# Cuspidal Behavior of Surface Mobility of InSb

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The conductivity and Hall effect of thin slabs of very pure InSb are measured under the influence of the ac field effect. From the field-effect curves between 78 and 295°K, the surface carrier densities and the surface mobilities of the electrons and holes are determined. The electron surface mobility follows qualitatively the transport theory with diffuse surface scattering in its dependence on both the surface potential and the scattering parameter $r_n$. In the case of $r_n \geqslant 2.5$ (above 200°K), a second conductivity minimum is exhibited which can be well explained by a negative electron surface mobility and a cuspidal behavior of the mobility near the flat-band point. Thus the nonlocal case of the surface-transport theory treated by Greene is observed experimentally.

IN the volume of semiconductor crystals, charge carriers reach a constant mean velocity in an applied electric field. The resulting drift mobility is limited by scattering processes with impurity atoms, lattice defects, or phonons. The surface itself is a very sharp disturbance of the periodic crystal lattice. Consequently, the charge carriers are also scattered by the surface. Since the work of Schrieffer,[1] two models are discussed in the literature,[2] that of diffuse, amnetic scattering and that of specular surface scattering.

Figure 1 shows the calculated relative surface mobility $\mu_{\nu s}/\mu_{\nu b}$ ($s$ denotes surface, $b$ bulk, and $\nu$ carrier type) as a function of the surface potential $v_s$, which is a common expression of the band bending at the surface:

$$v_s = (E_{cs} - E_{cb})/k_0T, \tag{1}$$

where $E_c$ is the energy of the lower edge of the conduction band, and $k_0T$ is the thermal energy. If $v_s=0$, there is no potential barrier between surface and bulk (flat-band case). The curves were calculated using the formulas of Goldstein *et al.*[3] for nearly intrinsic InSb and with the assumption of diffuse scattering by the surface. The decrease in surface mobility with increasing accumulation of charge carriers in the space-charge layer becomes stronger as the parameter $r_\nu$ is increased. The scattering parameter $r_\nu$ marks the ratio of the mean free path $\lambda_\nu$ of the charge carriers to the Debye length $L_D$ which approximates the thickness of the space-charge layer. We have

$$r_\nu = \frac{\lambda_\nu}{L_D} = \mu_{\nu b}\left(\frac{2m_\nu^*}{\epsilon \times \epsilon_0}\right)^{1/2} (n_b + p_b)^{1/2}, \tag{2}$$

where $\mu_{\nu b}$ is the bulk mobility of the carrier type $\nu$, $m_\nu^*$ is the effective mass, $n_b$ and $p_b$ are the electron and hole concentration in the bulk, and $\epsilon$, $\epsilon_0$ are the dielectric constant of the semiconductor and the free space, respectively. $r_\nu$ is thus a unique function of the temperature $T$ because the properties of the semiconductor $\mu_{\nu b}$, $n_b$, $p_b$, and $m_\nu^*$ are dependent on temperature.

If the mean free path becomes equal to or greater than the Debye length ($r_\nu \geq 1$), the derivative of the surface mobility has a discontinuity at $v_s=0$ and the mobility becomes negative. Greene[4] has treated this nonlocal case of the surface transport theory thoroughly. As a consequence of such cuspidal behavior of the surface mobility, the surface conductivity would have to show some anomaly near $v_s=0$. It is difficult to reach the nonlocal case in Ge and Si, because $r_n$ ($n$ denotes electrons) is everywhere less than 1. With InSb at 77°K, however, Davis[5] obtained $r_n=2.9$. In spite of this large value, he could not discover any anomaly in the surface conductivity and the field-effect mobility. Therefore, Greene[4] modified the boundary condition of diffuse scattering in his theory for avoiding the cuspidal behavior of the surface mobility.

Measurements were made of the conductivity and the Hall effect of InSb at temperatures between 77 and 295°K. The requirements for the nonlocal case of the transport theory are well met, the parameter $r_n$ attaining values between 0.8 (at 145°K) and 5.0 (at 295°K).

