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Experimental Study of Electron-Beam Driven Semiconductor Devices for Use in a Digital Memory

Abstract: A novel method of electronic storage is proposed, in which an electron beam would be used to drive active and passive semiconductor devices to perform the functions of a digital memory, including those of nondestructive read-out and reset. Principally to ascertain what speeds and output signals might be currently obtained if the storage method were implemented, an experimental study was made of the response to a bombarding electron beam of commercial "four-layer" and surface-barrier diodes which could function in the proposed store respectively as storage diodes and read-out diodes. Data presented on the Shockley Laboratories' silicon 4N20D "four-layer" diode give the reduction of firing voltage caused by the bombardment as a function of beam current and bombardment duration. It is found that a beam current as weak as 0.2 μamp can fire a diode in 1/5 μsec. Three types of germanium surface-barrier diodes were studied for maximum speed of response to the bombarding beam current pulse and for charge multiplication. The "fastest" unit tested was a Philco 2N502 transistor modified for beam access to the base region by removal of the emitter dot. This unit could be bombarded to produce a 50 nsec pulse of 0.4 v peak across a 1000-ohm load. In the light of these data and of circuit and semiconductor device theory, a preliminary discussion is presented of the feasibility of a store providing a read-in rate of 5 megapulses/sec, a read-out rate of 15 megapulses/sec and a read-out signal ratio of stored ONES to stored ZEROES of 50 to 1.

Introduction

Several years ago storage tubes of the Williams type, in which charge is deposited and stored temporarily on a homogeneous insulator, were a subject of intense development activity. Matters of spot size, tube size, tube life, et cetera, were considered, and subsequently some electrostatically focussed and deflected beams of a few microamperes were designed for focused spot diameters of 10 to 20 mils over a two-inch square area.[1] With these small beam currents and with desired write and read times of at most a microsecond or so, the deposited charge was small and output signals resulting from the neutralization of this charge were in the millivolt range. Signal amplification was necessary and there was a noise problem.

It has been known for some time that the action of the beam may be greatly enhanced by employing the phenomenon of bombardment-induced conductivity. For instance, an electron impinging with an energy of 10,000 ev upon germanium comes to rest in the germanium in about 10^{-11} sec and produces some 3000 holes and 3000 electrons along its path.[2] If electrodes are so attached that these charges are collected as fast as they are produced, then a bombardment-induced current 3000 times the beam current will flow in the semiconductor. It is thus possible for a relatively weak electron beam to generate currents within the tube envelope in excess of several milliamperes, and potentials in the range of volts rather than millivolts. Since such signals can readily drive transistor circuits, it now becomes practical to consider what sorts of semiconductor circuits would be suitable for the storage of digital information under control of the electron beam. In this paper the storage potential of one basic storage circuit containing a bistable semiconducting diode is examined. It is shown how the circuit may, in principle, be driven by the beam

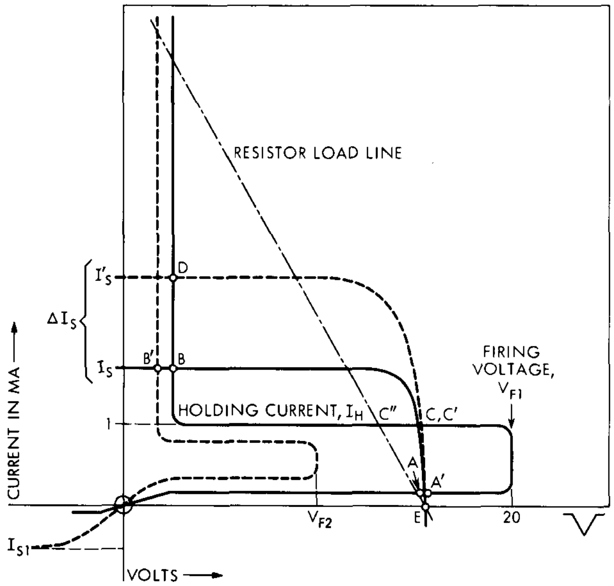


Figure 1a **Graphical analysis of current in series circuit containing four-layer *PNPN* diode and current-limited diode.**

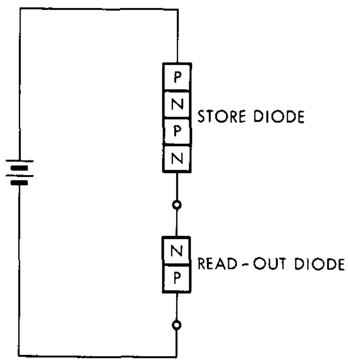


Figure 1b **Circuit containing four-layer diode and *PN* junction diode as a current-limited load.**

to provide all the functions of a storage cell, including nondestructive read-out and reset. The storage capacity of a memory consisting of a plurality of these cells is calculated in terms of read-out signal, read-out rate, and circuit parameters. An experimental investigation was undertaken to ascertain whether there is sufficient compatibility between standard techniques in cathode ray tube practice and existing semiconductor devices to provide read-in and read-out rates in excess of ten megapulses/sec and to yield read-out signals in the range of volts at these speeds. The most promising commercially available semiconductor units, judged according to expected response speed and beam accessibility, were chosen for this purpose. An operable storage cell could not be constructed of the selected units, unfortunately, because the dc electrical characteristics were not compatible. Consequently, electron-bombardment-induced conductivity studies were carried out on the cell components in separate test circuits. Speed and charge multiplication measurements were made in such a manner that inferences might then be drawn which would be helpful in the design of a large-signal, high-speed storage tube. Previous work in this field has not been done with these ends in view.[3]

Design of the storage cell

In the past few years, a number of bistable semiconducting diodes and triodes have been invented which can be triggered from one stable state to the other in less than 0.1 μsec. A list of these, with nominal turn-on times, would include the "four-layer" *PNPN* diode[4] (10^{-8} sec), the positive-gap diode[5] (5×10^{-9} sec), the avalanche injection diode[6] (5×10^{-9} sec), the avalanche transistor[7] (5×10^{-9} sec), and the tunnel diode[8] (10^{-9} sec). Because each of these devices has a state of low conductance, it would be expected that the increase in conductance induced by electron bombardment of the semiconducting material would sufficiently modify the voltage-current characteristic so as to trigger it from its low conductance, or OFF state, to its high conductance, or ON state. In Fig. 1a, a voltage-current characteristic is shown whose form is typical of "four-layer" *PNPN* diodes and is representative of the other bistable devices just listed, except the tunnel diode for which the labels V and I must be interchanged. If the bistable diode is connected in series with a battery and a load resistor, then the series current which can flow is shown graphically in Fig. 1a by the intersection of the dot-dash resistor load-line and the diode characteristic curve. The condition for turning the bistable diode on is that the beam should decrease the firing voltage, V_{F1}, of the diode to a value V_{F2}, which is less than the voltage indicated at point C. To minimize the necessary lowering of the firing voltage and to minimize the power dissipation in the ON state, the load line shown in Fig. 1a as solid line ECB is desirable. This is the characteristic of a current-limited device; it can be provided in two-terminal form by a back-biased *PN* junction diode whose saturation current is purposely increased to approximately one milliampere. For experimental purposes, saturation currents as large as this are readily achieved by raising the diode temperature 20 to 30°C and/or by shining light on the unit. The circuit diagram in Fig. 1b shows a *PN* junction diode used as a current-limited load element. This circuit is stable at points A and B of Fig. 1a.

