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Charge Measurement

Saps Buchman
Stanford University

John Mester
Stanford University

Timothy J. Sumner
Imperial College

Electric charge, a basic property of elementary particles, is defined by convention as negative for the electron and positive for the proton. In 1910, Robert Andrews Millikan (1868–1953) demonstrated the quantization and determined the value of the elementary charge by measuring the motion of small charged droplets in an adjustable electric field. The SI unit of charge, the *coulomb* (*C*), is defined in terms of base SI units as:

$$1 \text{ coulomb} = 1 \text{ ampere} \times 1 \text{ second} \tag{8.1a}$$

In terms of fundamental physical constants, the coulomb is measured in units of the elementary charge *e*:

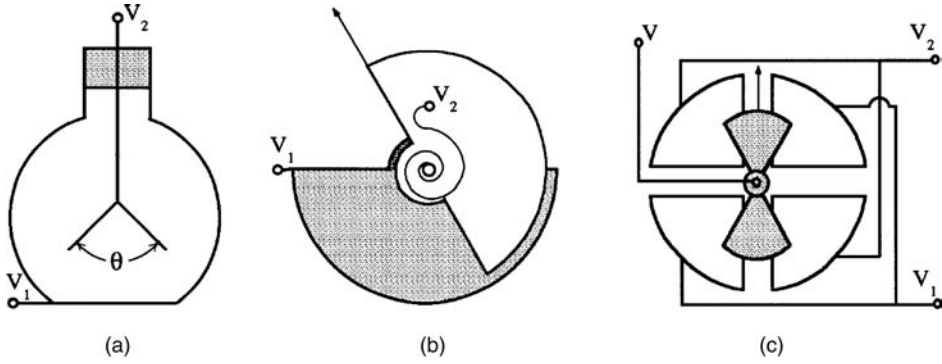$$1 \text{ C} = 1.60217733 \times 10^{19} \, e \tag{8.1b}$$

where the relative uncertainty in the value of the elementary charge is 0.30 ppm [1].

Charge measurement is widely used in electronics, physics, radiology, and light and particle detection, as well as in technologies involving charged particles or droplets (as for example, toners used in copiers). Measuring charge is also the method of choice for determining the average value for small and/or noisy electric currents by utilizing time integration. The two standard classes of charge-measuring devices are the electrostatic voltmeters and the charge amplifiers.

Electrostatic instruments function by measuring the mechanical displacement caused by the deflecting torques produced by electric fields on charged conductors [2,3]. Electrostatic voltmeters also serve as charge-measurement devices, using the fact that charge is a function of voltage and instrument capacitance. This class of instruments can be optimized for a very wide range of measurements, from about 100 V to 100 kV full-scale, with custom devices capable of measuring voltages in excess of 200 kV. The accuracy of electrostatic voltmeters is about 1% of full scale, with typical time constants of about 3 s. Their insulation resistance is between $10^{10} \, \Omega$ and $10^{15} \, \Omega$, with instrument capacitances in the range of 1 pF to 500 pF. Figure 8.1 gives a schematic representation of several types of electrostatic voltmeters.

Modern electronic instruments have replaced in great measure the *electrostatic voltmeters* as devices of choice for the measurement of charge. The charge amplifier is used for the measurement of charge or charge variation [4]. Figure 8.2 shows the basic configuration of the charge amplifier. The equality of charges on C_1 and C_f results in:

$$v_{\text{o}} = \frac{C_1}{C_{\text{f}}} v_{\text{i}} \quad \text{or} \quad \Delta v_{\text{o}} = \frac{C_1}{C_{\text{f}}} \Delta v_{\text{i}} \tag{8.2}$$

