RADIOTRONICS

VOL. 26, No. 2

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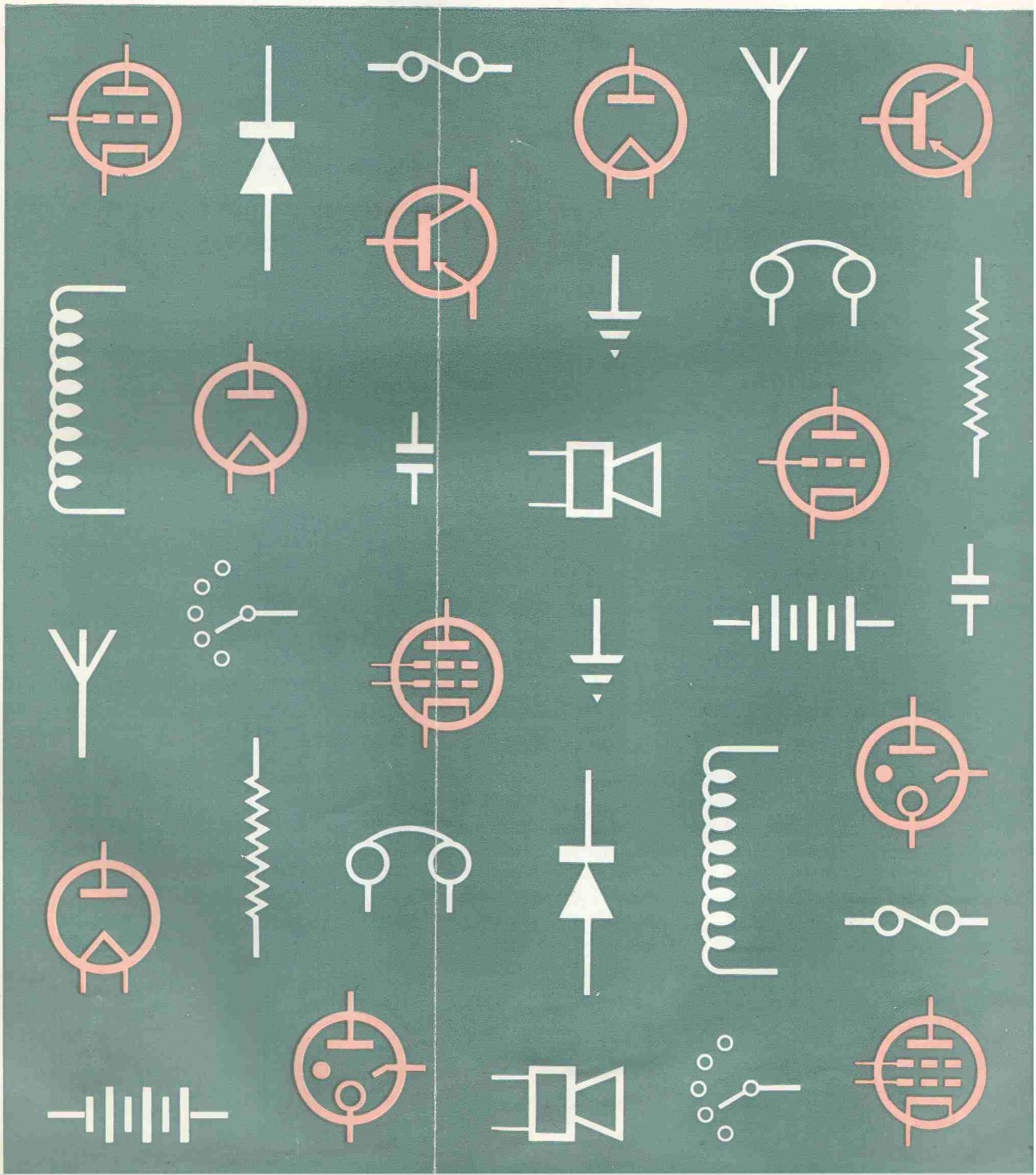

AN AWV PUBLICATION

"RADIOTRONICS" SUBSCRIPTION RENEWALS

Dozens of readers have complained that they did not receive the pink subscription renewal memorandum card mentioned in last November's copy. These cards, as readers will realise, are in effect similar to a bill, in that they are asking for a remittance. They were therefore mailed only to readers whose subscriptions were due to expire with the December 1960 issue.

Every complaint has been checked, and in every case where a pink card was not sent, the subscription is still current through 1961; no further payment was required therefore.

In cases where readers who did not receive a card still sent in a remittance, this has been credited to them by advancing the currency of their existing subscriptions by one year. No other notice of this fact will be given, and the matter will be automatically adjusted as future renewals are sent out.

RADIOTRONICS

Vol. 26, No. 2, 1961

Editor, Bernard J. Simpson

IN THIS ISSUE

Radiotronics is published twelve times a year by the Wireless Press for Amalgamated Wireless Valve Company Pty. Ltd. The annual subscription rate in Australasia is 10/-, in U.S.A. and other dollar countries $1.50, and in all other countries 12/6.

Subscribers should promptly notify Radiotronics, Box 2516, G.P.O., Sydney, and also the local Post Office of any change of address, allowing one month for the change to become effective.

CORRECTION

Last month we published data on RCA tunnel diodes. Due to an error in the original data received, the voltage ratings and characteristics were quoted in "volts." Please read all voltages as "millivolts," instead of "volts."

PHOTOCONDUCTIVITY

By

DR. R. H. BUBE*

A photoconductor is a material whose electrical conductivity can be increased by the absorption of light or other suitable radiation. Thus, photoconductors are useful both as radiation detectors (ultraviolet, visible, infrared, electrons, X rays, gamma rays, nuclear particles) and as radiation-controlled electrical switches.

Although photoconductivity was first discovered in 1873 by Willoughby Smith while investigating selenium as a resistor in underwater cables, actual progress in understanding and material development has awaited the recent leap forward in all solid-state physics which was activated by the development of the transistor. Photoconducting cells were made only of selenium, copper oxide, or thallous sulfide up to 1940; today, commercial cells use none of these, but are based almost exclusively on germanium, silicon, cadmium sulfide, cadmium selenide, lead sulfide, lead selenide, or lead telluride, all resulting from recent developments. It was not until the end of World War II that detection of infrared radiation by the lead-sulfide-type photoconductors proved superior to former thermoelectric or bolometric methods. Fig. 2 shows the intrinsic photoconductivity response as a function of incident wavelength for a number of typical photoconductors.

In many cases, photoconducting cells today perform the same functions previously performed by photoemissive cells, with the advantages of decreased size and cost, and increased ease of operation. The solid-state photoconductor cell bears the same relationship to the photoemissive vacuum phototube as the solid-state diode bears to the thermionic-emissive vacuum diode. The photoconducting television camera tube, the vidicon, is partially replacing the photoemissive tube, the image orthicon. Photoconductors currently play a role also in computers and a whole host of detection and control systems, including street-light control, headlight control and dimming, camera-iris setting, and automobile rear-view mirror orientation. At the developmental level, photoconductors are a part of experimental picture-display and light-amplifier systems, where the properties of the photoconductor are beneficially combined with those of electroluminescent materials. Photoconductivity itself is one of the basic tools of solid-state research, being used to determine carrier lifetime, carrier mobility, trapping phenomena, imperfection-level location, and capture cross-sections of imperfection centres for free carriers.

Research in photoconductivity embraces a wide area of chemistry, physics, crystallography, and metallurgy. Photoconductors may be inorganic or organic, insulators or semiconductors, crystalline or amorphous; they may be used in the form of single crystals or microcrystalline powders; thin sintered, evaporated, chemically deposited, or sputtered layers; or thick sintered pellets. [1]

In this paper we shall concentrate mainly on the physical processes underlying photoconductivity and the applications which have been made of the preparation of useful cells still lies in the

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made at developing a phenomenological theory of photoconductivity, but a considerable portion of the preparation of useful cells still lies in the realm of synthesis art.

Fig. 1 shows several photoconducting cells utilizing cadmium sulfide or cadmium selenide as the photoconducting material. What we shall say here is directly applicable to this type of photoconducting material, and with certain appropriate modifications, to other types of material as well.

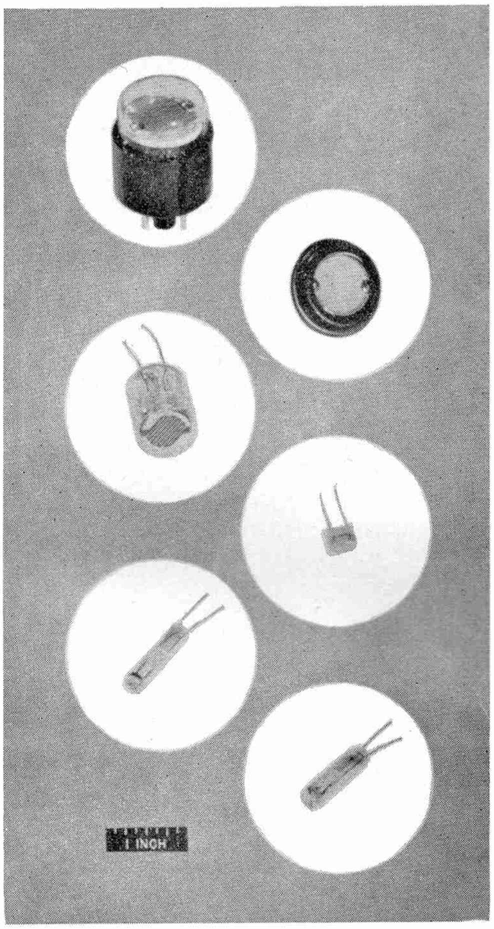

Fig. 1 — Commercial or developmental (prefix C) photoconducting cells now being produced by RCA. From Top to Bottom: CdS sintered-layer, glass-enclosed Cell 6957; same layer, metal-enclosed Cell 7163; CdSe sintered-layer, glass-enclosed Cell C7218; single-crystal Cds Cell 6694A; CdSe sintered-layer Cell C7230; Cds sintered-layer Cell 7412. These cells, because of their incorporated impurities, are sensitive over a wide range of wavelengths: CdS cells, 0.33 to 0.74μ; CdSe cells 0.35 to 0.87μ. Sensitivity lies in the range of amperes per lumen, about one-tenth that obtainable with a multiplier phototube such as the 931A.

