Space-charge layers on Ge surfaces. II. High-frequency conductivity and cyclotron resonance

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We examine the high-frequency conductivity and cyclotron resonance of electrons in a space-charge layer on a Ge (111) surface. It is shown from the frequency dependence of the infrared absorption that the surface carriers are localized or at least strongly perturbed for densities $N_s \lesssim 1 \times 10^{12}$ cm^{-2}. The cyclotron resonance shows a shift of the resonance to low magnetic field at such densities. Only above $\sim 2 \times 10^{12}$ cm^{-2} is the free-electron cyclotron mass observed.

I. INTRODUCTION

A previous paper[1] has studied electrons in subbands on Ge surfaces. For the (111) surface, the occupancy of several subbands has been established. Marked differences of the mobility for the occupied subbands have been noted.

The present work concerns the high-frequency conduction and cyclotron resonance of the surface electrons. The perturbation of the subbands by imperfections of the insulator-semiconductor interface makes necessary a careful appraisal of the far-infrared absorption. The cyclotron resonance must be considered with proper regard for the perturbations and for the different groups of carriers.

II. EXPERIMENTAL NOTES

Samples are fabricated according to the prescription in Ref. 1. The sample A has been referred to in the previous work. Samples J and K are both p-type ($N_A \sim 2 \times 10^{14}$ cm^{-3}) material, with NaOCl-polished (111) surfaces and lacquer coating.

Sample A has been cut deliberately in the shape of a wedge with a slope that is adequate to avoid interference effects.[2,3] The other two samples have back surfaces as cut with an abrasive string saw and without subsequent polish. Our experience is that this provides adequate insurance against unwanted interference effects for the wavelengths employed here.

The cyclotron resonance and hf absorption is measured in the spectrometer and according to the techniques described by Abstreiter *et al.*[4] The apparatus is modified to permit also the measurement of the C-V relation and, with the addition of a magic-Tee bridge, the microwave conductivity.

For normally incident, linearly polarized far-infrared radiation the fractional absorption P is related to the relative change in transmitted intensity T caused by the layer with conductivity per square $\sigma_{xx\square}$ as

$$P \cong 1 - T \cong \frac{8\pi}{cL} \mathrm{Re}\,\sigma_{xx\square}(H, \omega) \quad . \tag{1}$$

The relation applies with sufficient accuracy for $P \leq 0.1$. The insulating layer has been assumed thin compared to the wavelength. Here $L = 1 + n_{\mathrm{Ge}} + 120\pi/R_\square$, with n_{Ge} the refractive index of Ge and $R_\square$ the resistance per square of the gate electrode in ohms (typically $R_\square \sim 1000\ \Omega$). The conductivity $\sigma_{xx\square}$ is to be expressed in cgs esu. Since all the various factors are known, the measured fractional change in transmission provides an absolute measure of the conductivity. Because of the difficult mode configuration in the waveguide, and the use of a magic-Tee bridge, the microwave measurement cannot be expressed in absolute units.

III. HIGH-FREQUENCY CONDUCTIVITY

We previously noted[1] the considerable imperfections of the polished Ge-lacquer interface which express themselves in a high density of interface states and reduced carrier mobility. At low-electron concentration N_s, we must expect a considerable perturbation of the carriers. If there occurs localization, the measured absorption cannot be related to a free-electron-like Drude conductivity.[5] In addition, throughout the relevant range of N_s, two or more groups of carriers will simultaneously occupy the surface layer.

The perturbation of electrons on Ge is shown up dramatically in the data of Fig. 1. Sample J has the hysteretic C-V curve for up-down sweeps of the voltage as in the upper part of the figure. The general features of such a curve have been discussed previously.[1] The only notable difference lies with the variation of C to the right of the line marked V_T and drawn to coincide with the rapidly rising C in the down-sweep. The rapid rise has been identified with the equilibrium decrease of the depletion length. It

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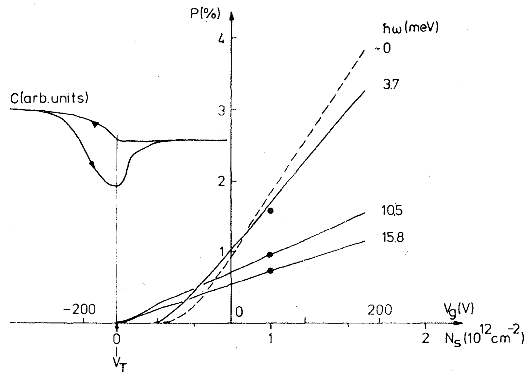

FIG. 1. Hysteretic up-down C-V curve and the related percentage absorption at 4 different $\hbar\omega$ values. For 10.5 meV and above a unique threshold, V_T, that coincides with the sharp rise of C in the down-sweep, can be identified. The solid points at $N_s = 1\times10^{12}$ cm^{-2} are a fit to a Drude frequency dependence for this sample. The $\hbar\omega \sim 0$ (microwaves) curve is in terms of arbitrary units, but has been scaled to the Drude value (open circle).

was shown that for sample D the onset of dc conductivity at 4.2 K lies just somewhat above this point (compare Fig. 3, Ref. 1).

