ELECTROMETERS

An electrometer is a sensitive, high input impedance instrument used for specialized measurements of dc voltage, dc current, and resistance. An electrometer may also measure electrical charge (a coulombmeter). Superficially, an electrometer is an elegant dc multimeter. In reality, an electrometer is a specialized voltage and current measurement device possessing exceptionally high impedance. This very high input impedance, more than any other technical criterion, is the distinguishing characteristic of instruments in the electrometer class. The similarity to a dc multimeter makes electrometer use fairly intuitive, although a thorough appreciation of performance determinants (e.g., noise and settling time) and careful control of materials, lead routing, and other fixturing details are essential to obtaining the full accuracy and resolution within the capabilities of these exceptional instruments.

Few instruments in measurement science can exceed the electrometer's dynamic range of units. A quality electrometer is capable of presenting very small [atto-amperes (aA) (10^{-18} A)] and very large [petaohms (PΩ) (10^{15} Ω)] units of measure unfamiliar even to experienced equipment users. The general reader will find the standard prefix definitions in Table 1 helpful.

The term electrometer is found in the earliest literature of the electrical sciences—it was employed in the contemporary sense by none other than James Clerk Maxwell (1). Instruments capable of measuring very small currents are sometimes called electrometers, although such usage may be a misnomer (this will be discussed below in "Applications, Current Measurements").

Interestingly, the *IEEE Standard Dictionary of Electrical and Electronics Terms* has no definition of an electrometer, although it tells the reader an electrometer tube is "a vacuum tube having a very low control-electrode conductance to facilitate the measurement of extremely small direct current or voltage" [(2), p. 425]. Lack of specificity is not uncommon, as similar findings are evident in some standard handbooks for electrical and electronics engineers (3), physicists (4), and in textbooks (5–7). For purposes of the following discussion, an electrometer is taken to be an instrument which, as a consequence of possessing exceptionally high input impedance, may be used to make sensitive measurements of voltage, current, and charge.

However ill-defined an electrometer may be in a formal dictionary sense, an electrometer has certain characteristic features. Foremost among the electrometer's defining features is exceptionally high input impedance. Input impedances are measured in hundreds of teraohms [(TΩ) (10^{12} Ω)] or even in petaohms in better quality commercial equipment. The electrometer's high input impedance is responsible for many of the instrument's operating characteristics. Other significant features of an electrometer are the ability to measure small voltages, small currents, and low-level electrical charges. These features alone, however, do not necessarily place an instrument in the electrometer class, for many higher quality, general purpose instruments can measure signals in the microvolt and submicroampere range *if source impedance is low.*

Voltage or current measurement is so commonplace as to be unremarkable in routine laboratory work. This situation prevails because most sensors and virtually all amplifiers present low output impedance to the external world. Instrument makers have gone to considerable pains to make measurement equipment simple to use in very general situations. Even inexpensive instruments have input impedances in the megohm range (clearly, this discussion excludes voltage and current measurements for audio, RF, and other specific applications where impedance matching is a major consideration or where electrometer time constants are prohibitively long). Laboratory quality instruments present relatively high input impedances to the typically low impedance sources producing signals to be measured.

Some measurement applications require an instrument with exceptionally high input impedance because the source itself has unusually high output impedance. Examples of such high impedance signal sources are large-ratio voltage dividers used in high-voltage measurements, ECG scalp electrodes, pH probes, ionization chambers, large resistances, photodiodes, dielectric measurements, and certain semiconductor measurements. The electrometer's high input impedance is required to prevent or reduce circuit loading by the measuring instrument, that is, undesired voltage or current dividers established between source output impedance and measurement device input impedance.

The electrometer's high input impedance is difficult to establish and maintain, is influenced by many subtle error sources, and is also the ultimate reason why electrometers are fundamentally dc or, at best, very low frequency instruments. Shunt capacitance at the instrument input is a physical reality that cannot be entirely eliminated, and the interaction of input shunt capacitance and source resistance establishes the frequency limit of the instrument. This frequency limit is so low as to make an electrometer a dc instrument, and the associated input settling time is a consideration of considerable importance.