The electrical effect of bombarding a reverse-biased *PN* junction diode with a one-microampere, 10 kv electron beam is to increase the saturation current of the diode by several milliamperes, i.e. by the bombardment-induced current. Bombardment-induced voltages of about 0.5 v with an open circuit, in the case of germanium, are also to be expected. This effect will be ignored for the moment but will be dealt with later in relation to the read-out signal ratio of stored ONES to stored ZEROES. The modified characteristics during beam bombardment are shown for both diodes as dashed lines in Fig. 1. These beam-induced changes in electrical characteristics can be used to provide storage and nondestructive read-out of storage in the following way: If the bistable diode, specifically, the four-layer diode of Fig. 1a, is OFF (at A in Fig. 1a) then there is no increase of current in the series circuit when the PN junction diode is bombarded because the OFF diode virtually opens the series circuit. This is shown in Fig. 1a by the fact that points A and A' lie close together. If the four-layer diode is ON (point B) then the series current can be increased by the amount ΔI_s during bombardment. This change is represented in Fig. 1a by the change of operating point from B to D. The current increase may be sensed in a circuit external to the cathode ray tube and the ON or stored ONE condition of the bistable diode can be ascertained. Conversely, the absence of current increase in response to bombardment indicates the OFF or stored ZERO condition. This read-out method is seen to be nondestructive.

In Fig. 2, a storage cell capable of storing one bit of information is shown. An inductive coil of negligible resistance is connected in the circuit to sense changes in the current during read-out without affecting the dc bias. An additional diode is included to illustrate how the beam may be used to selectively reset a storage diode from its ON to its OFF condition. By connecting this diode to a source of potential higher than the bias on the four-layer diode, the four-layer diode may be turned off provided that the current through the reset diode during bombardment is adequate to supply the sum of the saturated back currents I_s and I_{s1} of the read-out and storage diodes, respectively. Note that I_s is greater than the holding current, I_H.

In Fig. 3 a number of storage cells are shown connected in parallel with a common load conveniently situated outside the tube envelope; this constitutes a storage row. It is seen that a zero resistance common load such as the inductive coil shown in Fig. 2, but preferably the shorted line shown in Fig. 3, is highly desirable so that the dc bias voltage on each OFF storage diode will be independent of the number of diodes which may be ON in the storage row. Added advantages gained by using a current-limited diode instead of a resistor as a load for the bistable diode now become apparent. Consider that the beam strikes the read-out diode of Cell No. 1 and that this cell is storing a ONE, i.e., the storage diode is on. Typically, the series current increases by 1 ma and this flows into a shorted line of 1000 ohms characteristic impedance. This load has in shunt with it the resistance of other storage cells in various ON and OFF states. Notice, however, that if a ZERO is stored (storage diode OFF) the ac (or dynamic) resistance seen from point P is the one megohm forward resistance of the four-layer diode in series with the 1000 ohm dynamic resistance of the read-out diode; hence the total dynamic resistance is one megohm. If a ONE is stored, the four-layer diode exhibits a few ohms resistance, but it is in series with a PN junction in saturation whose slope resistance can be several hundred thousand ohms. The total series dynamic resistance is perhaps 100,000 ohms. Insofar as shunt resistance is concerned, perhaps 100 cells can be connected in parallel before the current from a bombarded cell to the external load is appreciably reduced by the pulse current drawn by the remaining storage cells. At high speeds of serial read-out, the shunt capacitance is the more important consideration. Here again, it is seen that irrespective of whether a ONE or a ZERO is stored, one or the other of the storage or read-out diodes contains a back-biased junction whose capacitance can be as low as a few picofarads. This capacitance is in series with that of the other diode, which may be quite large, but the total capacitance is small. We shall assume for simplicity in what follows that each cell adds a capacitance C_1 in shunt with the common load both when a ONE and when a ZERO is

Figure 2 **Storage cell with reset feature.**

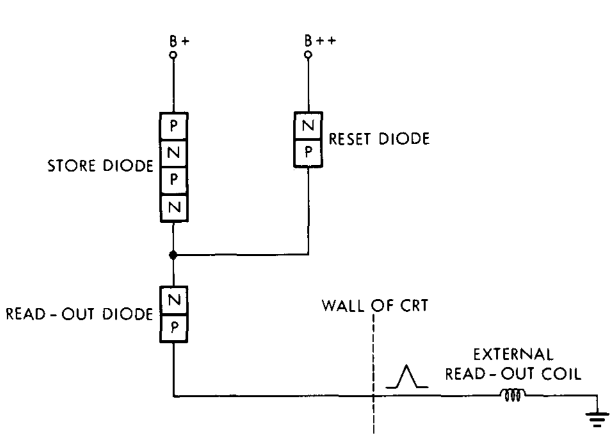
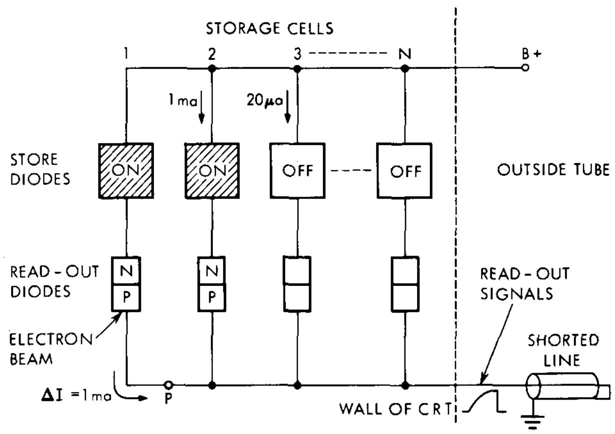


Figure 3 **A row of storage cells.**



stored. The equivalent circuit shown in Fig. 4 is appropriate for describing the build-up of the read-out signal when the beam strikes a read-out diode in series with a conducting storage diode. A rectangular bombardment-induced current pulse is assumed for simplicity. In the more representative case that the RC time constant of the load resistor and shunt capacitance is at least several times longer than the duration of the current pulse, a charge $Q = \int \Delta I dt$ is delivered to capacitor C, and raises the potential across C to $e_{\max} = Q/C$. Afterwards, this charge leaks off C through R with time constant RC. A delay line clipper may be used, as shown in Fig. 3, to eliminate this discharge period. For a rectangular current pulse of duration Δt, the charge Q is

$$Q = \Delta I \cdot \Delta t\,. \tag{1}$$

If G hole-electron pairs are produced by each primary electron, and if all minority carriers are collected in a time short compared with Δt, then the induced current pulse will be G times the beam current I_B; thus

