# Temperature Dependence of Electron-Bombardment-Induced Conductivity in MgO. II*

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Previous measurements of the temperature dependence of the electrical conductivity induced in single crystals of MgO by bombardment with 1.3-Mev electrons over the temperature range 290°K–600°K have been extended to 100°K. Two crystals from different sources were investigated.

The bombardment-induced current, $I_c$, varies linearly with primary current, $I_p$, at 298°K and at 105°K. However, in certain cases measurements of $I_c$ vs applied voltage, $V_c$, reveal a deviation from Ohmic behavior which is enhanced at low temperature.

The bombardment-induced conductivity exhibits a maximum near 250°K. Both crystals display a temperature dependence at low temperatures which is consistent with the power-law relationship $I_c/I_p=kT^m$, where $m=3.3$ and 3.8, respectively.

A rising non-Ohmic $I_c$ vs $V_c$ characteristic appears to be dependent upon the magnitude of the applied field, the onset occurring at $3\times10^4$ v/cm. Collision ionization and warm carrier phenomena, rather than surface effects, probably account for the observed results.

It is impossible to ascribe the temperature dependence of the bombardment-induced conductivity solely to the temperature variation of the carrier mobility. The results can be explained in terms of change with temperature of both the lifetime and mobility of the charge carriers. A combination of optical mode (polaron), acoustical mode, and ionized impurity scattering is assumed, in addition to a temperature-dependent capture cross section for the carrier. The theoretical curve fits the experimental data satisfactorily, and gives reasonable values for the parameters.

## I. INTRODUCTION

A BEAM of high-energy electrons in passing through a normally insulating crystal produces hole-electron pairs uniformly through the bulk of the material. While they remain mobile, these holes and electrons drifting under the influence of an applied electric field constitute a measurable current. Information concerning the drift mobility and lifetime of charge carriers in the conduction band of insulators may be obtained from observations of this bombardment-induced conductivity.[1]

Investigations of this phenomenon in MgO have previously been conducted in the temperature range 290°K–600°K.[2] These experiments revealed that the bombardment-induced conductivity was linearly dependent upon the voltage applied between electrodes on the surfaces of the crystal, as well as upon the magnitude of the primary electron beam current passing through. Furthermore, the nature of the temperature dependence of the bombardment-induced conductivity in MgO indicated that at least two scattering mechanisms must be affecting the mobility of the carriers. It appeared that the charge carriers were scattered both by the acoustical and the optical modes (polaron scattering) of lattice vibration.

Since it was suspected that the influence of other scattering mechanisms might become detectable at lower temperatures, the measurements have subsequently been extended down to approximately 100°K. The new experimental results, and the theoretical interpretation of all the available data over the accessible range of temperatures (100°K–600°K), are discussed in the present paper.

## II. EXPERIMENTAL PROCEDURE

The experimental arrangement was essentially the same as that described previously.[2] In the present case, however, the experimental tube was immersed in a tank which could be filled with liquid nitrogen. Provisions were made to establish good thermal contact between the MgO crystal and the liquid air bath, and to reduce to a minimum heat conduction through support rods and wires. The temperature was measured directly on the face of the target immediately adjacent to the area traversed by the primary beam by means of an iron-constantan thermocouple secured to a section of the silver coating deposited on the crystal face.

The bombardment-induced current was recorded frequently during both the cooling and warming cycles. Since, in general, about four hours elapsed after the introduction of liquid nitrogen before the entire system reached equilibrium, it was feasible to conduct observations while the system was in a transient state thermally. Subsidiary tests established that any errors arising from temperature gradients across the crystal are much smaller than those inherent in the measurements of primary and bombardment-induced currents. Furthermore, no hysteresis effects were observed. In addition, an attempt was made to detect heating of the specimen by the primary beam. Very small temperature changes (tenths of a degree) were observed with a primary current of 0.6 ma. Beam intensities were an order of magnitude lower during all of the measurements.

Although the circuit arrangement was essentially the same as that utilized previously,[1,2] several modifications have improved the precision of the measurements. The primary (beam) current ($I_p$) and the secondary

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[1] M. A. Pomerantz, R. A. Shatas, and J. F. Marshall, Phys. Rev. **99**, 489 (1955).

[2] J. F. Marshall, M. A. Pomerantz, and R. A. Shatas, Phys. Rev. **106**, 432 (1957); hereafter referred to as I.

(crystal) current ($I_c$) were displayed simultaneously by a Tektronics 551 dual beam oscilloscope, whereas in the earlier experiments, the primary current was measured by an integrating meter. Although single pulse measurements are feasible, the beam was usually pulsed repetitively because operation of the 1.3-Mev linear electron accelerator is more stable under these conditions. During the present experiments, the linear accelerator was normally operated at a repetition rate of 10 pulses per second with a primary current of 0.060 ma. The energy distribution of the primary electrons peaks sharply at 1.3±0.1 Mev, and the beam content below 1.0 Mev is negligible.

