Temperature Dependence of Electron-Bombardment-Induced Conductivity in MgO†

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The dependence upon temperature of the electrical conductivity induced in thin single crystals of MgO by bombardment with high-energy electrons which pass through the targets with negligible energy loss has been measured over the temperature range 200° K–600° K. The experimental data are in accord with a theory which ascribes the observed decrease in conductivity as the temperature is raised to the predicted variation in the mobility of the charge carriers. The effects of scattering by both the optical modes and the acoustical modes of vibration of the lattice must be taken into account, since neither the $\exp(\Theta/T)$ relationship resulting from the first type of interaction nor the $T^{-\frac{3}{2}}$ law arising from the second individually fits all of the data. The experiments also indicate that the concentration of trapping centers remains essentially constant over the temperature range investigated. The lifetime of the carriers is approximately 5×10^{-10} sec, and the trap density is estimated to be 10^{17}–10^{18} cm^{-3}.

I. INTRODUCTION

WHEN a beam of high-energy electrons passes through a thin single crystal of MgO, internal secondary electrons produced uniformly along the path of the primary are lifted from the filled band to the conduction band.[1] These carriers, as well as the corresponding holes in the filled band, remain mobile for an extremely short time until they are captured by trapping centers in the crystal. However, when an electric field is applied, a current is observed which under typical conditions is an order of magnitude greater than the primary current.

In view of the fact that the bombardment-induced current is proportional to the mobility of the carriers, measurements of its variation with temperature provide a basis for comparing mobility theory with experiment. Furthermore, information regarding the characteristics of the traps can be deduced from the nature of the temperature dependence, since the bombardment-induced conductivity is also a function of the density of trapping centers. Therefore, a series of measurements was conducted over the temperature range 200°K–600°K, the limits being imposed by certain experimental considerations.

II. EXPERIMENTAL PROCEDURE

Figure 1 is a schematic diagram of the experimental arrangement. The crystal is clamped between flattened Ni wire supports which bear upon silver surfaces on the two faces. The glass tube is attached directly to the vacuum system of the electron accelerator by means of the O-ring flange. The length of the leads is such that the press is outside the oven, thereby avoiding electrical leakages which arise at elevated temperatures. The low-temperature measurements are obtained with the tube sealed into a metal tank which is filled with a mixture of alcohol and dry ice. The temperature is measured with a chromel-alumel thermocouple (not shown) mounted adjacent to the crystal.

The 1.3-Mev electron beam from the linear accelerator passes through the graphite collimator, then penetrates through the thin crystal with negligible energy loss (approximately 150 kev) and is finally stopped by the graphite collector. The primary current, I_p, is measured by means of an integrating micro-microammeter. The corresponding 1-μsec bombardment-induced conductivity pulses, I_c, are displayed oscillographically, and, in the present experiments, the primary current is adjusted at each temperature to produce a fixed pulse height. Space-charge effects resulting from the trapping of charge carriers are eliminated by reversing the polarity of the crystal voltage, V_c, subsequent to each successive pulse at the repetition rate of 10 pps by a flip-flop circuit.[2] For sufficiently small values of I_c, no buildup of space-charge is detectable during an individual pulse, and it has been established in auxiliary experiments that the present measurements represent space-charge-free conditions.

The $\frac{3}{4}$ in.$\times\frac{3}{4}$ in. targets are cleaved from large single crystals of commercially-produced fused magnesia,[3] and are ground to a thickness of approximately 0.010 in. Two specimens were prepared from entirely different batches to determine whether the results are dependent upon the history of the particular melt and possible differences in impurity content.

The most extensive series of measurements was obtained with one of the crystals in the raw state, which is characterized by a stoichiometric excess of oxygen (V-centers) as revealed by optical absorption measurements. This specimen was subsequently re-examined after it was bleached by vacuum-firing at 1400°C for two hours. This treatment removes the color centers, but does not alter the concentration of other impurities to an extent detectable by spectrographic analysis.

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[1] Pomerantz, Shatas, and Marshall, Phys. Rev. 99, 489 (1955).
[2] Schematic diagram of circuit is shown in reference 1.
[3] Optical quality periclase produced by Norton Company, Worcester, Massachusetts, under the trade name "Magnorite."

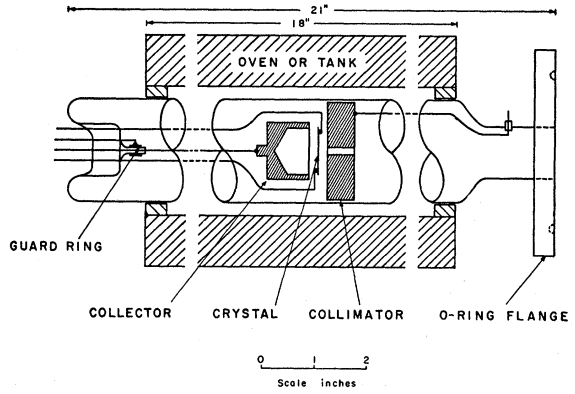

FIG. 1. Schematic diagram of the experimental tube.

