Oscillatory Magnetoconductance of p-Type Inversion Layers in Si Surfaces*†

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We report the observation of Shubnikov–de Haas oscillations in the conductivity of surface holes in a p-type inversion layer of Si. The hole plasma is shown to be two dimensional. The effective mass varies from about $0.6m_0$ to $1m_0$ in the carrier concentration range $(1 \text{ to } 3.5)\times 10^{12}$ cm^{-2}. It is proposed that the nonparabolic nature of Si valence band as well as many-body interaction affects the value of the effective mass. The hole gas is found to exist in one valley. Unexpected oscillations in the conductivity at low carrier concentration (less than 8×10^{11} cm^{-2}) are reported.

During the last few years much progress has been made in our understanding of the behavior of charged carriers on the surfaces of semiconductors. The ability to vary the surface concentration, n_s, of charged carriers makes such systems suitable for studying many-body effects. The experimental techniques employed in the study of such systems have generally been limited to the measurement of channel conductivity and capacitance. However, Wheeler and Ralston[1] have observed direct transitions between the quantized sub-bands and more recently, by suitably altered geometry, cyclotron resonance has been observed in the n-type inversion layer of Si.[2,3] Most of the investigations have been limited to surface electrons which form a two-dimensional electron gas (2DEG). Our understanding of surface carriers would be incomplete without a corresponding study of surface holes. There are two reasons why studies of surface holes have not been active. First, holes generally tend to have lower mobilities than electrons and consequently such studies as cyclotron resonance and Shubnikov–de Haas (SdH) oscillation, which require sufficiently large scattering time τ, have not been feasible. Second, the theoretical interpretation of the behavior of surface holes is complicated due to the fact that the valence band of silicon is highly nonparabolic. It appears that appropriate investigations are feasible.

Some of the experimental difficulties have been surmounted with the production of high mobility p-channel devices. One of us (Y.C.C.) has prepared samples which have channel mobilities greater than 2500 cm^2/V sec.[4] Successful observation of SdH oscillations requires that $\omega_c\tau \sim 1$, where ω_c is the cyclotron frequency. This requirement is satisfied in the liquid helium range of temperatures, for magnetic fields greater than about 50 kOe.

In an inversion layer, carrier motion perpendicular to the surface is quantized.[5] A series of energy levels, called "electric sub-bands" are formed, the number of series being equal to the number of effective masses. The top of the valence band in Si consists of two types of hole bands, namely heavy and light, degenerate at $k=0$. In the calculation using the effective-mass approximation the heavy hole forms the ground-state energy level.

The density of states ρ can be expressed as a function of the energy E at $T=0$ as

$$\rho(E) = 2\pi g_s g_v m^*(E)/h^2,$$

where g_s and g_v are spin and valley degeneracies, respectively, and $m^*(E)$ is the effective mass [which in general can be expressed as $m^*(n_s)$]. A well-known example of such a system is the 2DEG in Si.[5]

The two-dimensional hole gas (2DHG) in Si is in the valence band. The dispersion relation for holes in the bulk is approximately given by[6]

$$E(k) = -(\hbar^2/2m_0)\{Ak^2 \pm [B^2k^4 + C^2(k_x^2k_y^2 + k_y^2k_z^2 + k_z^2k_x^2)]^{1/2}\},$$

where A, B, and C are constants and the plus and minus signs refer to light and heavy holes. The cross terms in the dispersion relation appear even when the holes are confined to the surface thus making the evaluation of dk/dE complicated.

In the presence of a normal magnetic field B, the states are further quantized into Landau levels and the density of states is given by a series of broadened levels centered at energies given by

$$E_c = (l+\gamma)e\hbar B/m^*(n_s) + sg^*(n_s)\beta B,$$

where β is the Bohr magneton, $s=\pm\frac{1}{2}$ and $l=0, 1, 2, \ldots$; we have indicated that g^*, the g factor, may be carrier-concentration dependent as in the case of a 2DEG.[7] In general the phase factor γ deviates from the value $\frac{1}{2}$ for nonparabolic dispersion relations. The concentration-dependent effective mass makes the Landau level spacing nonuniform in energy. SdH oscillations occur in the conductivity because of the periodic density of states. In analogy with the three-dimensional case, temperature dependence of the amplitude of oscillations is[8]

$$a \sim T[\sinh(2\pi^2 kT/\hbar\omega_c)]^{-1},$$

from which an effective mass can be determined as was previously done in the case of a 2DEG.[9]

Experiments were carried out on circular field-effect transistors with source-drain width of 288 μm and average circumference of 1378 μm. Two sets of samples, one with {100} surface and the other with {111} surface, were used and the oxide thicknesses were 1400 and 1900 Å, respectively. The experiments were performed in liquid helium range of temperatures. A Bitter magnet capable of producing fields up to 150 kOe was used. The usual ac technique was used to measure the channel conductance and transconductance.[10]