CHARACTERIZING PROPERTIES

There are four properties of a photoconductor (together with their variation with excitation intensity and temperature) which serve to characterize it; (1) dark conductivity, (2) spectral response, (3) speed to response, and (4) photosensitivity. Fig. 3 and 4 should be consulted as a background to the following discussion.

Dark Conductivity

The conductivity in the dark depends on the band gap of the material, and on the density and type of imperfections which are present. In insulators (room-temperature conductivity less than about 10^{-6}/ohm-cm) the density of free carriers in the dark because of thermal excitation is usually much less than the density of free carriers created by photoexcitation. In semiconductors (conductivity greater than 10^{-6}/ohm-cm, but less than 10^{2}/ohm-cm) the density of free carriers in the dark is usually greater than the density of photo-excited carriers. This intrinsic difference between insulators and semiconductors affects not only some aspects of their photoconductivity behaviour, but also the conditions under which photoconducting cells are used. Insulating photoconductors are usually operated at room temperature with steady radiation. Semiconducting photoconductors are usually operated at low temperatures with intermittent radiation to produce an alternating signal suitable for amplification.

Spectral Response

In a pure material, light of energy less than the band gap cannot create free carriers, and therefore cannot give rise to photoconductivity. Photoconductivity results from excitation by light of energy equal to or greater than the band gap (Fig. 3, transition 1), and ceases abruptly when the energy of the light decreases to a value smaller than the band gap. Actually, a maximum response is usually found at a light energy very close to that of the band gap; the decrease in response for higher-energy light results from the complete absorption of this light in surface regions of the photoconductor which have an intrinsically lower photosensitivity than the volume.

When imperfections are present (Fig. 3, transition 2), less energy is required to excite an electron from the imperfection level to the conduction band than is required to excite across the band gap. The presence of such imperfections shows up therefore as additional response for light of energy less than the band gap, i.e., as a response to the long-wavelength side of that associated with the pure material. The lowest-energy light able to give the imperfection response serves

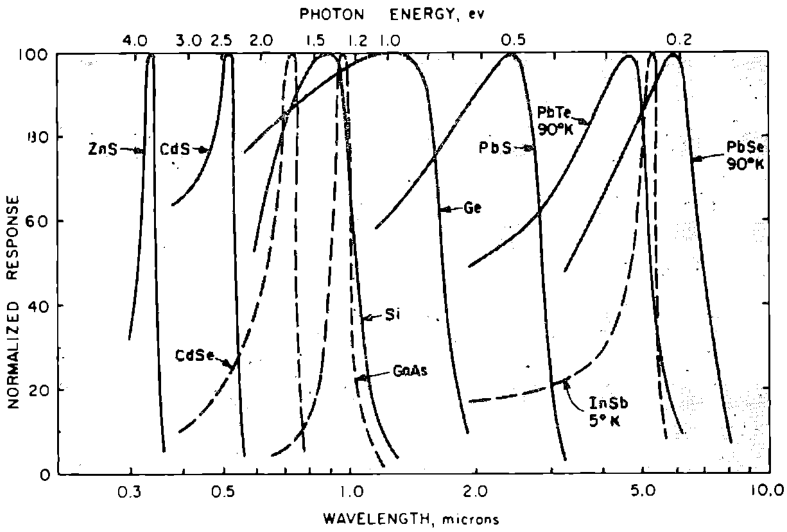

Fig. 2 — Intrinsic photoconductivity response of typical photoconductors vs. wavelength, where "intrinsic" means response of the material itself without incorporated impurities. Impurities extend response to longer wavelength than the intrinsic response. Intrinsic responses extend from the ultraviolet ($<0.4\mu$) through the visible (0.4 to 0.7μ) into the infrared ($>0.7\mu$).

to locate the level with respect to the bottom of the conduction band.

Speed of Response

Trapping centres are those which temporarily remove electrons from the free state and then return them to the free state at a later time when sufficient thermal energy has been supplied from crystal vibrations (Fig. 3, transitions 5 and 6). In a material with no trapping effects, the speed of response would be identical with the lifetime of the free electrons. In actual practice, particularly for low-light-intensity excitation, the observed speed of response is many orders of magnitude less than would be expected from the lifetime. The occurrence of these rise and decay times much greater than the lifetime is caused by trapping of free carriers. Trapping lengthens the rise time by removing photoexcited free electrons from the free state and requiring a time elapse for a steady state to be set up between the new density of free electrons and the new occupancy of trapping centres. Trapping lengthens the decay time by slowly releasing trapped electrons after the excitation has been terminated. In the case of low-intensity excitation, the density of trapped electrons may greatly exceed the density of free electrons, so that the decay time is really given by the time required to free an electron from a trap, rather than by the free lifetime determined by recombination between a free electron and a hole captured at a recombination centre.

Photosensitivity

The value assigned to the photosensitivity of a photoconductor is in converting light energy into electrical current. There are at least three ways of defining this utility which are in common use.

(1) Minimum detectable excitation required to give a signal equal to the noise. This definition of sensitivity is applied principally to detectors of infrared radiation, like lead-sulfide photoconductors. The minimum detectable excitation, expressed in terms of radiation power, is about 10^{-12} watt to give signal equal to noise in such photoconductors.

(2) Photocurrent per unit light intensity at fixed applied field. This definition of sensitivity has been called specific sensitivity, and has been expressed in units of cm^2/ohm-watt. It is obtained by multiplying the conductance by the square of the electrode spacing and dividing by the total radiation power absorbed.

$$\text{Specific Sensitivity } S = \frac{\dfrac{\Delta i}{V} l^2}{P} \quad \text{............ (1)}$$

where Δi is the photocurrent, V is the applied voltage, l is the electrode spacing, and P is the absorbed radiation power. The specific sensitivity is independent of cell geometry or light intensity, provided that the photocurrent varies linearly with applied field and light intensity. The most sensitive cadmium-sulfide and cadmium-selenide photoconductors have specific sensitivities near unity. The sensitivities of several forms of cadmium sulfide are summarized in Table 1.

(3) Photoconductivity gain, i.e., the number of electrons passing between electrodes for each photon absorbed. This definition is perhaps the most useful for many practical considerations.

An analysis of the effects described in Fig. 4 shows that this gain can be expressed:[2]

$$\text{Gain} = \frac{\text{Lifetime of free electron}}{\text{Transit time of free electron}} \qquad (2)$$

If τ is the lifetime of a free electron, and if we express the transit time of a free electron between electrodes separated by a distance 1 as this distance divided by its velocity, then

$$\text{Gain} = \frac{\tau\mu V}{1^2} \qquad (3)$$

where μ is the electron mobility, and V is the applied voltage. Gains of 10^4 have been observed in cadmium sulfide cells.

Lifetime, Key Photoconductivity Parameter

It is evident from Equation (3) that the μ product forms a kind of figure of merit for a photoconductor. The mobility μ is more or less fixed by our choice of material but for any given material the lifetime τ can vary over wide limits. In insensitive cadmium sulfide, the electron lifetime is of the order of 1 microsecond, whereas in sensitive cadmium sulfide the electron lifetime is of the order of milliseconds. The lifetime τ itself depends on the recombination process (Fig. 3, transition 4) in the following way:

$$\tau = \frac{1}{vS_nN_r} \qquad (4)$$

Here, N_r is the density of recombination centres. i.e., the density of those centres which have captured photo-excited holes. S_n has the dimensions of area and is called the capture cross-section of these centres for free electrons. v is the thermal velocity of a free electron.

The product vS_n represents the total volume swept out in one second by a recombination centre. The magnitude of the capture cross-section depends directly on the chemical nature of the centre. A centre with a coulomb attraction for the carrier under consideration has a capture cross-section of about $10^{-13}cm^2$. A neutral centre has approximately a geometric cross-section of $10^{-15}cm^2$. Centres which are charged such that there is a Coulomb repulsion of the carrier under consideration may have cross-sections as small as 10^{-20} cm^2. Each imperfection centre is characterized by two cross-sections: one for holes and one for electrons. Quite often these two cross-sections are widely different: in sensitive cadmium sulfide crystals, for example, the capture cross-section of centres B for holes is 10^6 times larger than the capture cross-section of these centres for electrons (after a hole has been captured).[3]

Maximum Performance

Assuming that the material parameters τ and μ have been fixed, the photoconductivity gain of equation (3) can still be increased by increasing the applied voltage or by decreasing the electrode spacing. Although equation (3) indicates no limit to which such an increase can be pushed, there

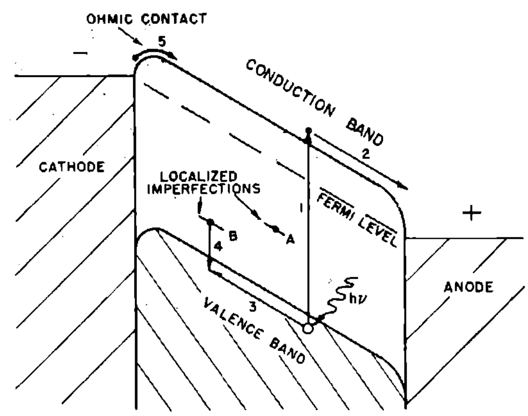

Fig. 3 — Basic electronic processes in a photoconductor, here specifically for an n-type photoconductor like CdS. (Arrows indicate electron transitions.) (1) Excitation of host crystal by absorption of light with energy equal to or greater than the band gap; for each photon absorbed, one electron-hole pair is formed. (2) Excitation of a bound electron at an imperfection level; imperfections may be either impurities or crystal defects such as vacancies. (3) Capture of a photo-excited hole by an imperfection centre. (4) Capture of a photo-excited electron by a centre which has previously captured a photo-excited hole, resulting in recombination of the carriers. (5) Capture of a photo-excited electron by an electron-trapping centre. (6) Thermal freeing of a trapped electron. (7) Optical freeing of a trapped electron. (8) Optical freeing of a captured hole. (9) Thermal freeing of a captured hole. Transitions 1 and 2 determine spectral response; 3 and 4 determine free-electron lifetime and, hence, photosensitivity; 5 and 6 frequently determine speed of response; 7 causes stimulation of conductivity; 8 and 9 correspond to optical and thermal quenching of photoconductivity when the centres involved are those with small cross-section for free electrons. Transitions 3 and 4 may be either radiative, i.e., give rise to luminescence emission, or nonradiative.

are three physical phenomena which will terminate the applicability of equation (3) under the continued increase of applied field. These are (1) the injection of space-charge-limited current from the cathode, (2) impact ionization by free carriers, and (3) dielectric breakdown. Injected space-charge-limited current is usually encountered first with increasing applied field. Maximum gain is reached at that applied voltage at which the injected current is approximately equal to the photocurrent. Traps play a dual role: they give rise to long response times by filling and emptying during photoexcitation, as mentioned previously, but they also allow the achievement of higher maximum gain by increasing the maximum field which can be applied before space-charge-limited currents become important. Traps bring about the latter effect by capturing the injected carriers.