Table 1. Standard Prefix Definitions

Symbol	Prefix	Exponent
y	yocto-	10^{-24}
z	zepto-	10^{-21}
a	atto-	10^{-18}
f	femto-	10^{-15}
p	pico-	10^{-12}
n	nano-	10^{-9}
μ	micro-	10^{-6}
m	milli-	10^{-3}
–	–	–
k	kilo-	10^{3}
M	mega-	10^{6}
G	giga-	10^{9}
T	terra-	10^{12}
P	peta-	10^{15}
E	exa-	10^{18}
Z	zetta-	10^{21}
Y	yotta-	10^{24}

The significance of input impedance is easily appreciated in the context of voltage measurements (for example, as in an oscilloscope). If we wish to determine the voltage across a circuit impedance Z_c, a very high impedance measurement circuit with impedance Z_m, produces little or no circuit disturbance. An ideal measurement circuit with infinite input impedance (infinite resistance with zero capacitance) would produce no circuit disturbance at all. The circuit impedance in parallel with the ideal measurement circuit produces a net impedance that is the circuit impedance itself, that is,

$$Z_p = \frac{Z_c Z_m}{Z_c + Z_m} \tag{1}$$

and

$$\lim_{Z_m \to \infty} Z_P = Z_c \tag{2}$$

Although measurement device impedance may be very large, it is not infinite for a physically realizable instrument. Thus, as source impedance increases, the error produced by the measurement device's finite input impedance becomes an increasingly greater contribution to total measurement error. A measurement device of the electrometer class closely approximates the theoretical idealization of infinite input impedance near dc, thereby reducing circuit-loading effects and improving voltage-transfer accuracy.

Many general instrument users experience input impedance problems only at higher frequencies, when shunt capacitance of common instrument inputs can no longer be neglected. The most familiar example of this phenomenon is high-frequency signal attenuation produced by the shunt capacitance of an oscilloscope probe. The −3 dBV response frequency and net impedance of the probe's parallel RC input are well known. As operating frequency increases, probe capacitance reduces the oscilloscope's net input impedance. At sufficiently high frequency, probe capacitance begins to influence and then dominate circuit response. Said another way, as impedance decreases with frequency, the oscilloscope probe places an increasingly greater load on the circuit being measured. The same effects are observed in the interplay between generalized source and measurement impedances, making discussions of oscilloscope probe losses instructive to the general reader as analogous background information (8–10).

The need to avoid input circuit loading is a major consideration requiring the use of an electrometer (the other is noise). Consider the simple circuit of Fig. 1, which represents the low-frequency impedances of a pH electrode (R_e) and the measuring instrument (R_m). Let the voltage actually produced by the pH electrode be V_e, and the voltage actually transferred to the voltage measurement circuit be V_m. By simple voltage division, the low-frequency signal transferred to the input of the voltage measurement elements is given by

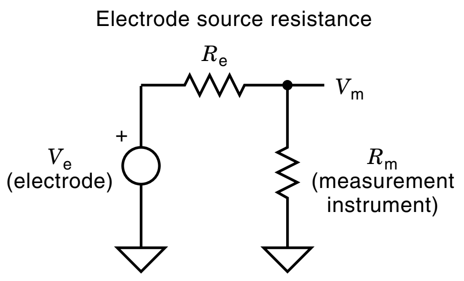

Figure 1. pH electrode source resistance and measurement circuit input resistance form voltage divider.

$$V_m = \left(\frac{R_m}{R_e + R_m}\right) V_e \tag{3}$$

If, for example, a pH electrode has 100 MΩ source impedance (11), a common voltage measurement instrument with 10 MΩ input impedance would introduce a grossly unacceptable measurement error, even though the same 10 MΩ impedance would be thoroughly satisfactory for general laboratory work. An input impedance of 1 GΩ would be only just acceptable, forming a voltage divider transferring roughly 90% of the electrode signal voltage (at best) to the voltage-measurement elements. An input impedance of nearly 10 GΩ is required if the measuring instrument is to transfer 99% of the pH electrode voltage to the voltage-measuring circuit elements.

Establishing and maintaining input impedances in the high GΩ and TΩ ranges is no simple task. Minuscule error currents, ordinarily negligible and themselves difficult to measure directly, become serious errors. Tiny shunt capacitances in combination with such large impedances severely limit the electrometer's time-domain performance. Thermal effects, humidity, dust, circuit board contaminants, vibration, thermocouple effects, material properties, and other considerations all weigh heavily in electrometer design. The old political adage applies: the devil is in the details.

APPLICATIONS

The electrometer's superficial similarity to a dc multimeter makes fundamental instrument application simple and intuitive. Although electrometer application basics are easy to appreciate, it is not simple to obtain the greatest possible accuracy and resolution from the instrument. Error sources can be very subtle, and test fixturing is unusually important. The following material provides an introduction to the use and application of electrometers and related instruments. Little design-related information is included. Excellent introductions to design considerations are available in (17) and in the instrumentation and measurement literature.

Noise Analysis

Electrometer performance analysis is tied intimately to noise analysis. The performance of any measurement instrument is ultimately limited by noise. Noise analysis is especially important to understanding electrometer applications properly because electrometers routinely tread the edge of the theoretical noise limit. A few major results from noise analysis are given below. The more advanced reader will wish to consult other references for a detailed treatment. Noise analysis is covered in a great many texts, and only a few representative examples are cited. Communication theory is a comfortable context for many readers (12–14), more specific discussions [see (15,16)] are useful for their treatment of specific noise mechanisms.