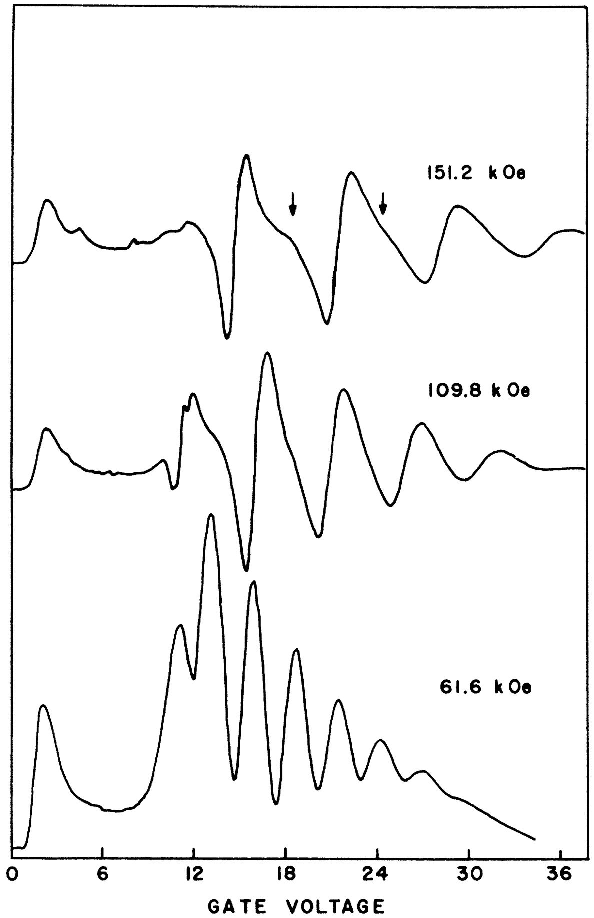

FIG. 1. Transconductance curves at magnetic fields of 61.6, 109.8, and 151.2 kOe. The scale for vertical axis is arbitrary. The horizontal axis shows gate voltage in volts. Arrows indicate the structure in transconductance due to the removal of spin degeneracy.

Figure 1 shows three typical transconductance curves at magnetic fields of 61.6, 109.8, and 151.2 kOe. The oscillations become less sinusoidal as the magnetic field is increased. Arrows in the highest field curve indicate the beginning of oscillations due to the removal of spin degeneracy. The amplitude of oscillations in transconductance decays rapidly as the gate voltage is increased. The reason for this is the decrease in mobility at high gate voltages[4] so that $\omega_c\tau$ becomes smaller than 1. At present we have no explanation for the appearance of the first peak in the transconductance. It can be seen to be relatively unaffected by changes in the magnetic field.

One of the fundamental properties of a two-dimensional system is that the number of states per Landau level is a constant. For each value of the magnetic field the period in gate voltage and thus the hole density is a constant indicating the existence of a 2DHG. This was further confirmed by studying changes in the period for different orientations of the sample in the magnetic field. The changes in period followed the cosine law to better than 1%, thus indicating that only the normal component of the magnetic field determines the orbital quantization energy. Lines drawn through the different order levels at high gate voltage all extrapolate to the same gate voltage, which is within 0.5 V of the mobile carrier threshold as determined from Hall mobility measurements.

In the carrier concentration range studied (up to 1×10^{13} cm^{-2}) we do not find any change in the period of SdH oscillations in gate voltage.[11] This

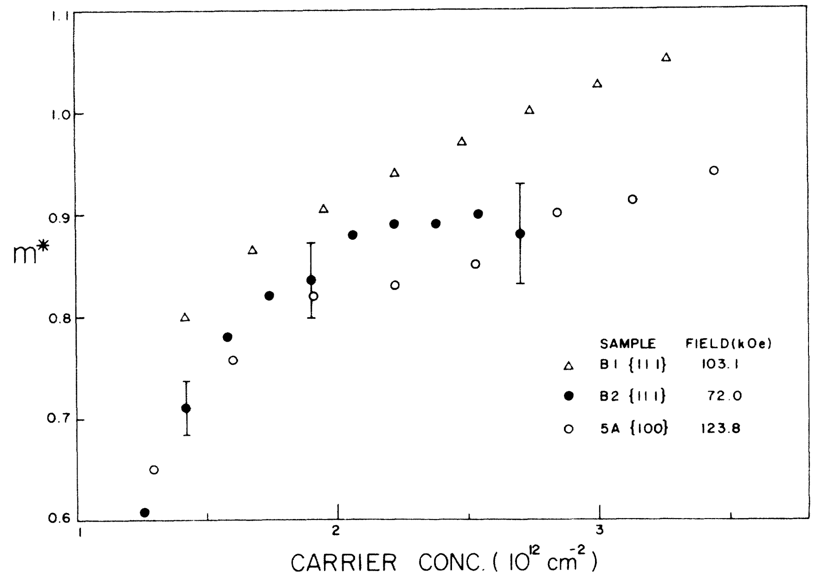

FIG. 2. Normalized effective mass as a function of carrier concentration.

