# VIII-5.

# Galvanomagnetic Properties of Surface Layers in Indium Arsenide

# S. KAWAJI and Y. KAWAGUCHI

## Department of Physics, Gakushuin University, Mejiro, Tokyo, Japan

The Corbino magnetoresistance of *n*-type surface layers on *p*-type indium arsenide crystals was measured as a function of electric field at the surface. The surface carrier mobility became greater as the surface carrier concentration became higher at  $4.2^{\circ}$ K. However, the mobility had a peak and decreased beyond some values of carrier concentrations at 68°K and 77°K. These behaviors of the mobility is explained by a model based on the carrier scattering associated mainly with charged centers and partly with surface correlated lattice vibration in a two dimensional energy band.

#### §1. Introduction

Anomalous behaviors of the Hall coefficient of *p*-type indium arsenide crystals were observed by several authors and attributed to the effect of the *n*-type surface layer on the crystals.<sup>1</sup>) Recent investigations for atomically clean surfaces<sup>2</sup>) as well as metal-semiconductor contact<sup>3</sup> showed also that this material has a degenerate *n*-type surface layer even on the *p*-type bulk. Moreover, an unusual behavior which is attributable to quantum effect associated with narrow surface space charge region was observed in surface field effect on high magnetic field magnetoresistance of surface layers of *p*-type crystals.<sup>4</sup>)

Quantum effects associated with the motion of carriers perpendicular to the surface due to a narrow potential well were discussed for cleaned germanium surfaces,<sup>5~7)</sup> for oxidized silicon surfaces,<sup>8)</sup> for indium antimonide surfaces,<sup>9)</sup> for germanium grain boundary<sup>10)</sup> and for the broadening of the space charge layer.<sup>11)</sup>

In the present paper, results of the Corbino magnetoresistance experiments for n-type surface layers of p-type indium arsenide will be presented. Temperature and carrier concentration dependence of the electron mobility in the surface layer will be discussed by a model which is based on the scattering process which is ruled mainly by charged centers and partly surface correlated lattice vibrations in a two dimensional energy band.

#### §2. Experimental

A *p*-type indium arsenide single crystal with a hole concentration of  $2.6 \times 10^{16}$ /cm<sup>3</sup> in the

extrinsic range was cut to a disk whose surfaces were parallel to {111}. The surfaces of the specimen were polished by  $10 \mu$  abrasive and etched in the mixture of  $H_2SO_4$ :  $H_2O_2$ :  $H_2O =$ 1:1:1. Corbino type electrodes were made by evaporation of metallic tin. Diameter of the inner electrode was 2 mm and that of the outer one was 9 mm. Field effect arrangement was made by sandwitching a mylar sheet of one half mil thick as a dielectric spacer between a crystal surface and an aluminum foil. This arrangement was made on both surfaces of the specimen. The sample was immersed directly into liquid helium or nitrogen.

The magnetoresistance versus magnetic field strength up to 25 kOe was measured by recording the voltage drop between two Corbino electrodes. The voltage drop was kept less than 10 mV. No change of the sample resistance was observed when the voltage drop was raised up to several tens of mV. No rectification was observed by changing the polarity of the current. These facts and the magnitude of the resistance show that the evaporated tin electrodes were ohmic for *n*-type surface layer and that the electric current did not flow through the p-type bulk. The electron concentration in the surface layer was changed by applying a dc voltage to one of the field effect electrode while the field effect electrode on the opposite surface was grounded.

The mobility was determined from the magnetoresistance at weak magnetic field ( $\omega \tau < 1$ ). Then, the electron concentration was determined from the surface conductance at zero magnetic field.

### §3. Results and Discussion

The data depend on sample and ambient condition. But, the general feature of the data for different samples are consistent. Therefore, typical data are shown in the present paper.



Fig. 1. Changes in the magneto-resistance by voltages applied to the field effect electrode at 77°K.



Fig. 2. Mobility vs. surface carrier concentration at 4.2°K, 68°K and 77°K.

Examples of the changes in the magnetoresistance by the electric field at the surface are shown in Fig. 1. The mobilities as a function of the carrier concentration at  $4.2^{\circ}$ ,  $68^{\circ}$  and  $77^{\circ}$ K are shown in Fig. 2.

The results are summarized as the following. (1) The electron concentration in the surface layer is almost independent of temperature. (2) The mobility is also almost independent of temperature in the region of low carrier concentration. (3) The mobility becomes higher as the carrier concentration becomes higher at  $4.2^{\circ}$ K, however, it has a peak and begins to decrease at some carrier concentration at  $68^{\circ}$ K and  $77^{\circ}$ K. The former is independent of sample, however, the latter depends on sample.

These results can be well explained by a following model.

