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SURVEY OF SOLID-STATE DEVICES

Much of the noteworthy electronic progress during the past twenty years has been made in the area of solid-state research. This work started so quietly as to attract little attention but snowballed rapidly and has produced many of the glamour components of electronics.

Progress in solid-state research and development has resulted from increased understanding of the behavior of certain solid materials, notably semiconductors, in electric circuits. The materials employed in some solid-state devices are true semiconductors. Examples of such devices are diodes, transistors, rectifiers, and photocells. Materials used in other solid-state devices are not semiconductors. Examples of the latter devices are non-linear resistors, non-linear capacitors, ferroelectric cells, electro-luminescent cells, and Hall-effect devices.

Solid-state components are applied widely in modern electronics for a variety of functions including rectification, amplification, control, modification of currents or voltages, frequency conversion, harmonic generation, conversion of light into electricity, production of light, and production of d-c voltage. In most instances, solid-state devices are simpler than other components which will perform the same functions, and in some instances they are miniature as well.

As a simple survey of the art, this article purposes to show the scope of solid-state applications and to direct attention to individual components, their operating principles, and present state of development. A bibliography is presented for more detailed reference.

Diodes

Diodes are made from specially-processed semiconductor materials. The diode essentially is a small rectifier which is applied to radio and television detection, light-duty rectification (as in low-current power supplies, meter circuits, d-c relay operation from ac, etc.), signal conversion, d-c restoration, modulation, demodulation, harmonic generation, and switching and clamping in computers. There are, of course, many other uses.

The principal semiconductor materials employed in high-frequency diodes are germanium and silicon. The material is doped with an impurity material to render it either N-type (conducting principally by means of electrons) or P-type (conducting principally by means of holes). In the manufacture of a diode, a junction is suitably formed between an N-type and P-type layer of the same semiconductor. Commercial diodes are available in two types of fabrication: junction and point-contact. However, the latter is essentially a junction-type unit also, since in its manufacture a heavy current pulse electroforms a region of opposite type (P or N) directly under the point of contact between the whisker and semiconductor. Because current will flow more readily in one direction through the junction of a diode than in the opposite direction, rectification is made possible.

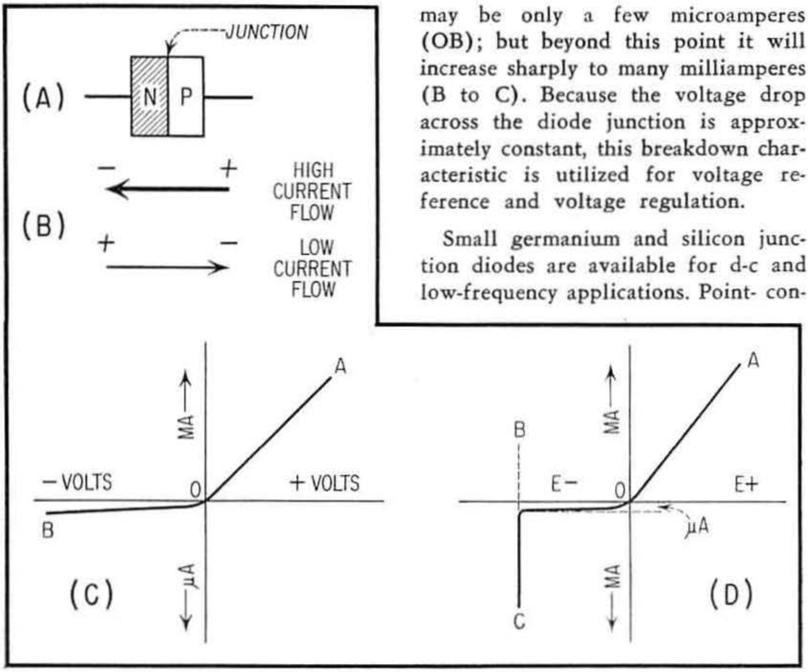

Fig. 1. Diode and Rectifier Characteristics.

Figure 1 illustrates the principal characteristics of the semiconductor diode. Figure 1(A) shows the basic arrangement of the junction structure. Maximum (forward) current flows when the P-layer is biased positive with respect to the N-layer (See Figure 1B). Minimum (reverse) current flows when the P-layer is negative. The plot in Figure 1(C) illustrates this assymetrical flow: Forward current flows from O to A, and reverse current from O to B.