External noise sources, including the interaction of test articles and cabling with electrical, magnetic, and propagating electromagnetic fields, can be attenuated, minimized, or eliminated by test fixture design and shielding. External noise effects are not to be trivialized and are discussed later, but there is often some redress for external noise effects. Internal noise sources, such as thermal noise (Johnson noise) of resistors, shot noise from movement of charge carriers in amplifier input bias currents, and low-frequency ($1/f$) noise, are major noise sources within the electrometer itself. These internal noise sources exist in any physical device and ultimately establish the noise floor (hence, the ultimate sensitivity limit) of the electrometer, even if all external noise sources were reduced to zero.

These same noise mechanisms also exist in source impedances. Proper appreciation of the best theoretically possible noise limit is essential if the user is to obtain reliable measurements from any instrument.

Thermal noise and shot noise are the most common noise mechanisms governing the performance limits of measurement systems, and their significance to electrometer applications is considerable. Root mean square (rms) thermal noise current is given by

$$i_{\mathrm{T,rms}} = \sqrt{\frac{4kT}{R}(\mathrm{NBW})} \tag{4}$$

where k is Boltzmann's constant (1.38×10^{-23} J/K), T is temperature in kelvins, R is resistance in Ω, and NBW is noise bandwidth in hertz. Root mean square shot noise is given by

$$i_{\mathrm{s,rms}} = \sqrt{2qI_{\mathrm{B}}(\mathrm{NBW})} \tag{5}$$

where q is electron charge (1.60×10^{-19} C), I_{B} is bias current in amperes, and NBW is noise bandwidth in hertz. These noise currents may be converted to equivalent noise voltages using knowledge of circuit impedances.

Consider the electrometer input stage. Thermal noise is an explicit function of absolute temperature. Because semiconductor device bias currents vary (ordinarily, they increase) with temperature, shot noise is also a function of absolute temperature and noise bandwidth. Noise signals produced by various mechanisms are often treated as random white Gaussian signals, allowing individual noise components to be combined as a quadrature sum. Although $1/f$ noise is not Gaussian because of its frequency dependence, $1/f$ noise is often included in an overall noise envelope, a piecewise linear fit including the effects of major noise sources. In the near-dc regime of the electrometer, $1/f$ noise is incorporated in the lumped specified noise performance (regardless of origin) of the instrument.

Although noise considerations are sometimes ignored in routine work, noise relationships are important determinants of electrometer performance and must be understood. The instrument designer understands that noise bandwidth and input bias currents must be minimized and that temperature should be maintained at a reasonable level. The instrument user must recognize that certain physical realities (e.g., noise) impose limits on instrument performance and that both system design and instrument specifications must conform to these realities. For example, a specification requiring or implying 1 nV resolution from a 1 MHz bandwidth source should be recognized for what it is: a practical impossibility. Although an electrometer generates measurements with apparent precision, the user can avoid embarrassment by interpreting instrument measurements in the light of the theoretical noise limits of the problem.

Time Constant

Electrometers are distinguished from other test instruments by their uncommonly high input impedance. As Fig. 2 demonstrates, the electrometer input circuit may be represented by a resistance R_{m} and a capacitance C_{m}. In a voltage measurement configuration, the signal source impedance R_{s} and the electrometer input impedance form a voltage divider connection.

In this case, the voltage transfer function in the Laplace transform domain is obtained as

$$\frac{V_{\mathrm{out}}(s)}{V_{\mathrm{in}}(s)} = \frac{R_{\mathrm{m}}}{R_{\mathrm{s}} + R_{\mathrm{m}}}\left[\frac{1}{1 + sC_{\mathrm{m}}R_{\mathrm{p}}}\right] \tag{6}$$

where

$$R_{\mathrm{p}} = \frac{R_{\mathrm{s}}R_{\mathrm{m}}}{R_{\mathrm{s}} + R_{\mathrm{m}}} \tag{7}$$

The equivalent time-domain step response is the familiar first-order step response given by

$$V_0(t) = (1 - e^{-t/\tau})u(t) \tag{8}$$

where $u(t)$ is the unit step function and $\tau = C_{\mathrm{m}}R_{\mathrm{p}}$ is the time constant.

