HP AN128

APPLICATION NOTE 128

APPLICATIONS OF A DC CONSTANT CURRENT SOURCE

HEWLETT PACKARD

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CURRENT SOURCES

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COVER: A Model 6186B DC Current Source is used to produce the reverse characteristic of a 6.2V, 400mW zener diode. The test setup used is that of Figure 15 in the text except that the horizontal and vertical connections are interchanged and the horizontal channel is connected directly across the zener diode with reverse polarity. The oscilloscope displays voltage horizontally (1V/cm) and current vertically (6mA/cm). Current modulation is 100 percent, causing the current to swing over the full range from zero at the top right of the curve to 36mA at the bottom of the curve.

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CURRENT SOURCES

Q – What common factor relates the following actions: Measuring resistance, performing a coulometric titration, measuring semiconductor breakdown voltages, operating IMPATT diodes, testing electrolytic capacitors, measuring transistor h-parameters, calibrating meters, and measuring magnetic field intensity?

A – Constant current. All of the above measurements or processes (and more) can be accomplished simply and easily using Hewlett-Packard's CCB Series precision constant current sources.

What is a constant current source? Defined, it is a current generator that will supply any output voltage necessary to keep its output current constant, regardless of the resistance of the load connected to it. It will supply this same constant current at zero voltage to a short circuit, and will try to supply the same current at infinite voltage to an open circuit. This can be contrasted with the characteristic of a constant voltage source, in which the output *current* changes to keep the output *voltage* constant regardless of the size of the load connected. Sources of the latter type are more familiar, perhaps because most common power sources (batteries, the ac power line, laboratory power supplies, etc.) as well as most sources of electrical energy found in nature all approximate constant voltage sources.

The key word here is *approximate*. In practice, a voltage source cannot supply infinite current, nor can a current source supply infinite voltage. In fact, most common laboratory type constant voltage supplies have a current limit that limits the maximum current supplied to the load. Similarly, a constant current source should have a voltage limit (preferably adjustable) that limits the maximum voltage appearing across the load.

DESIRABLE CHARACTERISTICS

The voltage limit requirement is only one of many characteristics that a practical current source should possess—others include excellent output current regulation, a means of measuring the output voltage without degrading the regulation, low output capacitance with corresponding high output impedance at high frequencies, and rapid programming ability.[1]

Regulation

Regulation is a measure of the "constancy" of a constant current source. It is defined as the change in output current that occurs when the load is changed from a short circuit to the value that requires the current source to supply the full output voltage. Regulation is thus the most basic specification of a constant current source. As an illustration, consider making accurate resistance measurements ranging from several ohms to several hundred thousand ohms—as the resistance changes, the current must remain constant for accurate resistance measurements. Generally, the regulation of the constant current source should be a factor of ten better than the desired measurement accuracy.

APPLICATIONS

The measurements and processes discussed in this Application Note are divided into three main categories:

¶ Resistance Measurements
¶ Semiconductor Device Measurements and Related Applications
¶ Component Testing

In each of these areas, several applications are explored in detail.[2] In addition, a final section entitled "Other Applications" gives a brief description of several less common applications.

RESISTANCE MEASUREMENTS

What can you do with constant current? One of the prime applications is resistance measurement. The principle is Ohm's law: If a known current is put through an unknown resistance, the measured voltage drop is directly proportional to the resistance. In essence, this reduces resistance measurements to voltage measurements. The very high accuracy that can be achieved using this method of measuring resistance, in combination with the ease of performing the measurement, make this method the preferred one in many situations.

The following four practical examples are only a few of the many possible applications of constant current resistance measurement. Included are:

¶ Silicon Wafer Resistivity (Four-Point Measurement)
¶ Production Line Resistance Testing, Grading, and Trimming
¶ Measuring Contact Resistance
¶ Temperature Measurement by the ΔR Method

The information in these four application descriptions is detailed enough so that the reader can immediately perform the measurement without referring to other literature. However, in several of the measurements described later in this Application Note, reference to the constant current source operating manual will be necessary.

Silicon Wafer Resistivity (Four-Point Measurement)

Measurement of the resistivity of silicon slices used in manufacturing semiconductors is well suited to the constant current method. Resistivity (ρ) is defined as the resistance in ohms that a unit volume of material offers to the flow of current. Resistivity is measured in ohm·cm.

Why would you want to know the resistivity? Simple. In the development and manufacture of integrated circuits, it's indispensible. For example, suppose in a given process an impurity such as boron or phosphorus is being diffused into a silicon wafer. The diffusion changes the electrical characteristics of the silicon, that is, the resistivity (along with other properties). By measuring the resistivity, the density (concentration) of the impurity at the surface or throughout the entire wafer can be found, and thus the effectiveness of the diffusion process can be evaluated.

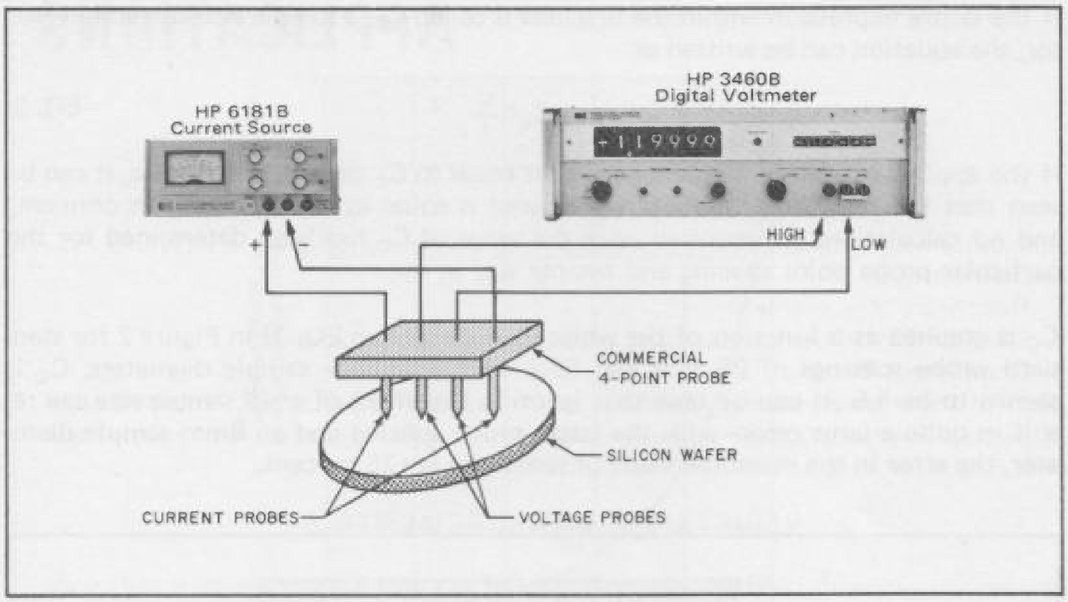

FIGURE 1. Four-point probe method of measuring silicon wafer resistivity.

By far the most common method used in making this measurement is the four-point probe method. As shown in Figure 1, the silicon wafer sample is contacted by a probe containing four in-line contact points. The outer two contacts supply a constant current through the sample, and the inner two contacts measure the voltage drop across a portion of the sample. The use of four probes rather than two avoids the error caused by contact resistance. If the current and voltage were to use the same contact, there would be an IR drop across the probe-to-sample contact resistance and in the body of the probe itself between the sample surface and the connection to the voltmeter lead. This could cause a significant error when measuring low resistivities (0.005Ω·cm to 1.0Ω·cm) where the IR drop may begin to approach the magnitude of the sample voltage.

By choosing an appropriate value of current to be supplied to the sample, the resistivity measurement can be greatly simplified. Selecting the exact value of current for any particular measurement requires that the resistivity be given in terms of the sample size and four-point probe geometry as follows:

$$\rho = \frac{Vt}{I}\left[\frac{\pi}{\ln 2 + \ln\left(\frac{(\frac{d}{s})^2 + 3}{(\frac{d}{s})^2 - 3}\right)}\right] \qquad \text{EQ. 1}$$

where ρ is the resistivity in ohm·cm, V is the measured voltage in millivolts, I is the applied current in milliamperes, t is the thickness of the wafer in centimeters, d is the diameter of the wafer in centimeters, and s is the voltage probe point spacing in centimeters.[3] This expression is valid only for circular, thin slices, where the thickness is less than one half the voltage probe spacing. Comparable expressions for other sample geometries can be found in the extensive literature on silicon wafer resistivity measurements.

If the entire expression within the brackets is called C_C, a sample size correction factor, the equation can be written as:

$$\rho = C_C t \frac{V}{I} \qquad \text{EQ. 2}$$

If the applied current in milliamperes is set equal to C_C times the thickness, it can be seen that the number of millivolts measured is equal to the resistivity in ohm·cm, and *no* calculations are required once the value of C_C has been determined for the particular probe point spacing and sample size in use.

C_C is graphed as a function of the wafer diameter (from EQ. 1) in Figure 2 for standard probe spacings of 25 mils and 62.5 mils. For large sample diameters, C_C is shown to be 4.5. It can be seen that ignoring the effect of small sample size can result in quite a large error—with the latter probe spacing and an 8mm sample diameter, the error in the measured value of resistivity is +25 percent.

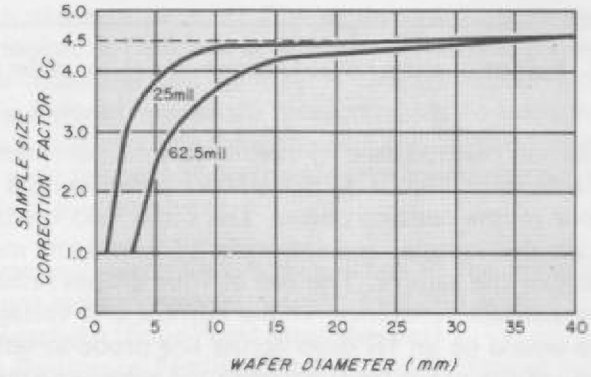

FIGURE 2. Resistivity correction factor C_C vs sample size diameter for common voltage probe spacings of 25 and 62.5 mils.

In addition to the error due to sample size, there are three other factors affecting the accuracy of the measurement. First, the above formulas have been derived for a measurement made in the center of the wafer. Other probe locations require greater corrections—Figure 3 shows the measurement error as the probe is moved away from the center of a 20mm diameter wafer. [**4**] Second, the heating of the wafer by the applied current must be considered, since typical temperature coefficients of resistivity for zone-refined silicon rods vary between 0.5%/°C and 1.5%/°C. It is difficult to specify a maximum current that can be used, but in general, currents over 10mA will definitely begin to cause heating difficulties. The relatively high temperature coefficient also points out the need for control of the ambient temperature if accurate results are to be achieved. The third factor is the mechanical construction of the four-point probe itself. Four-point probes are commercially available from several hundred dollars to several thousand. Most of these are rigidly constructed with very close tolerances on the probe assembly, thus minimizing errors due to probe wander. In addition, most probes are equipped with mechanisms that automatically adjust the contact pressure, thereby eliminating another error-causing variable.