The samples were rectangular slabs (7 mm×1 mm, 10 to 100 $\mu$ thick) of monocrystalline pure InSb (impurity concentration $n_D < 10^{14}$ cm$^{-3}$, $\mu_{nb}$ (77°K) $> 5\times 10^5$ cm$^2$/Vs). The large surfaces had the (111) or (110) orientation. The mechanically and chemically etched and polished surfaces exhibited no damage layer; the roughness was very low, the depth of irregularities being less than 0.05 $\mu$, while the mean distance between these was of the order of 200 $\mu$. A conventional field-effect arrangement was used: A 50-cps alternating voltage of up to 400 V was capacitively applied to the surface over a 4-$\mu$ Mylar sheet. The alternating signal to be measured was amplified and displayed on the screen of an oscilloscope as a function of the field-effect field intensity. By stationary measurements, relate changes of the conductivity of the order of $10^{-5}$ could be detected.

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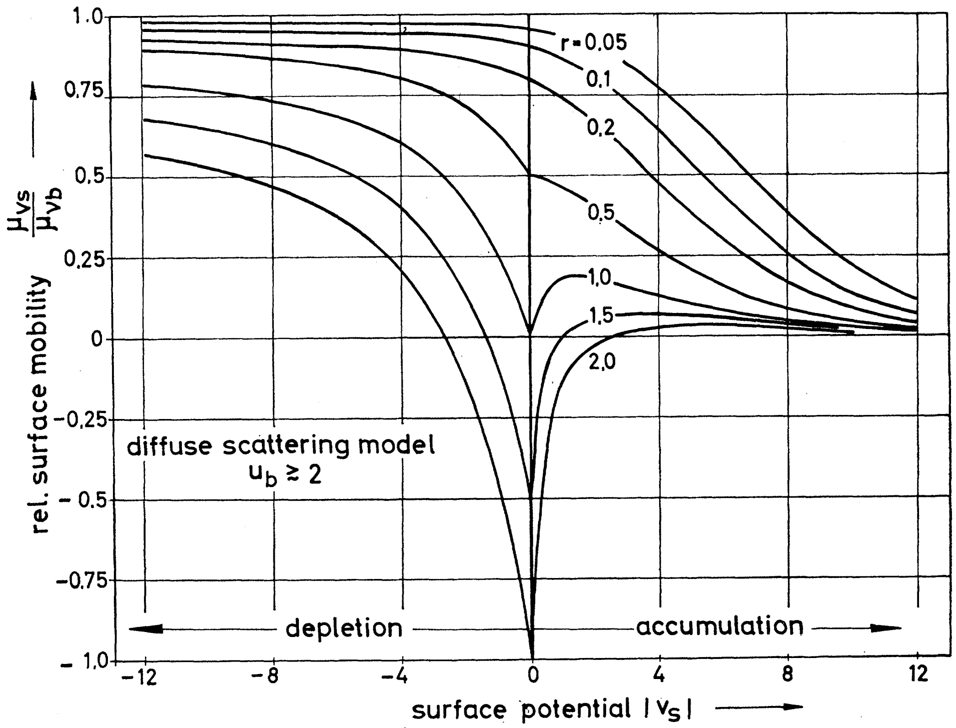


FIG. 1. Surface mobility relative to the bulk mobility $\mu_{\nu s}/\mu_{\nu b}$ ($\nu=n$, $p$ denotes the carrier type) as a function of the surface potential $v_s$. The parameter is $r_\nu=\lambda_\nu/L_D$ ($\lambda_\nu$ is the mean free path, and $L_D$ the Debye screening length).

Figure 2 shows the measured field-effect curves of the conductivity $\sigma_0$ at the temperatures $T=78$, 174, and 295°K, respectively. Below 200°K the conductivity minimum is situated at negative field intensities $E_z$, and its position depends only on the doping concentration $n_D$, the mobility fraction of the electrons and holes, and the occupation of the surface states. Above 200°K a new, second minimum arises at the right-hand side of the first, becomes more pronounced with increasing temperature, and alone determines the shape of the curve at 295°K. The position of the former minimum is still noticeable by an inflection point. This anomalous behavior of the conductivity change due to the field effect is caused either by the number of occupied surface states or by the surface-scattering process. The described effect can be found in nearly all samples and is more or less pronounced.