Although realizable electrometers do not actually possess infinite real input impedance, it is very frequently true that $R_{\mathrm{m}} \gg R_{\mathrm{s}}$. If R_{m} is sufficiently large with respect to R_{s}, as it often will be, then the result given in Eq. (6) simplifies to

$$\frac{V_{\mathrm{out}}(s)}{V_{\mathrm{in}}(s)} = \frac{1}{1 + sC_{\mathrm{m}}R_{\mathrm{s}}}$$

and the result given in Eq. (7) simplifies to $R_{\mathrm{p}} \cong R_{\mathrm{s}}$. The time constant, τ, is determined by the source resistance and electrometer input capacitance according to $\tau = C_{\mathrm{m}}R_{\mathrm{s}}$ when this approximation for R_{p} is used.

Previous discussion related the dc divider ratio to the overall signal measurement or voltage transfer accuracy. However, there is an associated time-domain response as given previously which introduces significant error if signal sam-

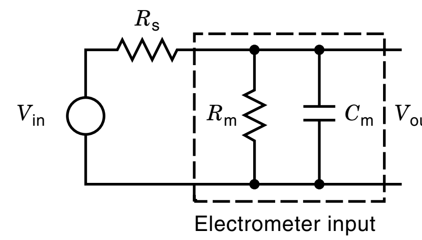

Figure 2. Equivalent circuit of source resistance and electrometer input impedance.

Table 2. Relationship Between Elapsed Time Constants and Relative Measurement Accuracy

Time Constants Elapsed ($\tau = RC$)	Fraction of Step Attained	Error (ppm)
τ	0.632121	367,879
2τ	0.864665	135,335
3τ	0.950213	49,787
4τ	0.981684	18,316
5τ	0.993262	6,738
6τ	0.997521	2,479
7τ	0.999088	912
8τ	0.999665	335
9τ	0.999878	122
10τ	0.999955	45
11τ	0.999983	17
12τ	0.999994	6
13τ	0.999998	2
14τ	>0.999999	<1

pling is done incorrectly. This time-domain consideration is often described as the settling time, that is, the amount of time required for an input step change to settle to within some arbitrary accuracy of the total step. Settling time is most often expressed in terms of the time constant τ. For example, if only a single time constant elapses between application of a step change and a measurement, evaluation of Eq. (8) reveals that only 63% of the step amplitude will be measured. Table 2 indicates the relationship between elapsed time constants and relative measurement accuracy. At least five time constants (5τ) must be allowed for settling if the step change is to be represented with 99% fidelity. In highly precise applications, those in which accuracies are measured in parts per million (ppm), settling times may be much longer. For example, fourteen time constants (14τ) are required for a settling error less than 1 ppm.

Thus, accuracy considerations require the passage of not one but many time constants before the instrument input settles. As shown in Table 2, a settling time of 4τ to 5τ, longer if possible, should be allowed to benefit from a good electrometer's basic accuracy. Settling time is a significant system constraint and is one of the reasons why an electrometer is a dc instrument.

Because an electrometer has very high input impedance, source resistance and input capacitance usually determine the input time constant. Response time is reduced only by reducing electrometer input capacitance or by reducing source resistance (which often is not possible). Various design and construction alternatives, such as driven guard cables, circuit board guard rings, and special mechanical structures are used to reduce input capacitance, thereby improving settling time (17). These techniques may increase net capacitance to ground.

Leakage Current

In the context of an electrometer, leakage current refers to tiny currents present in the instrument input leads. In an ideal instrument, leakage currents are identically zero. Readers familiar with operational amplifier design understand that similar leakage currents interact with circuit impedances to produce various categories of offset errors and other effects. This general problem is especially troublesome in electrometer design for at least two reasons.

First, electrometers are employed with signal sources having very large source impedance and, as noted already, the electrometer itself presents exceptionally high input impedance. Thus, instrument leakage current preferentially finds a path to signal common through the signal source impedance. In the voltage measurement mode, very small electrometer leakage currents through the relatively large signal source impedance can produce highly undesirable voltage offset components at the electrometer input. This is the familiar problem of input offset voltage production in operational amplifier design. In current and charge measurement modes, instrument leakage currents directly interfere with the current being measured.

Second, although the complication is less obvious, recall that shot noise is proportional to the square root of current. Thus, as leakage current increases, shot noise increases. Therefore, input leakage current produces two highly undesirable effects. It directly obscures or interferes with the parameter (voltage, current, or charge) being measured, and it contributes additional noise (uncertainty) to the measurement.

Careful attention to device selection, component matching, thermal environment, and details of assembly and fabrication minimize instrument leakage current. Special signal processing techniques may be used to reduce the apparent effects of signal leakage current, although primary emphasis should be on error prevention rather than error compensation.