An expression for the maximum gain as limited by current injection has been derived: [4]

$$G_{max} = \frac{\tau_O}{\tau_{RC}} \quad \frac{N_A}{N_t} \qquad (5)$$

Here τ_O is the observed response time, τ_{RC} is the product of the resistance R and the capacity C under operating conditions, i.e., the RC time constant or the dielectric relaxation time, N_A is the number of positive charges on the anode corresponding to the number of traps filled by the field - injected current, and N_t is the number of traps filled by the photoexcitation process (including the free electrons in N_t).

If the same traps are filled both by field-injected charge and by photoexcitation, then $N_A/N_t = 1$, and the maximum gain is limited to

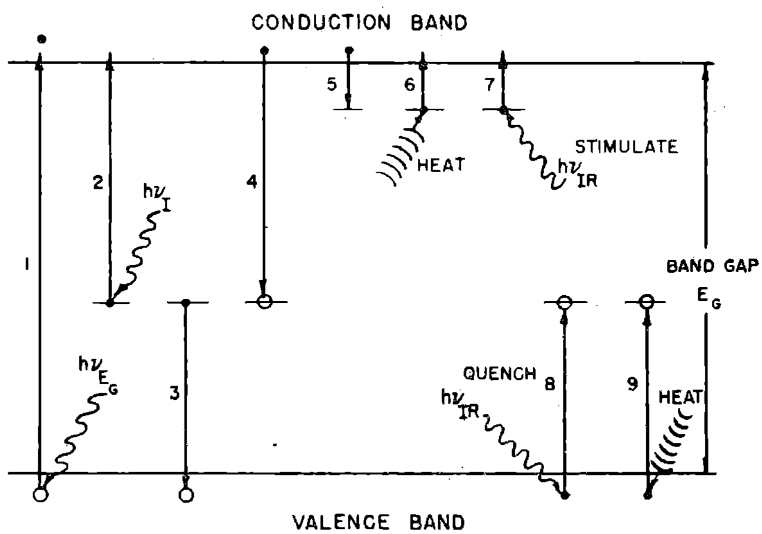

Fig. 4 — A photoconductor in operation, here specifically for an n-type photoconductor like CdS. Two ohmic metallic contacts to the photoconductor are assumed. (1) Absorption of a photon forms a free electron-hole pair. (2) Under the applied electric field, the photo-excited electron moves toward the anode. (3) Similarly, the photon-excited hole moves toward the cathode. (4) The hole is captured at an imperfection centre. (5) After the initial electron has left the photoconductor at the anode, the residual positive space charge due to the excess captured hole leads to the entrance of an electron into the photoconductor from the cathode. Photocurrent continues until a free electron recombines with the captured hole. In general, two types of centres can capture holes, indicated as centres A and B. Centres A have a large probability of capturing a free electron after having captured a hole; centres B have a small probability of capturing a free electron after having captured a hole. Centres A exist in all crystals in CdS, even the purest prepared to date; since they aid recombination, they cause low photosensitivity. If centres B are added deliberately, a sensitive photoconductor is produced; the net result of adding centres B is to reduce the number of centres A available for recombination by essentially keeping the centres A occupied by electrons.

TABLE I

Properties of Various Cadmium Sulfide Photoconducting Materials.

Material	Specific Sensitivity, cm^2/ohm watt	Electron Lifetime, sec.*	Response Time at 10^{-4} ft.-c, sec.
Impure CdS (Contains recombination centres such as Ni)	10^{-9}	10^{-10}	—
Pure CdS (No spectrographically detectable impurities)	10^{-5}	10^{-6}	—
Sensitive CdS (Contains deliberately incorporated impurities such as Cl and Cu)	10^{-1}	10^{-2}	10
Experimental Sensitive CdS (Contains only traces of iodine impurity)	10^{-1}	10^{-2}	10^{-1}

*Also the response time for very high light level excitation.

unity for many applications for which τ_O is approximately equal to τ_{RC}, such as the vidicon or the light amplifier. If, however, there are centres which are filled by field-injected charge, but are not filled by photoexcitation, the maximum gain [5], [6], [7] can exceed τ/τ_{RC}. Recombination centres (centres B) lying at the proper place in the forbidden gap (just above the Fermi level) meet these requirements. Alternatively, surface traps may capture the injected charge while photocurrent flows primarily through volume regions with a much smaller trap density.

Maximum practical performance of a photoconductor cell requires maximum G_{max}/τ_O, or maximum gain-bandwidth product. For a typical case of a sandwich-type cell, we can express this product:

$$\frac{G_{max}}{\tau_O} = Kn \frac{N_A}{N_t} \qquad (6)$$

where K is a constant depending only on the dielectric constant and the electron mobility of the photoconductor, and n is the density of free electrons. The gain-bandwidth product can therefore be maximized in three ways: (1) increasing the operating conductivity, (2) increasing the density of centres which capture field-injected charge but not photoexcited charge, and (3) decreasing the density of centres which capture photoexcited charge, i.e., the conventional electron trapping centres. The first of these is often ruled out since many applications of photoconductors have a maximum allowable conductivity. Both of the other alternatives involve appreciable difficulty in synthesis.

SUMMARY

This is the situation in photoconductivity today. Present research has met with some success in decreasing the density of trapping centres by careful control of purity and preparation, and scattered crystals have shown photoconductivity performance indicating values of N_A/N_t as high as 500. Table 1 compares the low-light speed of response of such experimental sensitive cadmium sulfide crystals with the standard sensitive crystals containing chloride and copper impurities. The immediate problem is to consolidate these advances made with single crystals and to determine whether they can be successfully carried over to other forms of photoconductors, such as powders and sintered layers. In addition, there are certainly many uses of photoconductors which do not require the limits of gain and speed to be pushed so intensely, so that a rapid growth in applications and developments over the next few years can be anticipated.

REFERENCES

[1] For a more complete description of photoconductors and photoconductivity, see R. H. Bube, Photoconductivity of Solids, John Wiley & Sons.
[2] A. Rose, RCA Rev. 12, 362 (1951); Phys. Rev. 97, 322 (1955); Proc. I.R.E. 43, 1850 (1955).
[3] R. H. Bube, Proc., I.R.E. 43, 1836 (1955); J Phys. Chem. Solids 1, 234 (1957).
[4] A. Rose and M. A. Lampert, RCA Rev. 20, 57 (1959); Phys. Rev. 113, 1227 (1959).
[5] R. W. Smith, RCA Rev. 20, 69 (1959).
[6] H. B. Devore, RCA Rev. 20, 79 (1959).
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SILICON POWER TRANSISTORS

AN APPLICATION GUIDE

This article describes the outstanding features of RCA silicon power transistors and the use of silicon transistors in many critical industrial and military applications. It gives construction details, a discussion of voltage ratings, thermal-stability conditions, and equivalent circuits for these transistors. It also gives design procedures and specific design equations for some of the most important circuits using these transistors, as well as performance data. As an additional aid to circuit designers, a complete list of typical " h " and " hybrid-pi " parameters is also included.

The RCA line of silicon power transistors consists of three families: medium-power types, intermediate-power types, and high-power types. These three families provide the designer with a comprehensive line of silicon transistors for use in a variety of applications operating at levels ranging from a few milliamperes up to more than 200 watts.

Table 1 lists some of the most significant characteristics of the types in each family. The significance of some of these characteristics is discussed below in the sections on construction, voltage ratings, and thermal stability conditions. The use of these characteristics is illustrated by equivalent circuits and examples of actual circuit designs.

TRANSISTOR CONSTRUCTION DETAILS

There are two general types of n-p-n diffused-silicon transistors: the diffused-base type and the diffused-junction type. The diffused-base type is constructed by diffusing first a p-type base region and then an n-type emitter region into one side of an n-type silicon pellet which forms the collector region. The diffused-junction type, on the other hand, is made by simultaneously diffusing an n-type emitter and an n-type collector into opposite sides of a p-type silicon pellet which forms the base region. Because close control of silicon-pellet shape is not required for the diffused-base type, most manufacturers of silicon power transistors have preferred to make this type. RCA, however, has chosen the diffused-junction technique for its silicon power transistors because transistors made by this process have considerably lower saturation resistance and base resistance than do the diffused-base types. In addition, the h_{FE} of the diffused-junction structure is more uniform than that of the diffused-base type and falls off less at high-current levels.

All three families of RCA silicon power transistors are made by the diffused-junction process. They differ mainly in the size of pellet and the emitter dot. The cross section of a portion of a wafer with the junctions already formed is shown in Fig. 1.

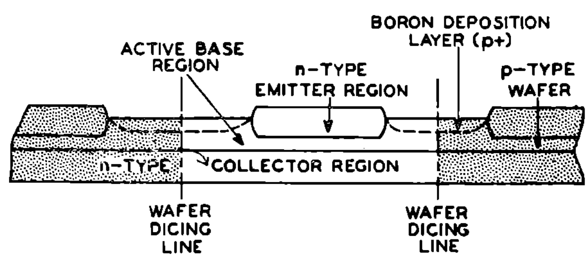

Fig. 1—Cross Section of a Diffused-Junction Silicon Transistor Wafer.

