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Frequency dependence of surface cyclotron resonance in Si

G. Abstreiter* and J. F. Koch
Physik-Department, Technische Universität München, 8046 Garching, Germany

P. Goy and Y. Couder
École Normale Supérieure, Paris, France

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Cyclotron resonance on the (100) surface of Si is investigated at frequencies between 94 and 891 GHz. The cyclotron mass, especially its dependence on surface electron density, is found to be independent of frequency in our samples. An increase of the scattering rate with magnetic field is observed.

I. INTRODUCTION

Cyclotron resonance of electrons in a space-charge layer on the (100) surface of Si has been reported in several recent publications.[1-4] A number of interesting physical features have emerged in this work. While on the whole the theory of Ando and Uemura[5,6] provides a satisfactory description of the resonance, there are a number of observations that lack adequate explanation.

The observed increase of the cyclotron effective mass m_c^* with decreasing surface electron density n_s represents such a puzzle. This rise figures prominently in our data[4,7] at densities below 1×10^{12} cm^{-2}. A recent publication by Kennedy *et al.*[3] fails to observe the increasing cyclotron mass under similar experimental conditions. Instead a dependence of m_c^* on the experimental frequency, in particular on the parameter $\omega\tau$, is reported. Our present concern is to explore such possible frequency dependence, especially as it relates to the dependence of m_c^* on n_s at 4.2 K. Two other observations, that still need to be accounted for, may in some way be related to the dependence of m_c^* on n_s. There has been observed a marked upward shift of the resonance with increasing temperature.[8] In raising the temperature from 4.2 to 65 K an enhancement of the resonance mass by 30% has been reported. With the application of pressure a substantial rise of m_c^* has been found.[9]

II. EXPERIMENTAL ASPECTS

The experiments make use of a transmission spectrometer similar to that described earlier.[1,4] The radiation is provided by several carcinotrons with frequencies ranging almost continuously from 94 to 473 GHz. Measurements at 891 GHz are made with an HCN laser source. The sample is mounted inside a liquid-helium cryostat at the end of an RG-98 waveguide. The radiation is coupled to the sample through a 2-mm-diam hole in a 1-mm-thick metal plate.

The samples are metal-oxide-semiconductor (MOS) capacitors on 6-Ω cm (100) p-type Si provided by the Siemens Forschungslaboratorium. n-type samples, used in these experiments, had a nominal resistivity of 10 Ω cm. Oxide thickness was typically 2200 Å.

Radiation transmitted through the sample is focused by a cone onto a carbon resistance bolometer, mounted at the end of the light pipe. The resistor is insensitive to magnetic fields less than 5 T. We record the transmitted power as a function of magnetic field at fixed surface electron density n_s. The magnetic field of up to 6 T is provided by a superconducting solenoid calibrated for a fixed polarity of the current leads.

Because the samples are in the form of plane parallel slabs, interference effects due to multiple internal reflection influence both line shape and amplitude of the resonance signals.[4,10,11] As discussed in Ref. 4, the transmission is a periodic function of the radiation wavelength λ. A sample of thickness d is characterized by the dimensionless parameter $y=2nd/\lambda-N$. n is the sample refractive index and N a suitable integer, chosen such that $0\leq y<1$. In the present experiments we observed the expected oscillatory variation of resonance amplitude with wavelength. Using the calculations as in Ref. 4, we were able to account and correct for interference effects.

At frequencies below 150 GHz, diffraction at the 2-mm coupling hole acts to diffuse the radiation. This makes the application of the calculation, which is based on a plane wave at normal incidence, unreliable. For data at 94 GHz we found that a good fit was obtained for $y=0$, as would be expected for completely diffuse radiation.

III. RESULTS AND DISCUSSION

Figure 1 shows a set of experimental traces of the resonance at three different frequencies. In particular, it shows how the resonance evolves from the low $\omega\tau$ magnetoconductivity curve, to a distinct peak at higher $\omega\tau$. The curves show the change in transmitted intensity $P(H)$, normalized to the absorption maximum $P_{\max}$.

