mately 40, so that even in the extreme anomalous region, $kl \gg 1$, we can still have $a \ll 1$, which gives a negligible correction to the frequency. In more recent experiments Bowers[8] has observed the higher harmonics in a thin slab of sodium, and for $kl \sim 8$ no measurable deviation from the linear ω vs k^2 relation was detected. Here $a = (kl/\omega_c\tau) \sim 0.2$, so that Eq. (7) predicts a correction of only 1%, which is less than the experimental error.

When $a \gg 1$ we find from Eq. (6) that

$$\omega = \pm k^2c^2/4\pi(\sigma_{xy} \mp i\sigma_{xx}). \quad (8)$$

If k is real, then ω is complex, and the wave is damped exponentially in time. This would be observed in the free decay of a standing wave when the wave vector is fixed by the sample dimensions. Because, from Eq. (4) $\sigma_{xx} \gg \sigma_{xy}$, the complex frequency is

$$\omega \cong \pm (k^2c^2\sigma_{xy}/4\pi\sigma_{xx}^2)[1 \pm i(\sigma_{xx}/\sigma_{xy})]$$
$$= \pm k^2(cH_0/4\pi ne)(16/3\pi^2)[1 \pm i(\pi a/4)]. \quad (9)$$

Thus for $a \gg 1$ the oscillations will be completely damped out.

The author would like to thank C. Kittel for his helpful advice and encouragement, and thanks also go to R. Bowers for original suggestion of the problem, and to R. G. Chambers who communicated and discussed his results.

[8] R. Bowers (private communication).

PHYSICAL REVIEW VOLUME 129, NUMBER 6 15 MARCH 1963

Mobility of Electrons in Silver Chloride at High Electric Field*

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(Received 22 October 1962)

The mobility of electrons in specially purified AgCl crystals at high electric field has been investigated in order to clarify the scattering mechanism of fast electrons in ionic crystals. A fast-pulse technique was adopted to observe both the transient photoconductivity and the Hall mobility for photoelectrons. The experimental results show that the mobility of fast electrons at low temperatures is a decreasing function of electric field. An energy dissipation mechanism similar to the scattering due to the acoustical mode of lattice vibration is suggested for these fast electrons.

THE theory of the polaron in ionic crystals usually applies to a "slow electron" in thermal equilibrium with the crystal lattice. As the electron gains energy from an electric field, departing from thermal equilibrium, it is expected that the "slow electron" concept will begin to fail and, in addition, certain differences in the scattering mechanism of electrons may take place. The mobility of electrons in AgCl under high electric field has been investigated in order to clarify these points.[1]

The experiment was made possible by using high-purity crystals zone-refined in a chlorine atmosphere. A total of more than 100 zones was passed through the length of the AgCl ingots contained in quartz tubes. It has been found that the Hall mobility of electrons, μ_H, is greater than $10^4 \text{cm}^2/\text{V sec}$ below 40°K in annealed samples cut out of such ingots.[2]

A fast-pulse technique was adopted to observe both the transient photoconductivity and the Hall mobility μ_H for photoelectrons.[3] Short light pulses having a duration of the order of 1 μsec excite electrons out of the full band into the conduction band during the maximum of a longer electric field pulse whose repetition rate was less than one per second. The transient photoresponse was determined by observing pulse height on an oscilloscope due to the drift motion of carriers in an electric field perpendicular to plane parallel electrodes. The Hall mobility of electrons was measured using the electrode geometry of Redfield.[4]

A typical example of observed pulse heights (proportional to induced charge per pulse, Q) versus electric field is shown in Fig. 1 for a pure AgCl crystal at $T = 6.5$°K. Since the "Schubweg" of electrons, $\mu_d E\tau_t$, is short (negligible saturation or collection effect) and positive holes are much less mobile than electrons in AgCl at low temperatures, Q is given by

$$Q = ne\mu_d E\tau_t/D, \quad (1)$$

where n is the number of electrons released by the light pulse in the volume of crystal; e, the electronic charge; μ_d, the drift mobility of electrons; E, the electric field; τ_t, the average life time of an electron before trapping; and D is the thickness of the crystal.

* Supported in part by the U. S. Air Force Office of Scientific Research.
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[1] T. Masumi, Bull. Am. Phys. Soc. 7, 38 (1962).
[2] T. Masumi and F. C. Brown, Bull. Am. Phys. Soc. 6, 131 (1961). T. Masumi and F. C. Brown (to be published).
[3] K. Kobayashi and F. C. Brown, Phys. Rev. 113, 507 (1959).
[4] A. G. Redfield, Phys. Rev. 94, 526 (1954).