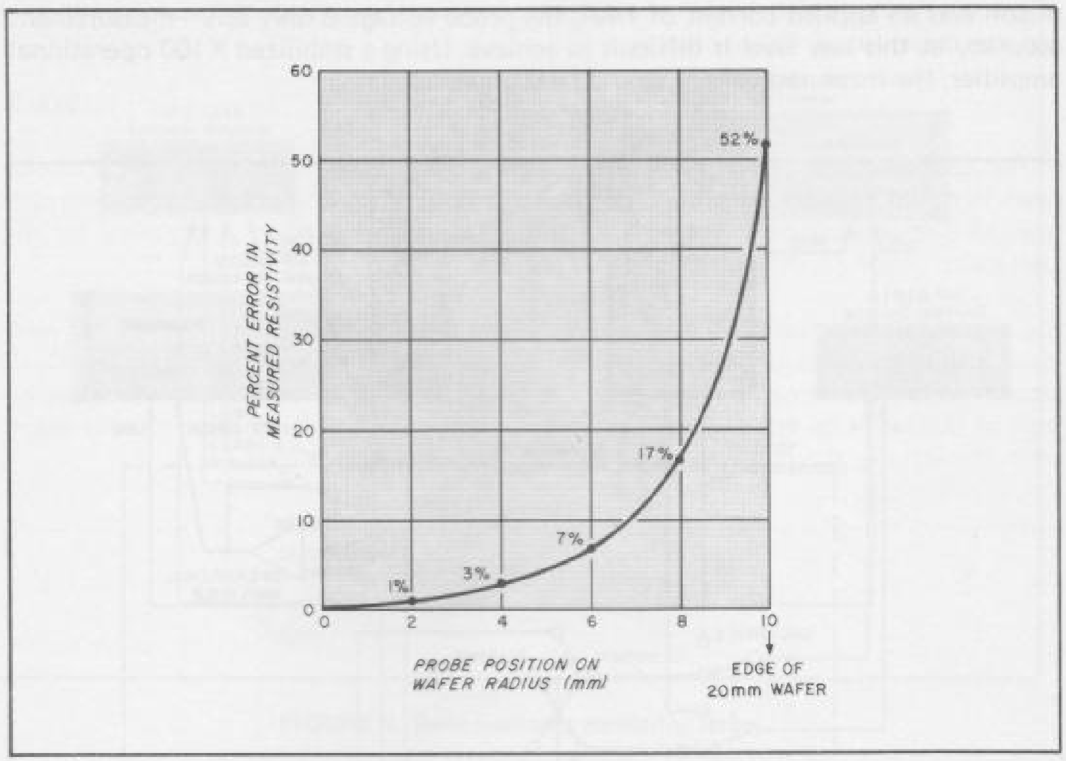

FIGURE 3. Percent error in measured resistivity as four-point probe is moved away from center of 20mm diameter wafer.

There are several minor sophistications that can be included in the measurement. The first of these is a "calibrate—measure" switch. As shown in Figure 4, an external precision ammeter can be connected to the current source in the "calibrate" position to allow accurately setting the current to the desired value. The second sophistication is the use of the voltage limit control on the constant current source. Applying too high an initial contact voltage to very thin wafers or wafers bearing very thin surface films can quite easily break down the wafer or film. With the voltage limit set to a value slightly above the maximum voltage expected to be measured, the samples are protected from the damage that otherwise might occur when the probe is first touched to the sample. A third sophistication is the use of a polarity reversing switch placed in the current leads of the probe in such a manner as to reverse the direction of current flow through the sample. Reversing the current allows the contact between the probe and the wafer surface to be checked for undesired diode action. An alternate technique involves the use of the range switch on the current source to check the contact condition. If poor contact is suspected due to heavy surface oxide or other problems, the range switch can be switched to the next highest (or lowest) range, increasing or decreasing the current by a factor of 10. If the measured voltage does not change by the same factor (within the two percent range switching tolerance), the probe-to-surface contact is behaving in a non-linear fashion and should be adjusted. Caution should be exercised in using this checking method at currents over approximately 10mA in order to avoid undesirable heating effects. A final sophistication is the use of an operational amplifier to amplify the probe voltage when measuring very low resistivities. For example, with a sample of 0.005Ω·cm silicon and an applied current of 1mA, the probe voltage is only 5μV—measurement accuracy at this low level is difficult to achieve. Using a stabilized X100 operational amplifier, the measured voltage would be 0.5mV.

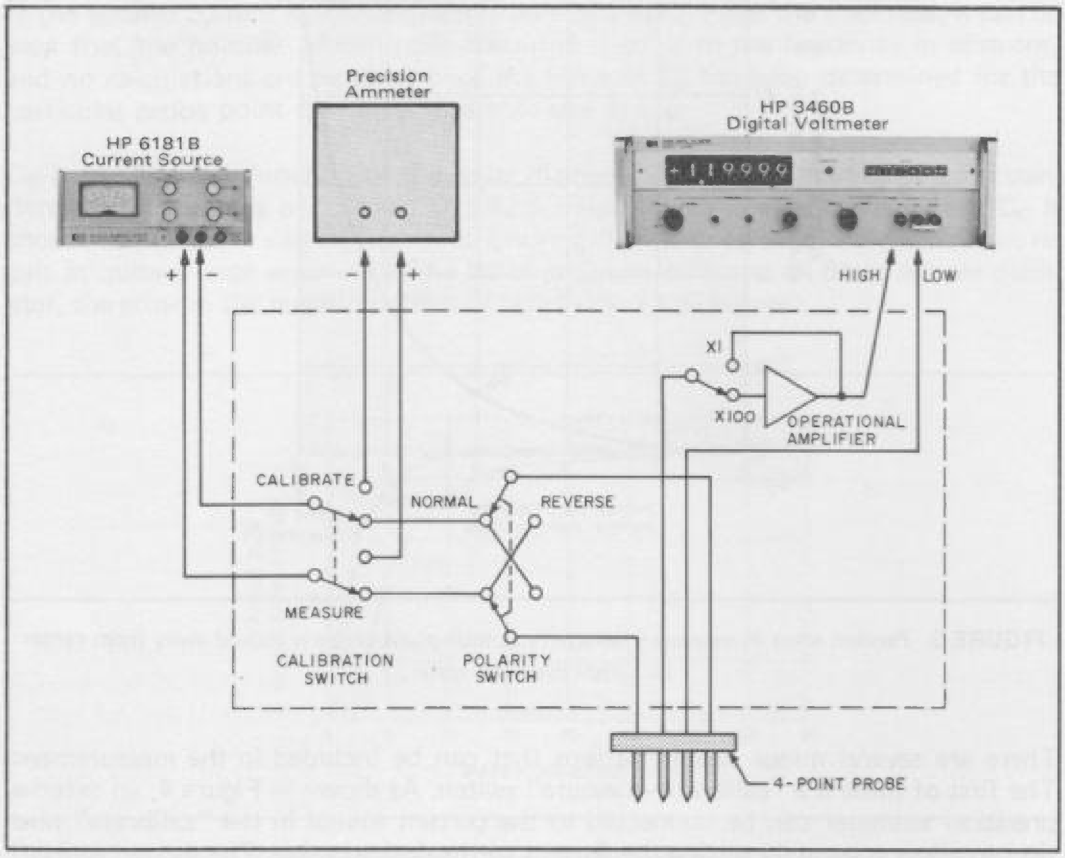

FIGURE 4. Four-point probe setup with added sophistications.

Production Line Resistance Testing, Grading, and Trimming

A constant current source can serve as an integral part of a resistor production line test setup. The heart of the measurement is still the same: Ohm's law. A known current is put through an unknown resistance, and the measured voltage drop across the resistor is directly proportional to the resistance.

A typical production line application is in the grading process. A production line may be set up to produce a resistor of a given value ±10 percent. The resulting resistors are then measured and graded by how close they are to the nominal value. The current source is set to provide a fixed current in multiples of milliamperes such that the voltmeter reads directly in kilohms or any convenient multiple thereof (e.g., at 0.1mA, 1V equals 10kΩ). As shown in Figure 5, the voltmeter is connected to the meter terminal of the current source in order to avoid the measurement error associated with connecting the meter across the resistance being measured. However, since the voltmeter is effectively sensing at the current source output terminals,

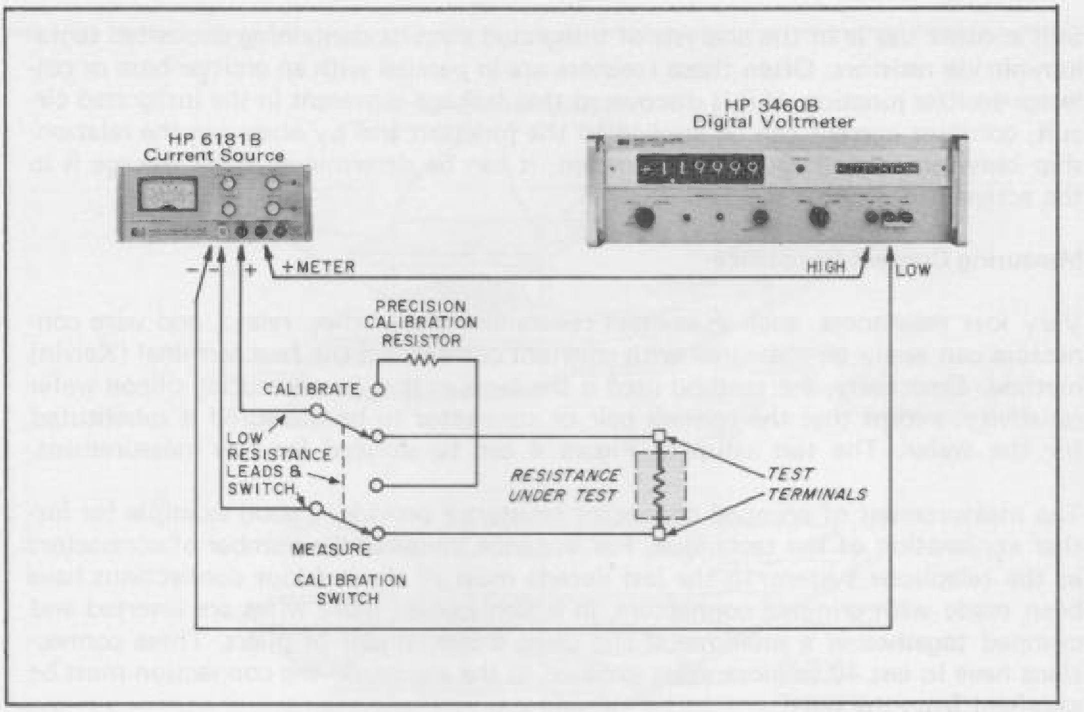

FIGURE 5. Basic resistance measuring setup.

the resistance of the leads connecting the test terminals to the current source and the contact resistance of the calibration switch must both be as low as possible. To accurately set the current, a precision resistor (0.01 or 0.001 percent) can be connected across the current source by means of the calibration switch and the current can be adjusted for an exact voltmeter reading. The voltage limit control can be set to eliminate high voltages appearing across the test terminals when one resistor is removed and another inserted.

