FIG. 3. Mobility of holes and electrons in indium antimonide as a function of temperature.

carrier is important, the carrier mobility is given by the expression

$$\mu = 0.85R\sigma. \tag{4}$$

Figure 3 is a plot of the carrier mobilities given by Eq. (4) as a function of temperature. The values for holes were taken from the extrinsic range of samples A and B. It is assumed that these follow a $T^{-\frac{3}{2}}$ law at high temperatures since it is not possible to determine the hole mobilities in the intrinsic range. Low temperature electron mobilities are obtained from sample C, and it is assumed that $R\sigma$ closely approximates the electron mobilities in all samples in the intrinsic range. This assumption is felt to be valid because the large value of b (approximately 85) in the in-

TABLE I. Carrier concentration and energy gap of InSb.

		ΔE (ev)	
$T°K$	$(np)^{\frac{1}{2}}$	$M^*=1$	$M^*=0.083$
150	2.3×10^{13}	0.33	0.24
200	6.8×10^{14}	0.34	0.21
300	2.1×10^{16}	0.37	0.18
400	1.1×10^{17}	0.41	0.15
500	3.0×10^{17}	0.45	0.12

trinsic range predicts a negligible contribution of holes to R and σ at temperatures somewhat above the temperature of Hall reversal. The electron mobility obtained in this manner seems to follow a $T^{-\frac{3}{2}}$ law at high temperatures.

From the carrier mobilities in Fig. 3, the conductivities in Fig. 2, and Eq. (2), it is possible to evaluate n and p as a function of temperature. The procedure is quite similar to that described by Pearson and Bardeen.[6] The solid line curves in Figs. 1 and 2 were obtained using these values of n and p, the mobilities of Fig. 3 and Eqs. (2) and (3). The close fit of the curves and the experimental points demonstrates the mutual consistency of Hall effect and conductivity data with the assumed mobilities. The large maximum in R just above the temperature of Hall reversal is a direct consequence of the large value of b.

From conductivity data, Welker has estimated an energy gap of 0.53 electron volts in InSb.[1] However, it is difficult to obtain a value for the forbidden energy gap ΔE from data of this kind since the effective masses of electrons M_n and holes M_p are

unknown. The simple theoretical expression for n and p as a function of T, the absolute temperature, is

$$(np)^{\frac{1}{2}}=4.9\times10^{15}(M^*)^{\frac{3}{2}}T^{\frac{3}{2}}\exp(-\Delta E/2kT), \tag{5}$$

where k is the Boltzmann constant and $M^*=(M_nM_p)^{\frac{1}{2}}/M$. M is the free electron mass. Table I gives values of $(np)^{\frac{1}{2}}$ as a function of the absolute temperature. These values are the same for all three samples as one would expect. The last two columns of the table give ΔE for two different values of M^*. For $M^*=0.083$, ΔE is 0.18 ev at room temperature, which is the value estimated from infrared absorption measurements performed by Briggs at this laboratory.[7] This effective mass leads to a temperature coefficient of the energy gap of approximately -4×10^{-4} ev per degree at room temperature. This agrees very well with the temperature coefficient of the infrared limit of absorption between room temperature and 77°K.

We wish to thank J. A. Burton and F. J. Morin for their helpful discussion of the results.

[1] H. Welker, Z. Naturforsch. 7a, 744 (1952); see also Z. Naturforsch. 8a, 248 (1953).
[2] Breckenridge, Hosler, and Oshinsky, Bull. Am. Phys. Soc. 28, No. 2, 45 (1953).
[3] G. L. Pearson and M. Tanenbaum, Phys. Rev. 90, 153 (1953).
[4] W. G. Pfann, Trans. Am. Inst. Mining Met. Engrs. 194, 747 (1952).
[5] G. K. Teal and J. B. Little, Phys. Rev. 78, 647 (1950).
[6] G. L. Pearson and J. Bardeen, Phys. Rev. 75, 865 (1949).
[7] H. B. Briggs (to be published).