The present data were obtained with the identical MgO crystal (hereafter designated NC)[3] utilized in the earlier investigations.[2] Because of the surprising nature of the results, another crystal (hereafter designated IRC) was obtained from a different source,[4] and the measurements were repeated.

The crystals were ground down to thicknesses of 0.02 cm in order to reduce the energy loss of the primary beam to a negligible amount. Metallic electrodes were then deposited upon the faces. The targets were not subjected to any heat treatment, but were retained in the original "raw" state. Such crystals are characterized by appreciable optical absorption in the ultraviolet at 5 ev.

In order to determine whether the electrodes might introduce extraneous effects, a series of measurements of crystal current vs applied voltage was made with one crystal the thickness of which was varied. Observations were initially conducted alternately with silver print electrodes, then with evaporated gold-silver, then with silver print. The crystal was then ground to one half its original thickness, and the sequence repeated. Finally, the thickness was reduced further. The three thicknesses were 0.065 cm, 0.032 cm, and 0.018 cm, respectively. After corrections were made for primary electrons stopped in the thick target, the results were consistent with the assumption that the bombardment-induced conductivity is proportional to $d^{-1}$ [see Eq. (1) below]. Hence, the electric fields in the crystal are uniform. Furthermore, the nature of the electrodes did not affect the measurements. Evaporated silver electrodes utilized in subsequent experiments yielded the same results as silver print and evaporated gold-silver.

The technique of reversing the electrode polarity after each pulse was again utilized to eliminate space charge effects.[1]

### III. EXPERIMENTAL RESULTS

The dependence of the bombardment-induced current ($I_c$) upon the primary current ($I_p$) for the NC crystal is shown in Fig. 1. Measurements were conducted at

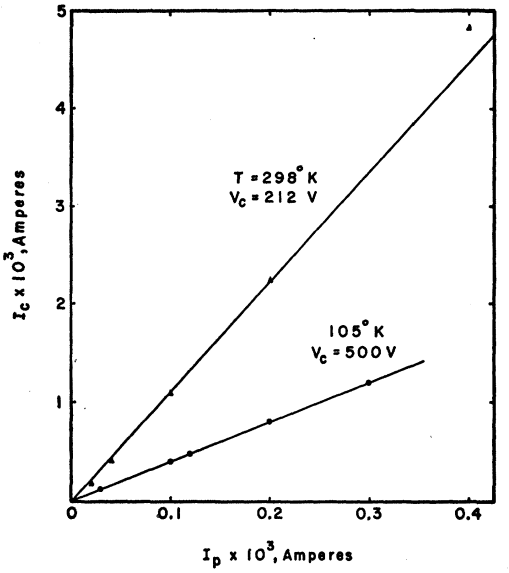


FIG. 1. The dependence of the induced current, $I_c$, upon primary current, $I_p$, for the NC crystal at two temperatures. Crystal thickness=0.018 cm.

298°K and at 105°K, respectively, with two different applied voltages, $V_c$. It is seen that the curves are linear within the experimental uncertainty as reported previously.[1] Figure 2 shows the results for the IRC crystal. The ratio $I_c/I_p$ at fixed $V_c$ is also constant in this case.

Figure 3 is a plot of $I_c$ vs $V_c$ ($I_p$=0.06 ma) for the NC crystal at room temperature and at 107°K, respectively. A slight deviation from Ohmic behavior occurs at 298°K. Owing to several circumstances, this departure had not been detected previously. The MgO crystal was somewhat thicker during the earlier measurements (0.025 cm as compared with 0.018 cm currently, the decrease resulting from the repeated removal of coatings) and hence the electric field corresponding to a given $V_c$ was smaller. Furthermore, the experimental uncertainty was somewhat greater in the previous investigations. The extent of the errors in measurement in the present experiments is indicated by the scatter of the points in Fig. 3. The procedure now followed, essentially a null method, involves adjusting $V_c$ to attain predetermined values of $I_c/I_p$ by matching the $I_c$ and $I_p$ pulses oscillographically with different amplifier gain ratios. Consequently, the uncertainty is reflected entirely in $V_c$.

At low temperature, the non-Ohmic behavior is even more dramatic. The measurements shown in Fig. 1 have revealed that the shape of the $I_c$ vs $V_c$ curve is independent of $I_p$ over a range of primary current from 0.03 to 0.3 ma in the present case. This suggests that even in the region of appreciable departure from Ohmic behavior ($V_c$=700 volts), $I_c$ indeed represents a true bombardment-induced current.