Testing thin-film chip resistors is an application in which the main problem is one of heating. When an ohmmeter (digital or analog) is used as the measuring instrument. the current supplied to the resistor is usually of the order of 1mA. This is too much current to be passed through a typical micropower chip resistor rated for only 25mW maximum dissipation. However, controlled currents of 1 to 10μA are ideal for this purpose, since heating problems are eliminated. On the other hand, if the heating effect *is* desired (e.g., in value trimming by oxidation with pulsed dc), it is readily available. The voltage limit control is particularly useful in working with thin-film chip resistors, since application of too high a voltage can very easily cause arcing and breakdown on chips where the resistance tracks are only 1 mil apart and film thicknesses are typically 500 Angstroms.

The constant current resistance measurement technique is also useful in trimming operations based on abrasive or laser methods. For instance, some thin-film resistors are vacuum deposited in a matrix pattern on a silicon substrate. Connection branches are provided in the matrix pattern so that by removing one branch with a laser, the value is changed by a small percentage. The resistance can be continuously monitored with constant current while this operation is taking place.

Still another use is in the analysis of integrated circuits containing deposited tantalum-nitride resistors. Often these resistors are in parallel with an emitter-base or collector-emitter junction. If it is discovered that leakage is present in the integrated circuit, constant current can be applied to the junction and by observing the relationship between the voltage and the current, it can be determined if the leakage is in the active device or the resistor.

Measuring Contact Resistance

Very low resistances, such as contact resistances of switches, relays, and wire connectors can easily be measured with constant current and the four terminal (Kelvin) method. Essentially, the method used is the same as that for measuring silicon wafer resistivity, except that the contact pair or connector to be measured is substituted for the wafer. The test setup of Figure 4 can be utilized for this measurement.

The measurement of crimped connector resistance provides a good example for further explanation of the technique. For instance, consider the number of connectors in the telephone system. In the last decade most of the outdoor connections have been made with crimped connectors, in which two or more wires are inserted and crimped together in a small metal clip using a special pair of pliers. These connections have to last 40 or more years exposed to the elements—the connection must be excellent from the start.

Four terminal resistance measurements in combination with a cycling oven provide a versatile means of evaluating such connectors. Typical initial resistance for the type of connector described above is 3mΩ; a quality connector (and connection) will not increase in resistance by more than a factor of three after aging in an oven cycled from −40°F to +140°F more than a hundred times.

Figure 6 shows two possible methods of making this measurement on a large-scale basis. In both cases, the connectors (20 or more) are mounted on a PC card by soldering the wires protruding from the connectors to pads on the card; the test current in both cases is supplied to the connector through a pair of tracks leading to edge-connector fingers. In version (A), a moveable voltage sensing probe (part of the framework into which the PC card is plugged) contacts the pads to which the connector wires are soldered. Because voltage sensing is accomplished directly at the connector, the effect of resistance in the current supply leads is eliminated, and only the connector resistance is measured. Version (B) utilizes the same principle except that instead of sensing the voltage drop across the connector with a moveable probe, another pair of tracks is brought out from the connector pads. This method has the advantage of simplicity, since no moving parts are required. Typical currents used in this measurement range from 1mA to 100mA; however, currents in the upper end of this range may result in heating problems or film breakdown—if a poorly aged connector with heavy surface film is being evaluated, high test currents may actually break down the film and destroy the resistance value being measured.

Resistance measurements such as described in this and the previous application (production line resistance testing) lend themselves particularly well to computer automation. The current output and voltage limit of the constant current source can be controlled by a computer through a D/A interface; output resistance readings can be punched on paper tape or other output medium. In the resistance trimming oper-

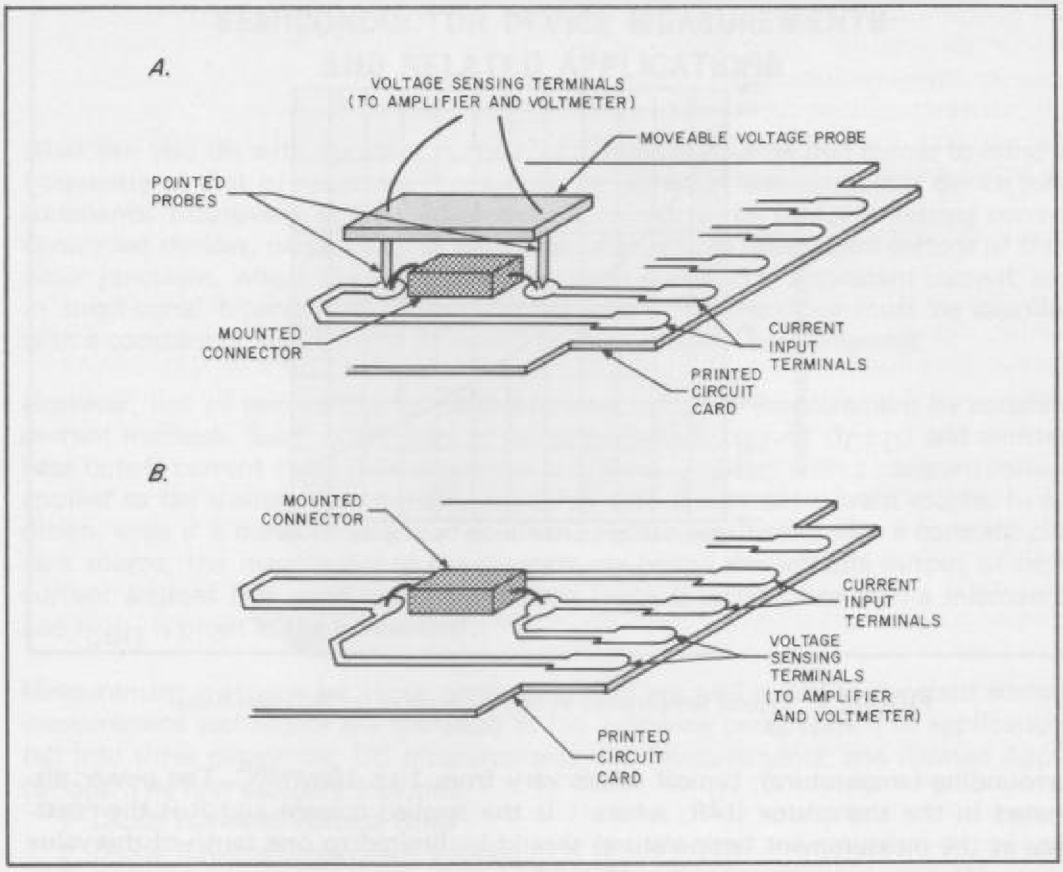

FIGURE 6. Two methods of measuring crimped connector resistance.

ation, a feedback system can be set up in which resistance measurements are fed back to the controlling computer to determine when the resistance is close to the desired value. Systems such as these, utilizing the versatility of a remotely programmed constant current source, are limited in scope only by the imagination of the designer.

Temperature Measurement by the ΔR Method

A constant current source can be used to measure temperature by utilizing the change of resistance method. In its most direct form, the method consists of applying a constant current through a thermistor and monitoring the voltage across it via the meter terminal on the current source.

Thermistors, classified according to their resistance at $25^{\circ}C$, are available in a wide range of resistances and a variety of tolerances from 0.5 to 10 percent. With thermistors of the former tolerance, the manufacturer supplies a characteristic curve or table of values relating resistance and temperature. A typical curve for a $3k\Omega$ thermistor is shown in Figure 7.

Self-heating of the thermistor by the applied current is a factor that must be considered in this application. Most thermistor data sheets list the dissipation constant (the amount of power in milliwatts required to raise the thermistor $1^{\circ}C$ above the

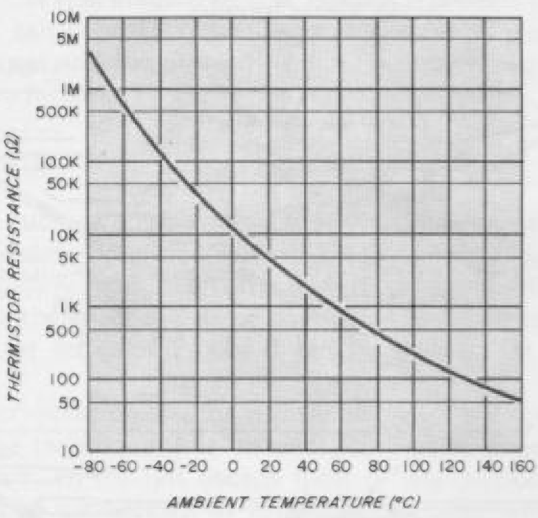

FIGURE 7. Typical temperature vs resistance curve for 3kΩ thermistor.

surrounding temperature); typical values vary from 1 to 10mW/°C. The power dissipated in the thermistor (I^2R, where I is the applied current and R is the resistance at the measurement temperature) should be limited to one tenth of this value if accurate measurements are to be achieved.

In some applications, a more indirect method of temperature measurement may be required. For example, suppose it is desired to find the actual operating temperature of the winding of a small shaded-pole motor in order to meet an Underwriter's Laboratory safety specification. The method (using the basic setup of Figure 5) is simple. First, a resistance reading is taken of the winding at room temperature. Second, the motor is heated up to operating temperature using whatever specification is required for the particular test (full load, stalled rotor, x hours of operation, etc.).

Third, power is removed from the winding, and the changing resistance of the winding is measured in set time intervals (typically five seconds) until it has partially cooled down (a DVM with a "hold" control is useful here). Extrapolation of this data yields the resistance of the winding at the instant the power was removed. Fourth, the following formula is used to determine the operating temperature:

$$T_{hot} = \frac{1}{K}\left(\frac{R_{hot}}{R_{cold}} + KT_{cold} - 1\right) \qquad \text{EQ. 3}$$

where T_{hot} is the operating temperature in °C, T_{cold} is the room temperature in °C, R_{hot} is the resistance ohms at the operating temperature, R_{cold} is the resistance in ohms at room temperature, and K is the temperature coefficient of resistivity of the winding material at room temperature. For both copper and aluminum (the two most commonly used materials), $K = 0.0039$. Values for other materials can be found by referring to almost any handbook.

SEMICONDUCTOR DEVICE MEASUREMENTS AND RELATED APPLICATIONS

What can you do with constant current? An application area that comes to mind as frequently as that of resistance measurements is that of semiconductor device measurements. Intuitively, one expects constant current to be useful in testing current controlled devices, particularly in such measurements as breakdown voltage of transistor junctions, where the breakdown voltage is specified at a constant current, and in small-signal h-parameter measurements, where the transistor must be supplied with a constant dc bias current on which ac modulation is superimposed.

However, not all semiconductor parameters are suited to measurement by constant current methods. Such parameters as collector leakage current (I_{CEO}) and emitter-base cutoff current (I_{CBO}) in which the current is specified with a constant *voltage* applied to the device are not easily measured with a constant current source. In addition, even if a method is devised to measure these parameters with a constant current source, the magnitudes of the currents are below the settable output of most current sources (for small signal transistors, I_{CEO} is usually less than a microamp, and I_{CBO} is often in the nanoamps).