FIGURE 8.1 Examples of the repulsion, attraction, and symmetrical mechanical configurations of electrostatic voltmeters: (a) gold-leaf electroscope, (b) schematic representation of an attraction electrostatic voltmeter, (c) a symmetric quadrant electrostatic voltmeter [2].
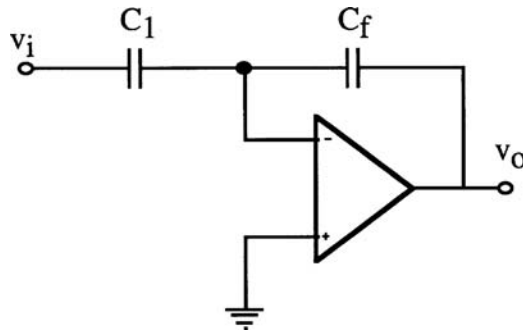

FIGURE 8.2 Basic concept of the charge amplifier. The output voltage is $v_o = C_1/C_f \times v_i$.

This same measurement principle is realized in the *electrometer*. The charge, Q, to be measured is transferred to the capacitor, C, and the value, V, of the voltage across the capacitor is measured: $Q = CV$. Figure 8.3 shows the block diagram for the typical digital electrometer [5]. Charge is measured in the coulomb mode, in which a capacitor C_f is connected across the operational amplifier, resulting in the input capacitance AC_f. Typical gain A for these amplifiers is in the range 10^4 to 10^6, making AC_f very large, and thus eliminating the problem of complete charge transfer to the input capacitor of the coulombmeter. Electrometers have input resistances in the range 10^{14} Ω to 10^{16} Ω, resulting in very long time constants, and thus minimizing the discharging of the capacitor. Typical leakage currents are 5×10^{-14} A to 5×10^{-16} A, again minimizing the variation in the charge. In the coulombmeter mode, electrometers can measure charges as low as 10^{-15} C and currents as low as 10^{-17} A.

Errors in charge-measuring instruments are caused by extraneous currents [5]. These currents are generated as thermal noise in the shunt resistance, by resistive leakage, and by triboelectric, piezoelectric, pyroelectric, electrochemical, and dielectric absorption effects. The coulombmeter function of the electrometers does not use internal resistors, thus eliminating this thermal noise source. Triboelectric charges due to friction between conductors and insulators can be minimized by using low-noise triaxial cables, and by reducing mechanical vibrations in the instrument. Under mechanical stress, certain insulators will generate electric charge due to piezoelectric effects. Judicious choices of materials and reduction of stress and mechanical motion can significantly reduce this effect.

Trace chemicals in the circuitry can give rise to electrochemical currents. It is therefore important to thoroughly clean and dry chemicals of all sensitive circuitry. Variations in voltages applied across insulators cause the separation and recombination of charges, and thus give rise to dielectric absorption
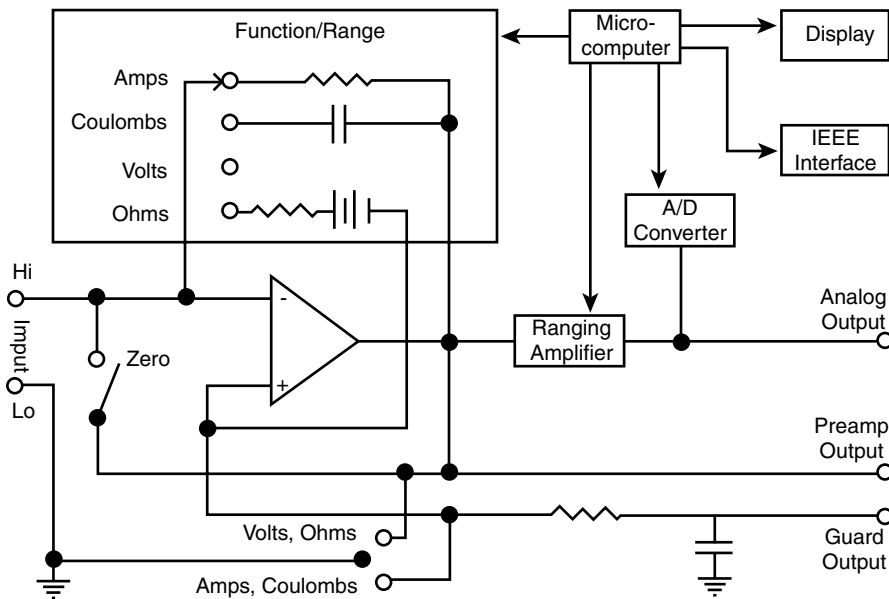
FIGURE 8.3 Conceptual block diagram of the digital electrometer. In the coulombs function, the charge to be determined is transferred to the corresponding capacitor, and the voltage across this capacitor is measured.