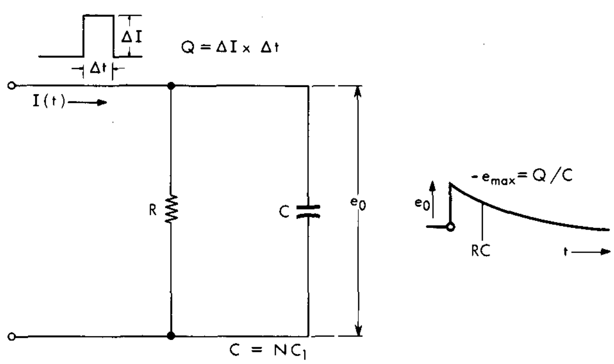
$$\Delta I = GI_B\,. \tag{2}$$

In a storage row of N cells, the capacitance in shunt with the load is $C = NC_1$; hence the peak signal at the output terminal from an N-bit row of storage is

$$e_{\max} = Q/NC_1 = GI_B\Delta t/NC_1\,. \tag{3}$$

For I_B, we might adopt the value of 1 microampere frequently used in the design of Williams tubes for long life. Values of the other parameters which are close to those reported in a later section are $G = 3000$, $\Delta t = 20$ nsec, and $C_1 = 2 \times 10^{-12}$ fd. For a 50-bit storage row ($N = 50$), it is then found from Eq. (3) that $e_{\max} = 0.6$ v. This is an encouraging trial estimate. The read-out rate would be $1/(2\Delta t) = 25$ megapulses/second. Further questions regarding the realization of a storage tube will be dealt with later on. In the experimental work to be described, measurement of the parameters occurring in Eq. (3) will occupy our attention.

Figure 4 **Equivalent circuit for read-out of a row of *N* storage cells.**



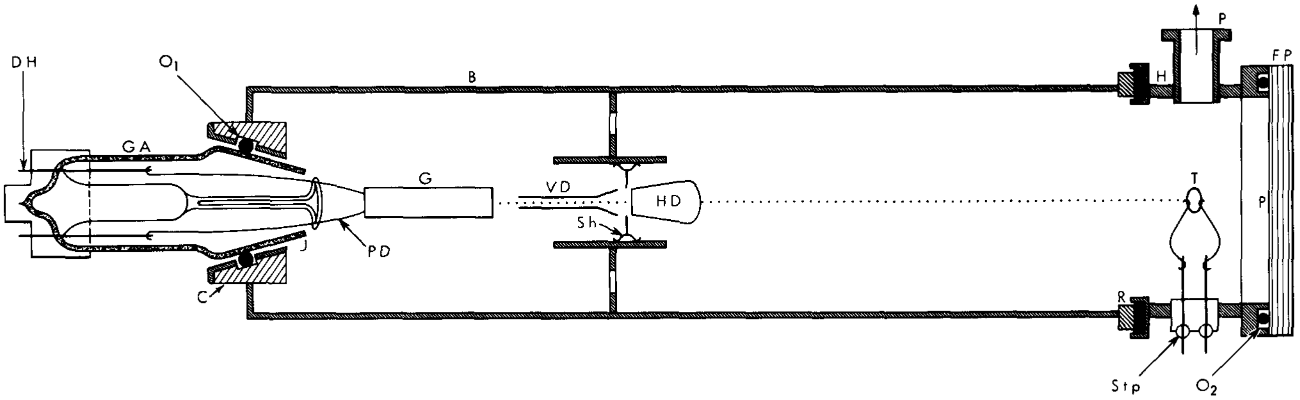
Apparatus

The demountable cathode ray tube assembly shown in Fig. 5 functions satisfactorily as an easily controlled source of bombarding electrons with kinetic energies variable from zero to 15,000 ev. The cathode ray tube includes the gun assembly GA and a brass can B, which functions as the tube envelope. The 5ATP7 gun assembly, which was purchased in the form shown,[9] has a tapered, ground glass joint, J. It is plugged into the can B through the mating, tapered hole in ring C. The vacuum seal is made by the greased, glass-against-metal joint and by the O-ring seal, O_1. In bell-jar fashion, can B is vacuum sealed to the header H by means of the flat, rubber gasket, R. The header contains the semiconductor targets, T. A glass face-plate, FP, thinly covered in its center area with phosphor layer, P, enables one to view the interior of the tube and to see the beam spot. The gun assembly contains a type of "snap-in" cathode which can be replaced in a matter of minutes.[9] It was necessary to maintain a vacuum better than 5×10^{-6} mm Hg to reduce cathode deterioration. An automatic nitrogen transfer unit was employed to facilitate this. The beam was electrostatically focused and deflected. By grouping the high voltage and the low voltage pins on opposite sides of the diheptal socket DH and the support PD, the cathode could then be operated 15,000 v below ground without arcing. The beam could not be focused to much better than 0.75 mm spot diameter at 10 μa beam current. With careful activation, beams up to 90 μa were drawn and the current density of the focused spot was much increased, although the beam diameter increased to 1.3 mm.

Design of read-out diodes

The basic design consideration of the read-out diode is that it produce a short read-out pulse. This requires that the current carriers produced in the germanium by the primary electrons be collected as quickly as possible. A similar situation is the collection of charge onto the plates of a parallel-plate ionization chamber when a fast particle passes between the plates. A back-biased p-n junction is such a parallel-plate ionization chamber; the depletion layer at the junction corresponds to the region of electric field between the plates, and the adjoining p and n regions correspond to the plates themselves. Many metal films on semiconductors form a similar structure. For present purposes, diodes differ in the manner in which their structures permit bombarding electrons to produce ionization more or less entirely within the depletion layer. It is desirable, of course, that all the secondary ionization be produced in the electric field region, but generally this is not the case and charges produced near the depletion layer must diffuse into it to be collected. It is interesting to calculate that if the transit time across the depletion layer were the sole consideration, the charge collection time onto the p and n layers should theoretically be as short as 10^{-11} sec, since

Figure 5 **Demountable cathode ray tube assembly.**



the depletion layer can readily be 10^{-4} cm thick, and the limiting electron drift velocity in germanium is 10^7 cm/sec. If one of the regions adjoining the depletion layer is made very thin, there is an opportunity of utilizing the full energy of the primary electron to produce secondaries entirely within the depletion layer. Two structures of this sort are: the surface-barrier diode consisting of a thin metallic film on a semiconductor surface,[10] and the "solar battery" diode consisting of a thin diffused layer of one conductivity type on the surface of a bulk of opposite type.[11] In this paper a report is made on some film diodes and on two kinds of diodes in which the ionization mainly occurs adjacent to the depletion layer.

Bombardment of metal film read-out diodes

Copper was evaporated from tungsten wire holders onto chemically etched (CP-4) 5 ohm-cm, *n*-type germanium wafers. The area and thickness of the film were nominally 1 mm^2 and 0.1 μ, respectively. The evaporator vacuum of 10^{-4} mm was created by a water-cooled, oil-diffusion pump. A wire pressure contact was made to the copper film. The diodes exhibited good rectifying characteristics. Of primary interest is the number of hole-electron pairs collected for each incident electron. This quantity which we shall call for simplicity the gain, G, is defined in this paper as G = number of secondary electrons/number of primary electrons. In Fig. 6, this quantity is plotted as a function of the primary charge, Q_{in}, deposited by a beam applied for increasing intervals of time. Q_{in} was calculated from the beam current data, the beam current profile, the diode dimensions, and the scan velocity. The collected charge was found by integrating the diode current waveform. The curve in Fig. 6 is for a typical diode of four similar ones. Inasmuch as the induced current disappeared at 4 kv as the beam voltage was lowered from 10 kv to 4 kv, it can be stated that at 10 kv the primaries enter the germanium after passage through the film with no less than 6000 ev of energy; thus we would expect a gain of no less than 6000 ev/3.7 ev/pair = 1600. The fact that a maximum gain of 400 was observed indicates severe hole-electron recombination. This would be the case if there were an oxide or an oil film at the interface between the copper and the germanium. It is possible that such a layer would exist on the present specimens. A second point to be noticed in Fig. 6 is that the gain falls off with increasing primary charge. This may result from a weakening of the field in the depletion layer by accumulated charge; recombination of the induced charge is then more pronounced because this charge is not swept away as fast. The shortest pulse observed was 1.5 μsec with the beam on the diode 0.3 μsec. That this pulse is so much longer than the estimated depletion layer transit time, of order 10^{-11} sec, is probably to be attributed to the trapping of charge and to its subsequent slow release. A detailed study of the pulse response of a gold film diode to heavy-particle bombardment has been given by Meyer.[10]