Measurement methods for those parameters that *are* well suited to constant current measurement techniques are discussed in the following paragraphs. The applications fall into three catagories: DC Measurements, AC Measurements, and Related Applications. The first category includes:

- ¶ Diode Forward Voltage Drop
- ¶ Diode Reverse Breakdown Voltage
- ¶ Diode Temperature Coefficient
- ¶ V-I Characteristic of Any Device
- ¶ Transistor Junction Reverse Breakdown Voltage
- ¶ Transistor DC (Static) Current Transfer Ratio
- ¶ Transistor Junction Saturation Voltage

Next, an explanation of the method used in modulating a constant current source is given as an aid in understanding the AC Measurement applications. Included in this category are:

- ¶ Zener Diode Dynamic Impedance
- ¶ Transistor h-Parameters

Finally, two applications are discussed in which the constant current source is used as an operating power supply rather than an evaluative instrument. Included in this category are:

- ¶ Operating IMPATT Diodes
- ¶ Operating Hall Effect Devices

Diode Forward Voltage Drop

As a first example of a constant current application in the semiconductor device area, consider the measurement of the forward voltage drop of a diode. A typical diode (PN junction) characteristic is shown in Figure 8. The maximum value of the forward voltage drop, V_F, is usually specified on data sheets at one or more values of forward current, I_F. For controlled conductance diodes (used in logic circuits to permit greater design margins or additional logic states), both the minimum and

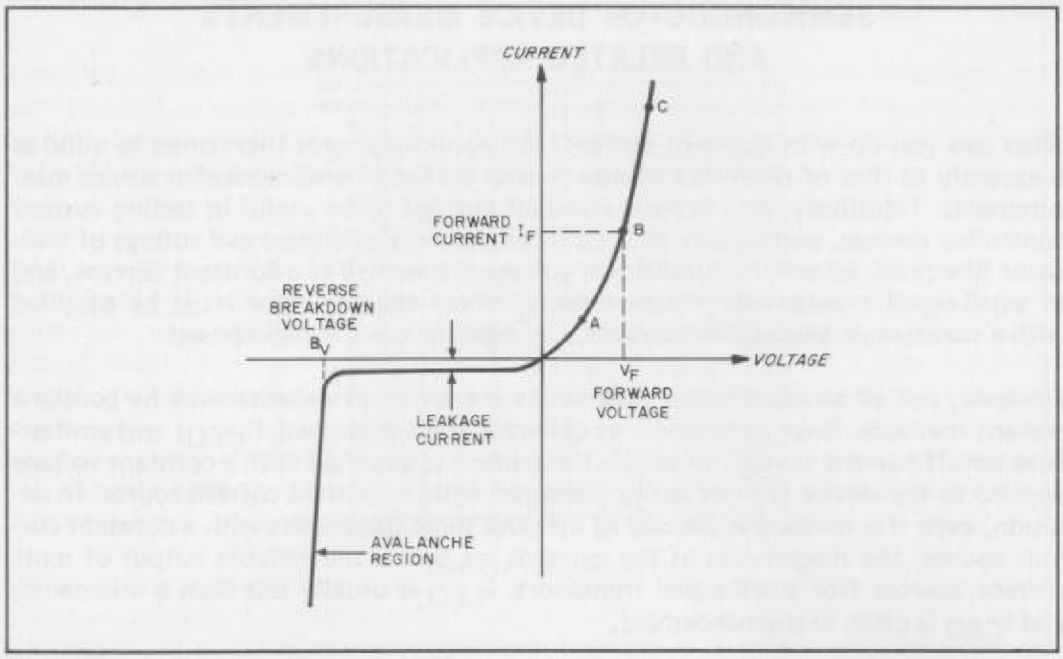

FIGURE 8. Characteristic V-I curve for diode (PN junction).

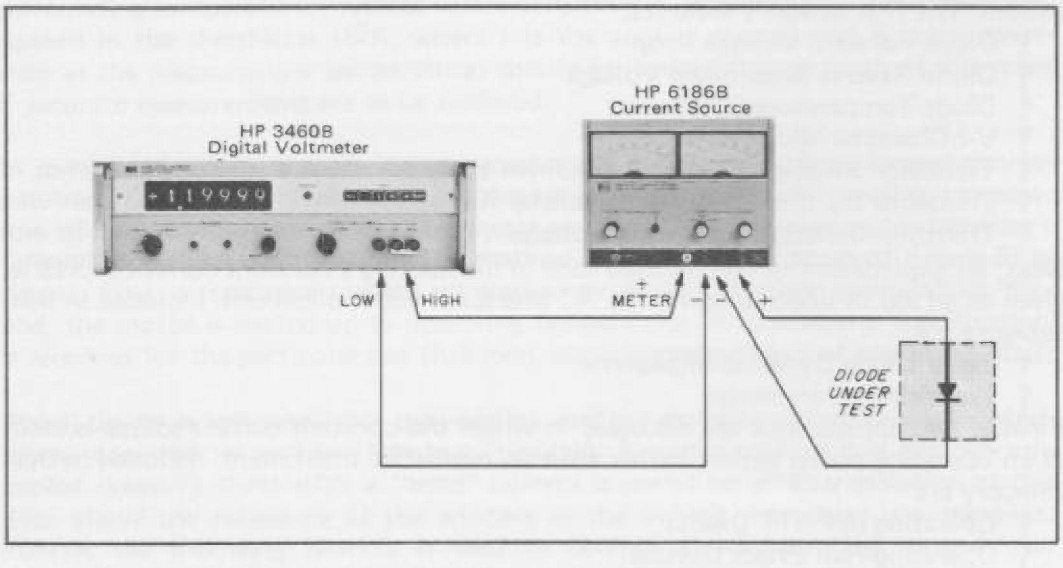

FIGURE 9. Basic test setup for measuring forward voltage drop of diode.

maximum values of forward voltage drop are specified at several different values of forward current. Measurement of this parameter entails simply putting a constant current through the diode in the forward direction, and measuring the voltage drop across it as shown in Figure 9. Selecting different values of forward current will move the measuring point along the characteristic curve—points A, B, and C in Figure 8 represent operating points at increasingly higher values of forward current.

Diode Reverse Breakdown Voltage

The minimum value of the reverse breakdown voltage (BV) is specified on diode data sheets at a fixed value of reverse current. In the same manner as forward voltage drop, this parameter is measured by simply applying a constant current through the diode in the reverse direction and measuring the voltage drop across it. The setup shown in Figure 9 can be utilized by reversing the diode.

Note that although the parameter being measured is a "breakdown" voltage, it is being measured non-destructively by virtue of the controlled current. The breakdown voltage as shown on the characteristic in Figure 8 is located at the beginning of the avalanche region. In this region, very large changes in reverse current result in only very small changes in reverse voltage. This means that if a constant voltage source were used to make this measurement, a very small change in output voltage could increase the reverse current (and thus the power dissipation) to the point where the diode fails. To avoid this possibility, the variable that must be controlled is the *current* rather than the voltage—thus the necessity for a constant current source.

When actually performing the measurement, varying the current supplied to the diode will move the operating point along the characteristic as in the forward voltage measurement, except in the reverse direction. However, because the magnitude of the leakage current shown in Figure 8 is so small (often less than 1 microampere for silicon signal diodes), the almost-horizontal portion of the characteristic will be traversed rapidly as the output of the current source is increased from zero. Increasing the current output above several microamperes will result in the measured reverse voltage increasing very slowly. When this occurs, it is definite indication that the diode is operating in the breakdown (avalanche) mode.

Zener voltage can be measured using this same procedure, since zener voltage is simply the reverse breakdown voltage of a diode *designed* to be operated in the zener or avalanche region. This parameter is usually specified on data sheets at a test current that results in a power dissipation of one quarter the maximum rated value for uncompensated zener diodes, or at the current resulting in minimum voltage temperature coefficient for reference (temperature compensated) zener diodes.

Diode Temperature Coefficient

With the addition of a temperature-controlled oven, the above measurement procedure can be used to determine the forward (or reverse) voltage temperature coefficient of a diode (or any other component). Connected as shown in Figure 9, the diode is placed in the oven (the current source remains outside the oven), the temperature is varied over the desired range, and the voltage is recorded at each desired temperature setting. Sufficient time should be allowed for the diode junction temperature to stabilize before taking each voltage reading. The forward voltage temperature coefficient of silicon signal diodes is typically 2mV/$^{\circ}$C; typical temperature coefficients of zener voltage vary from 25mV/$^{\circ}$C to essentially zero for reference diodes.

V-I Characteristic of Any Device

In essence, measuring the forward voltage drop and reverse breakdown voltage of a diode as has been described amounts to determining points on the characteristic.

For small signal transistors, I_C is typically 1 or 2mA, and B ranges from 20 to 400. It can therefore be seen that for a typical B of 100, the current supplied by the base current source will be 10 to 20μA—much too small a value to be read accurately from the front panel meter on the current source. Instead, the current must be measured with either a series ammeter as shown in Figure 12, or a small current monitoring resistor and a voltmeter.

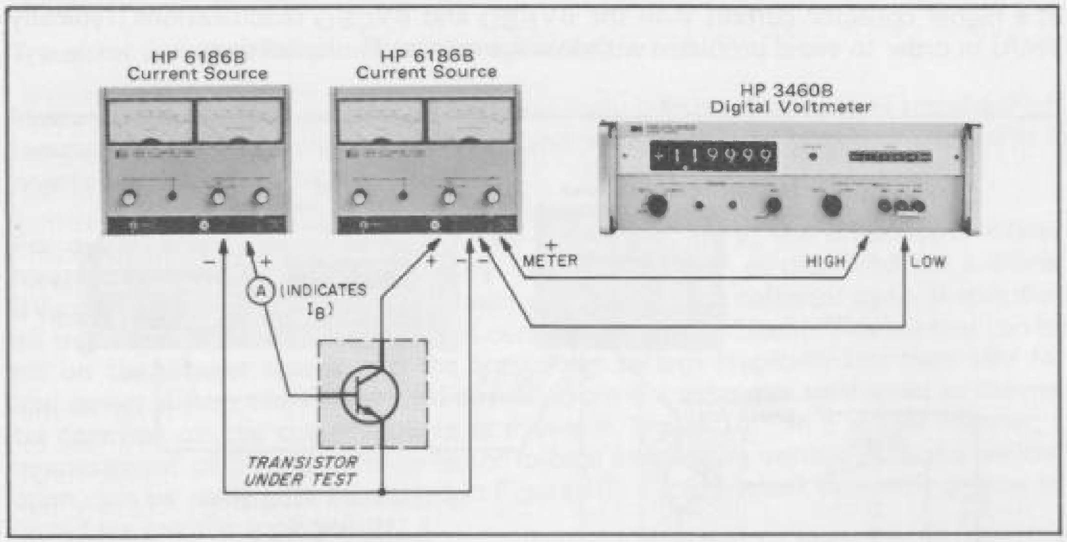

FIGURE 12. Measurement setup for common emitter dc current transfer ratio and junction saturation voltage.

