Temperature-Dependent Cyclotron Mass of Inversion-Layer Electrons in Si

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We have investigated the effect of temperature on the cyclotron resonance of electrons in an inversion layer on (100) Si between 4 and 80 K. With increasing temperature the resonance line is found to broaden and to shift considerably to higher resonance fields. The latter effect is strongest at low electron densities and, if interpreted as due to a temperature-dependent effective mass m_c^*, corresponds to changes in m_c^* in excess of 50%.

The recent observation of cyclotron resonance (CR) in electron inversion layers on Si[1-5] has contributed to a better understanding of the electronic properties of a quasi two-dimensional electron gas. The sample- and electron-density-dependent decrease of the CR field, observed at low electron densities n_s in inversion layers on (100) Si, was attributed to localization of electrons into states below the conduction-band edge.[3,6] To substantiate that claim we have now investigated the temperature dependence of the Cr position. With increasing temperature one expects the CR field in the regime of localization to approach that of unperturbed CR, i.e., a resonance field corresponding to an effective mass $m_c^*/m_0 = 0.19$.[1] Surprisingly we find, however, that with increasing temperature the CR field continuously increases and assumes values far above those expected for unperturbed CR. This increase is strongest at low n_s ($n_s \simeq 3\times 10^{11}$ cm^{-2}), but is also noticeable at $n_s \simeq 10^{12}$ cm^{-2}, at which the effect of localization is not observed in our samples. Though at present we have no satisfactory explanation for our observations, we suggest that they should be interpreted as due to a temperature-dependent effective mass m_c^*. The highest resonance field observed (at $T = 46$ K, $n_s = 3\times 10^{11}$ cm^{-2}) corresponds to $m_c^*/m_0 = 0.31$ which is more than 50% above the expected value of $m_c^*/m_0 = 0.19$.

The experiments are carried out at 890.7 GHz with use of a transmission arrangement described previously.[1] The temperature is measured and stabilized with a calibrated capacitance thermometer. The electron density n_s is square-wave modulated to achieve higher sensitivity than is possible with modulation of the magnetic field[1] or the incident laser radiation.[3] (To assure modulation of all inversion-layer electrons the modulation is applied on a negative bias voltage V_B smaller than the threshold voltage V_T.) Our samples are metal-oxide-semiconductor capacitors on 6-Ω-cm (100) p-Si substrates with a 2230-Å oxide layer, and lack source-drain contacts. Hence modulation of n_s can only be achieved when the sample is exposed to visible light of sufficient intensity.[1] The light intensity is adjusted to give a charging time ($\lesssim 10$ msec) much shorter than the modulation period (~ 170 msec). At a given gate voltage V_g the irradiation with light was found to decrease the CR linewidth by as much as 20% and to increase the CR amplitude (hence n_s). To determine quantitatively n_s and its variation with light we have measured the microwave magnetoconductivity at 4.2 K.[7] The amount of light necessary to obtain a sufficiently short charging time was found to increase n_s by about $(2\pm 0.5)\times 10^{11}$ cm^{-2}.

Figure 1 shows the change in transmission versus magnetic field H at $n_s = 5\times 10^{11}$ cm^{-2} and various temperatures. The asymmetry of the line shape is dominantly caused by multiple-internal-reflection effects in the Si substrate. With the known thickness and refractive index of the substrate we can, with an appropriate model for the dynamical conductivity, correct for these interference effects and extract from a best fit to the data the resonance field $H_0 = (c\omega/e)m_c^*$ and $\omega\tau$. Here we have used a classical model for the conductivity which at $T \gtrsim 20$ K and $\omega\tau \lesssim 3$ is a reasonable approximation to the more realistic model of Ando.[8] The systematic deviation of the data from the classical fit at low T and high $\omega\tau$, most noticeable at $H > H_0$ (see Fig. 1), can be explained by the $\sqrt{H}$ broadening proposed by Ando. Therefore the values for $\omega\tau$ quoted in the caption of Fig. 1 have to be understood as $\omega\tau$ at $H = H_0$. The details of the fit, including the effects of interference, will be discussed elsewhere.[4]

From the data in Fig. 1 we find H_0 and $\omega\tau$ to increase monotonically with temperature. The T-dependent part of the effective linewidth $1/\omega\tau$