parasitic currents. The solution is to limit the voltages applied to insulators used for high-sensitivity charge measurements to less than about 5 V.

Dielectric materials used in sensitive charge-measurement experiments should be selected for their high resistivity (low resistive leakage), low water absorptivity, and minimal piezoelectric, pyroelectric, triboelectric, and dielectric absorption effects. Sapphire and polyethylene are two examples of suitable materials. *Guarding* is used to minimize both shunt currents and errors associated with the capacitance of cables and connectors. The block diagram in Figure 8.3 shows typical guarding arrangements for modern electrometers.

8.1 Electrostatic Voltmeters

Electrostatic voltmeters and the more sensitive mechanical electrometers use an indicator to readout the position of a variable capacitor. Depending on their mechanical configuration, the electrostatic voltmeters can be categorized into three types: repulsion, attraction, and symmetrical [2, 3]. The moving system in the high-sensitivity instruments is suspended from a torsion filament, or pivoted in precision bearings to increase ruggedness. A wide variety of arrangements is used for the capacitative elements, including parallel plates, concentric cylinders, hinged plates, and others. Motion damping of the moving parts is provided by air or liquid damping vanes or by eddy current damping.

One of the oldest devices used to measure charge is the *gold leaf electroscope,* shown in Figure 8.1a. Thin leaves of gold are suspended from a conductive contact that leads out of a protective case through an insulator. As charge applied to the contact is transferred to the leaves, the leaves separate by a certain angle, the mutual repulsion being balanced by gravity. In principle, this device can also be used to measure the voltage difference between the contact electrode and the outer case, assuming the capacitance as a function of leaf separation angle is known. The electroscope is an example of a repulsion-type device, as is the Braun voltmeter in which the electroscope leaves are replaced by a balanced needle [2]. The delicate nature and low accuracy of this class of instruments limit their use in precise quantitative measurement applications.

An example of an attraction electrostatic voltmeter used for portable applications is shown in Figure 8.1b. While the fixed sector disk is held at V_1, the signal V_2 is applied to the movable sector disk through a coil spring that supplies the balancing torque. Opposite charges on the capacitor cause the movable plate to rotate until the electric attraction torque is balanced by the spring. If a voltage $V = V_1 - V_2$ is applied, the electric torque is given by [3]:

$$\tau = \frac{dU}{d\theta} = \frac{d\left(\frac{1}{2}CV^2\right)}{d\theta} = \frac{1}{2}V^2\frac{dC}{d\theta} \tag{8.3}$$

The balancing spring torque is proportional to angular displacement, so the angle at equilibrium is given by:

$$\frac{1}{2}V^2\frac{dC}{d\theta} = K\theta \tag{8.4}$$

Since the rotation is proportional to V^2, such an instrument can be used to measure ac voltages as well.

Symmetrical instruments are used for high-sensitivity, low-voltage measurements. The voltage is applied to a mobile element positioned between a symmetrical arrangement of positive and negative electrodes. Common mode displacement errors are thus reduced, and the measurement accuracy increased. One of the first devices sensitive enough to be called an "electrometer" was the quadrant electrometer shown schematically in Figure 8.1c. As a voltage difference, $V_1 - V_2$, is applied across the quadrant pairs, the indicator is attracted toward one pair and repelled by the other. The indicator is suspended by a wire allowing the stiffness of the suspension to be controlled by the potential V, so that the displacement is given by [2]:

$$\theta = K\left[\left(V_1 - V_2\right)\left(V - \frac{1}{2}\left(V_1 - V_2\right)\right)\right] \tag{8.5}$$

where K is the unloaded spring constant of the suspension.