Zener diodes are processed to exhibit a sharp breakdown (BC) when reverse-biased, as shown in Figure 1(D). Up to a predetermined value of reverse voltage, the reverse current may be only a few microamperes (OB); but beyond this point it will increase sharply to many milliamperes (B to C). Because the voltage drop across the diode junction is approximately constant, this breakdown characteristic is utilized for voltage reference and voltage regulation.

Small germanium and silicon junction diodes are available for d-c and low-frequency applications. Point-contact silicon diodes are usable up to several thousand megacycles. The maximum operating temperature for germanium is approximately 50°C, while that of silicon diodes is 200°C. The largest single application for diodes presently is in the digital computer where several thousand may be employed for switching, logic, clamping, and other purposes.

Selenium diodes have a somewhat different construction and, mainly because of their higher internal capacitance, are limited in use to frequencies lower than 50 kc.

Rectifiers

The principal use of semiconductor rectifiers is the conversion of ac to dc at useful power levels. Commercial types include copper oxide, magnesium-copper sulphide, selenium, germanium, and silicon. In some applications, germanium and silicon rapidly are superseding the other three types. Copper oxide rectifiers have been replaced almost entirely at high power levels by the other types which offer superior performance.

In the first three types, rectification is afforded by the junction between a crystalline semiconductor material (copper oxide, copper sulphide, or selenium) and a metal base plate (copper, magnesium, or aluminum, respectively) upon which it is spread or deposited in a layer. The maximum permissible current through the rectifier is a function of the junction area, and the maximum permissible voltage drop a function of the junction thickness. For increased voltage-handling ability, several rectifier plates usually are assembled in series in a "stack."

Plate-type selenium rectifiers cover the tremendous current range of more than 1 million to 1, their practical application extending all the way from small radio - type units (delivering a few milliamperes output current) to large power rectifiers delivering several thousand amperes output. The high internal capacitance of the selenium rectifier limits its efficient use to power frequencies.

Modern germanium and silicon power rectifiers may be regarded as "grown-up" diodes with the same essential junction arrangement as that shown in Figure 1(A). Advantages of these rectifiers over other types are smaller size, low internal capacitance (therefore higher - frequency operation), simpler mechanics, higher efficiency (up to 99%), higher applied and peak inverse voltages per rectifier cell, and in some instances better economy. Operation of germanium power rectifiers is limited to maximum ambient temperatures of approximately 65°C, without derating. Comparable silicon power rectifiers may be operated up to 200°C before derating.

Rectifiers processed to show a sharp current increase ("breakdown") at a predetermined reverse voltage serve as power-type Zener diodes.

Transistors

The transistor is a semiconductor device with two junctions (See Figure 2A). Going one step further than the diode, this device affords amplification and control, often at high gain ratios. Either N-type or P-type germanium or silicon may be employed as the semiconductor in a transistor, as in a diode. Layers of the opposite type are suitably processed into the material to produce either an NPN or PNP sandwich, the center layer (or **base**) standing in a circuit in a manner similar to the grid of a vacuum tube. One of the outside layers is termed **emitter**, since it serves to inject current carriers (electrons in the NPN unit, or holes in the PNP unit) into the base region; and the other outside layer is termed **collector** because (like the plate of a tube) it collects the carriers.

Figure 2(B) shows the basic common-emitter circuit for a PNP transistor. Base current i_b is supplied by Battery V_{BB}; collector current i_c by Battery V_{CC}. Because the base voltage is low, i_b is much smaller than i_c, although the base-emitter junction is

