we have plotted the integrated intensity of the (111) reflection as a function of temperature for the natural crystal. It is to be noted that, to within the accuracy of our experiment, there is no noticeable effect of a magnetic field on the transition or on the line intensity above and below the transition. Figure 2, curve *a* shows the results of another experiment with the same crystal in which only the peak intensity was measured as the sample was allowed to warm up. The agreement between these two method of observing the transition is satisfactory, and it can be concluded that the type of anisotropy transition predicted to occur does in fact occur at this temperature, and that the transition is quite sharp, i.e., of the order of 4° wide for the natural crystal. Curve *b* in Fig. 2 represents the peak height as a function of temperature for the synthetic crystal provided by Anderson. It is seen that the transition occurs at a temperature approximately 10° higher than in the natural crystal and appears to be somewhat wider. The higher transition temperature confirms the results of Anderson from resonance measurements.

We are indebted to Helen M. A. Urquhart for helpful assistance in orienting the crystal and in making some of the preliminary measurements and to Dr. P. W. Anderson for making available to us his synthetic crystal and discussing the results of his work with us in advance of publication.

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[1] F. J. Morin, Phys. Rev. **78**, 819 (1950).
[2] L. Néel, Ann. phys. **3**, 137 (1948); **4**, 249 (1949).
[3] Shull, Strauser, and Wollan, Phys. Rev. **83**, 333 (1951).
[4] H. M. A. Urquhart and J. E. Goldman, Phys. Rev. **91**, 435 (1953).
[5] Anderson, Meritt, Remeika, and Yager, Phys. Rev. **93**, 717 (1954).
[6] J. M. Hastings and L. M. Corliss, Revs. Modern Phys. **25**, 114 (1953).

Radiation Effects in Indium Antimonide

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INVESTIGATIONS of the effect of reactor irradiation on semiconductors have been extended to InSb, an intermetallic compound which has been extensively studied recently.[1–3] Polycrystalline specimens,[4] both *n* and *p* type, have been irradiated in the Oak Ridge graphite reactor at ~30°C. In contrast to Ge which has a relatively small neutron capture cross section,[5] with the result that effects due to transmutations are relatively minor compared to fast neutron lattice damage effects, the capture cross section for In is extremely large with the decay-product Sn, a donor impurity when substituted for an In atom. Thus, for the neutron energy spectrum encountered in the reactor, effects caused by transmutations are expected to be comparable to, if not greater than, those associated with lattice disordering.

The conductivity of a low-resistivity *n*-type InSb sample (initial electron concentration $n_0=4.8\times10^{18}$ cm^{-3}) decreases monotonically during irradiation, the decrease approaching saturation long before conversion to *p* type can occur. Analysis of the early part of the conductivity *vs* exposure curve indicates that the initial rate of electron removal is about four times that previously reported for *n*-type Ge.[6] Subsequent Hall coefficient and resistivity measurements indicate that an exposure of $\sim2\times10^{17}$ integrated fast-neutron flux $(nvt)_f$ decreases the electron concentration n and the electron mobility μ_n of this sample by 1.6×10^{18} cm^{-3} and by about a factor of 2, respectively. Since transmutations would tend to increase n, it is concluded that bombardment-produced lattice defects act as electron traps and predominate in this range of carrier concentration.

Because of its unusually large mobility ratio[3] $(\mu_n/\mu_p\cong85)$, *p*-type InSb is in the intrinsic range at 30°C for acceptor concentrations $<2\times10^{17}$ cm^{-3}. Consequently, for *p*-type specimens with moderate acceptor concentrations, conductivity *vs* exposure curves are not a sensitive index of the carrier concentration during irradiation. Instead it is necessary to use Hall coefficient and resistivity data as a function of temperature. Such data for an originally *p*-type sample after successive exposures are shown in Figs. 1 and 2. Except for a certain anomalous behavior in the low-temperature portion in the Hall coefficient curves during the early part of bombardment (Curves II, III, and IV, Fig. 1),[7]