The advantage of electrostatic instruments is that the only currents they draw at dc are the leakage current and the current needed to charge up the capacitive elements. High-performance symmetrical electrostatic instruments have leakage resistances in excess of 10^{16} Ω, sensitivities of better than 10 μV, and capacitances of 10 pF to 100 pF. They are capable of measuring charges as small as 10^{-16} C, and are sensitive to charge variations of 10^{-19} C.

Historically, as stated above, the symmetrical electrostatic voltmeters have been called "electrometers." Note that this can give rise to some confusion, as the term *electrometer* is presently also used for the electronic electrometer. This is a high-performance dc multimeter with special input characteristics and high sensitivity, capable of measuring voltage, current, resistance, and charge.

Modern noncontacting electrostatic voltmeters have been designed for voltage measurements up to the 100 kV range. An advantage of these instruments is that no physical or electric contact is required between the instrument and test surface, ensuring that no charge transfer takes place. Kawamura, Sakamoto, and Noto [6] report the design of an attraction-type device that uses a strain gage to determine the displacement of a movable plate electrode. Hsu and Muller [7] have constructed a micromechanical shutter to modulate the capacitance between the detector electrode and the potential surface to be measured. Trek Inc. [8] electrostatic voltmeters achieve a modulated capacitance to the test surface by electromechanically vibrating the detector electrode. Horenstein [9], Gunter [10], and MacDonald and Fallone [11] have employed noncontacting electrostatic voltmeters to determine the charge distributions on semiconductor and insulator surfaces. Tables 8.1 and 8.2 contain a selection of available commercial devices and manufacturers.

TABLE 8.1 Instruments Used in Charge Measurement Applications

Instrument Manufacturer	Model #	Description	Approximate Price
Advantest	TR8652	Electrometer	$2500.00
	R8340/8340A	Electrometer	$5400.00
	R8240	Digital electrometer	$2300.00
	TR8601	Micro current meter	$3500.00
	TR8641	Pico ammeter	$2500.00
Amptek	A101	Charge preamplifier	$300.00
	A111	Charge preamplifier	$375.00
	A203	Charge preamplifier/shaper	$300.00
	A225	Charge preamplifier/shaper	$395.00
	A250	Charge preamplifier	$420.00
EIS	ESH1-33	Electrostatic voltmeter	$1650.00–$5890.00[a]
	ESD1-11	Electrostatic voltmeter	$1465.00–$1740.00[a]
	CRV	Electrostatic peak voltmeter	$2100.00
Jennings	J-1005	RF kilovoltmeter	$5266.00
Keithley	610C	Electrometer	$4990.00
	614	Digital electrometer	$2490.00
	617	Programmable electrometer	$4690.00
	642	Digital electrometer	$9990.00
	6512	Electrometer	$2995.00
	6517	Electrometer	$4690.00
Kistler	5011B	Charge amplifier	$2700.00
	5995	Charge amplifier	$1095.00
	5395A	Charge calibrator	$11655.00
Monroe	168-3	Electrostatic voltmeter	$4975.00
	174-1	Electrostatic voltmeter	$5395.00
	244AL	Electrostatic millivoltmeter	$3695.00
	253-1	Nanocoulomb meter/Faraday cup	$1765.00
Nuclear Associates	37-720FW	Digital electrometer for dosimetry	$1234.00
Trek	320B	Electrostatic voltmeter	$1930.00
	341	Electrostatic voltmeter	$6900.00
	344	Electrostatic voltmeter	$2070.00
	362A	Electrostatic voltmeter	$2615.00
	368	Electrostatic voltmeter	$2440.00–$9160.00[a]

[a] Available in a range of specifications.