Similar data obtained with the IRC crystal are plotted in Fig. 4. The thickness of the crystal during

[3] Optical quality periclase produced by Norton Company, Worcester, Massachusetts, under the trade name "Magnorite."
[4] Infra-Red Development Company, Ltd., Hertfordshire, England.

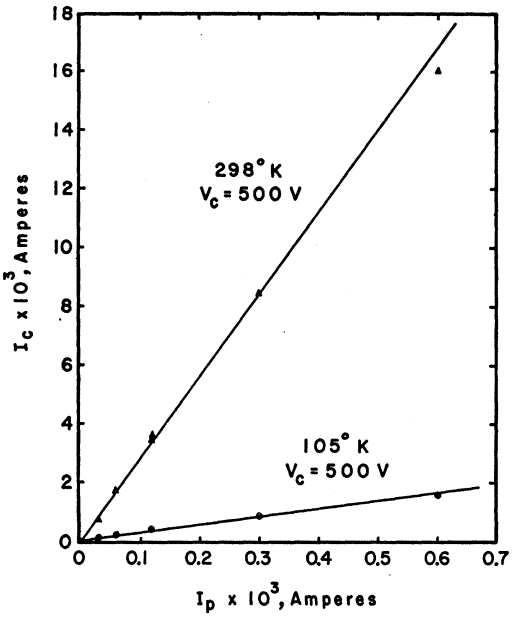


FIG. 2. $I_c$ vs $V_c$ for the IRC crystal at two temperatures. Crystal thickness=0.018 cm.

this set of measurements was 0.038 cm. It is difficult to detect any departure from Ohm's law either at room temperature or at 105°K. The thickness of this crystal was subsequently decreased to 0.018 cm, and measurements were repeated (Fig. 5). It is evident that, although in this case the conductivity is apparently Ohmic at 298°K, the behavior at 105°K is similar to that of the NC crystal. Furthermore, as in the other case, the crystal current varies linearly with primary current over a range of $I_p$ between 0.06 and 0.60 ma (Fig. 2). Another IRC crystal, the thickness of which was 0.065 cm, 0.032 cm, and 0.018 cm, respectively, during the measurements (see Sec. II), displayed Ohmic behavior at room temperature in all cases.

The bombardment-induced conductivity may be described by the following expression[1]:

$$I_c/I_p=\delta\tau^*\mu V_c/d, \qquad (1)$$

where $I_c$ and $I_p$ are the crystal current and the primary beam current, respectively, $V_c$ is the applied potential, $d$ is the crystal thickness, $\delta$ is the number of internally excited electron-hole pairs produced by one primary electron per cm of primary electron path, $\tau^*$ is the mean lifetime of the carrier in the conduction band, and $\mu$ is the average mobility of the carrier.

Figure 6 is a log-log plot of the temperature dependence of the quantity $\delta\tau^*\mu$ for the NC crystal. The dots represent data obtained while the temperature of the crystal was decreasing, whereas the crosses refer to the warming phase.

Data obtained previously[2] with the same crystal from room temperature upward are represented by triangles. The latter have been normalized to the new low-temperature measurements at room temperature, since in the earlier experiments facilities were not available for obtaining pulsed measurements of the primary beam. Consequently, since $I_p$ was determined by means of an integrating meter, the measurements of $I_c/I_p$ did not yield absolute values of $\delta\tau^*\mu$.

At all temperatures, $V_c$ never exceeded the value at which departure from Ohm's law occurred.

The points shown in Fig. 6 were obtained in a single run extending over a period of approximately eight hours. Data obtained during a number of similar runs were in good agreement. In general, a readjustment of the linear accelerator which always reduced the measured value of $I_c/I_p$ was required during the cooling cycle (at 130°K in Fig. 6). No subsequent alteration was necessary; hence, the warming phase is assigned somewhat greater weight. This situation is a consequence of the difference between the cooling and heating rates in the region of lower temperatures.

The single observation below room temperature reported previously[2] corresponded to a higher value of $\delta\tau^*\mu$ at 200°K than is consistent with the present results. This particular point is now considered to be in error.

The temperature dependence for the IRC crystal is plotted in Fig. 7. Owing to slight changes in the experimental conditions for the observations above room temperature, a normalization was also required in this case. The maximum temperature was limited by the fact that the present experimental arrangement is not readily adaptable to temperatures above 400°K. Again, the data in Fig. 7 comprise a single run, although repetition of the measurements has demonstrated the reproducibility of the results.

