problems that plague other solutions. The Model 2182A/622X combination allows making delta mode and differential conductance measurements faster and with less noise than the original Model 2182 design allowed. The Model 2182A will also work together with the Model 6221 to make pulse-mode measurements.

The 2182A/622X combination is ideal for a variety of applications, including resistance measurements, pulsed I-V measurements, and differential conductance measurements, providing significant advantages over earlier solutions like lock-in amplifiers or AC resistance bridges. The 2182A/622X combination is also well suited for many nanotechnology applications because it can measure resistance without dissipating much power into the device under test (DUT), which would otherwise invalidate results or even destroy the DUT.

An Easy-to-Use Delta Mode

Keithley originally created the delta mode method for measuring voltage and resistance for the Model 2182 and a triggerable external current source, such as the Model 2400 SourceMeter instrument. Basically, the delta mode automatically triggers the current source to alternate the signal polarity, and then triggers a nanovoltmeter reading at each polarity. This current reversal technique cancels out

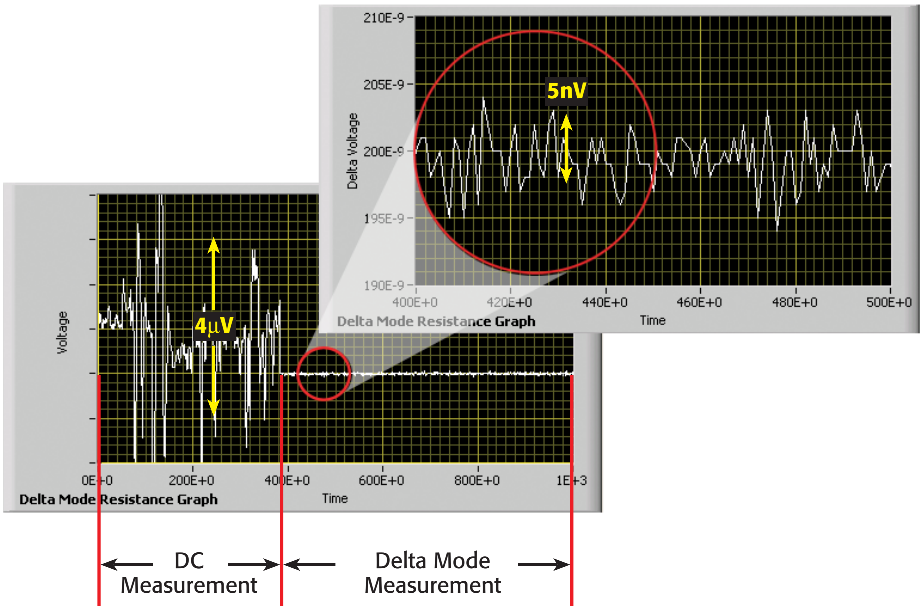


Figure 2. Results from a Model 2182A/6220 using the delta mode to measure a 10mΩ resistor with a 20µA test current. The free Model 6220/6221 instrument control example start-up software used here can be downloaded from www.keithley.com.

any constant thermoelectric offsets, so the results reflect the true value of the voltage being measured. The improved delta mode for the Model 2182A and the Model 622X current sources uses the same basic technique, but the way in which it's implemented has been simplified dramatically. The new technique can cancel thermoelectric offsets that drift over time (not just static offsets), produces results in half the time of the original technique, and allows the current source to control and configure the Model 2182A. Two key presses are all that's required to set up the measurement. The improved cancellation and higher reading rates reduce measurement noise to as little as 1nV.

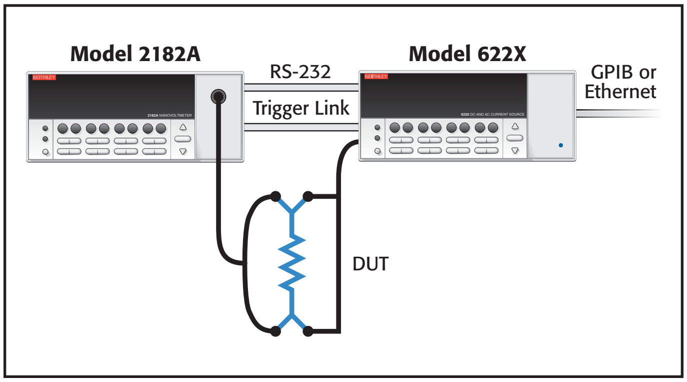


Figure 3. It's simple to connect the Model 2182A to the Model 6220 or 6221 to make a variety of measurements. The instrument control example start-up software available for the Model 622X current sources includes a step-by-step guide to setting up the instrumentation and making proper connections.

Differential Conductance Measurements

Characterizing non-linear tunneling devices and low temperature devices often requires measuring differential conductance (the derivative of a device's I-V curve). When used with a Model 622X current source, the Model 2182A is the industry's fastest, most complete solution for differential conductance measurements, providing 10X the speed and significantly lower noise than other instrumentation options. There's no need to average the results of multiple sweeps, because data can be obtained in a single measurement pass, reducing test time and minimizing the potential for measurement error.

Pulsed Testing with the Model 6221

When measuring small devices, introducing even tiny amounts of heat to the DUT can raise its temperature, skewing test results or even destroying the device. When used with the Model 2182A, the Model 6221's pulse capability minimizes the amount of power dissipated into a DUT. The Model 2182A/6221 combination synchronizes the pulse and measurement. A measurement can begin as soon as 16µs after the Model 6221 applies the pulse. The entire pulse, including a complete nanovolt measurement, can be as short as 50µs.

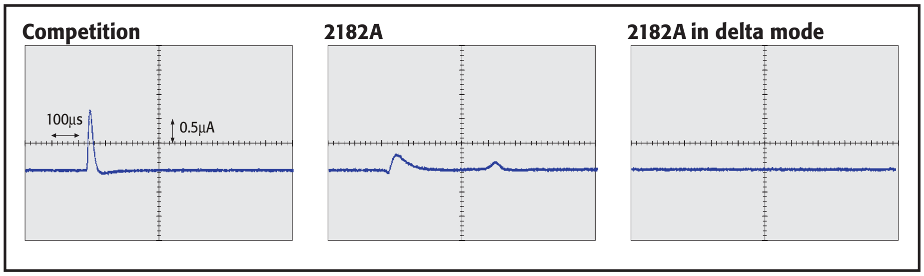


Figure 4. The Model 2182A produces the lowest transient currents of any nanovoltmeter available.

In the delta, differential conductance, and pulse modes, The Model 2182A produces virtually no transient currents, so it's ideal for characterizing devices that can be easily disrupted by current spikes (see **Figure 4**).

Metrology Applications

The Model 2182A combines the accuracy of a digital multimeter with low noise at high speeds for high-precision metrology applications. Its low noise, high signal observation time, fast measurement rates, and 2ppm accuracy provide the most cost-effective meter available today for applications such as intercomparison of voltage standards and direct measurements of resistance standards.

Nanotechnology Applications

The Model 2182A combined with the Model 622X current source or Series 2400 SourceMeter® instrument is a highly accurate and repeatable solution for measuring resistances on carbon nanotube based materials and silicon nanowires.

Research Applications

The Model 2182A's 1nV sensitivity, thermoelectric EMF cancellation, direct display of "true" voltage, ability to perform calculations, and high measurement speed makes it ideal for determining the characteristics of materials such as metals, low resistance filled plastics, and high and low temperature superconductors.

2182A Nanovoltmeter

Three Ways to Measure Nanovolts

DC nanovoltmeters. DC nanovoltmeters and sensitive DMMs both provide low noise DC voltage measurements by using long integration times and highly filtered readings to minimize the bandwidth near DC. Unfortunately, this approach has limitations, particularly the fact that thermal voltages develop in the sample and connections vary, so long integration times don't improve measurement precision. With a noise specification of just 6nV p-p, the Model 2182A is the lowest noise digital nanovoltmeter available.

AC technique. The limitations of the long integration and filtered readings technique have led many people to use an AC technique for measuring low resistances and voltages. In this method, an AC excitation is applied to the sample and the voltage is detected synchronously at the same frequency and an optimum phase. While this technique removes the varying DC component, in many experiments at high frequencies, users can experience problems related to phase shifts caused by spurious capacitance or the L/R time constant. At low frequencies, as the AC frequency is reduced to minimize phase shifts, amplifier noise increases.

The current reversal method. The Model 2182A is optimized for the current reversal method, which combines the advantages of both earlier approaches. In this technique, the DC test current is reversed, then the difference in voltage due to the difference in current is determined. Typically, this measurement is performed at a few hertz (a frequency just high enough for the current to be reversed before the thermal voltages can change). The Model 2182A's low noise performance at measurement times of a few hundred milliseconds to a few seconds means that the reversal period can be set quite small in comparison with the thermal time constant of the sample and the connections, effectively reducing the impact of thermal voltages.

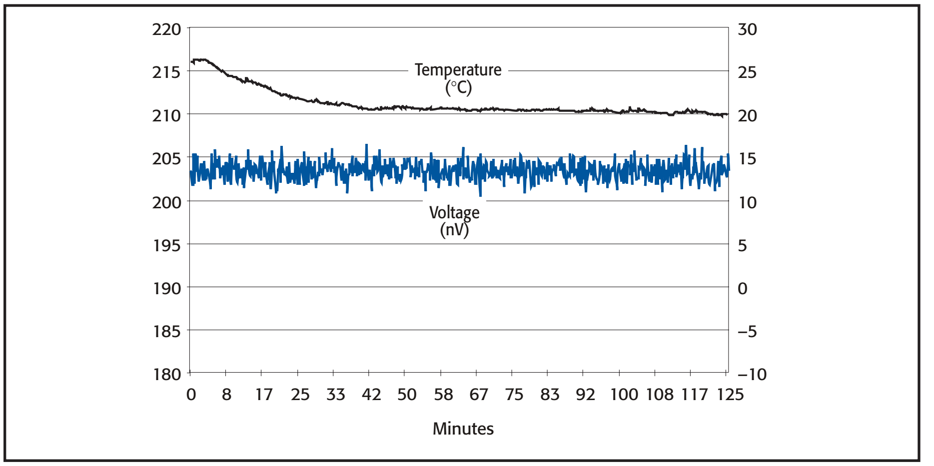


Figure 5. The Model 2182A's delta mode provides extremely stable results, even in the presence of large ambient temperature changes. In this challenging example, the 200nV signal results from a 20µA current sourced by a Model 6221 through a 10mΩ test resistor.

Optional Accessory: Model 2187-4 Low Thermal Test Lead Kit

The standard cabling provided with the Model 2182A Nanovoltmeter and Model 622X Current Sources provides everything normally needed to connect the instruments to each other and to the DUT. The Model 2187-4 Low Thermal Test Lead Kit is required when the cabling provided may not be sufficient for specific applications, such as when the DUT has special connection requirements. The kit includes an input cable with banana terminations, banana extensions, sprung-hook clips, alligator clips, needle probes, and spade lugs to accommodate virtually any DUT. The Model 2187-4 is also helpful when the DUT has roughly 1GΩ impedance or higher. In this case, measuring with the Model 2182A directly across the DUT will lead to loading errors. The Model 2187-4 Low Thermal Test Lead Kit provides a banana cable and banana jack extender to allow the Model 2182A to connect easily to the Model 622X's low impedance guard output, so the Model 2182A can measure the DUT voltage indirectly. This same configuration also removes the Model 2182A's input capacitance from the DUT, so it improves device response time, which may be critical for pulsed measurements.

Figure 6. Model 2187-4 Test Lead Kit

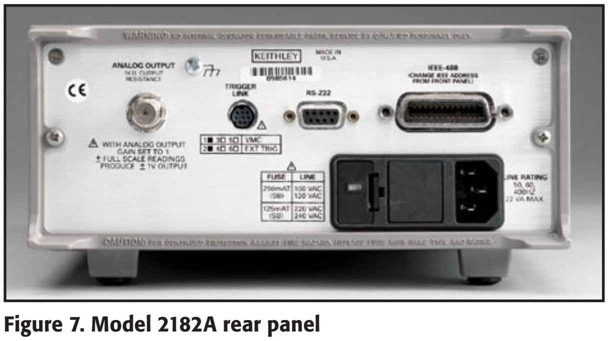


Figure 7. Model 2182A rear panel

2182A Nanovoltmeter

Volts Specifications (20% over range)

CONDITIONS: 1PLC with 10 reading digital filter or 5PLC with 2 reading digital filter.

Channel 1 Range	Resolution	Input Resistance	Accuracy: ±(ppm of reading + ppm of range) (ppm = parts per million) (e.g., 10ppm = 0.001%) 24 Hour[1] T_{CAL} ±1°C	90 Day T_{CAL} ±5°C	1 Year T_{CAL} ±5°C	2 Year T_{CAL} ±5°C	Temperature Coefficient 0°–18°C & 28°–50°C
10.000000 mV[2, 3, 4]	1 nV	>10 GΩ	20 + 4	40 + 4	50 + 4	60 + 4	(1 + 0.5)/°C
100.00000 mV	10 nV	>10 GΩ	10 + 3	25 + 3	30 + 4	40 + 5	(1 + 0.2)/°C
1.0000000 V	100 nV	>10 GΩ	7 + 2	18 + 2	25 + 2	32 + 3	(1 + 0.1)/°C
10.000000 V	1 µV	>10 GΩ	2 + 1[5]	18 + 2	25 + 2	32 + 3	(1 + 0.1)/°C
100.00000 V[4]	10 µV	10 MΩ ±1%	10 + 3	25 + 3	35 + 4	52 + 5	(1 + 0.5)/°C
Channel 2[6, 10]							
100.00000 mV	10 nV	>10 GΩ	10 + 6	25 + 6	30 + 7	40 + 7	(1 + 1)/°C
1.0000000 V	100 nV	>10 GΩ	7 + 2	18 + 2	25 + 2	32 + 3	(1 + 0.5)/°C
10.000000 V	1 µV	>10 GΩ	2 + 1[5]	18 + 2	25 + 2	32 + 3	(1 + 0.5)/°C

CHANNEL 1/CHANNEL 2 RATIO: For input signals ≥1% of the range, Ratio Accuracy = ±{[Channel 1 ppm of Reading + Channel 1 ppm of Range * (Channel 1 Range/Channel 1 Input)] + [Channel 2 ppm of Reading + Channel 2 ppm of Range * (Channel 2 Range/Channel 2 Input)]}.

DELTA (hardware-triggered coordination with Series 24XX, Series 26XXA, or Series 622X current sources for low noise R measurement): Accuracy = accuracy of selected Channel 1 range plus accuracy of I source range.

DELTA MEASUREMENT NOISE WITH 6220 or 6221: Typical 3nVrms/$\sqrt{Hz}$ (10mV range)[21]. 1Hz achieved with 1PLC, delay = 1ms, RPT filter = 23 (20 if 50Hz).

PULSE-MODE (WITH 6221): Line synchronized voltage measurements within current pulses from 50µs to 12ms, pulse repetition rate up to 12Hz.

PULSE MEASUREMENT NOISE (typical rms noise, R_{DUT}<10Ω): ±(0.009ppm of range*) / meas_time / $\sqrt{\text{pulse\_avg\_count}}$ + 3nV** / $\sqrt{(2 \cdot \text{meas\_time} \cdot \text{pulse\_avg\_count})}$ for 10mV range.

* 0.0028ppm for the 100mV range, 0.0016ppm for ranges 1V and above.

** 8nV/$\sqrt{Hz}$ for ranges above 10mV. meas_time (seconds) = pulsewidth – pulse_meas_delay in 33µs incr.

DC Noise Performance[7] (DC noise expressed in volts peak-to-peak)

Response time = time required for reading to be settled within noise levels from a stepped input, 60Hz operation.

Response Time	NPLC, Filter	Range 10 mV	100 mV	1 V	10 V	100 V	NMRR[8]	CMRR[9]
Channel 1								
25.0 s	5, 75	6 nV	20 nV	75 nV	750 nV	75 µV	110 dB	140 dB
4.0 s	5, 10	15 nV	50 nV	150 nV	1.5 µV	75 µV	100 dB	140 dB
1.0 s	1, 18	25 nV	175 nV	600 nV	2.5 µV	100 µV	95 dB	140 dB
667 ms	1, 10 or 5, 2	35 nV	250 nV	650 nV	3.3 µV	150 µV	90 dB	140 dB
60 ms	1, Off	70 nV	300 nV	700 nV	6.6 µV	300 µV	60 dB	140 dB
Channel 2[6, 10]								
25.0 s	5, 75	—	150 nV	200 nV	750 nV	—	110 dB	140 dB
4.0 s	5, 10	—	150 nV	200 nV	1.5 µV	—	100 dB	140 dB
1.0 s	1, 10 or 5, 2	—	175 nV	400 nV	2.5 µV	—	90 dB	140 dB
85 ms	1, Off	—	425 nV	1 µV	9.5 µV	—	60 dB	140 dB

VOLTAGE NOISE VS. SOURCE RESISTANCE[11]

(DC noise expressed in volts peak-to-peak)

Source Resistance	Noise	Analog Filter	Digital Filter
0 Ω	6 nV	Off	100
100 Ω	8 nV	Off	100
1 kΩ	15 nV	Off	100
10 kΩ	35 nV	Off	100
100 kΩ	100 nV	On	100
1 MΩ	350 nV	On	100

TEMPERATURE (Thermocouples)[12]

(Displayed in °C, °F, or K. Accuracy based on ITS-90, exclusive of thermocouple errors.)

TYPE	RANGE	RESOLUTION	ACCURACY 90 Day/1 Year 23° ±5°C Relative to Simulated Reference Junction
J	–200 to +760°C	0.001 °C	±0.2 °C
K	–200 to +1372°C	0.001 °C	±0.2 °C
N	–200 to +1300°C	0.001 °C	±0.2 °C
T	–200 to +400°C	0.001 °C	±0.2 °C
E	–200 to +1000°C	0.001 °C	±0.2 °C
R	0 to +1768°C	0.1 °C	±0.2 °C
S	0 to +1768°C	0.1 °C	±0.2 °C
B	+350 to +1820°C	0.1 °C	±0.2 °C

Operating Characteristics[13, 14]

60Hz (50Hz) Operation

Function	Digits	Readings/s	PLCs
DCV Channel 1, Channel 2, Thermocouple	7.5	3 (2)	5
	7.5[17, 19]	6 (4)	5
	6.5[18, 19]	18 (15)	1
	6.5[18, 19, 20]	45 (36)	1
	5.5[17, 19]	80 (72)	0.1
	4.5[16, 17, 19]	115 (105)	0.01
Channel 1/Channel 2 (Ratio), Delta with 24XX, Scan	7.5	1.5 (1.3)	5
	7.5[17, 19]	2.3 (2.1)	5
	6.5[18]	8.5 (7.5)	1
	6.5[18, 20]	20 (16)	1
	5.5[17]	30 (29)	0.1
	4.5[17]	41 (40)	0.01
Delta with 622X	6.5	47 (40.0)[22]	1

System Speeds[13, 15]

RANGE CHANGE TIME:[14] <40 ms (<50 ms).
FUNCTION CHANGE TIME:[14] <45 ms (<55 ms).
AUTORANGE TIME:[14] <60 ms (<70 ms).
ASCII READING TO RS-232 (19.2K Baud): 40/s (40/s).
MAX. INTERNAL TRIGGER RATE:[16] 120/s (120/s).
MAX. EXTERNAL TRIGGER RATE:[16] 120/s (120/s).

2182A Nanovoltmeter

Measurement Characteristics

A/D LINEARITY: ±(0.8ppm of reading + 0.5ppm of range).

FRONT AUTOZERO OFF ERROR
- **10mV–10V:** Add ±(8ppm of range + 500µV) for <10 minutes and ±1°C.
- NOTE: Offset voltage error does not apply for Delta Mode.

AUTOZERO OFF ERROR
- **10mV:** Add ±(8ppm of range + 100nV) for <10 minutes and ±1°C.
- **100mV–100V:** Add ±(8ppm of range + 10µV) for <10 minutes and ±1°C.
- NOTE: Offset voltage error does not apply for Delta Mode.

INPUT IMPEDANCE
- **10mV–10V:** >10GΩ, in parallel with <1.5nF (Front Filter ON).
- **10mV–10V:** >10GΩ, in parallel with <0.5nF (Front Filter OFF).
- **100V:** 10MΩ ±1%.

DC INPUT BIAS CURRENT: <60pA DC at 23°C, –10V to 5V. <120pA @ 23°C, 5V to 10V.

COMMON MODE CURRENT: <50nA p-p at 50Hz or 60Hz.

INPUT PROTECTION: 150V peak to any terminal. 70V peak Channel 1 LO to Channel 2 LO.

CHANNEL ISOLATION: >10GΩ.

EARTH ISOLATION: 350V peak, >10GΩ and <150pF any terminal to earth. Add 35pF/ft with Model 2107 Low Thermal Input Cable.

Analog Output

MAXIMUM OUTPUT: ±1.2V.

ACCURACY: ±(0.1% of output + 1mV).

OUTPUT RESISTANCE: 1kΩ ±5%.

GAIN: Adjustable from 10^{-9} to 10^{6}. With gain set to 1, a full range input will produce a 1V output.

OUTPUT REL: Selects the value of input that represents 0V at output. The reference value can be either programmed value or the value of the previous input.

Triggering and Memory

WINDOW FILTER SENSITIVITY: 0.01%, 0.1%, 1%, 10%, or full scale of range (none).

READING HOLD SENSITIVITY: 0.01%, 0.1%, 1%, or 10% of reading.

TRIGGER DELAY: 0 to 99 hours (1ms step size).

EXTERNAL TRIGGER DELAY: 2ms + <1ms jitter with auto zero off, trigger delay = 0.

MEMORY SIZE: 1024 readings.

Math Functions

Rel, Min/Max/Average/Std Dev/Peak-to-Peak (of stored reading), Limit Test, %, and mX+b with user-defined units displayed.

Remote Interface

Keithley 182 emulation.

GPIB (IEEE-488.2) and RS-232C.

SCPI (Standard Commands for Programmable Instruments).

GENERAL

POWER SUPPLY: 100V/120V/220V/240V.

LINE FREQUENCY: 50Hz, 60Hz, and 400Hz, automatically sensed at power-up.

POWER CONSUMPTION: 22VA.

MAGNETIC FIELD DENSITY: 10mV range 4.0s response noise tested to 500 gauss.

OPERATING ENVIRONMENT: Specified for 0° to 50°C. Specified to 80% RH at 35°C.

STORAGE ENVIRONMENT: –40° to 70°C.

EMC: Complies with European Union Directive 89/336/EEC (CE marking requirement), FCC part 15 class B, CISPR 11, IEC 801-2, IEC-801-3, IEC 801-4.

SAFETY: Complies with European Union Directive 73/23/EEC (low voltage directive); meets EN61010-1 safety standard. Installation category I.

VIBRATION: MIL-T-28800E Type III, Class 5.

WARM-UP: 2.5 hours to rated accuracy.

DIMENSIONS: Rack Mounting: 89mm high × 213mm wide × 370mm deep (3.5 in × 8.375 in × 14.563 in). **Bench Configuration (with handles and feet):** 104mm high × 238mm wide × 370mm deep (4.125 in × 9.375 in ×14.563 in).

SHIPPING WEIGHT: 5kg (11 lbs).

NOTES

1. Relative to calibration accuracy.
2. With Analog Filter on, add 20ppm of reading to listed specification.
3. When properly zeroed using REL function. If REL is not used, add 100nV to the range accuracy.
4. Specifications include the use of ACAL function. If ACAL is not used, add 9ppm of reading/°C from T_{CAL} to the listed specification. T_{CAL} is the internal temperature stored during ACAL.
5. For 5PLC with 2-reading Digital Filter. Use ±(4ppm of reading + 2ppm of range) for 1PLC with 10-reading Digital Filter.
6. Channel 2 must be referenced to Channel 1. Channel 2 HI must not exceed 125% (referenced to Channel 1 LO) of Channel 2 range selected.
7. Noise behavior using 2188 Low Thermal Short after 2.5 hour warm-up. ±1°C. Analog Filter off. Observation time = 10× response time or 2 minutes, whichever is less.
8. For L_{SYNC} On, line frequency ±0.1%. If L_{SYNC} Off, use 60dB.
9. For 1kΩ unbalance in LO lead. AC CMRR is 70dB.
10. For Low Q mode On, add the following to DC noise and range accuracy at stated response time: 200nV p-p @ 25s, 500nV p-p @ 4.0s, 1.2µV p-p @ 1s, and 5µV p-p @ 85ms.
11. After 2.5 hour warm-up, ±1°C, 5PLC, 2 minute observation time, Channel 1 10mV range only.
12. For Channel 1 or Channel 2, add 0.3°C for external reference junction. Add 2°C for internal reference junction.
13. Speeds are for 60Hz (50Hz) operation using factory defaults operating conditions (*RST). Autorange Off, Display Off, Trigger Delay = 0, Analog Output off.
14. Speeds include measurements and binary data transfer out the GPIB. Analog Filter On, 4 readings/s max.
15. Auto Zero Off, NPLC = 0.01.
16. 10mV range, 80 readings/s max.
17. Sample count = 1024, Auto Zero Off.
18. For L_{SYNC} On, reduce reading rate by 15%.
19. For Channel 2 Low Q mode Off, reduce reading rate by 30%.
20. Front Auto Zero off, Auto Zero off.
21. Applies to measurements of room temperature resistances <10Ω, Isource range ≤20µA.
22. Display off, delay 1ms.