Bombardment of jet-etched diodes

Assuming that the low gain observed for the evaporated film diodes may be attributed to metal-semiconductor interface conditions, one is faced with serious problems in judging how to increase the gain by controlling the preparation of the specimen. Another approach is to use the jet-etch technique, which gives good assurance that the germanium surface is clean at the instant of electrodeposition of the film onto the germanium. Such metallic contacts to germanium should and do collect and inject holes with high efficiency. Philco SB101 transistors employ this principal of junction preparation. Unfortunately, on these units the metal deposits constituting collector and emitter are so thick that a bombarding beam cannot penetrate to the underlying germanium. Furthermore, the lead wires themselves would obscure the junction areas almost completely if the beam were brought into the germanium base from the side of the metal deposit. However, because the base material is only a fraction of a mil thick in the high-speed transistors, the beam can be brought in from that side, provided that one of the electrodes can be removed. In these units it is not to be expected that the secondary charge is produced in the depletion layer, but rather adjacent to it. Because the collector is bigger than the emitter, it was decided to remove the latter so as to maximize the collected current. In the Philco SB101 and the Philco 2N502 units the indium emitter could readily be removed by rubbing on a drop of mercury. The structure of the diode units in cross-sectional view and the circuit diagram for measuring the pulse response are shown in Fig. 7.

An aperture plate, *AP*, having a hole in it somewhat smaller than the emitter, is laid against the base wafer with the hole centered upon the region previously occupied by the emitter. For the SB101 unit, the hole was 6 mils in diameter. *AP* is also connected electrically to the base tab, *BT*. Because of the inability of this unit to carry away heat in vacuum, a second aperture plate or protective plate, *PP*, is placed in front of the unit and is thermally connected to a heat sink, *HS*. The load resistor, *R*, is connected to the collector so that it does not receive the primary electrons which drain off through the base tab, thence through the battery, E_B, to ground. In Fig. 7 we have shown the distributed capacitance, C_d, from the collector to ground of the wiring and the oscilloscope. This capacitance, acting in parallel with the diode collector capacitance, receives the induced charge, which subsequently leaks off through the load resistor, R. In the lower trace of Fig. 8 is shown the response of the Philco SB101 unit to a bombarding electron beam swept back and forth across it by a 1 mc sine-wave sweep, as shown in the upper trace. In the lower trace, the diode is shown responding at a two-megapulse rate. Being positioned in the middle of the sweep, the diode is hit twice in each sweep cycle. The hit times are not accurately represented in Fig. 8 because the two traces are not quite synchronous. Because there are about 5 pf capacitance between collector and ground, and R=22,000 ohms, the discharge time constant is 110 nsec; hence, some of the 300 nanoseconds of the pulse is due to this capacitor discharge. We judge that these units are suited for a read-out rate of 2 megapulses/sec.

In Fig. 9 is shown the response of a modified Philco 2N502 transistor to a bombarding electron beam swept back and forth across it by a 1 Mc sine-wave sweep. The beam bombards the emitter region through a 3.7-mil hole in the aperture plate. The 4.6-mil diameter emitter dot has been dissolved off by mercury. Of principal interest is the pulse width measured at 10% of maximum amplitude; it is 50 nsec. Because the rise time of the oscilloscope amplifier is 14 nsec, the true pulse width is less than 50 nsec. The pulses are of unequal height because the out and return paths of the beam are not quite the same. The trace in Fig. 9 is broadened by some low-frequency pickup. When the bias was reduced from 13 v to zero, the pulse amplitudes in Fig. 9 fell by a factor of three. The fact that a pulse output was observed with no applied voltage indicates a bombardment-induced emf. Such an emf is expected by an analogy with the light-induced "photovoltage." A clearer picture of the pulse response to a stronger beam is shown in Fig. 10. The conditions are otherwise the same as for Fig. 9 but the scope trace

Figure 6 **Bombardment of *n*-type germanium through copper film contact.**
Ratio of collected electron charge to primary electron charge, G, plotted as a function of primary charge, Q_{in}. Beam accelerating voltage, 10 kv; beam diameter, ca. 30 mils.

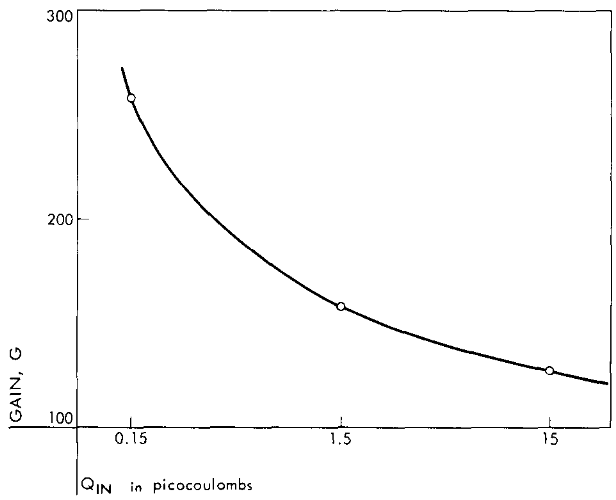
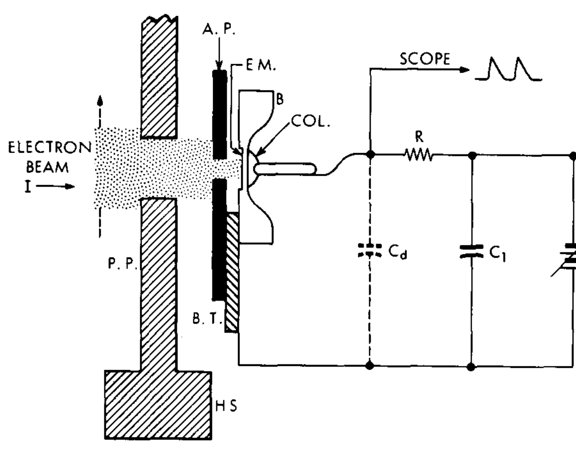


Figure 7 **Mounting assembly and pulse measuring circuit for bombardment study of modified Philco transistors.**