"Go-no go" measurements, more suited to production or quality control applications, can be made by utilizing the above procedure with the base current source set to a fixed, known current value. The collector-to-emitter voltage then becomes the measured variable—if V_{CE} as read on the meter is less than that given in the test specification, B for the transistor is greater than that required; if V_{CE} is greater than the value specified, B is less than the required value.

Transistor Junction Saturation Voltage

Another frequently used transistor parameter is $V_{CE(SAT)}$, the voltage from the collector to the emitter for a given I_C and I_B while biased in the collector saturation region. The value of $V_{CE(SAT)}$ is often of particular importance in computer applications where minimum and maximum values of the saturation voltage are frequently relied upon in the design. The measurement of this parameter utilizes the setup of Figure 12. The specified base and collector currents are set on the constant current sources, and $V_{CE(SAT)}$ is read directly from the voltmeter connected to the meter terminal of the collector current source. The currents specified are such that operation in the collector saturation region is guaranteed—if the transistor has a B of 100 specified at a collector current of 1mA, any base current greater than 10μA will saturate the transistor when the collector current is 1mA. A margin of safety is usually built into such measurements; in the above example, the actual base current specified might be 100μA in order to insure that the transistor is saturated. Typical values of $V_{CE(SAT)}$ for small-signal silicon transistors range from 0.1 to 0.5V.

AC Modulation Method

An ac-modulated constant current source is the ideal power supply for measuring semiconductor device incremental parameters, because it can simultaneously supply both a fixed dc current that biases the device into operation in its active region, and an ac current that produces incremental changes around this bias point. However, before delving into the actual procedures for these measurements, an explanation of the method used in modulating a current source is of value. [5]

As shown in Figure 13, the programming circuitry of the current source is arranged so that a constant current (I_P, called the programming current) flows through a reference resistor (R_R) and the front panel current control (R_P). Because R_P has a constant current flowing through it, varying the resistance varies the voltage (V_P, called the programming voltage) appearing at point "P". The output current of the instrument is held proportional to this potential. It can thus be seen that if the programming current is increased, the dc output current will increase because the potential at point "P" has increased, even though the position of the front panel current control has not been changed.

The programming current (0.5mA in the 6177B and 6181B, and 1.0mA in the 6186B) is constant for *any* dc output current. If an additional current (I_s) is added to the programming current, the dc output current will increase by a proportional amount.* For example, if the 1mA programming current is increased by 0.05mA, the dc output current will increase by five percent—if the dc output current were set to 50mA, it would increase to 52.5mA. Note that this same five percent increase in output current will occur at any output current setting. If the dc output is set to 5mA, the output current will increase to 5.25mA, because the percentage variation in output current is determined only by the increase in the programming current, and not by the level to which the dc output current is set.

This additional current (I_s) can be supplied from an oscillator as shown in Figure 13. Given the peak-to-peak value of the output voltage V_s and the desired magnitude of current I_s, the value of resistor R_X can be determined from Ohm's law. For example, if it is desired to vary the dc output current by ±10 percent around a dc value of 100mA, the 1mA programming current must vary ±10 percent, or I_s must be 0.2mA p-p. If the oscillator output voltage V_s is 5V p-p, resistor R_X must be 5V/0.2mA, or 25kΩ. Coupling capacitor C_C is necessary to prevent any dc present on the output of the oscillator from reaching summing point "S". The value of C_C should be such that its reactance at the operating frequency is less than 1/10th the magnitude of R_X. For example, if the oscillator were set for 100Hz in the example above, the reactance $X_C = 1/(2\pi fC)$ would be required to be less than 2.5kΩ; this would require a capacitor of at least 0.7μF.

There are two inherent limitations on the modulation process:

1. The dc output current can never swing below zero or above the rated output current of the current source if the output is to be undistorted. As an example, assume that an output current varying ±25 percent of its dc value ("25 percent modulation") is desired from a 250mA current source. Since the +25 percent portion of

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* *In this description and the following two applications with their associated figures, lower case subscripts indicate ac quantities and upper case subscripts indicate dc quantities.*

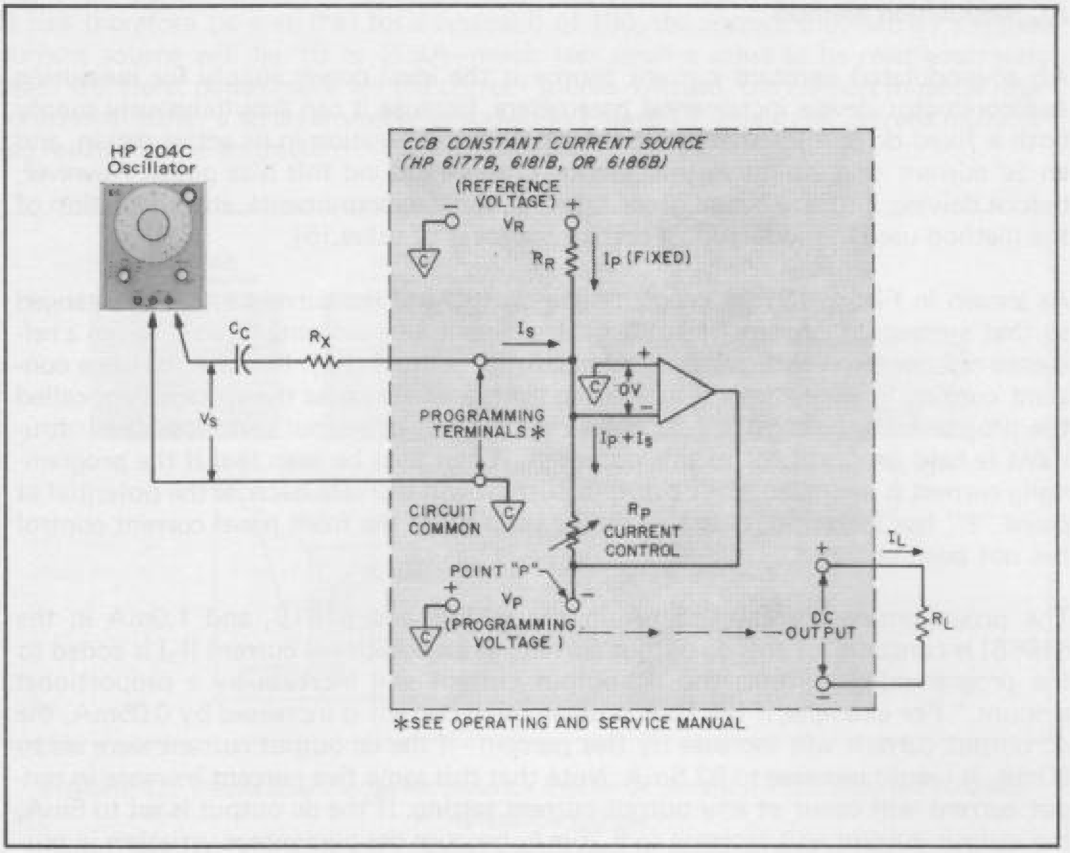

FIGURE 13. Representation of modulation scheme for constant current source.

the swing must not cause the dc output to exceed 250mA, the dc output of the current source cannot be set higher than 200mA.

2. The amplifiers in the current source place a definite limit on the maximum modulation frequency. This limitation is usually expressed as the maximum percentage modulation that may be used at a given frequency. CCB current sources are specified for 100 percent modulation up to 100Hz, decreasing linearly thereafter to a maximum of 10 percent at 1000Hz.

Zener Diode Dynamic Impedance

Zener diode incremental impedance (defined as the slope of the V-I curve, and usually of interest only in the breakdown region) can be easily measured using the method of modulating a current source just described. Zener impedance measurements are commonly used as a measure of the voltage regulating capability of the device.

Zener impedance is usually specified at two current values—the quarter power point (I_T), and a low value in the knee region (I_K) chosen such that a plot of impedance versus current on a log-log scale is essentially a straight line (see Figure 14).[6] Two additional parameters, the measurement frequency and the percentage modulation, are usually specified on diode data sheets—common values are frequencies of 60 or 1000Hz and modulations of 5 or 10 percent.

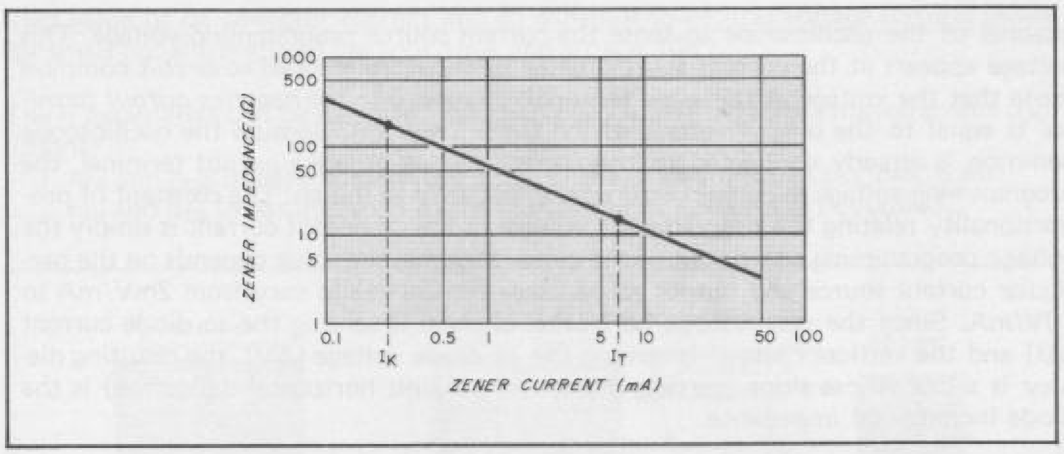

FIGURE 14. Zener diode impedance vs diode current for a 20V, 400mW, 1N968 diode.

The test setup of Figure 15 is used to perform the measurement. The constant current source supplies the specified value of dc bias current (I_T or I_K), the oscillator provides incremental output current changes (ΔI) around this bias value, and the vertical channel of the oscilloscope displays the ac voltage (ΔV) appearing across the diode. Series resistor R_X is selected as described under "AC Modulation Method" to provide the desired modulation percentage (and thus determine the value of ΔI). Calculating $\Delta V/\Delta I$ yields the zener dynamic impedance.

