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X-7. High Field Mobility of Photoelectrons in CdS

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High field behaviors of photoelectrons in CdS crystals have been investigated by the experiments of pulsive photo-Hall effect and photocurrent in the blocking electrode system. The Hall mobility increases initially and then decreases with the increase of electric field below 50°K. In the temperature range between 50°K and 100°K, the Hall mobility decreases monotonically with the increase of field. The field dependence of mobility are in good agreement with prediction based on scattering by superposition of the deformation and the piezoelectric potentials due to lattice waves.

§ 1. Introduction

Recently, many works have been published on the saturation and the oscillation of current at high electric field in CdS crystals.[1,2] These behaviors are explained in terms of the collective interaction between electrons and phonons.[3] On the other hand, the high field properties of electrons without collective interaction have not been investigated in detail on the piezoelectric crystals. In the present work, the field dependence of mobility has been determined for photoelectrons in the stable state of lattice wave.

Low field mobilities of photoelectrons in the CdS crystal are shown in Fig. 1* as a function of temperature. The Hall mobility μ_H is proportional to $\exp(\Theta/T)-1$ above 100°K (region I), and to $T^{-1/2}$ below 50°K (region III), where Θ is the Debye temperature of longitudinal wave. Fujita *et al.*,[4] have concluded, electrons are scattered by the longitudinal optical phonons (OMS) in the region I and by the piezoelectric potential due to acoustic one (PPS) in the region III, respectively. Anisotropy of factor 1.5 in Hall mobility over the temperature range where the scattering is mainly due to the piezoelectric effect, is described by anisotropies of the effective mass and the collision time of electrons.[5] In the region II, the deformation potential scattering (DPS) is proposed to be superposed on OMS and PPS in order to explain the experimental results of μ_H vs. T more accurately, from which the isotropic deformation potential E_d has been estimated to be 15 eV.

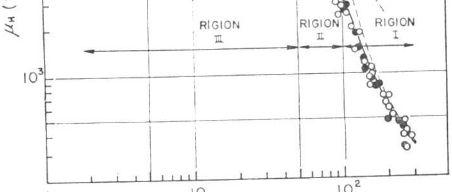

Fig. 1. Hall mobility of photoelectrons in a CdS crystal as a function of temperature, where open circles correspond to $\mu_{\perp c}$ and closed ones to $\mu_{\parallel c}$.

* Nearly same results were reported by Fujita *et al.*[4] but absolute values of μ_H below 50°K in Fig. 1 are a little larger than those in the former.

As mention above, different scatterings for electrons in CdS crystals contribute the field dependence of mobility at different temperatures. The collision time of electrons as a function of their velocity which is concerned with the scattering mechanism, leads to the characteristics of the high field mobility.[6] Experiments have been carried out in order to reveal the characteristics of hot electrons scattered mainly by the piezoelectric potential and to clarify the contribution of the deformation potential.

§ 2. Hot Electrons Scattered by Both Deformation and Piezoelectric Potentials

Since DPS and PPS are more dominant for the low field mobility than OMS below 78°K, we shall discuss the characteristics of the mobility of hot electrons due to superposition of DPS on PPS after the Sodha-Eastman method.[7]

The collision time of DPS and PPS as a function of the velocity of electrons v are expressed as

$$\tau_d = l/v\,, \qquad \text{for DPS}\,, \tag{1}$$

$$\tau_p = Av\,, \qquad \text{for PPS}\,, \tag{2}$$

where l is the mean free path of electrons and A is a constant. The drift mobility μ and the combined collision time τ are given by

$$\mu = \frac{e}{m^*}\left\langle \frac{1}{v^2}\frac{d}{dv}(\tau v^3)\right\rangle \tag{3}$$

$$\tau = \tau_d\tau_p/(\tau_d+\tau_p)\,. \tag{4}$$

Here $\langle\ \rangle$ denotes averaging over the velocity distribution of electrons.