III. EXPERIMENTAL RESULTS

The data are presented in the usual manner in Fig. 2, where the ordinate representing essentially the bombardment-induced current per unit primary current, $m=I_c/I_p$ (with V_c constant) is plotted on a logarithmic scale as a function of the reciprocal of the absolute temperature. The scatter of the points about the curve is attributable primarily to the performance of the linear accelerator rather than to changes in the characteristics of the crystal, and the data were entirely reproducible and constant over long periods of time within the indicated uncertainty.

Measurements with the bleached crystal revealed no changes in the magnitude of m over the entire temperature range. Furthermore, the second raw crystal manifested the same temperature dependence as that shown in Fig. 2, although the values of m_0 in absolute units differed by a constant factor.

IV. THEORETICAL DISCUSSION

Since the mean drift distance in the direction of the applied field is small compared with the thickness of the crystal, the bombardment-induced current per unit primary current, $m=I_c/I_p$, is given by[1]

$$m=\delta v V_c \tau/d, \tag{1}$$

where δ is the number of internal secondary electrons raised into the conduction band by one primary electron per cm of path, v is the average mobility of the carriers, V_c is the voltage applied across the target of thickness d, and τ the mean lifetime of the carriers. Hence, the yield per unit field, m_0, corresponding to an applied field of one volt per cm, is

$$m_0=\delta v \tau. \tag{2}$$

If we assume, following Fröhlich and Mott,[4] that the lifetime, τ, is independent of temperature, then m_0 should display the same temperature dependence as

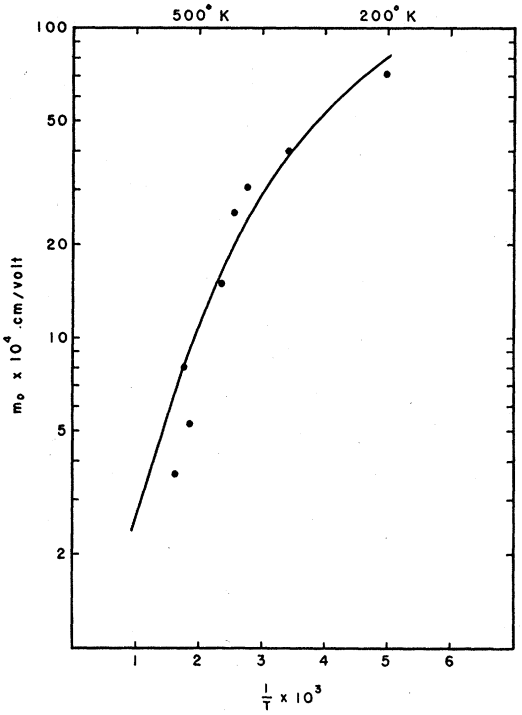

FIG. 2. Plot of the bombardment-induced conductivity as a function of temperature. The solid line represents Eq. (3) with the value of the constant B providing the best fit with the indicated experimental points.

the mobility of the charge carriers. Hence, for a given crystal,

$$m_0=Bv. \tag{3}$$

Theoretical treatment of the problem of the mobility of charge carriers in polar crystals has revealed that of the two alternative types of interaction which have been investigated, scattering by the optical mode ordinarily suffices to account for the experimental results in the temperature range encompassed by the present measurements.

In the present experiments, however, the general trend of the data indicates that more than one type of interaction with the lattice must be taken into account. This conclusion is based upon the fact that calculations of the effects of scattering by the optical modes of vibration result in an exponential dependence of the mobility upon reciprocal temperature, whereas as a consequence of scattering by the acoustical modes, the mobility is proportional to $T^{-\frac{3}{2}}$. Since, as is evident in Fig. 2, neither form fits all of the data, even approximately, both types of interaction must be considered. It can then be assumed[5] that the resultant mobility is given by

$$1/v=1/v_o+1/v_a. \tag{4}$$

Here v_o is the mobility determined by the interaction of the carriers with the optical modes of vibration of

[4] H. Fröhlich and N. F. Mott, Proc. Roy. Soc. (London) **A171**, 496 (1939).

[5] R. L. Petritz and W. W. Scanlon, Phys. Rev. **97**, 1620 (1955).

the lattice, and v_a the mobility determined by the interaction with the acoustical modes.

