Phenomenological line-shape analysis of cyclotron-resonance-induced conductivity of electrons on liquid helium

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Low-frequency magnetoconductivity measurements of two-dimensional surface electrons on liquid ^{4}He under cyclotron resonance conditions are reported here. At relatively low-electron densities, the cyclotron-resonance-induced conductivity line shape is a phenomenological combination of two resonances, which can be separated by fitting. The resonance which shows a decrease of the effective scattering time τ_{eff} with increasing driving field is studied here: the observed shift of the resonance, the resonance linewidth and the effective scattering frequency. It is found that the extracted τ_{eff} has a similar electric driving field dependence as published experimental results from zero-magnetic field, dc time-of-flight measurements.

Two-dimensional electron systems (2DES), localized on the surface of liquid helium have been studied widely by cyclotron resonance (CR) absorption techniques. The first experimental evidence for the 2D localization of surface charges was obtained by showing the shift in the CR position of the CR absorption line when the perpendicular magnetic field was tilted.[1] Another great merit of this technique was the observation of hot-electron effects, at temperatures below 1 K.[2] Both the shift of the position of the CR absorption resonance line and the change of the linewidth provide information on the fundamental transport parameters (e.g., effective mass change and scattering time) of the electron system.

A second widely used technique for studying these systems is the measurement of the conductivity of the 2DES with the use of Corbino geometry electrodes. In the so-called Sommer-Tanner measurement scheme, the submerged electrodes couple capacitively to the surface electrons. The complex impedance between the inner and outer Corbino electrode can be measured at low frequencies and can be related to the conductivity σ of the system. When a magnetic field is applied, the longitudinal conductivity tensor σ_{xx} can be extracted by using an equivalent circuit model.[3,4]

It is especially the combination of both CR absorption and conductivity techniques into cyclotron-resonance-induced conductivity (CRIC) measurements that has proven to be a powerful tool for the investigation of nonlinear transport properties of semiconductors.[5,6] It was previously shown[7] that CRIC can also be used for the investigation of 2DES on liquid ^{4}He. These preliminary results indicated that CRIC was due to resonant heating of the 2DES and it was suggested that two different competing mobility-change mechanisms were present at high driving fields. In the present paper, a CRIC experiment is described in which the magnetoconductivity (σ_{xx}) is measured under well defined Cyclotron Resonance conditions. Thanks to a fitting procedure, the CRIC resonance line shape can be separated into two different resonances, of which only the low-driving field CRIC lineshape will be quantitatively analyzed and discussed. An improvement with respect to Ref. 7 is the comparison of the results with zero-magnetic field dc time-of-flight measurements in terms of the normalized scattering frequency.

The experimental setup is given schematically in Fig. 1. The used experimental cell consists of a 40 to 60 GHz tunable microwave cavity with a Corbino geometry electrode mounted on a movable plunger. A dc bias voltage on both the wall (V_{GR}) and top plate (V_{TP}) of the cylindrical cavity confine the surface electrons radially and vertically (exerting the pressing field $E_{\perp}$). The Corbino geometry electrode consists of three concentric electrodes, which are all held on dc ground potential. Helium can be condensed into the cavity and the helium height can be determined by measuring the change in capacitance between the top plate and the Corbino electrode.

The used microwave system is based on an electron spin resonant cavity spectrometer,[8] and the (quality factor $Q \sim 3000$) cavity can be almost perfectly coupled to the wave guides. For a perfectly coupled cavity, the electric field component parallel to the surface $E_{\parallel}$ of the high frequency electromagnetic radiation was calculated from the TE_{011} mode-pattern inside the cavity at the position of the 2DES on the liquid ^{4}He surface. In this transverse electric resonant cavity mode, the microwave (MW) electric field has no z component and the in-plane MW magnetic field component is almost zero.[9] Here, we assume an accuracy of a factor of two for the calculated value of $E_{\parallel}$, a big improvement with respect to the used experimental setup of Ref. 7, where the exact electro-magnetic mode at the helium level was not precisely known, because a nonresonant cavity was used.

