

## I. PHYSICAL ELECTRONICS

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### A. PHYSICAL ELECTRONICS IN THE SOLID STATE

#### 1. SURFACE STATES ON SEMICONDUCTORS

A study is being made of the correlation between changes in the photoconductivity of germanium caused by surface treatments and the changes that occur in the contact potential of the germanium during these same treatments.

The tube designed for this experiment is equipped to hold a rectangular germanium sample in contact with kovar cups containing dry ice in acetone. The cups serve as lead-in wires, and two tantalum springs serve as voltage-drop probes. A hot tungsten ribbon, located inside a box, emits electrons that are accelerated toward the walls of the box. Some of them pass through two holes, located in the wall of this box and in a simple collimating baffle, are then deflected, and finally retarded by the germanium sample, which is connected to a variable voltage source through an electrometer. This electron-retardation scheme is used for measuring changes in the contact potential of the sample.

The ends of the sample were originally plated with gold, but this resulted in highly rectifying contacts. To remedy this, nickel tabs were soldered to the germanium with tin-lead solder containing a small amount of antimony. Similar tabs were provided for the probes. It was necessary to cover the probe tabs with wider nickel tabs because the bare solder has a lower work-function than the germanium and it collected the electrons that were repelled by the germanium, and thus flattened the retardation plot.

Another undesirable effect was the heating of the sample by radiation from the hot box containing the tungsten ribbon. The resistance of the sample, when the ribbon current and the accelerating voltage were turned on, increased slowly to 40 per cent of its value at dry-ice temperature. The temperature range was within the exhaustion range of the sample, and the number of free carriers was relatively constant. A nickel heat shield, with a hole through which light and electrons could pass, was placed near the sample. After some experimentation the baffle was connected to the +22.5-volt post of the 180-volt battery that was used to accelerate the electrons; the application of this voltage resulted in satisfactory focusing of the electrons. (It was close to a maximum of electron current versus baffle voltage.)

The most recent experiments show a less-than-linear response to light, both with and without a floodlight shining on the sample in addition to the chopped light used to measure the response. Without the floodlight there is also a little "roundness" in the oscilloscope trace of the response. This suggests that "slow states" and a decrease in lifetime with increasing light intensity make the response nonlinear. Bombarding the

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tube with a Tesla coil with vacuum in the tube usually increased the response, and bombarding it with oxygen in the tube usually decreased it. The bombarded oxygen, presumably containing ozone, increased the work-function of the germanium by approximately 0.2 volt. Flooding the sample with light decreased the work-function by approximately 0.03 volt, both before and after surface treatments. However, when the electron current is turned on, the work-function seems to rise slowly with time, and after a period of collecting higher electron currents on the sample, the work-function seems to increase, too. This suggests the existence of a high-resistance layer on the surface of the germanium, which can be charged with electrons arriving from outside.

Experiments are being performed to determine the time constants of the charging rate of this hypothetical layer. There seem to be two such constants – one of a fraction of a second, the other of a few seconds, at dry-ice temperature (at room temperature the constants are shorter). When an electron current was aimed at the sample during photoconductivity runs it decreased the photoresponse approximately one half, which indicates that an increase of the work-function decreases the lifetime by the same value.

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## 2. CHARACTERISTICS OF SEMICONDUCTOR JUNCTIONS

The reverse characteristics of silicon diodes are well explained by the Shockley-Read-Hall (1) carrier generation and recombination model. However, in attempts to extend this theory to the low-voltage and forward characteristics (2, 3) a number of approximations have been included that make the applicability of the results somewhat doubtful. Because the present work is an attempt to fit theory to experiment, the theory of carrier recombination and generation must be extended to include the low-voltage and forward characteristics.

If we make the reasonable assumptions that ionization of impurities is complete and that the quasi-Fermi levels are constant (though not equal) throughout the carrier region, Poisson's equation becomes

$$\frac{d^2\psi}{dx^2} = -\frac{q}{K\epsilon_0} [p - n + N_d - N_a]$$

where  $\psi$  is the potential. The carrier densities are determined by

$$p = n_i e^{\frac{q(\phi_p - \psi)}{kT}}$$

and

$$n = n_i e^{\frac{q(\psi - \phi_n)}{kT}}$$

where  $\phi_n$  and  $\phi_p$  are the quasi-Fermi levels for electrons and holes, respectively, and

we assume a linearly graded junction,

$$N_d - N_a = ax$$

where  $a$  is the impurity gradient. From the condition that  $p = n = n_i$  at  $x = 0$ , we must have  $\psi = 0$  at  $x = 0$  and  $\phi_p = -\phi_n$  everywhere. Letting  $P = q\psi/kT$ ,  $F = q\phi_p/kT$ , and

$$x = \left( \frac{kTK\epsilon_o}{q^2 a} \right)^{1/3} y$$

we can obtain Poisson's equation in the form

$$\frac{d^2 P}{dy^2} = M(e^P - e^{-P}) - y$$

where

$$M = \left( \frac{q^2}{kTK\epsilon_o a^2} \right)^{1/3} n_i e^F$$

This puts the equation for any junction at any temperature or applied voltage in terms of only one parameter.

Assuming that this equation has been solved and that we know  $P$  as a function of  $y$ , we find the recombination-generation current by integrating the recombination rate  $U$  across the transition region:

$$J_{rg} = q \int_{-y_o}^{y_o} U(P) dy$$

The recombination rate is given by

$$U = \frac{p_n - n_i^2}{(n + n_1) \tau_{po} + (p + p_1) \tau_{no}}$$

where  $p_1$  and  $n_1$  are the carrier densities corresponding to the energy  $\phi_t$  of the recombination centers, and  $\tau_{po}$  and  $\tau_{no}$  are the limiting lifetimes for p- and n-type material, respectively. If we make the substitutions

$$D = q(\psi - \phi_t)/kT$$

and

$$L = \ln(\tau_{po}/\tau_{no})^{1/2}$$

the current becomes

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$$J_{rg} = \frac{n_i}{(\tau_{no} \tau_{po})^{1/2}} \frac{e^{2F} - 1}{2 \cosh(D+L)} \left( \frac{kTK\epsilon_o}{q^2 a} \right)^{1/3} \cdot I(M, A, L)$$

where

$$I(M, A, L) = \int_0^{y_o} \left[ \frac{1}{e^A \cosh(P-L) + 1} + \frac{1}{e^A \cosh(P+L) + 1} \right]$$

and A is defined by

$$e^A = \frac{e^F}{\cosh(D+L)}$$

These two problems must be solved numerically, and they are being programmed for the IBM 704 computer by Miss Elizabeth J. Campbell, of the Joint Computing Group, M. I. T.

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References

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