implies that only the ground-state sub-band is occupied. The number of states per Landau level was found to be $\sim 4.9\times10^{10}$ carriers/cm^2 Wb. The expected degeneracy, excluding spin, is $\sim 2.4\times10^{10}$ carriers/cm^2 Wb. Thus $g_s g_v = 2$ and $g_v = 1$ since $g_s = 2$ for spin degeneracy.

Figure 2 shows the experimental values of the effective mass as a function of carrier concentration. Within experimental errors we find no significant difference in the values of m^* for samples with different surface orientations. We recall that the band-edge m^* is approximately $0.5m_0$ for the heavy hole which forms the ground-state sub-band. The masses as determined in this investigation are all greater than $0.5m_0$.

It is instructive to make a comparison between the effective mass of a 2DHG with that of a 2DEG in Si. Smith and Stiles[9] find that m^* of a 2DEG varies by about 10% in the relevant carrier concentration range. Janak[12] has suggested that this carrier-concentration dependence of m^* is due to electron-electron interactions. We note two significant differences between the cases of a 2DHG and a 2DEG in Si. The effective masses show opposite trends with respect to the carrier concentration and m^* for a 2DHG is a much stronger function of n_s than the corresponding m^* of a 2DEG. We believe that both these observations may be explained by the fact that the nonparabolic dispersion relation plays a more important role than many-body interactions in determining the effective mass of a 2DHG.

The importance of nonparabolicity has been emphasized by both Coleman, Bate, and Mize[13] and Sato, Takeishi, and Hara[14] in explaining mobility anisotropies of holes in Si inversion layers. These authors calculated m^* at limiting points of bulk constant-energy surfaces. If this model were applicable here, then it would imply multiple degeneracies for the ground-state sub-band. For example, there are four limiting points in a {100} surface implying fourfold degeneracy (excluding spin) for the ground-state sub-band. We have demonstrated that the ground-state sub-band is only singly degenerate (excluding spin). Hence, we conclude that more appropriate values of m^* can be obtained by considering cross sections of bulk constant-energy surfaces rather than only the limiting points, as was suggested by Maeda.[15]

Recently cyclotron resonance has been carried out by two groups on 2DEG in Si. The values of m^* measured by Abstreiter *et al.*[2] are comparable to those obtained by Smith and Stiles using SdH oscillations. Allen, Tsui, and Dalton,[3] also using cyclotron resonance, obtain m^* which has no obvious concentration dependence. It has been suggested that, in the absence of electron-lattice interactions, cyclotron resonance measures the "bare" mass while the mass derived from SdH oscillations is "dressed."[16] It is proposed that if cyclotron resonance is performed in a 2DHG this difference in the two measurement techniques can be exploited to determine the relative importance of nonparabolic dispersion relation and many-body effects.

Unexpected oscillations under high magnetic fields and in the low carrier concentration region ($n_s < 8\times10^{11}$ cm^{-2}) have been observed in the transconductance. Such splittings appear to be similar to what has been termed "valley splitting" in a 2DEG.[17] However, it has been shown that the 2DHG in Si has only one valley. Therefore, we believe that these splittings may be of a more fundamental nature than the removal of valley degeneracy. We are in the process of investigating this further.

A more complete understanding of the 2DHG requires investigation of other aspects of the system. Among these are such studies as changes in capacitance turnon as a function of magnetic field to determine the number and energy distribution of surface states, direct transitions between sub-bands, and cyclotron resonance. It is hoped that such studies will be stimulated by this report.

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Optical Absorption Threshold in Dilute Alkali-Metal—Rare-Gas Alloys*

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We report the optical absorption of Kr and Xe impurities in alkali-metal hosts. While the absorption threshold can be predicted accurately, the edge profile cannot be reconciled with current Hartree-Fock theories of optical excitations in metals.

We report and interpret optical absorption associated with rare-gas impurities in alkali-metal hosts. The observed transitions have a $p^6 \to p^5 s$ character near threshold, but lack the singularities observed (and predicted by Hartree-Fock theory)[1-3] for $L_{2,3}$ x-ray transitions of pure metals.[4] The smooth profiles observed in this work vary in amplitude from one host to the next in a way that appears to reflect the density of conduction states near E_F. It has not been possible to reconcile the observations with the current Hartree-Fock theory of absorption edges in metals.