Carrier Lifetime in Indium Antimonide

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The lifetime in well-compensated, single-crystal indium antimonide samples has been obtained as a function of temperature between 130° and 250°K. The results suggest that the lifetime is limited by radiative recombination at high temperatures and by a recombination center mechanism at low temperatures.

INTRODUCTION

ESTIMATES of lifetime in single crystals of indium antimonide have previously been obtained by photoelectromagnetic effect and photoconductivity[1] and from measurements of diffusion length.[2] It has been suggested that the lifetime in this material may be limited by radiative recombination.[3,4] Observation of recombination radiation[3] and an estimate of the room-temperature radiative recombination lifetime in specimens of various purity[4] has lent support to this idea. Calculation of the theoretical lifetime requires knowledge of the spectral absorption coefficient and index of refraction in the region of high absorption where adequate data have only recently become available.[5]

THEORY

The temperature dependence of the theoretical lifetime for radiative recombination has been obtained according to the theory of Van Roosbroeck and Shockley.[6] Spectral absorption data were taken from Oswald and Schade,[7] Avery,[8] and Gobeli and Fan.[5] The data of Gobeli and Fan cover the complete range from 2 to 7 μ, including the region of high absorption where the absorption coefficient levels off. The data of Oswald and Avery for pure material are in good agreement with the latter but extend only up to $\alpha=800$ cm^{-1}. The data of Avery for impure material are in agreement with those of Gobeli and Fan in the vicinity of 2 μ where the effect of the filling of the bottom of the conduction band is no longer significant, since the electron is excited to higher states when $h\nu \gg E_g$.[9]

The data of Gobeli and Fan and others give the spectral absorption at liquid nitrogen and room temperatures. To obtain the temperature dependence of the radiative recombination lifetime, absorption curves at other temperatures were obtained from the temperature dependence of the energy gap.[6] Equation (21) of reference 6 here takes the form

$$\frac{u}{u_0}=\frac{300}{T}+0.50\left(\frac{300}{T}-1\right), \tag{1}$$

where $u=h\nu/kT$, signifying that $f(u,T)=\alpha\lambda n^2/4\pi$ may be obtained by calculating $f(u_0,300)$ provided the absorption curve may be obtained by shifting the absorption edge according to the temperature dependence of the energy gap given by Oswald[10]:

$$E_g(T)=0.24-0.26\times10^{-3}T. \tag{2}$$

The index of refraction is 4.0 in the region $7<\lambda<16\,\mu$, according to Oswald and Schade,[6] and 3.75 for $1<\lambda<3\,\mu$ in impure material, according to Avery *et al.*[8] In the intermediate region, $3<\lambda<7\,\mu$, the index of refraction was obtained from the absorption coefficient through the Kramers-Kronig relations. The results are consistent with the experimental data and indicate a maximum at $\lambda=6.7\,\mu$ where the index of refraction $n=4.1$.

With these data, the lifetime for radiative recombination in intrinsic material is obtained from the following equations[6]:

$$\tau_i=n_i/2R, \tag{3}$$

where

$$R=1.785\times10^{22}\left(\frac{T}{300}\right)^4\int_{\mu 0}^{\infty}\frac{n^3k(u,T)u^3du}{e^u-1}, \tag{4}$$

n_i = intrinsic carrier density, and

$$k=\alpha\lambda/4\pi n. \tag{5}$$

Method of Measurement

Lifetimes for the decay of nonequilibrium hole-electron concentrations were obtained directly by oscilloscope observation of the conductivity of a thin rod following excitation by a pulsed high-energy electron beam. In these experiments, 2×10^{-8}-sec pulses of 700-kev electron from a Van de Graaff accelerator with a maximum beam intensity of 5×10^{14} electrons/cm^2 sec and a low repetition rate to minimize bombardment damage were utilized.[11] No changes in lifetime attributable to bombardment damage were observed.

[1] S. W. Kurnick *et al.*, Phys. Rev. **94**, 1791 (1954); S. W. Kurnick and R. N. Zitter, J. Appl. Phys. **27**, 278 (1956).
[2] D. G. Avery and D. P. Jenkins, J. Electronics **1**, 145 (1955).
[3] T. S. Moss and T. H. Hawkins, Phys. Rev. **101**, 1609 (1956).
[4] I. M. Mackintosh and J. W. Allen, Proc. Phys. Soc. (London) **B68**, 985 (1955).
[5] G. Gobeli and H. Y. Fan, Purdue University Semiconductor Quarterly Research Report, December, 1955 (unpublished).
[6] W. van Roosbroeck and W. Shockley, Phys. Rev. **94**, 1558 (1954).
[7] F. Oswald and R. Schade, Z. Naturforsch. **9A**, 611 (1954).
[8] D. G. Avery *et al.*, Proc. Phys. Soc. (London) **B67**, 761 (1954).
[9] E. Burstein, Phys. Rev. **93**, 632 (1954).
[10] F. Oswald, Z. Naturforsch. **10A**, 927 (1955).
[11] G. K. Wertheim, Bull. Am. Phys. Soc. Ser. II, **1**, 128 (1956).

