On the other hand, it appears to the writer that both LeClaire and Brinkman have rather oversimplified the problem with the result that they have overestimated the effect of jump activation energy. This may be illustrated for the case of vacancy diffusion in a two-dimensional hexagonal lattice as shown in Fig. 1. This figure represents a vacancy midway between planes 2 and 3, a situation produced by an atom that has jumped halfway from one plane into a vacancy on the other.

Evidently some of the energy $Q$ for jumping will be stored in the interactions between the neighbors and next neighbors of the jumping atom. This energy would appear to be furnished thermally from a source at temperature of $T_{2.5}$, about midway between that on planes 2 and 3, regardless of the jump direction. Only a fraction of the activation energy $Q$ will be furnished by the jumping atom itself.

This reasoning suggests that driving force for thermal diffusion will be smaller than that estimated from $Q$ and, hence, that the domination of mass transport by the concentration gradient, as originally predicted by the writer, will be greater than LeClaire and Brinkman conclude. The effects they discuss will play an important role, but it is difficult to see how a quantitative theory can be developed.

In the case of germanium, it may be remarked, there appears to be a good possibility[4] of measuring both the energy of formation of centers $U$ and jump energy $Q$. If $Q$ turns out to be less than $U$, a unique determination of the nature of the heat centers may be possible.

[1] A. D. LeClaire, this issue [Phys. Rev. **93**, 344 (1954)].
[2] J. A. Brinkman, preceding Letter [Phys. Rev. **93**, 345 (1954)].
[3] W. Shockley, Phys. Rev. **91**, 1563 (1953).
[4] R. A. Logan, Phys. Rev. **91**, 757–758 (1953).

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# Water Vapor and the "Channel" Effect in *n-p-n* Junction Transistors*

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Brown[1] has proposed two possible mechanisms for the formation of a "channel" or *n*-type conductivity layer on the normally *p*-type base region of an *n-p-n* transistor. These are (1) the accumulation of positive ions over the base region resulting from the electric field at the junctions, and (2) the ionization of neutral impurities on the surface due to the departure from equilibrium of the underlying semiconductor. These effects are generally attributed to small amounts of water vapor deposited on the surface although other contaminants have not been ruled out. Brown's observations on encapsuled units indicated that it takes several minutes to an hour to establish a channel after applying bias whereas recent work here indicates that this conditioning time decreases continuously with increasing water-vapor pressure to a value less than a millisecond near 100 percent relative humidity.

To examine further the effects of water vapor on "channel" formation, conductance, $G$, from emitter to collector was measured as a function of water-vapor pressure and applied reverse bias. The data shown in Fig. 1 were obtained on an etched[2] *n-p-n* bar having the same dimensions as that used by Brown and a *p*-type base resistivity of approximately 10 ohm-cm. The temperature was 25°C, and the ambient gas was nitrogen in all cases. Since Brown immersed his sample in liquid nitrogen after establishing a "channel," the surface charge was "frozen" at a fixed value; however, the present data indicate that the charge is increasing with applied bias since no "pinch-off" is observed. Furthermore, the apparent $1/V$ relationship (as indicated by the solid lines) points to the following explanation of the effect.

