We wish to thank Frank Wagner, Jr. for assistance in operating the spectrometer and Jack May for his aid in the computations. A more detailed report of this work will be submitted to this Journal.

[1] L. R. Shepherd, Research 1, 671 (1948).
[2] Ter-Pogossian, Cook, Goddard, and Robinson, Phys. Rev. **76**, 909 (1949). See in particular note added in proof.
[3] Hirzel, Stolland- and Waffler, Helv. Phys. Acta **20**, 241 (1947).
[4] Cork, Shreffler, and Fowler, Phys. Rev. **73**, 1220 (1948).
[5] D. Walker, Proc. Phys. Soc. London **62A**, 799 (1949) reports 33.11 ±0.23 days for the half-life of Ce^{141}.
[6] Edith Haggstrom, Phys. Rev. **62**, 144 (1942). The line at 221 kev was not reported, but can be seen in her Fig. 5; we estimated it to be 220 kev. Also, P. W. Levy, Phys. Rev. **72**, 352 (1947).
[7] A. H. Wapstra, Physica **16**, 33 (1950).
[8] C. E. Mandeville and E. Shapiro, Phys. Rev. **75**, 1834 (1949) report β-γ-coincidences to 90 mg/cm² of Al, about 0.33 Mev β-range.
[9] Bunyan, Lundby, and Walker, Proc. Phys. Soc. London **62A**, 253 (1949).
[10] Maria G. Mayer, Phys. Rev. **78**, 16 (1950) and private communication.
[11] J. E. Mack, Rev. Mod. Phys. **22**, 64 (1950).
[12] S. M. Dancoff and P. Morrison, Phys. Rev. **55**, 122 (1939).
[13] E. J. Konopinski, Rev. Mod. Phys. **15**, 209 (1943).

Temperature Dependence of the Energy Gap in Germanium from Conductivity and Hall Data*

V. A. JOHNSON AND H. Y. FAN
Purdue University, Lafayette, Indiana

July 5, 1950

OPTICAL absorption experiments, measurements of the threshold of internal photoelectric effects, and consideration of crystal volume change with temperature all show that the energy gaps in silicon and germanium decrease with rising temperature.[1] The same result has been obtained by analysis of the high temperature resistivity and Hall data for silicon.[2] We describe here the calculation of the temperature dependence of the energy gap in germanium from high temperature (500°K to 850°K) conductivity and Hall data.

The free electron concentration, n_e, and hole concentration, n_h, in a semiconductor in thermal equilibrium[3] are related by

$$n_e n_h = A^2 T^3 \exp(-E_G/kT), \tag{1}$$

where E_G is the energy gap between the full and conduction bands, and

$$A^2 = 32h^{-6}(m_e m_h)^{\frac{3}{2}}(\pi k)^3, \tag{2}$$

where k is the Boltzmann constant, h the Planck constant, and m_e and m_h the effective electron and hole masses. If $m_e \approx m_h \approx m_0$, the free electron mass, then $A = 4.84 \times 10^{15}$ cm^{-3} deg.$^{-\frac{3}{2}}$. If one writes

$$E_G = E_G{}^0 + (\partial E_G/\partial T)T, \tag{3}$$

then

$$(n_e n_h/T^3)^{\frac{1}{2}} = A' \exp\{-E_G{}^0/(2kT)\}, \tag{4}$$

where

$$A' = A \exp\{-(\partial E_G/\partial T)/(2k)\}. \tag{5}$$

The n_e and n_h values at various temperatures, high enough for impurity scattering to be negligible, were calculated from the measured conductivity (σ) and Hall coefficient (R) curves for several N-type germanium samples.[4] First, c, the ratio of electron to hole mobility, is calculated from

$$1 - \frac{1}{c} = \frac{-3\pi eR(\sigma/eb_e)^2/8 - N}{(\sigma/eb_e) - N}, \tag{6}$$

where b_e is the electron mobility and N the electron density at exhaustion. In view of recent measurements[5] and calculations[6] pertaining to electron mobility in germanium, we used $b_e = 17 \times 10^6 T^{-\frac{3}{2}}$ cm²/volt-sec. Thus c is found to be approximately 1.5 for all samples. Then n_h is calculated from