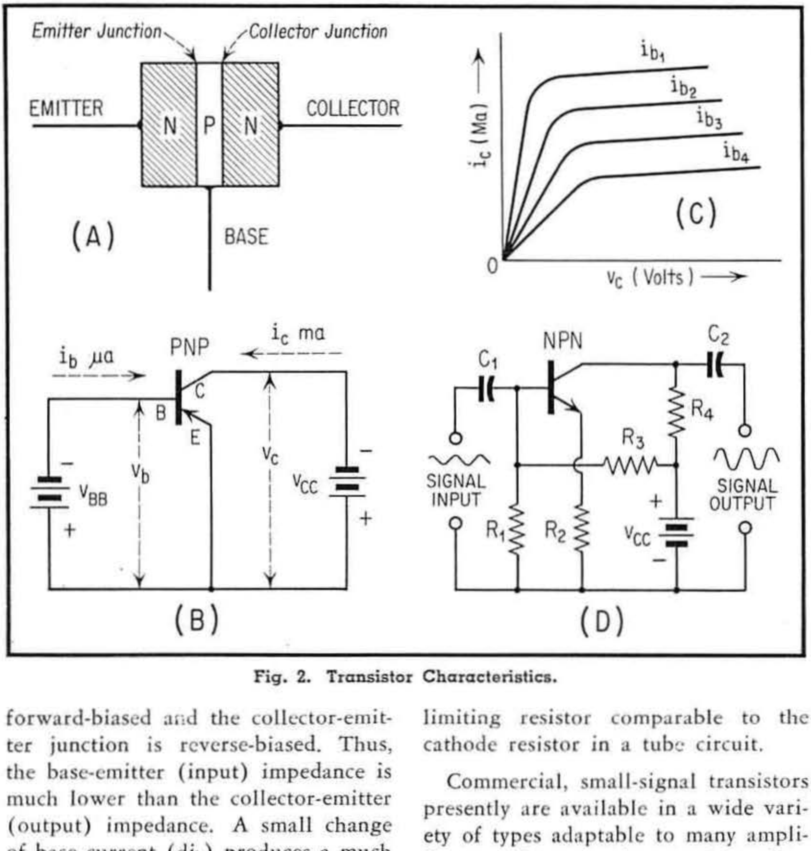

Fig. 2. Transistor Characteristics.

forward-biased and the collector-emitter junction is reverse-biased. Thus, the base-emitter (input) impedance is much lower than the collector-emitter (output) impedance. A small change of base current (di_b) produces a much larger change (di_c) in collector current. Thus, the ratio di_c/di_b expresses the current amplification (gain) of the transistor. Figure 2(C) illustrates operation of the transistor. These plots are seen to resemble the typical family of characteristic curves for a pentode tube.

Figure 2(D) shows a typical RC-coupled a-f amplifier stage employing an NPN transistor. Here, positive base bias is supplied from the collector battery, V_{cc}, through the voltage divider, R_1-R_3. Resistor R_2 is an emitter current-limiting resistor comparable to the cathode resistor in a tube circuit.

Commercial, small-signal transistors presently are available in a wide variety of types adaptable to many amplifier, oscillator, and control applications. While only the triode type is shown in Figure 2, tetrodes also are available. The maximum operating frequency of commercial small-signal types is approximately 100 Mc for triodes and 200 Mc for tetrodes. (Oscillation is obtainable up to 600 Mc in some types). Newly-developed commercial triodes have cutoff frequencies up to 750 Mc. Experimental transistors have been operated at much higher frequencies in the laboratory. The maximum permissible small-signal power dissipation is approximately 200 milliwatts. The maximum operating temperature for germanium transistors is approximately 85°C; the maximum for silicon transistors is 150°C.

Power transistors have essentially the same basic arrangement as small-signal units (Figure 2A) but their junctions have been designed for higher power dissipation. Typical medium-power transistors have maximum dissipation ratings up to approximately 1 watt and collector current ratings up to approximately 60 ma. Depending upon type, commercial high-power transistors have maximum power dissipation ratings up to 50 watts, collector current up to 20 amperes, and collector voltage up to 120 v. Because of increased junction capacitance and other factors, power transistor operation presently is limited to audio frequencies.

Lately, a new power-transistor-type semiconductor device, the controlled **rectifier,** has appeared. This unit is capable of handling large amounts of power and behaves in a manner similar to the thyratron tube.

Non-Linear Resistors

A special type of 2-terminal solid-state device is the non-linear resistor. This component is employed wherever a non-ohmic variation of current (against a linear variation of applied voltage) is desired.

In direct-current circuits, a semiconductor diode could function as a non-linear resistor, since its current does not vary linearly with voltage. (See Figures 1C and 1D). However, the rectifying properties of the diode restrict its resistor applications mainly to dc.