Thermal and Electrical Properties and Crystal Structure of Tungsten Oxide at High Temperatures

SHOZO SAWADA
Institute of Science and Technology, University of Tokyo, Tokyo, Japan
(Received June 8, 1953)

RECENTLY Kehl et al.[1] found an anomalous behavior of tungsten oxide near 900°C by a differential thermal analysis. Although we had also independently observed an anomaly of thermal dilatation (an expansion in heating), we happened to know that Foëx[2] had already reported this anomaly. In view of the above situation, the results of our measurements of thermal dilatation of tungsten oxide will be omitted and those on specific heat and dc resistance between 600°C and 1050°C will be reported briefly here.

The specific heat was measured by a conduction calorimeter of the same type as the one used previously,[3] improved to enable us to make reliable measurements at higher temperatures. Figure 1
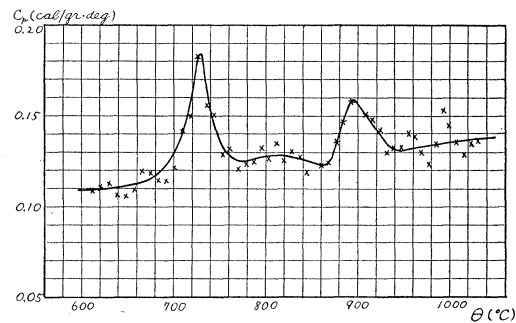

FIG. 1. Specific heat vs temperature.

shows the specific heat measured in heating, in which two anomalies of about 450 cal/M and 280 cal/M are seen near 730°C and 900°C, respectively, the entropy changes being 0.45 cal/M-deg and 0.23 cal/M-deg, respectively. The specific-heat value in our previous letter[3] should be considered as rather preliminary, although the size of the anomaly at 730°C reported there agrees well with the present one.
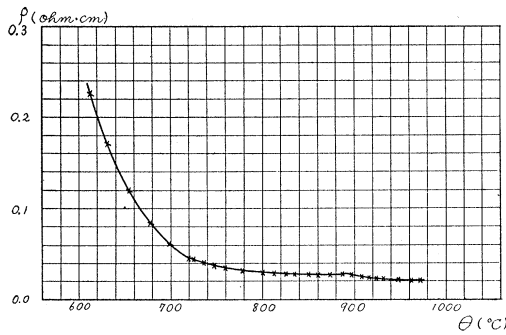
FIG. 2. Specific resistance *vs* temperature.

The dc resistance of ceramic samples was measured by the usual potentiometer method. Figure 2 shows the specific resistance measured in cooling as a function of temperature, in which a slight maximum and a break are seen near 890°C and 720°C, respectively. Further, it is notable that the specific resistance increases slowly with decreasing temperature above 720°C, although it increases exponentially below this temperature as in the usual semiconductors.

Kehl *et al.*[1] and Wyart and Foëx[4] did not observe any change of crystal structure near 910°C. Our measurement of lattice constants by the powder photograph method, however, revealed that, in heating, both the *a* and *c* axes, and therefore *v* (the lattice volume), increase slightly near this temperature, although the crystal system does not change.

The author wishes to thank Professor T. Muto for his kind criticism and advice.

[1] Kehl, Hay, and Wahl, J. Appl. Phys. **23**, 212 (1952).
[2] M. Foëx, Compt. rend. **220**, 917 (1945).
[3] Sawada, Ando, and Nomura, Phys. Rev. **84**, 1054 (1951).
[4] J. Wyart and M. Foëx, Compt. rend. **232**, 2459 (1951).

Effect of Transit Time on Ge Rectifier Behavior*

R. BRAY AND B. R. GOSSICK
Purdue University, Lafayette, Indiana
(Received June 8, 1953)

THE phenomenon of hole-injection and consequent conductivity-modulation[1] is the main factor responsible for the low spreading resistance in the forward direction of the high back voltage (hbv) Ge point contact rectifiers. Long lifetimes and transit times associated with this effect are responsible[2] for the well-known decrease in rectification efficiency of these rectifiers at high frequency. Their frequency dependence was first investigated in detail by Yearian,[3] who measured the rectified dc current output as a function of sinusoidal ac voltage for frequencies up to 60 Mc/sec. Deviations from low-frequency behavior became noticeable at 100 kc/sec, with the current output becoming steadily smaller with increasing frequency. Relatively, the deviations were greatest for voltages above 0.6-volt rms, suggesting that the frequency-dependent element was the spreading resistance.