TABLE I

ELECTRICAL CHARACTERISTICS OF RCA SILICON POWER TRANSISTORS

Type	MAXIMUM COLLECTOR-TO-EMITTER VOLTAGE		MAXIMUM DC COLLECTOR CURRENT	MAXIMUM COLLECTOR CUTOFF CURRENT	DC CURRENT TRANSFER RATIO			MAXIMUM SATURATION RESISTANCE					
	V_{CEX} Emitter-to-Base Reverse Biased (volts)	$V_{CEO(sus)}$ Sustaining (Base-Open) (volts)	I_C (amperes)	I_{CBO} (At DC Collector-to-Base Volts V_{CB} = 30) (μa)	h_{FE} (At Indicated DC Collector Amperes I_C)			R_S (At Indicated DC Collector Amperes I_C and DC Base Amperes I_B) (ohms)					
					I_C = 0.2	I_C = 0.75	I_C = 1.5	I_C = 0.2 I_B = 0.01	I_C = 0.2 I_B = 0.02	I_C = 0.75 I_B = 0.075	I_C = 0.25 I_B = 0.04	I_C = 1.5 I_B = 0.1	I_C = 1.5 I_B = 0.3
Medium-Power Types: Transistor Dissipation = 4 watts JEDEC TO-5 Outline Case Temperature = 25° C													
2N1479	60	40	1.5	10	15-75	-	-	-	7	-	-	-	-
2N1480	100	55	1.5	10	15-75	-	-	-	7	-	-	-	-
2N1481	60	40	1.5	10	35-100	-	-	7	-	-	-	-	-
2N1482	100	55	1.5	10	35-100	-	-	7	-	-	-	-	-
Intermediate-Power Types: Transistor Dissipation = 15 watts JEDEC TO-8 Outline Case Temperature = 25° C													
2N1483	60	40	3	15	-	15-75	-	-	-	2.67	-	-	-
2N1484	100	55	3	15	-	15-75	-	-	-	2.67	-	-	-
2N1485	60	40	3	15	-	35-100	-	-	-	-	1	-	-
2N1486	100	55	3	15	-	35-100	-	-	-	-	1	-	-
High-Power Types: Transistor Dissipation = 60 watts JEDEC TO-3 Outline Case Temperature = 25° C													
2N1487	60	40	6	25	-	-	10-50	-	-	-	-	-	2
2N1488	100	55	6	25	-	-	10-50	-	-	-	-	-	2
2N1489	60	40	6	25	-	-	25-75	-	-	-	-	0.67	-
2N1490	100	55	6	25	-	-	25-75	-	-	-	-	0.67	-
Transistor Dissipation = 60 watts JEDEC TO-36 Outline Case-Seat Temperature = 25° C													
2N1511	60	40	6	25	-	-	10-50	-	-	-	-	-	2
2N1512	100	55	6	25	-	-	10-50	-	-	-	-	-	2
2N1513	60	40	6	25	-	-	25-75	-	-	-	-	0.67	-
2N1514	100	55	6	25	-	-	25-75	-	-	-	-	0.67	-

In the manufacture of these transistors a prediffused phosphorus layer is first deposited on each side of a p-type silicon wafer. The actual emitter dots are formed on one side of the wafer by silk-screen mask-and-etch processes. The phosphorus layers are then diffused into the wafer to form the collector and emitter junctions. This diffusion takes place in a p-type atmosphere (boron) which substantially reduces the base resistivity on the emitter side of the wafer. It is this boron diffusion of the base that gives these transistors a low value of extrinsic base resistance and preferential emitter injection into the active base region. This diffusion technique also accounts for the low saturation resistance and reduced fall-off of h_{FE} for RCA silicon power transistors.

VOLTAGE RATINGS

Several different voltage-rating systems have been used in attempts to classify transistors to meet the voltage requirements of specific applications. However, a comprehensive rating system, which includes the limiting circuit conditions and can easily be understood, is needed. Such a system of voltage ratings is used for RCA silicon power transistors. This system is based on the regions of operation shown in Fig. 2 for the common-emitter condition with constant-current input to the base.

$V_{\alpha M} = 1$ is the voltage at which the product of alpha (α) and the collector avalanche multiplication factor (M) is unity ($\alpha M = 1$). Although the locus of ($V_{\alpha M = 1}$) is shown as a vertical straight line, the actual locus curves outward at both high and low values of I_C because of the variation of α with I_C.

V_{CEO} is the collector-to-emitter voltage with base open.

V_{CER} is the collector-to-emitter voltage with resistance (R) between base and emitter.

V_{CEX} is the collector-to-emitter voltage with reverse bias voltage between base and emitter.

V_{SUS} (sustaining voltage) is the value of a specific voltage measured at a point where a large change in collector current produces only a small change in voltage.

V_A is the voltage at which breakdown of the collector-base diode occurs due to avalanche multiplication (also known as " bulk break ").

Regions A and B are described briefly below :

Region A—This region is bounded othen I_C axis by the maximum I_C rating, and on the voltage axis by the V_{CEO} rating measured under sustaining conditions $V_{CEO(sus)}$. As shown in Fig. 2, $V_{CEO(sus)}$ approximates $V_{\alpha M = 1}$. This relationship is evident because the collector current under V_{CEO} conditions is :

$$I_{CEO} = (h_{FE} + 1)\, I_{CBO}$$

For $V_{CEO(sus)}$, $I_{CEO} \rightarrow \infty$ in the limit while I_{CBO} remains finite ; therefore, $h_{FE} \rightarrow \infty$ and

$$h_{FE} = \frac{\alpha M}{1 - \alpha M}$$

Consequently, $M = 1$, or $V_{CEO(sus)}$ approximates the voltage at which $\alpha M = 1$.

Operation anywhere in region A is permissible provided transient power-dissipation ratings (discussed later under " Maximum Dissipation Based on $T_j(max)$") are not exceeded and precautions are taken to prevent thermal runaway.

Region B—This region is bounded on the V_{CE} axis by $V_{CEO}(sus)$ and the maximum permissible value of collector-to-emitter voltage under various input conditions [$V_{CE}(max)$]. The maximum value of V_{CE} ranges from a low of V_{CEO} for forward-biased input conditions to a high value of V_{CEX} for reverse-biased input conditions with zero source resistance. Values of $V_{CE}(max)$ for other input conditions are given below. Region B is restricted on the I_C axis to the I_{CBO} locus and the locus of points of zero dynamic resistance of the family of V_{CE} curves for different input conditions (V_{CEO}, V_{CER}, and V_{CEX}).

The $V_{CEO(sus)}$, V_{CEX}, and $I_C(max)$ ratings which help determine regions A and B for each RCA silicon power transistor type may be found in Table 1 or the published data for these types. For a given set of input conditions (see circuit for region B in Fig. 2), the maximum value of V_{CE} that determines the maximum boundary for region B is given empirically by the following equations. These equations are valid only for RCA silicon power transistors for the conditions shown :

For $R > 500$ ohms, $V_{BE} = 0$

$$V_{CE}(max) = \frac{500}{R}\left[V_{CEX} - V_{CEO(sus)}\right] + V_{CEO(sus)} \qquad (1)$$

For $R < 500$ ohms, $V_{BE} = 0$ and For $R > 500$ ohms, $V_{BE} = -R \times 10^{-3}$ volts (reverse bias between base and emitter)

$$V_{CE}(max) = V_{CEX} \qquad (2)$$

where R is the equivalent series resistance between base and emitter.

From the applications point of view, Region A is the safe operating region for all circuits in which the base-emitter diode is forward biased under both transient and dc conditions. Operation outside this region with the base-emitter diode forward

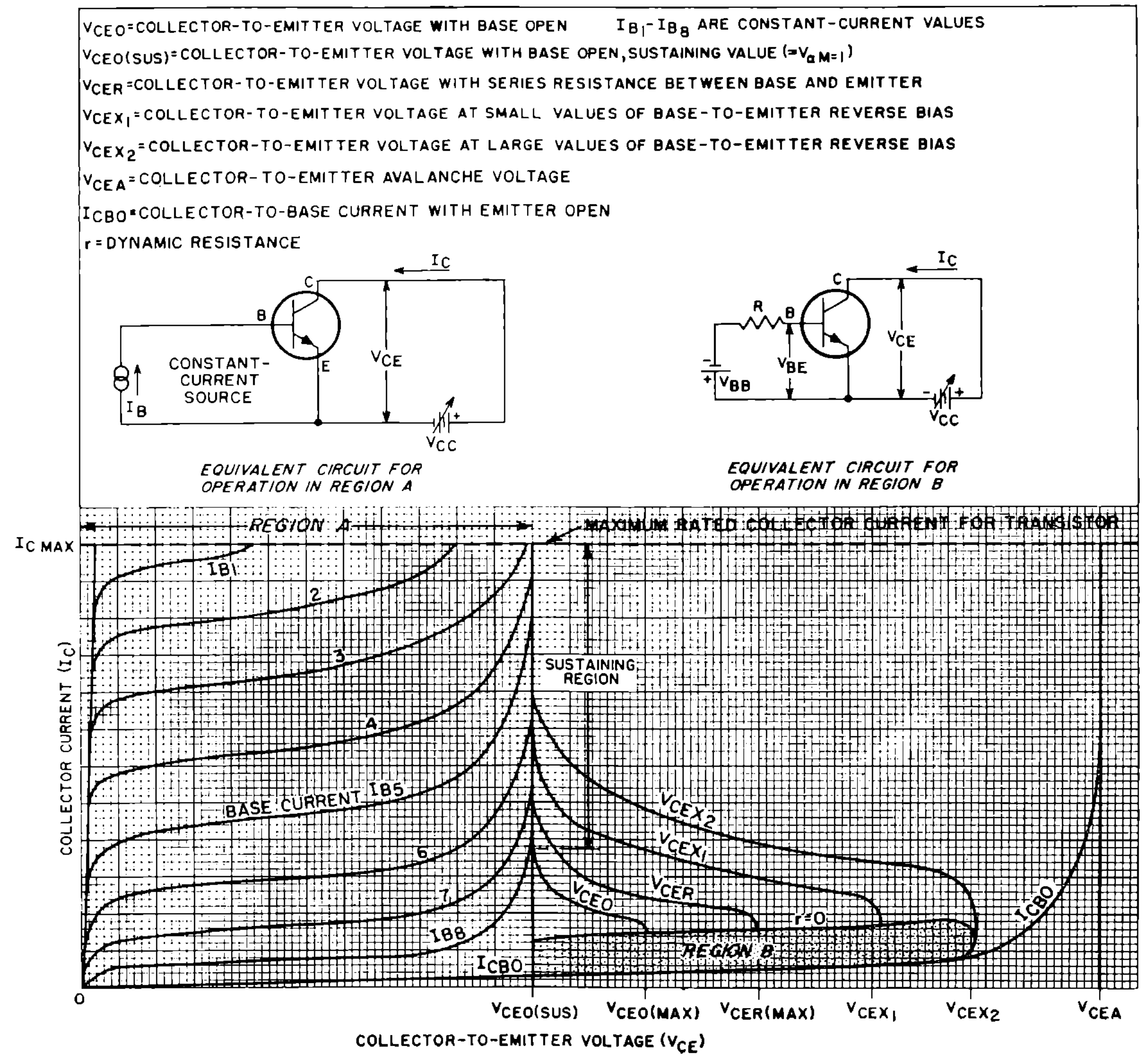

Fig. 2—Regions of Permissible Operation for RCA Silicon Power Transistors with Basic Circuits for Each Region.

biased (constant-current operation) should be avoided. Region B is a special region in which operation is permissible only to the $V_{CE}(max)$ value for a given input condition, as outlined above.