Now we shall assume the distribution function* of electron as

$$N(v)dv = N_0 \exp(-\lambda v^2)v^2 dv\,, \tag{5}$$

where $\lambda = m^*/2k_0T_e$ and k_0 is the Boltzmann constant. At a low field, the electron temperature T_e is equal to the lattice one T_0. From eqs. (1), (3) and (5), the low field mobility due to DPS is

$$\mu_{d0} = \frac{4el\lambda_0^{1/2}}{3m^*\sqrt{\pi}}\,. \tag{6}$$

By the same procedure, the low field mobility only due to PPS is

$$\mu_{p0} = \frac{8Ae\lambda_0^{-1/2}}{3m^*\sqrt{\pi}}\,. \tag{7}$$

With a parameter of

$$a = \mu_{d0}/\mu_{p0}\,, \tag{8}$$

the collision time in eq. (4) is

$$\tau = \frac{lv}{v^2+(2a/\lambda_0)}\,. \tag{9}$$

The drift mobility due to both DPS and PPS is obtained by eqs. (3), (5) and (9),

$$\mu = \frac{4el\lambda_0^{1/2}}{3m^*\sqrt{\pi}}(\lambda/\lambda_0)^{1/2}\int_0^\infty \frac{2u^5\exp(-u^2)}{u^2+(2a/x^2)}du\,, \tag{10}$$

where $u=\lambda^{1/2}v$, and $x=(\lambda_0/\lambda)^{1/2}$. Therefore,

$$\mu = \mu_{d0}x^{-1}F(2a/x^2)\,, \tag{11}$$

with a quantity $F(z)$ calculated numerically by Dingle,[9]

$$F(z) = \int_0^\infty \frac{2u^5\exp(-u^2)}{u^2+z}du\,. \tag{12}$$

In the calculation of the energy losses, we shall consider only DPS in the first approximation, since the energy loss by PPS is much smaller than that by DPS. Shockley has shown that the average energy loss due to DPS is given by[10]

$$(d\varepsilon/dt)_c = -\frac{8c^2m^*}{e\sqrt{\pi\lambda}}(x^2-1) \tag{13}$$

where c is the sound velocity of longitudinal wave. The energy gain from the field is

$$(d\varepsilon/dt)_f = e\mu E^2 \tag{14}$$

In the steady state,

$$(d\varepsilon/dt)_c + (d\varepsilon/dt)_f = 0 \tag{15}$$

From eqs. (11), (13), (14) and (15), the relation between x and E is obtained;

$$E^2 = \frac{32c^2x^2(x^2-1)}{3\pi\mu_{d0}^2F(2a/x^2)}\,. \tag{16}$$

The combination of eqs. (11) and (16) gives the field dependence of the drift mobility. The results are shown in Fig. 2 with different values of the parameter a. The curve of $a=0$ corresponds to the case of DPS only.

§ 3. Experimentals and Results

Highly resistive crystals, made by the Piper-Polich method,[11] were cut into about $5\times5\times1$ mm^3. Experiments of the photocurrent were carried out by a pulsive illumination about 490 mμ light. The photoresponse Q as a function of E at different temperatures are shown in Fig. 3. The non-linearity of Q vs. E at 300°K is explained in terms of saturation of the "Schubweg" of photoelectrons with the increase of E, since the curve fits well to the Hecht formula.[12] Other curves corresponding to 78°K, 4.2°K, and 1.8°K are not conformable to the Hecht formula so that they may be due to the characteristics of mobility of hot electrons, if the life time of electrons is not affected by the field.

In the experiments of photo-Hall effect, the Kobayashi-Brown method[13] was improved so that difficulties in the contact and the space charge polarization should be excluded completely. The light longer than 560 mμ was used in order to excite electrons uniformly over the specimen. The total number of electrons about 10^9/cc are

* Although the present theory is rather conventional compared with the Saito-Uemura one in which accurate distributions of hot electrons are introduced by solving the Boltzmann equation,[8] experimental results can be explained by the former as well as by the latter.