6220
6221

DC Current Source
AC and DC Current Source

6220 and 6221

- **Source and sink (programmable load) 100fA to 100mA**
- **$10^{14}\Omega$ output impedance ensures stable current sourcing into variable loads**
- **65000-point source memory allows executing comprehensive test current sweeps directly from the current source**
- **Built-in RS-232, GPIB, Trigger Link, and digital I/O interfaces**
- **Reconfigurable triax output simplifies matching the application's guarding requirements**
- **Model 220 emulation mode eliminates need to reprogram existing applications**

6221 Only

- **Source AC currents from 4pA to 210mA peak to peak for AC characterization of components and materials. The 6221's 10MHz output update rate generates smooth sine waves up to 100kHz**
- **Built-in standard and arbitrary waveform generators with 1mHz to 100kHz frequency range. Applications include use as a complex programmable load or sensor signal and for noise emulation**
- **Programmable pulse widths as short as 5µs, limiting power dissipation in delicate components. Supports pulsed I-V measurements down to 50µs when used with Model 2182A Nanovoltmeter**
- **Built-in Ethernet interface for easy remote control without a GPIB controller card**

The Model 6220 DC Current Source and Model 6221 AC and DC Current Source combine ease of use with exceptionally low current noise. Low current sourcing is critical to applications in test environments ranging from R&D to production, especially in the semiconductor, nanotechnology, and superconductor industries. High sourcing accuracy and built-in control functions make the Models 6220 and 6221 ideal for applications like Hall measurements, resistance measurements using delta mode, pulsed measurements, and differential conductance measurements.

The need for precision, low current sourcing. Device testing and characterization for today's very small and power-efficient electronics requires sourcing low current levels, which demands the use of a precision, low current source. Lower stimulus currents produce lower—and harder to measure—voltages across the device. Combining the Model 6220 or 6221 with a Model 2182A Nanovoltmeter makes it possible to address both of these challenges.

AC current source and current source waveform generator. The Model 6221 is the only low current AC source on the market. Before its introduction, researchers and engineers were forced to build their own AC current sources. This cost-effective source provides better accuracy, consistency, reliability, and robustness than "home-made" solutions. The Model 6221 is also the only commercially available current source waveform generator, which greatly simplifies creating and outputting complex waveforms.

Simple programming. Both current sources are fully programmable via the front panel controls or from an external controller via RS-232 or GPIB interfaces; the Model 6221 also features an Ethernet interface for remote control from anywhere there's an Ethernet connection. Both instruments can source DC currents from 100fA to 105mA; the Model 6221 can also source AC currents from 4pA to 210mA peak to peak. The output voltage compliance of either source can be set from 0.1V to 105V in 10mV steps. Voltage compliance (which limits the amount of voltage applied when sourcing a current) is critical for applications in which overvoltages could damage the device under test (DUT).

Drop-in replacement for the Model 220 current source. These instruments build upon Keithley's popular Model 220 Programmable Current Source; a Model 220 emulation mode makes it easy to replace a Model 220 with a Model 6220/6221 in an existing application without rewriting the control code.

Define and execute current ramps easily. Both the Models 6220 and 6221 offer tools for defining current ramps and stepping through predefined sequences of up to 65,536 output values using a trigger or a timer. Both sources support linear, logarithmic, and custom sweeps.

APPLICATIONS

- **Nanotechnology**
  - **Differential conductance**
  - **Pulsed sourcing and resistance**
- **Optoelectronics**
  - **Pulsed I-V**
- **Replacement for AC resistance bridges (when used with Model 2182A)**
  - **Measuring resistance with low power**
- **Replacement for lock-in amplifiers (when used with Model 2182A)**
  - **Measuring resistance with low noise**

6220
6221

DC Current Source
AC and DC Current Source

Ordering Information

6220 DC Precision Current Source

6221 AC and DC Current Source

6220/2182A Complete Delta Mode System, w/DC Current Source, Nanovoltmeter, and all necessary cables (GPIB cables not included)

6221/2182A Complete Delta Mode System, w/AC and DC Current Source, Nanovoltmeter, and all necessary cables (GPIB cables not included)

Accessories Supplied

237-ALG-2	6.6 ft (2m), Low Noise, Input Cable with Triax-to-Alligator Clips
8501-2	6.6 ft (2m) Trigger Link Cable to connect 622x to 2182A
CA-180-3A	Ethernet Crossover Cable (6221 only)
CA-351	Communication Cable between 2182A and 622x
CS-1195-2	Safety Interlock Connector

Instruction manual on CD

Getting Started manual (hardcopy)

Software (downloadable)

ACCESSORIES AVAILABLE

7006-*	GPIB Cable with Straight-On Connector
7007-1	Shielded IEEE-488 Cable, 1m (3.3 ft)
7007-2	Shielded IEEE-488 Cable, 2m (6.6 ft)
7078-TRX-5	5 ft (1.5m), Low Noise, Triax-to-Triax Cable (Male on Both Ends)
KPCI-488LPA	IEEE-488 Interface/Controller for the PCI Bus
KUSB-488B	IEEE-488 USB-to-GPIB Interface Adapter

SERVICES AVAILABLE

6220-3Y-EW	1-year factory warranty extended to 3 years from date of shipment
6221-3Y-EW	1-year factory warranty extended to 3 years from date of shipment
C/6220-3Y-ISO	3 (ISO-17025 accredited) calibrations within 3 years of purchase*
C/6221-3Y-ISO	3 (ISO-17025 accredited) calibrations within 3 years of purchase*

*Not available in all countries

The Model 6221's combination of high source resolution and megahertz update rates makes it capable of emulating high fidelity current signals that are indistinguishable from analog current ramps.

Free Instrument Control Example Start-up Software

The instrument control example software available for the sources simplifies both performing basic sourcing tasks and coordinating complex measurement functions with the Keithley Model 2182A. The software, developed in the LabVIEW® programming environment, includes a step-by-step measurement guide that helps users set up their instruments and make proper connections, as well as program basic sourcing functions. The advanced tools in the package support delta mode, differential conductance, and pulse mode measurements. From this package, users can print out the instrument commands for any of the pre-programmed functions, which provides a starting point for incorporating these functions into customized applications.

Differential Conductance

Differential conductance measurements are among the most important and critical measurements made on non-linear tunneling devices and on low temperature devices. Mathematically, differential conductance is the derivative of a device's I-V curve. The Model 6220 or 6221, combined with the Model 2182A Nanovoltmeter, is the industry's most complete solution for differential conductance measurements. Together, these instruments are also the fastest solution available, providing 10× the speed and significantly lower noise than other options. Data can be obtained in a single measurement pass, rather than by averaging the result of multiple sweeps, which is both time-consuming and prone to error. The Model 622X and Model 2182A are also easy to use because the combination can be treated as a single instrument. Their simple connections eliminate the isolation and noise current problems that plague other solutions.

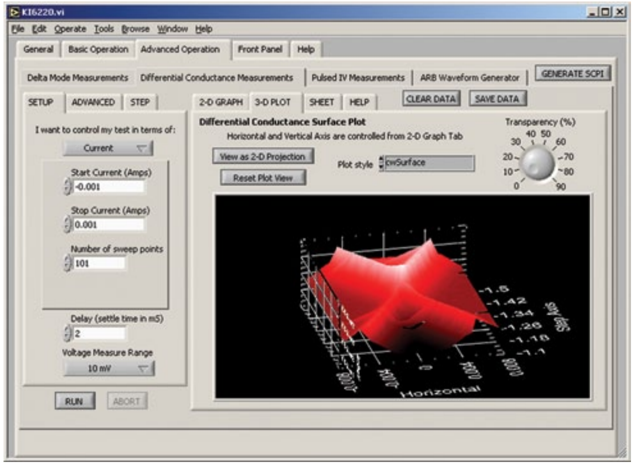


Figure 1. Perform, analyze, and display differential conductance measurements.

Delta Mode

Keithley originally developed the delta mode method for making low noise measurements of voltages and resistances for use with the Model 2182 Nanovoltmeter and a triggerable external current source. Essentially, the delta mode automatically triggers the current source to alternate the signal polarity, then triggers a nanovoltmeter reading at each polarity. This current reversal technique cancels out any constant thermoelectric offsets, ensuring the results reflect the true value of the voltage.

This same basic technique has been incorporated into the Model 622X and Model 2182A delta mode, but its implementation has been dramatically enhanced and simplified. The technique can now cancel thermoelectric offsets that drift over time, produce results in half the time of the previous technique, and allow the source to control and configure the nanovoltmeter, so setting up the measurement takes just two key presses. The improved cancellation and higher reading rate reduces measurement noise to as little as 1nV.

DC Current Source
AC and DC Current Source

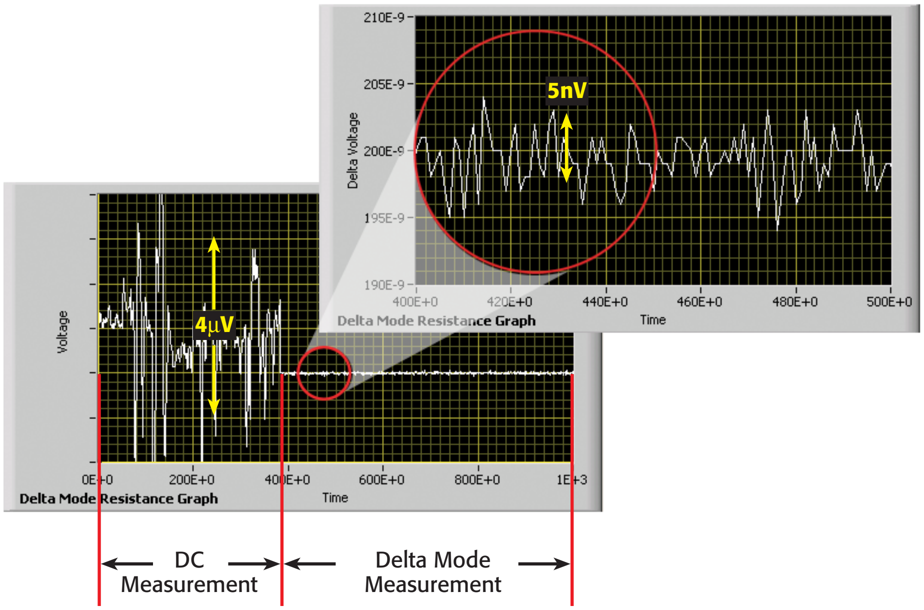


Figure 2. Delta mode offers 1000-to-1 noise reduction.

The delta mode enables measuring low voltages and resistances accurately. Once the Model 622X and the Model 2182A are connected properly, the user simply presses the current source's Delta button, followed by the Trigger button, which starts the test. The Model 622X and the Model 2182A work together seamlessly and can be controlled via the GPIB interface (GPIB or Ethernet with the Model 6221). The free example control software available for the Model 622X includes a tutorial that "walks" users through the delta mode setup process.

Pulsed Tests

Even small amounts of heat introduced by the measurement process itself can raise the DUT's temperature, skewing test results or even destroying the device. The Model 6221's pulse measurement capability minimizes the amount of power dissipated into a DUT by offering maximum flexibility when making pulsed measurements, allowing users to program the optimal pulse current amplitude, pulse interval, pulse width, and other pulse parameters.

The Model 6221 makes short pulses (and reductions in heat dissipation) possible with microsecond rise times on all ranges. The Model 6221/2182A combination synchronizes the pulse and measurement—a measurement can begin as soon as 16μs after the Model 6221 applies the pulse. The entire pulse, including a complete nanovolt measurement, can be as short as 50μs. Line synchronization between the Model 6221 and Model 2182A eliminates power line related noise.

Standard and Arbitrary Waveform Generator

The Model 6221 is the only low current AC source on the market. It can be programmed to generate both basic waveforms (sine, square, triangle, and ramp) and customizable waveforms with an arbitrary waveform generator (ARB) that supports defining waveforms point by point. It can generate waveforms at frequencies ranging from 1mHz to 100kHz at an output update rate of 10 megasamples/second.

Performance Superior to AC Resistance Bridges and Lock-In Amplifiers

The Model 622X/2182A combination provides many advantages over AC resistance bridges and lock-in amplifiers, including lower noise, lower current sourcing, lower voltage measurements, less power dissipation into DUTs, and lower cost. It also eliminates the need for a current pre-amplifier.

Models 6220 and 6221 vs. Homemade Current Sources

Many researchers and engineers who need a current source attempt to get by with a voltage source and series resistor instead. This is often the case when an AC current is needed. This is because, until the introduction of the Model 6220/6221, no AC current sources were available on the market. However, homemade current sources have several disadvantages vs. true current sources:

- **Homemade Current Sources Don't Have Voltage Compliance.** You may want to be sure the voltage at the terminals of your homemade "current source" never exceeds a certain limit (for example, 1–2V in the case of many optoelectronic devices). The most straightforward way to accomplish this is to reduce the voltage source to that level. This requires the series resistor to be reduced to attain the desired current. If you want to program a different current, you must change the resistor while the voltage is held constant! Another possibility is to place a protection circuit in parallel with the DUT. These do not have precise voltage control and always act as a parallel device, stealing some of the programmed current intended for the DUT.
- **Homemade Current Sources Can't Have Predictable Output.** With a homemade "current source" made of a voltage source and series resistor, the impedance of the DUT forms a voltage divider. If the DUT resistance is entirely predictable, the current can be known, but if the DUT resistance is unknown or changes, as most devices do, then the current isn't a simple function of the voltage applied. The best way to make the source predictable is to use a very high value series resistor (and accordingly high voltage source), which is in direct contradiction with the need for compliance.

  While it's possible to know (if not control) the actual current coming from such an unpredictable source, this also comes at a cost. This can be done with a supplemental measurement of the current, such as using a voltmeter to measure the voltage drop across the series resistor. This measurement can be used as feedback to alter the voltage source or simply recorded. Either way, it requires additional equipment, which adds complexity or error. To make matters worse, if the homemade current source is made to be moderately predictable by using a large series resistor, this readback would require using an electrometer to ensure accuracy.

DC Current Source
AC and DC Current Source

The Model 6221 can also expand the capabilities of lock-in amplifiers in applications that already employ them. For example, its clean signals and its output synchronization signal make it an ideal output source for lock-in applications such as measuring second and third harmonic device response.

Model 2182A Nanovoltmeter

The Model 2182A expands upon the capabilities of Keithley's original Model 2182 Nanovoltmeter. Although the Model 6220 and 6221 are compatible with the Model 2182, delta mode and differential conductance measurements require approximately twice as long to complete with the Model 2182 as with the Model 2182A. Unlike the Model 2182A, the Model 2182 does not support pulse mode measurements.

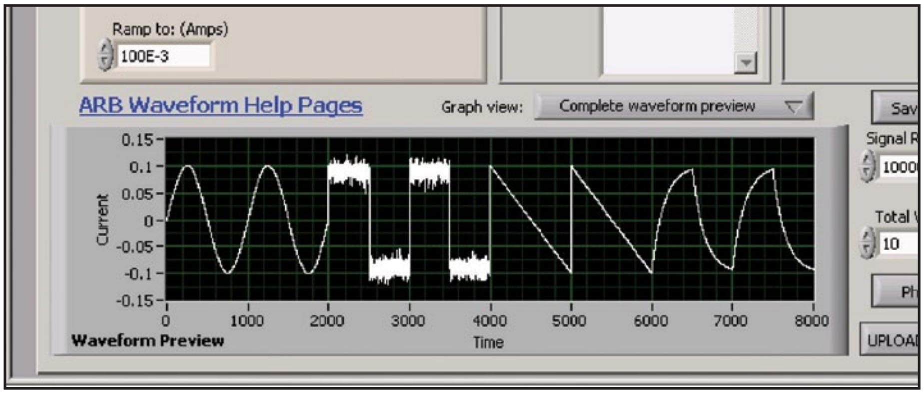


Figure 4. The Model 6221 and the free example start-up control software make it easy to create complex waveforms by adding, multiplying, stringing together, or applying filters to standard wave shapes.

APPLICATIONS OF 622X/2182A COMBINATION:

- Easy instrument coordination and intuitive example software simplifies setup and operation in many applications.
- Measure resistances from 10nΩ to 100MΩ. One measurement system for wide ranging devices.
- Low noise alternative to AC resistance bridges and lock-in amplifiers for measuring resistances.
- Coordinates pulsing and measurement with pulse widths as short as 50µs (6221 only).
- Measures differential conductance up to 10× faster and with lower noise than earlier solutions allow. Differential conductance is an important parameter in semiconductor research for describing density of states in bulk material.
- Delta mode reduces noise in low resistance measurements by a factor of 1000.
- For low impedance Hall measurements, the delta mode operation of the Model 622X/2182A combination provides industry-leading noise performance and rejection of contact potentials. For higher impedance Hall measurements (greater than 100MΩ), the Model 4200-SCS can replace the current source, switching, and multiple high impedance voltage measurement channels. This provides a complete solution with pre-programmed test projects.

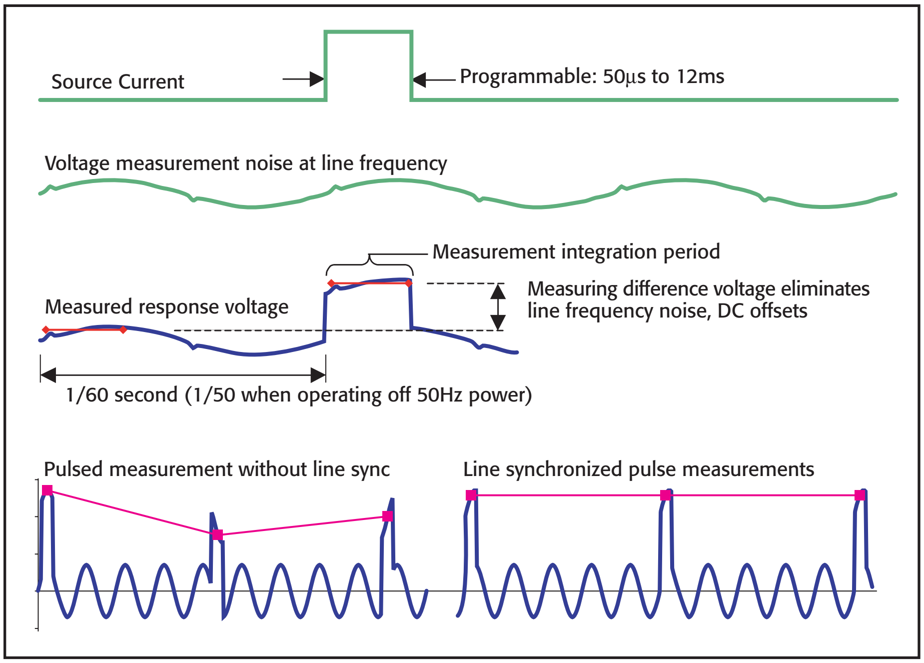


Figure 3. Measurements are line synchronized to minimize 50/60Hz interference.

6220
6221

DC Current Source
AC and DC Current Source

Source Specifications

					6221 Only		Settling Time [1, 2] (1% of Final Value)	
Range (+5% over range)	Accuracy (1 Year) 23°C ±5°C ±(% rdg. + amps)	Programming Resolution	Temperature Coefficient/°C 0°–18°C & 28°–50°C	Typical Noise (peak-peak)/RMS [3] 0.1Hz–10Hz	Typical Noise (peak-peak)/RMS [3] 10Hz–(Bw)	Output Response Bandwidth (BW) Into Short	Output Response Fast (Typical[3]) (6221 Only)	6220, 6221 with Output Response Slow (Max.)
2 nA	0.4 % + 2 pA	100 fA	0.02 % + 200 fA	400 / 80 fA	250 / 50 pA	10 kHz	90 µs	100 µs
20 nA	0.3 % + 10 pA	1 pA	0.02 % + 200 fA	4 / 0.8 pA	250 / 50 pA	10 kHz	90 µs	100 µs
200 nA	0.3 % + 100 pA	10 pA	0.02 % + 2 pA	20 / 4 pA	2.5 / 0.5 nA	100 kHz	30 µs	100 µs
2 µA	0.1 % + 1 nA	100 pA	0.01 % + 20 pA	200 / 40 pA	25 / 5.0 nA	1 MHz	4 µs	100 µs
20 µA	0.05% + 10 nA	1 nA	0.005% + 200 pA	2 / 0.4 nA	500 / 100 nA	1 MHz	2 µs	100 µs
200 µA	0.05% + 100 nA	10 nA	0.005% + 2 nA	20 / 4 nA	1.0 / 0.2 µA	1 MHz	2 µs	100 µs
2 mA	0.05% + 1 µA	100 nA	0.005% + 20 nA	200 / 40 nA	5.0 / 1 µA	1 MHz	2 µs	100 µs
20 mA	0.05% + 10 µA	1 µA	0.005% + 200 nA	2 / 0.4 µA	20 / 4.0 µA	1 MHz	2 µs	100 µs
100 mA	0.1 % + 50 µA	10 µA	0.01 % + 2 µA	10 / 2 µA	100 / 20 µA	1 MHz	3 µs	100 µs

ADDITIONAL SOURCE SPECIFICATIONS

OUTPUT RESISTANCE: >$10^{14}\Omega$ (2nA/20nA range).

OUTPUT CAPACITANCE: <10pF, <100pF Filter ON (2nA/20nA range).

LOAD IMPEDANCE: Stable into 10µH typical, 100µH for 6220, or for 6221 with Output Response SLOW.

VOLTAGE LIMIT (Compliance): Bipolar voltage limit set with single value. 0.1V to 105V in 0.01V programmable steps.

MAX. OUTPUT POWER: 11W, four quadrant source or sink operation.

GUARD OUTPUT ACCURACY: ±1mV for output currents <2mA (excluding output lead voltage drop).

PROGRAM MEMORY: Number of Locations: 64K. Offers point-by-point control and triggering, e.g. sweeps.

MAX. TRIGGER RATE: 1000/s.

RMS NOISE 10Hz–20MHz (2nA–20mA Range): Less than 1mVrms, 5mVp-p (into 50Ω load).

SOURCE NOTES

1. Settling times are specified into a resistive load, with a maximum resistance equal to $2V/I_{full\ scale}$ of range. See manual for other load conditions.
2. Settling times to 0.1% of final value are typically <2× of 1% settling times.
3. Typical values are non warranted, apply at 23°C, represent the 50th percentile, and are provided solely as useful information.

2182A MEASUREMENT FUNCTIONS

DUT RESISTANCE: Up to 1GΩ (1ns) (100MΩ limit for pulse mode).

DELTA MODE RESISTANCE MEASUREMENTS AND DIFFERENTIAL CONDUCTANCE: Controls Keithley Model 2182A Nanovoltmeter at up to 24Hz reversal rate (2182 at up to 12Hz).

PULSE MEASUREMENTS (6221 ONLY):

Pulse Widths: 50µs to 12ms, 1pA to 100mA.

Repetition Interval: 83.3ms to 5s.

ARBITRARY FUNCTION GENERATOR (6221 only)

WAVEFORMS: Sine, Square, Ramp, and 4 user defined arbitrary waveforms.

FREQUENCY RANGE: 1mHz to 100kHz.[5]

FREQUENCY ACCURACY[4]: ±100ppm (1 year).

SAMPLE RATE: 10 MSPS.

AMPLITUDE: 4pA to 210mA peak-peak into loads up to $10^{12}\Omega$.

AMPLITUDE RESOLUTION: 16 bits (including sign).

AMPLITUDE ACCURACY (<10kHz): [5]

Magnitude: ±(1% rdg + 0.2% range).

Offset: ±(0.2% rdg + 0.2% range).

SINE WAVE CHARACTERISTICS:

Amplitude Flatness: Less than 1dB up to 100kHz.[6]

SQUARE WAVE CHARACTERISTICS:

Overshoot: 2.5% max.[6]

Variable Duty Cycle: [4] Settable to 1µs min. pulse duration, 0.01% programming resolution.