At 94 GHz the experimental curve can be fit satisfactorily to a calculation of transmission through the plane parallel slab assuming no interference effects, i.e., $y=0$. The known sample thickness ($d=0.353$ mm) and radiation wavelength give $y=0.75$. For normal incidence of the radiation one expects a curve that shows a marked effect of multiple internal reflection. In this particular instance, however, the 2-mm hole of the sample holder acts as a diffuser of the 3-mm radiation. One consequently averages the effective sample thickness in a manner similar to the wedge shaped samples used in the work of Kennedy *et al.*[3] Data derived from this very-low-frequency curve are consistent with other data, but are not used in later discussion because of the uncertanties in the fit procedure.

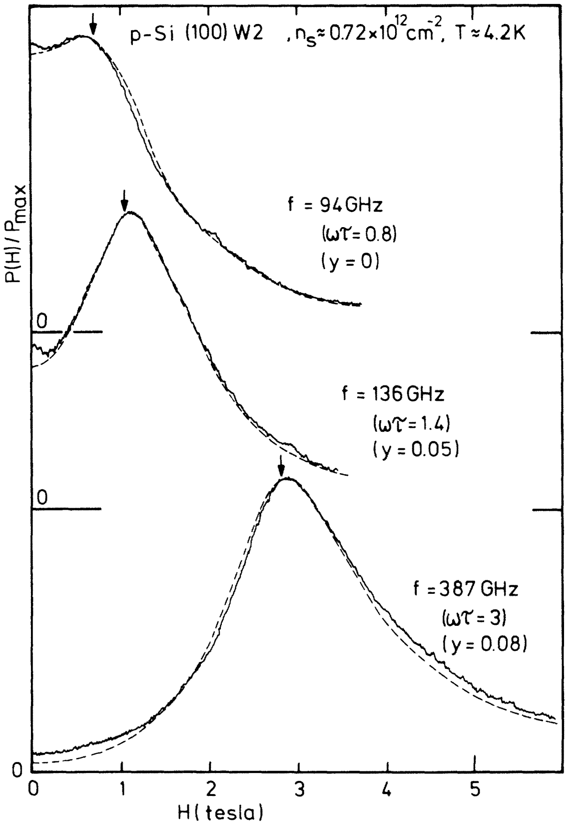

FIG. 1. Curves give the change of transmitted power caused by the space-charge layer electrons as a function of the magnetic field H. The curves are normalized to $P_{\max}$, the maximal change of transmitted energy, in such a way that each trace extends from 0 to 1 on the x axis. The effect is to match up the peak amplitudes of measured and calculated curves. Typical values of $P_{\max}$ are of order 10% of the transmitted intensity in the absence of the space-charge layer.

The data curves marked 136 and 387 GHz are judiciously chosen such that interference effects are small. They are described well by a calculation that makes use of small values of y, close to those derived from the measured sample thickness. In each case the calculation takes $\omega\tau$ as a constant, independent of magnetic field. As shown in Ref. 4, this provides for a satisfactory determination of the $\omega\tau$ at resonance, and the effective mass. A comparison of the calculation involving the constant and field-dependent τ is contained in that work. There is a tendency of the fit curve to fall a little below the experimental trace on the high-field side of the resonance, when the constant τ description is used. In the traces of Fig. 1 the position of the resonance is identified by an arrow.

The calculation assumes strictly linear polarization of the high-frequency electromagnetic fields in the surface layer. The ill-defined geometry of an overmoded waveguide and 2-mm-diam coupling hole in the sample mounting, beg the question to what extent there may be preferential circular polarization. The elementary test of reversing the magnetic field and checking for any changes in the data curve was not done for the original samples. It was thought undesirable in that it would perturb the magnetic field calibration. A subsequent check at 891 GHz showed that at this high frequency there was no significant degree of circular polarization.