Figure 8 shows a comparison between the results

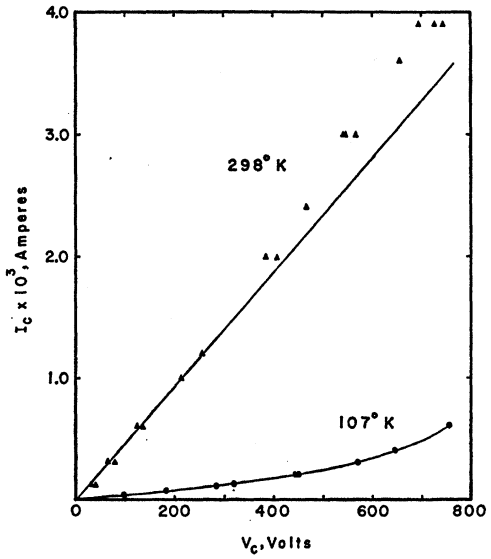


FIG. 3. The dependence of the induced current, $I_c$, upon applied potential, $V_c$, for the NC crystal at two temperatures. Crystal thickness=0.018 cm, $I_p$=0.06 ma.

obtained with the two crystals procured from widely different sources. The agreement is indeed remarkable.

In both cases, the experimental uncertainty near the maximum of the curve is indicated by the scatter of the points. Although the slight deviations between the dots and crosses in both Fig. 6 and Fig. 7 might have been attributed to a difference between the temperatures of the bombarded region and the thermocouple during the transient thermal conditions, the required temperature difference of 5° appears excessive with the present experimental arrangement. Hence, the observed differences are ascribed to changes in the alignment of the beam and operation of the linear accelerator.

Both crystals display a temperature dependence at low temperature which is consistent with a power law relationship $I_c/I_p=kT^m$. However, the data are not sufficiently extensive to preclude the possibility that the bombardment-induced conductivity follows an exponential law. If a power law dependence is assumed, $m=3.3$ and 3.8 for the NC and IRC crystals, respectively. The maximum of the NC curve in Fig. 6 occurs at a slightly lower temperature than that of the IRC curve.

## IV. DISCUSSION

The existence of a rising non-Ohmic $I_c$ vs $V_c$ curve is not in itself surprising, as has been pointed out by Smith and Rose.[5] This may arise from various phenomena, such as field emission from the electrodes or traps or from the valence bands, poor contacts, collision ionization of the trapped or valence electrons, warm carrier effects, or space-charge limited currents. Comparison of Figs. 4 and 5 indicates that the effect depends upon the magnitude of the applied field (the onset of the departure from Ohm's law occurring at $3\times10^4$v/cm).

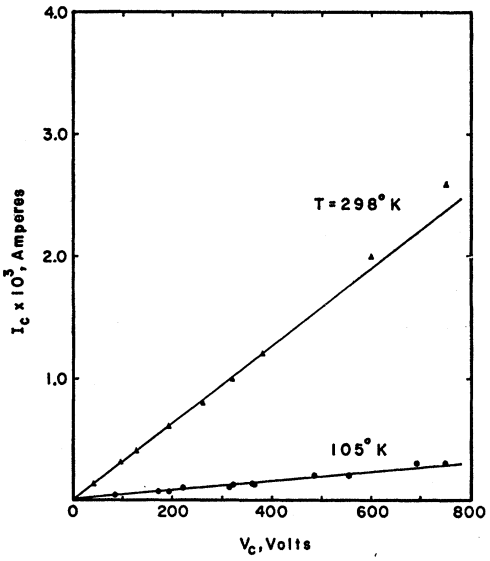


FIG. 4. $I_c$ vs $V_c$ for the IRC crystal at two temperatures. Crystal thickness=0.038 cm, $I_p$=0.06 ma.

[5] R. W. Smith and A. Rose, Phys. Rev. **97**, 1531 (1955).

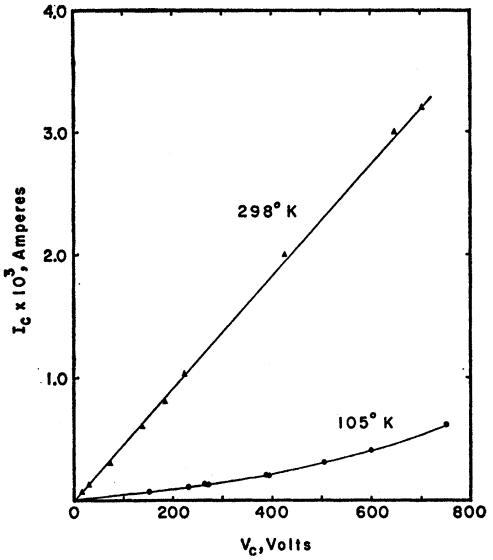


FIG. 5. $I_c$ vs $V_c$ for the IRC crystal at two temperatures. Same crystal as in Fig. 4, but thickness=0.018 cm. $I_p$=0.06 ma.