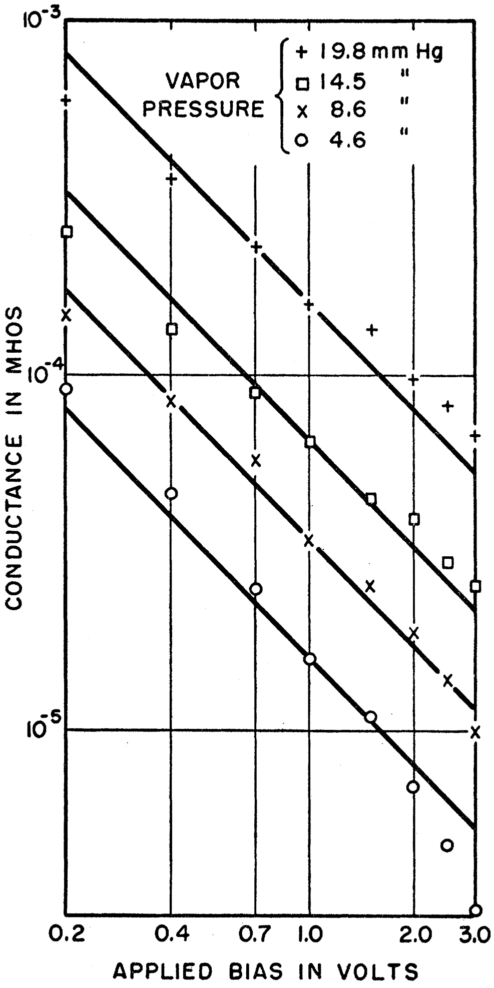

FIG. 1. Channel conductance *versus* applied bias at several values of water-vapor pressure.

On the basis of the second mechanism proposed by Brown, $N_s$ ionizable impurities per cm² are assumed to be on the surface, having an excitation energy, $\psi_D$, as shown in Fig. 2. These impurities are of donor type, and their density is assumed to increase with increasing vapor pressure. The net positive surface charge may then be written

$$Q_s = qN_s \exp[-q(\psi_s+\psi_D-\phi_n)/kT]; \tag{1}$$

and by use of Eq. (6), reference 1, with the notation of Fig. 2, the conductance is found to be

$$G \propto \left\{ V_A - 2\psi_p + \frac{kT}{q}\left[\exp\left(\frac{q(\psi_s-\psi_p-\phi_n)}{kT}\right)-1\right]\right\}^{\frac{1}{2}} - (V_A-2\psi_p)^{\frac{1}{2}}, \tag{2}$$

since $G$ is proportional to the number of conduction electrons, which is, in turn, proportional to the difference between the total field at the surface and that due to the acceptor ions alone. For most of the data considered, $V_A$ is much greater than any of the other terms under the radicals in Eq. (2); therefore,

$$Q_s \propto \sqrt{V_A}, \tag{3}$$

since the first term in Eq. (2) represents the total field at the surface. Furthermore, the exponential in Eq. (2) is much greater than unity and is inversely proportional to $Q_s/N_s$ from Eq. (1).

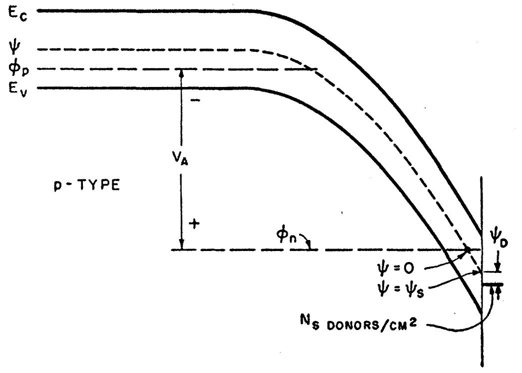

FIG. 2. Energy diagram at surface of $p$-type material.

Therefore,

$$G=k_1\left\{\left(V_A-2\psi_p+\frac{k_2N_s}{\sqrt{V_A}}\right)^{\frac{1}{2}}-(V_A-2\psi_p)^{\frac{1}{2}}\right\}\approx\frac{k_1k_2N_s}{2V_A}, \tag{4}$$

where $k_1$ and $k_2$ are constants directly calculable from the theory. The more detailed theory, which avoids the above approximations, gives:

$$10^{10}<N_s\exp(-q\psi_D/kT)<10^{12}\text{ cm}^{-2} \tag{5}$$

over the range of vapor pressure used. If the electron mobility is less than that of the bulk and surface states are included in the calculation, the shape of the curves is unchanged; however, the magnitude of $N_s$ given above is not completely accurate. It should be emphasized that the states, $N_s$, differ markedly from those discussed by Bardeen and Brattain[2] and by Brown[1] since their ionization time, as evidenced by the "channel" formation time, is much too long and since they are also a function of water-vapor pressure contrary to the first authors' observation. Further speculation on the above model suggests that these impurities might act as hole generators, thus producing increased reverse currents in junction transistors and diodes, and, if $N_s$ has a random fluctuation, an excess noise component. Hole generation is quite conceivable in this picture since the fields at the surface are high enough to cause direct tunneling from the valence band to the ionized impurities. If the impurity levels are considered to be embedded in an oxide layer on the surface, then the rapid decrease of buildup time with increasing vapor pressure (and, consequently, $N_s$) can be explained by assuming that the rate of transfer of electrons from impurities to the semiconductor increases rapidly with $N_s$.