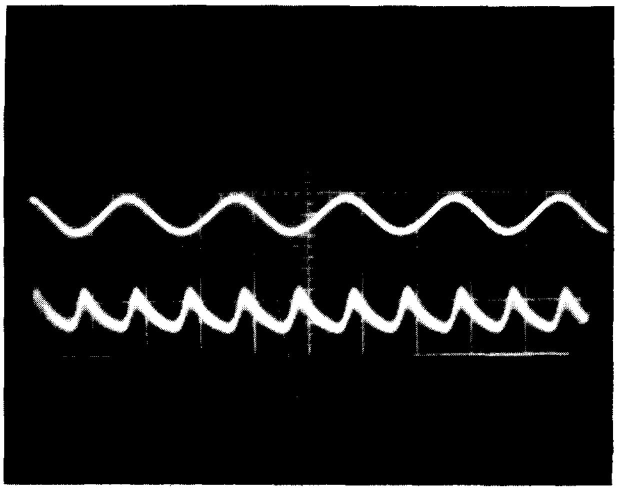


Figure 8 **Response of Philco SB101 unit in circuit of Figure 7.**
Upper trace: one megacycle sinusoidal sweep; lower trace: diode is in middle of sweep and responds at a rate of two megapulses/sec. Accelerating voltage 10 kv, load resistor $R = 22$ kohm. Vertical scale, 0.5 v/cm; horizontal scale, 5.0 μsec/cm.

has been shifted so that only one pulse is visible. The pulse width at 10 per cent of maximum amplitude is 50 nsec and the pulse amplitude is 0.4 v. It is worth noting that the maximum pulse rates, viz., 2 and 20 megapulses/sec, found for the bombardment response of the transistors SB101 and 2N502 are in the same ratio as the α-cutoff frequencies quoted by the manufacturer. This indicates that the same mechanism which limits the frequency response of these units used as transistors is acting also when the units are bombarded.

Measurement of charge gain in a modified 2N502 transistor

A measurement of the charge gain, G, was made for the Philco 2N502 unit by determining the ratio of the electron charge flowing out of the diode (less the primary charge), Q_{ind}, to the primary electron charge impinging on the semiconductor material, Q_{beam}. The former charge was calculated as the time integral of the induced current pulse. Q_{beam} is by definition the time integral of the beam-current which passes through the hole in the aperture plate of diameter D, as the beam-current profile sweeps across the hole with constant velocity, v. Because of several difficulties in measuring this current integral, an indirect method was used. A Gaussian beam-current profile was assumed, i.e., that the current distribution along a line passing through the beam center varied as $\exp(-x^2/b^2)$, and then the impinging charge, Q_{beam}, was found by integration to be

$$Q_{\text{beam}} = \frac{\sqrt{\pi}}{2} I_B \left(\frac{D}{2b}\right)^2 \left(\frac{2b}{v}\right), \tag{4}$$

where I_B is the total beam current. Since the induced current pulse was approximately triangular, the area under the current pulse curve was

$$Q_{\text{ind}} = \tfrac{1}{2}(\Delta I)_{\text{max}} \cdot \Delta t = \frac{1}{2} \frac{(\Delta V)_{\text{max}}}{R_L} \cdot \Delta t , \tag{5}$$

where R_L is the diode load resistance. The measured values in Eq. (5) were $(\Delta V)_{\text{max}} = 0.07$ v, $R_L = 1000$ ohm, $\Delta t = 60$ nsec; thus $Q_{\text{ind}} = 2.1 \times 10^{-12}$ coulomb.

The beam sweep velocity could be calculated from the length, $2A$, of the beam trace seen on a phosphor screen a short distance away from the target, and the frequency of the sinusoidally deflected beam, f. Since the trace coordinate, x, varies as $x = A \sin 2\pi ft$, the sweep speed, v, at the center of the sweep, is

$$v = 2\pi Af . \tag{6}$$

In this instance $2A = 3.2$ cm, $f = 0.67$ mc/sec, so $v = 0.67 \times 10^7$ cm/sec. This figure lowers to $v = 0.60 \times 10^7$ cm/sec when correction is made for the distance between target and trace. A static measurement of the focused beam diameter was made by measuring the beam displacement required to increase the beam current, collected in a positively-biased metal cup, from 5% to 95% of full value. The rim of the cup and the target diode were in about the same beam-image plane. A value for D_B of 1 mm was found, and this gives a value for $b = 1/4$ mm. With the values $D = 0.092$ mm, $b = 0.25$ mm, $v = 0.6 \times 10^7$ cm/sec, and $I_B = 3$ μa, it is calculated from Eq. (4) that $Q_{\text{beam}} = 0.73 \times 10^{-15}$ coulomb. Thus $G = Q_{\text{ind}}/Q_{\text{beam}} = 2900$. The maximum expected value at 10 kv is $10{,}000/3.7 = 2700$. Apart from the several assumptions made, uncertainties in the numerous measured parameters alone make the measured value of G uncertain to plus or minus twenty percent, the major uncertainty coming from the value of D_B. A partial interpretation of the current pulse in Fig. 9 can now be made, knowing the values of v and D_B. The beam passes across the diode in a period $(D_B + D)/v = 20$ nsec, which is, within experimental error, the observed time of rise of the pulse to peak value. Hence the diode and associated circuitry are responding impulsively, i.e. to deposited charge, and not synchronously to the beam current. This result is further confirmed by the observation that when the load resistor was increased to 22 kohm from 1 kohm, the pulse height only doubled, whereas the decay time increased twenty-fold. From the decay constant with a 22-kohm load, a capacitance of 9 pf is obtained. A plausible interpretation of the pulse shown in Fig. 9 can be given in terms of the charging and discharging of this capacitance. Since the rise time of the scope amplifier is 14 nsec, it is difficult, however, to draw further conclusions regarding the details of the response.

Bombardment of "four-layer" *PNPN* diodes

A fast, bistable, semiconductor diode which was found to be amenable to bombardment studies and is commercially available is the Shockley Laboratories' 4N20D "Four-Layer Diode". A thin, circular wafer of silicon, 20 mils in diameter and 1.5 mils thick, is held by gold-plated, 15-mil-diameter wires, which press on the broad faces from opposite sides. When light is shone on the edge of the wafer, it was found that the firing voltage could be lowered by any desired amount, depending upon the intensity of illumination. In fact, the property of bistability could be eliminated by sufficiently intense illumination. Illumination of the broad faces of the wafer had little effect on lowering the firing voltage. As a result of these observations, the electron beam was always directed at the edge of the wafer. The need for bombarding in this manner is of importance when the stability of the electrical characteristics with repeated bombardment is in question. Three *p-n* junctions come to the surface at the thin edge of the wafer and some changes in electrical characteristics might be anticipated, but this did not turn out to be the case. Of primary interest for high read-in speeds is the length of time the beam must be applied to an OFF diode to turn it ON. Two methods were used to determine this time duration called the "ON-time" in what follows. In the first method, the beam was moved across the diode with known velocity and the beam diameter was measured with slow scan by using the four-layer diode as a narrow collector of a "slice" of the beam. Dividing the beam diameter plus the diode thickness by the beam velocity gave the ON-time. In the second method, the diode was used to measure the current pulse delivered by the beam; the duration of this pulse was taken as the ON-time. For simplicity, a variable rate of scan was obtained by applying an exponentially rising wave to the deflection plates. Using the four-layer diode to measure the beam-induced current, the time interval between the start of the sweep and the time the diode was hit was measured. The scan velocity was then easily calculated once it was known where the hit occurred on the sweep waveform. Also of interest is the amount of lowering of the firing voltage by beams of different strength and scan velocity. This is best measured with the aid of the load line BCE of Fig. 1. The lowering $(V_{F1} - V_{F2})$, is measured by setting battery voltage, E, first to where the diode fires in the absence of the beam, and second to where the diode just fires when the beam is swept across the unit; these points are then, respectively, equal to V_{F1} and V_{F2} because the load line CE is almost vertical.