Jitter (RMS): 100ns + 0.1% of period.[6]

RAMP WAVE CHARACTERISTICS:

Linearity: <0.1% of peak output up to 10kHz.[6]

ARBITRARY WAVE CHARACTERISTICS:

Waveform Length: 2 to 64K points.

Jitter (RMS): 100ns + 0.1% of period.[6]

WAVEFORM NOTES

4. Minimum realizable duty cycle is limited by current range response and load impedance.
5. Amplitude accuracy is applicable into a maximum resistive load of $2V/I_{full\ scale}$ of range. Amplitude attenuation will occur at higher frequencies dependent upon current range and load impedance.
6. These specifications are only valid for the 20mA range and a 50Ω load.

GENERAL

COMMON MODE VOLTAGE: 250V rms, DC to 60Hz.

COMMON MODE ISOLATION: >$10^{9}\Omega$, <2nF.

SOURCE OUTPUT MODES: Fixed DC level, Memory List.

REMOTE INTERFACE:

IEEE-488 and RS-232C.

SCPI (Standard Commands for Programmable Instruments).

DDC (command language compatible with Keithley Model 220).

PASSWORD PROTECTION: 11 characters.

DIGITAL INTERFACE:

Handler Interface: Start of test, end of test, 3 category bits, +5V@300mA supply.

Digital I/O: 1 trigger input, 4 TTL/Relay Drive outputs (33V@500mA, diode clamped).

OUTPUT CONNECTIONS:

Teflon insulated 3-lug triax connector for output.

Banana safety jack for GUARD, OUTPUT LO.

Screw terminal for CHASSIS.

DB-9 connector for EXTERNAL TRIGGER INPUT, OUTPUT, and DIGITAL I/O.

Two position screw terminal for INTERLOCK.

INTERLOCK: Maximum 10Ω external circuit impedance.

POWER SUPPLY: 100V to 240V rms, 50–60Hz.

POWER CONSUMPTION: 120VA.

ENVIRONMENT:

For Indoor Use Only: Maximum 2000m above sea level.

Operating: 0°–50°C, 70%R.H. up to 35°C. Derate 3% R.H./°C, 35°–50°C.

Storage: –25°C to 65°C, guaranteed by design.

EMC: Conforms to European Union Directive 89/336/EEC, EN 61326-1.

SAFETY: Conforms to European Union Directive 73/23/EEC, EN61010-1.

VIBRATION: MIL-PRF-28800F Class 3, Random.

WARMUP: 1 hour to rated accuracies.

Passive Cooling: No fan.

DIMENSIONS:

Rack Mounting: 89mm high × 213mm wide × 370mm deep (3.5 in. × 8.375 in. × 14.563 in.).

Bench Configuration (with handle and feet): 104mm high × 238mm wide × 370mm deep (4.125 in. × 9.375 in. × 14.563 in.).

Series 3700A

System Switch/Multimeter and Plug-In Cards

- **Combines the functions of a system switch and a high performance multimeter**
- **LXI Class B compliance with IEEE 1588 time synchronization**
- **3½- to 7½-digit measurement resolution**
- **Embedded Test Script Processor (TSP®) offers unparalleled system automation, throughput, and flexibility**
- **Extended low ohms (1Ω) range with 100nΩ resolution**
- **Extended low current (10µA) range with 1pA resolution**
- **>14,000 readings/second**
- **Low noise, <0.1ppm rms noise on 10VDC range**
- **Expanded dry circuit range (2kΩ)**
- **Four-wire open lead detection (source and sense lines)**

For more information about Series 3700A systems, see page 136.

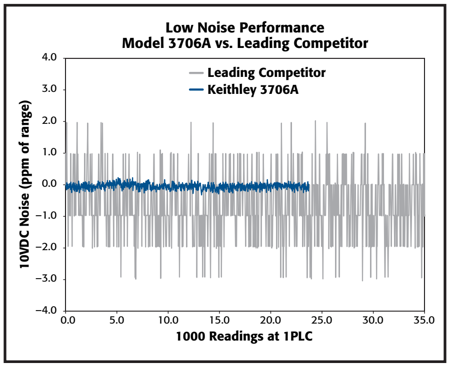
A Series 3700A system combines the functionality of an instrument grade relay switching system with a high performance multimeter. Integrating the multimeter within the mainframe ensures you of a high quality signal path from each channel to the multimeter. This tightly integrated switch and measurement system can meet the demanding application requirements of a functional test system or provide the flexibility needed in stand-alone data acquisition and measurement applications. It is ideal for multiple pin count applications where relay switching can be used to connect multiple devices to source and measurement instruments.

The high performance multimeter in the Series 3700A offers low noise, high stability 3½- to 7½-digit readings for leading-edge measurement performance. This flexible resolution supplies a DC reading rate from >14,000 readings/second at 3½ digits to 60 readings/second at 7½ digits, offering customers maximum reading throughput and accuracy. The multimeter also provides an expanded low ohms (1Ω) range, low current (10µA) range, and dry circuit (1Ω to 1kΩ) range, extending utility beyond typical DMM applications.

The multimeter supports 13 built-in measurement functions, including: DCV, ACV, DCI, ACI, frequency, period, two-wire ohms, four-wire ohms, three-wire RTD temperature, four-wire RTD temperature, thermocouple temperature, thermistor temperature, and continuity. In-rack calibration is supported, which reduces both maintenance and calibration time. Onboard memory can store up to 650,000 readings, and the USB device port provides easy transfer of data to memory sticks.

Single-Channel Reading Rates

Resolution	DCV/ 2-Wire Ohms	4-Wire Ohms
7½ Digits (1 NPLC)	60	29
6½ Digits (0.2 NPLC)	295	120
5½ Digits (0.06 NPLC)	935	285
4½ Digits (0.006 NPLC)	6,200	580
3½ Digits (0.0005 NPLC)	14,000	650



Compare the Model 3706A's 10V DC noise and speed performance with that of the leading competitor. All the data was taken at 1PLC with a low thermal short applied to the input, which resulted in 10× lower noise and 7× faster measurements for the Model 3706A.

APPLICATIONS

- **System- and rack-level signal referencing**
- **Power supply burn-in testing (PC, network, telecom)**
- **Low ohms testing (contacts, connectors, relays)**
- **Temperature profiling**
- **Plant/environment monitoring and control**
- **Automotive and aerospace systems**
- **Consumer product certification/ testing laboratories**

Technical Information

Low Current/High Resistance Measurements

An ammeter is an instrument for measuring electric current flow, calibrated in amperes. There are two main types of ammeter architectures: shunt ammeters and feedback ammeters.

Shunt vs. Feedback Ammeters

Shunt ammeters are the most common type and work in many applications; feedback ammeters are more appropriate when measuring small currents; their use is growing because the typical magnitude of the test currents used today is decreasing. However, choosing the proper ammeter depends not only on the magnitude of the current, but also on characteristics (most typically, the impedance) of the device under test (DUT).

Shunt Ammeters: DMMs

Shunt ammeters are the most common ammeter type and are found in almost all digital multimeters (DMMs). These meters measure current by developing a voltage at the input terminal that is proportional to the current being measured (**Figure 1**).

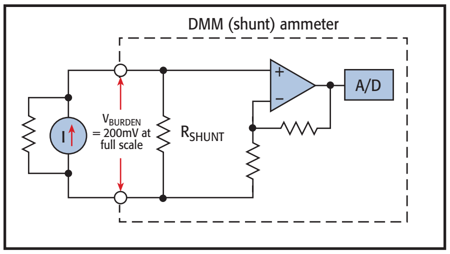


Figure 1

The main drawback associated with shunt ammeters is their fundamentally high input impedance design. This drawback becomes more significant with decreasing current, because a larger shunt resistor must be used in order to develop a measurable voltage. However, as long as the shunt resistor is significantly smaller than the resistance of the DUT and the currents to be measured are not very small (not much lower than microamp level [10^{-6}A]), shunt ammeters work fine.

Voltage Burden

The terminal voltage of an ammeter is called the voltage burden. This voltage burden developed across the meter could result in significantly lower current through the load than before the meter was inserted, therefore, the ammeter can't read the current it was intended to measure.

An ideal ammeter would not alter the current flowing in the circuit path, so it would have zero resistance and zero voltage burden. A real ammeter will always introduce a non-zero voltage burden. In general, the error term caused by an ammeter is stated as the ammeter's voltage burden divided by the resistance of the DUT. A shunt ammeter's voltage burden is typically on the order of hundreds of millivolts.

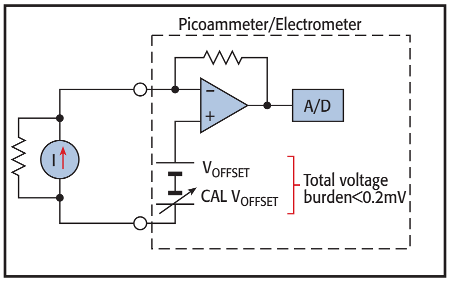


Figure 2

Feedback Ammeter

Feedback ammeters are closer to "ideal" than shunt ammeters, and should be used for current measurements of microamps or less (10^{-6}A) or where it is especially critical to have an ammeter with low input impedance. Instead of developing a voltage across the terminals of the ammeter, a feedback ammeter develops a voltage across the feedback path of a high gain operational amplifier (**Figure 2**). This voltage is also proportional to the current to be measured; however, it is no longer observed at the input of the instrument, but only through the output voltage of the op-amp. The input voltage is equal to the output voltage divided by the op-amp gain (typically 100,000), so the voltage burden has now typically been reduced to microvolts. The feedback ammeter architecture results in low voltage burden, so it produces less error when measuring small currents and when measuring currents generated by low impedance devices. Keithley electrometers and picoammeters employ feedback ammeter technology.

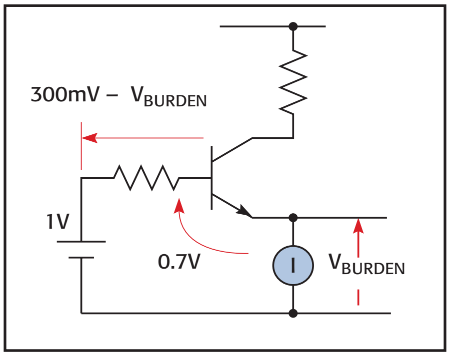


Figure 3

Figure 3 illustrates the problems caused by high voltage burden when measuring the emitter current of a transistor. Even though the basic current measurement could be well within the measuring capability of the DMM, the DMM's voltage burden significantly reduces the voltage applied to the DUT, resulting in lower measured emitter current than intended. If a picoammeter or electrometer were used instead, the voltage burden would cause a negligible change in emitter current.

Sources of Generated Current Error

Low current measurements are subject to a number of error sources that can have a serious impact on measurement accuracy. All ammeters will generate some small current that flows even when the input is open. These offset currents can be partially nulled by enabling the instrument current suppress. External leakage currents are additional sources of error; therefore, making properly guarded and/or shielded connections is important. The source impedance of the DUT will also affect the noise performance of the ammeter. In addition, there are other extraneous generated currents in the test system that could add to the desired current, causing errors. The following paragraphs discuss various types of generated currents and how to minimize their impact on the measurements.

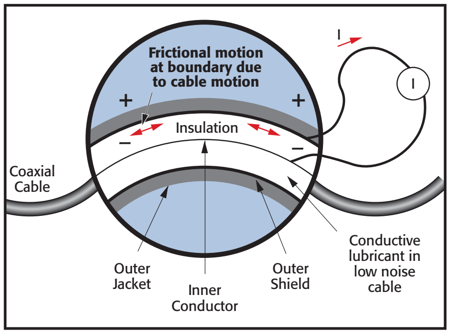


Figure 4

Triboelectric effects are created by charge imbalance due to frictional effects between a conductor and an insulator, as shown in **Figure 4**. Keithley's low noise cables greatly reduce this effect by introducing an inner insulator of polyethylene coated with graphite underneath the outer shield. The graphite provides lubrication and a conducting equipotential cylinder to equalize charges and minimize the charge generated.

Piezoelectric currents are generated when mechanical stress is applied to certain crystalline materials when used for insulated terminals and interconnecting hardware. In some plastics, pockets of stored charge cause the material to behave in a manner similar to piezoelectric materials. An example of a terminal with a piezoelectric insulator is shown in **Figure 5**. To minimize the current due to this effect, remove mechanical stresses from the insulator and use insulating materials with minimal piezoelectric and stored charge effects.

Technical Information

Low Current/High Resistance Measurements

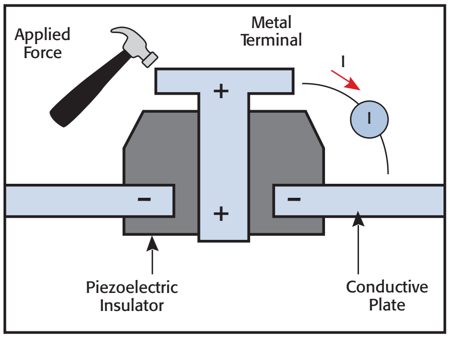


Figure 5

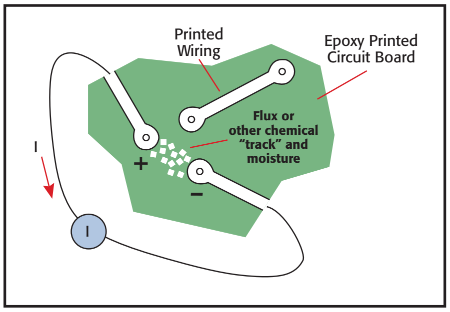


Figure 6

Contamination and humidity can produce error currents, which arise from electrochemical effects that occur when contaminants (in the form of ionic chemicals) create weak "batteries" between two conductors on a circuit board. For example, commonly used epoxy printed circuit boards, if not thoroughly cleaned of etching solution, flux, oils, salts (e.g., fingerprints) or other contaminants, can generate currents of a few nanoamps between conductors (see **Figure 6**). To avoid the effects of contamination and humidity, select insulators that resist water absorption and keep humidity to moderate levels. Also, keep all insulators clean and free of contamination.

Figure 7 summarizes approximate magnitudes of the various currents.

High Resistance Measurements

For high resistance measurements (>1GΩ), a constant voltage is most often applied across the unknown resistance. The resulting current is measured from an ammeter placed in series, and the resistance can be found using Ohm's law (R= V/I). This method of applying a voltage and measuring the current (as opposed to applying a current and measuring the voltage), is preferred for high resistance measurements, because high resistances often change as a function of applied voltage. Therefore, it's important to measure the resistance at a relevant and controllable voltage. This method most often requires measuring low currents using an electrometer or picoammeter. All the low current techniques and error sources described in previous paragraphs also apply here.

Leakage currents are typical sources of error in high resistance measurements. They are generated by unwanted high resistance paths (leakage resistance) between the measurement circuit and nearby voltage sources; they can be reduced by employing proper guarding techniques, using clean, quality insulators, and minimizing humidity.

Typical resistance values of various insulating materials are shown in **Figure 8**. Absorbed moisture may also change the resistance of certain insulators by orders of magnitude. **Table 1** shows a qualitative description of water absorption and other effects.

Alternating Polarity Method

When measuring materials with very high resistivity, background currents may cause significant measurement errors. They may be due to charge stored in the material (dielectric absorption), static or triboelectric charge, or piezoelectric effects.

The Alternating Polarity Method can virtually eliminate the effects of background currents in the sample. In this method, a bias voltage of positive polarity is applied, then the current is measured after a predetermined delay. Next, the polarity is reversed and the current is measured again, using the same delay. The polarity reversal process can be repeated any number of times. The resistance is calculated based on a weighted average of the most recent current measurements.

		PROPERTY		
Volume Resistivity (Ohm-cm)	Material	Resistance to Water Absorption	Minimal Piezoelectric Effects	Minimal Triboelectric Effects
10^{16} – 10^{18}Ω	Sapphire	+	+	0
10^{17} – 10^{18}Ω	Teflon®	+	–	–
10^{14} – 10^{18}Ω	Polyethylene	0	+	0
10^{12} – 10^{18}Ω	Polystyrene	0	0	–
10^{17} – 10^{18}Ω	Kel-F®	+	0	–
10^{12} – 10^{14}Ω	Ceramic	–	0	+
10^{12} – 10^{14}Ω	Nylon	–	0	–
10^{10} – 10^{17}Ω	Glass Epoxy	–	0	–
10^{10} – 10^{15}Ω	PVC	+	0	0
10^{5} – 10^{12}Ω	Phenolic	–	+	+

KEY: + Material very good in regard to the property.
0 Material moderately good in regard to the property.
– Material weak in regard to the property.

Table 1

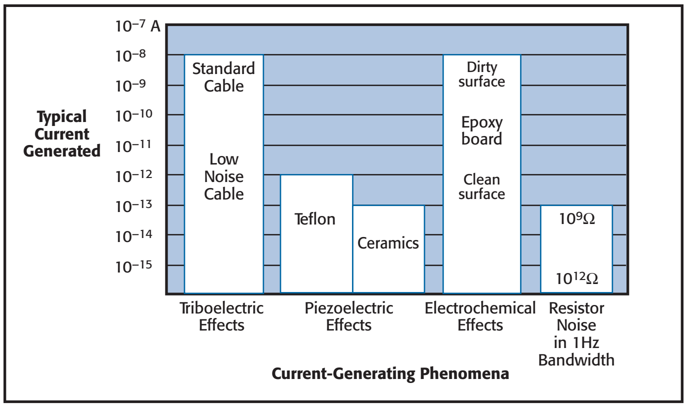


Figure 7

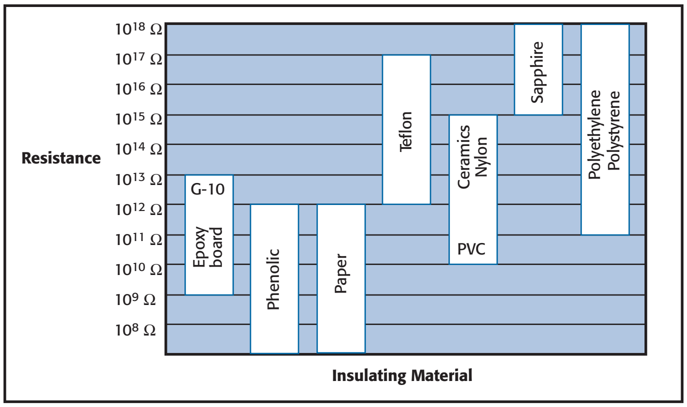


Figure 8

Selector Guide

Low Current/High Resistance Measurements

Selector Guide: Picoammeters, Electrometers, Source Measurement Unit (SMU) Instruments

(Measurement)

	Current Amplifier	Picoammeters			Electrometers		Source Measurement Unit (SMU) Instruments
MODEL	**428-PROG**	**6485**	**6487**	**2502**	**6514**	**6517B**	**6430**
Page	117	107	110	114	119	123	48
CURRENT MEASURE							
From[1]	1.2 fA	20 fA	20 fA	15 fA	<1 fA	<1 fA	400 aA
To	10 mA	20 mA	20 mA	20 mA	20 mA	20 mA	100 mA
VOLTAGE MEASURE							
From[2]					10 μV	10 μV	10 μV
To					200 V	200 V	200 V
RESISTANCE MEASURE[4]							
From[5]			10 Ω		10 Ω	100 Ω	100 μΩ
To[6]			1 PΩ		200 GΩ	10 PΩ[3]	10 PΩ[3]
CHARGE MEASURE							
From[2]					10 fC	10 fC	
To					20 μC	2 μC	
FEATURES							
Input Connection	BNC	BNC	3 Slot Triax	3 Slot Triax	3 Slot Triax	3 Slot Triax	3 Slot Triax
IEEE-488	•	•	•	•	•	•	•
RS-232		•	•	•	•	•	•
Guard					•	•	•
CE	•	•	•	•	•	•	•
Other	2 μs rise time. 10^{11}V/A gain.	5½ digits. Autoranging. 1000 rdg/s.	5½ digits. Built-in 500V source. Alternating voltage method for HI-R sweeps.	5½ digits. Dual channel. Built-in 100V source per channel.	5½ digits. Replaces Models 6512, 617-HIQ.	5½ digits. Built-in ±1kV source. Temperature, RH measurements. Alternating polarity method for HI-R. Plug-in switch cards available. Replaces 6517A.	SourceMeter with Remote PreAmp to minimize cable noise.

NOTES

1. Includes noise.
2. Digital resolution limit. Noise may have to be added.
3. PΩ (Petaohms) = 10^{15}Ω.
4. Resistance is measured with the Model 237 using Source V/Measure I or Source I/Measure V, but not directly displayed.
5. Lowest resistance measurable with better than 1% accuracy.
6. Highest resistance measurable with better than 10% accuracy.

Selector Guide

Low Current/High Resistance Measurements

Selector Guide: Sources and Source Measurement Unit (SMU) Instruments *(Sourcing)*

	Current Sources		Voltage Source	Source Measurement Unit (SMU) Instruments	
MODEL	**6220**	**6221**	**248**	**237**	**6430**
Page	97	97	315	53	48
Current Source	•	•		•	•
Voltage Source			•	•	•
Sink	•	•	•	•	•
CURRENT OUTPUT					
Accuracy[1]	2 pA	2 pA DC 4 pA AC		450 fA	10 fA
Resolution[2]	100 fA	100 fA (DC & AC)		100 fA	50 aA
Maximum	±105 mA	±105 mA		±100 mA	±105 mA
VOLTAGE OUTPUT					
From			±1.5 V	±100 µV	±5 µV
To			±5000 V	±1100 V	±210 V
POWER OUTPUT	11 W	11 W	25 W	11 W	2.2 W
CURRENT LIMIT			5.25 mA	1 pA to 100 mA	1 fA to 105 mA
VOLTAGE LIMIT	105 V	105 V	0 to 5000 V	1 mV to 1100 V	0.2 mV to 210 V
ACCURACY (±Setting)					
I	0.05%	0.05%		0.05%	0.03%
V			0.01%	0.03%	0.02%
FEATURES					
Output Connector	3 Slot Triax	3 Slot Triax	SHV High Voltage Coax	Two 3 Slot Triax	3 Slot Triax
Ethernet		•			
RS-232	•	•			•
IEEE-488	•	•	•	•	•
Memory	65,000 pt.	65,000 pt.		1000 pt.	2500 pt.
Remote Sense				•	•
Current Source Guard	•	•		•	•
CE	•	•	•	•	•
Other	Controls 2182A for low-power resistance and I-V measurements.	AC and DC current source. ARB waveforms up to 100kHz. Controls 2182A like 6220, adds pulsed I-V.	Voltage monitor output. Programmable voltage limit.	Source/measure capability. Pulse mode. High speed. Built-in waveforms.	

1. Best absolute accuracy of source.
2. Resolution for lowest range, smallest change in current that source can provide.

6485

Picoammeter

- **Cost-effective low current measurement solution**
- **10fA resolution**
- **5½-digit resolution**
- **<200µV burden voltage**
- **Up to 1000 readings/second**
- **Built-in Model 485 emulation mode**
- **IEEE-488 and RS-232 interfaces**
- **Analog output**

The 5½-digit Model 6485 Picoammeter combines Keithley's expertise in sensitive current measurement instrumentation with enhanced speed and a robust design. With eight current measurement ranges and high speed autoranging, this cost-effective instrument can measure currents from 20fA to 20mA, taking measurements at speeds up to 1000 readings per second.

The Model 6485's 10fA resolution and superior sensitivity make it well suited for characterizing low current phenomena, while its 20mA range lets it measure currents high enough for applications such as measuring 4-20mA sensor loops.

Although it employs the latest current measurement technology, it is significantly less expensive than other instruments that perform similar functions, such as optical power meters, competitive picoammeters, or user-designed solutions. With a price that's comparable to a general purpose DMM, the Model 6485 makes picoamp-level measurements affordable for virtually any laboratory or production floor.

Low Voltage Burden and Higher Accuracy

While DMMs typically employ shunt ammeter circuitry to measure current, the Model 6485 is a feedback picoammeter. This design reduces voltage burden by several orders of magnitude, resulting in a voltage burden of less than 200µV on the lower measurement ranges. The low voltage burden makes the Model 6485 function much more like an ideal ammeter than a DMM, so it can make current measurements with high accuracy, even in circuits with very low source voltages.

	Model 485	Model 6485
Current Ranges	2nA–2mA	2nA–20mA
Voltage Burden	200µV	200µV (1mV on 20mA range)
Reading Rate	3/s	1000/s
Digits	4½	5½
Analog Output	Yes	Yes
Battery Option	Yes	No
Storage Buffer	100 points	2500 points

Successor to the Model 485

The Model 6485 builds on the strengths of one of Keithley's most popular picoammeters, the Model 485, offering an additional 20mA measurement range, as well as much higher measurement speeds. With a top speed of up to 1000 readings per second, the Model 6485 is the fastest picoammeter Keithley has ever made. It offers ten times greater resolution than the Model 485 on every range. A time-stamped 2500-reading data buffer provides minimum, maximum, and standard deviation statistics. A built-in emulation mode simplifies upgrading existing applications originally configured with a Model 485. This emulation mode makes it possible to control the Model 6485 with any custom code written to control the Model 485. Refer to the comparison table for additional information.