Figure 1 is the more general case. All samples show the C-V hysteresis above V_T to a greater or less extent. Linked with it is the delayed onset of microwave conduction as in the lower part of the figure. Notable dc conductivity only starts with $N_s = 2.5\times10^{11}$ cm^{-2} above V_T. Particular care must be taken in obtaining reliable results for the on-off modulated absorption because, as the C-V curve shows, the minority charge is not even reaching the surface fast enough to maintain equilibrium during the slow (~1 min) sweep of the voltage. The upsweep of the capacitance curve above V_T depends on the sweep rate. To measure the absorption curves in Fig. 1 we make use of the lowest possible on-off chopping frequency (1–3 Hz) and use an off-voltage well below V_T. By using in addition a small amount of light from an LED (light-emitting diode) the full surface charge can be modulated. A check on full modulation is made by registering the charging current. The effect of the light for the $N_A \sim 2\times10^{14}$ cm^{-3} samples is a small (~10 V) shift of all the absorption curves to the left (Fig. 3, Ref. 1).

We measure the percentage absorptions in Fig. 1 when full on-off modulation is assured. The broken line gives the microwave absorption (uncalibrated). Raising the frequency to $\hbar\omega = 3.7$ meV moves the onset considerably to the left. Further increases, to 10.5 and 15.8 meV of radiation energy, result in an onset very near the position marked as V_T. It is now evident why we must think of this high-frequency onset of absorption as the genuine threshold for the occupancy of inversion charge in the surface. In Ref. 1 allowance has been made for such an identification of V_T in the construction of Fig. 9.

The absorption versus frequency relation as we find it in Ge is clearly not free-electron-like at low N_s. For $N_s \approx 1\times10^{12}$ cm^{-2} in Fig. 1 we expect the occupancy of two subbands[1] with $N_s^0 \cong 0.8\times10^{12}$ cm^{-2} and $N_s^1 \cong 0.2\times10^{12}$ cm^{-2}. Assuming a Drude conductivity in the form

$$\sigma_{xx\square}(\omega) = \sum_{n=0,1} \frac{N_s^n e^2 \tau_n / m^*}{1+\omega^2\tau_n^2} \tag{2}$$

to calculate the absorption, Eq. (1) requires $\tau_1 = 1.0\times10^{-13}$ sec and $\tau_0 = 0.2\times10^{-13}$ sec in order to fit the three points shown with dots in the figure. The result is reasonable when one compares with lifetimes as determined in Ref. 1. Nevertheless, this cannot be taken as proof of free-electron behavior. For one, the N_s value lies just above the densities where localization was noted. Second, we find in cyclotron resonance evidence for a considerable perturbation-induced shift of the resonance when $N_s \sim 1\times10^{12}$ cm^{-2}.

The dilemma faced when we try to fit Drude behavior at the upper range of N_s in Fig. 1 is that with great certainty at least three subbands are occupied. The number of parameters is too large to meaningfully compare with present data.

IV. CYCLOTRON RESONANCE

Already the first Ge work[6] indicated that cyclotron resonance can be observed on (111) Ge. That particular measurement was not carried out to sufficiently high field to show the entire resonance line. Moreover, the data was given in terms of the absorption normalized to the zero-field value and thus covered up a serious discrepancy. Weber *et al.*[6] equated the carrier density for the resonance with that of the Shubnikov–de Haas period, i.e., about $\frac{1}{5}$ of the total charge.

We have repeated the measurement in a similar sample at the density of the original experiments. The curve in Fig. 2 is for $N_s = 2.5\times10^{12}$ cm^{-2}, which corresponds to $N_s^1 \approx 0.5\times10^{12}$ cm^{-2}. The range of field is sufficient to make a meaningful fit to the absorption calculated according to the usual prescription[4] in absolute terms. If we insist on a one-carrier description that matches the height and width at resonance, then $N_s = 2.2\times10^{12}$ cm^{-2} and $\tau = 1.0\times10^{-13}$ sec. The experimental uncertainty of this particular measurement of absorption is such that these numbers are reliable to ±10%. We can definitely preclude the possibility that only (as was assumed in Ref. 6) the carriers N_s^1 contribute to the resonance. The resonance position corresponds to the expected cyclotron mass 0.08 m_0.