Samples were cut from single crystals of indium antimonide, and after etching in CP4 (without bromine) had dimensions approximating 0.010×0.035×0.625 in. End contacts were made by indium alloying in an inert atmosphere. The samples were then soldered to a copper frame and enclosed in a 0.5-in. i.d. copper thermal radiation shield having a port to admit the electron beam and to define the bombarded area while also protecting the end contacts from direct bombardment. The target chamber was at a pressure of approximately 1 μ so that the sample temperature could be adequately controlled via the copper frame which was attached to an all-metal Dewar having provisions for heating as well as cooling. The sample temperature was measured by a thermocouple at the point of attachment to the frame.

Three samples, having the following characteristics, were measured.

Sample No.	N_d-N_a	Dimension (in.)	Crystal
$1-n$	2.3×10^{14}	0.008×0.038	InSb 28*K*3
$2-p$	-1.7×10^{15}	0.010×0.034	InSb 28*K*4
$3-p$	-3.0×10^{14}	0.012×0.034	InSb 28*K*3

The net donor or acceptor concentrations were determined from conductivity measurements which gave results similar to those of Hrostowski *et al.*[12]

The low-temperature limit of the region in which data can be obtained in p-type material is reached when the decay becomes shorter than 10^{-8} sec. In n-type material, data could be obtained to liquid nitrogen temperature. At high temperature there is little difference between n- and p-type material, both being intrinsic. The upper temperature limit here is set by signal amplitude, which becomes small as the thermal equilibrium electron concentration becomes much larger than the bombardment injection level. In addition the decreasing sample resistance, in conjunction with the maximum allowable power dissipation in the sample, limits the voltage that may be applied across it.

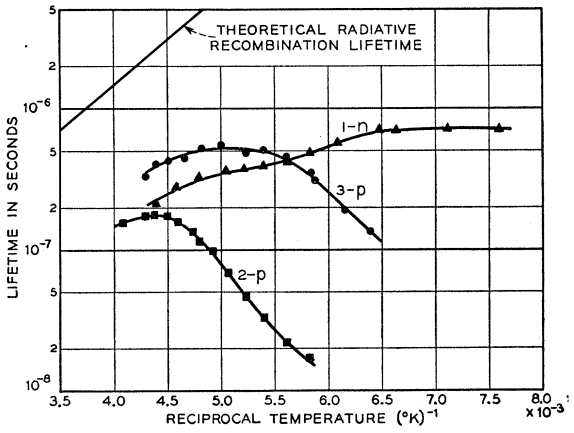
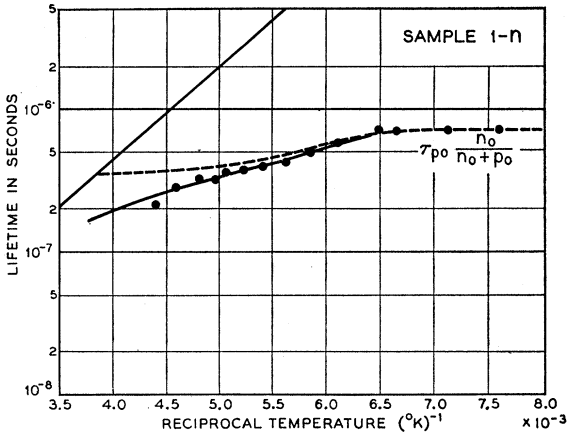
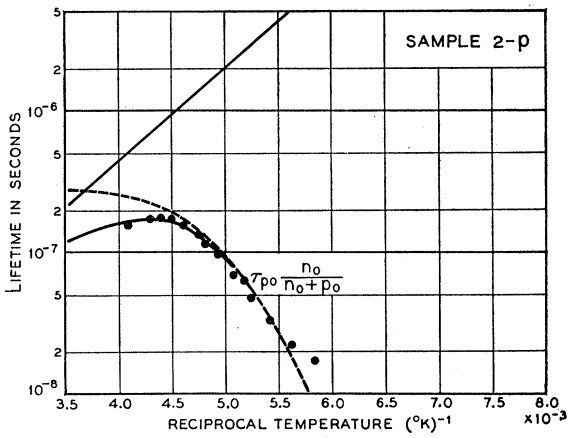


FIG. 1. Observed carrier lifetime in InSb as a function of reciprocal temperature.