8.2   Charge Amplifiers

The conversion of a charge, Q, into a measurement voltage involves at some stage the transfer of that charge onto a reference capacitor, C_r. The voltage, V_r, developed across the capacitor gives a measure of the charge as $Q = V_r/C_r$. There are two basic amplifier configurations for carrying out such measurements using the reference capacitor in either a *shunt* or *feedback* arrangement.

Shunt Amplifiers

Figure 8.4 shows a typical circuit in which the reference capacitor is used in a shunt mode. In this example, it is assumed that the charge that is to be measured is the result of the integrated current delivered by a time-dependent current source, $i(t)$. With the measurement circuit disconnected (switch in position s2), the charge on the source capacitor, C_s, at time τ will be $Q = \int_0^c i(t)\mathrm{d}t$ (assuming Q starts from zero at $t = 0$) and the output voltage, V_o, will be zero, as the input voltage to the (ideal) operational amplifier is zero. On closing the switch in position s1, the charge on C_s will then be shared between it and C_r and:

TABLE 8.2   Instrument Manufacturers

|	
Advantest Corporation	Kistler Intrumente AG
Shinjuku-NS Building 4-1	CH-8408 Winterthur, Switzerland
Nishi-Shinjuku 2-Chome, Shinjuku-ku	
Tokyo 163-08 Japan	Monroe Electronics
	100 Housel Ave.
Amptek Inc.	Lyndonville, NY 14098
6 De Angelo Drive	
Bedford, MA 01730	Nuclear Associates
	Div. of Victoreen, Inc.
Electrical Instrument Service Inc.	100 Voice Rd.
Sensitive Research Instruments	P.O. Box 349
25 Dock St.	Carle Place, NY 11514-0349
Mount Vernon, NY 10550	
	Trek Incorporated
Jennings Technology Corporation	3922 Salt Works Rd.
970 McLaughlin Ave.	P.O. Box 728
San Jose, CA 95122	Medina, NY 14103
Keithley Instruments Inc.	
28775 Aurora Road	
Cleveland, OH 44139	
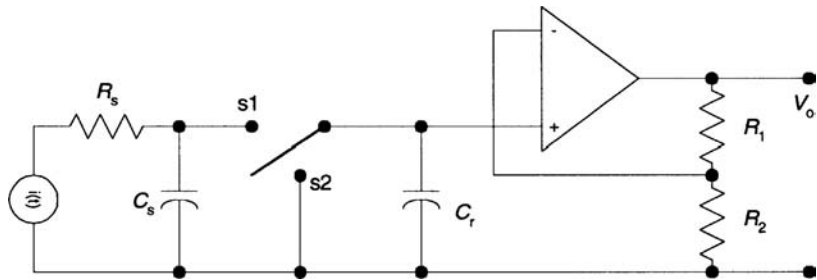
FIGURE 8.4 Schematic representation of a charge amplifier using a shunt reference capacitor. With the switch in position s1, the measurement circuit is connected and the charge is proportional to the output voltage and to the sum $C_s + C_r$. Note the significant sensitivity to C_s.

$$V_o = \left(\frac{R_1 + R_2}{R_2} \right) \frac{Q}{C_s + C_r} \qquad (8.6)$$

In order to accurately relate the output voltage to the charge Q, not only does the gain of the non-inverting amplifier and the reference capacitance need to be known, which is relatively straightforward, but it is also necessary to know the source capacitance. This is not always easy to determine. The effect of any uncertainty in the value of C_s can be reduced by increasing the value of the reference capacitor to the point where it dominates the total capacitance. However, in so doing, the output voltage is also reduced and the measurement becomes more difficult. The dependence of the measurement on C_s is one of the main limitations to this simple method of charge measurement. In addition, any leakage currents into the input of the operational amplifier, through the capacitors, or back into the source circuitry during the measurement period will affect the result. For the most accurate measurements of low charge levels, *feedback amplifiers* are more commonly used.
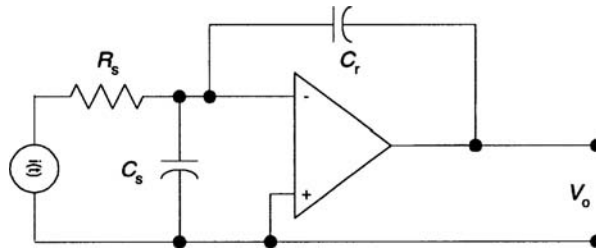
FIGURE 8.5 Schematic representation of a charge amplifier with reference feedback capacitor. The charge is proportional to the output voltage and to the sum $C_s + AC_r$, where A is the amplifier gain. Note the reduced sensitivity to C_s.