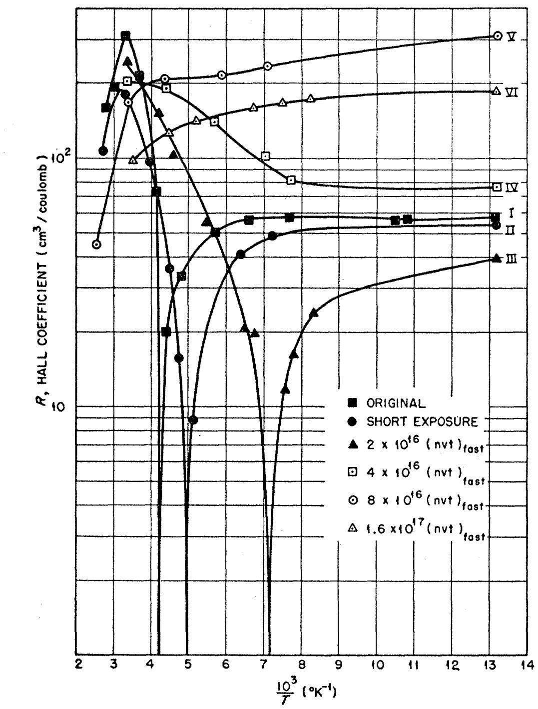

FIG. 1. Hall coefficient of InSb as a function of temperature after various exposures in the reactor.

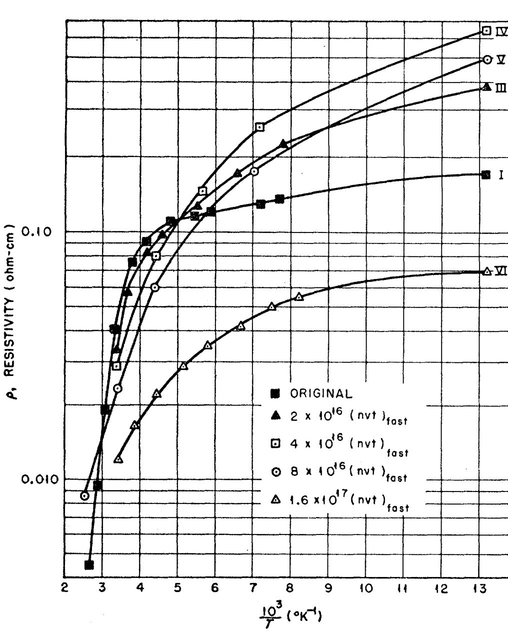

FIG. 2. Resistivity of InSb as a function of temperature after various exposures.

these data show a progressive decrease in hole concentration and conversion to n type. Such behavior is expected because of transmutations.

In order to separate the effects due to transmutations from those due to lattice defects, a second p-type sample was (1) exposed to $\sim 2.5\times 10^{17}(nvt)_f$, (2) subsequently annealed at 350°C for 16 hours, and (3) then, while shielded from thermal and resonance neutrons with Cd and In foil, exposed to an additional $2.5\times 10^{17}(nvt)_f$. Hall coefficient and resistivity curves taken after each of these operations are shown in Fig. 3. The first exposure

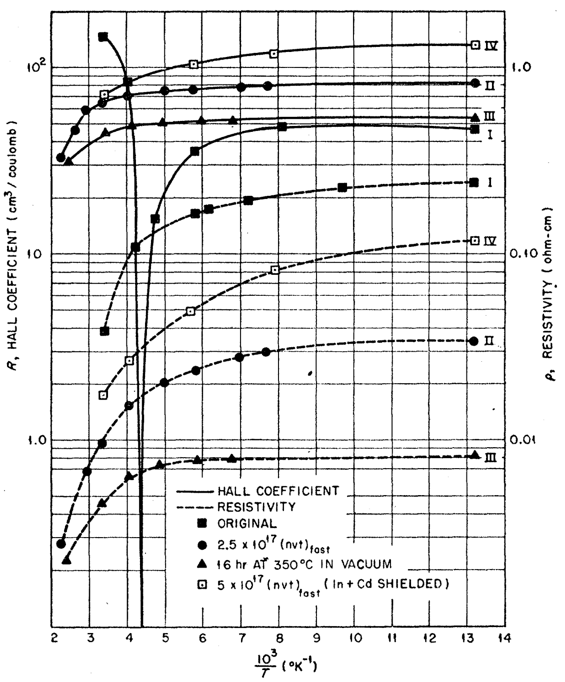

FIG. 3. Hall coefficient and resistivity of irradiated InSb. The Hall coefficient curves are denoted by R and the resistivity curves by ρ.

converts the sample to n type (Curves II) in the expected manner. The heat treatment presumably anneals the lattice defects, thereby causing an increase in both n and μ_n (Curves III). On further irradiation, the specimen being shielded from thermal neutrons, both the Hall coefficient and resistivity are increased (Curves IV). The results of the last two operations, in agreement with the findings for n-type material, indicate strongly that fast neutron induced lattice defects act as electron traps in InSb.

