XI. TRANSISTOR AND DIODE STUDIES*

Prof. H. J. Zimmermann
Prof. R. B. Adler
Prof. S. J. Mason
Dr. W. D. Jackson
C. R. Hurtig
A. Lipsky
R. B. Martindale
R. E. Nelson

A. TEMPERATURE COEFFICIENT OF SILICON JUNCTION TRANSITION CAPACITY

The transition capacity of a PN junction is a useful nonlinear capacitor because it is relatively insensitive to temperature changes.

In order to evaluate this capacity for purposes that require low-temperature sensitivities, the capacity-versus-temperature characteristics of 10 Texas Instruments Inc. (T. I.) 650C silicon junction diodes were measured. All measurements were made at zero bias. At this bias the mean capacity was 141 μμf, and the spread was from 56 to 256 μμf. Two samples were measured over a temperature range of 25-100°C. The others were measured over a range of 25-50°C. A typical curve is shown in Fig. XI-1. It was found that the capacity varied linearly with temperature up to 50°C, after which it increased at a slightly greater rate. The mean temperature coefficient of the 10 diodes was 642 ppm/°C and the spread was from 595 to 715 ppm/°C.

Measurements were made on a capacity bridge at an operating frequency of 1 mc. To hold nonlinear effects to a minimum, a signal level of 20 mv was used across the diode. The temperature was varied by an oven which was designed for use with these

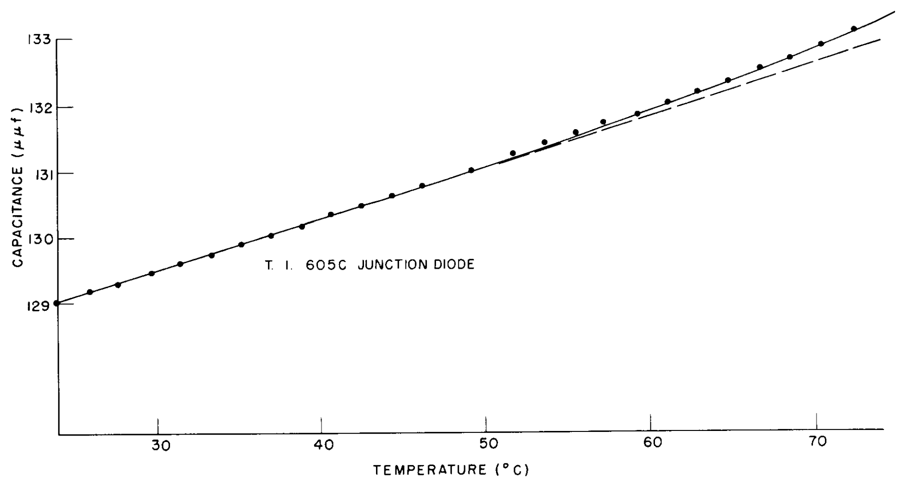

Fig. XI-1. Temperature dependence of the transition capacitance of a silicon junction diode.

---

*This research was supported in part by Purchase Order DDL-B187 with Lincoln Laboratory, which is supported by the Department of the Army, the Department of the Navy, and the Department of the Air Force under Contract AF19(122)-458 with M. I. T.

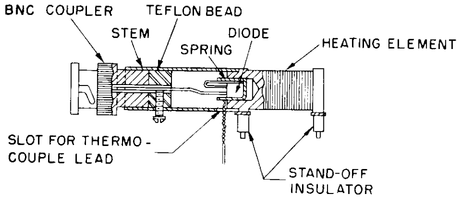

Fig. XI-2. Disassembled oven for temperature measurements of junction diodes.

diodes. The oven was also designed to shield the diode electrically, to minimize lead length, to allow reasonably rapid data taking, and to allow for convenient diode changing.

For ease in changing diodes, the oven was built in three sections: a stem, a heating element, and a spring. The disassembled oven is shown in Fig. XI-2.

The stem is a brass cylinder with a cable connector at one end. A small tube running along the axis of the cylinder connects the diode to the center conductor. The diode lead fits into the tube, and contact is ensured by a setscrew.

The heating element is a copper bar that is heated by resistance wire wound around it. The large mass of the bar serves to smooth out the effects of rapid variations in ambient temperature. One end of the bar is machined down to slip into the stem. The diode fits into a hole in this end.

The spring is used as a shim to give a tight fit between the diode and the walls of the heating element. One lead of the diode is grounded by placing it between the diode and the spring. In order to read the actual diode temperature as closely as possible, the thermocouple is soldered to the spring.