Feedback Amplifiers

Figure 8.5 shows a circuit where the reference capacitor now provides the feedback path around the operational amplifier. The output voltage from this configuration for a given charge Q transfer from the source is then:

$$V_o = \frac{AQ}{C_S + AC_r} \qquad (8.7)$$

where A is the open-loop gain of the operational amplifier. For most situations, $AC_r > C_s$ and the charge measurement becomes independent of the source capacitance. In addition, the inverting input to the operational amplifier is kept close to ground potential, reducing the magnitude of leakage currents in that part of the circuit. However, in contrast to these two benefits is the new problem that the input bias current for the operational amplifier is integrated by the feedback capacitor, producing a continual drift in the output voltage. Several solutions have been used to overcome this problem, including the use of a parallel feedback resistor, R_f, which suppresses the integrating behavior at low frequencies (periods longer than $R_f C_r$), balancing the bias current with another externally provided current, and incorporating a reset switch that discharges the circuit each time the output voltage ramps beyond a set trigger level.

The sensitivity of feedback amplifiers depends on the noise sources operating within any specific application. The most impressive performance is obtained by amplifiers integrated into CCD chips (charge coupled devices) that can, under the right operational conditions, provide sensitivities measured in terms of a few electron charges. To illustrate the important parameters involved in the design of ultralow noise charge preamplifiers for CCD-type applications, consider the circuit shown in Figure 8.6. The source (detector) is now shown as a biased photodiode, which is assumed to be producing individual bursts of charge each time a photon (an X-ray, for example) interacts in it. In this example, the photodiode is coupled to the amplifier using a large value capacitor, C_c. This blocks the direct current path from the diode bias supply, V_b, but provides a low impedance path for the short-duration charge deposits. The preamplifier is a variant on that shown in Figure 8.5, in which there is now a parallel feedback resistor to provide baseline restoration on long time scales and an FET transistor to reduce the effect of the operational amplifier input bias current by virtue of its high current gain factor, β.

In practice, the dominant noise contributions in most applications of this type come from Johnson (current) noise in the bias and feedback resistors, shot noise on the photodiode bias current, voltage noise across the FET, and finally the inevitable $1/f$ component. The two resistors effectively feed thermal current noise into the input of the integrator. Similarly, the shot noise associated with the photodiode bias current feeds into the input. Together, these components are known as *parallel* noise and the total parallel noise charge is given by:
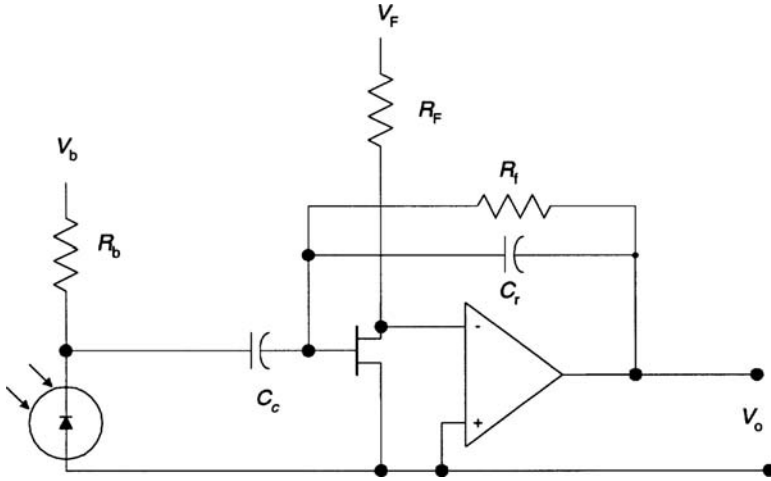
FIGURE 8.6 Typical ultralow noise charge preamplifier configuration for charge pulse readout from ionization type radiation detectors (e.g., X-ray detection using photodiodes or CCDs). The large capacitor C_c provides a low impedance path for the short charge deposit pulses, while the parallel feedback resistor provides baseline restoration on long time scales. An FET transistor reduces the effect of the operational amplifier input bias current.