It does not appear that this can be attributed to the nature of the electrodes, since the effect has been reproduced a number of times with both silver and gold electrodes. On the other hand, since the shape of the non-Ohmic $I_c$ vs $V_c$ curves at low temperature is independent of $I_p$, it is suggested that collision ionization and warm carrier phenomena may account for the observed results. The linear dependence of $I_c$ upon $I_p$ at all values of $V_c$ demonstrates that the charge carriers produced by the bombarding beam are responsible for the non-Ohmic as well as the ohmic behavior at low fields. The observed results are most likely produced by a bulk phenomenon in the crystal rather than by surface effects. The mechanism responsible for this non-Ohmic behavior cannot be conclusively identified without further investigations involving considerably higher fields than can be applied in the present experimental arrangement. With this in mind, the present discussion of the temperature dependence of the bombardment-induced conductivity will be confined to the Ohmic region.

The temperature dependence of the bombardment-induced conductivity in MgO has previously been ascribed solely to the variation in carrier mobility.[2] As heretofore, it is assumed, for simplicity, that only one carrier is mobile. In the previous description, in order to fit the data above room temperature, it was necessary to invoke two carrier scattering mechanisms: (a) scattering by the acoustical vibrations of the lattice,[6,7] and (b) polaron scattering[8] associated with the optical modes of vibration.

[6] F. Seitz, Phys. Rev. **73**, 549 (1948).

[7] J. Bardeen and W. Shockley, Phys. Rev. **80**, 72 (1950).

[8] For a review of the various theories of carrier transport in ionic crystals see the article by S. Haken, in *Halbleiterprobleme II*, edited by W. Schottky (Friedr. Vieweg and Sohn, Braunschweig, 1955).

The present results in the low-temperature region reveal that this cannot be entirely correct. An examination of the rapid increase in the bombardment-induced conductivity as a function of temperature below 250°K indicates that no known scattering mechanism, and thus no known temperature dependence of the mobility *alone* can explain this behavior. Scattering by ionized impurities may give as high as a $T^{\frac{3}{2}}$ behavior,[9] whereas other mechanisms, such as scattering by neutral impurities, are even less temperature dependent.[10] The results shown in Figs. 6 and 7 must therefore be attributed to a combination of the effects of temperature upon $\tau^*$, the recombination lifetime of the bombardment-produced carriers, and upon $\mu$, the carrier mobility. It is, of course, highly unlikely that $\delta$ in Eq. (1) is appreciably temperature dependent.

Under the conditions of these experiments, (a) the bombardment-induced conductivity is linearly dependent upon $I_p$; (b) dark conductivity[11] cannot be observed; and (c) there is no appreciable buildup of space charge during the microsecond pulse. The recombination lifetime for a simple system having one type of recombination center in the energy gap is then given by[12]:

$$\tau^*=1/N_rS_n\langle v\rangle+1/N_rS_p\langle v\rangle, \tag{2}$$

where

$$\langle v\rangle=(4kT/m\pi)^{\frac{1}{2}};\quad S=\langle vS(E)\rangle/\langle v\rangle.$$

Here $S_n$ is the capture cross section of the centers for a free electron when unoccupied, and $S_p$ is the corresponding capture cross section for a free hole when occupied by an electron. $N_r$ is the density of recombination centers and $\langle v\rangle$ is the average thermal velocity of the carriers. We assume that the centers are initially neutral, in which case the data suggest that $S_p<S_n$ above 100°K, so that, in the temperature range of interest,

$$\tau^*=1/N_rS_p\langle v\rangle. \tag{3}$$

Recent experimental work with Ge and Si,[13] and theoretical analysis by Lax,[14] have shown that the capture cross section of centers having charge opposite from the carrier may be from $10^{-12}$ to $10^{-15}$ cm$^2$ and varies with temperature as $T^{-n}$ where $n$ is found to have values in Ge and Si ranging from 1 to 4 for various types of impurities.[14] In addition, it has been found that neutral centers may have large cross sections ($10^{-15}$ cm$^2$) independent of temperature.

Of course, since MgO is an ionic crystal, the situation is expected to be more complicated than for Ge and Si because of the lattice polarization. At low temperature, the Lax theory of cascade capture depends very little upon the details of the center. The electron makes a transition into an excited state having a large orbit, and whether it is captured or not is determined in these excited states. The subsequent time spent in losing energy in trickling down into the ground state of the center does not effect the capture cross section. As the temperature is raised, the cross section varies as $T^{-4}$, and lower lying states with smaller orbits become increasingly important. It is expected that at high temperature the details of the centers should become important and hence the Lax theory becomes invalid. A calculation for MgO indicates that this theory is not applicable for this material at temperatues over 100°K.