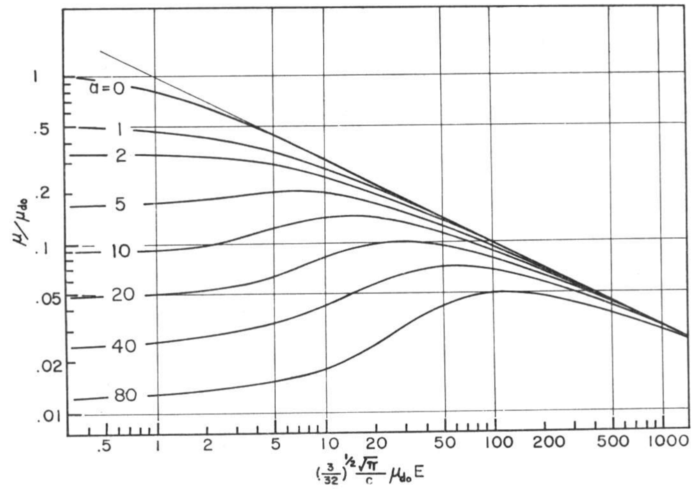

Fig. 2. Theoretical curves of the drift mobility, μ vs. the field, E, with different values of the parameter, a.

created by a light pulse of about 1 μsec duration, so that the collective phonon would not be induced. The Hall mobility μ_H, the pulse height *PH*, and the photoresponse Q, at 4.2°K as a function of E are shown in Fig. 4. The error in relative magnitude of μ_H at a constant temperature is less than 5%. The pulse height means the transversely induced charge in the longitudinal electric field and the vertical magnetic field, which is approximately proportional to $\mu_H^2 E$.[4] In Fig. 5 are shown μ_H vs. E at different temperatures. The mobility μ_H at low temperatures varies with the increase of E, while μ_H at 300°K is constant because of the low drift velocity due to the low value of μ_H, 350 $cm^2/V \cdot sec$.

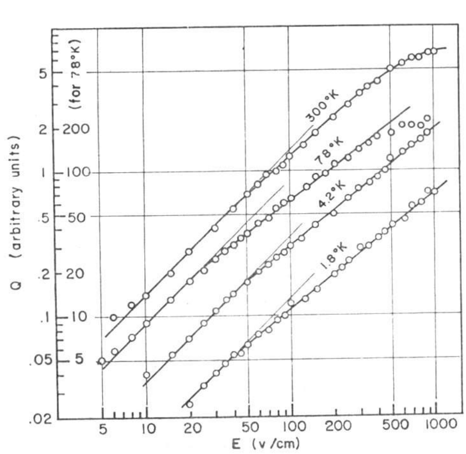

Fig. 3. Photoresponse, Q, as a function of the field, E, at different temperatures.

§ 4. Discussions

Experimental results in Fig. 5 are compared with theoretical curves in Fig. 2 in order to determined the values of a and μ_{d0} at different temperatures and directions, where μ_H is assumed to be equal to the drift one, μ. By fitting the experimental curve of μ_H vs. E at 78°K to a suitable theoretical curve in Fig. 2, we obtain that $a=1.0$ and $\mu_{d0}=1.02\times10^4$ $cm^2/V \cdot sec$. The value of a at different temperatures are determined by the above method as given in the 3rd column of Table I, denoted as $a(\mu-E)$. On the other hand, the values of μ_{d0} are estimated to be 3.9×10^5 $cm^2/V \cdot sec$ at 6.8°K, 8.2×10^5 $cm^2/V \cdot sec$ at 4.2°K and 2.9×10^6 $cm/V \cdot sec$ at 1.8°K as tabulated in the 6th column, when the value of μ_{d0} at 78°K is extrapolated