The influence of the surface states can be separated from the influence of the scattering process by measurements of the Hall effect.

According to our experiments, the amount of the change of the Hall coefficient $\Delta R/R^2$ in relation to $R^2$ decreases at high negative field intensities $E_z$ (hole accumulation) and also decreases, but more rapidly, with increasing positive $E_z$ (electron accumulation).

The intermediate maximum of the absolute Hall coefficient has a position similar to the corresponding conductivity minimum below 200°K. However it scarcely changes its position above 200°K with increasing temperature, in contrast to the conductivity minimum. Also, there is no maximum of the Hall

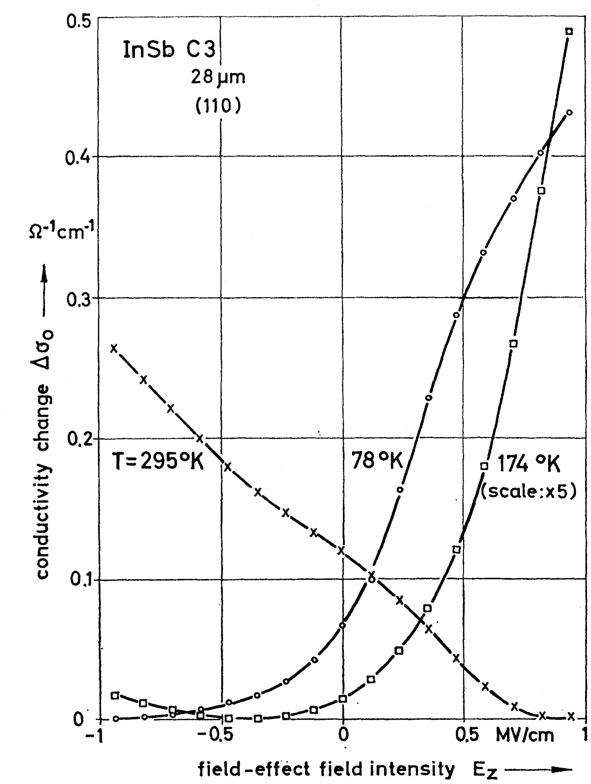


FIG. 2. Change of the conductivity $\Delta\sigma_0$ due to the field effect as a function of the field-effect field intensity $E_z$ for the sample C3 (thickness 28 $\mu$m) for the temperatures $T=78$, 174, and 295°K. $E_z>0$: electron accumulation; $E_z<0$: hole accumulation; bulk conductivity $\sigma_0$ for the respective temperatures: 5.0, 8.3, and 210 $\Omega^{-1}$ cm$^{-1}$.