Other types of non-linear resistor are available, however, and these ex-

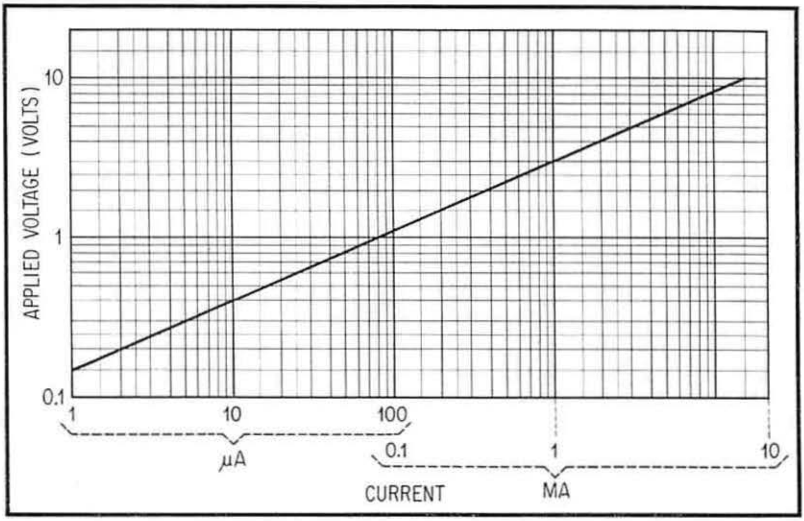

Fig.3. Characteristics of Non-Linear Resistor.

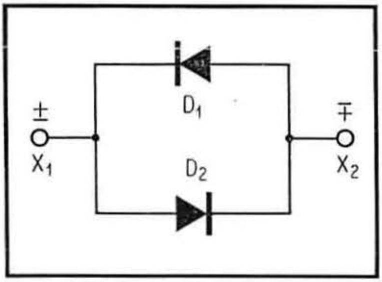

Fig. 4. Dual-Diode Non-Linear Resistor.

hibit no rectifying properties. One such resistor is the Thyrite type. In Thyrite, the current varies as a power of the applied voltage (a-c or d-c), that power depending upon the predetermined constitution of the material. Thyrite resistors are commercially available in a number of sizes and shapes and for use at various power levels. Thyrite resistors are made from silicon carbide.

Figure 3 shows the approximate current-voltage relationship for one type of Thyrite resistor. This plot has been made for a voltage variation from 0.1 to 10 v and a corresponding current variation from 1 microampere to 20 milliamperes. Note that the current changes in value more than 100 to 1 (from 1 μa to 100 μa) in response to a voltage variation of 10 to 1 (from 0.1 v to 1 v).

Figure 4 shows the connection of two semiconductor diodes to form a non-linear resistor suitable for limited use on ac. When Terminal X_1 is positive, Diode D_2 conducts forward current; and when X_2 is positive, D_1 conducts. In this way, both halves of the a-c cycle are accommodated. By using high-back-resistance diodes, current during the reverse half-cycle is minimized.

Since for a linear voltage rise, the rate of current rise through a non-linear resistor is somewhat greater than linear (Figure 3), the current waveform will be distorted when compared with the voltage waveform. The current through a non-linear resistor accordingly is rich in harmonics, especially odd-numbered ones. Figure 5 shows the non-linear IE characteristic curve for a Thyrite resistor. Its shape readily accounts for the distortion of an applied ac.

Non-linear resistors are employed for voltage regulation, current-rate multiplication, harmonic generation, oscillator stabilization, amplitude limiting, and surge suppression (especially lightning arresting).

The **thermistor** also is a solid-state non-linear resistor. It may be employed in some circuits in which Thyrite or other non-linear resistors usually are operated, since it works on either ac or dc. However, the main useful property of the thermistor is the sensitivity of its resistance to temperature. This component is widely used as a temperature sensor or as a bolometer

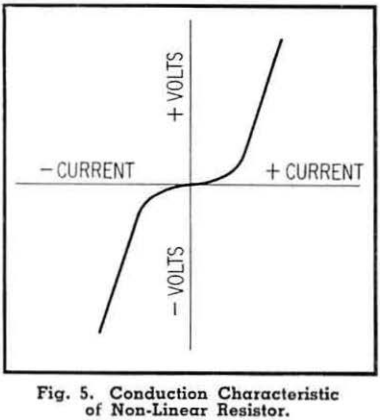

Fig. 5. Conduction Characteristic of Non-Linear Resistor.

in such instruments as temperature bridges, pyrometers, microwave power meters, etc. Thermistors are made from suitable oxides.