As an example of the $V_{CE}(max)$ allowed for a given application, find $V_{CE}(max)$ for the 2N1486 for two conditions: (1) $R = 1000$ ohms, $V_{BE} = 0$ volts; (2) $R = 0$ ohms, $V_{BE} = 0$ volts.

For the 2N1486: $V_{CEO(sus)} = 55$ volts, $V_{CEX} = 100$ volts

Condition (1):

From equation (1)

$$V_{CE}(max) = \frac{500}{1000}\left[100 - 55\right] + 55 = \frac{45}{2} + 55$$

$$= 77{\cdot}5 \text{ volts}$$

Condition (2):

From equation (2)

$$V_{CE}(max) = V_{CEX}(max) = V_{CEX} = 100 \text{ volts}$$

The $V_{CE}(max)$ value should always be determined for the specific application such as for class B amplifiers, dc-to-dc converters, switches, and similar circuits that operate in region B. In many cases, the selection of supply-voltage and input conditions for a circuit design of this type is limited by this value of $V_{CE}(max)$.

The system of voltage ratings based on operation in regions A and B applies only for the common-emitter, constant-base-current condition. Because the constant-base-current condition results in the lowest set of voltages, this rating system is somewhat conservative for cases where external emitter resistance is included. In such cases, use must be

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MAGNETIC-MEMORY DEVICES

This article briefly reviews and defines the basic parameters of magnetic circuits, and the special parameters used to express the performance capabilities of ferrite magnetic cores, aperture plates, and transfluxors in coincident-current or switching applications.

FERRITE CORES

Magnetic Fundamentals

In a magnetic circuit, each point has a Magnetomotive Force (F) which acts to create the flux lines which complete the magnetic circuit. This force is produced either by a net unbalance of the electron spins in an atom or by an electric current, and is measured in gilberts. If the magnetomotive force is produced by electron spin in the atomic structure, each atom acts as a battery trying to create a flux line which will loop the atom and return to its source. If the magnetomotive force is produced by an electric current, the resulting flux lines are normal (at 90°) to the path of the creating current, and thus follow circular paths around the conductor carrying the current. An electrically-induced magnetomotive force (F) is proportional to the current (I) and may be expressed by the equation $F = 0.4\pi I$, where I is in amperes and F is in gilberts. The equation for the magnetomotive force produced by parallel wires carrying the same current I in the same direction is $F = 0.4\pi NI$, where N is the number of wires. The magnetic equivalent of current is Flux (ϕ), and the impedance of a medium to the creation of a flux line is a quantity known as Reluctance (R).

The space rate of change or gradient of a magnetomotive force is called the Magnetizing Force (H), and is expressed in oersteds. This quantity is given by the equation $H = dF/dL$, where F is in gilberts and L is the length of the flux path in centimetres. When the flux path is circular, as it is for a current flowing through a wire, the equation for magnetizing force is $H = \frac{F}{2\pi r}$, where r is the radius of the flux in centimetres. Therefore, at a given radius r from a wire carrying a current of I amperes,

$$H = \frac{0.4\pi I}{2\pi r} = \frac{0.2I}{r}$$

In the analysis of a magnetic material, it is generally necessary to consider not just one flux line, but the number of flux lines which permeates a given cross-sectional area. Therefore, an additional parameter, Flux Density (B) is employed. This parameter B is equal to $d\phi/da$, where $d\phi$ is the incremental number of flux lines and da the incremental cross-sectional area.

Hysteresis Characteristics

In practical ferromagnetic materials, including ferrites, flux density (B) is not directly proportional to magnetizing force (H) for all values of H. This nonuniform relationship is called hysteresis. The hysteresis characteristic of a material is usually shown as a closed curve or "loop" of B as a function of H. The hysteresis curves of some ferrites have relatively flat tops and bottoms and nearly vertical sides. Such ferrites are known as "square-loop" types.

Fig. 1 shows the hysteresis curve of a typical "square-loop" ferrite. If it is assumed that initially the material is not magnetized, the curve starts at the centre, where B = O, H = 0. When H is applied for the first time, the flux density B increases nonuniformly, approximately as shown by the S-shaped curve in the upper-righthand quadrant, and reaches a maximum or saturation value of $+B_m$ at a magnetizing force $+H_m$. If H is then reduced, B decreases very slowly, and does not return to zero until the magnetizing force has been reversed and has reached a value $-H_c$. As the reverse magnetizing force is increased beyond $-H_c$, the flux density again increases and reaches a maximum or saturation value $-B_m$ at $-H_m$. For all subsequent applications of H the loop has the symmetrical form indicated by the path $-B_m$, $+H_c$, $+B_m$, $-H_c$, $-B_m$.

Operating Principles of Ferrite Cores

The operation of a ferrite core in a switching application may be explained in terms of the hysteresis loop shown in Fig. 2. A change in the state (magnetization) of the core from $-B_r$ to $+B_r$, or vice versa, produces a large change in flux density. When a wire is in proximity to the core, the change in flux density will induce a voltage in the wire.

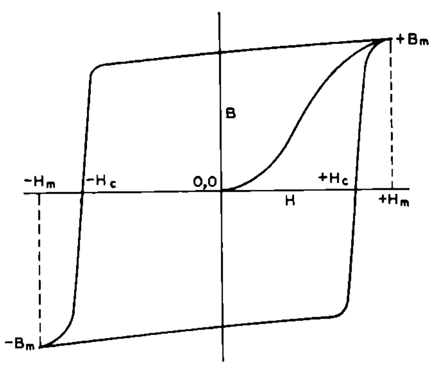

Fig. 1 — "Square-loop" hysteresis characteristic of a typical ferrite core.

Assume that the $-B_r$ state represents "1", and that the $+B_r$ state represents "0". Assume also that the core is its $-B_r$ or "1" state. If a current pulse producing a magnetizing force $+H_m$ is applied to the core, this pulse will switch the core to its $+B_r$ or "0" state, and provide a high output voltage. If a second current pulse producing a magnetizing force $+H_m$ is then applied to the core, the flux density will change only slightly, and a small output voltage will be produced.

A ferrite core for coincident-current applications must have magnetic properties such that when the core is in either its $+B_r$ ("0") or its

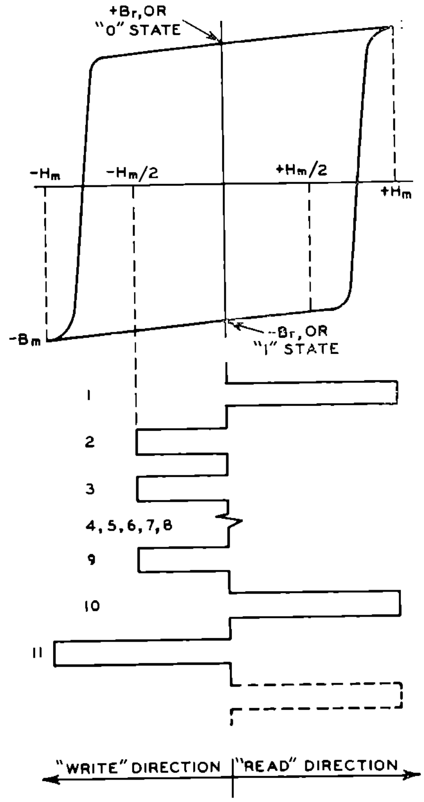

Fig. 2 — Magnetization characteristic and pulse-programme sequence illustrating the operation of a ferrite core in a coincident-current or switching application.

$-B_r$ ("1") state, the flux will not reverse when a magnetizing force of one half that required to switch the core (i.e., $-H_m/2$ or $+H_m/2$) is applied. Application of such a force should also produce very little change in flux density and a very small output voltage. Thus if the core is in its $-B_r$ or "1" state, and a series of current pulses each producing a magnetizing force $+H_m/2$ is applied, the first few pulses of the series should produce only slight degradation of the "1" state, and the remainder should produce no further change. The degraded state produced by the first few pulses is called the "Disturbed 1" state. Conversely, application to a core in the $+B_r$ or "0" state of a series of pulses producing a magnetizing force $-H_m/2$ should produce a "Disturbed 0" state.

The pulse programme shown below the hysteresis loop in Fig. 2 is a programme of the type employed in the testing of ferrite memory cores, and employed to generate the data shown in Fig. 3 and 4. It produces the following sequence of events: Pulse No. 1 "reads" an "undisturbed 1" output signal (uV_1) which was "written" by Pulse No. 11 of the previous cycle.

When Pulse No. 1 is completed, the core is left in its "undisturbed 0" state.

Pulses Nos. 2 through 9 are "partial-write" pulses which degrade the core to the "disturbed 0" state, but do not produce switching. Pulse No. 10 returns the core to the "undisturbed 0" state and reads the "disturbed 0" output signal (dV_Z). Pulse No. 11 switches the core to the "undisturbed 1" state.

Driving Current

Consider a small ferrite toroid having a wire carrying a driving current (I) running through its centre. The magnetizing force at any point in the toroid is $H = 0.2I/r$, where r is the mean radius of the toroid.