A. H. Lipsky

B. TEMPERATURE DEPENDENCE OF FORWARD-BIASED JUNCTION DIODES

The temperature dependence of the static characteristic of a junction diode in the forward-biased condition is important in many transistor and diode applications. Since the most readily available published work (1) deals with this problem in an approximate manner, a more complete analysis is given here.

The equation for the diode current of a plane-parallel junction diode (2) is

$$I = I_s \left[\exp\left(\frac{qV}{KT}\right) - 1 \right] \tag{1}$$

where I_s is the saturation current of the diode, q is the electronic charge, K is Boltzmann's constant, and T is the junction temperature in °K. It should be pointed out that many junction diodes, especially silicon diodes, do not follow this relation for small values of the current. Under reverse bias the diode current does not saturate. This fact is attributed to a surface leakage current which, for silicon, may be much larger than the current flowing through the junctions. In forward bias, most junction

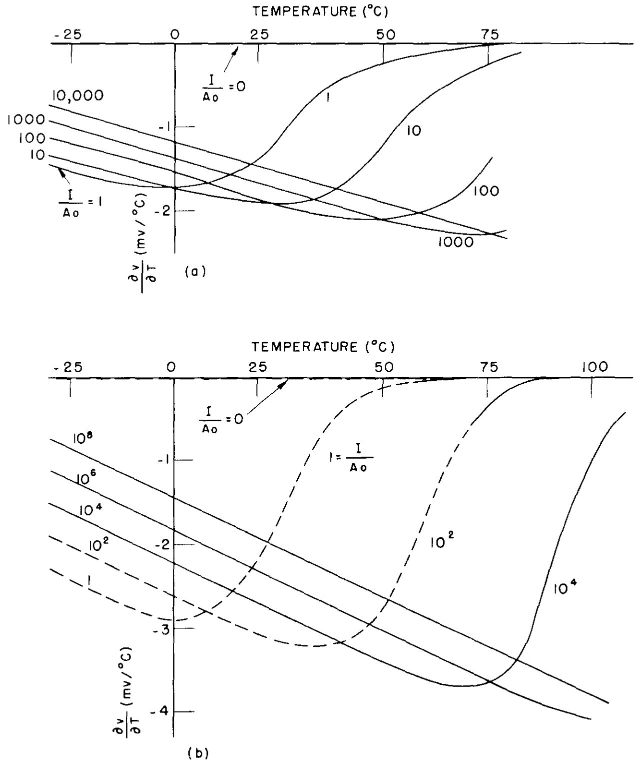

Fig. XI-3. Temperature coefficient of the forward-biased voltage of junction diodes: (a) germanium diodes; (b) silicon diodes.

diodes follow the relation given by Eq. 1 over a wide range of current. At high currents, the end resistance of the diode and enhanced injection cause departures from the characteristic given by Eq. 1, and at low forward currents leakage may again become important. We shall restrict our consideration of temperature dependence to the range in which Eq. 1 is valid.

The saturation current of a junction diode has a temperature dependence given by

$$I_s = A_o \exp\left[k(T_j - T_o)\right] \tag{2}$$

where A_o is the value of I_s at a reference temperature T_o (usually taken as 25°C), T_j is the temperature of the diode junction, and k is a constant determined in part by the energy gap of the diode material. Thus the diode current is

$$I = A_o \exp\left[k(T_j - T_o)\right] \left[\exp\left(\frac{qV}{KT}\right) - 1\right] \tag{3}$$

or

$$V = \frac{KT}{q} \ln \left[\frac{I}{A_o \exp\left[k(T_j - T_o)\right]} + 1 \right] \tag{4}$$

The temperature dependence of this voltage is

$$\frac{dV}{dT} = -\frac{kKT}{q} \left[\frac{\frac{I}{A_o} \exp(-k\Delta T)}{\frac{I}{A_o} \exp(-k\Delta T) + 1} \right] + \frac{K}{q} \ln \left[\frac{I}{A_o} \exp(-k\Delta T) + 1 \right] \tag{5}$$

where $\Delta T = T_j - T_o$. The temperature coefficient of the diode voltage is shown in Fig. XI-3 for both germanium and silicon diodes. The figure for each type consists of a family of curves plotted as a function of temperature, with the ratio of diode current (I) to saturation current (A_o) used as the parameter.