Ammeter

Electrometers are dc instruments optimized for sensitivity and accuracy at low (usually microampere and lower) current levels. Many contemporary commercial instruments have maximum input currents of 20 mA, making them of limited utility as general-purpose ammeters. Older instrument designs still in production have higher maximum input current ratings, although full-scale input current is still usually less than 1 A. An electrometer may be used to measure the voltage developed across an external current shunt with great accuracy. Although this approach extends the useful full-scale current range of the composite measurement system, long settling time, limited maximum input current, and cost usually contraindicate using an electrometer as a general-purpose ammeter.

Current Measurement. Current measurement applications include tasks, such as photodiode responses, photodiode dark current variations with temperature, semiconductor current measurements, and other measurement problems characterized by the need to measure small currents and also by the need to handle a wide dynamic range of signal currents. Commercial instruments in computer-controlled test sets accommodate the dynamic range problem by CPU-generated instrument range changes or by the use of logarithmic outputs. The literature contains descriptions of application-specific current measurement devices which approach the dynamic range problem in other ways.

Electrometers are widely employed for low-level current measurement. A device known as a *shunt picoammeter* is an electrometer variant with an input current shunt optimized specifically for low-level current measurements. The differences between an electrometer-based shunt picoammeter and an electrometer are not necessarily substantial, as the two instruments are fundamentally the same in most respects. Identifiable differences between an electrometer and a shunt picoammeter are associated with the shunt resistor and other optimizations for current measurement. The shunt picoammeter has a somewhat lower voltage burden, somewhat faster response time, somewhat reduced sensitivity, and lower cost (17) than an electrometer. This optimization is obtained at the expense of overall versatility.

One especially common and useful application circuit deserves special consideration in this discussion. This circuit, usually called a *transimpedance amplifier* or *feedback picoammeter* (also a current-to-voltage converter) is widely used to measure small currents in a multitude of applications, for example, in conjunction with photodiode detectors in computed tomography (CT) detectors and similar low-signal tasks. Because transimpedance amplifiers are used to measure very small currents, they and apparatus using them are sometimes erroneously described as electrometers, a practice difficult to discourage in the absence of a formal definition of an electrometer. Not all authorities agree that the transimpedance amplifier configuration constitutes an electrometer. One school of thought maintains that the transimpedance amplifier is a picoammeter but *not* an electrometer, although papers can be found in the engineering literature which make the equivalence. Nevertheless, the transimpedance amplifier configuration clearly provides useful analog signal processing of very small currents.

The transimpedance amplifier uses an inverting amplifier connection, as shown in Fig. 3. Assuming an ideal operational amplifier having zero input current, the amplifier's output produces an output current equal exactly to the input current I_i appearing on the inverting input, thereby satisfying Kirchhoff's current law. To do so, the amplifier output voltage V_o, must satisfy the relationship

$$V_o = -R_f I_i$$

The feedback resistance R_f, is often nothing more than a single resistance. In many cases, a plurality of feedback resistances are switch selectable. The choice of multiple feedback resistances is advantageous when a wide dynamic range is anticipated.

Several features should be apparent. The input of the amplifier is a virtual ground, making the input impedance of the device a great deal less than what would normally be considered useful for electrometer applications. It also requires that the signal source behave like an ideal current source. Current errors are dominated by the input bias current of the amplifier, although these errors are relatively low with contemporary FET-input devices. The transimpedance configuration is highly desirable when something other than near-dc operation is required. The −3 dBV frequency is established primarily by the feedback resistor R_f and capacitance associated with the feedback resistor.

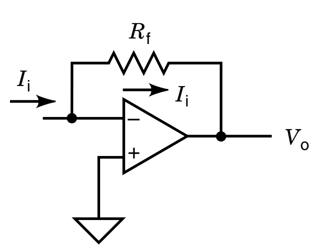

Figure 3. Transimpedance amplifier used as picoammeter.

Charge Measurement

Electrometers measure charge in at least two ways. Charge may be determined by current integration using a feedback picoammeter with a standard capacitor rather than a resistor in the feedback loop, or charge may be determined by accurately measuring the voltage produced when the charge is transferred into a known (standard) capacitor. In both types of measurement, charge measurement is made possible by the electrometer's exceptionally low input bias currents. The virtual absence of instrument bias current introduces little error into the integration of an external current. In the case of stored charge measurement, the near-zero instrument input bias current removes or deposits almost no charge from or into a known external capacitance, allowing charge to be determined directly from the relationship $Q = CV$.

In a closely related application, electrometer measurements can be used for experimentally estimating small unknown capacitances by determining the charge transferred from a standard capacitor to an unknown capacitor under conditions in which charge must be conserved.