The electron energy levels near the surface can be approximated by a model shown in Fig. 3. Here, the potential is linear in the surface region where the electrons are confined. Outside of this region is described by the Schottky potential.

The electric field at the surface in the semiconductor,  $\alpha$ , is determined from the electric charges in the surface space charge region which is consist of the ionized acceptors and the electrons in the surface layer. The ground and next higher energy levels of the kinetic motion perpendicular to the surface of an electron in



Fig. 3. Energy level model at the surface of a *p*-type indium arsenide.

Table I.

$N_s$ (cm <sup>-2</sup> )	$(\mathbf{V/cm})^{\alpha}$	$Z_0$ (cm)	$\begin{array}{c} E_0\\ (\mathrm{eV}) \end{array}$	$\stackrel{E_1}{(\mathrm{eV})}$	$\mathop{E_F}\limits_{(\mathrm{eV})}$
1×1011	7.60×104	1.39×10 <sup>-6</sup>	0.099	0.165	0.109
2×1011	8.45×104	1.31×10 <sup>-6</sup>	0.111	0.18	0.130
3×1011	9.73×104	$1.25 \times 10^{-6}$	0.122	0.19	0.151
4×1011	1.10×10 <sup>5</sup>	1.22×10 <sup>-6</sup>	0.133	0.205	0.172
5×1011	1.23×10 <sup>5</sup>	1.16×10-6	0.142	0.215	0.190
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the potential well shown in Fig. 3 as  $E_0$ , and  $E_1$ , respectively, are calculated for different surface carrier concentration,  $N_s$ , in Table I. Here,  $E_0$  is calculated analytically for the linear potential well,<sup>6)</sup> and  $E_1$  is calculated numerically for the potential well in which the linear one and the Schottky approximation is connected at  $E_0$ . In this calculation, the effective mass of an electron and the dielectric constant are taken to be 0.025 m and 14, respectively.

In Table I,  $(E_1-E_0)$  is much greater than kT. Therefore, the electron motion perpendicular to the surface is considered to be quantized. Moreover, the Fermi level,  $E_F$ , lies below  $E_1$ . Therefore, the electron state is well described by a simple two dimensional energy band in which the density of state is given by  $N(E)=4\pi m^*/h^2$ , where  $m^*$  is the effective mass of an electron and h is Planck's constant.

The result (1) indicates that the surface carriers are degenerate. This agrees with the present model. The result (2) indicates that the lattice vibration does not play main role in carrier scattering process.

One possible scattering mechanism is that by the surface. However, the momentum of the carriers perpendicular to the surface is fixed in the two dimensional band, therefore, the diffuse surface scattering in the sense of the three dimensional band does not exist in the present case. A somewhat different scattering process due to the surface may play some roles. The topography of the etched indium arsenide surfaces should be wavy. The amplitude of the topographical wave is probably greater than the thickness of the surface conductive layer of about 100 Å. But, its wavelength is considered to be much longer than the amplitude. Consequently, the wavy thin conductive layer is smooth for the carriers. However, some parts with short wavelength in topography may reflect the carriers. The scattering by this process is expected to be important for the carriers with shorter wave length. The result (3) suggests that this process does not play an important role at 4.2°K and in the low carrier concentration region at 68°K and 77°K. Therefore, charged centers are expected to play the most important role in the mobility.

A two dimensional version of the Conwell-Weisskopf<sup>12)</sup> formula is given by following way. The differential cross-section for Rutherford scattering in two dimension is given by

$$\sigma(\theta) = \frac{e^2}{2\varepsilon m^* V^2} \operatorname{cosec}^2\left(\frac{\theta}{2}\right) \qquad (1)$$

where e is the electronic charges,  $\varepsilon$  is the dielectric constant and V is the electron velocity. Taking the cut off distance of the Coulomb field,  $r_m$ , by  $(2r_m)^{-2} = N_I$ , where  $N_I$  is the surface concentration of charged centers, the relaxation time is given by

$$\tau = \frac{\varepsilon m^* V}{2e^2 N_I} \left( \tan^{-1} \frac{\varepsilon m^* V^2}{2e^2 \sqrt{N_I}} \right)^{-1} .$$
 (2)

For 4.2°K,  $(E_F - E_0) \gg kT$  is established, therefore, the constant relaxation time determined from the Fermi velocity can be employed in the mobility formula. In this case, the mobility is given by

$$\mu = \frac{\varepsilon h \sqrt{N_s}}{2\sqrt{2\pi}em^* N_I} \left( \tan^{-1} \frac{\varepsilon h^2 N_s}{4\pi m^* e^2 \sqrt{N_I}} \right)^{-1}.$$
 (3)

Charged centers responsible for the scattering are the charged surface states and charged acceptors in the conductive layer. The energy distribution of the surface states is not known. But, the charged surface state concentration is a decreasing function of  $N_s$ . Thickness of the conductive layer is also decreasing function of  $N_s$ . Therefore, the mobility is expected to be an increasing function of  $N_s$  in the power greater than  $\frac{1}{2}$ . The concentrations of charged centers,  $N_I$  (cal) which give the mobility measured at 4.2°K are given in Table II. The charged surface states are considered to be the main scatterers.