The traces of Fig. 1 show a deviation from the fit curve that suggests some degree of preferential polarization in the cyclotron resonance inactive mode. At the very lowest frequency, and $\omega\tau \leq 1$, this would make for a serious error in the determination of m_c^*. Already at $\omega\tau=1.5$, and taking the ratio of left-to-right polarized radiation as 2:1, the calculation shows a shift in the resonance position by only 3%. The possible error appears sufficiently small to be included in the estimated uncertainties. The polarization ratio of 2:1 most probably is an overestimate. Data curves such as those in Fig. 1 were repeated with additional different samples in somewhat different mounting. In these runs the small negative slope that had been found for sample $W2$ was not seen. The mass values, and the rise of m_c^* with n_s, were substantially the same as those derived for sample $W2$.

The data in Fig. 2 summarize the results of cyclotron resonance measurements for n_s below 1.5×10^{12} cm^{-2} at different frequencies. In each case the effective mass is evaluated from a fit to calculation that takes account of $\omega\tau$ and the interference effect. The rise of m_c^* with decreasing n_s is found to be essentially the same at all frequencies. It agrees with that reported earlier in different n- and p-type samples at 891 GHz.[4,7] The relative shift with changing n_s at a given frequency is known to an accuracy which is about one-half of the estimated error bar entered in the figure. There is a notable upward shift already by $n_s=0.7\times10^{12}$ cm^{-2}, which is the lowest density considered in Ref. 3. We are led to conclude that, whatever the physical mechanism of the upward shift in our samples may be, it is independent of the applied magnetic field and frequency.

In a comparison of m_c^* at different frequencies the full estimated errors, indicated by the vertical lines, must be considered. These take account of the uncertainties incurred in the fitting procedure using linear polarization, possible errors in the field and frequency determination, linewidth and the signal to noise ratio for the experimental curves. The data in Fig. 2 lead us to conclude that the cyclotron mass is essentially independent of frequency. Only the data points at 136 GHz show a tendency to fall consistently higher. This is also the one set of data with the largest uncertainty. We simply do not reproduce the strong frequency dependence originally claimed by Kennedy *et al.*[12] for their samples. This publication found an increasing m_c^* with decreasing frequency; specifically $m_c^*=0.193m_0$ at 1572 GHz, $m_c^*=0.207m_0$ at 762 GHz, and $m_c^*=0.230m_0$ at 336 GHz. These numbers are quoted for $n_s=1.5\times10^{12}$ cm^{-2}. At a comparable density we find $m_c^*=(0.198\pm0.005)m_0$, independent of frequency to within the stated error.

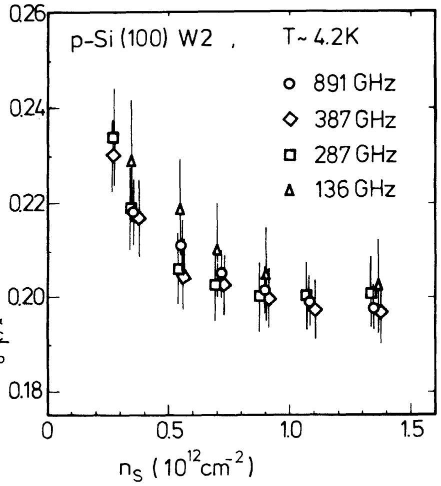

FIG. 2. Cyclotron effective mass as a function of electron density at different frequencies.

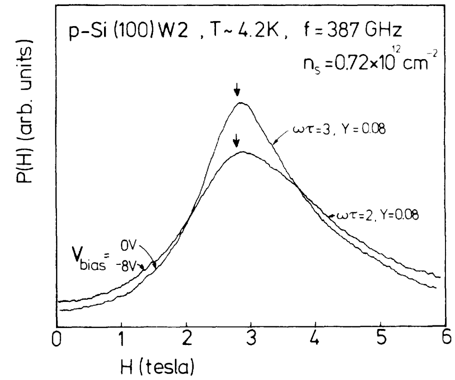

FIG. 3. Surface cyclotron resonance with applied substrate bias voltage. The resonance position is identified in a fit to the curves with parameters as entered on the figure.

