Hot-Electron Effects in Semiconducting Cadmium Sulfide

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By using a nanosecond-pulse technique, hot-electron effects of semiconducting cadmium sulfide were investigated without the collective-phonon-buildup phenomenon. At 300 K, the current deviated from Ohm's law above values of the electric field of 5×10^4 V/cm, which was interpreted as due to the increase of electron drift mobility. At 77 K, the drift mobility due to the deformation-potential scattering was greatly influenced by the electron-trapping effect. At 4.2 K, the drift mobility was independent of electric field between 3×10^3 and 1×10^4 V/cm, which was well understood by assuming the effect of the hot-electron-caused disturbance of the phonon distribution.

Studies of electron-phonon interactions in cadmium sulfide have been made so far along two lines. One is concerned with the stimulated emission of phonons which cause the saturation of electric current.[1] The other is related to the spontaneous emission of phonons,[2] in which the state of the lattice wave is stable and hot-electron effects have been studied in photoconductive crystals.[3] It seems important to understand the relation between the stimulated and the spontaneous emission of phonons in strongly piezoelectric crystals. As a first step to that purpose, we report in this paper hot-electron effects in "semiconducting" cadmium sulfide observed without the collective-phonon-buildup phenomenon.

Single-crystal samples were cut out from ingots of Eagle-Picher "UHP" crystal. Two samples 1.0 and 0.15 mm in length were used. The sample was etched by H_3PO_4 and $K_2Cr_2O_7$.[4] Indium electrodes alloyed into cadmium sulfide in a flow of H_2 gas preserved the low-field Ohmic properties over the whole range of temperatures. The sample was inserted into a 50-Ω coaxial line (GR874). A pulse generator (Microwave Associates 961DA) supplied a high-voltage pulse, whose duration time and repetition rate were 2 nsec and 50 Hz, respectively. The current pulse in the dark state was picked up by a 50-Ω standard resistance, delayed, attenuated, fed into a sampling oscilloscope, and recorded. The rise time of the set up was shorter than 500 psec. A typical example of current pulse is shown in Fig. 1. The oscillation is due to a spurious effect inherent from the pulse generator. This gave about 5% errors in the current value. Current-saturation measurements done at 300 K showed that the drift mobility μ_d and the carrier concentration n of the sample were 290 $cm^2/V\,sec$ and 7.2×10^{15} cm^{-3}, respectively.

In Fig. 1 is also shown current vs field relation at 300, 77, and 4.2 K. The voltage was applied perpendicular to the c axis.[5] At 300 K, the current changes with the electric field keeping the linear relationship up to 5×10^4 V/cm. Above 5×10^4 V/cm, the curve begins to deviate from the linear relations and increases with increasing electric field strength. At 77 K, the current keeps the linear

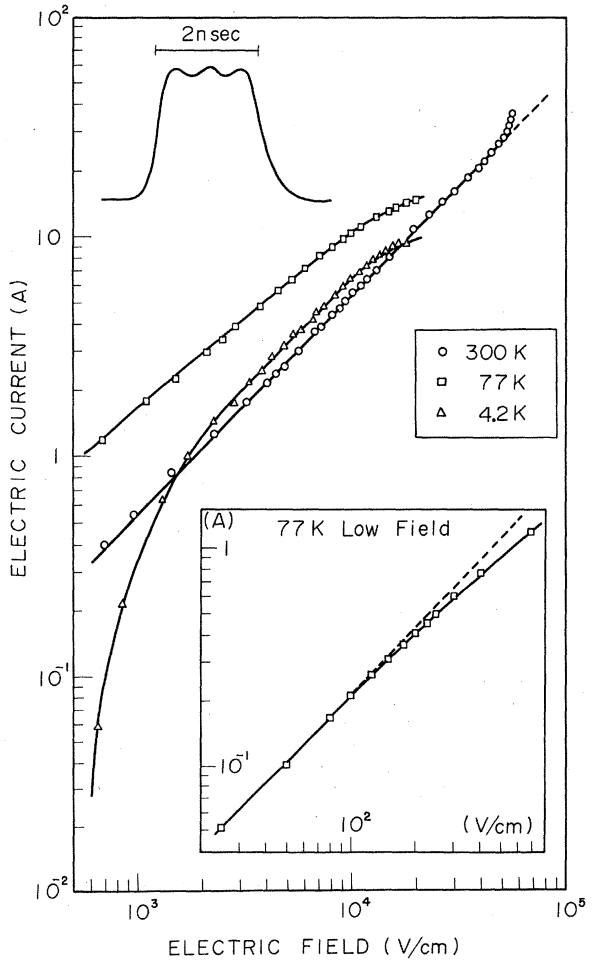

FIG. 1. Current vs field relation of semiconducting cadmium sulfide at 300, 77, and 4.2 K. The current-pulse form is also shown.