These preliminary studies indicate that (1) donor impurities are introduced into InSb by transmutations in the expected manner, and (2) lattice defects introduced by fast neutron bombardment act as electron traps in n-type material. Data are insufficient at the present time to show whether these defects behave predominantly as acceptors or hole traps in p-type material.

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[1] H. Welker, Z. Naturforsch. **7a**, 744 (1952).
[2] Breckenridge, Holzer, and Oshinsky, Phys. Rev. **91**, 243 (1953).
[3] M. Tanenbaum and J. P. Maita, Phys. Rev. **91**, 1009 (1953).
[4] We are indebted to Miss Louise Roth of Purdue University for the samples used in these experiments.
[5] Cleland, Lark-Horovitz, and Pigg, Phys. Rev. **78**, 814 (1950).
[6] J. H. Crawford, Jr., and K. Lark-Horovitz, Phys. Rev. **78**, 815 (1950).
[7] Because of the large capture cross section of In, there is an appreciable attenuation of the thermal neutron flux toward the center of the specimen. Hence the concentration of Sn impurity is expected to be significantly higher at the surface than at the interior of the specimen. Such an effect may possibly explain these anomalies, since one might expect the Hall voltage of a p-type interior and that of an n-type exterior to neutralize each other to some extent.

Incoherent Neutron Scattering by Polycrystals

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IN evaluating the total incoherent cross section σ of a polycrystal, it is customary to decompose σ into partial cross sections σ_l for the production or destruction of l phonons:

$$\sigma=\sum_{l=0}^{\infty}\sigma_l. \tag{1}$$

The convergence of (1) becomes progressively poorer with increasing neutron energy and the structure of the higher terms is exceedingly complicated.[1] Furthermore, it results from the extensive numerical calculations of Squires[2] for magnesium that in this case, at a temperature about twice the Debye temperature θ, the terms with $l>1$ give a sizable contribution to the cross section even at zero-incident neutron energy.

The separate consideration of one-phonon processes has some merit in the study of the energy distribution of the scattered neutrons and of coherent effects.[3] Because of the existence of strong compensation effects, however, (1) is not a reasonable expansion for the total incoherent cross section. This may be illustrated by the example of the static approximation, which neglects the energy changes in the scattering process. Here σ is independent of neutron energy and temperature, while the partial cross sections σ_l depend on these quantities by

$$\sigma_l/\sigma=\frac{1}{l!}\frac{1}{x}\int_0^x t^l e^{-t}dt=x^{-1}-e^{-x}\sum_{m=0}\frac{x^{m-1}}{m!}, \tag{2}$$

with $x=4k^2\alpha(T)$. (k is the wave number of the incident neutron, $\alpha(T)$ the mean-square nuclear displacement, and T the temperature.)

In a previous paper[4] a simple asymptotic expression for the cross section has been derived without recourse to (1) and has been explicitly evaluated in the Debye approximation. For heavy nuclei this expression holds as soon as the neutron energy is slightly larger than the Debye temperature, and for lighter nuclei at somewhat higher energies. There remains, however, the problem of finding a simple and accurate representation of the cross section valid for all energies. This may be achieved by using a procedure, which has previously been discussed for the particular case of an oscillator at zero temperature.[4] It consists in expressing the neutron variables (wavelength, velocity) in terms of the neutron energy E and thereupon expanding the cross section in powers of the ratio M^{-1} of neutron to nuclear mass:

$$\sigma=s+\sum_{n=1}\sigma^{(n)}M^{-n}, \tag{3}$$

where s is the bound incoherent nuclear cross section. In contrast to (1), the expansion (3) converges rapidly for all energies provided that M is moderately large compared to both one and T/θ. Under these conditions, which are well satisfied in most practical cases for temperatures right up to the melting point, σ is well represented at all energies by

$$\sigma=s+\sigma^{(1)}/M+\sigma^{(2)}/M^2, \tag{4}$$

and often the contribution of $\sigma^{(2)}$ amounts to a small correction only. Furthermore, the structure of $\sigma^{(1)}$ and $\sigma^{(2)}$ is considerably simpler than even that of σ_1 and σ_2, and thus the evaluation of the cross section in the Debye approximation becomes a relatively easy matter.

TABLE I. The coefficients in the expression (5) for the cross section.

n	a_n	b_n	c_n	d_n	e_n	f_n	g_n
0	1.2	0.4286	0.0556	1.3221	2.1141	0.7410	−0.1044
2	5	1.5	0.1786	−8.0590	3.8562	1.6600	0.1877
3	−12	0	−0.3333	0	0	0	0
4	5.25	0.825	0.0825	−41.042	−5.439	−1.262	0.2666
5	0	0	0	96	0	5.333	0