The larger the radius of the toroid, the larger the driving current (I) required to produce a given flux density (B). For example, the relation between driving current and magnetizing force in

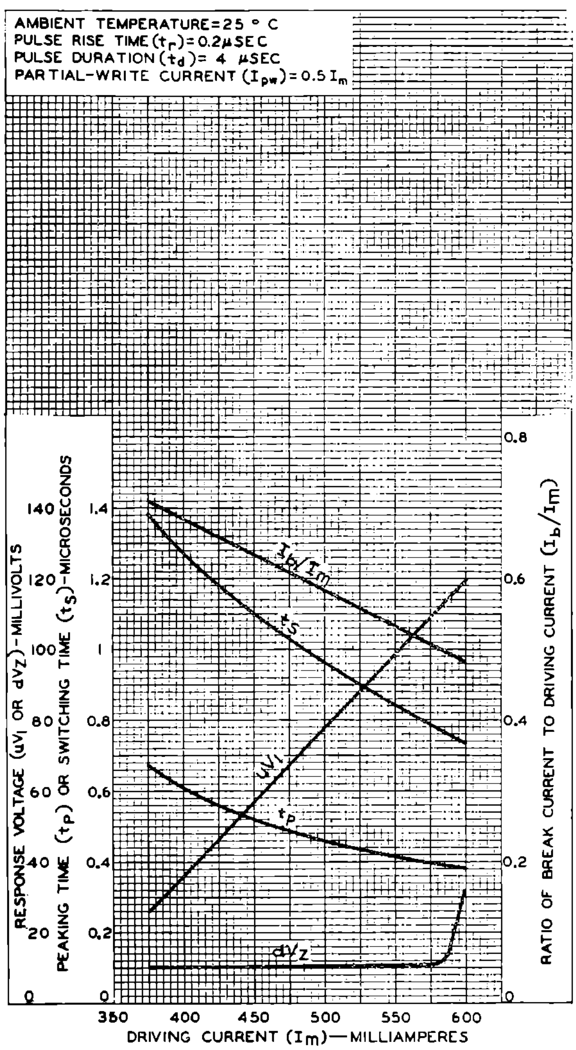

Fig. 3 — Average characteristics of a typical ferrite core.

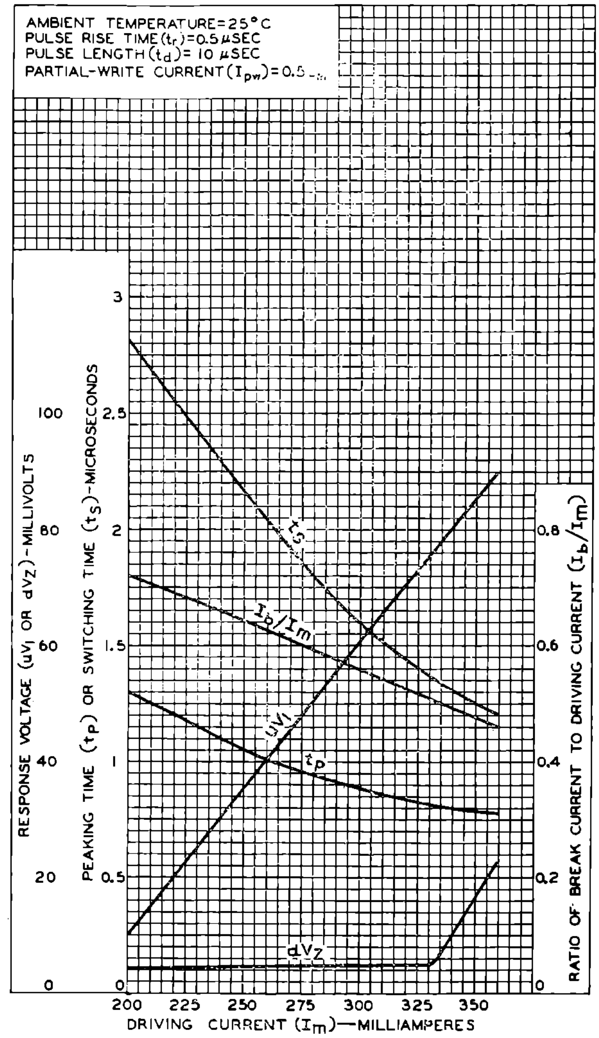

Fig. 4 — Average characteristics of a further typical ferrite core for comparison with Fig. 3.

an 0.050" (OD) x 0.030" (ID) core is $I = 0.252H$ or $H = 3.96\ I$. The relation for a 0.080" x 0.050" core is $I = 0.41\ H$ or $H = 2.44\ I$. It is evident that a given magnetizing force can be generated in a 0.050" x 0.030" core with about 0.25/0.41 or 60% of the current required for a 0.080" x 0.050" core.

Ferrite-Core Characteristics

The most important considerations in the selection of a ferrite core for magnetic-memory or switching applications are its driving-current requirements and switching time (also known as turnover time). Other considerations (which depend upon the application) are "undisturbed 1" response voltage, peaking time, "disturbed 0" response voltage, and break current.

DEFINITIONS

Full Driving Current (I_m) is the peak value of the current pulse required to switch a core from its "1" state to its "0" state, or vice versa.

A core in the "1" state or "0" state which has been switched to that state by a Full-Driving-Current pulse and has not subsequently been subjected to other pulses is said to be in the "Undisturbed 1" or "Undisturbed 0" state.

Partial-Write Current (I_{pw}) as used in this article is any value of driving current which disturbs the magnetization of a core in the "0" state, but does not switch the core to the "1" state. A core which has been subjected to one or more Partial-Write-Current pulses is said to be in the "Disturbed 0" state.

Pulse Rise Time (t_r) is the time interval between the instant the driving current rises to 10 per cent of its peak value and the instant it rises to 90 per cent of its peak value.

Pulse Duration (t_d) is the time interval between the instant the driving current rises to 90 per cent of its peak value and the instant it falls to 90 per cent of its peak value.

"Undisturbed 1" Response Voltage (uV_1) is the peak value of the output voltage produced when a core which is in its "Undisturbed 1" state is subjected to a "READ" current pulse having a peak value I_m.

"Disturbed 0" Response Voltage (dV_z) is the value of the output voltage produced when a core which is in its "Disturbed 0" state is subjected to a "READ" current pulse having a peak value I_m.

Switching Time (t_s) is the time interval between the instant the driving current rises to 10 per cent of its peak value and the instant the "Undisturbed 1" response voltage (uV_1) decays to 10 per cent of its peak value.

Peaking Time (t_p) is the time interval between the instant the driving current rises to 10 per cent of its peak value and the instant the "Undisturbed 1" response voltage reaches its peak value.

Break Current (I_b) is the maximum Partial-Write Current (I_{pw}) at a given Full Driving Current (I_m) which a core in the "0" state will tolerate without any substantial increase in the amplitude of the "Disturbed 0" Response Voltage (dV_z).

Coincident-Current Characteristics

Ranges of ferrite cores for coincident-current applications are available. As a matter of interest it may be useful to look at the characteristics of two cores for use in 2-to-1 coincident-current work. The two cores chosen as examples are those for which the average characteristics are shown in Fig. 3 and 4, the RCA 224M 1 and 225M 1 respectively. Both of these cores are quite small in size; they are dimensioned 0.05 inch x 0.03 inch x 0.015 inch. Other cores come in larger or smaller sizes according to application. The characteristics of these two types are as follows, quoted at an ambient temperature of 25°C.

	224M 1	225M 1	
t_s	0.95	2.1	μs
t_p	0.45	1.0	μs
uV_1	75	40	mv
dV_z	10	5	mv
I_m	500	260	ma
I_{pw}	250	130	ma
t_r	0.2	0.5	μs

The switching (turnover) time t_s as a function of the applied magnetizing force in oersteds for these two types is shown in Fig. 5. The peaking time t_p for these types is shown in Fig. 6, also as a function of the applied magnetizing force.

Switching or Shift-Register Applications

Ferrite cores for this application are of course basically similar to those for coincident current work, but are specially designed for switching work. Many of these types have characteristic similar to those of tape-wound magnetic cores. Two types taken as samples are the RCA XF-4003 and XF-4008. These have the same physical dimensions as the 224M 1 and 225M 1 mentioned above, and the electrical characteristics are:

	XF-4003	XF-4008	
t_s	2.6	13	μs
t_p	1.45	6.5	μs
uV_1	24	2.0	mv
dV_z	3	3.5	mv
I_m	190	40	ma
I_{pw}	95	20	ma
t_r	0.5	0.5	μs

The switching (turnover) time t_s and the peaking time t_p for these switching types are also shown in Fig. 5 and 6 as a function of the applied magnetizing force.

MEMORY PLANES

Memory planes are frames into which ferrite cores can be mounted in arrays. Such a frame is shown in Fig. 7 which illustrates an aluminium-frame memory plane with teflon-insulated terminals, housing 1024 ferrite cores. This memory plane is therefore capable of storing 1024 "bits" of information. This particular frame, although light in weight, is very rugged. From the photograph it will be seen that the frame is designed for either end or side mounting, and can be stacked with similar frames.

Fig. 11 is a photograph of a new, rugged RCA memory plane assembly consisting of two mats made of laminated glass-base phenolic material. The mats contain 4096 cores (64 x 64) each, providing a total of 8192 bits in an assembly only 5½ inches square and ¼ inch thick, including terminals. In addition to its small volume, this assembly provides relatively short

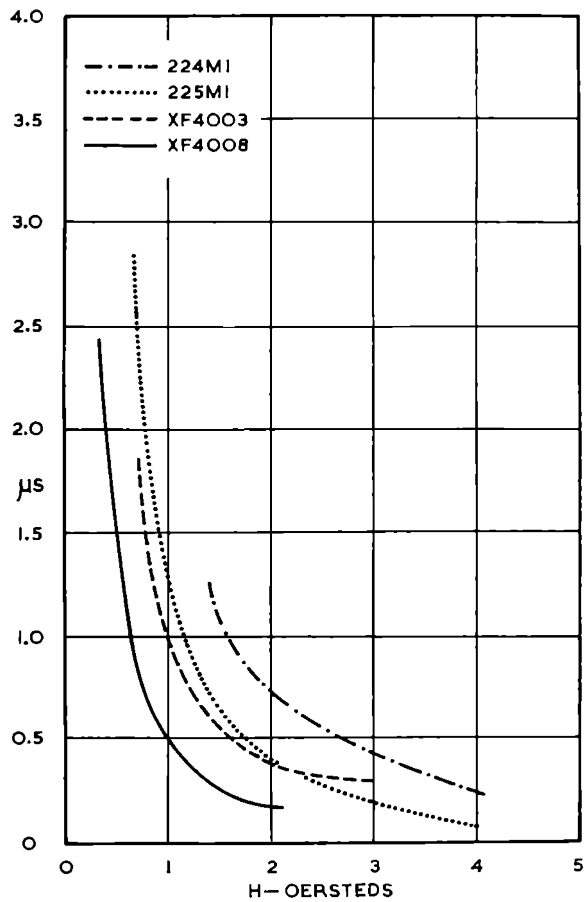

Fig. 5 — Switching time (t_s) in microseconds of typical ferrite cores as a function of applied magnetizing force (H) in oersteds for switching applications.