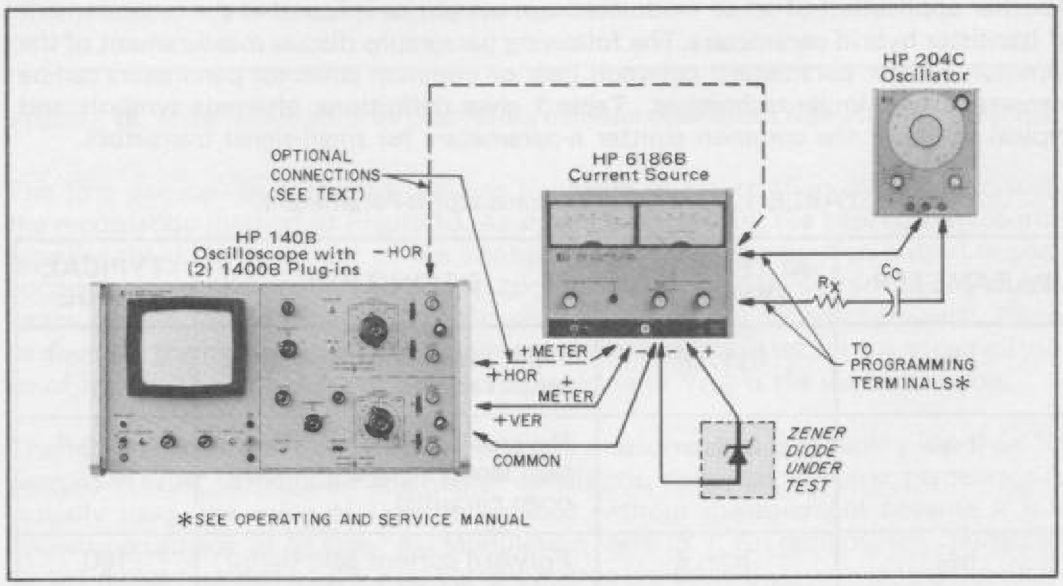

FIGURE 15. Test setup for measuring zener diode incremental impedance.

Note that each time a new bias current is selected, the magnitude of ΔI changes, since it is a fixed percentage of the bias current. A more convenient method of performing this measurement at many different values of bias current utilizes the "optional connections" shown in Figure 15. These connections allow the horizontal channel of the oscilloscope to sense the current source programming voltage. This voltage appears at the current source meter terminal, referenced to *circuit* common (note that the voltage at the same terminal referenced to the *negative output terminal* is equal to the output voltage of the current source). Because the oscilloscope common is already connected to the current source negative output terminal, the programming voltage must be measured *differentially* as shown. The constant of proportionality relating the programming voltage to the dc output current is simply the voltage programming coefficient of the current source; the value depends on the particular current source and output range used—typical values vary from 2mV/mA to 10V/mA. Since the oscilloscope horizontal channel is sensing the ac diode current (ΔI) and the vertical channel is sensing the ac diode voltage (ΔV), the resulting display is a line whose slope (vertical deflection per unit horizontal deflection) is the diode incremental impedance.

When measuring very low incremental impedances (less than one ohm) at relatively high frequencies (above 500Hz), the line displayed on the oscilloscope may be an ellipse rather than a straight line. This effect is caused by the phase shift inherent in the current source amplifier at higher frequencies. The effect can be eliminated by connecting the oscilloscope vertical amplifier directly across the diode under test rather than to the meter terminal as shown in Figure 15. Since the impedance of the diode is much less than the input impedance of the oscilloscope (1 ohm versus 1 megohm), the current source regulation will not suffer any measurable degradation.

Transistor h-Parameters

Another application of an ac modulated current source is found in the measurement of transistor hybrid parameters. The following paragraphs discuss measurement of the common emitter parameters; common base or common collector parameters can be measured using similar techniques. Table 1 gives definitions, alternate symbols, and typical values of the common emitter h-parameters for small-signal transistors.

TABLE 1. Small-Signal Transistor h-Parameters

PARAMETER	ALTERNATE SYMBOLS	DEFINITION	TYPICAL VALUE
h_{ie}	h_{11}, r_n	Input impedance (v_{be}/i_b), output short circuited.	2 kilohms
h_{re}	h_{12}, μ	Reverse voltage amplification factor (v_{be}/v_{ce}), input open circuited.	5×10^{-4}
h_{fe}	h_{21}, β	Forward current gain (i_c/i_b), output short circuited.	100
h_{oe}	h_{22}, g_o	Output admittance (i_c/v_{ce}), input open circuited.	10μmhos

Since the exact values of these parameters are dependent upon the quiescent operating point of the transistor, they are usually given on transistor data sheets at a specified value of dc collector current and dc collector-to-emitter voltage (typical values for small signal-transistors are I_C = 1mA and V_{CE} = 10V).

The h-parameters can be separated into two pairs according to the measurement conditions:

1. h_{re} and h_{oe} (measured with the input to the transistor open circuited), and
2. h_{ie} and h_{fe} (measured with the output of the transistor short circuited).

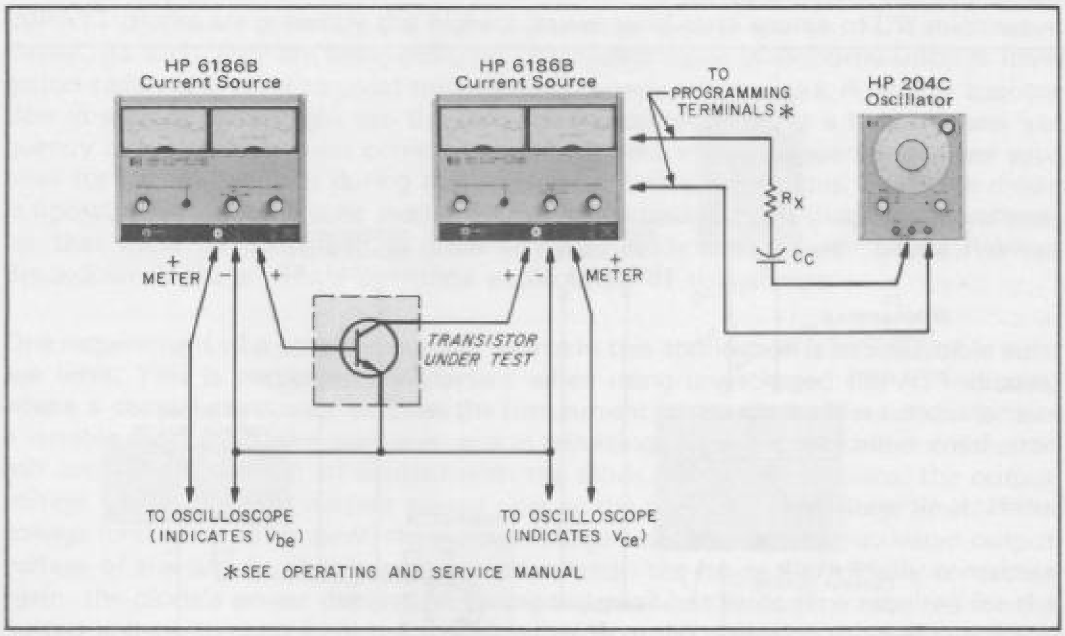

FIGURE 16. Measurement setup for determining transistor open-circuit h-parameters h_{re} and h_{fe}.

The first pair can be measured utilizing the setup of Figure 16 in combination with the modulation method of Figure 13. As shown in Figure 16, the base current source supplies the dc base current to the transistor (I_B), while its very high output impedance acts as an open circuit to any ac component of the base current (I_b). The collector current source supplies both the dc (I_C) and ac (I_c) collector currents. When performing the measurements, the collector current source is set for the specified value of I_C, and the base current source is adjusted until V_{CE} is the specified value.

The modulation percentage used in these two measurements is generally less than 10 percent in order to maintain small-signal conditions; note that whatever percentage is actually used, the value of I_c is determined without measurement because it is a known percentage of I_C (see "AC Modulation Method"). An oscilloscope connected to the meter terminal on the base current source indicates V_{be}; connecting the oscilloscope to the meter terminal on the collector current source indicates V_{ce}. Knowing these three ac values, $h_{re} = (V_{be}/V_{ce})$ and $h_{oe} = (I_c/V_{ce})$ can be readily calculated.

Figure 17 shows a suggested method of measuring the second pair of parameters. The method features the use of a constant voltage source to provide the required ac short circuit on the transistor output. The dc and ac collector currents are measured by connecting a differential oscilloscope across resistor R2; the value of R2 should be the smallest value that will permit measurement of I_c. For example, with an ossilloscope of 100μV/cm sensitivity and an I_c of 100μA, R2 would be 1Ω. The value of R2 detracts directly from the accuracy of the h_{fe} and h_{ie} measurements, because as R2 becomes larger, the transistor output no longer sees an ac short circuit. The exact value of the error will vary depending upon the magnitudes of R2, V_{ce}, I_b, and the parameters themselves, but for the typical values given above and in Table 1, the error will be less than one percent.

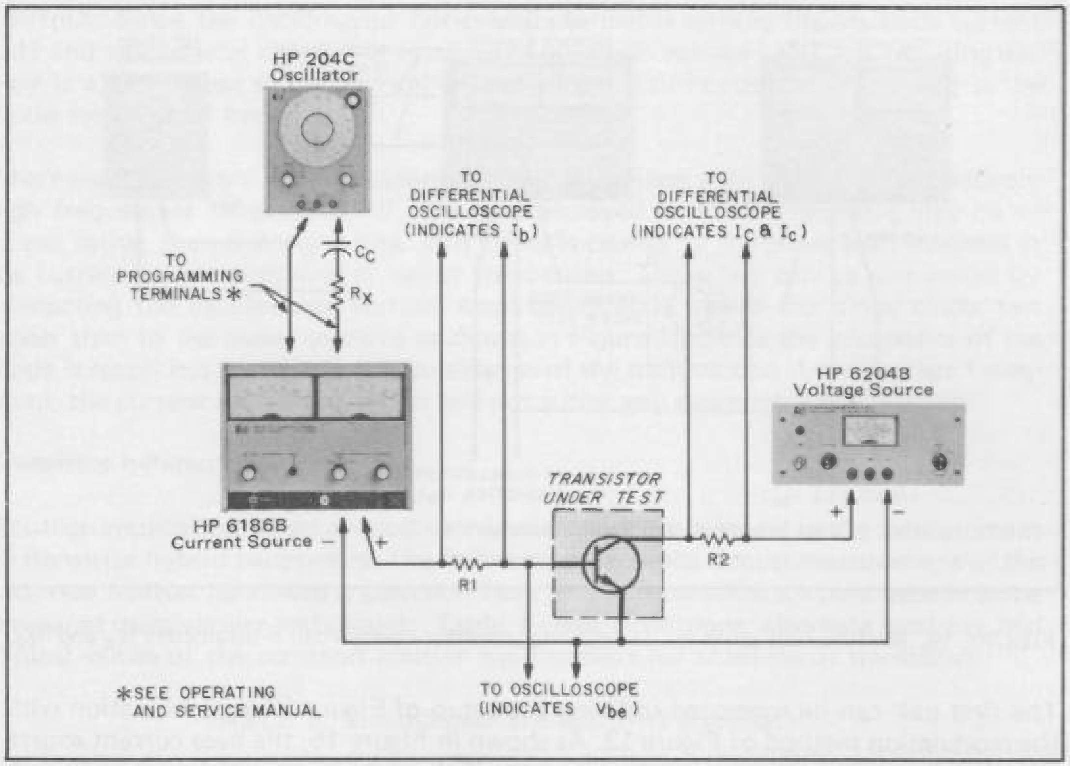

FIGURE 17. Measurement setup for determining transistor short-circuit h-parameters h_{ie} and h_{fe}.