When do you need a picoammeter?

Measuring low DC currents often demands a lot more than a digital multimeter (DMM) can deliver. Generally, DMMs lack the sensitivity required to measure currents less than 100nA. Even at higher currents, a DMM's input voltage drop (voltage burden) of hundreds of millivolts can make accurate current measurements impossible. Electrometers can measure low currents very accurately, but the circuitry needed to measure extremely low currents, combined with functions like voltage, resistance, and charge measurement, can increase an electrometer's cost significantly. The Model 6485 Picoammeter combines the economy and ease of use of a DMM with low current sensitivity near that of an electrometer.

6485

Picoammeter

Ordering Information

6485	Picoammeter

Accessories Supplied

CAP-18	Protective Shield/ Cap (2-lug)
4801	Low Noise BNC Input Cable, 1.2m (4 ft)

APPLICATIONS

- Beam monitoring and radiation monitoring
- Leakage current testing in insulators, switches, relays, and other components
- SEM beam current measurements
- Galvanic coupling measurements
- Optoelectronic device testing and characterization
- Optical fiber alignment
- Circuit test and analysis in DCLF circuits
- Sensor characterization
- I-V measurements of semiconductors and other devices
- Nanoelectronic device characterization
- Capacitor leakage
- Teaching labs

Features that Expand Test and Measurement Flexibility

- **Scaled voltage analog output.** This output allows the Model 6485 to transmit measurement results to devices like DMMs, data acquisition boards, oscilloscopes, or strip chart recorders.
- **220V overload protection.** This high overload protection and a robust design let the Model 6485 withstand abusive overflows.
- **One-touch front panel design.** Functions can be configured easily with the push of a button, without complicated function menus.
- **Built-in Trigger Link interface.** The Trigger Link interface simplifies synchronizing the Model 6485 with other instruments and voltage sources. This interface combines six independent selectable trigger lines on a single connector for simple, direct control over all instruments in a system.
- **RS-232 and IEEE-488 interfaces.** These interfaces make it easy to integrate the Model 6485 into automated test and measurement systems.
- **Display on/off switch.** For research on light-sensitive components, such as measuring the dark currents of photodiodes, the front panel display can be switched off to avoid introducing light that could significantly reduce the accuracy of the results.
- **REL and LOG functions.** The Model 6485 can make relative readings with respect to a baseline value or display the logarithm of the absolute value of the measured current.
- **Resistance calculations.** The Model 6485 can calculate resistance by dividing an externally sourced voltage value by the measured current.
- **Rear panel BNC inputs.** Inexpensive, easy-to-use BNC cables can be employed, rather than more expensive triax cables.

ACCESSORIES AVAILABLE

CABLES

4802-10	Low Noise BNC Input Cable, 3m (10 ft)
4803	Low Noise Cable Kit
7007-1	Shielded IEEE-488 Cable, 1m (3.3 ft)
7007-2	Shielded IEEE-488 Cable, 2m (6.6 ft)
7007-4	Shielded IEEE-488 Cable, 4m (13.1 ft)
7009-5	RS-232 Cable
7754-3	BNC to Alligator Cable, 0.9m (3 ft)
8607	Banana Cable set for Analog Output
8501-1	Trigger Link Cable with Male Micro-DIN Connectors at each End, 1m (3.3 ft)
8501-2	Trigger Link Cable with Male Micro-DIN Connectors at each End, 2m (6.6 ft)
8502	Micro-DIN to 6 BNCs Adapter Box. Includes one 8501-1
8503	DIN-to-BNC Trigger Cable

ADAPTERS

CS-565	BNC Barrel
7078-TRX-BNC	Female BNC to 3-Slot Male Triax for connecting BNC cable into triax fixture

RACK MOUNT KITS

4288-1	Single Fixed Rack Mounting Kit
4288-2	Dual Fixed Rack Mounting Kit

GPIB INTERFACES

KPCI-488LPA	IEEE-488 Interface/Controller for the PCI Bus
KUSB-488B	IEEE-488 USB-to-GPIB Interface Adapter

SERVICES AVAILABLE

6485-3Y-EW	1-year factory warranty extended to 3 years from date of shipment
C/6485-3Y-ISO	3 (ISO-17025 accredited) calibrations within 3 years of purchase*
TRN-LLM-1-C	Course: Making Accurate Low-Level Measurements

*Not available in all countries

6485 Picoammeter

Range	5½ Digit Default Resolution	Accuracy (1 Year)[1] ±(% rdg. + offset) 18°–28°C, 0–70% RH	Typical RMS Noise[2]	Analog Rise Time[3] (10% to 90%)
2 nA	10 fA	0.4 % + 400 fA	20 fA	8 ms
20 nA	100 fA	0.4 % + 1 pA	100 fA	8 ms
200 nA	1 pA	0.2 % + 10 pA	1 pA	500 µs
2 µA	10 pA	0.15% + 100 pA	10 pA	500 µs
20 µA	100 pA	0.1 % + 1 nA	100 pA	500 µs
200 µA	1 nA	0.1 % + 10 nA	1 nA	500 µs
2 mA	10 nA	0.1 % + 100 nA	10 nA	500 µs
20 mA	100 nA	0.1 % + 1 µA	100 nA	500 µs

TEMPERATURE COEFFICIENT: 0°–18°C & 28°–50°C. For each °C, add 0.1 × (% rdg + offset) to accuracy spec.

INPUT VOLTAGE BURDEN: <200µV on all ranges except <1mV on 20mA range.

MAXIMUM INPUT CAPACITANCE: Stable to 10nF on all nA ranges and 2µA range; 1µF on 20µA and 200µA ranges, and on mA ranges.

MAXIMUM COMMON MODE VOLTAGE: 42V.

MAXIMUM CONTINUOUS INPUT VOLTAGE: 220 VDC.

ISOLATION (Meter COMMON to chassis): Typically >5×10¹¹Ω in parallel with <1nF.

NMRR[1] (50 or 60Hz): 60dB.

ANALOG OUTPUT: Scaled voltage output (inverting 2V full scale on all ranges) 3% ±2mV, 1kΩ impedance.

NOTES

1. At 1 PLC – limited to 60 rdgs/second under this condition.
2. At 6 PLC, 1 standard deviation, 100 readings, filter off, capped input – limited to 10 rdgs/sec under this condition.
3. Measured at analog output with resistive load >100kΩ.

IEEE-488 BUS IMPLEMENTATION

MULTILINE COMMANDS: DCL, LLO, SDC, GET, GTL, UNT, UNL, SPE, SPD.

IMPLEMENTATION: SCPI (IEEE-488.2, SCPI-1996.0); DDC (IEEE-488.1).

UNILINE COMMANDS: IFC, REN, EOI, SRQ, ATN.

INTERFACE FUNCTIONS: SH1, AH1, T5, TE0, L4, LE0, SR1, RL1, PP0, DC1, DT1, C0, E1.

PROGRAMMABLE PARAMETERS: Range, Zero Check, Zero Correct, EOI (DDC mode only), Trigger, Terminator (DDC mode only), Calibration (SCPI mode only), Display Format, SRQ, REL, Output Format, V-offset Cal.

ADDRESS MODES: TALK ONLY and ADDRESSABLE.

LANGUAGE EMULATION: Keithley Model 485 emulation via DDC mode.

RS-232 IMPLEMENTATION:
- **Supports**: SCPI 1996.0.
- **Baud Rates:** 300, 600, 1200, 2400, 4800, 9600, 19.2k, 38.4k, 57.6k.
- **Protocols:** Xon/Xoff, 7 or 8 bit ASCII, parity-odd/even/none.
- **Connector:** DB-9 TXD/RXD/GND.

GENERAL

INPUT CONNECTOR: BNC on rear panel.

DISPLAY: 12 character vacuum fluorescent.

RANGING: Automatic or manual.

OVERRANGE INDICATION: Display reads "OVRFLOW."

CONVERSION TIME: Selectable 0.01 PLC to 60 PLC (50 PLC under 50Hz operation). (Adjustable from 200µs to 1s)

READING RATE:
To internal buffer: 1000 readings/second[1]
To IEEE-488 bus: 900 readings/second[1, 2]

Notes:
1. 0.01 PLC, digital filters off, front panel off, auto zero off.
2. Binary transfer mode. IEEE-488.1.

BUFFER: Stores up to 2500 readings.

PROGRAMS: Provide front panel access to IEEE address, choice of engineering units or scientific notation, and digital calibration.

EMC: Conforms with European Union Directive 89/336/EEC, EN61326-1.

SAFETY: Conforms with European Union Directive 73/23/EEC, EN61010-1.

TRIGGER LINE: Available, see manual for usage.

DIGITAL FILTER: Median and averaging (selectable from 2 to 100 readings).

ENVIRONMENT:
- **Operating:** 0°–50°C; relative humidity 70% non-condensing, up to 35°C. Above 35°C, derate humidity by 3% for each °C.
- **Storage:** –25° to +65°C.

WARM-UP: 1 hour to rated accuracy (see manual for recommended procedure).

POWER: 100–120V or 220–240V, 50–60Hz, 30VA.

PHYSICAL:
- **Case Dimensions:** 90mm high × 214mm wide × 369mm deep (3½ in. × 8⅜ in. × 14⁹⁄₁₆ in.).
- **Working Dimensions:** From front of case to rear including power cord and IEEE-488 connector: 394mm (15.5 in).
- **Net Weight:** <2.8 kg (<6.1 lbs).
- **Shipping Weight:** <5 kg (<11 lbs).

6487

Picoammeter/Voltage Source

- 10fA resolution
- 5½-digit resolution
- <200µV burden voltage
- Alternating Voltage method ohms measurements
- Automated voltage sweeps for I-V characterization
- Floating measurements up to 500V
- Up to 1000 readings/second
- Built-in Model 486 and 487 emulation mode
- IEEE-488 and RS-232 interfaces
- Analog output
- Digital I/O

The 5½-digit Model 6487 Picoammeter/Voltage Source improves on the measurement capability of the award-winning Model 6485, and adds a high resolution 500V source. It provides higher accuracy and faster rise times than the 6485, as well as a damping function for use with capacitive devices. With eight current measurement ranges and high speed autoranging, this cost-effective instrument can measure currents from 20fA to 20mA, take measurements at speeds up to 1000 readings per second, and source voltage from 200μV to 505V.

The Model 6487's 10fA resolution, superior sensitivity, voltage sweeping, and Alternating Voltage resistance measurements make it well suited for characterizing low current devices. Using the latest current measurement technology, it is significantly less expensive than other instruments that perform similar functions, such as optical power meters, tera-ohmmeters, competitive picoammeters, or user-designed solutions. With a price that's comparable to a high-end DMM, the Model 6487 makes picoamp-level measurements affordable for virtually any laboratory or production floor.

Low Voltage Burden and Higher Accuracy

While DMMs typically employ shunt ammeter circuitry to measure current, the Model 6487 is a feedback picoammeter. This design reduces voltage burden by several orders of magnitude, resulting in a voltage burden of less than 200μV on the lower measurement ranges. The low voltage burden makes the Model 6487 function much more like an ideal ammeter than a DMM, so it can make current measurements with high accuracy, even in circuits with very low source voltages.

Successor to the Model 487

The Model 6487 builds on the strengths of one of Keithley's most popular picoammeters, the Model 487, offering an additional 20mA measurement range, as well as much higher measurement speeds, up to 1000 readings per second. It simplifies device characterization with built-in voltage sweeping capability and the Alternating Voltage method for high resistances. A time-stamped 3000-reading data buffer provides minimum, maximum, and standard deviation statistics. A built-in emulation mode makes it possible to control the Model 6487 with any custom code written to control the Model 487.

	Model 487	Model 6487
Current Ranges	2 nA–2 mA	2 nA–20 mA
Voltage Burden	200 μV	200 μV (1 mV on 20 mA range)
Reading Rate	Up to 180/s	Up to 1000/s
Voltage Sweeps	No	Yes
Alternating Voltage Ohms	No	Yes
Analog Output	Yes (non-inverting)	Yes (inverting)
Storage Buffer	512 points	3000 points
Best V Source Resolution	1 mV	0.2 mV

Features that Expand Test and Measurement Flexibility

- **Direct resistance measurements.** Optimized for resistances from 50Ω to 5×10^{14}Ω using the Source Voltage/Measure Current method.
- **Alternating Voltage method resistance measurements.** This method improves resistance measurements on devices with high background current or high noise. It extends the measurable resistance range up to 10^{16}Ω.
- **500V overload protection.** This high overload protection and a robust design let the Model 6487 tolerate abusive overflows, including accidentally shorting the voltage source directly into the ammeter.

6487

Picoammeter/Voltage Source

Ordering Information

6487	Picoammeter/ Voltage Source

Accessories Supplied

CA-186-1B	Ground Connection Cable, Banana to Screw-Lug
CAP-31	Protective Shield/ Cap (3-lug)
CS-459	Safety Interlock Plug
7078-TRX-3	Low Noise Triax Input Cable, 1m (3 ft)
8607	High Voltage Banana Cable Set for Voltage Source Output

APPLICATIONS

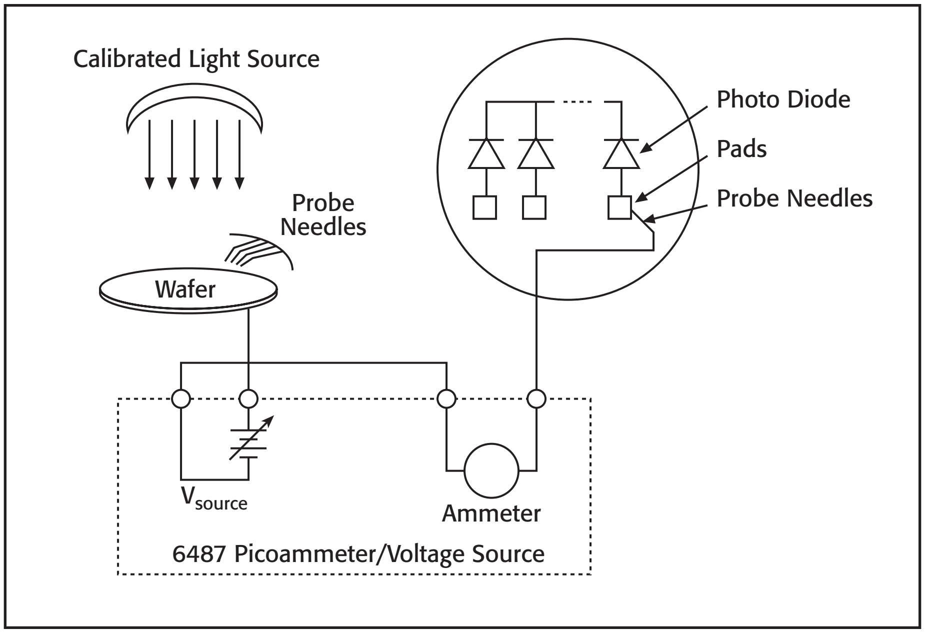
- Resistance/resistivity measurements
- Beam monitoring and radiation monitoring
- Leakage current testing in insulators, switches, relays, and other components
- Galvanic coupling measurements
- I-V characterization on semiconductor and optoelectronic devices
- Fiber alignment
- Circuit test and analysis in DCLF circuits
- Sensor characterization
- Capacitor leakage

- **Rear panel triax input.** This allows the picoammeter to be used in floating operation, up to 500V. When not floating, the addition of a triax to BNC adapter allows inexpensive, easy-to-use BNC cables to be employed, rather than more expensive triaxial cables.
- **RS-232 and IEEE-488 interfaces.** These interfaces make it easy to integrate the Model 6487 into automated test and measurement systems.
- **Scaled voltage analog output.** This output allows the Model 6487 to transmit measurement results to devices like DMMs, data acquisition cards, oscilloscopes, or strip chart recorders.
- **Built-in Trigger Link interface.** The Trigger Link interface simplifies synchronizing the Model 6487 with other instruments and voltage sources. This interface combines six independent selectable trigger lines on a single connector for simple, direct control over all instruments in a system.
- **Display on/off switch.** For research on light-sensitive components, such as measuring the dark currents of photodiodes or I-V measurements on unpackaged semiconductors, the front panel display can be switched off to avoid introducing light that could significantly reduce the accuracy of the results.
- **One-touch front panel design.** Functions can be configured easily with the push of a button, without complicated function menus.

A Broad Range of Low Current Applications

Wafer-Level Photodiode Testing

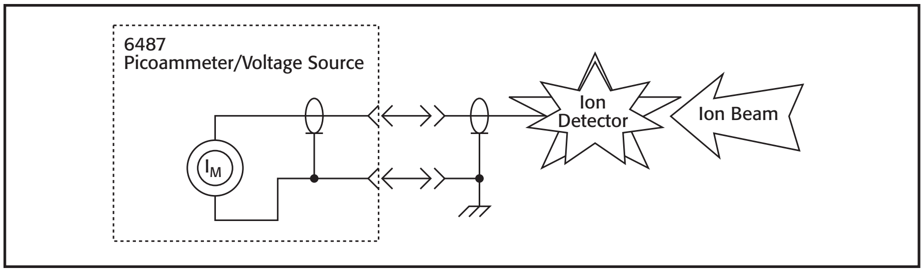
The Model 6487 Picoammeter/Voltage Source can be paired with a calibrated light source and a probing fixture to create a cost-effective photodiode test system. Multiple Model 6487s can be connected to the DUT's probe pads to provide photocurrent readings or, with the addition of a switch matrix, one picoammeter can take current measurements from multiple pads. In the first step of the measurement process, performed in total darkness, the Model 6487 produces a voltage sweep and then measures the resulting dark current. In the second step, a voltage bias is applied and the resulting photocurrent is measured while the light level is increased in calibrated steps. The same basic test configuration can be used for testing positive intrinsic negative (PIN) and avalanche photodiodes (APDs). The 6487's high resolution on the 10V source range provides superior sweeping and biasing when small biases are required. The 500V source capability is necessary to bias APDs.



6487 Picoammeter/Voltage Source

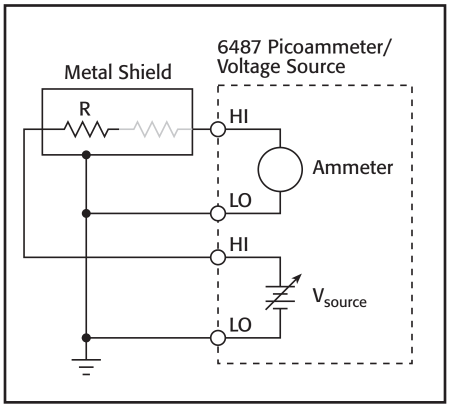
Monitoring and Control of Focused Ion Beam Currents

In semiconductor fabrication, focused ion beam systems are often used for nanometer-scale imaging, micromachining, and mapping. Careful monitoring of the magnitude of the beam current with an ion detector is critical. The ion detector generates a secondary current that's proportional to the current of the primary ion beam. When this secondary current is measured, it can be used to control the intensity of the primary beam. However, this secondary current is very low, often just a few picoamps, so the instrumentation measuring it must provide high measurement accuracy and repeatability, as well as sub-picoamp resolution. The Model 6487's wide measurement range and 5½-digit resolution make it ideal for this application. Signal connections to the Model 6487 are made through the instrument's triax connector. Often, a detector may require high voltage to attract ions, making the 6487's 500V source a necessity.



High Resistance Measurements

The Model 6487 Picoammeter can be used to measure high resistances (>1GΩ) in applications such as insulation resistance testing. A constant voltage is placed in series with the unknown resistance and the picoammeter. The voltage drop across the picoammeter is negligible, so all the voltage appears across the unknown resistance. The resulting current is measured by the picoammeter and the resistance is calculated using Ohm's Law (R = V/I). To prevent generated current due to electrostatic interference, the unknown resistance is housed in a shielded test fixture. A small series resistor may be added to reduce noise if the unknown resistor has high stray capacitance across it.



When do you need a picoammeter?

Measuring low DC currents often demands a lot more than a digital multimeter can deliver. Generally, DMMs lack the sensitivity required to measure currents less than 100nA. Even at higher currents, a DMM's input voltage drop (voltage burden) of hundreds of millivolts can make accurate current measurements impossible. Electrometers can measure low currents very accurately, but the circuitry needed to measure extremely low currents, combined with functions like voltage, resistance, and charge measurement, can increase an electrometer's cost significantly. The Model 6487 Picoammeter/Voltage Source combines the economy and ease of use of a DMM with low current sensitivity near that of an electrometer.

ACCESSORIES AVAILABLE

CABLES

6517-ILC-3	Interlock Cable for 8009 Resistivity Test Fixture
7007-1	Shielded IEEE-488 Cable, 1m (3.3 ft)
7007-2	Shielded IEEE-488 Cable, 2m (6.6 ft)
7007-4	Shielded IEEE-488 Cable, 4m (13.1 ft)
7078-TRX-10	Low Noise Triax Cable, 3.0m (10 ft)
7078-TRX-20	Low Noise Triax Cable, 6.0m (20 ft)
8501-*	Trigger Link Cable with male Micro-DIN connectors at each end, 1m or 2m (3.3 ft or 6.6 ft)

ADAPTERS

237-TRX-BAR	Triax Barrel
7078-TRX-BNC	Triax-to-BNC Adapter

TEST FIXTURES

8009	Resistivity Test Fixture

RACK MOUNT KITS

4288-*	Single or Dual Fixed Rack Mounting Kit

GPIB INTERFACES

KPCI-488LPA	IEEE-488 Interface/Controller for the PCI Bus
KUSB-488B	IEEE-488 USB-to-GPIB Interface Adapter

SERVICES AVAILABLE

6487-3Y-EW	1-year factory warranty extended to 3 years from date of shipment
C/6487-3Y-ISO	3 (ISO-17025 accredited) calibrations within 3 years of purchase*
TRN-LLM-1-C	Course: Making Accurate Low-Level Measurements

*Not available in all countries

Picoammeter/Voltage Source

Range	5½ Digit Default Resolution	Accuracy (1 Year) [1] ±(% rdg. + offset) 18°–28°C, 0–70% RH	Typical RMS Noise [2]	Typical Analog Rise Time (10% to 90%) [3] Damping [4] Off	On
2 nA	10 fA	0.3 % + 400 fA	20 fA	4 ms	80 ms
20 nA	100 fA	0.2 % + 1 pA	20 fA	4 ms	80 ms
200 nA	1 pA	0.15% + 10 pA	1 pA	300 µs	1 ms
2 µA	10 pA	0.15% + 100 pA	1 pA	300 µs	1 ms
20 µA	100 pA	0.1 % + 1 nA	100 pA	110 µs	110 µs
200 µA	1 nA	0.1 % + 10 nA	100 pA	110 µs	110 µs
2 mA	10 nA	0.1 % + 100 nA	10 nA	110 µs	110 µs
20 mA	100 nA	0.1 % + 1 µA	10 nA	110 µs	110 µs

TEMPERATURE COEFFICIENT: 0°–18°C & 28°–50°C. For each °C, add 0.1 × (% rdg + offset) to accuracy spec.

INPUT VOLTAGE BURDEN: <200µV on all ranges except <1mV on 20mA range.

MAXIMUM INPUT CAPACITANCE: Stable to 10nF on all nA ranges and 2µA range; 1µF on 20µA and 200µA ranges, and on mA ranges.

MAXIMUM CONTINUOUS INPUT VOLTAGE: 505 VDC.

NMRR[1]: (50 or 60Hz): 60dB.

ISOLATION (Ammeter Common or Voltage Source to chassis): Typically $>1\times10^{11}\Omega$ in parallel with <1nF.

MAXIMUM COMMON MODE VOLTAGE (between chassis and voltage source or ammeter): 505 VDC.

ANALOG OUTPUT: Scaled voltage output (inverting 2V full scale on all ranges): 2.5% ±2mV.

ANALOG OUTPUT IMPEDANCE[3]: <100Ω, DC–2kHz.

