

FIG. 1. Potential barriers at the contact between excess and defect semiconductors.

slightly removed from the ground or conduction bands. It may be of interest to note that lead sulfide shows an analogous distribution of levels, the metallic centers being connected with excess lead and the electronegative centers with oxygen impurity. In the course of work on the photo-effects in lead sulfide³ it was found at this establishment that a thin layer of the material could exhibit photo-voltaic and rectifying properties that are not associated with a contact with metallic electrodes.^{4,5} A theory of the contact between excess and defect semiconductors has been developed to account for these phenomena.⁶ In particular, the case of the rectifying effect appears to be worth brief mention here.

Figure 1 gives the energy-level distribution at the boundary between regions of excess and defect conductivity. Case (a) corresponds to imperfect contact between, for example, two crystals, while case (b) would correspond to a continuous variation of impurity concentration. The width of the transition region in case (b) will be given by $(\epsilon\xi/\pi Ne^2)^{1/2}$ where ϵ is the dielectric constant and ξ is the displacement of the levels. As long as the width of this region is comparable with the mean free path of the electrons (about 100Å in lead sulfide), both cases can be

subjected to the same mathematical treatment. In fact experimental results indicate a value of about 30Å.

There are three contributions to the current across the boundary, the flow of electrons between conduction bands, J_{22} , between ground bands, J_{11} , and between the top of the ground band on the left of the boundary and the conduction band on the right, J_{12} . The latter component is present only when the applied voltage is sufficient for the appropriate bands to overlap. The following approximations can be obtained for the three components of current density:

$$J_{11} = (kT e^2 / 2\pi m) \frac{1}{2} n_h D_{11} e^{-\xi/kT} (1 - e^{-eV/kT}),$$

$$J_{22} = (kT e^2 / 2\pi m) \frac{1}{2} n_e D_{22} e^{-\xi/kT} (1 - e^{-eV/kT}),$$

$$J_{12} = (2\pi e m / h^3) D_{12} (\xi - E_0 - eV)^2; \quad J_{12} = 0 \quad \text{for } V < 0.$$

n_h is the concentration of holes on the left of the boundary and n_e the concentration of electrons on the right. D_{11} , D_{22} , and D_{12} are the appropriate penetration probabilities.

Figure 2 shows the theoretical rectifying curves at room temperature and -80°C based on these formulae, together with experimental points. The broken curves apply to a cell containing five elements in series.

In view of the similarity in energy-level distribution between lead sulfide and silicon-germanium, it should be possible to apply the theory advanced for lead sulfide to the latter materials, and also, if sufficiently close contact could be made between *N*- and *P*-type samples of, say, silicon, to observe rectifying and photo-voltaic effects. The results briefly reported by Brattain⁷ seem to indicate that such effects do occur.

¹ J. Bardeen, Phys. Rev. **71**, 717 (1947).

² W. E. Meyerhof, Phys. Rev. **71**, 727 (1947).

³ J. Starkiewicz, L. Sosnowski, and O. Simpson, Nature **158**, 28 (1946).

⁴ L. Sosnowski, J. Starkiewicz, and O. Simpson, Nature **159**, 818 (1947).

⁵ A.R.L. Report: ARL/R8/E320, to be published.

⁶ A.R.L. Report: ARL/R9/E320, to be published.

⁷ W. H. Brattain, Phys. Rev. **69**, 628 (1946).

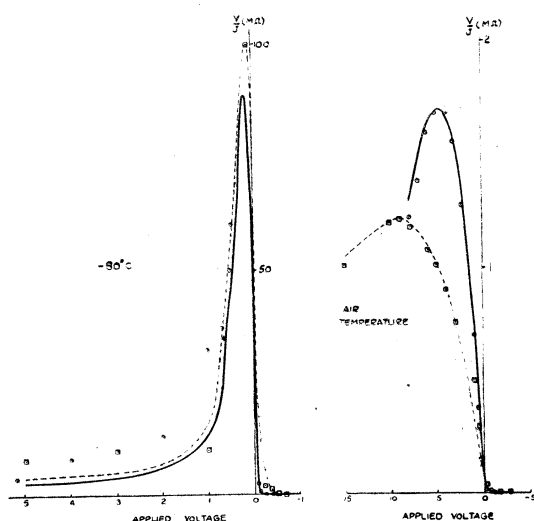


FIG. 2. Theoretical rectifying curves at air temperature and -80°C with experimental points added.

Determination of the Molecular Law of Force from Self-Diffusion Coefficients

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EXPERIMENTAL results have recently appeared for the room temperature self-diffusion coefficients of uranium hexafluoride¹ and methane.² In both cases, the authors relate the molecular-force law to the ratio $\rho D/\eta$, where ρ is the density, D the self-diffusion coefficient, and η the coefficient of viscosity. It seems desirable to point out that force laws based on values of the above ratio are likely to be incorrect.