The author is indebted to J. A. Morton and K. D. Smith of the Bell Telephone Laboratories, who supplied the sample crystals, and to M. Green and G. I. Hitchcox of this laboratory for aid in the experimental aspects of the work.

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[1] W. L. Brown, Phys. Rev. 91, 518 (1953).

[2] The treatment is the same as that described on page 8 of J. Bardeen and W. L. Brattain, Bell System Tech. J. 32, 1 (1953).

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# Radiation from CdS Crystals Generated by DC Electric Fields

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BÖER and Kummel[1] report radiation from CdS crystals immersed in liquid air and subjected to dc fields ~$10^5$ volts/cm. At these fields the current is observed to rise abruptly (but reversibly) and radiation (red and green) is observed at currents just under those that normally cause the crystal to break down thermally. Böer and Kummel interpret the rapid rise current to collision ionization by conduction electrons that have been accelerated to several volts energy by the applied field. The radiation is described as "luminescence" caused by the energetic electrons.

The purpose of this letter is to describe work in this laboratory on CdS crystals that indicates at least two types of radiation can be generated electrically, and that the fields may be an order of magnitude or more lower than reported by Böer and Kummel.

The emission from a crystal depends on its conductivity and past history. One type of radiation, observed in the more conducting crystals, is best described as incandescence. It is red or straw-colored emission and has been obtained at dc electric fields $\lesssim 150$ volts/cm when the current is of the order of tens of milliamperes. The crystals are operating near thermal breakdown. The emission is independent of the electrode configuration and material, and is observed at room temperature.

Another type of electrically-excited radiation is green emission (often unaccompanied by red) from more insulating crystals at dc electric fields ~$10^3$ volts/cm. Green emission has been obtained from CdS crystals several mm long with In electrodes. The emission is most intense around the positive electrode and tapers off in intensity over an appreciable fraction of the spacing between electrodes, often appearing to flow and ripple. The current is usually low and of the order of several hundred $\mu$a.

Recently[2,3] we have reported space-charge-limited currents drawn through thin insulating CdS crystals using ohmic contacts of In or Ga. These currents increase as a high-power function of the voltage even at low fields ($10^2$–$10^3$ volts/cm). The fact that the current increased more rapidly with voltage than theory predicted was ascribed to the presence of traps. These insulating crystals have been subjected to fields ~$10^3$ volts/cm and green (and red) emission observed. This configuration most nearly approximates that used by Böer and Kummel.

It is seen then that green emission can be obtained from CdS crystals at dc electric fields an order of magnitude or more lower than reported by Böer and Kummel. There is a question whether fields of this magnitude can impart several volts energy to an electron as would be required for collision ionization. Although there is little concrete evidence for hole conduction in CdS, it is possible that there is some hole injection at the positive electrode. This could account for the intense green emission emanating from the positive electrode.

[1] K. W. Böer and U. Kummel, Z. physik. Chem. 200, 190 (1952).

[2] R. W. Smith and A. Rose, Phys. Rev. 92, 857 (1953).

[3] A. Rose and R. W. Smith, Phys. Rev. 92, 857 (1953).

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# Solution of the Boltzmann Equation for Maxwellian Molecules*

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THE Boltzmann integrodifferential equation for monatomic gases has been studied extensively in two limiting cases. When the mean free path is small compared to the relevant lengths of the problem (wavelength of sound, thickness of shock front, dimensions of container, etc.), the Enskog-Chapman method applies.[1] The method is defective in that general microscopic boundary conditions cannot be satisfied. It becomes unwieldy for mean free paths of the order of the relevant length and breaks down entirely when the flow is sensitive to boundary conditions on the distribution function. For mean free paths large compared to a container dimension, Jaffé[2] gave a procedure for solving the Bolzmann equation by successive approximations and satisfying general boundary conditions. This method breaks down at higher pressures. In view of the present active interest in