VOLTAGE SOURCE:

Range (Max.)	Step Size (typical)	Accuracy [5] ±(% prog. + offset) 18°–28°C, 0–70% R.H.	Noise (p-p) 0.1–10 Hz	Temperature Coefficient	Typical Rise Time [6, 8] (10%–90%)	Typical Fall Time [7, 8] (90%–10%)
±10.100	200 µV	0.1 % + 1 mV	<50 µV	(0.005% + 20 µV)/°C	250 µs	150 µs
±50.500	1 mV	0.1 % + 4 mV	<150 µV	(0.005% + 200 µV)/°C	250 µs	300 µs
±505.00	10 mV	0.15% + 40 mV	<1.5 mV	(0.008% + 2 mV)/°C	4.5 ms	1 ms

SELECTABLE CURRENT LIMIT: 2.5mA, 250µA, 25µA for 50V and 500V ranges, 25mA additional limit for 10V range. All current limits are –20%/+35% of nominal.

WIDEBAND NOISE [9]: <30mVp-p 0.1Hz–20MHz.

TYPICAL TIME STABILITY: ±(0.003% + 1mV) over 24 hours at constant temperature (within 1°C, between 18°–28°C, after 5 minute settling).

OUTPUT RESISTANCE: <2.5Ω.

VOLTAGE SWEEPS: Supports linear voltage sweeps on fixed source range, one current or resistance measurement per step. Maximum sweep rate: 200 steps per second. Maximum step count 3000. Optional delay between step and measure.

RESISTANCE MEASUREMENT (V/I): Used with voltage source; resistance calculated from voltage setting and measured current. Accuracy is based on voltage source accuracy plus ammeter accuracy. Typical accuracy better than 0.6% for readings between 1kΩ and 1TΩ.

ALTERNATING VOLTAGE RESISTANCE MEASUREMENT: Offers alternating voltage resistance measurements for resistances from $10^9\Omega$ to $10^{15}\Omega$. Alternates between 0V and user-selectable voltage up to ±505V.

NOTES

1. At 1 PLC – limited to 60 rdgs/s under this condition.
2. At 6 PLC, 1 standard deviation, 100 readings, filter off, capped input – limited to 10 rdgs/sec under this condition.
3. Measured at analog output with resistive load >2kΩ.
4. Maximum rise time can be up to 25% greater.
5. Accuracy does not include output resistance/load regulation.
6. Rise Time is from 0V to ± full-scale voltage (increasing magnitude).
7. Fall Time is from ± full-scale voltage to 0V (decreasing magnitude).
8. For capacitive loads, add C·ΔV/ILimit to rise time, and C·ΔV/1mA to fall time.
9. Measured with LO connected to chassis ground.

REMOTE OPERATION

IEEE-488 BUS IMPLEMENTATION: SCPI (IEEE-488.2, SCPI-1996.0); DDC (IEEE-488.1).

LANGUAGE EMULATION: Keithley Model 486/487 emulation via DDC mode.

RS-232 IMPLEMENTATION:
- **Supports:** SCPI 1996.0.
- **Baud Rates:** 300, 600, 1200, 2400, 4800, 9600, 19.2k, 38.4k, 57.6k.
- **Protocols:** Xon/Xoff, 7 or 8 bit ASCII, parity-odd/even/none.
- **Connector:** DB-9 TXD/RXD/GND.

GENERAL

AMMETER INPUT CONNECTOR: Three lug triaxial on rear panel.

ANALOG OUTPUT CONNECTOR: Two banana jacks on rear panel.

VOLTAGE SOURCE OUTPUT CONNECTOR: Two banana jacks on rear panel.

INTERLOCK CONNECTOR: 4 pin DIN.

TRIGGER LINE: Available, see manual for usage.

DISPLAY: 12 character vacuum fluorescent.

DIGITAL FILTER: Median and averaging (selectable from 2 to 100 readings).

RANGING: Automatic or manual.

AUTORANGING TIME[3]: <250ms (analog filter off, 1PLC).

OVERRANGE INDICATION: Display reads "OVRFLOW."

CONVERSION TIME: Selectable 0.01PLC to 60PLC (50PLC under 50Hz operation). (Adjustable from 200µs to 1s)

READING RATE:
- To internal buffer 1000 readings/second[1]
- To IEEE-488 bus 900 readings/second[1, 2]

BUFFER: Stores up to 3000 readings.

PROGRAMS: Provide front panel access to IEEE address, choice of engineering units or scientific notation, and digital calibration.

EMC: Conforms with European Union Directive 89/336/EEC, EN61326-1.

SAFETY: Conforms with European Union Directive 73/23/EEC, EN61010-1, CAT I.

ENVIRONMENT:
- **Operating:** 0°–50°C; relative humidity 70% non-condensing, up to 35°C. Above 35°C, derate humidity by 3% for each °C.
- **Storage:** –10°C to +65°C.

WARM-UP: 1 hour to rated accuracy (see manual for recommended procedure).

POWER: 100–120V or 220–240V, 50–60Hz, (50VA).

PHYSICAL:
- **Case Dimensions:** 90mm high × 214mm wide × 369mm deep (3½ in. × 8⅜ in. × 14⁹⁄₁₆ in.).
- **Working Dimensions:** From front of case to rear including power cord and IEEE-488 connector: 394mm (15.5 inches).

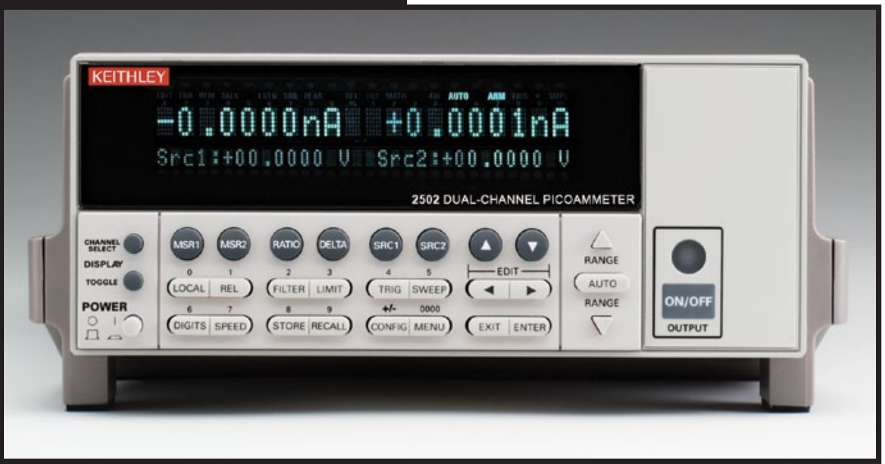
NET WEIGHT: <4.7 kg (<10.3 lbs).

NOTES

1. 0.01PLC, digital filters off, front panel off, auto zero off.
2. Binary transfer mode. IEEE-488.1.
3. Measured from trigger in to meter complete.

2502

Dual-Channel Picoammeter



- Dual-channel instrument for optical power measurements, beam measurements, and nanoscale materials and device research
- ±100V source for bias requirements
- Measure photodetector current from 1fA to 20mA
- 1fA current measurement resolution
- Measure optical power directly when used with Model 2500INT Integrating Sphere
- 0–10V analog output for high resolution optical power feedback
- Provides a high accuracy, high speed fiber alignment solution
- Supports assembly process, final testing, parts binning, and specification
- Allows faster alignment of the fiber with the laser diode's optimum light emitting region
- Combines fiber alignment and device characterization processes
- User-programmable photodetector calibration coefficients
- 3000-point buffer memory on each channel allows data transfer after test completion
- Digital I/O and Trigger Link for binning and sweep test operations
- IEEE-488 and RS-232 interfaces

The Model 2502 Dual-Channel Picoammeter provides two independent picoammeter-voltage source channels for a wide range of low level measurement applications including laser diode testing. The Model 2502 is also designed to increase the throughput of Keithley's LIV (light-current-voltage) test system for production testing of laser diode modules (LDMs). Developed in close cooperation with leading manufacturers of LDMs for fiberoptic telecommunication networks, this dual-channel instrument has features that make it easy to synchronize with other system elements for tight control over optical power measurements. The Model 2502 features a high speed analog output that allows using the LIV test system at the fiber alignment stage of the LDM manufacturing process.

Through the use of buffer memory and a Trigger Link interface that's unique to Keithley instruments, the Model 2502 can offer the fastest throughput available today for LIV testing of laser diode modules. These instruments are ruggedly engineered to meet the reliability and repeatability demands of continuous operation in round-the-clock production environments.

Low-Level, High Speed Measurements

The Model 2502 combines Keithley's expertise in low-level current measurements with high speed current measurement capabilities. Each channel of this instrument consists of a voltage source paired with a high speed picoammeter. Each of the two channels has an independent picoammeter and voltage source with measurements made simultaneously across both channels.

Part of a High Speed LIV Test System

In a laser diode module DC/CW test stand, the Model 2502 provides the voltage bias to both the back facet monitor diode and a Model 2500INT Integrating Sphere or to a fiber-coupled photodetector. At the same time it applies the voltage biases, it measures the current outputs of the two photodetectors and converts these outputs to measurements of optical power. The conversion is performed with the user-programmed calibration coefficient for the wavelength of the laser diode module. Fast, accurate measurements of optical power are critical for analyzing the coupling efficiency and optical power characteristics of the laser diode being tested. When testing modules with multiple detectors, the Model 2502 packs more testing capabilities into less test rack space.

Fiber Alignment

The Model 2502's built-in high speed analog output makes it suitable for precision fiber alignment tasks. This instrument combines the ability to align the optical fiber quickly and accurately with a laser diode's optimum light emitting region and the capability to make precision LIV measurements, all in the same test fixture. The Model 2502's wide dynamic range allows early beam skirt detection, reducing the time required for fiber alignment. An LIV sweep can be performed during the alignment process to optimize fiber location for an entire operating range. High speed feedback minimizes delays in the alignment process, so it's unnecessary to sacrifice alignment speed to ensure accurate device characterization.

Wide Dynamic Measurement Range

The Model 2502 offers low current measurement ranges from 2nA to 20mA in decade steps. This provides for all photodetector current measurement ranges for testing laser diodes and LEDs in applications such as LIV testing, LED total radiance measurements, measurements of cross-talk and insertion loss on optical switches,

Model 2502 rear panel

KEITHLEY

A GREATER MEASURE OF CONFIDENCE

2502

Dual-Channel Picoammeter

Ordering Information

2502 **Dual-Channel Picoammeter**

Accessories Supplied

User's Manual

ACCESSORIES AVAILABLE

7007-1	Shielded IEEE-488 Cable, 1m (3.3 ft)
7007-2	Shielded IEEE-488 Cable, 2m (6.6 ft)
7009-5	Shielded RS-232 Cable
7078-TRX-3	Low Noise Triax Cable, 0.9m (3 ft)
8501-1	Trigger Link Cable, 1m (3.3 ft)
KPCI-488LPA	IEEE-488 Interface/Controller for the PCI Bus
KUSB-488B	IEEE-488 USB-to-GPIB Interface Adapter

SERVICES AVAILABLE

2502-3Y-EW	1-year factory warranty extended to 3 years from date of shipment
C/2502-3Y-DATA	3 (Z540-1 compliant) calibrations within 3 years of purchase*

*Not available in all countries

and many others. The Model 2502 meets industry testing requirements for the transmitter as well as pump laser modules. The extensive current measurement range provides excellent sensitivity and resolution for beam current and radiation monitoring measurements.

APPLICATIONS
- **Scanning electron microscope (SEM) beam measurements**

Production testing of:
- **Laser diode modules**
- **Chip on submount laser diodes**
- **LEDs**
- **Passive optical components**
- **Laser diode bars**
- **Fiber alignment**

High Accuracy Dark Current Measurements

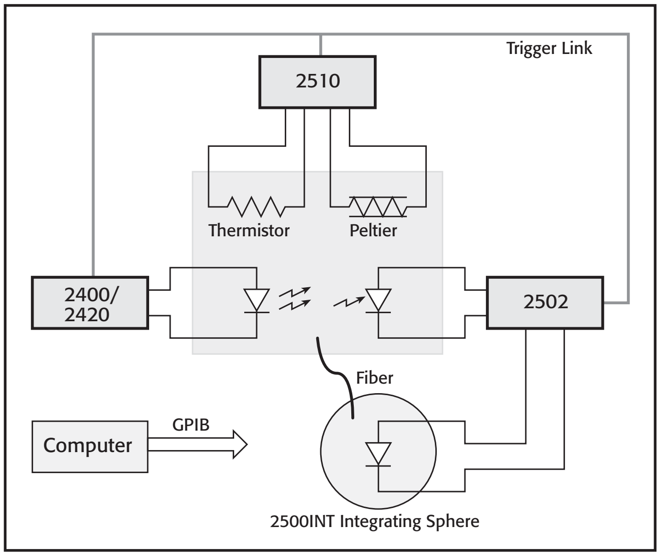
The Model 2502's 2nA current measurement range is ideal for measuring dark currents and other low currents with 1fA resolution. Once the level of dark current has been determined, the instrument's REL function automatically subtracts the dark current as an offset so the measured values are more accurate for optical power measurements.

Voltage Bias Capability

The Model 2502 provides a choice of voltage bias ranges: ±10V or ±100V. This choice gives the system integrator the ability to match the bias range more closely to the type of photodetector being tested, typically ±10V for large area photodetectors and ±100V for avalanche-type photodetectors. This ability to match the bias to the photodetector ensures improved measurement linearity and accuracy. Also, the 100V range provides a source voltage for an SEM target bias supply.

High Testing Throughput

The Model 2502 is capable of taking 900 readings/second per channel at 4½-digit resolution. This speed is comparable with the measurement speed of the Model 2400 SourceMeter instrument, which is often used in conjunction with the Model 2502 to perform optoelectronic device test and characterization. Both instruments support Trigger Link (a proprietary "hardware handshaking" triggering system that's unique to Keithley products) and buffer memory. When programmed to execute a sweep, Trigger Link ensures measurement integrity by keeping the source and measurement functions working in lock step while the buffer memories record the measurements. Together, source memory, buffer memory, and Trigger Link eliminate GPIB traffic during a test sweep, improving test throughput dramatically.



The Model 2502 is designed for tight integration with other Keithley instruments that are often used in LIV test systems for laser diode modules. These other instruments include the Model 2400 SourceMeter® and Model 2510 TEC SourceMeter instruments.

Ratio and Delta Measurements

The Model 2502 can provide ratio or delta measurements between the two completely isolated channels, such as the ratio of the back facet monitor detector to the fiber-coupled photodetector at varying levels of input current. These functions can be accessed via the front panel or the GPIB interface. For test setups with multiple detectors, this capability allows for targeted control capabilities for the laser diode module.

Programmable Limits and Filters

As with most Keithley instruments, the Model 2502's current and voltage limits can be programmed to ensure device protection during critical points such as start of test, etc. These instruments also provide Average and Median filters, which can be applied to the data stored in the buffer memory.

Adaptable to Evolving DUT Requirements

Unlike optical power meters with integrated detectors, the Model 2502 allows the user to choose from a wide range of measurement capabilities simply by selecting an appropriate photodetector and programming the calibration coefficient of this detector at the wavelength of choice.

Interface Options

To speed and simplify system integration and control, the Model 2502 includes the Trigger Link feature and digital I/O lines, as well as standard IEEE-488 and RS-232 interfaces. The Trigger Link feature combines six independent software selectable trigger lines on a single connector for simple, direct control over all instruments in a system. This feature is especially useful for reducing total test time if the test involves a sweep. The Model 2502 can sweep through a series of measurements based on triggers received from other instruments. The digital I/O lines simplify external handler control and binning operations.

The Model 2502 Dual-Channel Picoammeter can measure and display either photodiode current or optical power for two photodiodes with appropriate user-supplied optical power gain/wavelength calibration factors.

The Model 2502 includes an analog output jack on the rear panel for each channel.

Measurement Specifications

Range	Maximum Resolution	Accuracy[1, 2] 23°C ±5°C ±(% rdg. + offset)	Temperature Coefficient 0°–18°C & 28°–50°C ±(%rdg. + offset)/°C	Dc Input Impedance[3] (Maximum)
2.000000 nA	1 fA	1.00% + 2 pA	0.01 + 200 fA	20 kΩ
20.00000 nA	10 fA	0.40% + 2 pA	0.01 + 200 fA	20 kΩ
200.0000 nA	100 fA	0.30% + 200 pA	0.02 + 20 pA	200 Ω
2.000000 µA	1 pA	0.20% + 200 pA	0.02 + 20 pA	200 Ω
20.00000 µA	10 pA	0.10% + 20 nA	0.01 + 2 nA	2.0 Ω
200.0000 µA	100 pA	0.10% + 20 nA	0.01 + 2 nA	2.0 Ω
2.000000 mA	1 nA	0.10% + 2 µA	0.02 + 200 nA	0.2 Ω
20.00000 mA	10 nA	0.10% + 2 µA	0.02 + 200 nA	0.2 Ω

MAXIMUM INPUT: ±20.0mA.

TYPICAL SPEED AND NOISE REJECTION[4]

Digits	Readings/s GPIB (SCPI)	Readings/s GPIB (488.1)	NPLC	NMRR
4½	700	900	0.01	—
5½	460	475	0.1	—
6½	58	58	1	60 dB

PHOTODIODE VOLTAGE BIAS SPECIFICATIONS[2]

Range	Resolution	Accuracy 23°C ±5°C	Maximum Current	Load Regulation[5]	Temperature Coefficient
0 to ±10 V	<400 µV	±(0.15% of setting + 5 mV)	20 mA	< 0.30%, 0 to 20 mA	150 ppm/°C
0 to ±100 V	<4 mV	±(0.3% of setting + 50 mV)	20 mA	< 0.30%, 0 to 20 mA	300 ppm/°C

ANALOG OUTPUT SPECIFICATIONS

OUTPUT VOLTAGE RANGE[9]: Output is inverting: –10V out for positive full scale input.
+10V out for negative full scale input.

OUPUT IMPEDANCE: 1kΩ typical.

Range	Accuracy 23°C ±5°C ±(%output + offset)	Temperature Coefficient 0°–18°C & 28°–50°C ±(%output + offset)/°C	Rise Time Typical (10% to 90%)
2.000000 nA	6.0% + 90 mV	0.30% + 7 mV	6.1 ms
20.00000 nA	3.0% + 9 mV	0.11% + 700 µV	6.1 ms
200.0000 nA	6.0% + 90 mV	0.30% + 4 mV	395 µs
2.000000 µA	3.0% + 9 mV	0.11% + 400 µV	395 µs
20.00000 µA	6.0% + 90 mV	0.30% + 4 mV	135 µs
200.0000 µA	2.5% + 9 mV	0.11% + 400 µV	135 µs
2.000000 mA	6.0% + 90 mV	0.30% + 4 mV	21 µs
20.00000 mA	2.5% + 9 mV	0.11% + 400 µV	21 µs

GENERAL

Typical Noise Floor Measurement Specification[6]

Range	Typical Noise Floor RMS (1 STDEV), 100 Samples: 0.01 NPLC	0.1 NPLC	1.0 NPLC	10 NPLC
2.000000 nA	2 pA	1 pA	40 fA	15 fA
20.00000 nA	2 pA	1 pA	40 fA	15 fA
200.0000 nA	200 pA	100 pA	2 pA	500 fA
2.000000 µA	200 pA	100 pA	2 pA	500 fA
20.00000 µA	20 nA	10 nA	200 pA	50 pA
200.0000 µA	20 nA	10 nA	200 pA	50 pA
2.000000 mA	2 µA	1 µA	25 nA	5 nA
20.00000 mA	2 µA	1 µA	25 nA	5 nA

SOURCE CAPACITANCE: Stable to 10.0nF typical.
INPUT BIAS CURRENT[7]: 50fA max. @ 23°C.
INPUT VOLTAGE BURDEN[8]: 4.0mV max.
VOLTAGE SOURCE SLEW RATE: 3.0ms/V typical.
COMMON MODE VOLTAGE: 200VDC.
COMMON MODE ISOLATION: Typically $10^9\Omega$ in parallel with 150nF.
OVERRANGE: 105% of measurement range.
MEMORY BUFFER: 6000 readings (two 3000 point buffers). Includes selected measured value(s) and time stamp.
PROGRAMMABILITY: IEEE-488 (SCPI-1995.0), RS-232, five user-definable power-up states plus factory default and *RST.
DIGITAL INTERFACE:
Enable: Active low input.
Handler Interface: Start of test, end of test, 3 category bits. +5V @ 300mA supply.
Digital I/O: 1 trigger input, 4 TTL/Relay Drive outputs (33V @ 500mA, diode clamped).
POWER SUPPLY: 100V/120V/220V/240V ±10%.
LINE FREQUENCY: 50, 60Hz.
POWER DISSIPATION: 60VA.
EMC: Complies with European Union Directive 89/336/EEC.
VIBRATION: MIL-T-28800F Random Class 3.
SAFETY: Complies with European Directive 73/23/EEC.
WARM-UP: 1 hour to rated accuracy.
DIMENSIONS: 89mm high × 213mm wide × 370mm deep (3½ in × 8⅜ in × 14⁹⁄₁₆ in). **Bench configuration (with handle and feet):** 104mm high × 238mm wide × 370mm deep (4⅛ in × 9⅜ in × 14⁹⁄₁₆ in).
WEIGHT: 23.1kg (10.5 lbs).
ENVIRONMENT:
Operating: 0°–50°C, 70% R.H. up to 35°C non-condensing. Derate 3% R.H./°C, 35°–50°C.
Storage: –25° to 65°C, non-condensing.

NOTES

1. Speed = Normal (1.0 NPLC), Filter On.
2. 1 year.
3. Measured as ΔVin/ΔIin at full scale (and zero) input currents.
4. Dual channel, internal trigger, measure only, display off, Autorange off, Auto Zero off, source delay = 0, filters off, limits off, CALC5 and CALC6 off, 60Hz.
5. Measured as ΔVin/ΔIin at full scale (20mA) and zero load currents.
6. Noise floor measured as rms (1 standard deviation), 100 samples, Filter off, open (capped) input.
7. Specification by design.
8. Measured (at input triax) as ΔVin at full scale (20mA) vs. zero input currents.
9. The analog output voltage for each channel is referenced to that channel's floating ground.

428-PROG

Programmable Current Amplifier

- **2µs rise time**
- **1.2fA rms noise**
- **Up to 10^{11} V/A gain**
- **IEEE-488 interface**

Ordering Information

428-PROG **Programmable Current Amplifier with IEEE-488 Interface**

ACCESSORIES AVAILABLE

CABLES	
4801	Low Noise BNC Input Cable, 1.2m (4 ft)
7007-1	Shielded IEEE-488 Cable, 1m (3.3 ft)
7007-2	Shielded IEEE-488 Cable, 2m (6.6 ft)
ADAPTERS	
7078-TRX-BNC	3-Slot Male Triax to Female BNC Adapter
KPCI-488LPA	IEEE-488 Interface/Controller for the PCI Bus
KUSB-488B	IEEE-488 USB-to-GPIB Interface Adapter (requires 7010 Adapter)
RACK MOUNTS	
4288-1	Single Fixed Rack Mount Kit
4288-2	Dual Fixed Rack Mount Kit

SERVICES AVAILABLE

428-PROG-3Y-EW	1-year factory warranty extended to 3 years from date of shipment

APPLICATIONS

The Model 428-PROG satisfies a broad range of applications in research and device labs due to its cost-effective ability to amplify fast, low currents. A few of these applications include:

Biochemistry Measurements:
- Ion channel currents through cell walls and membranes

Beam Position Monitoring:
- Used on electron storage rings and synchrotrons

Surface Science Studies:
- Scanning Tunneling Electron Microscope system amplifier
- Observation of secondary electron emission, as in X-ray and beam line currents

Laser and Light Measurements:
- Fast, sensitive amplifier for use with PMTs and photodiodes
- Analysis of fast photoconductive materials
- IR detector amplifier

Transient Phenomena:
- Current DLTS studies
- Breakdown in devices and dielectric materials

The Model 428-PROG Programmable Current Amplifier converts fast, small currents to a voltage, which can be easily digitized or displayed by an oscilloscope, waveform analyzer, or data acquisition system. It uses a sophisticated "feedback current" circuit to achieve both fast rise times and sub-picoamp noise. The gain of the Model 428-PROG is adjustable in decade increments from 10^3V/A to 10^{11}V/A, with selectable rise times from 2μs to 300ms.

The Model 428-PROG offers fast response at low current levels, which is unmatched by either electrometers or picoammeters. The nine current amplification ranges allow the greatest flexibility in making speed/noise tradeoffs. The Model 428-PROG can be used with any of Keithley's data acquisition boards to implement a very cost-effective, low current measurement system with wide bandwidth and fast response.

The Model 428-PROG incorporates a second-order Bessel-function filter that minimizes noise without increasing rise time on high-gain ranges. This can be defeated in situations where 6dB/octave roll-off is desired, as in control loops of scanning tunneling electron microscopes.

Input and output connections to the Model 428-PROG are made with BNC connectors. INPUT HI is connected to a programmable ±5V supply, which permits suitable bias voltages to be applied to devices-under-test or current collectors. This eliminates the need for a separate bias supply.