If the molecules of a gas are considered to be point centers repelling with a force C/r^ν , where C and ν are constants and r is the separation distance between two molecules, $\rho D/\eta$ may be evaluated for certain values of ν from tables given by Chapman and Cowling.³ For example, for $\nu=5$, $\rho D/\eta=1.551$; for $\nu=\infty$, $\rho D/\eta=1.204$; and for intermediate ν values, the ratio lies between the above

values. There are several reasons, however, why such information is of little use. First, at laboratory temperatures, the transport properties of gases depend upon molecular interactions which must be represented as a combination of attractive and repulsive forces. Second, it is possible to obtain essentially the same $\rho D/\eta$ values for different molecular-force models which are not demonstrably equivalent. This is illustrated by recent calculations of low temperature transport properties of gaseous helium by use of an interaction potential consisting of two repulsive and three attractive terms.⁴ These calculations predict a value of 1.18 for $\rho D/\eta$ at 300°K in close agreement with the value of 1.20 for classical hard spheres. And yet, a classical hard-sphere model has on many occasions been shown to be incapable of representing the transport properties of gaseous helium as a function of temperature, in agreement with quantum-mechanical calculations which show the need for both repulsive and attractive terms in the interaction potential.

Table I, from a paper on the self-diffusion coefficient of neon by Groth and Sussner,⁵ shows that other gases besides helium have $\rho D/\eta$ values which lead to incorrect laws of force if interpreted on the basis of point-repelling molecules, since hydrogen has the "hardest" and xenon the "softest" force field of the group.

TABLE I.

Gas	$\rho D/\eta$ at 20°C
H ₂	1.37 ₀ ±0.003
Ne	1.27 ₆ ±0.006
Kr	1.30 ±0.06
Xe	1.24 ±0.06

It should be pointed out that, for the reasons already given, the temperature variation of the coefficient of viscosity ($\eta \propto T^{1/2}(\nu^{-1})$ for point-repelling molecules) provides no better information about the law of force than the ratio $\rho D/\eta$ or the temperature dependence of D if it were known. Chapman and Cowling⁶ summarize the difficulty with respect to both D and η in their statement that "viscosity data throw light on the appropriateness of a formula for the molecular field derived by other means, but by themselves they do not give unambiguous information as to the field."

¹ E. P. Ney and F. C. Armistead, *Phys. Rev.* **71**, 14 (1947).

² E. B. Winn and E. P. Ney, *Phys. Rev.* **72**, 77 (1947).

³ S. Chapman and T. G. Cowling, *Mathematical Theory of Non-Uniform Gases* (Cambridge University Press, Teddington, England, 1939), pp. 172 and 198.

⁴ I. Amdur, *J. Chem. Phys.* **15**, 482 (1947).

⁵ W. Groth and E. Sussner, *Zeits. f. physik. Chemie* **193**, 296 (1944).

⁶ Reference 3, p. 229.

Diamond as a Gamma-Ray Counter

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CONSIDERABLE interest has been evinced in the use of crystals as counters for nuclear radiations since the report by van Heerden¹ in 1945 on the successful use of

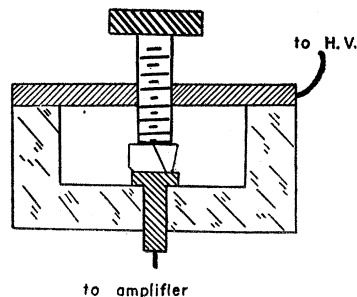


FIG. 1.

silver chloride crystals for this purpose. Silver chloride crystals suffer the serious disadvantage that they must be cooled to liquid-air temperatures to reduce the spontaneous random conduction in these crystals at room temperatures.

Although van Heerden tried a single specimen of diamond he was unsuccessful in obtaining counting. However Woolridge, Ahearn, and Burton² have subsequently found that diamonds will count alpha-particles when electrodes are applied to a surface with a small separation. This counting effect, of course, arises in the surface layer of the crystal.

Diamond does not require cooling to operate as a counter and therefore it can well prove to be a convenient detector. It is of considerable interest to determine whether it responds to gamma-rays. Since the absorption per unit volume for this type of radiation is much greater in diamond than in a Geiger-Müller counter, considerable increase in volume sensitivity for gamma-rays can be anticipated. To survey the possibilities of diamonds as gamma-ray counters approximately 100 industrial diamonds of roughly $\frac{1}{4}$ -carat size have been tested. These diamonds were in their natural state. They were held in a simple compression mounting shown schematically in Fig. 1 in which the high voltage electrode pressed against one side of the crystal and the electrode leading to the grid of the first amplifier tube was in contact with the opposite face. From the total number tested two were found to give excellent response to radium gamma-rays and several others showed some response. The diamonds which gave good response were single crystals free from obvious flaws and water-white. This substantiates the general ideas of crystal conduction and those regarding properties required for counting.

The pulses delivered by the diamond are quite small, requiring considerable amplification for convenient observation. However many of the pulses are at least 10 times the background noise of the crystal plus that of the amplifying system so that no difficulty is encountered in recording them. The variation in pulse size indicates that they originate at random throughout the effective volume of the crystal.

¹ van Heerden, N. V. Noord-Hollandsche Uitgevers Maatschappij (1945).

² E. D. Woolridge, A. J. Ahearn, and J. A. Burton, *Phys. Rev.* **71**, 913 (1947).