Voltmeter

Voltage measurement is among the most common applications for electrometers. Just as manufacturers produce an electrometer variant for optimized low-level current measurement (the picoammeter), manufacturers also produce an electrometer variant optimized for low-level voltage measurement, commonly called a *nanovoltmeter.* Although optimized for small voltage measurements, nanovoltmeters ordinarily do not possess the exceptionally high input impedance associated with true electrometers because measuring exceptionally small voltages assumes lower source impedances. If this were not the case, source thermal noise would easily obscure the measurement. Nanovoltmeter optimization sacrifices the ability to work with the highest possible source impedances. It is usually not cost-effective to use an electrometer or nanovoltmeter as a general-purpose voltmeter.

Resistance Measurement

Electrometers are especially useful for measuring very high resistances or resistivities. This ability usually requires a current source in the electrometer, a configuration sometimes called a "source-measurement" combination. The electrometer measures current driven through the unknown resistance and also measures the resulting voltage developed across the unknown.

Sensitivity and Resolution

The sensitivity of an instrument is the smallest quantity that can be measured. Resolution, a closely related concept, is the smallest quantity that can be displayed. The resolution of an electrometer, as that of any other instrument, depends on

Table 3. Instrument Minimum Resolvable Inputs and Maximum Full-Scale Inputs

Digits	Model	Volts	Amps	Coulombs	Ohms	R_{in} (max)
			Electrometer[a]—Minimum Resolvable Input / Maximum Input			
Analog	610C	10 μV/100 V	1 fA/300 mA	1 fC/10 μC	1 Ω/100 TΩ	100 TΩ
4½	614	10 μV/20 V	10 fA/2 mA	10 fC/20 nC	1 Ω/200 GΩ	50 TΩ
4½	617	10 μV/200 V	100 aA/20 mA	10 fC/20 nC	100 mΩ/10 PΩ	200 TΩ
4½	642	20 μV/11 V	10 aA/100 nA	800 aC/100 pC	N/A	10 PΩ
4½	6512	10 μV/200 V	100 aA/20 mA	10 fC/20 nC	100 mΩ/200 GΩ	200 TΩ
5½	6517A	10 μV/200V	100 aA/20 mA	10 fC/2 μC	10 Ω/100 PΩ	200 TΩ
			Nanovoltmeter[a]—Minimum Resolvable Input / Maximum Input			
Analog	155	±1 μV/±1 kV				100 MΩ
6½	182	1 nV/3 mV				10 GΩ
7½	HP 34420A	100 pV/100 V				10 GΩ
			Picoammeter[a]—Minimum Resolvable Input / Maximum Input			
3½	480		1 pA/2 mA			
4½	485		100 fA/2 mA			
5½	486/487		10 fA/2 mA			
3½	HP4140B		1 fA/pA (est)			

[a] Model numbers given are manufactured by Keithley Instruments, Cleveland, OH, unless otherwise specified.

full-scale amplitude and quantization accuracy (a digital display is assumed). At this time, most commercial instruments have 4½ digit displays and a 20,000 : 1 ratio between full-scale signal and the minimum resolvable quantity corresponding to that full-scale signal. On the instrument's most sensitive scale, sensitivity and resolution become essentially the same thing. In the discussion which follows, sensitivity is used in the sense of the smallest measurable quantity capable of display on the most sensitive scale.

The state of the art progresses rapidly. The minimum resolvable inputs (best resolutions) and maximum full-scale inputs shown in Table 3 are typical now of contemporary commercial instruments.

It is worth remembering that the quantity of charge associated with a single electron is roughly 0.160 aC, thus, a sensitivity of 100 aA corresponds to a current of roughly 629 electrons per second. The notion of electrical current is a macroscopic concept in which large numbers of charged particles (electrons) are in motion per unit time. At current levels measured in hundreds of attoamperes, measurement specialists often begin to speak of "electron counting," for the notion of electrical current as a macroscopic behavioral average begins to break down. Current fluctuations become more pronounced. At the most fundamental level, each electron carries a 0.160 aC packet of electrical charge. When only relatively few electrons are in motion, the concept of electrical current increasingly becomes a statistic of average rates of arrival. Similarly, the ability to resolve electrical charge in steps of 10 fC corresponds to charge quantization in steps of slightly less than 63,000 electrons.

Commercial electrometers usually have voltage sensitivities of 10 μV out of 200 mV full scale. On resistance measurements, resolutions usually range from 100 mΩ (out of a 2 kΩ full scale) to 1 GΩ (out of 200 TΩ full scale). Resistance measurements are most often implemented using a constant current source to drive the device under test with Kelvin connections to the voltmeter section. Resistance is a calculated value that takes advantage of the electrometer's ability to make high-resolution voltage and current measurements.

Nanovoltmeters are electrometer-like instruments optimized for measuring small voltages. Nanovoltmeters do not possess the exceptionally high input impedance of a true electrometer, although they can hardly be regarded as low input impedance devices. At the present time, a high-quality standard commercial instrument is sensitive to 1 nV out of a full-scale signal of 3 mV.