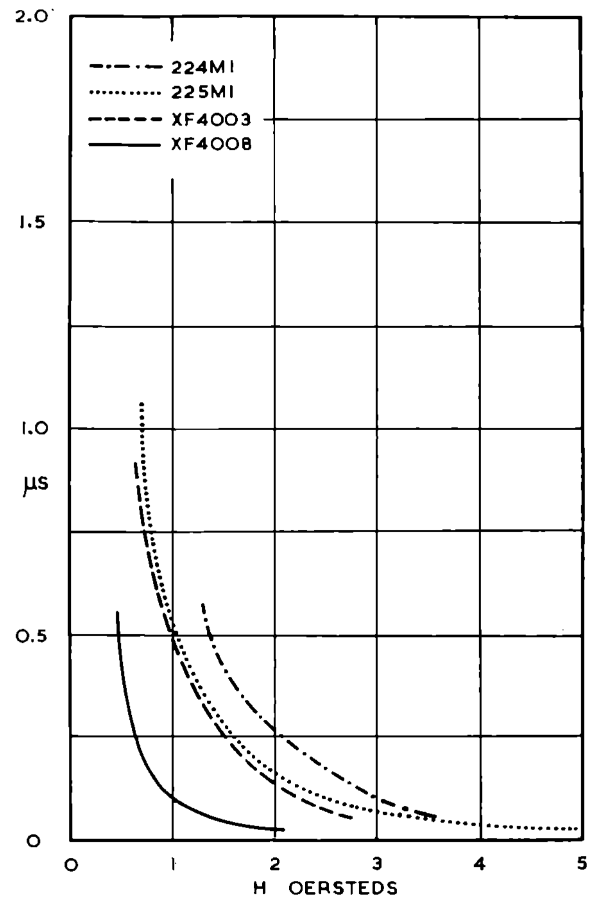

Fig. 6 — Peaking time (t_p) in microseconds of typical ferrite cores as a function of applied magnetizing force (H) in oersteds for switching applications.

leads, a feature of prime importance in very-high-speed applications. The combination of two mats in a single assembly simplifies stacking and reduces the number of external connections necessary.

APERTURE PLATES

It is possible to use in some cases an aperture plate instead of a memory plane. Instead of the memory plane, consisting of a frame or mat carrying lots of individual ferrite cores, the aperture plate is one solid ferrite plate containing a large number of holes or apertures, arranged in uniformly-spaced parallel rows. Each hole and the portion of the plate around it serves in lieu of a separate and discrete ferrite core. The apertures are interconnected by plated conductors which can be arranged to provide any wiring configuration used in conventional magnetic memory planes.

An aperture plate provides, in a single unit occupying only a fraction of a cubic inch, the magnetic equivalent of a conventional memory plane composed of individual ferrite cores, wires, and a frame. A typical aperture plate providing 256 apertures (and therefore capable of storing 256 "bits" of information) measures only 0.88 inches square and is 25 thousandths of an inch thick.

TRANSFLUXORS

A transfluxor is a magnetic core made of material having a "square-loop" hysteresis characteristic, and provided with two or more apertures which divide the core into three or more flux paths or "legs". By the use of simple windings through the apertures to control the transfer of flux among the legs, a transfluxor can store data in either of two magnetic states and simultaneously provide "nondestructive" readout of the stored data — that is, it can deliver electrical output signals indicating the stored data without change in its magnetic state. The "nondestructive" readout, furthermore, can be obtained at any desired level between zero and the maximum output capability of the particular transfluxor employed. This level can be established by a single "setting" pulse.

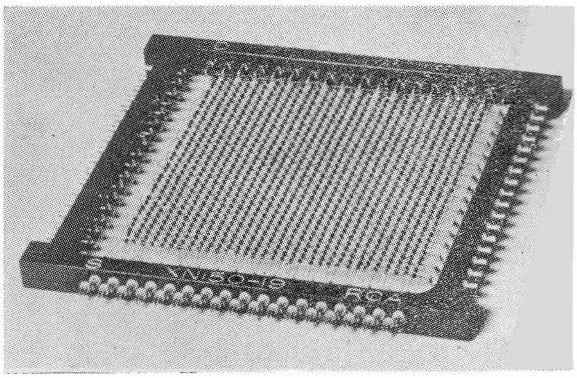

Fig. 7 — 1024-core (32 x 32) aluminium-frame memory plane with Teflon - insulated brass terminals.

These features also permit a transfluxor to control the transmission of ac power at any desired level up to its maximum output capability.

The basic principle of operation of the transfluxor is that the use of two or more apertures in a core creates 3 or more distinct flux paths or legs. The controlled transfer of flux between these legs provides the unique output characteristic of this device.

Transfluxors were described and their mode of operation explained in "Radiotronics" Vol. 25 No. 5, May, 1960.

Random-Access Memory with Nondestructive Read-Out

An array of transfluxors can be used as a random-access memory with so-called nondestructive read-out; i.e., one in which the read-out is obtained without changing at any time the physical state representing the information. The two stored states are the blocked and unblocked remanent conditions of the transfluxor (Fig. 9). Current coincidence can be utilized for selection, as is done in conventional core memories. Consider two selecting windings on leg 1 and two selecting winding on leg 3 of each transfluxor. Let these windings be connected in series by rows and columns as shown for simplicity by single linking wires in Fig. 9. Address-selecting writing pulses are applied simultaneously to one row and one column winding linking leg 1. The additive effect of these pulses on the selected transfluxor at the intersection of the row and column windings is sufficient to produce a setting, but the amplitude of the pulses is insufficient to affect the transfluxors on which they act singly. The direction of the writing pulses determines whether the selected transfluxor is set to the blocked or unblocked condition. Reading, based also on current-coincidence selection, is obtained by applying pulses of the proper amplitude to the selected row and column winding linking leg 3. A read-out is obtained by a pair of pulses on each selecting line, one in the prime and one in the drive directions. As a result, fluxes in legs 2 and 3 reverse back-and-forth and return to their initial state, if the transfluxor is unblocked; or remain in that initial state, if the transfluxor is blocked. These flux reversals can be detected as induced voltages on a common read-out winding linking leg 3 of all transfluxors. (See Fig. 9).

Coincident-current selections for write-in and read-out are possible because there are thresholds below which pulses linking leg 1 and leg 3 produce negligible flux changes. The coincident-current-selecting principle can be extended to the simultaneous addressing of many plane arrays used in parallel by using selective inhibiting of the planes, as is customary with core memories.

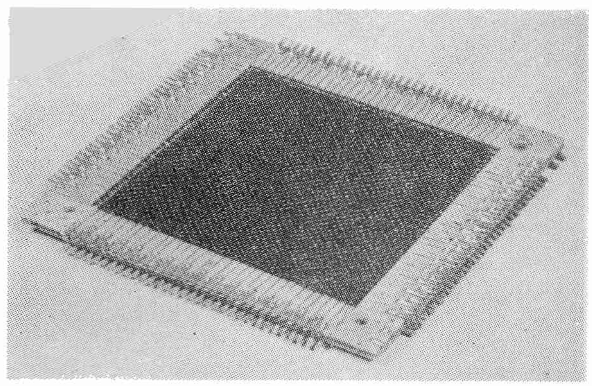

Fig. 8 — New two-mat memory-plane assembly providing 8192 bits in a space only 5-$\frac{1}{4}$" x 5-$\frac{1}{4}$" x $\frac{1}{4}$" overall.

Read-out from a magnetic storage device is necessarily dynamic, since induced voltages are possible only by changing flux. Nevertheless, in the transfluxor memory, the read-out may be considered to be "nondestructive", because the flux in leg 1 is not altered by the interrogating pulses, retains at all times the stored information, and yet its value determines whether or not flux in legs 2 and 3 will be interchanged as a result of interrogation. The second interrogating pulse is necessary to restore the altered stages of legs 2 and 3 due to the first, in a manner similar to the "rewrite" pulse in destructive read-out memories required when a read-out signal is obtained. This rewrite pulse is usually obtained from the read-out circuits. In the case of the transfluxor, the unconditional occurrence of this pulse at every read-out is not dependent on the presence of the read-out signal.

Read-out circuits for a transfluxor coincident-current memory can be simple since no feedback into the write-in circuits is required. An additional and perhaps more important advantage is the possibility of simultaneously writing-in and reading-out on two unrelated addresses, by energizing the proper lines of the independent write-in and read-out selecting grids. This possibility may speed up the operation and simplify the logic of some types of computing machines.

Channel Selector

Transfluxors may be used to select any one channel out of several channels for transmission of modulated signals. The transmission from (or to) a common channel to (or from) each one of a number of selectable channels is controlled by a transfluxor. All transfluxors are blocked except one which is set and which determines the selected channel.

A channel selector for selecting one out of $N = 2^n$ channels in response to n binary pulsed signals is illustrated in Fig. 10 for the case of eight channels and three binary inputs. The selection system is similar to that used in combinatorial decoding switches using conventional cores. Each binary input feeds a pair of conductors, one of which links No. 1 leg for one half of the transfluxors; and the other conductor, the other half of the transfluxors. The division of transfluxors in halves by the various input pairs is by juxtaposed halves, interlaced quarters, interlaced eights, etc., so that the pattern of linkages is according to a binary code. To select a channel, current is sent through one or the other conductor in each pair in a direction tending to block the transfluxors which are linked by these conductors. For every combination of inputs there will be one transfluxor, and one only, which is not linked by conductors carrying the blocking currents. The transfluxor thus selected is then set by a current pulse sent through a winding which links leg 2 of all transfluxors. The setting pulse, occurring while the selecting current pulses are on, has insufficient amplitude to overcome the blocking effect of even a single one of these blocking currents and therefore sets only the selected noninhibited transfluxor. The setting is to maximum, but there is no danger of oversetting, since leg 2 is used for setting and the region of flux change during selection is around the large aperture only. The selected transfluxor remains set until a different combination of input pulses is applied to the selector, at which time a new transfluxor is set and the previously selected one is automatically blocked.

Flux changes around the small aperture are possible only in the selected unblocked transfluxor of which the output magnetic circuit may be considered to be a regular transformer. Since a transformer transmits in either direction, the selector can be used either to transmit from the common channel to a selected channel or vice-versa, depending on which channel corresponds to the primary winding.