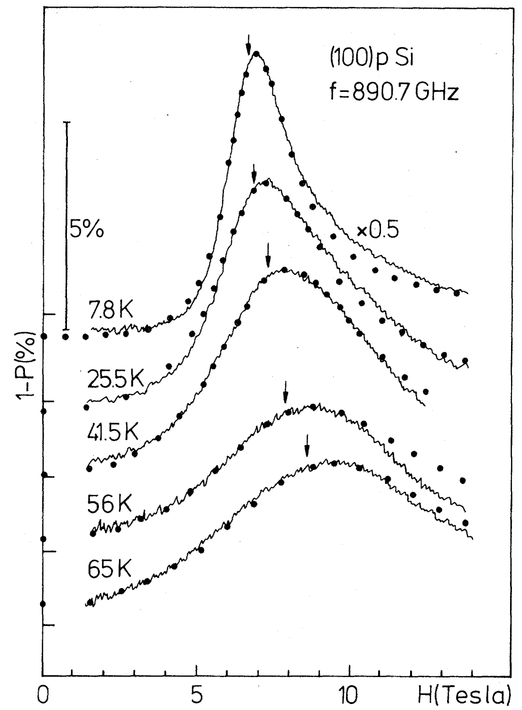

FIG. 1. Relative change in the transmitted power P versus magnetic field H at gate voltage $V_g = 4V$ ($n_s \simeq 5 \times 10^{11}$ cm^{-2}) and various temperatures. The dots are best fits to the line shape as discussed in the text. From the fits to the line shape we obtain values for m_c^*/m_0 of 0.210, 0.217, 0.232, 0.250, and 0.272, and for $\omega\tau$ of 6, 3.2, 2.5, 2, and 1.8 for the temperatures 7.8, 25.5, 41.5, 56, and 65 K, respectively. The corresponding values of H_0 are marked by arrows.

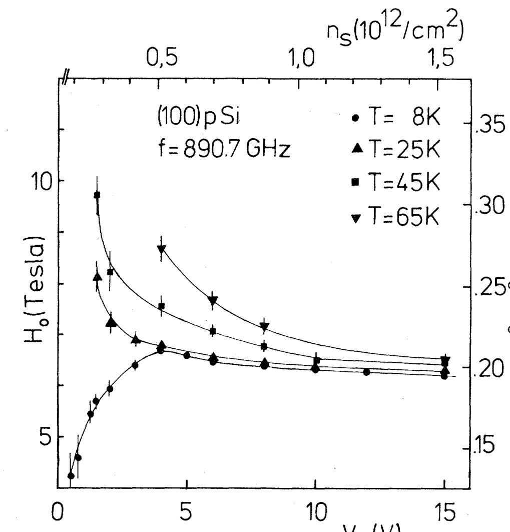

FIG. 2. Dependence of the resonance field H_0 on gate voltage V_g, i.e., electron density n_s, and temperature T. The lines are meant only to serve as a visual aid.

varies approximately linearly with T. Above $n_s \simeq 5 \times 10^{11}$ cm^{-2} the slope of the T-dependent part of $1/\omega\tau$ versus T is nearly independent of n_s and is $7.5 \times 10^{-3} \pm 20\%$ K^{-1}. The temperature dependence of the linewidth is thought to arise dominantly from phonon scattering[9] and will be discussed in detail in a later report.[10] In Fig. 1 the absolute values of the calculated amplitude are adjusted only slightly ($< \pm 20\%$) to fit the data. The variation between the calculated and measured amplitudes is not correlated with temperature and can be fully explained by variations in n_s and the inaccuracy to which $\omega\tau$ can be determined. Within the given accuracy the integrated strength of the resonance is independent of T.

In Fig. 2 the resonance field H_0 is shown as a function of n_s with temperature as parameter. At temperatures above 50 K the absorption line shapes had to be slightly corrected for bulk absorption of thermally excited holes which causes the laser intensity incident on the inversion layer to be magnetic-field dependent. At low temperatures ($T \lesssim 10$ K) we observe with decreasing n_s first a rise in H_0 and then, below $n_s \simeq 5 \times 10^{11}$ cm^{-2}, a decrease in H_0 which is attributed to electron localization.[3] Already at $T = 25$ K the effect of localization seems to be lifted completely and we see a continuous increase of H_0 with decreasing n_s. The T dependence of H_0 increases with decreasing n_s and, at a given n_s, does not appear to level off at the highest temperatures. Only for $n_s \gtrsim 1.5 \times 10^{12}$ cm^{-2} a T dependence of H_0 cannot be established beyond error. At a given n_s there appears to be a correlation between the increase in $1/\omega\tau$ and H_0 with temperature. Up to 25 K $1/\omega\tau$ has increased very little as has H_0 outside the regime of localization. Above 25 K we observe a stronger increase of H_0 as well as $1/\omega\tau$ with T. However, for fixed $\omega\tau$ at a varying T we also find a strong variation of H_0 with n_s. For example, at $n_s \simeq 3 \times 10^{11}$ cm^{-2} and $T = 45$ K we have the same $\omega\tau$ (~ 1.8) as at $n_s = 1.5 \times 10^{12}$ cm^{-2} and $T = 65$ K, but H_0 is 9.7 and 6.5 T for the two cases, respectively. Frequency-dependent CR investigations in samples from the same batch at low temperatures[11] show that at sufficiently high n_s (above the regime of localization) and $\omega\tau \gtrsim 2$ no variation of H_0 with $\omega\tau$ can be established, when the frequency is varied between 890 and

280 GHz, and that the variation of H_0 with n_s is independent of frequency. Hence any convincing model that might explain the T dependence of H_0 observed here will have to predict a variation of H_0 with both n_s and T even at constant $\omega\tau$.