For applications where voltage offset errors exist, the ZERO CHECK and OFFSET functions can be used, thereby maintaining maximum instrument accuracy. Current suppression is also available up to 5mA, useful for suppressing background currents, such as dark currents.

The Model 428-PROG also incorporates an exterior design with simple front panel operation, improved display, and convenient system integration. Pushbutton controls have an LED to indicate if that function is activated. The display features three selectable intensities (bright, dim, and off) for use in light-sensitive environments. All setup values can be displayed from the front panel. An IEEE-488 interface is included.

The Model 428-PROG as Preamplifier to an Oscilloscope

The Model 428-PROG can be connected to an oscilloscope or waveform digitizer to display very low currents in real time.

Converts small, fast currents to a voltage

Gain Setting V/A	Accuracy[1] 18°–28°C ±(% input + offset)	Accuracy[1] Temperature Coefficient ±(% input + offset)/°C	Low Noise[2] Rise Time[3] (10%–90%) ms	Low Noise[2] Noise rms	Maximum Speed Rise Time[3] (10%–90%) μs[4]	Maximum Speed Noise rms[4]	DC Input Resistance
10^3	0.45 + 1.2 μA	0.01 + 40 nA	0.1	90 nA	2	100 nA	< 0.6Ω
10^4	0.31 + 120 nA	0.01 + 4 nA	0.1	9 nA	2	15 nA	< 0.7Ω
10^5	0.31 + 12 nA	0.01 + 400 pA	0.1	900 pA	5	2 nA	< 1.6Ω
10^6	0.34 + 1.2 nA	0.01 + 40 pA	0.1	90 pA	10	500 pA	< 10 Ω
10^7	0.5 + 122 pA	0.015 + 4.3 pA	0.1	9 pA	15	200 pA	< 100 Ω
10^8	1.4 + 14 pA	0.015 + 700 fA	1	0.5 pA	40	30 pA	< 1kΩ
10^9	2.5 + 3 pA	0.025 + 300 fA	10	50 fA	100	10 pA	< 10kΩ
10^{10}	2.5 + 1.6 pA	0.025 + 250 fA	100	4 fA	250	2 pA	< 100kΩ
10^{11} [5]	2.7 + 1.6 pA	0.028 + 250 fA	300	1.2 fA	250	2 pA	< 100kΩ

NOTES

1. When properly zeroed using zero correct.
2. Selectable filtering will improve noise specifications; see operator's manual for details (typical value shown).
3. Bandwidth = 0.35/rise time.
4. With up to 100pF shunt capacitance; autofilter on; low pass filter off.
5. 10^{11} setting is 10^{10} setting with GAIN ×10 enabled; other entries are for GAIN ×10 disabled.

SPECIFICATIONS

INPUT:

Voltage Burden: <200μV (18°–28°C) for inputs <100μA; <10mV for inputs ≥ 100μA; 20μV/°C temperature coefficient.

Maximum Overload: 100V on 10^4 to 10^{11}V/A ranges; 10V on 10^3V/A range. Higher voltage sources must be current limited at 10mA.

OUTPUT:

Range: ±10V, 1mA; bias voltage off.

Impedance: <100Ω DC–175kHz.

LOW PASS FILTER:

Ranges: 10μs to 300ms (±25%) in 1, 3, 10 sequence or OFF.

Attenuation: 12dB/octave.

GAIN ×10: Rise time, noise, and input resistance are unchanged when selecting GAIN ×10; gain accuracy and temperature coefficient are degraded by 0.2% and 0.003%/°C respectively.

CURRENT SUPPRESSION

Range	Resolution	Accuracy ±(%setting + offset)
±5 nA	1 pA	3.0 + 10 pA
±50 nA	10 pA	1.6 + 100 pA
±500 nA	100 pA	0.8 + 1 nA
±5 μA	1 nA	0.7 + 10 nA
±50 μA	10 nA	0.6 + 100 nA
±500 μA	100 nA	0.6 + 1 μA
±5 mA	1 μA	0.6 + 10 μA

BIAS VOLTAGE:

Range: ±5V.

Resolution: 2.5mV.

Accuracy: ±(1.1%rdg + 25mV).

Model 428-PROG rear panel

GENERAL

DISPLAY: Ten character alphanumeric LED display with normal/dim/off intensity control.

REAR PANEL CONNECTORS:

Input BNC: Common connected to chassis through 1kΩ.

Output BNC: Common connected to chassis.

IEEE-488 Connector

5-Way Binding Post: Connected to chassis.

EMI/RFI: Complies with the RF interference limits of FCC Part 15 Class B and VDE 0871 Class B.

EMC: Conforms to European Union Directive 89/336/EEC.

SAFETY: Conforms to European Union Directive 73/23/EEC (meets EN61010-1/IEC 1010).

WARM-UP: 1 hour to rated accuracy.

ENVIRONMENT: Operating: 0°–50°C, <70% R.H. up to 35°C; linearly derate R.H. 3%/°C up to 50°C. **Storage:** –25°C to 65°C.

POWER: 105–125VAC or 210–250VAC, switch selected. (90–110/180–220VAC available.) 50Hz or 60Hz. 45VA maximum.

DIMENSIONS: 90mm high × 213mm wide × 397mm deep (3½ in × 8⅜ in × 15⅝ in).

IEEE-488 BUS IMPLEMENTATION

PROGRAMMABLE PARAMETERS: All parameters and controls programmable except for IEEE-488 bus address.

EXECUTION SPEED: (measured from DAV true to RFD true on bus).
Zero Correct & Auto Suppression commands: <3s.
Save/Recall Configuration commands: <500ms.
All other commands: <40ms.

6514

Programmable Electrometer

The Model 6514 Electrometer combines flexible interfacing capabilities with current sensitivity, charge measurement capabilities, resolution, and speed that are equal or superior to our earlier electrometers. The Model 6514's built-in IEEE-488, RS-232, and digital I/O interfaces make it simple to configure fully automated, high speed systems for low-level testing.

The 5½-digit Model 6514 is designed for applications that demand fast, yet precise measurements of low currents, voltages from high resistance sources, charges, or high resistances.

The Model 6514's exceptional measurement performance comes at an affordable price. While its cost is comparable with that of many high end DMMs, the Model 6514 offers far greater current sensitivity and significantly lower voltage burden (as low as 20µV) than other instruments can provide.

- **<1fA noise**
- **>200TΩ input impedance on voltage measurements**
- **Charge measurements from 10fC to 20µC**
- **High speed—up to 1200 readings/second**
- **Interfaces readily with switches, computers, and component handlers**
- **Cancels voltage and current offsets easily**

R&D on a Budget

The Model 6514 offers the flexibility and sensitivity needed for a wide array of experiments, providing better data far faster than older electrometer designs. Applications include measuring currents from light detectors and other sensors, beam experiments, and measuring resistances using a current source. In addition to use by researchers in areas such as physics, optics, and materials science, the Model 6514's affordable price makes it an attractive alternative to high end DMMs for low current measurement applications, such as testing resistance and leakage current in switches, relays, and other components. For more information on how the Model 6514 does this, refer to the section titled "Low Voltage Burden."

The Model 6514 builds on the features and capabilities of the Keithley electrometers that preceded it. For example, like those instruments, a built-in constant current source simplifies measuring resistance.

Two analog outputs—a 2V output and a preamp output—are available for recording data with strip-chart recorders.

Ordering Information

6514	**Programmable Electrometer**

Accessories Supplied

237-ALG-2 Low Noise Triax Cable, 3-Slot Triax to Alligator Clips, 2m (6.6 ft)

ACCESSORIES AVAILABLE

CABLES

237-ALG-2	Low Noise Triax Cable, 3-Slot Triax to Alligator Clips
7007-1	Shielded IEEE-488 Cable, 1m (3.3 ft)
7007-2	Shielded IEEE-488 Cable, 2m (6.6 ft)
7009-5	RS-232 Cable
7078-TRX-3	Low Noise Triax Cable, 3-Slot Triax Connectors, 0.9m (3 ft)
7078-TRX-10	Low Noise Triax Cable, 3-Slot Triax Connectors, 3m (10 ft)
7078-TRX-20	Low Noise Triax Cable, 3-Slot Triax Connectors, 6m (20 ft)
8501-1	Trigger-Link Cable, 1m (3.3 ft)
8501-2	Trigger-Link Cable, 2m (6.6 ft)

RACK MOUNT KITS

4288-1	Single Fixed Rack Mounting Kit
4288-2	Dual Fixed Rack Mounting Kit

ADAPTERS

7078-TRX-BNC	3-Lug Triax to BNC Adapter
237-TRX-NG	Triax Male-Female Adapter with Guard Disconnected
237-TRX-T	3-Slot Male Triax to Dual 3-Lug Female Triax Tee Adapter
237-TRX-TBC	3-Lug Female Triax Bulkhead Connector (1.1kV rated)
7078-TRX-TBC	3-Lug Female Triax Bulkhead Connector with Cap

GPIB INTERFACES

KPCI-488LPA	IEEE-488 Interface/Controller for the PCI Bus
KUSB-488B	IEEE-488 USB-to-GPIB Interface Adapter

SERVICES AVAILABLE

6514-3Y-EW	1-year factory warranty extended to 3 years from date of shipment
C/6514-3Y-ISO	3 (ISO-17025 accredited) calibrations within 3 years of purchase*
TRN-LLM-1-C	Course: Making Accurate Low-Level Measurements

*Not available in all countries

Economical Component Testing

Once, electrometers were simply considered too slow to keep up with the high throughput that production test applications demand. The Model 6514 is designed for fast, sensitive measurements, providing speeds up to 1200 readings per second with fast integration or 17 measurements per second with 60Hz line-cycle integration. It offers 10fA resolution on 2nA signals, settling to within 10% of the final value in just 15ms. A normal-mode rejection ratio (NMRR) of 60dB allows making accurate low current measurements, even in the presence of line frequency induced currents, which is a common concern in production floor environments. The instrument's sensitivity makes it easy to determine the leakage resistance on capacitances up to 10nF or even on higher capacitances when a series resistor is used.

While the Model 6514 can be easily operated manually using the front panel controls, it can also be externally controlled for automated test applications. Built-in IEEE-488 and RS-232 interfaces make it possible to program all instrument functions over the bus through a computer controller. The instrument's interfaces also simplify integrating external hardware, such as sources, switching systems, or other instruments, into the test system. A digital I/O interface can be used to link the Model 6514 to many popular component handlers for tight systems integration in binning, sorting, and similar applications.

These features make the Model 6514 a powerful, low cost tool for systems designed to test optical devices and leakage resistance on low-value capacitors, switches, and other devices, particularly when the test system already includes a voltage source or when the source current/measure voltage technique is used to determine resistance.

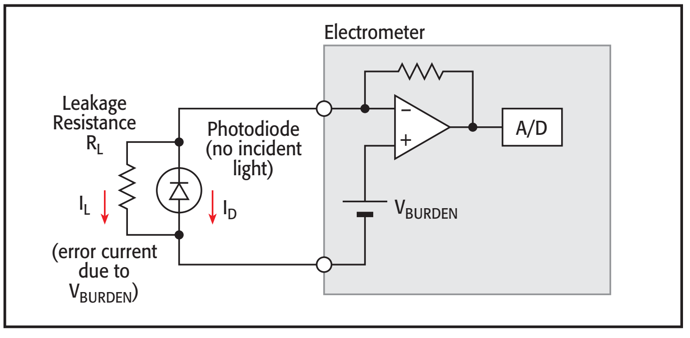


Figure 1. Dark Current Measurement with Burden Voltage Uncorrected

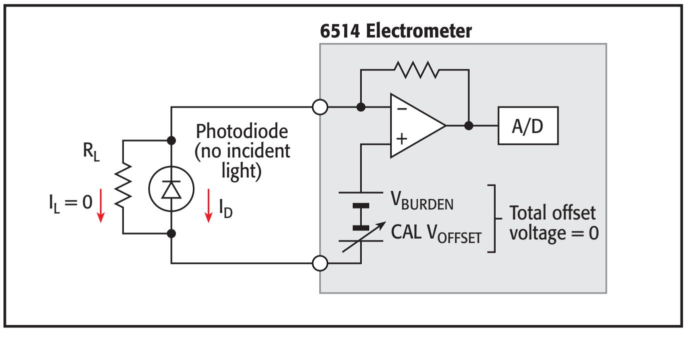


Figure 2. Dark Current Measurement with Burden Voltage Corrected

Low Voltage Burden

The Model 6514's feedback ammeter design minimizes voltage offsets in the input circuitry, which can affect current measurement accuracy. The instrument also allows active cancellation of its input voltage and current offsets, either manually via the front panel controls or over the bus with IEEE-488 commands.

Dark Current Measurements

When measuring dark currents (**Figure 1**) from a device such as a photodiode, the ammeter reads the sum of two different currents. The first current is the dark current (I_D) generated by the detector with no light falling upon the device (in other words, the signal of interest); the second one is the leakage current (I_L) generated by the voltage burden (V_{BURDEN}) appearing at the terminals of the ammeter. In a feedback ammeter, the primary "voltage burden" is the amplifier offset voltage. This leakage current represents an error current. Without the use of cancellation techniques, $I_L = V_{BURDEN}/R_L$. **Figure 2** illustrates how the Model 6514's CAL V_{OFFSET} is adjusted to cancel V_{BURDEN} to within the voltage noise level of a few microvolts, so the measured current is only the true dark current (I_D) of the photodiode. In a similar manner, offset currents can also be cancelled. Earlier electrometers used an internal numerical correction technique in which the voltage burden was still present, so the measured dark current included the error term $I_L = V_{BURDEN}/R_L$.

Voltage Burden and Measurement Error

Electrometers provide current measurement with lower terminal voltage than is possible when making DMM measurements. As shown in **Figure 3**, DMMs measure current using a shunt resistance that develops a voltage (typically 200mV full-range) in the input circuit. This creates a terminal voltage (V_{BURDEN}) of about 200mV, thereby lowering the measured current. Electrometers reduce this terminal voltage by using the feedback ammeter configuration illustrated in **Figure 1**. The Model 6514 lowers this terminal voltage still further—to the level of the voltage noise—by canceling out the small offset voltage that remains, as shown in **Figure 2**. Any error signals that remain are negligible in comparison to those that can occur when measuring current with a DMM.

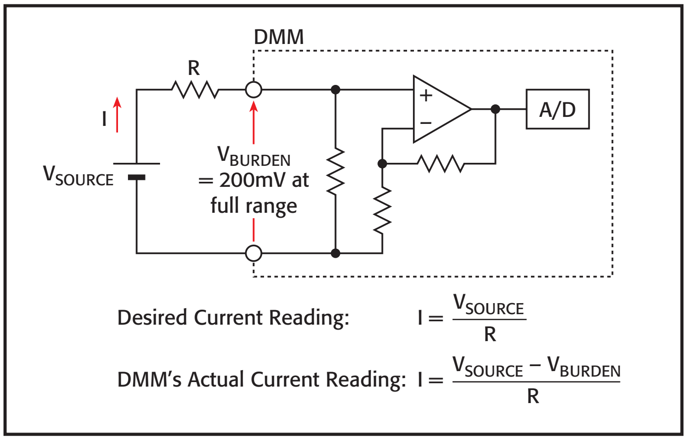


Figure 3. Errors Due to Burden Voltage when Measuring with a DMM

The example below compares a DMM's voltage burden errors with the 6514's.

If: $V_{SOURCE} = 1V, \ R = 50k\Omega$

The desired current reading is: $I = \dfrac{1V}{50k\Omega} = 20\mu A$

Actual Reading (20µA range on DMM): $V_{BURDEN} = 200mV$

$$I = \frac{1V - 200mV}{50k\Omega} = \frac{800mV}{50k\Omega} = 16\mu A$$ = 20% Burden error with a DMM

Refer to Figure 3.

6514 Actual Reading: $V_{BURDEN} = 10\mu V$

$$I = \frac{0.999990V}{50k\Omega} = 19.9998\mu A$$ = **0.001% Burden error with the 6514**

Refer to Figure 2.

DMM Offset Currents

Typically, offset currents in DMMs are tens or hundreds of picoamps, which severely limits their low current measuring capabilities compared to the Model 6514 with 3fA input bias current.

APPLICATIONS

- **High resistivity measurements**
- **Leakage currents**
- **Ion selective electrode measurements**
- **pH measurements**
- **Conductivity cells**
- **Potentiometry**

VOLTS

Range	5½-Digit Resolution	Accuracy (1 Year)[1] 18°–28°C ±(%rdg+counts)	Temperature Coefficient 0°–18°C & 28°–50°C ±(%rdg+counts)/°C
2 V	10 µV	0.025 + 4	0.003 + 2
20 V	100 µV	0.025 + 3	0.002 + 1
200 V	1 mV	0.06 + 3	0.002 + 1

NOTES

1. When properly zeroed, 5½-digit. Rate: Slow (100ms integration time).

NMRR: 60dB on 2V, 20V, >55dB on 200V, at 50Hz or 60Hz ±0.1%.

CMRR: >120dB at DC, 50Hz or 60Hz.

INPUT IMPEDANCE: >200TΩ in parallel with 20pF, <2pF guarded (10MΩ with zero check on).

SMALL SIGNAL BANDWIDTH AT PREAMP OUTPUT: Typically 100kHz (–3dB).

AMPS

Range	5½-Digit Resolution	Accuracy (1 Year)[1] 18°–28°C ±(%rdg+counts)	Temperature Coefficient 0°–18°C & 28°–50°C ±(%rdg+counts)/°C
20 pA	100 aA[2]	1 + 30	0.1 + 5
200 pA	1 fA[2]	1 + 5	0.1 + 1
2 nA	10 fA	0.2 + 30	0.1 + 2
20 nA	100 fA	0.2 + 5	0.03 + 1
200 nA	1 pA	0.2 + 5	0.03 + 1
2 µA	10 pA	0.1 + 10	0.005 + 2
20 µA	100 pA	0.1 + 5	0.005 + 1
200 µA	1 nA	0.1 + 5	0.005 + 1
2 mA	10 nA	0.1 + 10	0.008 + 2
20 mA	100 nA	0.1 + 5	0.008 + 1

NOTES

1. When properly zeroed, 5½-digit. Rate: Slow (100ms integration time).
2. aA = 10^{-18}A, fA = 10^{-15}A.

INPUT BIAS CURRENT: <3fA at T_{CAL} (user adjustable). Temperature coefficient = 0.5fA/°C.

INPUT BIAS CURRENT NOISE: <750aA p-p (capped input), 0.1Hz to 10Hz bandwidth, damping on. Digital filter = 40 readings.

INPUT VOLTAGE BURDEN at T_{CAL} ±1°C (user adjustable):
<20µV on 20pA, 2nA, 20nA, 2µA, 20µA ranges.
<100µV on 200pA, 200nA, 200µA ranges.
<2mV on 2mA range.
<4mV on 20mA range.

TEMPERATURE COEFFICIENT OF INPUT VOLTAGE BURDEN: <10µV/°C on pA, nA, µA ranges.

PREAMP SETTLING TIME (to 10% of final value): 2.5s typical on pA ranges, damping off, 3s typical on pA ranges damping on, 15ms on nA ranges, 5ms on µA and mA ranges.

NMRR: >95dB on pA, 60dB on nA, µA, and mA ranges at 50Hz or 60Hz ±0.1%. Digital Filter = 40.

OHMS

Range	5½-Digit Resolution	Accuracy (1 Year)[1] 18°–28°C ±(% rdg+counts)	Temperature Coefficient 0°–18°C & 28°–50°C ±(% rdg+counts)/°C	Test Current (nominal)
2 kΩ	10 mΩ	0.20 + 10	0.01 + 2	0.9 mA
20 kΩ	100 mΩ	0.15 + 3	0.01 + 1	0.9 mA
200 kΩ	1 Ω	0.25 + 3	0.01 + 1	0.9 mA
2 MΩ	10 Ω	0.25 + 4	0.02 + 2	0.9 µA
20 MΩ	100 Ω	0.25 + 3	0.02 + 1	0.9 µA
200 MΩ	1 kΩ	0.30 + 3	0.02 + 1	0.9 µA
2 GΩ	10 kΩ	1.5 + 4	0.04 + 2	0.9 nA
20 GΩ	100 kΩ	1.5 + 3	0.04 + 1	0.9 nA
200 GΩ	1 MΩ	1.5 + 3	0.04 + 1	0.9 nA

NOTES

1. When properly zeroed, 5½-digit. Rate: Slow (100ms integration time).

MAXIMUM OPEN CIRCUIT VOLTAGE: 250V DC.

PREAMP SETTLING TIME (To 10% of final reading with <100pF input capacitance): 2kΩ through 200kΩ: 2ms; 20MΩ through 200MΩ: 90ms. 2GΩ through 200GΩ: 1s.

6514 Programmable Electrometer

COULOMBS

Range	6½-Digit Resolution	Accuracy (1 Year)[1, 2] 18°–28°C ±(%rdg+counts)	Temperature Coefficient 0°–18°C & 28°–50°C ±(%rdg+counts)/°C
20 nC	10 fC	0.4 + 50	0.04 + 10
200 nC	100 fC	0.4 + 50	0.04 + 10
2 μC	1 pC	1 + 50	0.05 + 10
20 μC	10 pC	1 + 50	0.05 + 10

Notes:

1. Charge acquisition time must be <1000s, derate 2% for each additional 10,000s.
2. When properly zeroed, 6½-digit. Rate: Slow (100ms integration time).

INPUT BIAS CURRENT: <4fA at T_{CAL}. Temperature coefficient = 0.5fA/°C.

IEEE-488 BUS IMPLEMENTATION

MULTILINE COMMANDS: DCL, LLO, SDC, GET, GTL, UNT, UNL, SPE, SPD.

IMPLEMENTATION: SCPI (IEEE-488.2, SCPI-1996.0); DDC (IEEE-488.1).

UNILINE COMMANDS: IFC, REN, EOI, SRQ, ATN.

INTERFACE FUNCTIONS: SH1, AH1, T5, TE0, L4, LE0, SR1, RL1, PP0, DC1, DT1, C0, E1.

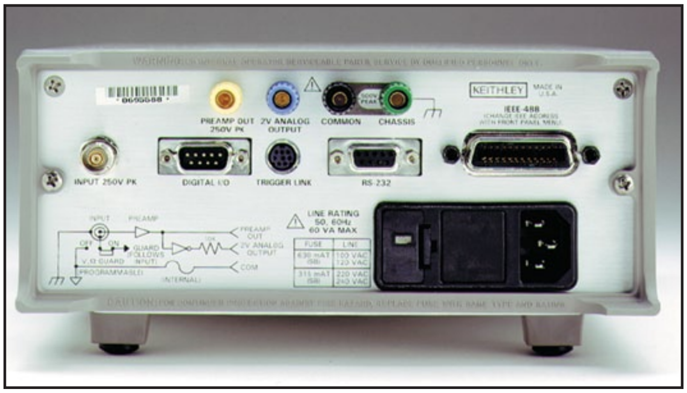
PROGRAMMABLE PARAMETERS: Function, Range, Zero Check, Zero Correct, EOI (DDC mode only), Trigger, Terminator (DDC mode only), Data Storage 2500 Storage, Calibration (SCPI mode only), Display Format, SRQ, REL, Output Format, Guard, V-offset Cal, I-offset Cal.

ADDRESS MODES: TALK ONLY and ADDRESSABLE.

LANGUAGE EMULATION: 6512, 617, 617-HIQ emulation via DDC mode.

TRIGGER TO READING DONE: 150ms typical, with external trigger.

RS-232 IMPLEMENTATION:
- **Supports:** SCPI 1996.0.
- **Baud Rates:** 300, 600, 1200, 2400, 4800, 9600, 19.2k, 38.4k, 57.6k.
- **Protocols:** Xon/Xoff, 7 or 8 bit ASCII, parity-odd/even/none.
- **Connector:** DB-9 TXD/RXD/GND.



Model 6514 rear panel

GENERAL

OVERRANGE INDICATION: Display reads "OVRFLOW."

RANGING: Automatic or manual.

CONVERSION TIME: Selectable 0.01PLC to 10PLC.

PROGRAMS: Provide front panel access to IEEE address, choice of engineering units or scientific notation, and digital calibration.

MAXIMUM INPUT: 250V peak, DC to 60Hz sine wave; 10s per minute maximum on mA ranges.

MAXIMUM COMMON MODE VOLTAGE (DC to 60Hz sine wave): Electrometer, 500V peak.

ISOLATION (Meter COMMON to chassis): Typically $10^{10}\Omega$ in parallel with 500pF.

INPUT CONNECTOR: Three lug triaxial on rear panel.

