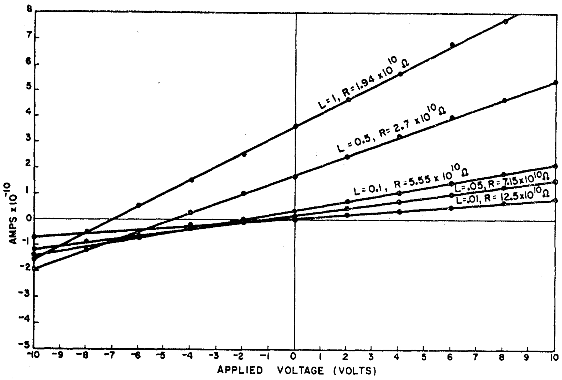

FIG. 3. Current through film *vs* applied voltage. Relative light intensities and corresponding film resistances are as shown. Intercepts on the ordinate and the abscissa are the short-circuit current and the open-circuit voltage, respectively.

with the space charge layers at grain boundaries. Whatever their location, however, the crystallographic ordering process which produces the additive arrangement of these elements is a major factor yet to be explained.

† This work was supported by the Evans Signal Corps Laboratories.

[1] L. Pensak, Phys. Rev. **109**, 601 (1958), preceding letter.
[2] M. B. Prince, J. Appl. Phys. **26**, 534 (1955).
[3] J. J. Loferski, J. Appl. Phys. **27**, 777 (1956).

New Phenomenon in Narrow Germanium *p-n* Junctions

LEO ESAKI
Tokyo Tsushin Kogyo, Limited, Shinagawa, Tokyo, Japan
(Received October 11, 1957)

IN the course of studying the internal field emission in very narrow germanium *p-n* junctions, we have found an anomalous current-voltage characteristic in the forward direction, as illustrated in Fig. 1. In this *p-n* junction, which was fabricated by alloying techniques, the acceptor concentration in the *p*-type side and the donor concentration in the *n*-type side are, respectively, 1.6×10^{19} cm^{-3} and approximately 10^{19} cm^{-3}. The maximum of the curve was observed at 0.035 ± 0.005 volt in every specimen. It was ascertained that the specimens were reproducibly produced and showed a general behavior relatively independent of temperature. In the range over 0.3 volt in the forward direction, the current-voltage curve could be fitted almost quantitatively by the well-known relation: $I=I_s[\exp(qV/kT)-1]$. This junction diode is more conductive in the reverse direction than in the forward direction. In this respect it agrees with the rectification direction predicted by Wilson, Frenkel, and Joffe, and Nordheim 25 years ago.[1]

The energy diagram of Fig. 2 is proposed for the case

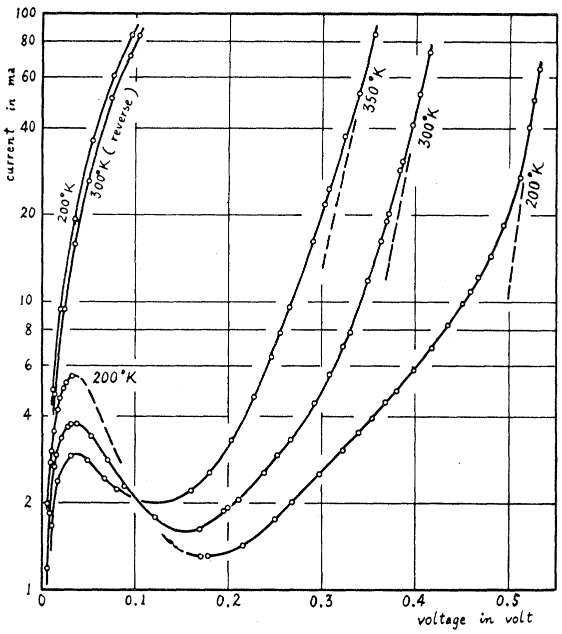

FIG. 1. Semilog plots of the measured current-voltage characteristic at 200°K, 300°K, and 350°K.

in which no voltage is applied to the junction, though the band scheme may be, at best, a poor approximation for such a narrow junction. (The remarkably large values observed in the capacity measurement indicated that the junction width is approximately 150 angstroms, which results in a built-in field as large as 5×10^5 volts/cm.)[2] In the reverse direction and even in the forward direction for low voltage, the current might be carried only by internal field emission and the possibility of an avalanche might be completely excluded because the breakdown occurs at much less than the threshold voltage for electron-hole pair production.[3] Owing to the large density of electrons and holes, their distribution should become degenerate; the Fermi level in the *p*-type side will be 0.06 ev below the top of the valence band, E_v, and that in the *n*-type side will lie above the bottom of the conduction band, E_c. At zero bias, the field emission current $I_{v\to c}$ from the valence band to the empty state of the conduction band and the current

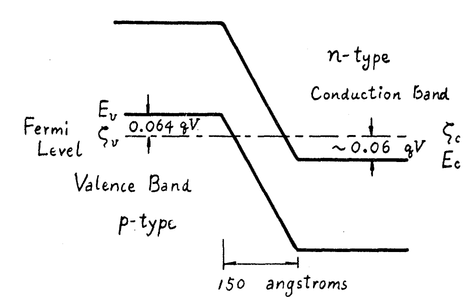

FIG. 2. Energy diagram of the *p-n* junction at 300°K and no bias voltage.