relation up to about 1×10^2 V/cm. Above 1×10^2 V/cm, the current begins to deviate gradually from the Ohmic relation. The rate of the current increase becomes smaller with increasing electric field. It is expected that current value will tend to saturate above 2×10^4 V/cm. The behavior of this current-field relation was not appreciably changed up to about 10-nsec pulse duration. At 4.2 K, the low-field conductivity seems very small. The current value increases rapidly between 6×10^2 and 1×10^3 V/cm. As the field becomes larger, the rate of current increase becomes gradually smaller. Between 3×10^3 and 1×10^4 V/cm, the current increases keeping the linear relationship with the electric field. Above 1×10^4 V/cm, the current increases with increasing electric field more slowly than linearly. The field dependence of the drift mobility is shown in Fig. 2. As is expected from Fig. 1, the μ_d value at 300 K is independent of electric field up to 5×10^4 V/cm, and increases above 5×10^4 V/cm. At 77 K, μ_d decreases with increasing electric field above 1×10^2 V/cm. At 4.2 K, μ_d is independent of the electric field between 3×10^3 and 1×10^4 V/cm. Above 1×10^4 V/cm, μ_d decreases with increasing electric field.

The trap-controlled drift mobility μ_d is expressed by $\mu_d=\mu_H[n/(n+n_t)]$, where μ_H is the Hall mobility and both n and n_t are the densities of free and trapped carriers, respectively.[6] At 300 K, it is natural to assume $n\gg n_t$ and $\mu_d\approx\mu_H$. At this temperature, electrons will be scattered mainly by longitudinal polar optical phonons.[7] The electron mobility coming from polar scattering will not be sensitive to the electric field when the Debye temperature Θ is about the same as the lattice temperature.[8] Since $k\Theta$ is about 0.04 eV, the behavior of the current curve is not inconsistent with the estimated one. The breakdown field E_0 defined by the field representing a measure of the strength of coupling to polar optical modes is expressed by $E_0=m^*e\omega_l(1/\kappa_\infty-1/\kappa_0)/\hbar$, where m^* is effective mass of electrons, ω_l is the longitudinal-optical-mode frequency, and κ_0 and κ_∞ are the dielectric constants for zero and infinite frequencies, respectively.[2] If we put $m^*=0.2m$, $\hbar\omega_l=0.038$ eV,[7] $\kappa_\infty=5$, $\kappa_0=9$,[9] then we obtain $E_0=1.3\times10^5$ V/cm. It is suggested that the electron mobility will increase around $0.5E_0$.[8] In our case, the drift velocity attains about 10^7 cm/sec around 3×10^4 V/cm, and electron temperature should attain lattice temperature around this field based on the electron-temperature approximation. Thus, the nonlinear relation in the current vs field curve observed above 5×10^4 V/cm may be due to the increase of the electron temperature. Our case is different from that of insulating cadmium sulfide.[10] It should be remarked that the drift velocity around 3×10^4 V/cm is about 50 times larger than that of sound velocity 2×10^5 cm/sec, and no appearence of current instability was found even at the maximum field. At 77 K, the current-saturation measurements yielded $\mu_d=1.2\times10^3$ cm^2/V sec, which is smaller than the Hall-mobility value.[7] This may be due to the increase of n_t or the trapping time.[6] It is estimated that trap time and free time are 0.6 and 0.2 nsec, respectively.[6] This is not inconsistent with the decrease of drift mobility. Because of the difficulty of obtaining the field dependence of the trapping time, we assume for simplicity that the trapping time will be independent of electric field, and the tendency of the μ_d-vs-E curve will be similar to that of μ_H-vs-E curve at higher electric fields. At this temperature, the deformation-potential scattering and the piezoelectric-potential scattering will contribute to the field dependence of μ_H or μ_d. Because of the different dependence of the collision time on electron velocity, the former will be predominant at higher electric fields. The rôle of the deformation potential is also understandable from the fact that the nonlinear effect appears to set in around 1×10^2 V/cm, where the drift velocity of an electron attains the sound velocity. If so, the field dependence of the mobility should be proportional to $E^{-1/2}$. The experimental results below 1×10^4 V/cm, however, deviate from this relation, and the rate of the mobility decrease is slower than that of the estimation. This difference might be coming from the trapping effect. Between 1×10^4 and 2×10^4 V/cm, the field dependence of mobility may be interpreted as due to acoustical-mode scattering only. It should be also remarked that the drift velocity attains about 40 times larger than the sound velocity at the maximum field of 2×10^4 V/cm, and no instability takes place within a nsec time duration.