2V ANALOG OUTPUT: 2V for full range input. Inverting in Amps and Coulombs mode. Output impedance 10kΩ.

PREAMP OUTPUT: Provides a guard output for Volts measurements. Can be used as an inverting output or with external feedback in Amps and Coulombs modes.

DIGITAL INTERFACE:
- **Handler Interface:** Start of test, end of test, 3 category bits.
- **Digital I/O:** 1 Trigger input, 4 outputs with 500mA sink capability.
- **Connector:** 9 pin D subminiature, male pins.

EMC: Conforms with European Union Directive 89/336/EEC EN55011, EN50082-1, EN61000-3-2, EN61000-3-3, FCC part 15 class B.

SAFETY: Conforms with European Union Directive 73/23/EEC EN61010-1.

GUARD: Switchable voltage and ohm guard available.

TRIGGER LINE: Available, see manual for usage.

READING STORAGE: 2500 readings.

READING RATE:

To internal buffer	1200 readings/second[1]
To IEEE-488 bus	500 readings/second[1, 3]
To front panel	17 readings/second at 60Hz;[2] 15 readings/second at 50Hz.[2]

Notes:

1. 0.01PLC, digital filters off, front panel off, auto zero off.
2. 1.00PLC, digital filters off.
3. Binary transfer mode.

DIGITAL FILTER: Median and averaging (selectable from 2 to 100 readings).

DAMPING: User selectable on Amps function.

ENVIRONMENT:
- **Operating:** 0°–50°C; relative humidity 70% non-condensing, up to 35°C.
- **Storage:** –25° to +65°C.

WARM-UP: 1 hour to rated accuracy (see manual for recommended procedure).

POWER: 90–125V or 210–250V, 50–60Hz, 60VA.

PHYSICAL:
- **Case Dimensions:** 90mm high × 214mm wide × 369mm deep (3½ in. × 8⅜ in. × 14⁹⁄₁₆ in.).
- **Working Dimensions:** From front of case to rear including power cord and IEEE-488 connector: 15.5 inches.
- **Net Weight:** <4.6kg (<10.1 lbs).
- **Shipping Weight:** <9.5kg (<21 lbs).

6517B

Electrometer/High Resistance Meter

- **Measures resistances up to $10^{16}\Omega$**
- **1fA–20mA current measurement range**
- **<20µV burden voltage on lowest current ranges**
- **200TΩ input impedance**
- **<3fA bias current**
- **Up to 425 rdgs/s**
- **0.75fA p-p noise**
- **Built-in ±1kV voltage source**
- **Unique voltage reversal method for high resistance measurements**
- **Optional plug-in scanner cards**

Keithley's 5½-digit Model 6517B Electrometer/High Resistance Meter offers accuracy and sensitivity specifications unmatched by any other meter of this type. It also offers a variety of features that simplify measuring high resistances and the resistivity of insulating materials. With reading rates of up to 425 readings/second, the Model 6517B is also significantly faster than competitive electrometers, so it offers a quick, easy way to measure low-level currents.

Exceptional Performance Specifications

The half-rack-sized Model 6517B has a special low current input amplifier with an input bias current of <3fA with just 0.75fA p-p (peak-to-peak) noise and <20µV burden voltage on the lowest range. The input impedance for voltage and resistance measurements is 200TΩ for near-ideal circuit loading. These specifications ensure the accuracy and sensitivity needed for accurate low current and high impedance voltage, resistance, and charge measurements in areas of research such as physics, optics, nanotechnology, and materials science. A built-in ±1kV voltage source with sweep capability simplifies performing leakage, breakdown, and resistance testing, as well as volume (Ω-cm) and surface resistivity (Ω/square) measurements on insulating materials.

Wide Measurement Ranges

The Model 6517B offers full autoranging over the full span of ranges on current, resistance, voltage, and charge measurements:

- Current measurements from 1fA to 20mA
- Voltage measurements from 10µV to 200V
- Resistance measurements from 50Ω to $10^{16}\Omega$
- Charge measurements from 10fC to 2µC

Improved High Resistivity Measurements

Many test applications require measuring high levels of resistivity (surface or volume) of materials. The conventional method of making these measurements is to apply a sufficiently large voltage to a sample, measure the current that flows through the sample, then calculate the resistance using Ohm's Law (R=V/I). While high resistance materials and devices produce very small currents that are difficult to measure accurately, Keithley's electrometers and picoammeters are used successfully for such measurements.

Even with high quality instrumentation, inherent background currents in the material can make these measurements difficult to perform accurately. Insulating materials, polymers, and plastics typically exhibit background currents due to piezoelectric effects, capacitive elements charged by static electricity, and polarization effects. These background currents are often equal to or greater than the current stimulated by the applied voltage. In these cases, the result is often unstable, providing inaccurate resistance or resistivity readings or even erroneous negative values. Keithley's Model 6517B is designed to solve these problems and provides consistent, repeatable, and accurate measurements for a wide variety of materials and components, especially when used in combination with the Model 8009 Resistivity Test Fixture.

Alternating Polarity Method

The Model 6517B uses the Alternating Polarity method, which virtually eliminates the effect of any background currents in the sample. First and second order drifts of the background currents are also canceled out. The Alternating Polarity method applies a voltage of positive polarity, then the current is measured after a specified delay (Measure Time). Next, the polarity is reversed and the current measured again, using the same delay. This process is repeated continuously, and the resistance is calculated based on a weighted average of the four most recent current measurements. This method typically

6517B Electrometer/High Resistance Meter

Ordering Information

6517B **Electrometer/High Resistance Meter**

Accessories Supplied

237-ALG-2 Low Noise Triax Cable, 3-slot Triax to Alligator Clips, 2m (6.6 ft)

8607 Safety High Voltage Dual Test Leads

6517-TP Thermocouple Bead Probe

CS-1305 Interlock Connector

ACCESSORIES AVAILABLE

CABLES	
6517B-ILC-3	Interlock Cable
7007-1	Shielded IEEE-488 Cable, 1m (3.2 ft)
7007-2	Shielded IEEE-488 Cable, 2m (6.5 ft)
7009-5	RS-232 Cable
7078-TRX-3	Low Noise Triax Cable, 3-Slot Triax Connectors, 0.9m (3 ft)
7078-TRX-10	Low Noise Triax Cable, 3-Slot Triax Connectors, 3m (10 ft)
7078-TRX-20	Low Noise Triax Cable, 3-Slot Triax Connectors, 6m (20 ft)
8501-1	Trigger Link Cable, 1m (3.3 ft)
8501-2	Trigger Link Cable, 2m (6.6 ft)
8503	Trigger Link Cable to 2 male BNCs, 1m (3.3 ft)
8607	1kV Source Banana Cables
PROBES	
6517-RH	Humidity Probe with Extension Cable
6517-TP	Temperature Bead Probe (included with 6517B)
TEST FIXTURE	
8009	Resistivity Test Fixture
OTHER	
CS-1305	Interlock Connector
ADAPTERS	
237-BNC-TRX	Male BNC to 3-Lug Female Triax Adapter
237-TRX-NG	Triax Male-Female Adapter with Guard Disconnected
237-TRX-T	3-Slot Male Triax to Dual 3-Lug Female Triax Tee Adapter
237-TRX-TBC	3-Lug Female Triax Bulkhead Connector (1.1kV rated)
7078-TRX-BNC	3-Slot Male Triax to BNC Adapter
7078-TRX-GND	3-Slot Male Triax to BNC Adapter with guard removed
7078-TRX-TBC	3-Lug Female Triax Bulkhead Connector with Cap
RACK MOUNT KITS	
4288-1	Single Fixed Rack Mounting Kit
4288-2	Dual Fixed Rack Mounting Kit
SCANNER CARDS	
6521	Low Current Scanner Card
6522	Voltage/Low Current Scanner Card
GPIB INTERFACES	
KPCI-488LPA	IEEE-488 Interface/Controller for the PCI Bus
KUSB-488B	IEEE-488 USB-to-GPIB Interface Adapter

produces a highly repeatable, accurate measurement of resistance (or resistivity) by the seventh reversal on most materials (i.e., by discarding the first three readings). For example, a 1mm-thick sample of $10^{14}\Omega$-cm material can be measured with 0.3% repeatability in the Model 8009 test fixture, provided the background current changes less than 200fA over a 15-second period.

Simple DMM-like Operation

The Model 6517B is designed for easy, DMM-like operation via the front panel, with single-button control of important functions such as resistance measurement. It can also be controlled via a built-in IEEE-488 interface, which makes it possible to program all functions over the bus through a computer controller.

High Accuracy High Resistance Measurements

The Model 6517B offers a number of features and capabilities that help ensure the accuracy of high resistance measurement applications. For example, the built-in voltage source simplifies determining the relationship between an insulator's resistivity and the level of source voltage used. It is well suited for capacitor leakage and insulation resistance measurements, tests of the surface insulation resistance of printed circuit boards, voltage coefficient testing of resistors, and diode leakage characterization.

Temperature and Humidity Stamping

Humidity and temperature can influence the resistivity values of materials significantly. To help you make accurate comparisons of readings acquired under varying conditions, the Model 6517B offers a built-in type K thermocouple and an optional Model 6517-RH Relative Humidity Probe. A built-in data storage buffer allows recording and recalling readings stamped with the time, temperature, and relative humidity at which they were acquired.

Accessories Extend Measurement Capabilities

A variety of optional accessories can be used to extend the Model 6517B's applications and enhance its performance.

Scanner Cards. Two scanner cards are available to simplify scanning multiple signals. Either card can be easily inserted in the option slot of the instrument's back panel. The Model 6521 Scanner Card offers ten channels of low-level current scanning. The Model 6522 Scanner Card provides ten channels of high impedance voltage switching or low current switching.

Test Fixture. The Model 8009 Resistivity Chamber is a guarded test fixture for measuring volume and surface resistivities of sample materials. It has stainless-steel electrodes built to ASTM standards. The fixture's electrode dimensions are pre-programmed into the Model 6517B, so there's no need to calculate those values then enter them manually. This accessory is designed to protect you from contact with potentially hazardous voltages —opening the lid of the chamber automatically turns off the Model 6517B's voltage source.

Applications

The Model 6517B is well suited for low current and high impedance voltage, resistance, and charge measurements in areas of research such as physics, optics, and materials science. Its extremely low voltage burden makes it particularly appropriate for use in solar cell applications, and its built-in voltage source and low current sensitivity make it an excellent solution for high resistance measurements of nanomaterials such as polymer based nanowires. Its high speed and ease of use also make it an excellent choice for quality control, product engineering, and production test applications involving leakage, breakdown, and resistance testing. Volume and surface resistivity measurements on nonconductive materials are particularly enhanced by the Model 6517B's voltage reversal method. The Model 6517B is also well suited for electrochemistry applications such as ion selective electrode and pH measurements, conductivity cells, and potentiometry.

Model 6517B Enhancements

The Model 6517B is an updated version, replacing the earlier Model 6517A, which was introduced in 1996. Software applications created for the Model 6517A using SCPI commands can run without modifications on the Model 6517B. However, the Model 6517B does offer some useful enhancements to the earlier design. Its internal battery-backed memory buffer can now store up to 50,000 readings, allowing users to log test results for longer periods and to store more data associated with those readings. The new model also provides faster reading rates to the internal buffer (up to 425 readings/second) and to external memory via the IEEE bus (up to 400 readings/second). Several connector modifications have been incorporated to address modern connectivity and safety requirements.

VOLTS

5½-DIGIT RANGE	RESOLUTION	ACCURACY (1 Year)[1] 18°–28°C ±(%rdg+counts)	TEMPERATURE COEFFICIENT 0°–18°C & 28°–50°C ±(%rdg+counts)/°C
2 V	10 µV	0.025 + 4	0.003 + 2
20 V	100 µV	0.025 + 3	0.002 + 1
200 V	1 mV	0.06 + 3	0.002 + 1

NMRR: 2V and 20V ranges >60dB, 200V range >55dB. 50Hz or 60Hz[2].

CMRR: >120dB at DC, 50Hz or 60Hz.

INPUT IMPEDANCE: >200TΩ in parallel with 20pF, <2pF guarded (1MΩ with zero check on).

SMALL SIGNAL BANDWIDTH AT PREAMP OUTPUT: Typically 100kHz (–3dB).

NOTES

1. When properly zeroed, 5½-digit, 1 PLC (power line cycle), median filter on, digital filter = 10 readings.
2. Line sync on.

AMPS

5½-DIGIT RANGE	RESOLUTION	ACCURACY (1 Year)[1] 18°–28°C ±(%rdg+counts)	TEMPERATURE COEFFICIENT 0°–18°C & 28°–50°C ±(%rdg+counts)/°C
20 pA	100 aA[2]	1 + 30	0.1 + 5
200 pA	1 fA[2]	1 + 5	0.1 + 1
2 nA	10 fA	0.2 + 30	0.1 + 2
20 nA	100 fA	0.2 + 5	0.03 + 1
200 nA	1 pA	0.2 + 5	0.03 + 1
2 µA	10 pA	0.1 + 10	0.005 + 2
20 µA	100 pA	0.1 + 5	0.005 + 1
200 µA	1 nA	0.1 + 5	0.005 + 1
2 mA	10 nA	0.1 + 10	0.008 + 2
20 mA	100 nA	0.1 + 5	0.008 + 1

INPUT BIAS CURRENT: <3fA at T_{CAL}. Temperature coefficient = 0.5fA/°C, 20pA range.

INPUT BIAS CURRENT NOISE: <750aA p-p (capped input), 0.1Hz to 10Hz bandwidth, damping on. Digital filter = 40 readings, 20pA range.

INPUT VOLTAGE BURDEN at T_{CAL} ±1°C:
<20µV on 20pA, 2nA, 20nA, 2µA, and 20µA ranges.
<100µV on 200pA, 200nA, and 200µA ranges.
<2mV on 2mA range. <5mV on 20mA range.

TEMPERATURE COEFFICIENT OF INPUT VOLTAGE BURDEN: <10µV/°C on pA, nA, and µA ranges.

PREAMP SETTLING TIME (to 10% of final value) Typical: 0.5sec (damping off) 2.0 sec (damping on) on pA ranges. 15msec on nA ranges damping off, 1msec on µA ranges damping off. 500µsec on mA ranges damping off.

NMRR: >60dB on all ranges at 50Hz or 60Hz[3].

NOTES

1. When properly zeroed, 5½-digit, 1PLC (power line cycle), median filter on, digital filter = 10 readings.
2. aA = 10^{-18}A, fA = 10^{-15}A.
3. Line sync on.

OHMS (Normal Method)

RANGE	5½-DIGIT RESOLUTION	ACCURACY[1] (10–100% Range) 18°–28°C (1 Year) ±(% rdg+counts)	TEMPERATURE COEFFICIENT (10–100% Range) 0°–18°C & 28°–50°C ±(% rdg+counts)	AUTO V SOURCE	AMPS RANGE
2 MΩ	10 Ω	0.125 + 1	0.01 + 1	40 V	200 µA
20 MΩ	100 Ω	0.125 + 1	0.01 + 1	40 V	20 µA
200 MΩ	1 kΩ	0.15 + 1	0.015 + 1	40 V	2 µA
2 GΩ	10 kΩ	0.225 + 1	0.035 + 1	40 V	200 nA
20 GΩ	100 kΩ	0.225 + 1	0.035 + 1	40 V	20 nA
200 GΩ	1 MΩ	0.35 + 1	0.110 + 1	40 V	2 nA
2 TΩ	10 MΩ	0.35 + 1	0.110 + 1	400 V	2 nA
20 TΩ	100 MΩ	1.025 + 1	0.105 + 1	400 V	200 pA
200 TΩ	1 GΩ	1.15 + 1	0.125 + 1	400 V	20 pA

NOTES

1. Specifications are for auto V-source ohms, when properly zeroed, 5½-digit, 1PLC, median filter on, digital filter = 10 readings. If user selectable voltage is required, use manual mode. Manual mode displays resistance (up to 10^{18}Ω) calculated from measured current. Accuracy is equal to accuracy of V-source plus accuracy of selected Amps range.

PREAMP SETTLING TIME: Add voltage source settling time to preamp settling time in Amps specification. Ranges over 20GΩ require additional settling based on the characteristics of the load.

OHMS (ALTERNATING POLARITY METHOD)

The alternating polarity sequence compensates for the background (offset) currents of the material or device under test. Maximum tolerable offset up to full scale of the current range used.

Using Keithley 8009 fixture

REPEATABILITY: $\Delta I_{BG} \times R/V_{ALT}$ + 0.1% (1σ) (instrument temperature constant ±1°C).

ACCURACY: $(V_{SRC}Err + I_{MEAS}Err \times R)/V_{ALT}$

where: ΔI_{BG} is a measured, typical background current noise from the sample and fixture.
V_{ALT} is the alternating polarity voltage used.
$V_{SRC}Err$ is the accuracy (in volts) of the voltage source using V_{ALT} as the setting.
$I_{MEAS}Err$ is the accuracy (in amps) of the ammeter using V_{ALT}/R as the reading.

VOLTAGE SOURCE

RANGE	5½-DIGIT RESOLUTION	ACCURACY (1 Year) 18°–28°C ±(% setting + offset)	TEMPERATURE COEFFICIENT 0°–18°C & 28°–50°C ±(% setting+offset)/°C
100 V	5 mV	0.15 + 10 mV	0.005 + 1 mV
1000 V	50 mV	0.15 + 100 mV	0.005 + 10 mV

MAXIMUM OUTPUT CURRENT:
100V Range: ±10mA, hardware short circuit protection at <14mA.
1000V Range: ±1mA, hardware short circuit protection at <1.4mA.

SETTLING TIME:
100V Range: <8ms to rated accuracy.
1000V Range: <50ms to rated accuracy.

NOISE (typical):
100V Range: <2.6mV rms.
1000V Range: <2.9mV rms.

6517B Electrometer/High Resistance Meter

COULOMBS

RANGE	5½-DIGIT RESOLUTION	ACCURACY (1 Year)[1, 2] 18°–28°C ±(%rdg+counts)	TEMPERATURE COEFFICIENT 0°–18°C & 28°–50°C ±(%rdg+counts)/°C
2 nC	10 fC	0.4 + 5	0.04 + 3
20 nC	100 fC	0.4 + 5	0.04 + 1
200 nC	1 pC	0.4 + 5	0.04 + 1
2 µC	10 pC	0.4 + 5	0.04 + 1

NOTES

1. Specifications apply immediately after charge acquisition. Add

$$\left(4fA + \frac{|Q_{AV}|}{RC}\right) T_A$$

where T_A = period of time in seconds between the coulombs zero and measurement and Q_{AV} = average charge measured over T_A, and RC = 300,000 typical.

2. When properly zeroed, 5½-digit, 1PLC (power line cycle), median filter on, digital filter = 10 readings.

INPUT BIAS CURRENT: <4fA at T_{CAL}. Temperature coefficient = 0.5fA/°C, 2nC range.

TEMPERATURE (Thermocouple)

THERMOCOUPLE TYPE	RANGE	ACCURACY (1 Year)[1] 18°–28°C ±(% rdg + °C)
K	–25°C to 150°C	±(0.3% + 1.5°C)

NOTES

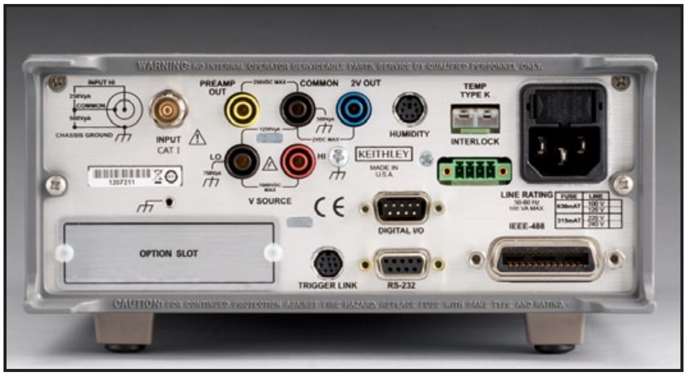
1. Excluding probe errors, T_{cal} ± 5°C, 1 PLC integration time.

HUMIDITY

RANGE	ACCURACY (1 Year)[1] 18°–28°C, ±(% rdg + % RH)
0–100%	±(0.3% +0.5)

NOTES

1. Humidity probe accuracy must be added. This is ±3% RH for Model 6517-RH, up to 65°C probe environment, not to exceed 85°C.



Model 6517B rear panel

IEEE-488 BUS IMPLEMENTATION

IMPLEMENTATION: SCPI (IEEE-488.2, SCPI-1999.0).

TRIGGER TO READING DONE: 150ms typical, with external trigger.

RS-232 IMPLEMENTATION: Supports: SCPI 1991.0. **Baud Rates:** 300, 600, 1200, 2400, 4800, 9600, 19.2k, 38.4k, 57.6k, and 115.2k.

FLOW CONTROL: None, Xon/Xoff.

CONNECTOR: DB-9 TXD/RXD/GND.

GENERAL

OVERRANGE INDICATION: Display reads "OVERFLOW" for readings >105% of range. The display reads "OUT OF LIMIT" for excessive overrange conditions.

RANGING: Automatic or manual.

CONVERSION TIME: Selectable 0.01PLC to 10PLC.

MAXIMUM INPUT: 250V peak, DC to 60Hz sine wave; 10sec per minute maximum on mA ranges.

MAXIMUM COMMON MODE VOLTAGE (DC to 60Hz sine wave): Electrometer, 500V peak; V Source, 750V peak.

ISOLATION (Meter COMMON to chassis): >$10^{10}\Omega$, <500pF.

INPUT CONNECTOR: Three lug triaxial on rear panel.

2V ANALOG OUTPUT: 2V for full range input. Non-inverting in Volts mode, inverting when measuring Amps, Ohms, or Coulombs. Output impedance 10kΩ.

PREAMP OUTPUT: Provides a guard output for Volts measurements. Can be used as an inverting output or with external feedback in Amps and Coulombs modes.

EXTERNAL TRIGGER: TTL compatible External Trigger and Electrometer Complete.

GUARD: Switchable voltage guard available.

DIGITAL I/O AND TRIGGER LINE: Available, see manual for usage.

EMC: Conforms to European Union Directive 89/336/EEC, EN 61326-1.

SAFETY: Conforms to European Union Directive 73/23/EEC, EN 61010-1.

READING STORAGE: 50,000.

READING RATES:
- **To Internal Buffer:** 425 readings/second[1].
- **To IEEE-488 Bus:** 400 readings/second[1, 2].
- **Bus Transfer:** 3300 readings/second[2].

1. 0.01PLC, digital filters off, front panel off, temperature + RH off, Line Sync off.
2. Binary transfer mode.

DIGITAL FILTER: Median and averaging.

ENVIRONMENT: Operating: 0°–50°C; relative humidity 70% non-condensing, up to 35°C. **Storage:** –25° to +65°C.

ALTITUDE: Maximum 2000 meters above sea level per EN 61010-1.

WARM-UP: 1 hour to rated accuracy (see manual for recommended procedure).

POWER: User selectable 100, 120, 220, 240VAC ±10%; 50/60Hz, 100VA max.

PHYSICAL: Case Dimensions: 90mm high × 214mm wide × 369mm deep (3½ in. × 8½ in. × 14½ in.).

Working Dimensions: From front of case to rear including power cord and IEEE-488 connector: 15.5 inches.

Net Weight: 5.4kg (11.8 lbs.).

Shipping Weight: 6.9kg (15.11 lbs.).

SERVICES AVAILABLE

6517B-3Y-EW	1-year factory warranty extended to 3 years from date of shipment
C/6517B-3Y-ISO	3 (ISO-17025 accredited) calibrations within 3 years of purchase*
TRN-LLM-1-C	Course: Making Accurate Low-Level Measurements

*Not available in all countries

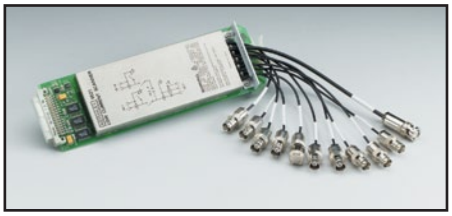
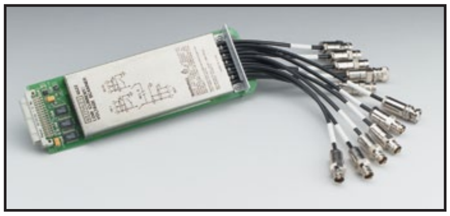
6521
6522

- 10 channels of multiplex switching
- Install directly in 6517B's option slot
- Choose from low current scanning or high impedance voltage switching with low current switching
- <200μV contact potential
- <1pA offset current
- Compatible with Keithley's Model 6517 and 6517A Electrometers

Ordering Information

6521	Low Current, 10-channel Scanner Card
6522	Low Current, High Impedance Voltage, High Resistance, 10-channel Scanner Card

Low Current, 10-channel Scanner Cards for 6517B

Two optional 10-channel plug-in scanner cards are available to extend the measurement performance of the Model 6517B Electrometer/High Resistance Meter. The cards install directly into the option slot in the back panel of the Model 6517B. The cards are also compatible with the Models 6517A and 6517.