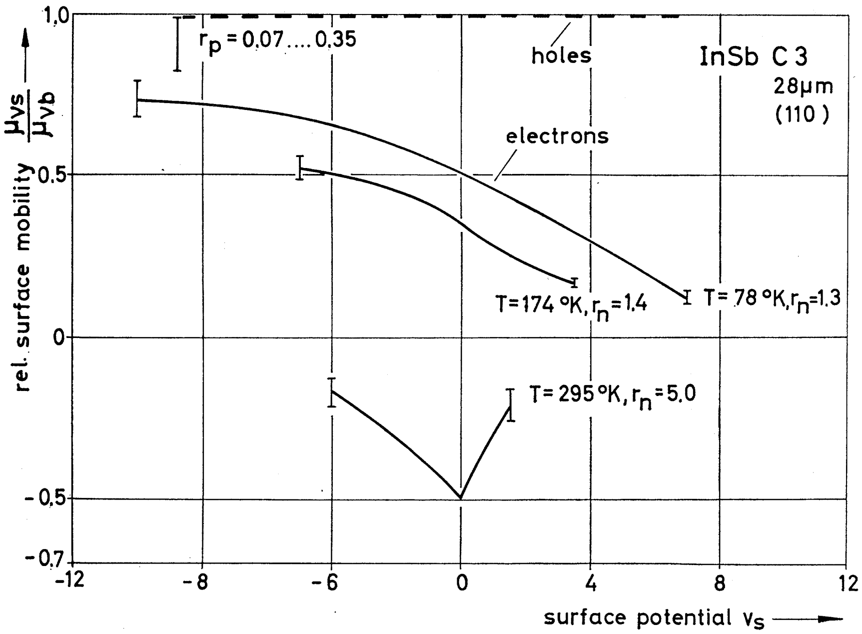


FIG. 3. Surface mobility relative to the bulk mobility $\mu_{vs}/\mu_{vb}$ as a function of the surface potential $v_s$. Dashed line: $\nu = p$, hole mobility; solid line: $\nu = n$, electron mobility. Parameter is the temperature $T$ and the scattering parameter $r_\nu = f(T)$.

coefficient which corresponds to the anomalous second conductivity minimum.

In the case of an electron accumulation layer, one obtains

$$\Delta\sigma_0 \approx e\mu_{ns}\Delta N, \quad \Delta R/R^2 \approx e\Delta N. \tag{3}$$

($\Delta N$ is the excess surface density of the electrons.) It follows from these relations and the experiments that the anomalous conductivity change is definitely caused by a special type of surface scattering, while the number of the mobile charge carriers suffers no essential variation with temperature. The surface mobility $\mu_{ns}$ of the electrons must decrease to such an extent that the conductivity is still decreasing in spite of the increasing surface density of electrons, until it again increases after passing the second minimum because of the now very large electron accumulation.

With the aid of the simple two-conductor two-band model[6] which is based on the mutual interaction between the surface and the bulk region and the hole and the electron band, one can determine the functions $E_z(v_s)$, $\Delta N(v_s)$, and $\mu_{\nu s}(v_s)$ by matching the theoretical to the experimental curves. As a main result one obtains the relative surface mobilities $\mu_{ps}/\mu_{pb}$ and $\mu_{ns}/\mu_{nb}$ of the holes and electrons which are plotted in Fig. 3 as a function of the surface potential $v_s$ for various temperatures.

The hole surface mobility $\mu_{ps}$ remains constant through the whole range of band bending and is equal to the bulk mobility $\mu_{pb}$. The plotted limits of error mark the tolerances within which there is the best fitting of the theoretical to the experimental curves. The electron surface mobility, however, decreases with increasing electron accumulation ($v_s \geq 0$), more markedly the higher the temperature. For every temperature, one can calculate the scattering parameter $r_\nu$ from Eq. (2) because of the knowledge of the bulk properties of InSb. The electron surface mobility exhibits an inverted cusp at $v_s = 0$, and becomes negative if $r_n > 2.5$ or $T > 200$°K. The cuspidal behavior and the negative value of the surface mobility $\mu_{ns}$ are the reasons for the second conductivity minimum (Fig. 2, 295°K). The position of the maximum of the Hall coefficient is only slightly influenced by the behavior of the surface mobility. The threshold value of $r_n = 2.5$ found in our experiments explains why Davis[4,5] did not detect any anomaly with $n$-type InSb at 77°K, reaching as a maximum $r_n = 2.9$. Comparison of the experimental surface mobilities in Fig. 3 and the values in Fig. 1, calculated on the assumption of diffuse scattering, shows that the electron surface mobility follows qualitatively the theory obtained with the boundary condition of complete amnetic scattering both in the dependence on the surface potential and on the scattering parameter and thus the temperature. At the same value of $r_n$, however, the reduction of the mobility due to the surface scattering is stronger in theory than in experiment. As an example, the cusp of the mobility curve of $r_n = 5.0$ (Fig. 3) lies appreciably above the curve predicted by the theory (in Fig. 1, the curve $r_\nu = 5.0$ would have a cusp at $\mu_s/\mu_b = -4.0$).