In the case of scattering by the optical modes, Low and Pines[6] find:

$$v_o=\frac{1}{2\alpha\omega}\frac{e}{m^*}\frac{1}{[1+(\alpha/6)]^3}f(\alpha)\exp(\Theta/T), \quad (5)$$

where

$$\alpha=\frac{e^2}{\hbar}\left(\frac{m}{2\hbar\omega}\right)^{\frac{1}{2}}\left(\frac{\kappa-\kappa_0}{\kappa\kappa_0}\right)\left(\frac{m^*}{m}\right)^{\frac{1}{2}}, \quad (6)$$

$$\Theta=\hbar\omega/k. \quad (7)$$

Here, m is the free electron mass, m^* is the effective carrier mass, ω is the angular frequency of longitudinal optical modes, κ and κ_0 are the static and high-frequency dielectric constants respectively, and $f(\alpha)$ is a slowly-varying function of α. For MgO, we have[6-9]

$f(\alpha)\approx 1.2$,

$\kappa=9.8$, $\kappa_0=2.95$,

$\omega=\left(\frac{\kappa}{\kappa_0}\right)^{\frac{1}{2}}\frac{2\pi c}{\lambda}$,

$\lambda=$fundamental infrared absorption wavelength

$=15.3\,\mu$,

$\Theta=1710°$ K.

Substituting these values into Eq. (5), and assuming that $m^*=m$, we obtain

$$v_o=0.71\exp(\Theta/T)\ \text{cm}^2/\text{volt sec}. \quad (8)$$

The interaction with the acoustical modes of vibration has been investigated by Seitz,[10] with the result

$$v_a=\frac{2^{\frac{1}{2}}6^{\frac{1}{3}}}{4\pi^{5/6}}\frac{eh^2k^2T_0^2M}{m^{*\frac{5}{2}}aC^2(kT)^{\frac{3}{2}}}, \quad (9)$$

where T_0 is the Debye temperature, a is the lattice spacing, and M is the mass of the atoms in the crystal, which is taken to be equal to the reduced mass of the Mg—O pair. In the present calculations, C, a parameter involving the wave functions of the charge carriers, is assumed to have the approximate value $1.7\times10^{-2}T_0$ ev, as given by Seitz. For MgO, we have

$$M=(1/M_{\text{Mg}}+1/M_{\text{O}})^{-1}=1.6\times10^{-23}\ \text{g},$$

$$a=4.2\times10^{-8}\ \text{cm}.$$

Hence, with $m^*=m$,

$$v_a=2.1\times10^5T^{-\frac{3}{2}}. \quad (10)$$

From Eqs. (8), (10), and (4), we obtain for the mobility:

$$v=[1.4\exp(-\Theta/T)+4.8\times10^{-6}T^{\frac{3}{2}}]^{-1}\ \text{cm}^2/\text{volt sec}. \quad (11)$$

The calculated temperature dependence of m_0 [see Eq. (3)], with the value of B providing the best fit with the experimental points, is plotted in Fig. 2. The agreement between theory and experiment confirms the validity of the assumption that τ, and consequently the concentration of trapping centers, is independent of temperature.

In the foregoing discussion, it has been tacitly assumed that only one type of carrier contributes to the conductivity. The presence of both electrons and holes, however, would change only the magnitudes of the constants in Eq. (11) and since the calculated value of the coefficient of $T^{\frac{3}{2}}$ can only be regarded as approximate in any event, the results would not be altered significantly.

The value of the constant $B=\delta\tau$ is found to be 1.1×10^{-4} cm^{-1} sec. If we assume that on the average the primary energy loss per internal secondary electron is of the order of 30 ev, then $\delta\approx2\times10^5$ cm^{-1}, and $\tau\approx5\times10^{-10}$ sec.

On the assumption that the capture cross section, σ, of the trapping centers is of the order of 10^{-15} to 10^{-16} cm^2, the number of traps per cm^3 is $N=1/(u_0\sigma\tau)$ $\approx10^{17}-10^{18}$ cm^{-3}, where u_0 is the average thermal velocity of the charge carriers. This density is not inconsistent with the known impurity content of the specimen as determined by spectroscopic analysis.[11]

[6] F. E. Low and D. Pines, Phys. Rev. **98**, 414 (1955).
[7] N. F. Mott and R. W. Gurney in *Electronic Processes in Ionic Crystals* (Oxford University Press, New York, 1940), p. 12.
[8] Lyddane, Sachs, and Teller, Phys. Rev. **59**, 673 (1941).
[9] C. V. Raman, Proc. Indian Acad. Sci. **26A**, 388 (1947).
[10] F. Seitz, Phys. Rev. **73**, 549 (1948).
[11] Spectrographic analyses were performed by the University of Missouri Spectrographic Service.