At a fixed temperature and with a constant number of photons absorbed per light pulse, Eq. (1) states that Q should depend linearly on E corresponding to Ohm's law, assuming μ_d and τ_t are independent of E. Any deviation from Ohm's law could be attributed to the change either of μ_d or of τ_t. The departure from linearity in Fig. 1 is considered to be mainly due to a decrease in mobility as indicated in Fig. 2 which is a plot of the relation between the electric field and the relative ratio of Hall mobility μ_H to the low-field Hall mobility μ_{H0} at $T=10.8°K$. Here, the electric field is given by the average component $\bar{E}_x$[4]. A thick spacer was used as described in reference 4, so that $\bar{E}_x$ is very nearly the field applied to the resistance film electrode. The temperature difference between Figs. 1 and 2 is probably not very important. A recent experiment on the magnetoresistance effect in silver halides[5] also indicates the decrease of mobility as the electric field increases. The departures from linearity at high electric field seen in Figs. 1 and 2 were not found for pure crystals at $T=77°K$. In the case of impure crystals at low temperatures (below 12°K), the high-electric-field effect was observed to set in at much higher values of electric field.[6]

Experimental data on the mobility of electrons in AgCl at low electric field[2] show that the scattering of slow electrons at low temperatures near $T=10°K$ is structure dependent and perhaps mainly due to charged impurity centers. However, such a scattering mechanism is likely to be less important for the scattering of fast electrons.[7] Besides, it cannot provide the energy transfer mechanism for fast electrons in a high electric field. Some type of inelastic scattering, such as due to lattice vibrations, becomes increasingly important at high fields. At low fields, Fig. 1 shows that Ohm's law

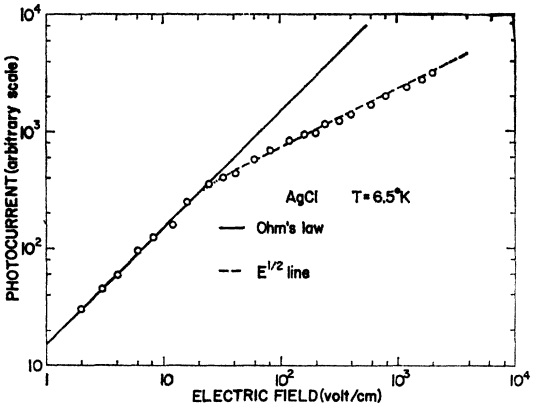

FIG. 1. Pulse height vs electric field for a pure AgCl crystal at $T=6.5°K$. The observed pulse height is proportional to the transient photocurrent.

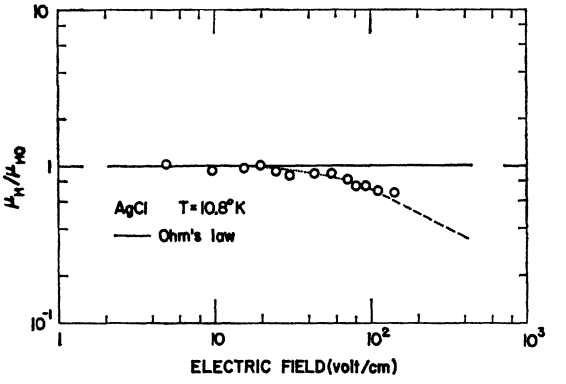

FIG. 2. Relative ratio of the Hall mobility of electrons μ_H to the low-field Hall mobility μ_{H0} for a pure AgCl crystal at $T=10.8°K$ as a function of the effective electric field.

is valid. At higher fields, the observed $E^{1/2}$ dependence suggests that a scattering mechanism whose scattering probability increases proportional to electron speed, v_1, becomes important if the energy lost per collision for fast electrons is assumed proportional to v_1^2. This scattering mechanism might be due to the acoustical mode of lattice vibration.[8]

As previously reported,[2] the Hall mobility of an electron in these high-purity AgCl crystals below 40°K down to 4°K is quite high (e.g., $\mu_{H0}=2\times10^4 cm^2/Vsec$), whereas the velocity of the longitudinal acoustic wave, c_s, is rather small ($c_s=3.29\times10^5 cm/sec$ for AgCl[9]). Consequently, one expects hot electron phenomena to set in at fairly low electric fields. Actually, an estimate of the critical drift velocity v_{dc} for departure from Ohm's law gives a value comparable with the sound velocity, c_s. A rather low experimental value of v_{dc} indicates an energy dissipation mechanism in which the average energy lost per collision is quite small, such as by the acoustical phonons.

Although there still remain open a few questions concerning such as the failure of the "slow electron" concept in the polaron theory[10] and the behaviours of trapping time τ_t, at very high electric fields, it appears conceivable that a higher energy conduction electron interacts mainly with the acoustical mode of lattice vibration, at least, in the region where the electron velocity is only moderately large. The importance of the acoustical mode of lattice vibration for the scattering of high-energy electrons in ionic crystals was noted several years ago by Seitz.[11]

The author would like to acknowledge the assistance of Professor Frederick C. Brown and also the support of the Nishina Memorial Foundation, Tokyo, Japan.

[5] H. H. Tippins and F. C. Brown, Phys. Rev. **129**, 2554 (1963).
[6] T. Masumi and F. C. Brown (to be published).
[7] E. M. Conwell, Phys. Rev. **90**, 769 (1953).
[8] W. Shockley, Bell System Tech. J. **30**, 991 (1951).
[9] D. L. Arenberg, J. Appl. Phys. **21**, 941 (1950).
[10] Yu I. Gorkum and K. B. Tolpygo, Bull. Acad. Sci. (U.S.S.R.) 24, 91 (1960). (Columbia Translations.)
[11] F. Seitz, Phys. Rev. **76**, 1376 (1949).