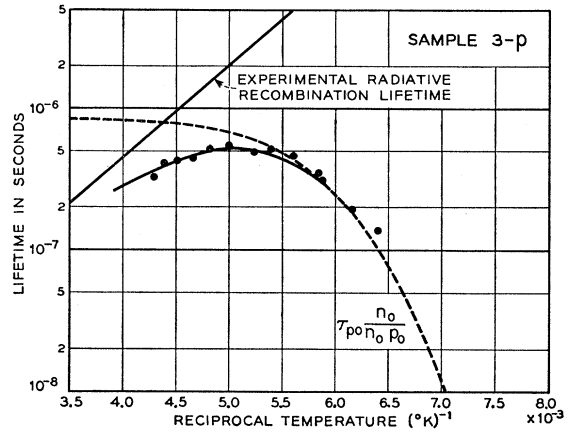
[12] R. J. Hrostowski *et al.*, Phys. Rev. **100**, 1672 (1955).



(a)



(b)



(c)

FIG. 2. Comparison of calculated and observed carrier lifetimes in InSb.

RESULTS

The decay of the bombardment conductivity in these samples, obtained from photographs of oscilloscope displays, can be represented by a single exponential function, whose time constant is here called the life-

time. No deviation from this simple mode of decay was observed in the region where lifetimes could be measured. In p-type material, a second longer decay appeared near liquid nitrogen temperature, suggestive of a trapping process. This effect was absent in n-type material.

The measured lifetimes all fall well below the theoretical lifetime for radiative recombination, Fig. 1. The behavior of the lifetime in the low-temperature region suggests that a recombination center mechanism may be dominant. In particular the difference between n- and p-type material is consistently accounted for on the assumptions of a single species of recombination centers, lying well below the middle of the forbidden gap and having $\tau_{p0} \gg \tau_{n0}$. Under these conditions the lifetime, τ, given by Hall and Shockley and Read,[13]

$$\tau = \tau_{p0}\left(\frac{n_0+n_1}{n_0+p_0}\right)+\tau_{n0}\left(\frac{p_0+p_1}{n_0+p_0}\right), \tag{6}$$

reduces to

$$\tau = \tau_{p0}\left(\frac{n_0}{n_0+p_0}\right) \tag{7}$$

in n-type material, and to

$$\tau = \tau_{p0}\left(\frac{n_0}{n_0+p_0}\right)+\tau_{p0}\left(\frac{n_1}{n_0+p_0}\right) \tag{8}$$

in p-type material where the magnitude of the $n_1/(n_0+p_0)$ contribution will be small if the level lies sufficiently below the Fermi level. These functions have been computed, using the intrinsic carrier concentration given by Hrostowski,[12] and fit the data adequately at low temperatures if one assumes that τ_{p0} is independent of temperature (Fig. 2, dotted lines). The value of τ_{p0} determined by this fit varies by a factor of three in these samples, indicative of varying trap concentrations. The deviation noted in the p-type sample with higher net acceptor concentration is consistent with the appearance of the second term of Eq. (8). The systematic deviation of the data from these curves at higher temperatures appears to be a property of the material itself rather than a property of an impurity. This is suggested by the fact that an *identical curve* representing another recombination mechanism reduces all three computed lifetimes functions to agreement with the data. We identify this curve with radiative recombination since it has the same temperature dependence as the theoretical radiative recombination lifetime. However, it lies a factor of three below the theoretical value.

[13] R. N. Hall, Phys. Rev. **87**, 387 (1952); W. Shockley and W. T. Read, Phys. Rev. **87**, 835 (1952).

DISCUSSION

The results suggest that radiative recombination is the dominant process which limits lifetime in these specimens near room temperature. The difference between the theoretical radiative recombination lifetime and that obtained experimentally may in part be due to the high absorption coefficient at the maximum of the integrand of Eq. (4). There the absorption length is only two wavelengths in InSb so that the broadening of the photon levels may be significant.[6]

Other processes that cannot be entirely ruled out are surface recombination and temperature-dependent trap cross sections. The importance of surface recombination was investigated by measuring the decay time of bombardment conductivity in a second p-type sample cut from crystal 28K3. The lifetime was obtained between 160°K and 230°K with the crystal 0.028×0.102 in. in cross section. The crystal was then etched to 0.010 ×0.079 in. and the lifetime remeasured. The data obtained under these two conditions agree within 5%, indicating that the surface recombination velocity is no greater than 2000 cm/sec and the surface lifetime greater than 6 μsec.

The picture could be seriously distorted if the recombination cross section were to exhibit a pronounced temperature dependence. The only case treated theoretically, the "giant traps" discussed by Lax,[14] decrease in cross section with increasing temperature and, if applicable, would require an even shorter radiative recombination lifetime. However, such an interpretation is not alone able to account for the deviations from the recombination center lifetime since the deviation is not by the same factor in the three samples at a given temperature.

With these reservations, the lifetime in indium antimonide may be interpreted in terms of radiative recombination and a recombination-center mechanism.

ACKNOWLEDGMENTS

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[14] M. Lax, Bull. Am. Phys. Soc. Ser. II, **1**, 128 (1956).