The hole surface mobility ($r_p < 0.3$) does not show any reduction. The discrepancies can be caused by experimental difficulties and by an oversimplified theoretical model:

[6] E. Preuss, thesis, University of Munich, 1969 (unpublished).

(1) The model makes use of the local Boltzmann theory even in the nonlocal case.

(2) The theory is valid only for constant relaxation times neglecting any quantization effects.[7]

(3) The electrons suffer not only diffuse scattering (a rough estimation suggests a 20 to 70% fraction of specular scattering).

(4) The measuring is disturbed by the fact that the surface is not absolutely smooth and, therefore the field intensity is not constant [$L_D$ (300°K) = 0.03 $\mu$].

Although our measurements are not in quantitative agreement with the theory, our experimental work confirms very well the predictions made for the nonlocal case by the surface-transport theory.

I wish to express my sincere appreciation to Professor H. Welker and Dr. H. Weiss, who made many valuable suggestions. I am indebted to Dr. H. Pfleiderer for several discussions.

[7] R. F. Greene, Surface Sci. 2, 101 (1964).

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# Oscillatory Photoconductivity of GaSb under a Magnetic Field*

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The spectral oscillation of intrinsic photoconductivity in GaSb has been studied under applied magnetic fields. There is a shift of the minima to higher photon energies corresponding to an increase of the energy gap under a magnetic field. More strikingly, additional structures appear in the spectrum. The oscillation is more pronounced with longitudinal magnetic fields than with transverse fields. The spectrum is interpreted by considering transitions between Landau bands of the conduction band and those of the valence band. Under a longitudinal field, a minimum in photoconductivity may occur when the energy of photoexcited electrons, after the emsision of LO phonons if the initial energy is sufficiently high, is close to a Landau level. As expected, the oscillation is weaker under a transverse field and may even appear to be reversed.

## I. INTRODUCTION

Spectral oscillations of photoconductivity with a frequency interval related to the LO phonon energy have been studied extensively in recent years.[1] The condition for the oscillations to occur is that the time $\tau_{\mathrm{op}}$ required for the emission of optical phonons is short in comparison with the lifetime $\tau_l$ of the carriers. Under this condition, the carriers will have for the most part of their lifetime an energy limited to the range below $\hbar\omega_0$, the energy of a longitudinal optical phonon. Another necessary condition is that within this range the energy of carriers does not change too fast in comparison with the carrier lifetime. Otherwise, the photogenerated carriers would be all thermalized. Under the condition

$$\tau_\epsilon > \tau_l > \tau_{\mathrm{op}},$$

$\tau_\epsilon$ being an energy relaxation time, the energy distribution of photogenerated carriers depends on $h\nu$, oscillating within the range below $\hbar\omega_0$[2]. This effect is basically the origin of the oscillatory photoconductivity.

An oscillation can be produced through the energy dependence of mobility as well as through an energy dependence of carrier lifetime. The oscillation of intrinsic photoconductivity in GaSb was attributed to the mobility variation in zero magnetic field.[2] If a narrow energy distribution of carriers is indeed obtained under photoexcitation, additional structure may appear in the spectrum under an applied magnetic field as the carrier energy passes through the Landau levels. We are not concerned with the effect of magneto-oscillations in absorption which is observable only for sufficiently thin samples and is easily avoided in measurements of intrinsic photoconductivity. In fact, most of the additional structures do not coincide with the expected variation of absorption. A magnetic field produces a variation of density of states which may cause the scattering to vary with the carrier energy, introducing consequently structures in the photoconductive spectrum. Impurity states and exciton states associated with a higher Landau level are unstable and should be much less effective for recombination than those associated with the lowest Landau levels. It is therefore unlikely that the effect is connected with the carrier lifetime.

We have measured the intrinsic photoconductivity of $p$-type GaSb under magnetic fields up to 80 kG, in

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[2] M. A. Habegger and H. Y. Fan, Phys. Rev. Letters 12, 99 (1964).