A particularly simple scheme for both achieving the desired load line for biasing the diode and for resetting the four-layer diode repetitively is shown in Fig. 11. There, the characteristic of the two-terminal "black box" between points A and B gives just the required load line BCE when the toggle, T_1, is open. When T_1 is closed, the transistor switch is cut off and this turns off the four-layer diode. When T_1 is then opened, the circuit goes to point A in Fig. 1 and the diode is reset. By appropriate timing of the action of T_1 and of a sweep pulse generator, the following sequence of events could be brought about: beam sweeps across biased four-layer diode; diode fires; beam stops moving; transistor switch closes, turning the diode off

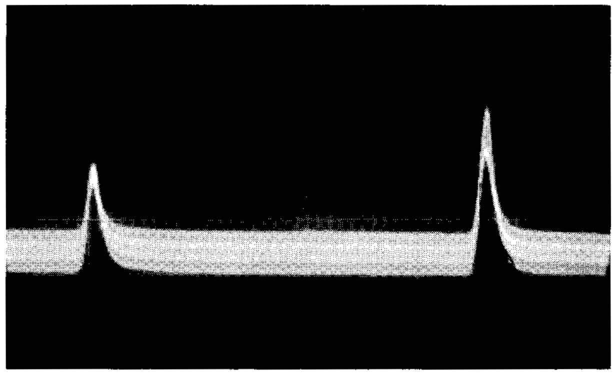


Figure 9 **Response of Philco 2N502 unit in circuit of Figure 7.**
Pulse width is 50 nsec at 10% of peak voltage. Accelerating voltage 10 kv; collector bias 13 v; peak voltage of largest pulse is 50 mv; load resistor R = 1 kohm. Some 60-cycle pick-up is in evidence in the vertical position of the trace. Vertical scale, 0.02 v/cm; horizontal scale, 0.1 μsec/cm.

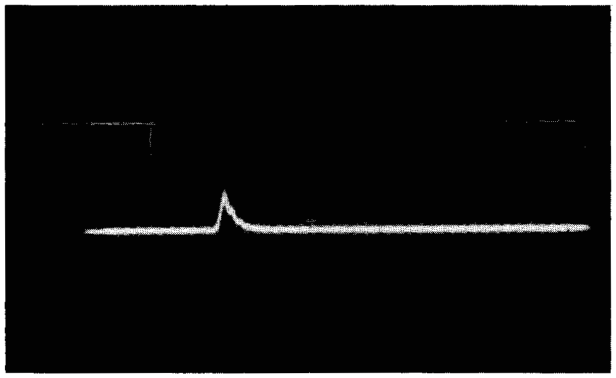


Figure 10 **Response of Philco 2N502 unit with beam current increased so as to yield pulse 0.4 v at peak.**
Width is 50 nsec at 10% of peak; 10 v bias on collector; accelerating voltage 10 kv; load resistor R = 1 kohm. Vertical scale, 0.5 v/cm; horizontal scale, 0.1 μsec/cm.

Table 1 **Calculation of maximum read-in rates for two "four-layer" *PNPN* diodes (Shockley Laboratories' 4N20D).**

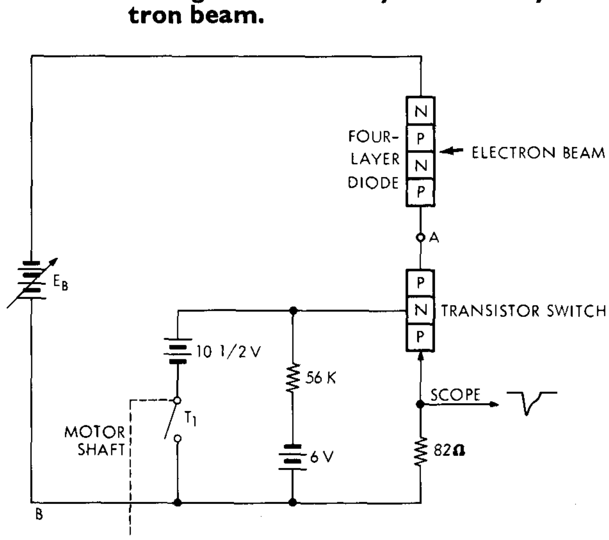
4N20D Unit	I_H (ma)	V_F (v)	I_B (μa)	i (μa)	Shift (v)	v cm/μsec	D (cm)	t_{ON} (sec)	RIR (pulses/sec)
#1	$7\frac{1}{2}$	23	18	2	1.6	0.47	0.10	2.1×10^{-7}	4.8×10^6
#2	1	$21\frac{1}{2}$	42	4	0.3	0.60	0.10	1.7×10^{-7}	5.9×10^6

I_H is the holding current; V_F, firing voltage (cf. Fig. 1); I_B, beam current; i, peak of bombardment-induced current pulse just *before diode fires*;"shift", reduction of firing voltage by beam; v, the beam scan velocity; D, the beam diameter; t_{ON}, the time the beam spends on the diode; RIR, the read-in rate, $= 1/t_{ON}$.

and holding it off; beam returns quickly across the diode, which cannot fire; transistor switch opens, resetting the diode. Data taken on two diodes is shown in Table 1. The procedure was to set the beam at maximum intensity, and then to increase the sweep velocity until the diode fired reliably with a one-volt reduction of the firing voltage. This procedure established the minimum time the beam need be on the diode to effect triggering, i.e., it yields the minimum ON-time. By taking the reciprocal of the minimum ON-time, one obtains a figure for the maximum pulse read-in rate (Column "RIR") for a beam of a given current. This supposes, in an operating storage cell, that as soon as the beam leaves one diode it would immediately begin to bombard the next one. The duration of the induced current pulse was observed to agree with the calculated ON-time given in Table 1. It is of interest to note that the induced current is surprisingly small.