Because a great many small-current applications do not require the expense, versatility, and exceptional sensitivity of a full-blown electrometer, some instruments are optimized for small current measurements and reduced cost. These instruments are called picoammeters. As their name suggests, the available sensitivity is usually 1 pA, although at least one commercial picoammeter instrument has an advertised sensitivity of 1 fA. Picoammeters are exceptionally useful for laboratory work, as they accommodate the current measurement requirements of a large percentage of precision applications.

Nullmeter

One common early use of electrometers was to indicate null, or zero voltage, in precision bridges. This application is still important, and variations of the concept are found in servo loops and certain other automatic control applications where it is desirable to drive a loop to a null condition.

Oddly enough, nulling applications are somewhat vulnerable to an infrequently considered, yet surprisingly difficult, type of error, namely, the difficulty in determining exactly what is zero volts. A small piece of copper wire (a shorting bar) across the input terminals does not provide a completely satisfactory answer to this seemingly simple question, because such a simple approach is vulnerable to subtle thermocouple and low-level motion effects.

In response to this need and for calibration checks, instrument manufacturers have special electrometer accessories known as *low thermal shorting plugs.* These assemblies are indeed little more than sophisticated shorting bars, but they are important because they allow the user to verify that an indicated zero volt reading or null actually represents a zero volt differential when thermal and mechanical effects are controlled. The material of all connecting wires needs to be known.

Circuit of Electrometers

Complex networks of more than one electrometer require good measurement practices. The particular sensitivity of electrometer-class instruments demands careful consideration of the physical locations and connections of apparatus. Unanticipated input capacitance increases, low-level ground loops, thermal gradients, poor isolation practices, and lack of good shielding from stray fields are all common problems in low-level test applications. An electrometer in the test environment does not, by itself, make such problems more acute, but the consequences of poor test practices may be more severe because of the high impedance of the signal source (the fact that an electrometer is employed suggests that the signal source is a high-impedance source as well).

Many general instrument users are aware that thermocouple effects perturb delicate dc measurements. Most general users are surprised to learn that simple movement and vibration of the wire interconnecting test articles and test apparatus are a significant problem due to the triboelectric effect, the generation of small voltages as a conductor moves within an insulator. Likewise, a wire moving or swinging in a magnetic field gives rise to undesired signals by electromagnetic induction, just as in an electric generator. Insulator deformation can result in piezoelectric behavior which generates error signals. Such considerations as relative humidity, dust, and cleanliness of the apparatus often have major impact when the investigator wishes to partition signal currents into current bins smaller than one fA. Dust adhering to a fingerprint across two circuit traces represents a surprisingly low impedance (relative to impedances of several hundred TΩ or higher), especially on a humid day. For these reasons, some commercial instruments have ancillary displays of temperature and relative humidity on the electrometer face.

Measurement Standards

The ability to measure fundamental electrical quantities, namely, voltage, current, and charge, with such sensitivities is quite remarkable. Various circuit elements, such as voltage references, digitizers (A/D converters), amplifiers, and related functional devices, can be isolated and refined during the normal course of engineering development. The process of insuring that measurements made worldwide respond uniformly to the same potential differences is one aspect of the problem of measurement standards. The actual primary standards themselves, for example, the standard volt, are the province of various national laboratories and international standard-setting bodies [in the United States, the National Institute of Science and Technology (NIST)].

Development and maintenance of standard units is a fascinating study in its own right but is outside the scope of this article. The instrument user is normally unconcerned with measurement standards other than to ensure that the instrument is properly calibrated periodically. Measurement standards involve a multitiered system of primary standards (at the national and international level), secondary standards (calibrated to the primary standard), and working standards calibrated to secondary standards. For example, various national and international bodies determine what absolute potential difference constitutes the standard volt and maintain the physical artifacts producing the standard volt. The instrument manufacturer maintains standards traceable to the primary physical standard and makes sure that all subsequent operations (quantizations or otherwise) ultimately agree with the physical standards.

ADVANCED TOPICS

The manufacturer specifies performance of an electrometer instrument which may be considered to begin at the input connector. Mechanical and electrical details inside the instrument are carefully designed to maintain high input impedance and to reduce error contributions from a great many sources. Conceptually, the electrometer is a highly sophisticated dc multimeter, and the operating concepts are intuitive. The electrometer is an instrument capable of operating at the theoretical limit of source thermal noise, and there is little the user can do to improve on the instrument's performance. There is, however, much the user can do to degrade the instrument's performance if the external test apparatus is carelessly made. The advanced user ordinarily does not struggle with circuit details on the electrometer side of the input connector. The instrument manufacturer does that, but the advanced user expends effort to connect the test article to the instrument while minimizing stray leakage paths, electrostatic effects, piezoelectric effects, triboelectric effects, inductive coupling, thermocouple effects, and a great many other low-level problems.