With this in mind, we will assume that the lifetime in Eq. (3) is expressed by $\tau^*=\text{const}\ T^{n-\frac{1}{2}}$, where $n$, to be determined from the experimental data at low temperatures, describes the temperature dependence of the cross section for the capture of holes by the centers occupied by electrons.

In order to account for the high-temperature region in Fig. 6, we will assume that the mean scattering time, $\tau$, is determined by scattering by optical modes,[8] by

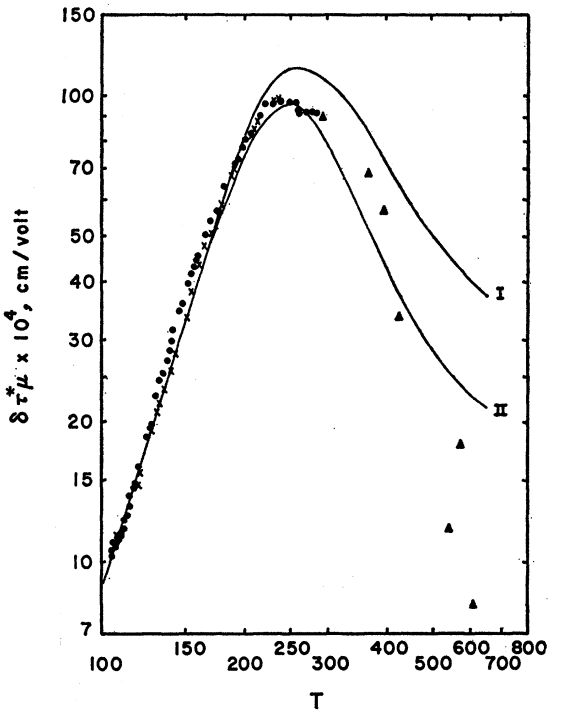


FIG. 6. $\delta\tau^*\mu$ vs temperature for the NC crystal. ● indicates temperature decreasing, and × temperature increasing; ▲ represents previously-published results,[2] normalized to low-temperature data at room temperature. Curve I shows the fit using Eq. (11); curve II shows the fit using Eq. (13).

[9] E. Conwell and V. W. Weisskopf, Phys. Rev. **77**, 388 (1950).
[10] F. J. Blatt, in *Solid-State Physics*, edited by F. Seitz and D. Turnbull (Academic Press, Inc., New York, 1956), Vol. 4.
[11] At high temperature (above 350°K) measurable post-bombardment conductivity has been observed following the pulse. This is discussed in R. A. Shatas, J. F. Marshall, and M. A. Pomerantz, Phys. Rev. **109**, 1953 (1958). It is caused by thermal re-emission into the conduction band of electrons temporarily trapped in shallow centers.
[12] E. S. Rittner, in *Proceedings of the Photoconductivity Conference in Atlantic City, 1954* edited by R. Breckenridge, B. R. Russell, and E. E. Hahn (John Wiley & Sons, Inc., New York, 1956).
[13] G. Bemski, Proc. Inst. Radio Engrs. **46**, 990 (1958).
[14] M. Lax, Phys. Rev. **119**, 1502 (1960).

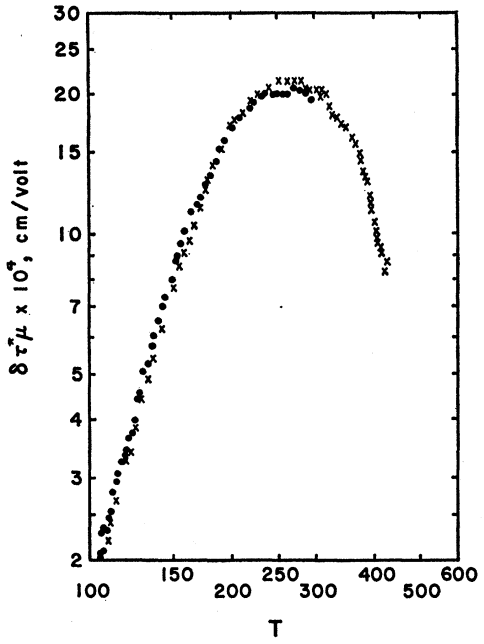


FIG. 7. $\delta\tau^*\mu$ vs temperature for the IRC crystal. ● indicates temperature decreasing and × temperature increasing.