There is less injection and consequently higher forward resistance at high frequency when the period of the forward swing is shorter than the transit time of the injected holes through the spreading resistance region, or shorter than the lifetime if that is the smaller quantity. To investigate the magnitude of the transit times involved in such effiects, forward *I−V* characteristics of hbv Ge rectifiers were measured under very fast pulse conditions. At the beginning of the pulse (rise time ∼0.007 μsec) the resistance was much higher than at the end of the pulse (0.4 μsec later), as illustrated in Fig. 1. The characteristic at the later time is inseparable from the dc characteristic, indicating that
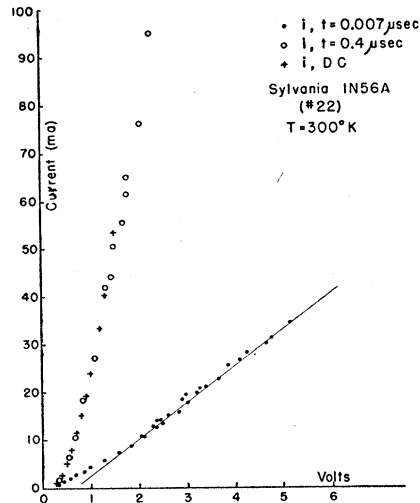

FIG. 1. Comparison of forward current-voltage characteristics of a high back voltage Ge point contact rectifier at beginning and at end of a pulse, and at dc.

transit times of less than 0.4 μsec are involved. Even at the beginning of the pulse, the resistance was already changing rapidly, so that the observed value need not represent the maximum attainable forward resistance. In *p−n* junction rectifiers, the bulk resistance contribution to the forward characteristic is not concentrated near the barrier, and resistance changes accordingly occur over longer time intervals. This is illustrated in Fig. 2 by forward *I−V* characteristics for a *p−n* junction. At the end of a 3.6μsec pulse the resistance is still much higher than at dc. In fact, little change occurs during the pulse interval. Figure 2 also shows the characteristic of the same junction at liquid nitrogen temperature. Pulse (0.2μsec) and dc measurements are indistinguishable. The implication drawn here is that the lifetime is very small at the low temperature, thereby severely limiting the depth of penetration of injected carriers and the conductivity modulation.

The reverse current of a hbv Ge rectifier would ordinarily have negligible influence on the dc rectified current produced by an ac signal. However, at high frequency, the holes injected during the forward swing, may be brought back and collected by the same contact during the reverse swing.[2] This may be called a "self-
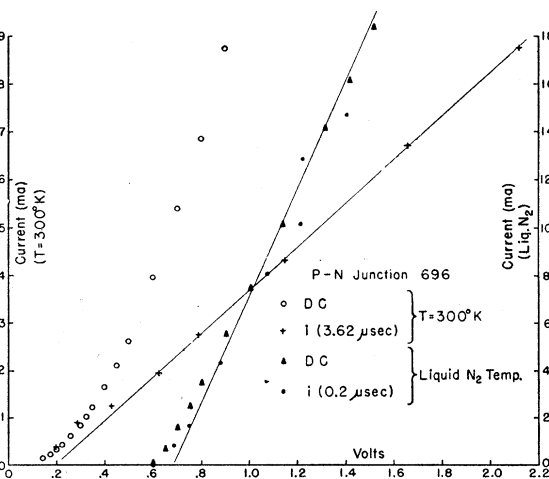

FIG. 2. Comparison of pulse and dc forward current-voltage characteristics for a *p−n* junction at *T* =300°C and at liquid N₂ temperature.