Let us consider the data of Unit #1, Table 1. For a 40-mil diameter, 18-μa beam, the primary electron charge deposited on the 20 mil $\times$ 1.5 mil exposed area of the diode during an ON-time of 2.1×10^{-7} sec is $Q_{\text{in}} = 0.9 \times 10^{-13}$ coulomb. With reference to Fig. 4, it is seen that if the RC time constant is much longer than the ON-time, as it is in the present case, then the collected charge Q_{out} is given by $e_{\max}\cdot C = Ri_{\max}\cdot C = (5 \times 10^3 \text{ ohms}) \times (2 \times 10^{-6} \text{ amp}) \times (200 \times 10^{-12} \text{ f}) = 20 \times 10^{-13}$ coulomb. Hence for each primary electron only 22 secondary electrons are collected. This does not compare at all with the gain expected of 10,000 v electrons impinging upon silicon which is probably close to 1700 (germanium value reduced by the ratio of the band-gaps of the two materials). If one assumes that only those secondary electrons produced in the depletion layer of the back-biased junction escape recombination, then only that fraction of Q_{in} which strikes the depletion layer should be effective. A junction biased at 25 v and almost undergoing avalanche would have a depletion layer width of about $w = 2 \times 25\text{ (v)}/10^5\text{ (v/cm)} = 5 \times 10^{-4}$ cm. Thus for a specimen 40×10^{-4} cm thick, only 1/8 of Q_{in} is effective; hence under this assumption each primary electron impinging upon the depletion layer produces 180 collected secondaries. Because this figure is still a factor of 10 below the expected value of 1700, strong surface recombination is indicated. A second point of interest is to understand how an induced current of only a few microamperes manages to fire the diode. A plausible explanation is that the induced current flows with great density through the edge of the silicon wafer, where it is bombarded by the electron beam, and this fires or initiates the firing of the diode at its edge. If, as in the example just studied, 2×10^{-12} coulomb of induced charge is collected in 2×10^{-7} sec, this means that an average current of 10^{-5} amp is induced in the diode. Since the 10 kv electrons penetrate the silicon to a depth of about 10^{-4} cm, the current flows through the rim of a circular sector of radius 2.5×10^{-2} cm and of sector angle no greater than π radians. The current density would thus be 1 amp/cm^2. This figure is of the order of the holding current density of Unit #1 in Table 1, which is 4 amp/cm^2. The agreement is perhaps good enough because the figures are not strictly comparable: the value 1 amp/cm^2 refers to a one-volt shift of firing voltage; whereas, the 4 amp/cm^2 figure refers to a current density sufficient to fire the diode. Larger

Figure 11 **Circuit to study reduction in firing voltage of a "four-layer" diode by electron beam.**



reductions in the firing voltage may be achieved by letting the beam stay on the diode longer and/or by increasing the beam current. These relationships are shown in Fig. 12. The reduction in firing voltage is plotted against the ON-time, which is calculated from the scan velocity and the beam diameter. The most important point to be noticed in Fig. 12 is that the firing voltage, 21.5 v, can be reduced by 6 v by an intercepted beam current of only 0.16 μa. This figure is calculated by reducing the beam current by the ratio of the exposed diode area to the area of the beam (cf. Fig. 12). Secondly, the shift is roughly proportional to the beam current, but tends to saturate for beam currents greater than 8 μa. Thirdly, the shift at first increases as the ON-time is increased and then levels off. An eventual leveling off is to be expected, of course, because the ON-time by definition includes time the beam spends on the diode after the diode has fired, and this extra time can be made arbitrarily long without changing the amount of shift observed. A final point to be mentioned in regard to the use of these diodes in a storage role is that there is a firing delay which can be as long as a microsecond if the beam is only just strong enough to fire the diode. The implications of this observation will be mentioned in the following section.

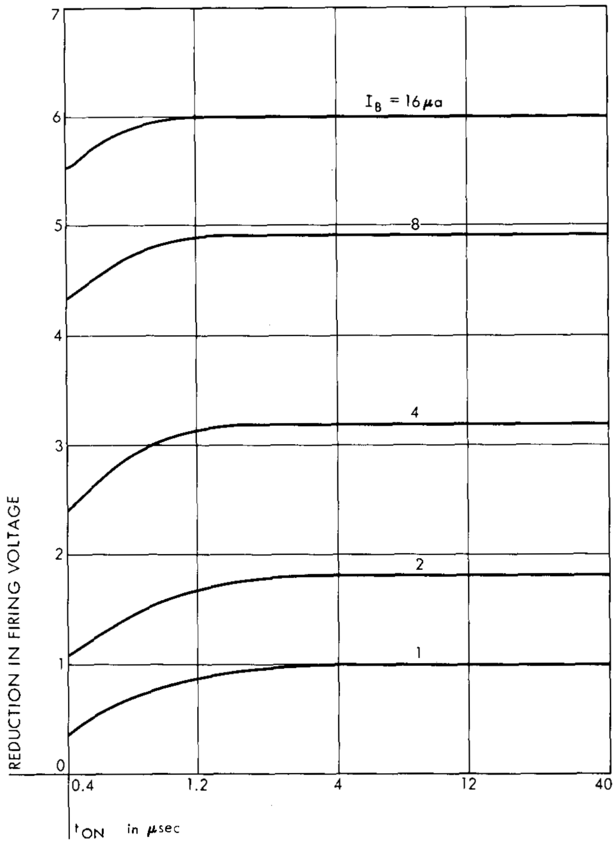


Figure 12 **Reduction of firing voltage of Shockley Laboratories' 4N20D "four-layer" diode by electron-beam bombardment.**
Shift is measured at constant beam current as a function of the time the beam spends on the diode (t_{ON}). Beam diameter 55 mils; projected edge of four-layer diode is 1.25 × 21 mils. One per cent of the beam current I_B, is intercepted by the diode. Diode firing voltage is 21.5 v; holding current 4 ma.

Feasibility of realizing a large-signal, high-speed storage tube

It is worth while to make some conservative extrapolations and additional uses of the data presented above to see what general sort of storage tube might be feasible. Considerations will be restricted to use of the Shockley Laboratories' 4N20D "four-layer" diode, and the modified Philco 2N502 transistor to avoid broadening the scope of this section unduly.

Power per bit: Accepting the circuit of Fig. 3 as a basic storage row, it is to be noted that quiescent power is dissipated only when the "four-layer" diode is conducting, because its OFF conductance is so low. This power is dissipated in the load diode. Depending somewhat on the tolerances one wishes to allow to assure positive firing and latching, this power is equal to the product of one-half the firing voltage times twice the holding current, which is $V_F \times I_H$. In a batch of the lowest power units which could be obtained from the vendor, this product ran from 20 v × 1 ma = 20 mw to 25 v × 8 ma = 200 mw. Without resorting to device design theory, it can be understood that the power can be reduced from these values by cutting a 6 mil-diameter wafer out of the present 20 mil-diameter wafer. The power for such smaller unit would be 20 v × 1/10 ma = 2 mw. Hence a reasonable expectation is a consumption of 2 mw/bit in the store. Note that no quiescent power would be dissipated in the shorted-line clipper (Fig. 3) were it to be used as external load.

Read-out rate: It has been previously shown that the 50-nsec response of the 2N502 unit to the beam is to be interpreted as the charging and discharging of a capacitance in shunt with the diode. Since this is just the behavior assumed for the derivation of Eq. (3) the discussion in that section is pertinent. Thus, if a 2N502 unit were to be used as the read-out diode in a storage row, and if its associated storage diode were ON then the diode would see as load the capacitance NC_1 of the other cells in parallel with the resistance R of the delay line clipper (cf. Fig. 3). The duration of the pulse would be unchanged but the peak voltage would be reduced. A read-out rate of 20 megapulses/second is thus to be inferred. We note that if the beam sweeps with velocity v, and the pulse rises to peak in time Δt, then the read-out diodes should be separated in space by the distance $v \times \Delta t$ for maximum read-out rate.