acoustical modes,[6,7] and by ionized imperfections.[9,10] The mobility is then given by

$$\mu=(e/m)\langle\tau\rangle, \tag{4}$$

where

$$1/\tau=1/\tau_o+1/\tau_a+1/\tau_i.$$

The relaxation time of the carrier for the optical modes is:

$$\tau_o=c\exp(1710/T), \tag{5}$$

where $c=4.0\times10^{-16}$ sec has been calculated from the theory of Low and Pines as applied to MgO.[2,15] The acoustical mode relaxation time is taken to be

$$\tau_a=\pi\hbar^4x^{-\frac{1}{2}}c_{ii}/\sqrt{2}m^{\frac{3}{2}}(kT)^{\frac{3}{2}}E_1^2=a(T)^{-\frac{3}{2}}x^{-\frac{1}{2}}, \tag{6}$$

where $c_{ii}$ is the average longitudinal elastic constant, $E_1$ is the deformation potential proportionality constant, and $x=\epsilon/kT$, $\epsilon$ being the carrier energy. The Conwell-Weisskopf expression for the relaxation time for the ionized imperfections is

$$\tau_i=\sqrt{2}m^{\frac{1}{2}}\epsilon_0^2(kT)^{\frac{3}{2}}x^{\frac{3}{2}}/\pi N_ie^4\ln[1+\epsilon_0^2x^2k^2T^2/e^4N_i^{\frac{2}{3}}]$$
$$\sim b(T)^{\frac{3}{2}}x^{\frac{3}{2}}, \tag{7}$$

where $\epsilon_0$ is the dielectric constant and $N_i$ the density of imperfections in the sample. Because the absolute magnitude of the mobility is not measured, it will be assumed for simplicity in fitting the theory to experiment that the temperature dependence of the logarithmic term can be neglected. The resultant mobility may be expressed as

$$\mu=(e/m)\tau_oF(A,I), \tag{8}$$

[15] F. E. Low and D. Pines, Phys. Rev. **91**, 193 (1953).

where

$$F(A,I)=\frac{4}{3\sqrt{\pi}}\int_0^\infty\frac{e^{-x}x^{\frac{3}{2}}dx}{1+Ax^{\frac{1}{2}}+Ix^{-\frac{1}{2}}}, \tag{9}$$

and

$$A=(\tau_o/\tau_a)x^{-\frac{1}{2}}=(c/a)(T)^{\frac{3}{2}}\exp(\theta/T),$$
$$I=(\tau_o/\tau_i)x^{\frac{3}{2}}\sim(c/b)(T)^{-\frac{3}{2}}\exp(\theta/T). \tag{10}$$

The bombardment-induced conductivity is given by

$$\delta\tau^*\mu=BT^{n-\frac{1}{2}}(e/m)\tau_oF(A,I). \tag{11}$$

The integrals $F(A,I)$ have been calculated over a certain range of parameters by Porfir'eva.[16] A fit of $\delta\tau^*\mu$, based upon these calculations and an adjustment of the theory to agree with the experimental results at low temperatures, is shown as curve I in Fig. 6. The values $c/a=4.7\times10^{-8}(°\text{K})^{-\frac{3}{2}}$ and $c/b=39(°\text{K})^{\frac{3}{2}}$ were used. The curve could be lowered, and a better fit obtained, with larger values of $A$. Unfortunately, the available calculations of $F(A,I)$ are not sufficiently extensive in this region to make this worthwhile. At the low-temperature extreme, these results determine $n$ to be 2.3 in Eq. (11). This is a reasonable value.

As an alternative procedure, the effects of scattering may be combined approximately by adding reciprocal mobilities:

$$1/\mu=1/\mu_o+1/\mu_a+1/\mu_i. \tag{12}$$

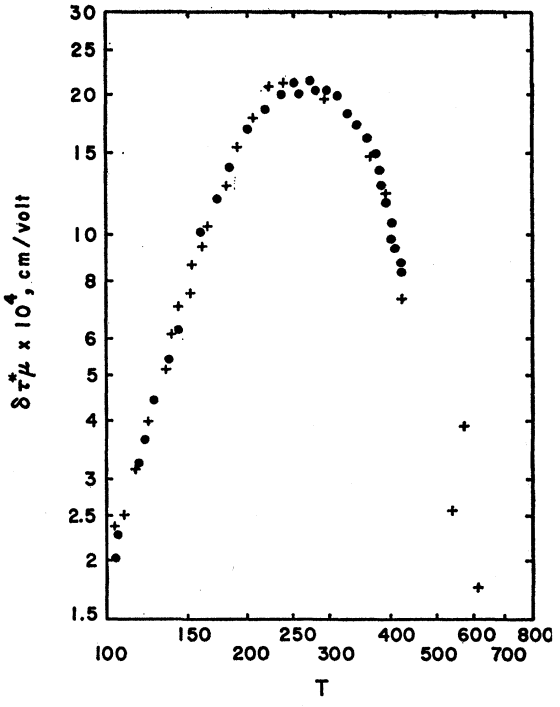


FIG. 8. Comparison of $\delta\tau^*\mu$ vs temperature for the two crystals from different sources. + represents the NC crystal and ● the IRC crystal. The two curves have been normalized at room temperature, and the density of data points (see Figs. 6 and 7) reduced.