Table II.

$\mu$ (4.2) (cm <sup>2</sup> / V·sec)	$N_I$ (cal) (cm <sup>-2</sup> )	$\mu$ (08) (cm <sup>2</sup> / V·sec)	$\mu (77)$ (cm <sup>2</sup> / V·sec)
5.1×10 <sup>3</sup>	4 ×10 <sup>11</sup>	6.7×10 <sup>3</sup>	6.8×10 <sup>3</sup>
8.9×10 <sup>3</sup>	2.5×1011	$1.3  imes 10^4$	$1.3 \times 10^{4}$
$1.1 \times 10^{4}$	2.4×1011	$1.5  imes 10^4$	$1.5  imes 10^4$
	$(cm^2/V \cdot sec)$ 5.1×10 <sup>3</sup> 8.9×10 <sup>3</sup> 1.1×10 <sup>4</sup>	$\begin{array}{c c c c c c c c c c c c c c c c c c c $	$\begin{array}{c c c c c c c c c c c c c c c c c c c $

The equilibrium concentration of charged surface states is estimated as  $6 \times 10^{11}$ /cm<sup>2</sup> from the equilibrium surface carrier concentration of  $1.5 \times 10^{11}$ /cm<sup>2</sup> and the number of the ionized acceptors in the space charge region. So,  $N_I$ (cal) in Table II are reasonable numbers.

At 68°K and 77°K, the Fermi level lies at the energy less than 10 kT above  $E_0$ . Therefore, the relaxation time should be averaged for electrons of different energy in the calculation of the mobility. The average,  $\langle \tau \rangle$ , is given in a two dimensional energy band by

$$\langle \tau \rangle = rac{\int \tau(E) E rac{\partial f_0}{\partial E} dE}{\int f_0(E) dE}$$
 (4)

where  $f_0(E)$  is the Fermi distribution function. Using the numbers of  $N_I(\text{cal})$  for 68°K and 77°K, the mobilities are calculated and shown in Table II as  $\mu$  (68) and  $\mu$  (77). The calculation of the average by eq. (4) is performed by simplifying the arctangent term to be equal to 1 and  $\partial f_0/\partial E$  to be -1/4kT and integrating the numerator from  $E_F - 2kT$  to  $E_F + 2kT$ .

 $\mu$  (68) and  $\mu$  (77)are greater than measured data. This difference is considered to show the effect of lattice vibration for carrier scattering at these temperatures. At high temperature, some of the carriers will be excited to the states in which the energy of the kinetic motion perpendicular to the surface is  $E_1$  but the kinetic energy in a plane parallel to the surface is very small. The relaxation time of these carriers determined mainly from the scattering due to the charged centers will be very small. Thus,



Fig. 4.  $E_0$ ,  $E_1$  and  $E_F$  vs. surface carrier concentration.

the carrier mobility is expected to decrease when the energy difference  $(E_1 - E_F)$  approaches to kT. As shown in Fig. 4, the energy difference  $(E_1 - E_F)$ calculated from the simple model in Fig. 3 is about 6kT at the surface carrier concentration of  $3 \times 10^{11}/\text{cm}^2$  where the decrease of the mobility is appreciable in Fig. 2. The model in Fig. 3 is probably too crude to explain quantitatively the phenomenon at high temperature. The broadening of the level  $E_0$  and  $E_1$  due to the surface roughness may explain the phenomenon.

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## DISCUSSION

Fowler, A. B.: On silicon surfaces the mobility varies approximately as  $\mu_s^{3/2}$  as presented by Prof. Kawaji's impurity scattering theory up to a maximum value where surface scattering dominates. This occurs at above  $10^{12}$  electrons/cm<sup>2</sup> depending on the substrate impurity concentration. At higher temperatures the mobility is far more complicated and depends on orientation.

Weiss, H.: The decrease in the magnetoresistance mobility at liquid nitrogen temperature

with increasing impurity concentration could be explained by a non-insulating p-n barrier at higher voltages as the resistance increases. To eliminate this effect one should measure the magneto-resistance with a constant voltage applied to the specimen and compare this result with measurement on constant current.

Kawaji, S.: It may be so. Magnetoresistance was measured at a constant current.