The more recent work of Kennedy *et al.*[3] has sought to link the effect of increasing mass with the decrease of $\omega\tau$, and not specifically the frequency ω. In these terms a comparison must take account of the fact that our samples have typically higher values of the relaxation time. It is necessary to compare data at correspondingly lower frequencies. Specifically Ref. 3 shows an approximately linear increase from $0.193m_0$ at $\omega\tau=5$ to $0.220m_0$ at $\omega\tau=2$ for $n_s=1.5\times10^{12}$ cm^{-2}. Nothing comparable to this rise is found in our data. At $n_s=1.35\times10^{12}$ cm^{-2} the points in Fig. 2 range from a low of $\omega\tau=1.1$ at 136 GHz to $\omega\tau=4.8$ at 891 GHz. Over this range in $\omega\tau$, $m_c^*=(0.198\pm0.005)m_0$.

An alternative test of the $\omega\tau$ dependence, one that does not involve scaling the frequency and concomitant uncertainties in interpretation of the data, is provided by the substrate bias effect.

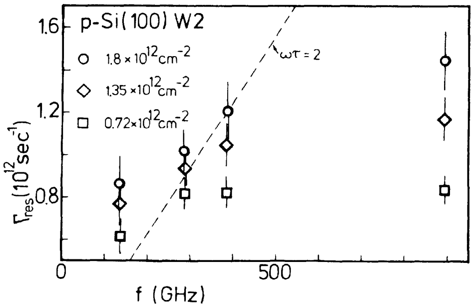

FIG. 4. Scattering rate parameter Γ_{res} as a function of frequency for three different densities. The points with $\omega\tau>2$ lie on the right-hand side of the dashed line.

It has been shown that in our samples the application of a negative substrate bias voltage causes a marked decrease in the scattering time.[4] The application of a bias of 8 V in the trace of Fig. 3 reduces the $\omega\tau$ at 387 GHz from 3.0 to 2.0. The curves are fit according to the usual procedure and the resonance is identified by the arrow as marked. No shift of the resonance can be discerned. According to Ref. 3 the expected shift is of order +5% and could have been identified.

The theory of surface cyclotron resonance[5,6] involves a field-dependent broadening of the resonance with increasing magnetic field. Frequency scaling experiments in principle provide a test of the predicted $H^{1/2}$ dependence for the scattering rate at resonance Γ_{res}. This relation is predicted to apply above $\omega\tau = 2$, and when short-range scattering predominates. Kennedy *et al.*[3] have found that the $H^{1/2}$ dependence provides a satisfactory description of their data at 1572 and 762 GHz. Nevertheless, uncertainties in the fit procedure are too great to conclude verification of an exact $H^{1/2}$ dependence.

In Fig. 4 we show Γ_{res} for the present experiments. The data points are entered for three different densities and range over a factor 6.5 in frequency. The dashed line is the "iso-$\omega\tau$" curve for $\omega\tau = 2$. Estimated error bars indicate the reliability of $\omega\tau$ determination. The data clearly show Γ_{res} to increase with frequency. An exact $H^{1/2}$ dependence, however, cannot be identified from the points above the $\omega\tau = 2$ line. In particular, the data points for $n_s = 0.72 \times 10^{12}$ cm^{-2} (at the mobility peak of our sample) fail to follow the predicted relation. A probable reason for this observation is that short range scattering is not predominant at this density. Our previous work[4] had noted a deviation from the theoretical description of scattering in the region of the mobility peak and below.

In summary, we must conclude that the frequency dependences reported by Kennedy *et al.*[3,12] are at least not universally applicable. Their "strong suggestion" that, with a reduction in $\omega\tau$, cyclotron resonance shows the effect of electron-electron interaction appears to us not tenable. This interaction has been shown[13] to account for the observed rise in the effective mass with decreasing n_s as observed in Shubnikov–de Haas oscillations.[14] According to present understanding of electron-electron interaction effects, one should not expect to observe their influence in the cyclotron resonance.[15,16] A second conclusion is that, whatever the mechanism for the observed rise of m_c^* with decreasing n_s may be, it is by and large frequency independent. The observed rise of m_c^* with increasing temperature,[8] it appears, has no counterpart with increasing frequency.

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*Present address: Max Planck Institut für Festkörperforschung, Büsnauerstrasse 171, 7 Stuttgart, Germany.

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