It is not possible to anticipate all problems that arise. Each application is different in its details, which is where the problems hide. Major considerations are introduced only briefly here. An excellent and detailed practical discussion is found in (17).

Input Guarding

Input guarding is the use of a driven guard structure around the input signal lines. This may be a guard conductor in a cable or guard ring traces on a circuit board. The practice is common in electrometer applications, and a guard connector is ordinarily available at the instrument input. The principle is to control guard ring potential so as to minimize potential difference between the input signal lines and surrounding structures, thereby nulling leakage current, although capacitance to ground increases. This is an important consideration, because instrument response time (settling time) is directly affected by input capacitance. Uncontrolled input capacitance introduces measurement error by allowing insufficient settling time for the measurement cycle.

Cable Selection and Preparation

In general, it is probably best to mount test cables rigidly so that capacitance and leakage are constant and controlled. This is not always possible. Specialty cables are available which provide shielding in the usual sense and also minimize triboelectric and other motion-related noise. Cable preparation is extremely important if the full benefits of specialty cables and connectors are to be realized.

Materials Selection

Materials employed as substrates, insulators, and stand-offs in the test apparatus substantially affect measurement quality. In large part, this dependence on materials is more pronounced in electrometer applications because source and instrument impedances are very high. Materials must be selected with the utmost care, and this often involves compromises between material properties, machining qualities, cost, and other factors.

Cleanliness

Thoroughly appropriate material selection can be defeated by lack of cleanliness. Surface contamination from skin oils, soldering residues, dust, and similar sources produces stray leakage paths which interfere with the intended signal path. This is especially true in relatively high humidity, and the combined effect of variable or elevated humidity and a contaminated surface can be very, very serious. Wear clean, lint-free gloves when you work on the apparatus or be prepared to clean it thoroughly after the work is complete.

Mechanical Rigidity

Mechanical rigidity of the test apparatus is important for several reasons. Triboelectric effects arise from the relative motions of a conductor and associated insulator. If there is no relative motion, there is no triboelectric effect. Additionally, some materials are more piezoelectric than others, and eliminating motion eliminates the opportunity for piezoelectric signal generation.

Electromagnetic Shielding

Electromagnetic shielding is employed to eliminate or minimize the effects of external (relative to the test article) electromagnetic fields. This topic is covered in great details in many sources (16). Low-frequency magnetic shielding is difficult to implement, but a reasonable number of options are available if the test cell volume is relatively small. Test leads and the test article together constitute an inductive loop. The effects of inductive signal pickup can be minimized by reducing loop area and by reorienting the loop geometry of the test apparatus relative to the interfering field source. Electrostatic shielding is ordinarily much simpler to implement.

Temperature Control

Temperature control is important because temperature is a consideration in thermal noise, semiconductor leakage current, thermocouple effects, and other similar phenomena. Semiconductor leakage currents, in particular, are strong functions of temperature. Measuring an offset voltage for later subtraction from a reading includes the tacit assumption that temperature (hence, offset) remains constant over the measurement interval. Thermal gradients across semiconductor devices can introduce unpredictable offset behavior, and for this reason most instruments have a specified warm-up period to guarantee full accuracy. Thermal gradients also arise from air flow around the test apparatus, and thus air flow should be controlled. Every connection in the test apparatus is a thermocouple junction, and temperature affects each of them.

Humidity Control

Humidity is a problem less obvious than temperature, but it also must be controlled. Humidity changes are especially troublesome because the insulating properties of dielectrics often depend on humidity. If someone handles a circuit board with bare hands and leaves a fingerprint across the measurement terminals, the resulting high (but finite) impedance leakage path strongly depends on relative humidity. Electrometers may have input impedances of 100 TΩ or more, the signal source being measured may have a source impedance measured in many GΩ. A leakage path, even one measured in hundreds of MΩ, can have a very detrimental impact on measurements. If a leakage path is a strong and highly variable function of relative humidity, as is true of many contamination paths, the effect can be very serious yet erratic.

Some upper end electrometers have built-in humidity indicators. This gives the operator an indication of the humidity inside the instrument, a consideration useful in obtaining the highest possible instrument accuracy, but humidity may very well exert a more serious influence on the test apparatus.

Light

The photoelectric effect was discovered early in the history of semiconductors. The photoelectric effect can be a problem during semiconductor measurements, especially measurements made at the die level. Diodes are especially light-sensitive, but care is warranted in all cases. If there is any question about the light-tightness of a device package, be aware that ambient light falling on the wrong junction can be a problem.

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ELECTROMETERS. See DOSIMETRY.