$$q_p = \sqrt{\left(\frac{4kT}{R_f + R_b} + 2eI_b(T)\right)\frac{1}{\Delta B}} \tag{8.8}$$

where k is Boltzmann's constant, e is the charge on the electron, T is absolute temperature, and ΔB is the bandwidth associated with the measurement that will depend on the details of subsequent shaping amplifier stages [12]. Voltage noise across the FET (and hence operational amplifier inputs) will arise from junction noise in the FET itself and from Johnson noise in its bias resistor, R_F. In practice, the FET junction noise usually dominates, in which case this *series* noise contribution is given by:

$$q_s = \sqrt{\varepsilon_n^2 C_{in}^2 \Delta B} \tag{8.9}$$

where ε_n is the junction voltage noise for the FET in $V\sqrt{Hz}^{-1}$ and C_{in} is the total capacitance seen at the gate of the FET. This will include both the source capacitance, the gate capacitance of the FET, and any stray capacitance. The total noise is then the quadrature sum of Equations 8.8 and 8.9. The different dependencies on the bandwidth for Equations 8.8 and 8.9 imply there will be some optimum bandwidth for the measurement and this will depend on the relative contributions from each. $1/f$ noise manifests itself as a bandwidth-independent term that again, must be added in quadrature. The Johnson noise associated with the resistors and FET junction will show a temperature dependence decreasing with $\sqrt{T}$. For the FET, this reduction does not continue indefinitely and there is usually an optimum temperature for the FET around 100 K. Photodiode bias currents also fall with decreasing temperature and, for silicon devices, this is about a factor of 2 for every 10 K drop in temperature. Most ultralow noise applications thus operate at reduced temperature, at least for the sensitive components. Bias resistors and feedback resistors are kept as high as possible (typically > 100 MΩ) and FETs are specially selected for low junction voltage noise (typically 1 nV$\sqrt{Hz}^{-1}$). Ideally, photodiode capacitances should be kept as low as possible and there is also an interplay between the FET junction noise, ε_n, and the FET gate capacitance that is affected by altering the FET bias current, which can be used to fine-tune the series noise component.

Finally, there is another noise component that can often be critical and difficult to deal with. This is from microphonics. There are two effects. First, the feedback reference capacitor is typically made as small as possible (<1 pF) to reduce the effect of noise in the following shaping amplifier stages. This

makes it sensitive to any stray capacitances and, if there are vibrations in the system that alter the local geometry, then this can change the feedback capacitance that changes the "gain" of the preamplifier. Second, the photodiode will be operating with some applied bias voltage (often several tens of volts) and any change in its apparent capacitance through mechanical movement of components will result in charge being moved around. These charge movements will be sensed by the charge amplifier. Ultralow noise applications that ignore mechanical stability in their design phase are in peril. Tables 8.1 and 8.2 contain a selection of available commercial devices and manufacturers.

8.3   Applications

The Millikan technique of measuring charges on particles suspended in electric fields continues to be developed for various applications. Kutsuwada et al. [13] use a modified Millikan experiment to measure the charge distribution on electrophotographic toner particles of various sizes. They show a comparison of the results obtained using an ordinary Millikan apparatus, and a modified system in which an additional ac electrode has been inserted in the hyperbolic quadrupole electrode assembly. The two methods agree to within a small multiplicative calibration factor. A different method of measuring the charge of toner particles uses the q/d meter [14] in which q and d refer, respectively, to the charge and the diameters of the particles. In the q/d meter, the charged particles are transported horizontally in a steady laminar air flow, and move vertically in an electric field until deposited on a registration electrode. The position at which the particle is deposited on the registration electrode defines the charge-to-diameter ratio. The size of the deposited particle is then measured, thus completing the determination of the charge distribution for various particle sizes.