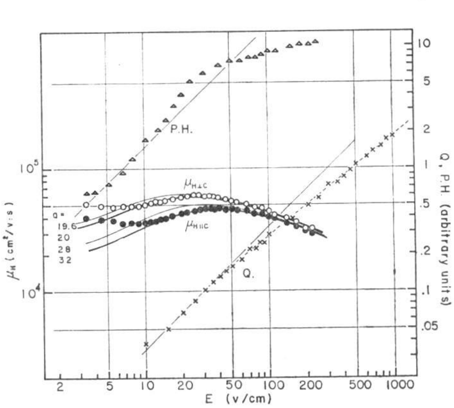

Fig. 4. The dependence of the Hall mobility, μ_H, the pulse height, *PH*, and the photoresponse, Q, on the applied field, E, at 4.2°K.

to fit the $T^{-3/2}$ law due to DPS. Therefore we can get the value of μ_{p0} at 78°K from the experimental combined mobility by using μ_{d0} at 78°K derived above. The values of μ_{p0} at different temperatures and for directions calculated by the $T^{-1/2}$ law due to PPS, are given in the 7th column. Theoretical values of a, denoted as $a(\mu-T)$, are obtained as tabulated in the 2nd column from eq. (8) using the values of μ_{d0} in the 6th column and μ_{p0} in the 7th column. It is noticed that the value of $a(\mu-T)$ are nearly equal to those of $a(\mu-E)$ at different conditions. Therefore the field dependence of the Hall mobility of photoelectrons is explained in terms of the characteristics of hot electrons scattered by both deformation and piezoelectric potentials. The deformation potential is estimated to be 15 eV from the value of μ_{d0} at 78°K, which agrees quite well with that deduced from the temperature dependence of μ_H.

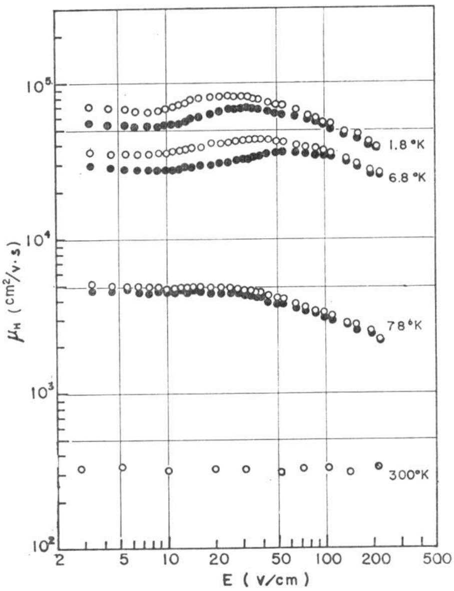

Fig. 5. The field dependence of the Hall mobility, μ_H, at different temperatures.

The field at which the mobility has the maximum values, is tabulated in the 4th column, denoted as $E_{\max}$ (I), by the calculation from the theoretical curves in Fig. 2 using the values of a in the 2nd column and μ_{d0} in the 6th one. The values of $E_{\max}$ (I) are comparable to the experimental values of $E_{\max}$ (II) as shown in 5th column.

Table I.

		a		$E_{\max}$ (V/cm)		μ_{d0}	μ_{p0}
		$(\mu-T)$	$(\mu-E)$	(I)	(II)	(cm²/V·sec)	(cm²/V·sec)
78°K	$\mu_{\perp c}$	1.0	1.0	—	—	1.02×10^4	1.02×10^4
	$\mu_{\parallel c}$	1.4	1.5				1.43×10^4
6.8°K	$\mu_{\perp c}$	11.5	10	35.4	45	3.9×10^5	3.4×10^4
	$\mu_{\parallel c}$	17.3	15	47.2	70		2.2×10^4
4.2°K	$\mu_{\perp c}$	19.6	20	24.1	26	8.2×10^5	4.3×10^4
	$\mu_{\parallel c}$	28.3	30	30.0	35		2.9×10^4
1.8°K	$\mu_{\perp c}$	43.9	50	16.6	20	2.9×10^6	6.6×10^4
	$\mu_{\parallel c}$	65.9	75	23.9	27		4.4×10^4

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