The selector of Fig. 10 is shown with valve drivers to illustrate fully a concrete example. However, in some applications core-driver circuits utilizing transistors are used for this purpose. For simplicity, single-turn windings are shown. Fig. 10b is a simplified representation of the selector, shown conventionally on Fig. 10a. The apertures of the transfluxors are represented by heavy horizontal lines which are assumed to be linked through by the vertical conductors when a 45° line is drawn at the intersection, the direction of inclination of the line denoting the direction of linkage.

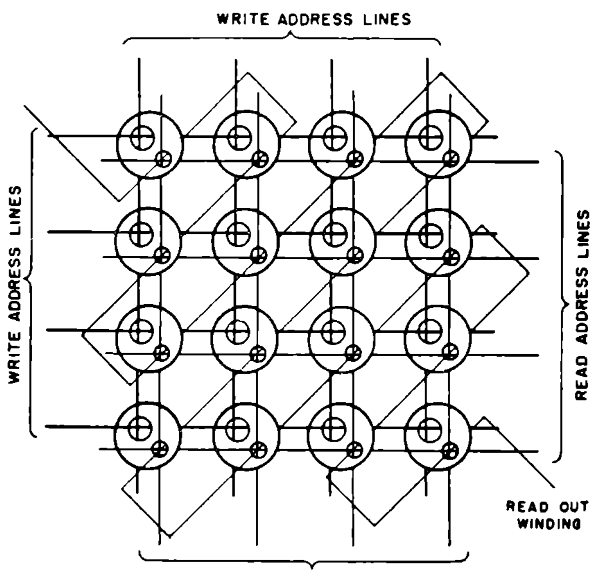

Fig. 9 — Array of transfluxors used as random access memory with nondestructive read-out.

More detailed information as to the theory of operation of transfluxors and configurations that can be used for many different applications will be found in the following references:

J. A. Rajchman and A. W. Lo, "The Transfluxor — A Magnetic Gate With Stored Variable Setting," RCA Rev., Vol. XVI, No. 2, pp. 303-311: June, 1955.

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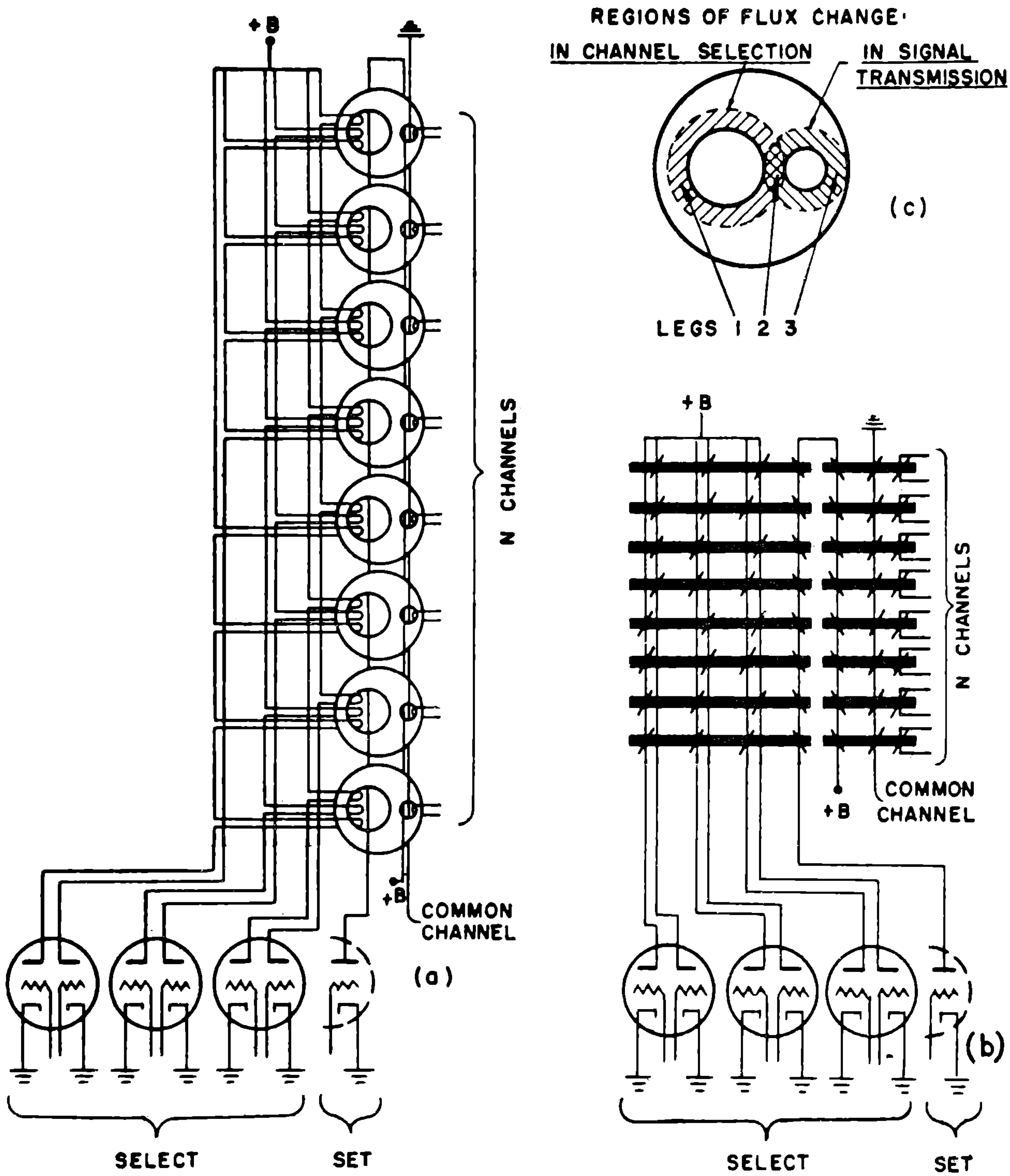

Fig. 10 — Transfluxor channel selector.

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U. F. Gianola and T. H. Crowley, "The Laddic — A Magnetic Device for Performing Logic," Bell System Technical Journal, Vol. 38, No. 1, pp. 45-72: January, 1959.

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H. D. Crane, "High Speed Magnetic Logic Systems Using Magnetic Elements and Connecting Wire Only," Proceedings of the IRE, Vol. 47, No. 1, pp. 63-74, January, 1959.

N. S. Prywes, "Diodeless Magnetic Core Shift Registers Utilizing Transfluxors," IRE Transactions on Electronic Computers, Vol. EC-7, No. 4, pp. 316-324, December, 1958.

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(With acknowledgments to Radio Corporation of America).

SILICON POWER TRANSISTORS

(Continued from page 31)

made of collector avalanche multiplication effects to determine maximum ratings.

For RCA silicon power transistors, the empirical formula for the avalanche multiplication factor (M) is

$$M = \frac{1}{1 - (V_{CB/200})^{3.5}} \qquad (3)$$

For the constant-base-current condition the voltage that separates region A and region B is $V_{\alpha M = 1}$ or the value of V_{CB} at which $M = 1/\alpha$. This voltage is given by

$$V_{\alpha M = 1} = 200 \sqrt[3.5]{1 - \alpha} \qquad (4)$$

Equation (4) may also be used when external emitter resistance (R_E) is included in the transistor circuit, provided alpha (α) is replaced by a "degenerate alpha" (α'). This substitution is necessary because of the negative feedback introduced by the emitter resistance. (Note : α' is not a transistor α, but rather a circuit current-transfer-ratio factor).

Thus :

$$\alpha' = \frac{R_B}{R_B + R_E} \alpha$$

where R_B is the equivalent series resistance of the external base-to-emitter circuit. (R_B can most easily be determined if the input circuit is replaced by its Thevenin equivalent circuit in which $R_T = R_B$).

With this substitution, equation (4) becomes :

$$V_{\alpha' M = 1} = 200 \sqrt[3.5]{1 - \frac{R_B}{R_B + R_E}\alpha} \qquad (5)$$

Under these conditions, the same regions A and B can be used provided $V_{\alpha M = 1}$, which was approximated by $V_{CEO(sus)}$, can be replaced by $V_{\alpha' M} = 1$ in Fig. 2 and in equation 1.

For example, find $V_{\alpha' M = 1}$ and $V_{CE}(max)$ for the 2N1486 with $h_{FE} = 50$ for : (1) $R_B = 5000$ ohms and $R_E = 0$ ohms ; (2) $R_B = 5000$ ohms and $R_E = 1000$ ohms. (Use $V_{\alpha M = 1}$ in place of $V_{CEO(sus)}$ in equation (1) for the $R_E = 0$ condition).

For $R_B = 5000$ ohms, $R_E = 0$; $\alpha = 0{\cdot}98$ ($h_{FE} = 50$)

$$V_{\alpha M = 1} = 200 \sqrt[3.5]{1 - 0{\cdot}98} = 200 \sqrt[3.5]{0{\cdot}02} = 200(0{\cdot}326)$$

$$V_{\alpha M = 1} = 65{\cdot}2 \text{ volts}$$

$$V_{CE}(max) = 0{\cdot}1\ (100 - 65{\cdot}2) + 65{\cdot}2 = 3{\cdot}5 + 65{\cdot}2 = 68{\cdot}7 \text{ volts}$$

For $R = R_B = 5000$ ohms, $R_E = 1000$ ohms

$$\alpha' = \frac{R_B}{R_B + R_E}\alpha = 0{\cdot}98\frac{(5000)}{(6000)} = 0{\cdot}82$$

$$V_{\alpha' M = 1} = 200 \sqrt[3.5]{1 - 0{\cdot}82} = 200(0{\cdot}612) = 122 \text{ volts}$$

This value of $V_{\alpha' M = 1}$ is greater than the published limit of V_{CEX} for the 2N1486 because only avalanche effects were considered, whereas the actual V_{CEX} rating must include the non-linear surface effects and punch-through voltage. Since voltage values computed from avalanche effects may run as high as 200 volts, all computed voltages greater than V_{CEX} must be discarded and the limit value of V_{CEX} used.

For this example :

$$V_{\alpha' M = 1} = V_{CEX} = 100 \text{ volts}$$
(published value for 2N1486)

(TO BE CONCLUDED)

ERRATA

In this issue, Photoconductivity, page 22, the last line should read:

of the phenomenon. A reasonable start has been

AWV