$$n_h = \{(\sigma/eb_e) - N\}(1 + 1/c)^{-1}, \tag{7}$$

and n_e from $n_h + N$. When $\ln\{(n_e n_h)^{\frac{1}{2}}/T^{\frac{3}{2}}\}$ is plotted *vs.* $1/T$, a straight line is obtained for each sample (Fig. 1). The slope is essentially the same for each sample and its value determines $E_G{}^0$ as about 0.73 ev. The average of the intercepts gives $A' = 9.2 \times 10^{15}$ cm^{-3} deg.$^{-\frac{3}{2}}$. By use of Eq. (5), one obtains $\partial E_G/\partial T = (-1.1 \pm 0.1) \times 10^{-4}$ ev/°K if $(m_e m_h/m_0{}^2)^{\frac{3}{4}} = 1$. This value compares well with the value calculated by Fan[1] by considering volume change and the thermal excitation of lattice vibrations, but is too low by a factor of 4 to agree with the optical measurements.[7] Two possibilities should be considered in connection with this discrepancy: (1) $\partial E_G/\partial T$ would have a larger negative value if $m_e m_h$ is less than $m_0{}^2$; and (2) the value of $\partial E_G/\partial T$ may be a function of temperature. However, since the R and σ data indicate that $\partial E_G/\partial T$ is constant between 500°K and 850°K, and the optical data indicate a constant value, four times larger, between 80°K and 300°K, it is not likely that one value changes to the other in the intervening temperature range; this point will be checked by extending the optical measurements to high temperatures.

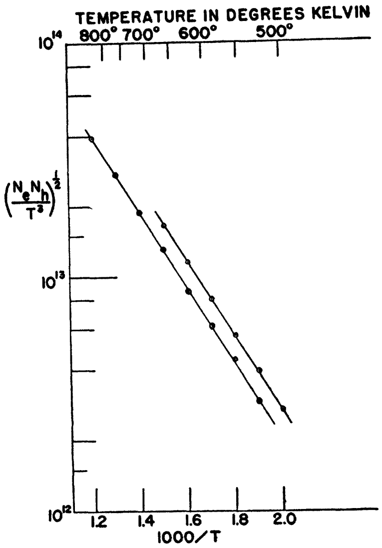

FIG. 1. Plot of $(n_e n_h/T^3)^{\frac{1}{2}}$ *vs.* $1/T$ for two of the germanium samples investigated. The n_e and n_h values are calculated from measured conductivities and Hall curves.

---

* Assisted by Signal Corps Contract.
[1] H. Y. Fan, Phys. Rev. **78**, 808 (1950). Additional references given here.
[2] G. L. Pearson and J. Bardeen, Phys. Rev. **75**, 865 (1949).
[3] A. H. Wilson, *The Theory of Metals* (Cambridge University Press, London, 1936), p. 67.
[4] Data from K. Lark-Horovitz, NDRC Report 14-585, pp. 27-33 (November 1945), unpublished.
[5] Pearson, Haynes, and Shockley, Phys. Rev. **78**, 295 (1950).
[6] V. A. Johnson and K. Lark-Horovitz, Phys. Rev. **79**, 409 (1950).
[7] M. Becker, private communication.

Emission of Neutral Radiation in Cosmic-Ray Stars

E. PICKUP AND L. VOYVODIC
Division of Physics, National Research Council, Ottawa, Canada

July 12, 1950

IN a search for electron pairs associated with meson showers in photographic emulsions we have so far obtained one fairly definite case of an identified electron pair associated with a 43-pronged star. We also find numerous electron pairs not obviously associated with stars,[1,2] with a fairly wide distribution in energy around several hundred Mev.

Figure 1 shows a photo-micrograph of the event, found in Ilford G5 emulsion (300μ) developed to make minimum ionization tracks particularly visible. The pair originates 120μ from the star center, inside a wide angle cone of about 15 shower particles. The electrons were identified by grain counting and multiple