The values used for the constants k were 0.09 and 0.14 for germanium and silicon, respectively. These values are close to the theoretical values. The measured temperature coefficients of the actual reverse current (I_{co}) of silicon diodes may be as low as 0.04. It is possible that these low values are attributable to the presence of leakage currents. If these leakage currents are not sensitive to the polarity of the applied voltage, the curves of Fig. XI-3 should be valid for high ratios of I/A_o, but not for ratios so high that end resistance becomes important. The two curves of the family for silicon diodes for low ratios of I/A_o are shown dotted, since the effects of leakage current may not be negligible.

For large values of the factor $I/A_o [\exp(k\Delta T)]$, Eq. 5 reduces to the simpler form

$$\frac{dV}{dT} \approx -\frac{kKT}{q} \left[1 + \frac{\Delta T}{T}\right] + \frac{K}{q} \ln \frac{I}{A_o} \tag{6}$$

C. R. Hurtig

References

1. J. S. Schaffner and R. F. Shea, Variation of the forward characteristics of junction diodes with temperature, Proc. IRE 43, 101 (1955).
2. W. Shockley, Electrons and Holes in Semiconductors (D. Van Nostrand Company, Inc., New York, 1950), p. 90.

C. CRYSTAL ADMITTANCE MEASUREMENTS

Measurements of the small-signal impedance parameters of types IN25, IN21, IN23, and IN26 silicon crystal rectifiers have been completed. The measurements

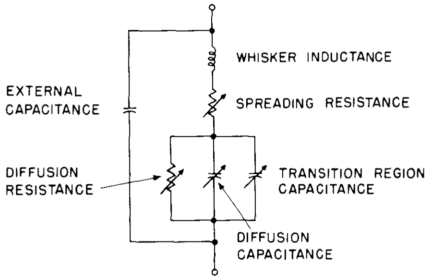

Fig. XI-4. A small-signal equivalent circuit for point-contact crystal rectifiers.

extended over the frequency range from direct current to 3000 mc at a bias voltage of -0.5 volt to +0.25 volt. These measurements were undertaken in an effort to determine the frequency at which the diffusion conductance and capacitance become seriously frequency-dependent and, in general, to examine the commonly accepted equivalent circuit of Fig. XI-4.

The computations needed for separating the barrier admittance from the complete equivalent circuit are in progress. The method that is presently being used to determine the spreading resistance as a function of bias is based on fitting a curve of the incremental resistance of the ideal barrier to a plot of the total measured dc incremental resistance. A previous attempt was made to obtain the dc incremental resistance from the static characteristics. Unfortunately, at high frequencies and small forward biases the equivalent series resistance of the combination of spreading resistance and barrier impedance is of the same order of magnitude as the spreading resistance alone. Therefore their difference is heavily dependent on the accuracy of the low-frequency spreading resistance determination; and it, in turn, hinges on the accuracy of the total incremental resistance at low frequencies. Direct low-frequency measurement of total incremental resistance versus bias will yield more accurate results than were achieved with the earlier graphical method.

R. B. Martindale, W. D. Jackson

D. POINT-CONTACT DIODE STATIC CHARACTERISTICS

The static characteristic of point-contact diodes is not fully understood. Recent analyses (1, 2) that take into account the voltage drop across the N-type base semiconductor, as well as the surface barrier under forward-bias conditions, fail to adequately describe diode behavior either in the low injection region, where the device should be ideal, or in the moderate injection region, where departure from ideal behavior begins. A hemispherical abrupt PN junction model is proposed which may yield a better fit to the experimental data. The resistivity of the P-region, however, is assumed to depend on the type of diode under discussion. Published discussions on bonded diodes with heavily doped P-regions are available (3). Conventional or formed diodes are considered to be PN junctions with a lightly doped P-region, in accordance with some microscopically probed evidence reported by Waltz (4). A derivation of the static properties of this type of diode structure was made, and numerical computations are being completed. A report including analyses of high injection in the forward direction, large reverse-voltage conditions, and the behavior of the incremental admittance versus frequency is being prepared.

R. E. Nelson

References

1. M. Cutler, Forward characteristics of germanium point contact rectifiers, J. Appl. Phys. 26, 949-954 (1955).
2. K. Lehovec, A. Marcus, and K. Schoeni, Current-voltage characteristics and hole injection factor of point contact rectifiers in the forward direction, Trans. IRE, vol. ED-3, no. 1, pp. 1-6 (1956).
3. H. L. Armstrong, E. D. Metz, and I. Weiman, Design theory and experiments for abrupt hemispherical P-N junction diodes, Trans. IRE, vol. ED-3, no. 2, pp. 86-96 (1956).
4. M. C. Waltz, On some transients in the pulse response of point-contact germanium diodes, Proc. IRE 40, 1483-1487 (1952).