The ac base current is measured by connecting a differential oscilloscope across R1. However, since R1 only adds to the already high output impedance of the current source, its presence has no effect on the accuracy of the parameter measurements. The value of R1 should be selected for convenience in measuring I_b—with an oscilloscope of 100μV/cm sensitivity and an I_b of 1μA, R1 is required to be at least 100Ω. When setting up the second pair of parameter measurements, the constant voltage source is set for the specified value of V_{CE}, and the constant current source is adjusted to obtain the specified value of I_C. The modulation percentage used in this pair of measurements is, as in the other pair, usually less than 10 percent. Once the three required ac values are determined (I_b, I_c, and V_{be}), $h_{fe} = (I_c/I_b)$ and $h_{ie} = (V_{be}/I_b)$ can be readily calculated.

Operating IMPATT Diodes

A constant current source can be used to advantage as an operating power supply for other semiconductor devices such as IMPATT diodes and Hall generators. IMPATT diodes (the name is an acronym derived from the terms IMPact ionization and Avalanche Transit Time) are junction devices that oscillate at microwave frequencies when operated in their avalanche region. Simply stated, such oscillations result because the total of (1) the delay between the applied voltage and the current generated by avalanche breakdown, and (2) the transit delay as the charge carriers travel through the diode, is equivalent to 180 degrees at microwave frequencies.

IMPATT diodes are presently the highest power solid-state source of CW microwave power. As such, they are being designed into systems such as air-borne Doppler navigation radars and point-to-point microwave communications links. A typical application in such systems might use the diode as a local oscillator in a heterodyned frequency converter. Constant current sources are very useful as operating power supplies for IMPATT diodes during the development of such systems. Since the diode is operating in the avalanche mode, the current supplied to the diode is the parameter that must be controlled in order to avoid diode failure (see "Diode Reverse Breakdown Voltage" for a complete explanation of this concept).

One requirement of a constant current source in this application is an adjustable voltage limit. This is particularly important when using unpackaged IMPATT diodes, where a coaxial conductor supplies the bias current to the diode. The conductor has a variable short for tuning purposes, and in adjusting this short, the center conductor can easily be lifted out of contact with the diode. When this happens, the output voltage of the constant current source rises to the setting of the voltage limit. If the voltage limit were not present, the output voltage would rise to the maximum output voltage of the supply. If this were to occur, when the diode was initially contacted again, the diode's power dissipation during the small but finite time required for the output voltage to drop from the maximum value to the operating value would greatly exceed the rated maximum and cause the diode to fail. By using the voltage limit to prevent the open circuit voltage from rising any significant amount above the operating voltage, this situation can be avoided. Another major advantage of a constant current source in this application is the absence of an output capacitor. The sudden load impedance change represented by the diode when it goes into avalanche breakdown would cause a destructive current surge from any capacitor connected across the output terminals. In addition to current surges, any such capacitance will often cause undesired oscillations in the bias circuit. Finally, in some applications, the dc power supplied to the diode must be pulsed; in these cases, rapid programming speed is required—here again, the absence of an output capacitor is a necessity.

Operating Hall Effect Devices

Another semiconductor application is operating Hall effect devices. Simply stated, the Hall effect is the generation of a voltage across opposite edges of an electrical conductor carrying current and placed in a magnetic field (see Figure 18). The basic Hall effect equation is:

$$V_H = wR_H \, (j \times B) \qquad \text{EQ. 4}$$

where V_H is the Hall output voltage, w is the width of the Hall plate, R_H is the Hall coefficient, j is the current density through the Hall plate, and B is the magnetic field strength. A more useful equation for practical Hall generators is:

$$V_H = Y_{IB} \, (I_C \times B) \qquad \text{EQ. 5}$$

where I_C is the control current and Y_{IB} is the open circuit sensitivity, a constant that takes into account the effects of geometry and other factors.[7] This equation indicates that the product of two inputs results in a voltage output. If either input is zero, the output is zero. If one input is held constant, the output is directly proportional to the other input.

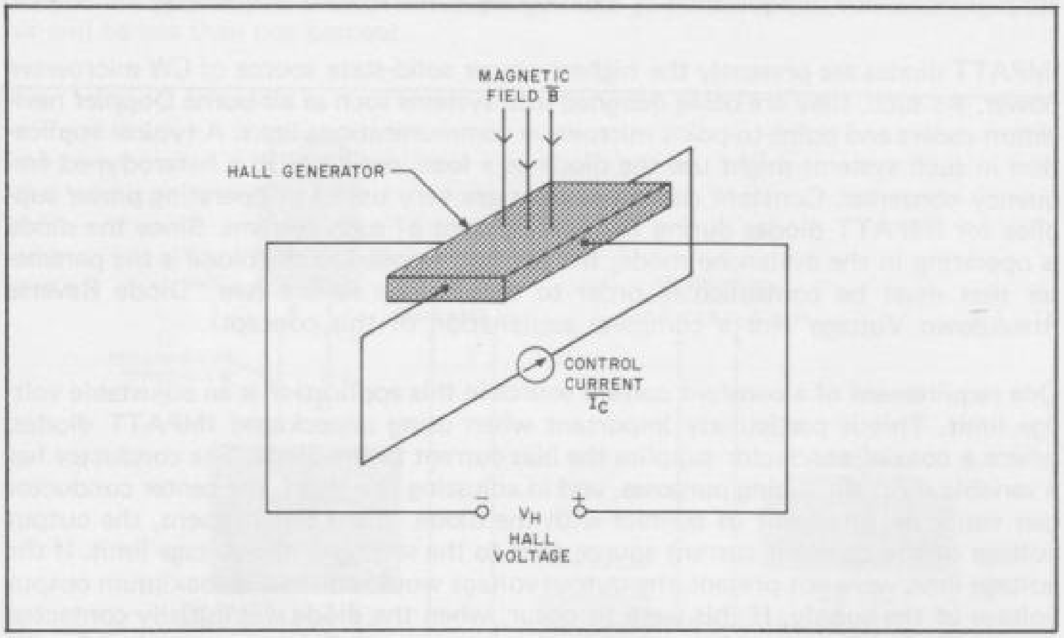

FIGURE 18. The Hall effect.

An obvious application of the Hall effect is to measure magnetic field strength by holding I_C constant and measuring V_H. Since the Hall output voltage is directly proportional to the current times the field strength, the current must be held absolutely constant to maintain high accuracy in the measurement–thus the necessity for a precision constant current source. The direction and polarity of the field can be determined as part of this measurement, since the output voltage polarity shown in Figure 18 reverses is the direction of the magnetic field reverses, and is a maximum when the lines of force are perpendicular to the plane of the element. AC fields may be measured using a dc control current; in this case the Hall output is an ac voltage at the frequency of the field with its magnitude proportional to the instantaneous value of flux density. Applying this output to an oscilloscope will allow observation of the true waveshape of the ac field.

When measuring magnetic field strength, the Hall output voltage is usually amplified with a differential amplifier in order to eliminate the zero field residual voltage (typically between 150μV and 1.5mV). Hall generators are available with open circuit sensitivity constants (Y_{IB}) from 20mV/G to 300mV/kG, allowing measurement of a wide range of field intensities.

Additional Hall generator characteristics affecting the accuracy and resolution of magnetic field intensity measurements are temperature coefficient, linearity, and physical dimensions. A typical temperature coefficient of the Hall output voltage is

0.06%/°C; this places a limitation upon the maximum accuracy that can be achieved without control of the ambient temperature. Hall generators with high basic linearity *and* individual linearity deviation curves are available to combat the second source of error (typical linearity specifications are 0.25 percent of reading from -10kG to +10kG, and 1.0 percent of reading from -30kG to +30kG). To achieve the highest possible resolution, the Hall element should be as small as possible in order to minimize output variation due to unequal sensitivity over the surface area; active areas as small as 0.01" x 0.02" are available.

Other applications of a Hall generator in combination with a constant current source are illustrated in Figure 19. Parts (A), (B), and (C) illustrate the use of the Hall generator as a linear or angular displacement transducer. Slight movement in the direction of the heavy arrows in Part (A) produces a large positive or negative output; movement in the direction of the heavy arrow in Part (B) produces approximately a linear output versus displacement; movement in the direction indicated by the heavy arrow in Part (C) produces an output voltage that is a sine function of the angle between the plane of the element and the direction of the magnetic lines of force.

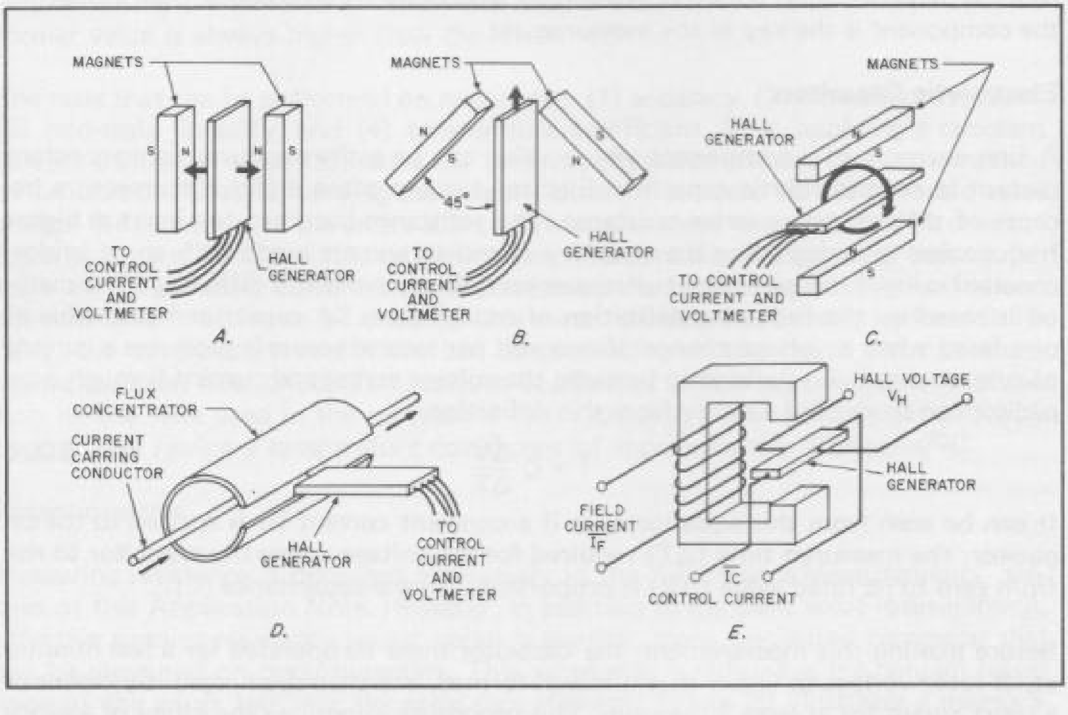

FIGURE 19. Parts A, B, and C: Linear and angular displacement transducers based on Hall effect. Part D: Current measurement utilizing Hall effect. Part E: Multiplier using Hall effect.