Because of the sensitivity of the thermistor to its own internal temperature, as well as to ambients, its resistance (which decreases with increasing temperature) and the resulting current it passes may not reach a final value until some instant after a voltage has been applied. This time delay is utilized in such circuit applications as contactless time-delay switching, or in imparting a delay interval (set by proportioning circuit resistances) to some other component with which it is connected in series.

Photocells

Solid-state photocells are of two types: **self - generating** (photovoltaic) and **photoconductive.** The self-generating type produces a d-c voltage directly as the result of its being illuminated. The photoconductive type undergoes a decrease in resistance when illuminated. The principal types of self-generating cells are selenium and silicon. The earlier copper-oxide photovoltaic cell has been supplanted largely by these two types. Photoconductive cells include cadmium sulphide, cadmium selenide, lead sulphide, and germanium photodiode types. The action of both self-generating and photoconductive cells results from the release of current carriers in the solid material by light energy.

Figure 6 illustrates the basic comparison of the two types. The self-generating cell is indicated in Figure 6(A). It delivers a d-c voltage which may be employed directly to actuate a microammeter or sensitive relay or to drive a d-c amplifer. The photoconductive cell in Figure 6(B) is connected in series with a battery and the load device (R_L) which is to be operated. The dark resistance of the cell is so high that virtually all of the battery voltage appears across the cell, and little or none across the load. Under illumination, the cell resistance falls to a very low value and the maximum voltage appears across the load.

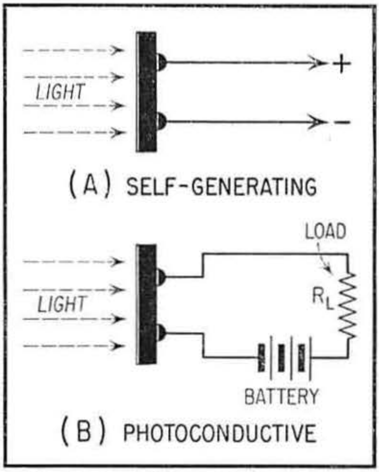

Fig. 6. Basic Photocell Comparison.

Depending upon size, type, light intensity, and load resistance, commercial selenium self-generating photocells deliver outputs up to 35 ma per square inch of exposed cell surface. Silicon photocells deliver up to 200 ma per square inch. The spectral response of the silicon cell peaks around a wavelength of 800 millimicrons; that of the selenium cell around 550 millimicrons.

Modern, miniature photoconductive cells of the cadmium selenide and cadmium sulphide types can withstand powerline a-c or d-c voltage levels and hence are capable of operating relays and other devices without amplification. Typical sensitivity provided by cells of these types is 100 to 600 microamperes output at 100 volts under illumination of 2 foot-candles.

The germanium photodiode is a photoconductive cell similar in construction to a semiconductor diode. In operation, this unit is reverse-biased by a maximum of 50 volts. The dark current is of the order of 10 μa, and the maximum current at 3000 lumens per square foot, 600 μa. The spectral response peaks in the infra-red region. The frequency response of the germanium photodiode permits operation up to 20 kc at approximately 65% of its 1-kc efficiency.

Still another solid-state light-sensitive device is the **phototransistor.** This is a 3-layer junction device similar to the small-signal transistor. Here, however, the current carriers are released by light energy rather than by an electrical signal input. A collector voltage is applied. The current amplification of the transistor structure thus is available, and this results in greater sensitivity than is afforded by the simpler photodiode.

Non-Linear Ceramic Capacitor

Capacitance is sensitive to applied voltage in a special 2-plate capacitor fabricated from high-Q solid dielectric material such as barium titanate. When such a capacitor is connected in series with an a-c source and a load, and the reactance of the capacitor is varied by means of a lower-frequency signal voltage, the a-c voltage appearing across the load will be proportional to the signal voltage. By properly choosing the circuit constants and source ("pump") frequency, amplification of the signal will be obtained. This is the principle of the dielectric amplifier.

The dielectric amplifier has the advantages of simplicity, relatively high frequency response, and high input impedance. Its principal disadvantages are the requirement of a high-frequency power supply and the temperature sensitivity of the dielectric.

Non-linear capacitors have been employed, in addition to amplification, for frequency multiplication, oscillation, frequency modulation, and remote tuning.