[16] N. N. Porfir'eva, Soviet Phys.-Solid State **1**, 794 (1959).

This may be in error by as much as 30% near the region in which all the scattering mechanisms are important, i.e., near the maximum of the curve in Fig. 6. On this basis, we obtain

$$\delta\tau^*\mu = BT^{n-\frac{3}{2}}[\exp(-\theta/T)+(c/a)T^{\frac{3}{2}}+(c/6b)T^{-\frac{3}{2}}]^{-1}, \quad (13)$$

where the logarithmic function in $\mu_i$, the mobility due to ionized scattering alone, has been taken to be a slowly varying function of temperatures as in Eq. (11). The results of a reasonable fit are shown as curve II in Fig. 6. The theoretical curve has again been adjusted to provide best fit at low temperature. As with curve I, $B$ is a scale parameter and is undetermined by the experiment. In this case, again $n=2.3$, $c/a=1\times10^{-7}(°\text{K})^{-\frac{3}{2}}$, and $c/b=30(°\text{K})^{\frac{3}{2}}$. We see that, in fact, $c/a$ is increased, providing an improved fit, although considering the errors in Eq. (12), the two curves I and II are probably equally reliable.

Both curves I and II are in reasonable agreement with the experimental results up to temperatures near 400°K, and here they begin to depart appreciably. This is a consequence of the influence of the temperature dependence of the lifetime at the high-temperature limit, where Eq. (13) becomes $BT^{1.8}\exp(\theta)$. The experimental results would correspond more closely to the proposed explanation if $\tau^*$ became less temperature dependent than $T^{1.8}$ above room temperature (i.e., if the capture cross section varied more slowly than $T^{-2.3}$). We have assumed that the lifetime obeys this law over the entire range of temperatures considered. The departure at high temperature certainly reflects this oversimplification.

On the basis of curve I, a calculation of $c$ from the polaron theory of Low and Pines[13] (the polaron mass and effective mass of the electron are assumed equal to $m_e$) leads to a determination of $a$. From Eq. (6) with $c_{ii}\approx c_{11}=2.9\times10^{12}$ dynes/cm$^2$,[17] $E_i$, the deformation interaction coupling constant, may be computed. The value, 2.6 ev, is quite reasonable; furthermore, increasing the ratio $c/a$ to improve the fit, as suggested, would increase $E_i$ in the direction of the known values for this constant in other materials.[18]

The ratio $c/b$ obtained from curve I determines $N_i$, the density of ionized impurities. This gives $2\times10^{18}$/cm$^3$, which is the order of magnitude of some of the impurities ordinarily present in MgO obtained from Norton Company.[19] It is probable that impurities in the crystal may undergo changes of valence under irradiation by the linear accelerator beam, and thereby contribute to the ionized impurity scattering. If this is the case, saturation must occur, as evidenced by the fact that no changes in the bombardment-induced conductivity with time of exposure to the beam have been observed. The NC crystal had previously been subjected to much radiation experience prior to the present experiments. On the contrary, the IRC crystal was fresh and in the "raw" state at the beginning of the work. However, as has been pointed out by Peria,[20] the crystal in the raw state has strong absorption in the ultraviolet at 4 ev, associated with iron in the $Fe^{3+}$ valence state. Depending upon the distance at which this charge is compensated in the lattice, this could act as the ionized impurity scatterer. This kind of speculation suggests that studying the effects of bleaching upon optical absorption and bombardment-induced conductivity simultaneously at low temperature may provide relevant information concerning the hypothesis put forward here to account for the temperature dependence of the bombardment-induced conductivity in MgO.

The value of $N_i=2\times10^{18}$/cm$^3$ also suggests that the logarithmic term in Eq. (7) may be important, and that $T_i$ may be a more slowly varying function of temperature than $T^{\frac{3}{2}}$. However, because the absolute values of the mobility are unknown, the fitting of the curves with the logarithmic term included becomes unrewardingly tedious, in view of the uncertainties in the various parameters and in the applicability of the theory to ionic materials. In addition, one might consider using a different cutoff,[21] such as the Debye-Hückel screening radius, in the theory. Because of the low density of charge carriers in the conduction band during bombardment, the logarithmic term is probably unimportant insofar as the temperature variation is concerned.

Other models relying upon the temperature dependence of the recombination lifetime alone could undoubtedly be developed to account for the temperature variation of the bombardment-induced conductivity in MgO. However, the present formulation has the advantage of simplicity. Although a multiple level recombination theory, as has been propounded by Klasens,[22] could be invoked, the versatility of such an analysis would seem to limit its usefulness.

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