Part (D) illustrates the use of the Hall generator to measure current (any conductor carrying current has an associated magnetic field around it whose magnitude is proportional to the current). Very small currents may be measured with the use of a flux concentrator as shown; for larger currents, the Hall generator need only be placed adjacent to the conductor. Currents ranging from milliamperes to kiloamperes can be measured in this manner with essentially zero losses and no electrical connection.

A final application of the combination of a Hall generator and a constant current source is the multiplier shown in Part (E) of Figure 19. The device has two inputs: the control current to the Hall generator (I_C), and the current through the field coil (I_F). Either input may be ac, dc, or any combination of ac and dc (the constant current source can be ac modulated as described under "AC Modulation Method" to produce such a combination signal with minimum effort). The output voltage (as shown in Equation 5) is the product of the two inputs. The multiplier may be used in such applications as modulators, analog multipliers, power transducers, variable attenuators, frequency doublers, and square law detectors.

COMPONENT TESTING

What can you do with constant current? Component testing is a less often considered application area. The following practical examples are only a few of the many possible applications of constant current in this field. Included are tests on:

¶ Electrolytic Capacitors
¶ Relays and Meters
¶ Potentiometers

In each of these tests, the ability to supply a constant *current* rather than voltage to the component is the key to the measurement.

Electrolytic Capacitors

A first example of a component whose value can be easily measured using constant current is an electrolytic capacitor. Electrolytics are often difficult to measure because of their effective series resistance. This resistance becomes dominant at higher frequencies, thus degrading the accuracy of measurements made with an ac bridge; constant current measurement techniques completely avoid this difficulty. The method is based on the following definition of capacitance: "A capacitor has a value of one farad when a voltage change of one volt per second across it produces a current of one ampere." A relationship between the voltage across and current through a capacitor can be derived directly from this definition:

$$I = C \frac{\Delta V}{\Delta T} \qquad \text{EQ. 6}$$

It can be seen from this equation that if a constant current (I) is applied to the capacitor, the measured time (ΔT) required for the voltage across the capacitor to rise from zero to its rated value (ΔV) is proportional to the capacitance (C).

Before making this measurement, the capacitor must be operated for a few minutes at its rated voltage to insure that it is well formed, and then discharged by means of a short circuit for at least 30 seconds. This procedure minimizes the effect of leakage current in the capacitor during the value measurement charging cycle. The long discharge period is necessary due to the occurance of polarization that often results in slight "re-volting" after a short-duration short circuit has been removed. Depending on the value and rated voltage of the capacitor under test, and the magnitude of the applied current, the measured time inverval can vary from 1 to 60 seconds. For example, with a 2,000μF 50Vdc electrolytic and an applied current of 10mA, the measured time interval (from EQ. 6) would be $(2 \times 10^{-3}F \times 50V)/10^{-2}A$ = 10 seconds.

"Build factor", a measure of the shelf life, is another parameter of electrolytic capacitors that can be characterized with constant current. The determination is straightforward: first, apply to the capacitor a known current of magnitude four to ten times the capacitor's rated leakage current. Second, measure the time required for the voltage across the capacitor to reach the rated value. If the capacitor has not been used for a long period of time, it must be reformed; the first charge cycle applied to the capacitor performs this function. Because the capacitor leaks at a level greater than normal during this first cycle, the charging time is longer. The ratio of this charging time to the theoretical charging time (or the charging time after the capacitor is fully formed) is called the build factor and is an indication of the shelf life—large values indicate poor shelf life.

Relays and Meters

Current-controlled devices are a constant current source's home ground. In particular, consider relays and meters—in both, the current applied to the device is the important parameter. A constant current source can be used to perform several production and quality control tests on both; for the former, the most important test is pull-in and drop-out currents. These current values, normally specified at room temperature, take on added significance at elevated temperatures—the values may be significantly different due to changes in coil resistance. The actual test is performed by simply noting the currents at which the relay armature pulls in and drops out; the former value is always higher than the latter.

The tests that can be preformed on meters are: (1) accuracy, (2) movement freedom, (3) mid-scale linearity, and (4) temperature coefficient. First, applying a constant current of known value facilitates the accuracy measurement and is an easy method of calibration. Second, varying the current slowly from zero to the full-scale value sweeps the pointer over the entire scale, allowing the meter movement to be checked for sticking and other mechanical difficulties. Third, setting the meter to exactly full scale with a constant current and then reducing the current by exactly half allows the mid-scale linearity to be checked (the meter should read exactly half-scale). Finally, the temperature coefficient can be checked with the aid of a temperature-controlled oven (see "Diode Temperature Coefficient"). This last parameter is a function of the wire used in the movement coil; typically, meter coils are wound with copper wire having a temperature coefficient of approximately 4000ppm/°C.

Potentiometers

Measuring resistance is discussed extensively in the "Resistance Measurements" section of this Application Note. However, in addition to the basic value measurement, effective running resistance (wiper noise) is another, more specialized parameter that can be measured on potentiometers. This parameter is defined as the contact resistance of the wiper touching the resistance element; Figure 20 illustrates a measurement technique. A constant current is supplied through the "A" portion of the potentiometer, producing a voltage with respect to ground (seen at the "plus" input to the horizontal amplifier) whose magnitude is proportional to the sum of the "A" portion resistance and the wiper contact resistance. The "minus" input of the horizontal amplifier sees only the voltage drop across the wiper contact resistance (note that no current flows through the "B" portion of the potentiometer). This voltage is subtracted from the voltage at the "plus" input by virtue of the differential input, leaving a voltage applied to the horizontal deflection plates that is proportional *only* to the percent rotation of the potentiometer. The single ended vertical amplifier, connected to the horizontal "minus" input, also sees only the voltage drop across the wiper contact resistance.

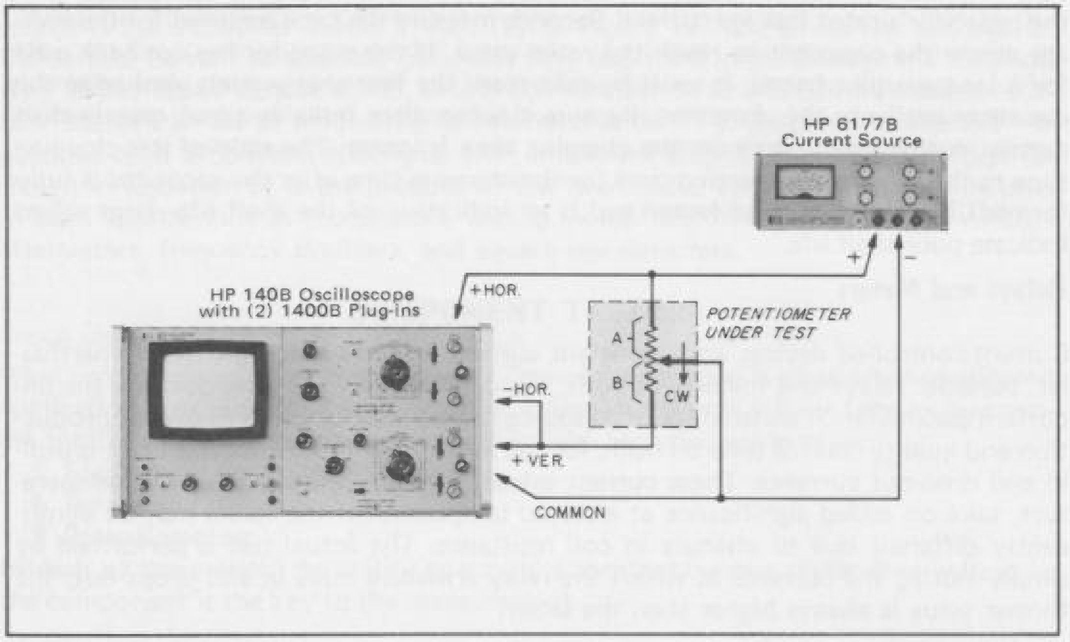

FIGURE 20. Test setup for measuring potentiometer effective running resistance.

The resulting display on the oscilloscope CRT is a spot that moves horizontally as the potentiometer is turned clockwise, and vertically in proportion to the effective running resistance. Appropriate amplifier sensitivities should be selected to keep the spot on-screen. For example, for a horizontal deflection of 10cm with an applied current of 1mA, the horizontal amplifier should be set to (0.1V/cm)/1kΩ of potentiometer resistance; with the vertical amplifier set to 5mV/cm, a vertical deflection of 5cm is equivalent to an effective running resistance of 25Ω.

OTHER APPLICATIONS

What can you do with constant current? There exists a variety of less common applications outside the three categories (Resistance Measurements, Semiconductor Device Measurements, and Component Testing) used in this Application Note. For instance, a constant current source finds many uses in electrochemical and cryogenic latoratories. Several such uses are briefly described in the following paragraphs.

In the Cryogenic Laboratory

Precision specific heat measurements at low temperatures by the heat pulse method require the application of an accurately known pulse of current for a known time to an electric heater. The current required may range from 10μA to 10mA; the time period is generally between 10 and 100 seconds. The use of a precision constant current source rather than a constant voltage supply to operate the resistive heating element (typically 1 kilohm) offers several advantages. First, the effect of variations in the resistance of the heater leads (due to changes in the liquid helium level) can be completely eliminated, because the constant current flowing through the heater is independent of the lead resistance. Second, the long term stability of a precision constant current source represents an advantage in both operating convenience and result reproducibility. For example, if the supply is remotely programmed with switched precision programming resistors to predetermined current levels, the current stability is such that during the actual experiment the values of current used need only be recorded from the programming switch rather than remeasured at each heat capacity measurement (such remeasurements heat the sample unnecessarily).

In the Electrochemical Laboratory

Constant current and electrochemistry are related by Faraday's laws of electrolysis. Simply stated, these are:

1. The amounts of primary product formed by electrolysis are directly proportional to the amount of electricity flowing.
2. The passage of a given quantity of electricity causes the amounts of primary products formed by electrolysis to be in the ratios of the chemical equivalents of those products.

The basic unit used for "amount of electricity flowing" is the coulomb; one coulomb is defined as a current of one ampere flowing for one second. It can thus be seen that the *current* is the parameter of interest in many electrochemical processes; a precision constant current source makes precise current control very simple.

The most common electrochemical process utilizing constant current is coulometric titration [8]. This analytic procedure involves removing one constituent of a solution by quantative electrolysis—that is, measuring the amount of a substance in a solution by measuring the number of coulombs (current magnitude times elapsed time) required to completely titrate the solution. One limitation on this procedure is that it must be 100 percent current efficient—all the current passing through the cell must be utilized in producing the final yield of electrolytic product.

Electrogravimetry and precision electroplating are two other electrochemical applications of constant current. The former process, similar in end result to coulometric titration, is a method of analytically determining the amount of a substance in a solution by deposition onto a weighed electrode. In the latter process, an electrode (such as that used in a pacemaker's implanted catheter) can be plated with a thin metal film of precisely known thickness.

Additional applications of constant current in the electrochemical laboratory include chronopotentiometry (a mass transfer technique for determining the concentration of a substance in a solution), and electrode kinetics (the study of the actual atomic mechanism of electrochemical reactions).

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