Semiconductor-Junction Capacitor

Operating similar to the non-linear ceramic capacitor is the semiconductor-junction capacitor. This is a specially-processed silicon junction, the capacitance of which varies with an applied reverse d-c bias voltage (upon which may be superimposed an a-c signal voltage). Like the ceramic unit, the voltage-variable diode capacitor has been employed for amplification, frequency modulation, automatic frequency control, frequency multiplication, remote tuning, and control operations. The desirable high-temperature operating characteristics of the silicon diode are available in the diode-capacitor, which gives the latter an advantage over the temperature-sensitive ceramic unit.

Commercial diode-capacitors are available in nominal capacitances from 3 to 250 $\mu\mu$fd. Capacitance changes up to 10 to 1 may be obtained by varying a d-c bias voltage. Because the d-c voltage reverse-biases the junction, the current flow is negligible, as low as

0.01 microampere in some instances. Hence, virtually no load is imposed upon the bias and input-signal sources.

Ferroelectric Cell

A ceramic-type non-linear 2-plate capacitor element, somewhat similar to the unit employed for dielectric amplification, exhibits a memory effect since it may be polarized in one direction or the other at will. The steep electrostatic hysteresis loop evidenced by certain single-crystal solids (notably, barium titanate, guanadine aluminum sulphate hexahydrate, and triglycene sulphate) give this property to the **ferroelectric cell.** Figure 7 shows such a loop.

Successive voltage pulses will polarize the cell either to Point A or Point B, the cell remaining in one state of polarization until switched to the opposite state by a voltage pulse of opposite polarity. This effect gives promise of use in computer memory circuits, as well as in electrostatic (ferroelectric) flip-flops, shift registers, and similar switching systems.

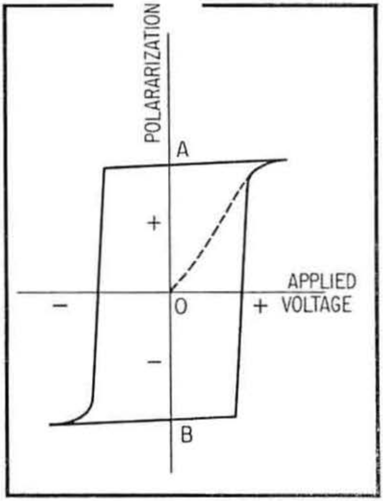

Fig. 7. Hysteresis Loop of Ferroelectric Cell.

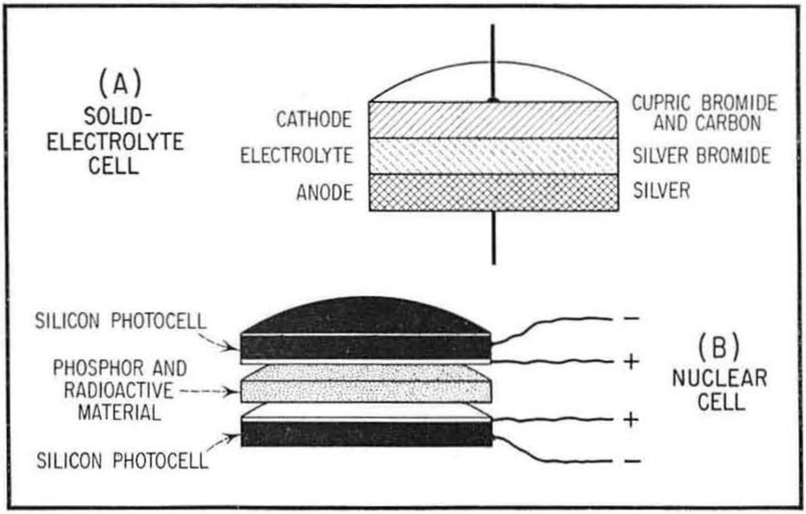

Fig. 8. Solid-State Battery Cells.

In this operation, the ferroelectric cell may be regarded as the dual of the ferrite core, another solid-state component but one which utilizes magnetic hysteresis.

Solid-State Batteries

Solid-state batteries of two types recently have been introduced. One employs a solid dielectric; the other utilizes radioactivity. Cells of both types are shown in Figure 8.

The first type, shown in Figure 8 (A), uses silver bromide as the dry solid dielectric. Cell action results from diffusion of positive silver ions through the solid silver bromide. In true electrochemical cell manner, one electrode material is consumed — in this instance, the silver anode. In its present state of development, this cell is a low-current device. Prelimary cells have delivered terminal voltages of approximately ¾ v. Fabricated as small buttons, they have extremely long storage life, good recovery characteristics, completely dry nature, and can be stacked to produce miniature, high-voltage, low-current batteries.