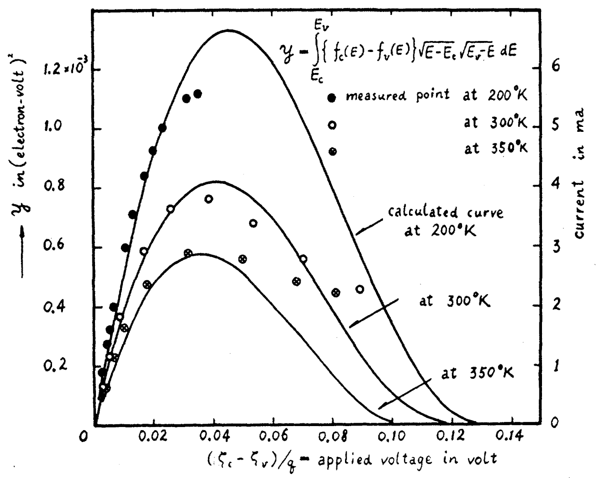

FIG. 3. Comparison of the current-voltage curves calculated with the measured points at 200°K, 300°K, and 350°K.

$I_{c\to v}$ from the conduction band to the empty state of the valence band should be detail-balanced. Expressions for $I_{c\to v}$ and $I_{v\to c}$ might be formulated as follows:

$$I_{c\to v} = A \int_{E_c}^{E_v} f_c(E)\rho_c(E)Z_{c\to v}\{1-f_v(E)\}\rho_v(E)dE,$$

$$I_{v\to c} = A \int_{E_c}^{E_v} f_v(E)\rho_v(E)Z_{v\to c}\{1-f_c(E)\}\rho_c(E)dE,$$

where $Z_{c\to v}$ and $Z_{v\to c}$ are the probabilities of penetrating the gap (these could be assumed to be approximately equal); $f_c(E)$ and $f_v(E)$ are the Fermi-Dirac distribution functions, namely, the probabilities that a quantum state is occupied in the conduction and valence bands, respectively; $\rho_c(E)$ and $\rho_v(E)$ are the energy level densities in the conduction and valence bands, respectively.

When the junction is slightly biased positively and negatively, the observed current I will be given by

$$I = I_{c\to v} - I_{v\to c} = A \int_{E_c}^{E_v} \{f_c(E) - f_v(E)\}Z\rho_c(E)\rho_v(E)dE.$$

From this equation, if Z may be considered to be almost constant in the small voltage range involved, we could calculate fairly well the current-voltage curve at a certain temperature, indicating the dynatron-type characteristic in the forward direction, as shown in Fig. 3.

Further experimental results and discussion will be published at a later time. The author wishes to thank Miss Y. Kurose for assistance in the experiment and the calculations.

[1] A. H. Wilson, Proc. Roy. Soc. (London) **A136**, 487 (1932); J. Frenkel and A. Joffe, Physik. Z. Sowjetunion **1**, 60 (1932); L. Nordheim, Z. Physik **75**, 434 (1932).
[2] McAfee, Ryder, Shockley, and Sparks, Phys. Rev. **83**, 650 (1951); C. Zener, Proc. Roy. Soc. (London) **145**, 523 (1934).
[3] S. L. Miller, Phys. Rev. **99**, 1234 (1955); A. G. Chynoweth and K. G. McKay, Phys. Rev. **106**, 418 (1957).

Ferromagnetism of a Zirconium-Zinc Compound

B. T. MATTHIAS AND R. M. BOZORTH
Bell Telephone Laboratories, Murray Hill, New Jersey
(Received December 2, 1957)

A COMPOUND of two superconducting elements, zirconium and zinc, with the approximate composition 1 Zr:2 Zn, has been found to become ferromagnetic below 35°K. The saturation moment is about 0.13 Bohr magneton per molecule (Fig. 1).

There are only a few ferromagnetic elements. They are Fe, Co, Ni, and some of the rare earth metals with partly empty 4f shells. No ferromagnetic intermetallic compounds are known that do not contain any of the afore-mentioned elements or Cr and Mn. The last two also occur in antiferromagnetic modifications. This has led to the tacit assumption that no ferromagnetism could occur in an intermetallic compound unless it contained at least one strongly paramagnetic element.

When one considers the fact that both zirconium and zinc are not magnetic (in addition to being superconductors), the ferromagnetism of this compound is therefore a rather remarkable phenomenon. It indicates that ferromagnetic and perhaps also antiferromagnetic compounds may be formed by the combination of many

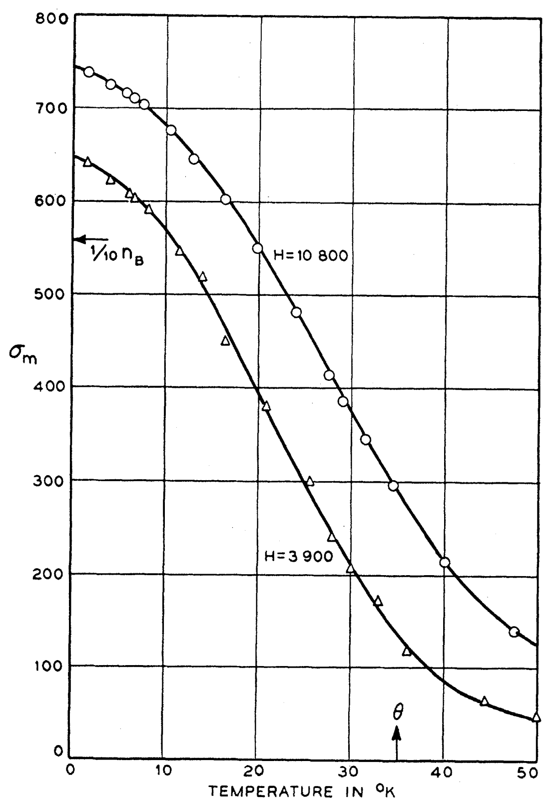

FIG. 1. Saturation moment *vs* temperature of a zirconium-zinc compound with the approximate composition of 1:2.