The most startling result of our experiments is the increase of H_0 with temperature and decreasing n_s far above $H_0=6.2$ T, the resonance field expected for unperturbed electrons under the assumption $m_c^*/m_0=0.195$.[4] One explanation one might think of is that the shift in H_0 results from thermal occupation of the sub-band E_0' belonging to the valley with $m_c^*/m_0=0.42$.[12] CR of those electrons would center at $H=13.4$ T and its low-field tail could cause a shift of the observed CR signal to higher fields. However, the observed absorption amplitude at $H=13.4$ T is too small to explain the shift in H_0. Also, if one estimates the relative occupation of E_0'[12] one obtains too small a value to predict a significant contribution to the observed resonance from CR in E_0' except at the highest temperatures. Finally, the observed resonance, its line shape as well as its strength, can be fully explained by a single CR centered at a temperature- and n_s-dependent H_0. It therefore is very unlikely that our results can be explained by thermal occupation of E_0'.

If we rule out occupation of E_0' as a possible explanation, we have to interpret our results as due to a temperature-dependent m_c^*. At present we can only speculate as to what might be the origin of such a temperature-dependent m_c^*. Temperature-dependent investigations of volume CR in Si[13] at microwave frequencies only find a weak increase (6% ± 3%) of m_c^* when T is raised to 100 K. From the observation of Shubnikov–de Haas oscillations in an electron inversion layer on (100) Si Smith and Stiles[14] extract an effective mass m^* which increases with decreasing n_s. This effect is attributed to electron-electron interactions. Calculations of the effect of electron-electron interactions on m^* as a function of the dimensionless parameter r_s,[15,16] which is a measure of the distance between electrons and relates to n_s by $r_s^2=(\pi a_0^2 n_s)^{-1}$ (a_0 is the Bohr radius scaled by the dielectric constant and effective mass of the medium), show that m^*/m_0 increases significantly with r_s above $r_s\simeq 1$. These calculations are carried out in the $T=0$-K limit. For temperatures of the order of the Fermi temperature T_F one naively expects the effect of electron-electron interaction on m^* to be temperature dependent since screening will change with temperature. In our experiments, with $3.7\gtrsim r_s\gtrsim 1$, and $0.1\lesssim T/T_F\lesssim 2$ ($T_F\simeq 35$ K at $n_s=5\times10^{11}$ cm^{-2}), we cover the temperature and r_s regions where one expects a considerable dependence of the quasiparticle mass m^* on r_s and T. In a homogeneous electron gas the CR mass m_c^* should not be dressed by electron-electron interactions, as Kohn pointed out.[17] However, the presence of scatterers in inversion layers introduces inhomogeneity, as is manifested, for example, by the appearance of subharmonic structure on the CR.[18,8] Further theoretical investigations should clarify whether in inversion layers electron-electron interactions might at least partially affect m_c^* and should consider the effect of finite temperatures on the electron-electron interaction.

Another many-body effect that might possibly explain a temperature- and n_s-dependent m_c^* is electron-phonon interaction. However, the CR data on bulk Si[13] show that electron-phonon interaction can only explain our observations if the electron-phonon coupling at the Si-SiO_2 interface is much stronger than in bulk Si. An indication for that is that the observed phonon scattering in inversion layers[9,10] is about an order of magnitude too large to be explained by the bulk deformation potential. Possibly the breaking of the symmetry at the Si-SiO_2 interface gives rise to a stronger electron-phonon interaction. The effect of screening on the electron-phonon interaction and its temperature dependence might explain the dependence of an electron-phonon-interaction–enhanced m_c^* on n_s and T. The observed effect, however, seems too strong to be explained by electron-phonon interaction.

At present we cannot explain satisfactorily the observed temperature dependence of H_0 by any of the mechanisms described above. If the interpretation as a temperature-dependent m_c^*, caused by many-body interactions, is correct, all previous temperature-dependent measurements in inversion layers have to be carefully reexamined. A frequency-dependent investigation of temperature-dependent effects is in progress and might help to clarify the experimental situation.

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Picosecond Optical Measurements of Band-to-Band Auger Recombination of High-Density Plasmas in Germanium

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The recombination kinetics of transient high-density electron-hole plasmas in germanium has been measured by time-resolved free-carrier absorption with picosecond optical pulses. Density-dependent recombination rates as high as 4×10^{9} sec^{-1} have been observed in plasmas with initial densities up to 3.4×10^{20} cm^{-3}. At this density the band-to-band Auger rate constant, $\gamma_3=n^{-3}\,\partial n/\partial t$, is found to be 1.1×10^{-31} cm^{6} sec^{-1} at room temperature in germanium.

At very high carrier densities in semiconductors, the third-order nonradiative band-to-band Auger effect can dominate all other recombination mechanisms such as radiative and surface recombination, and trapping at crystal defects. Theoretical estimates of the Auger rate constants and activation energies have been made for a number of materials, including InSb,[1] Ge,[2] Si,[2] and GaAs.[3,4] While experimental observations[5-8] have clearly demonstrated the existence of band-to-band Auger recombination, accurate determinations of the rate constants have proven to be more difficult to obtain.

Measurement techniques which have been used include the direct observation of decay tails of luminescence[8] and photoconductivity[5] following excitation by Q-switched lasers, and indirect measurements such as the intensity dependence