The experiments searching for fractional charges [15] make use of superconducting niobium spheres 0.25 mm in diameter, suspended in vacuum at 4.2 K in a magnetic field. The vertical position of the spheres is modulated by an alternating electric field and measured with an ultra-sensitive magnetometer. Positrons and electrons generated by radioactive sources are used to cancel all integer charges on the spheres. Fractional charges are detected and measured as that residual charging of the niobium spheres that cannot be neutralized by the integral charges from the radioactive sources. Although this experiment is sensitive to about 0.01 electron charges (10^{-21} C), it has produced no conclusive evidence of fractional charges.

A similar approach, using force modulation, is used for the noncontact measurement of charge on gyroscopes [16]. Out-of-phase equal forces are applied to an electrostatically suspended gyroscope at a frequency well within the suspension control bandwidth. The charge of the gyroscope is then proportional to modulation frequency component of the suspension control effort. The sensitivity of this method is about 10^{-12} C gyroscope charge, limited by the allowable modulation force and position sensor noise.

Noncontact measurement of charge on liquid drops in a microgravity environment can be also performed using field mill instruments [17]. A mechanical chopper is used to modulate the electric field induced by the spherical charge on a grounded sensing plate. The resulting alternating current from sensor to ground is a measure of the charge on the drop. In a refinement of this method, the modulation is achieved by varying the distance between charge and sensor. The authors [18] claim that this system provides an increase in sensitivity of 2 to 3 orders of magnitude over the original technique.

Optical sensors based on the Pockels effect [19] are used to measure the space-charge field in gaseous dielectrics. The Pockels effect involves the change in the birefringence of certain crystalline materials on the application of an electric field. In the measuring system, a circularly polarized beam is detected after passing through the Pockels sensor and a polarizing plate. The detected intensity varies linearly with the intensity of the electric field applied to the sensor. This system is capable of performing a vector measurement of the electric field produced by the space charge, determining both intensity and direction.

Optical methods of charge measurement are also used for particles whose physical structure depends on their charge. An example is the degree of dissociation of the end groups of polystyrene particles in colloidal solutions [20]. In this application, the intensities of the Raman scattering spectrum lines depend

on the degree of dissociation of the polystyrene end groups, and thus determine the charge of these particles.

A widely used application of charge measurement is as an integral element of radiation dosimetry. Radiation is passed through ionization chambers, where the generated ions are collected and the charge measured with electrometers. Ionization chambers used in dosimetry for radiation therapy have typical sensitivities in the range 0.02 nC R^{-1} to 0.2 nC R^{-1}. Coulombmeter electrometers with sensitivities of 1 pC to 10 pC are therefore required for this application.

Defining Terms

Charge, also **Electric charge:** A basic property of elementary particles, defined by convention as negative for the electron and positive for the proton. The SI unit of charge is the coulomb (**C**), defined as 1 ampere × 1 second.

Electrostatic instrument: An instrument that functions by measuring the mechanical displacement or strain caused by electric fields.

Electrostatic voltmeter: Electrostatic instrument used to measure charge. The charge is determined as a function of voltage and instrument capacitance.

Charge amplifier: Charge-measuring instrument. The charge is transferred to a reference capacitor and the resulting voltage across the capacitor is measured. Shunt and feedback versions of the charge amplifier have the reference capacitor used in shunt and feedback mode, respectively.

Electrometer: *Historic usage*, type of electrostatic voltmeter. *Modern usage*, electronic electrometer, a high-performance dc multimeter with special input characteristics and high sensitivity, capable of measuring voltage, current, resistance, and charge.

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