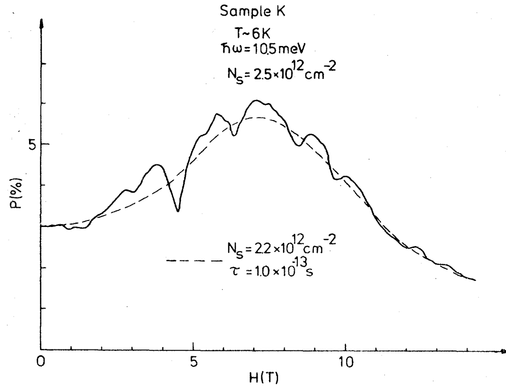

FIG. 2. Cyclotron resonance on Ge (111) at high N_s for an $N_D \sim 2\times10^{14}$ cm^{-3} sample. The structures on the broad curve are magnetoimpurity resonances.

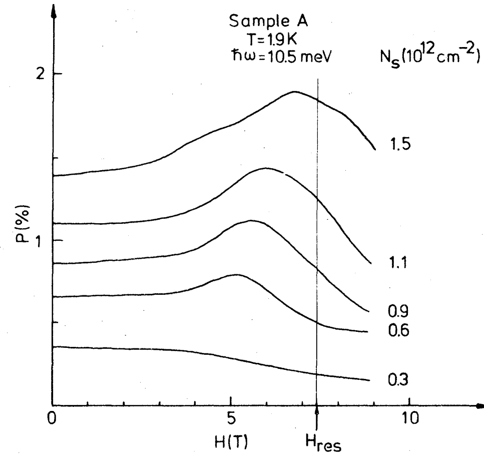

FIG. 3. Sequence of cyclotron resonance curves for $N_s \le 1.5\times10^{12}$ cm^{-2}. A shift of the resonance from the expected value H_{res} (vertical line) indicates the influence of surface perturbation and thus a deviation from free-electron behavior.

The one-carrier free-electron description of the resonance applies only for the highest N_s. We had noted in Ref. 1 that at such density the two subbands $n=0,1$ both contribute to the magneto-oscillatory conductivity with not very different τ. The N_s required to fit the absorption height is near the expected value for $N_s^0+N_s^1$. The accuracy of the measurement here is not sufficient to prove the expected occupancy of the high mass, $n=0'$, level from a difference in N_s between the known charge on the surface and that necessary for the fit. We note that 0′ electrons with $m_c^*=0.34\ m_0$, $\tau_{0'}\ge\tau_1$, and number estimated from Fig. 9 in Ref. 1 would contribute only about 2% of the absorption at resonance in Fig. 2.

The conclusion from Fig. 2 is that, at high N_s, m_c^* for the $n=0,1$ subbands is the free-electron value 0.08 m_0 and the Drude formula description is reasonable. Both of these fail at lower N_s. In Fig. 3 is shown the cyclotron resonance for sample A in a sequence of traces for different N_s. The N_s values are such that the carriers are mostly in the $n=0$ and 1 subbands and have quite different τ values ($\tau_1 >> \tau_0$). The strong shift of the peak to low fields is not free-carrier behavior. It cannot be fit or simulated with a two-carrier calculation with different τ and the N_s^0, N_s^1 from Fig. 9 in Ref. 1, if we insist on $m_c^*=0.08\ m_0$. An attempted description with a mass changed to $\sim$0.06 m_0 for the $N_s=0.9\times10^{12}$ cm^{-2} curve fails to produce reasonable results. At this point one must raise the question: If the $n=1$ electrons are sufficiently perturbed to have a 25% shift of the resonance, what is the effect on the $n=0$ subband? We conclude that it is not meaningful to take the variation of σ with H as free-electron-like when the resonance is shifted. Also, the frequency dependence examined in Sec. III at $N_s\sim1\times10^{12}$ cm^{-2} assuming $m_c^*=0.08\ m_0$ must be carefully reconsidered.

The downward shift of the Ge resonance has its counterpart in Si, where it has been described as a localization-induced shift.[7] By comparison with Si the Ge resonance does not show the rise of m_c^* with lowered N_s. The m_c^* increase in Si has been linked with partial occupancy of the heavy-mass valley. A similar occupation of the $m_c^*=0.34\ m_0$ valleys occurs for Ge.

An interesting, historical point with regard to the Ge work is that the cyclotron resonance, in particular the absolute value of the absorption at resonance, first indicated to us that practically all electrons participate in the resonance. Weber *et al.*[6] had talked of $\sim$80% "lost" carriers. The peculiar line shape at intermediate N_s (where the down shift is not large) first suggested two groups of carriers with different τ values.

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