The second type, illustrated by Figure 8(B), produces d-c voltage by a 2-step action: Exploding atoms in a suitable radioactive material, mixed with a phosphor in the center layer, causes a multitude of light flashes from the phosphor. These, in turn, actuate the silicon photocells which comprise the two outside layers, and these photocells deliver the d-c voltages.

This nuclear cell is tiny, preliminary models being less than dime-sized. These cells deliver low currents (of the order of microamperes). They have extremely long life. The two photocell outputs may be connected in series for potentials between ¼ and 1 volt. A contemporary, commercial nuclear battery delivers 5 kv open circuit and 3 kv at 50 $\mu\mu$a load.

Electroluminescent Cell

The production of light directly from the electrical excitation of a phosphor is accomplished in the **electroluminescent cell** or **panel.** This device is represented simply in Figure 9.

The phosphor layer is sandwiched between two outer glass plates. The inner surface of each glass plate is

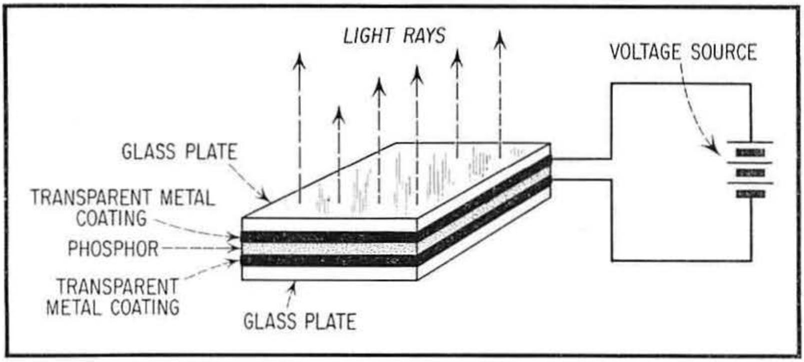

Fig. 9. Electroluminescent Cell.

coated with a transparent metallic film which permits electrical contact with the phosphor surface and at the same time allows light rays to pass through. The two films are connected to a suitable voltage source, usually between 600 v and several kv. Under the influence of the applied emf, the phosphor glows and the resulting light rays are readily transmitted out through the thin films and glass plates.

Combinations of electroluminescent cells and self-generating photocells have been used in several interesting applications such as light amplifiers, switching circuits, and relaxation oscillators.

Hall-Effect Devices

Research in intermetallic compounds, of which indium antimonide is a well-known example, has yielded useful new magnetoresistance components which utilize the Hall effect. This effect is the deflection of conduction electrons in a current-carrying body to the outer edge by a magnetic field applied transverse to the direction of current flow. The net result of the effect is a change in the resistance of the body.

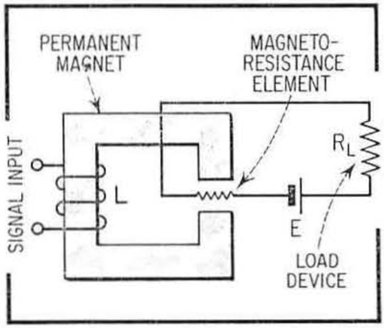

Fig. 10. Galvanomagnetic Amplifier.

Simple Hall-effect devices have been employed in a gauss-meter probe which delivers a d-c output proportional to the strength of an applied magnetic field, and as magnetosensitive resistors for rectification, current and voltage regulation, chopping, conversion, and various types of control.

Figure 10 shows the basic arrangement of a galvanomagnetic amplifier employing a small indium antimonide magnetoresistance element mounted in the air gap of a permanent magnet. A d-c voltage, E, is applied in series with the element and a load device, R_L. An a-c input-signal voltage applied to the magnet coil, L, modulates the intensity of the magnetic field in the gap, and accordingly varies the resistance of the element. The modulated resistance, in turn, modulates the flow of current from E through R_L. Power gains of the order of 40 db have been reported for single stages of this type, and cascaded stages have been employed in larger amplifiers.

Aside from indium antimonide, some of the other intermetallic compounds which are being used in developmental work include indium arsenide, aluminum antimonide, gallium phosphide, lead selenide, lead telluride, bismuth selenide, and bismuth telluride.

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