At 4.2 K, the impact-ionization process will take place below 3×10^3 V/cm.[6] It is supposed that

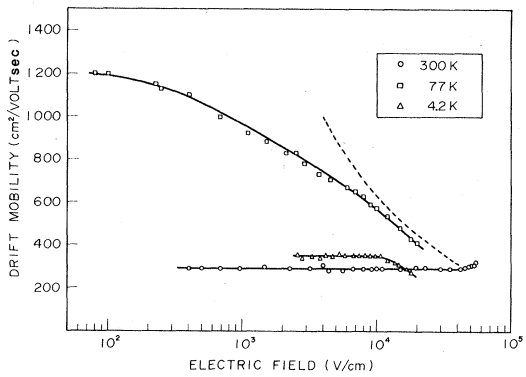

FIG. 2. Electric field dependence of drift mobility. The dashed line represents acoustical-mode scattering only.

above 3×10^3 V/cm, all the trapped electrons will be excited into the conduction band, and carrier densities will be constant. Therefore, the linear dependence of current on electric field suggests that the trap-free electron mobility will be independent of electric field between 3×10^3 and 1×10^4 V/cm. Among several possible mechanisms for the constant mobility, we will consider here the effect of the hot-electron-caused disturbance of the phonon distribution. Because of the high rate of phonon generation by hot electrons, and the weak phonon-phonon interaction at 4.2 K, it is expected that significant deviations from the thermal-equilibrium phonon distribution might be found at 4.2 K. This idea was presented theoretically by Paranjape[11] and Conwell,[12] and demonstrated in the case of covalent semiconductor such as n-type germanium.[13] In polar semiconductors, the same mechanism as that in covalent semiconductors is assumed for simplicity. According to Paranjape, when the scattering due to acoustical phonons prevails over other scattering mechanisms, the electric field dependence of the electron mobility is described by the relation $\mu_d \propto E^{-2(1-\beta)/(4-\beta)}$, where β is a constant depending on the phonon scattering mechanism, in which the lifetime of phonons $\tau(q)$ is expressed by $\tau(q)=\tau(q_0)\cdot(q_0/q)^\beta$. When $\beta=1$, it follows from this relation that the electron mobility should be independent of electric field. It is estimated that $\beta=0$ for the boundary scattering, and $\beta=1$ for phonons with energies in excess of thermal energies. The former is not important here because the time of sound propagation is much longer than the duration time of voltage pulse. Therefore, the observed linear relation of the current-vs-field curve between 3×10^3 and 1×10^4 V/cm is well understood by putting $\beta=1$ as far as the field dependence is concerned. Paranjape also suggests that when the electron temperature becomes sufficiently large, the effect of such a field-enhanced lattice scattering would gradually decrease. The observed $E^{-1/2}$ dependence above 1×10^4 V/cm suggests the appearence of the normal acoustical-phonon scattering effect.

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Low-Temperature Thermal Conductivity of p-Type Ge and Si

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The thermal conductivity of lightly doped p-type Ge and Si at low temperatures is calculated in terms of a single-mode phonon relaxation time due to elastic scattering by holes in the four-fold degenerate ground state together with boundary and isotopic scattering. Good agreement between the theory and experiment is obtained except at very low temperatures. The relation between the present theory and the mechanism responsible for the heat pulse and ultrasonic attenuation is briefly discussed.

I. INTRODUCTION

Large decreases of the thermal conductivity of lightly doped n-type Ge at low temperatures are caused by the phonon scattering by donor electrons.[1–4] Keyes[1] and Griffin and Carruthers[2] have