Compatibility of storage and read-out diodes: The main reason for the incompatibility which prevented us from constructing the storage cell of Fig. 1b with the 4N20D diode and the 2N502 unit in series connection was the large value of the holding current of the "four-layer" diode relative to the collector-base saturation current of the transistor. Reference to the transistor characteristic curves shows that a permissible operating condition is a collector-to-emitter voltage of 25 v, a 1/2 ma collector current, and a base current of 10 μa. Since the holding current can be brought down below 1/2 ma, as indicated at the beginning of this section, compatibility is assured with the encapsulated transistor. However, since operation must be *in vacuo* and since the emitter dot and lead must be removed, compatibility becomes a moot question because these conditions greatly diminish the capacity of the unit to dissipate heat. Although the desired increase in diode saturation current can readily be achieved by shining light on the unit, or, less desirably, by raising the temperature of the unit, this should be achieved by special fabrication of the diode.

Read-in rate: When the "four-layer" diode was in the test circuit of Fig. 11, the load upon it consisted of the several-hundred-picofarad collector capacitance of the power transistor series with the 82-ohm load resistor. It was found that the diode would fire after a 1/5 microsecond bombardment. Were the diode in a 200-bit storage row, the load upon it would consist of the low-resistance portion of the read-out diode's characteristic curve, designated AC in Fig. 1a, and a capacitance of several hundred picofarads (designated previously as NC_1) in shunt with an external load resistor of several hundred ohms. Because the loads are much the same, it is plausible to state that a read-in rate of 5 megapulses/second could be attained. If the beam is not strong enough, there will be a firing delay which is observed to be as long as one microsecond when the beam is just strong enough to fire the diode. This effect would have some bearing on the reliability of read-in, because if, during serial read-in of a row, several diodes were to fire simultaneously, the signal developed across the load could substantially reduce the voltage across unfired diodes and thus prevent their being fired by the beam. This problem is of little importance when the beam produces a large shift in firing voltage, but further experimentation is desirable.

Read-out ratio of stored ONES to stored ZEROES

An important question in the design of a digital store is the ratio of read-out pulses observed when stored ONES and stored ZEROES are interrogated. When the storage diode is ON (a ONE in storage), it exhibits such a low impedance to a 50-nsec current pulse that its loading on the read-out diode may be neglected. The output voltage is thus calculated by Eq. (3). When the storage diode is OFF, however, it exhibits a small ($\sim$2 pf) capacitance, which has been previously designated as C_1. The electron-bombardment induced open-circuit voltage, V_{oc}, dividing capacitatively across C_1 and NC_1, is now responsible for the output signal observed in this case. Using Eq. (3) for the signal observed when a ONE is stored, and the voltage V_{oc}/N obtained when a ZERO is stored, we obtain the read-out ratio r for a stored ONE to a stored ZERO:

$$r = (\Delta I \cdot \Delta t)/(C_1 \cdot V_{oc}) \, . \tag{7}$$

This is a most interesting result because it is independent of N. The device parameters determining V_{oc} have been intensively studied with the intent of maximizing V_{oc} for solar battery use,[12] but the theory may equally well be applied to determining how V_{oc} may be reduced. Inspection of the formula given by Prince (*loc. cit.*) shows, fortunately enough, that the direction of change of all the parameters so as to reduce V_{oc} would be such as to render the diode more suited to use as a read-out diode because high speed, saturation current and avalanche voltage would all be increased. To calculate r from Eq. (7), values of $\Delta I = 3 \times 10^{-3}$ amp, $\Delta t = 2 \times 10^{-8}$ sec and $C_1 = 2$ pf may again be used as was done in the example following Eq. (3). For V_{oc}, we may certainly choose a value less than the band gap of the material of the read-out diode. For germanium, this would be 0.7 v. With parameters having values as stated, Eq. (7) gives $r = 44$. For the Philco 2N502 unit, a lower value for V_{oc} may be obtained by extrapolating the following data: for $\Delta I = 50 \times 10^{-6}$ amp, V_{oc} was 40 mv. According to Prince (*loc. cit.*), $V_{oc} = 0.0575 \log_{10} \Delta I +$ const. Consequently, at $\Delta I = 3 \times 10^{-3}$ amp, V_{oc} would be 0.24 v. The ratio of signals calculated from Eq. (7) with this value of V_{oc}, would be $r = 130$. Of course, no attempt had been made to select the Philco 2N502 unit for a low value of V_{oc}.

The number of necessary output leads is to a considerable extent dictated by the use of the memory in a data processing system. We shall, therefore, merely note in passing that one reasonable subdivision of a 3000-bit store would be into 10 storage rows of 300 cells each. If values in the example following Eq. (3) are again used, the read-out signal expected according to Eq. (3) would be 0.1 v. at a rate of 25 megapulses/second. If any one read-out diode were to be interrogated repeatedly at this rate, it would have to dissipate a total power of 40 mw, which is not excessive for silicon units but might prove excessive for the germanium 2N502 unit, which is being considered in this section. Immediate interrogation after storage would be hindered by the firing delay revealed by our work. This time can be considerably shortened if the beam current impinging upon the "four-layer" diodes were increased above the very weak current of 0.2 μa attained in the present work.

The practicality of fabricating several thousand junction semiconductor devices and their interconnections on a plate a decimeter square is a problem which is under intensive study in several laboratories. One solution might be found along the lines indicated by Griesmer, Miller and Roth,[13] who have shown theoretically that by building some redundancy into cryogenic computers, successful operability may be largely assured against serious flaws in fabrication. A final point worth noting is that the large, fast, bombardment-induced signals provided by a unit such as the 2N502, which rise to one volt in 25 nsec, could greatly reduce feedback time in beam-positioning circuits. This could have an important bearing on the random access capabilities of the store proposed in this paper which has here only been considered from the standpoint of the speed of serial read-in and read-out of entire storage rows.

Conclusions

The electron-bombardment-induced conductivity effect has made it practical for us to drive with a 1 μa, 10-kv electron beam several types of semiconductor devices which could function as components of a high-speed digital memory. It was found that Shockley Laboratories' 4N20D silicon "four-layer" diodes could be triggered from a nonconducting to a conducting state by a 1/5 microsecond bombardment with a beam of 10 kv electrons whose current impinging on the diode was only 0.2 μa. Triggering occurred by reason of a temporary reduction of the firing voltage. This reduction was approximately proportional to the impinging beam current and was a function of the duration of bombardment. The largest observed reduction, from 22 to 16 v, was limited by available beam intensity and required only 0.2 μa of impinging beam current. The bombardment of a Philco 2N502 germanium transistor, modified for beam access to the base region by removal of the emitter dot, could produce a pulse as short as 50 nsec with a peak height of 0.7 v across a 1000-ohm load resistor. At a somewhat lower signal voltage than this, the maximum expected value of charge multiplication, viz., 2700 at 10 kv, was found to obtain; hence the 2N502 unit was functioning as a beam-current amplifier with a current gain approaching 3000 and a rise time of 25 nsec.

From a consideration of how Shockley Laboratories' 4N20D diodes and modified Philco 2N502 transistors might be expected to function in certain storage and read-out circuits, respectively, it is estimated that a digital store made with these units might have a power consumption of 2 mw per bit, a serial read-in rate of 5 megapulses/sec, and a serial read-out rate of 15 megapulses/sec. The ratio of read-out signals for stored ONES to stored ZEROES is estimated to be 50:1 on the basis of theory.

Acknowledgments

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