The Model 6521 Low Current Scanner Card is a 10-channel multiplexer, designed for switching low currents in multipoint testing applications or when the test configuration must be changed. Offset current on each channel is <1pA and high isolation is maintained between each channel (>$10^{15}\Omega$). The Model 6521 maintains the current path even when the channel is deselected, making it a true current switch. BNC input connectors help provide shielding for sensitive measurements and make the card compatible with low noise coaxial cables. The Model 6521 is well suited for automating reverse leakage tests on semiconductor junctions or gate leakage tests on FETs.

The Model 6522 Voltage/Low Current Scanner Card can provide up to ten channels of low-level current, high impedance voltage, high resistance, or charge switching. Although it is similar to the Model 6521 in many ways, the Model 6522's input connectors are 3-lug triax. The card can be software configured for high impedance voltage switching of up to 200V. Triaxial connectors make it possible to float the card 500V above ground and drive guard to 200V.

MODEL 6521 SPECIFICATIONS

CHANNELS PER CARD: 10.

FUNCTIONS: Amps.

CONTACT CONFIGURATION: Single pole, "break-before-make" for signal HI input. Signal LO is common for all 10 channels and output. When a channel is off, signal HI is connected to signal LO.

CONNECTOR TYPE: Inputs BNC, Outputs Triaxial.

SIGNAL LEVEL: 30V, 500mA, 10VA (resistive load).

CONTACT LIFE: >10^6 closures at maximum signal level; >10^7 closures at low signal levels.

CONTACT RESISTANCE: <1Ω.

CONTACT POTENTIAL: <200μV.

OFFSET CURRENT: <1pA (<30fA typical at 23°C, <60% RH).

ACTUATION TIME: 2ms.

COMMON MODE VOLTAGE: <30V peak.

ENVIRONMENT: Operating: 0° to 50°C up to 35°C at 70% R.H. **Storage:** –25° to 65°C.

MODEL 6522 SPECIFICATIONS

CHANNELS PER CARD: 10.

FUNCTIONS: Volts, Amps.

CONTACT CONFIGURATION: Single pole, "break-before-make" for signal HI input. Signal LO is common for all 10 channels and output. When a channel is off, signal HI is connected to signal LO. 6517B can also configure channels as voltage switches.

CONNECTOR TYPE: Inputs: Triaxial. Outputs: Triaxial.

SIGNAL LEVEL: 200V, 500mA, 10VA (resistive load).

CONTACT LIFE: >10^6 closures at maximum signal level; >10^7 closures at low signal levels.

CONTACT RESISTANCE: <1Ω.

CONTACT POTENTIAL: <200μV.

OFFSET CURRENT: <1pA (<30fA typical at 23°C, <60% RH).

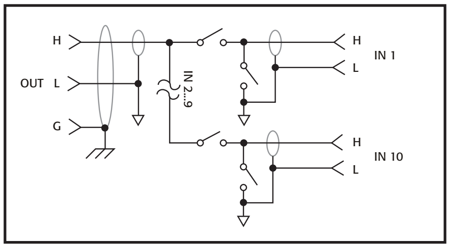
CHANNEL ISOLATION: >$10^{13}\Omega$, <0.3pF.

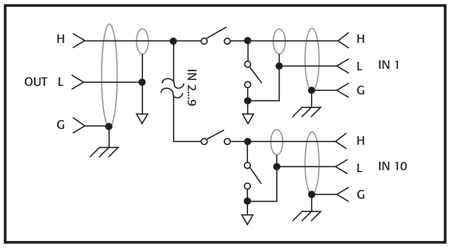
INPUT ISOLATION: >$10^{10}\Omega$, <125pF (Input HI to Input LO).

ACTUATION TIME: 2ms.

COMMON MODE VOLTAGE: <300V peak.

ENVIRONMENT: Operating: 0° to 50°C up to 35°C at 70% R.H. **Storage:** –25° to 65°C.





6220/6514/ 2000/7001

High Impedance Semiconductor Resistivity and Hall Effect Test Configurations

The Model 6220 Current Source offers material researchers ±0.1pA/step to ±105mA DC output, combined with $10^{14}\Omega$ output resistance.

The Model 6514 Electrometer provides >200TΩ input impedance and <3fA input bias current.

The Model 2000 6½-Digit Multimeter provides 0.1µV of sensitivity.

The Model 7001 Switch/Control Mainframe controls the 7152 4×5 Low Current Matrix Card, which provides contacts with <1pA offset current.

Ordering Information

6220	**DC Current Source**
6514	**Programmable Electrometer**
2000	**Digital Multimeter**

Options

7001	**Switch System**
7152	**4×5 Low Current Matrix Card**

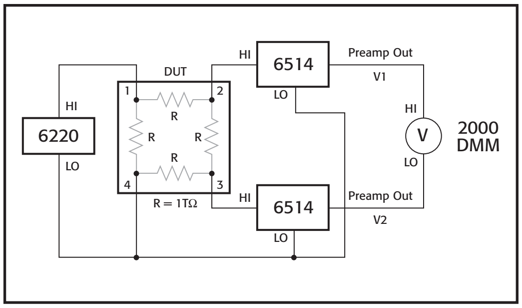
Alternative economical approaches to Hall coefficient and resistivity measurements

Occasionally, when working with samples with very high resistivity, semi-insulating GaAs, and similar materials with resistivities above $10^8\Omega$, alternative system configurations may be able to produce more reliable data than standard, pre-configured Hall Effect systems. Such systems demand careful shielding and guarding, and typically include a current source, two electrometer buffers, and an isolated voltmeter. The schematics show two suggested configurations for these high resistivity applications: one that requires manual switching and one with automated switching.

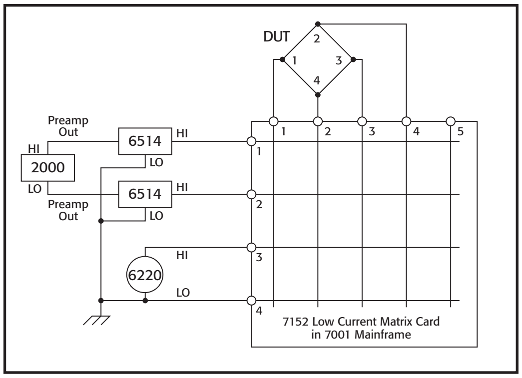
The range of the systems shown here is very wide. The high resistance end is limited by the minimum output of the current source. A current of 100pA can be supplied with an accuracy of about 2%. If the resistance of each leg of the sample is no more than 1TΩ, the maximum voltage developed will be 100V, within the range of the Model 6220 current source and the Model 6514 electrometer. This system will provide good results with samples as low as 1Ω per leg, if a test current level of 100mA is acceptable. Even at 100mΩ per leg, accuracy is approximately 2%.

Leakage currents are the most important sources of error, especially at very high resistances. One important advantage of this circuit is that a guard voltage is available for three of the sample terminals, which virtually eliminates both leakage currents and line capacitance. The fourth terminal is at circuit LO or ground potential and does not need guarding.

Call Keithley for additional guidance in selecting equipment for specific high resistivity applications.



The equipment configuration with manual switching (above) was developed for very high resistance van der Pauw or Hall Effect measurements. This measurement system includes a Model 6220 current source, two Model 6514 electrometers (used as unity-gain buffers), and a Model 2000 digital multimeter (DMM). The current source has a built-in guard, which minimizes the time constant of the current source and cable. The insulation resistance of the leads and supporting fixtures for the sample should be at least 100 times the DUT resistance (R). The entire sample holder must be shielded to avoid electrostatic pickup. If the sample is in a dewar, this should be part of the shield.



One Model 7152 Matrix Card, housed in a Model 7001 mainframe, is used to connect the electrometers and the current source to the sample. Two Model 6514 electrometers are used as unity gain buffers, and their output difference is measured with a Model 2000 DMM. To ensure faster measurement time, guarded measurements are made by turning the Guard switch ON for both of the Model 6514s, and by guarding the Model 6220 output. Call Keithley's Applications Department for cabling information.

ACCESSORIES AVAILABLE

7007-1	Shielded IEEE-488 Cable, 1m (3.3 ft)
7007-2	Shielded IEEE-488 Cable, 2m (6.6 ft)
7078-TRX-10	Triax Cable, 3m (10 ft)
KPCI-488LPA	IEEE-488 Interface/Controller for the PCI Bus
KUSB-488B	IEEE-488 USB-to-GPIB Interface Adapter

3390

50MHz Arbitrary Waveform/ Function Generator

BEST IN CLASS PERFORMANCE

- **50MHz sine wave frequency**
- **25MHz square wave frequency**
- **Arbitrary waveform generator with 256k-point, 14-bit resolution**
- **Built-in function generator capability includes: sine, square, triangle, noise, DC, etc.**
- **Precision pulses and square waves with fast (5ns) rise/fall times**
- **Built-in 10MHz external time base for multiple unit synchronization**
- **Built-in AM, FM, PM, FSK, PWM modulation**
- **Frequency sweep and burst capability**
- **Waveform creation software, KiWAVE, included**
- **LXI Class C compliance**

Keithley has paired the best-in-class performance of the Model 3390 Arbitrary Waveform/Function Generator with the best price in the industry to provide your applications with superior waveform generation functionality and flexibility at an unparalleled price.

From its fully featured Arbitrary Waveform Generator (ARB) to its high speed and ease-of-use, the Model 3390 is a complete signal generation solution for all your waveform application needs up to 50MHz.

Versatile Waveform Creation Capabilities

The Model 3390 generates highly stable and accurate waveforms that allow you to create almost any desired shape. It uses direct digital synthesis (DDS) techniques to achieve this level of performance and functionality.

The exceptional signal quality of the Model 3390 is a result of its high resolution, fast rise and fall times, and deep memory. This combined with its low price makes it the ideal solution for applications that use the 50MHz bandwidth and below. Lower speed instruments cannot provide the signal accuracy of the Model 3390, even at bandwidths they were specifically designed for.

Arbitrary Waveform Generation (ARB)

With the Model 3390, you can precisely replicate real world signals. This 14-bit ARB provides the ability to define waveforms with up to 256,000 data points and generate them at a sampling rate of 125MSamples/second. For ease of use, up to four user-defined waveforms can be stored in the onboard non-volatile memory.

Function Generation

Standard output waveforms can be created by pressing one button on the front panel. Ten standard waveforms are provided, including the basic sine, square, ramp, and triangle shapes. The Model 3390 offers the highest repetition rates of any instrument in its class, allowing you to better emulate the signals you need to test.

Pulse Generation

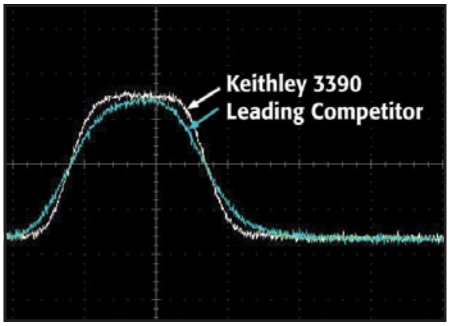
Pulse capabilities have become critically important as devices being tested have become smaller, more sensitive, and more complex. To accurately duplicate the signals these tiny devices receive, very clean pulses with crisp edges are mandatory, which is why the Model 3390 offers the fastest rise time (5ns) and cleanest pulse shapes for this class of instrument.

Modulating Waveforms

The ability of the Model 3390 to modulate at high internal frequencies allows you to accurately simulate real-world conditions. Modulate any of your signals with the built-in AM, FM, PM, PWM, or FSK source, or use your own external modulation source.

Noise Generation

Inject noise into your device under test with the press of a button. The adjustable amplitude and offset parameters control how much or how little noise is produced. The fast rise times and high speed capability provides the precise noise simulation your applications require.



The faster rise time results in cleaner pulses.

3390

50MHz Arbitrary Waveform/ Function Generator

Ordering Information

3390 **50MHz Arbitrary Waveform/Function Generator**

Accessories Supplied

Arbitrary Waveform Generator with power cord

One universal serial bus (USB) cable (USB-B-1)

One pattern generator cable (005-003-00003)

One Ethernet crossover cable (CA-180-3A)

CD-ROM containing user's manual

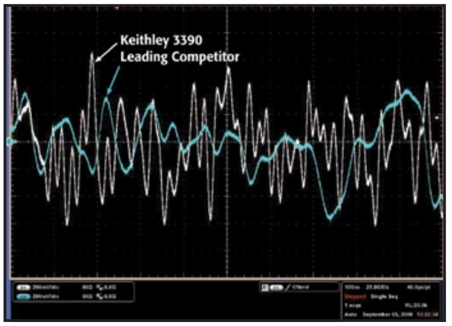
ACCESSORIES AVAILABLE

4299-3	Single Rack Mount Kit
4299-4	Dual Rack Mount Kit
7755	50Ω Feed Through Terminator
7051-2	General Purpose BNC to BNC Cable (2ft)
7007-1	Shielded GPIB Cable, 1m
USB-B-3	USB cable, Type A to Type B, 3m (10ft)
KPCI-488LPA	IEEE-488 Interface/Controller for the PCI bus
KUSB-488B	IEEE-488 USB-to-GPIB Interface Adapter

SERVICES AVAILABLE

3390-3Y-EW	1-year factory warranty extended to 3 years from date of shipment
C/3390-3Y-DATA	3 (Z540-1 compliant) calibrations within 3 years of purchase*

*Not available in all countries



The 20MHz noise bandwidth of the Model 3390 is 2× better than the competition's.

Pattern Generation

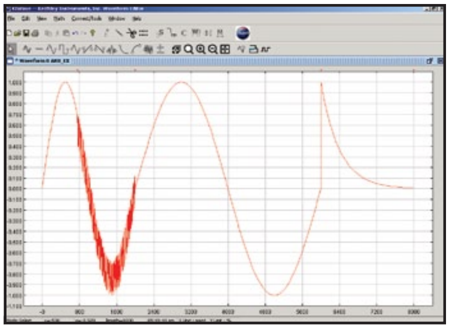
The Model 3390 is the only instrument in its class with a Digital Pattern mode. It provides the ability to transmit arbitrary 16-bit patterns via a multi-pin connector located on the rear panel of the instrument. This feature can be used for applications such as testing clock and data signals directly, sending simple protocols to devices under test, and simulating simple control functions. With Keithley's KiWAVE software package, you can easily create complex and long patterns, which the Model 3390 can generate at varying speeds and amplitudes.

10MHz External Reference Expands Flexibility

The built-in 10MHz external time base is included at no extra cost. This external time base makes it simple to control multiple instruments from the same source, connect multiple Model 3390s together, and synchronize multiple signals of any shape.

Ease of Use

This instrument is easy to use. In most cases, pressing one button on the front panel or performing one or two mouse clicks on your PC is all that is necessary to generate or modify a waveform. The KiWAVE software package helps you define and manage waveforms, apply filters to waveforms, and display waveforms on a PC. In addition, the GPIB, USB, LAN, and LXI interfaces can connect the Model 3390 to most devices under test, instruments, and test fixtures.



KiWAVE Waveform Editing Utility

LXI Class C Compliance

The Model 3390 supports the physical, programmable, LAN, and Web portions of the emerging LAN eXtensions for Instrumentation (LXI) standard. The instrument can be monitored and controlled from any location on the LAN network via its LXI Web page.

Model 3390 rear panel

3390

50MHz Arbitrary Waveform/ Function Generator

Specifications

DISPLAY: Graph mode for visual verification of signal settings.

CAPABILITY:
Standard Waveforms: Sine, Square, Ramp, Triangle, Pulse, Noise, DC.
Built-in Arbitrary Waveforms: Exponential Rise and Fall, Negative ramp, Sin(x)/x, Cardiac.

Waveform Characteristics

SINE

FREQUENCY: 1µHz to 50MHz.

AMPLITUDE FLATNESS [1, 2] **(Relative to 1kHz):** 0.1dB (<100kHz), 0.15dB (<5MHz), 0.3dB (<20MHz), 0.5dB (<50MHz).

HARMONIC DISTORTION [2, 3] **(Unit: dBc):**

DC to 20kHz:	–65(<1Vpp)	–65(≥1Vpp)
20kHz to 100kHz:	–65(<1Vpp)	–60(≥1Vpp)
100kHz to 1MHz:	–50(<1Vpp)	–45(≥1Vpp)
1MHz to 20MHz:	–40(<1Vpp)	–35(≥1Vpp)
20MHz to 50MHz:	–30(<1Vpp)	–30(≥1Vpp).

TOTAL HARMONIC DISTORTION [2, 3]**:** DC to 20kHz, V ≥ 0.5Vpp THD ≤ 0.06% (typical).

SPURIOUS [2, 4] **(non–harmonic): DC to 1MHz:** –70dBc. **1MHz to 50MHz:** –70dBc + 6dB/octave.

PHASE NOISE (10K Offset): –115 dBC/Hz, typical when f ≥ 1MHz, V ≥ 0.1Vpp.

SQUARE

FREQUENCY: 1µHz to 25MHz.

RISE/FALL TIME: <10ns.

OVERSHOOT: <2%.

VARIABLE DUTY CYCLE: 20% to 80% (to 10MHz), 40% to 60% (to 25MHz).

ASYMMETRY: 1% of period + 5ns (@ 50% duty).

JITTER (RMS): 1ns + 100ppm of period.

RAMP, TRIANGLE

FREQUENCY: 1µHz to 200kHz.

LINEARITY: <0.1% of peak output.

SYMMETRY: 0.0% ~ 100.0%.

PULSE

FREQUENCY: 500µHz to 10MHz.

PULSE WIDTH: 20ns minimum, 10ns res. (period ≤10s).

VARIABLE EDGE TIME: <10ns to 100ns.

OVERSHOOT: <2%.

JITTER (RMS): 300ps + 0.1ppm of period.

NOISE

BANDWIDTH: 20MHz typical.

ARBITRARY

FREQUENCY: 1µHz to 10MHz.

LENGTH: 2 to 256K.

RESOLUTION: 14 bits (including sign).

SAMPLE RATE: 125Msamples/s.

MIN RISE/FALL TIME: 30ns typical.

LINEARITY: <0.1% of peak output.

SETTLING TIME: <250ns to 0.5% of final value.

JITTER(RMS): 6ns + 30ppm.

NON-VOLATILE MEMORY: 4 waveforms * 256K points.

COMMON CHARACTERISTIC

FREQUENCY RESOLUTION: 1µHz.

AMPLITUDE RANGE: 10mVpp to 10Vpp in 50Ω, 20mVpp to 20Vpp in Hi-Z.

AMPLITUDE ACCURACY [1, 2] **(at 1kHz):** ±1% of setting ±1mVpp.

AMPLITUDE UNITS: Vpp, Vrms, dBm.

AMPLITUDE RESOLUTION: 4 digits.

DC OFFSET RANGE (Peak AC + DC): ±5V in 50Ω, ±10V in Hi-Z.

DC OFFSET ACCURACY [1, 2]**:** ±2% of offset setting, ±0.5% of amplitude setting.

DC OFFSET RESOLUTION: 4 digits.

MAIN OUTPUT IMPEDANCE: 50Ω typical.

MAIN OUTPUT ISOLATION: 42Vpk maximum to earth.

MAIN OUTPUT PROTECTION: Short-circuit protected; overload automatically disables main output.

INTERNAL FREQUENCY REFERENCE ACCURACY [5]**:** ±10ppm in 90 days, ±20ppm in 1 year.

EXTERNAL FREQUENCY REFERENCE STANDARD/OPTION: Standard.

EXTERNAL FREQUENCY INPUT:
Lock Range: 10MHz ±500Hz.
Level: 100mVpp ~ 5Vpp.
Impedance: 1kΩ typical, AC coupled.
Lock Time: <2 seconds.

EXTERNAL LOCK RANGE: 10MHz.

FREQUENCY OUTPUT:
Level: 632mVpp (0dBm), typical.
Impedance: 50Ω typical, AC coupled.

PHASE OFFSET:
Range: –360° to +360°.
Resolution: 0.001°.
Accuracy: 8ns.

MODULATION

MODULATION TYPE: AM, FM, PM, FSK, PWM, Sweep, and Burst.

AM

CARRIER: Sine, Square, Ramp, ARB.

SOURCE: Internal/External.

INTERNAL MODULATION: Sine, Square, Ramp, Triangle, Noise, ARB.

FREQUENCY (Internal): 2mHz to 20kHz.

DEPTH: 0.0% ~ 120.0%.

FM

CARRIER: Sine, Square, Ramp, ARB.

SOURCE: Internal/External.

INTERNAL MODULATION: Sine, Square, Ramp, Triangle, Noise, ARB.

FREQUENCY (Internal): 2mHz to 20kHz.

DEVIATION: DC ~ 25MHz.

PM

CARRIER: Sine, Square, Ramp, ARB.

SOURCE: Internal/External.

INTERNAL MODULATION: Sine, Square, Ramp, Triangle, Noise, ARB.

FREQUENCY (INTERNAL): 2mHz to 20kHz.

DEVIATION: 0.0° to 360°.

PWM

CARRIER: Pulse.

SOURCE: Internal/External.

INTERNAL MODULATION: Sine, Square, Ramp, Triangle, Noise, ARB.

FREQUENCY (INTERNAL): 2mHz to 20kHz.

DEVIATION: 0% ~ 100% of pulse width.

FSK

CARRIER: Sine, Square, Ramp, ARB.

SOURCE: Internal/External.

INTERNAL MODULATION: 50% duty cycle Square.

FREQUENCY (INTERNAL): 2mHz to 100kHz.

EXTERNAL MODULATION INPUT[6]

VOLTAGE RANGE: ±5V full scale.

INPUT RESISTANCE: 8.7kΩ typical.

BANDWIDTH: DC to 20kHz.

SWEEP

WAVEFORMS: Sine, Square, Ramp, ARB.

TYPE: Linear or logarithmic.

DIRECTION: Up or down.

SWEEP TIME: 1ms ~ 500s.

TRIGGER: Internal, External, or Manual.

MARKER: Falling edge of sync signal (programmable frequency).

50MHz Arbitrary Waveform/ Function Generator

BURST[7]

WAVEFORMS: Sine, Square, Ramp, Triangle, Noise, ARB.
TYPE: Internal/External.
START/STOP PHASE: –360° to +360°.
INTERNAL PERIOD: 1µs ~ 500s.
GATED SOURCE: External trigger.
TRIGGER SOURCE: Internal, External, or Manual.

TRIGGER INPUT

LEVEL: TTL compatible.
SLOPE: Rising or falling (selectable).
PULSE WIDTH: >100ns.
IMPEDANCE: >10kΩ, DC coupled.
LATENCY: <500ns.

TRIGGER OUTPUT

LEVEL: TTL compatible into ≥1kΩ.
PULSE WIDTH: >400ns.
OUTPUT IMPEDANCE: 50Ω typical.
MAXIMUM RATE: 1MHz.
FAN-OUT: ≤4 Keithley 3390s.

PATTERN MODE

CLOCK MAXIMUM RATE: 50MHz.
OUTPUT: Level: TTL compatible into ≥2kΩ.
Output Impedance: 110Ω typical.
PATTERN LENGTH: 2 to 256K.

GENERAL

POWER SUPPLY: CAT II 110–240VAC ±10%.
POWER CORD FREQUENCY: 50Hz to 60Hz.
POWER CONSUMPTION: 50VA max.
OPERATING ENVIRONMENT: 0° to 50°C.
STORAGE TEMPERATURE: –30° to 70°C.
INTERFACE: USB, LAN, LXI-C, GPIB.
LANGUAGE: SCPI-1993, IEEE-488.2.
DIMENSIONS: 107mm high × 224mm wide × 380mm deep (4.2 in. × 8.8 in. × 15 in.).
WEIGHT: 4.08kg.
SAFETY: Conforms with European Union Directive 73/23/EEC, EN 61010-1.
EMC: Conforms with European Union Directive 89/336/EEC, EN 61326-1.
WARM-UP: 1 hour.

NOTES

1. Add 10%/°C of spec for offset and amplitude for operation outside the range of 18° to 28°C.
2. Autorange enabled.
3. DC offset set to 0V.
4. Spurious output at low amplitude is –75dBm typical.
5. Add 1ppm/°C average for operation outside the range of 18° to 28°C.
6. FSK uses trigger input (1MHz maximum).
7. Sine and square waveforms above 10MHz are allowed only with an "infinite" burst count.