Our measurements were performed around $T = 1.4$ K where the elastic scattering of electrons with the helium gas atoms is the dominant scattering mechanism. The used electron densities are of order $n \sim 10^{11}$ m^{-2}. Figure 2(a) shows the change of the measured inverse normalized magnetoconductivity as a function of the microwave power or $E_{\parallel}$. At

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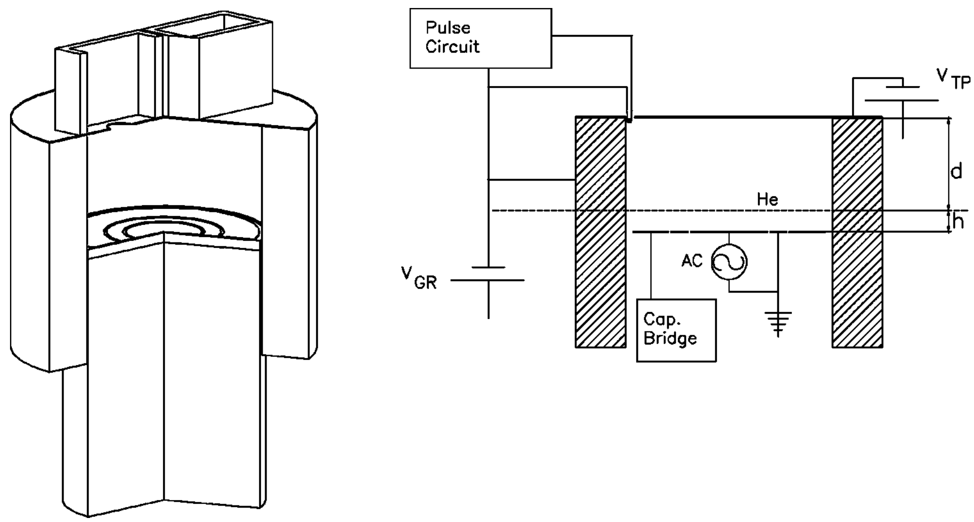

FIG. 1. (left) Tunable 40-60 GHz microwave cavity with Corbino geometry electrodes mounted on a movable plunger. (right) Schematic of measurement scheme for (grounded) electrodes and dc bias.

high microwave intensities an increase in $\Delta(\sigma_0/\sigma_{xx})$ is found, which is $E_\perp$ dependent and comes up at the resonant magnetic field which is expected for CR of free electrons. At low intensities, $\Delta(\sigma_0/\sigma_{xx})$ decreases with increasing driving field up to a certain electric threshold driving field where the positive peak starts to be visible. The broad dip is centered around a resonant magnetic field that is higher than expected for free electrons.

The experimental data hence show that except at very low-microwave intensities, the CRIC line shape consists of a combination of a negative change in $\Delta(\sigma_0/\sigma_{xx})$ or ''dip'' and a positive one or ''peak.'' In Fig. 2(b), $\Delta(\sigma_0/\sigma_{xx})$ is fitted to a combination of a Gaussian line for the dip and a Lorentzian line for the peak, resulting an excellent fitting quality, from which the amplitude [Fig. 2(c)], linewidth and resonant magnetic field position can be extracted.

It stands to reason to treat both resonances as coming from different physical origins, because of the difference in resonant magnetic field, the fact that the peak arises at a higher driving field and the linear, respectively exponential behavior of $\Delta(\sigma_0/\sigma_{xx})$ with increasing $E_\parallel$ for the dip and peak at the resonant magnetic field. This paper will be focused on the features of the dip resonance only which can be studied up to relatively high-driving fields by the described fitting procedure.

In Fig. 3(a) we have plotted the normalized line shift $\delta B/B_0$ of the fitted Gaussian for measurements at different frequencies and pressing field values. From this figure it can be seen that $\delta B/B_0$ is positive and decreases nonlinearly

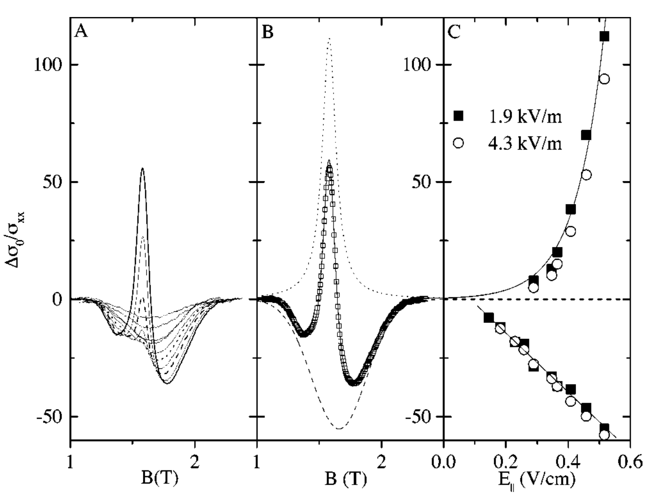

FIG. 2. (a) $\Delta(\sigma_0/\sigma_{xx})(B)$ for different microwave input-power values: from 0.06 μW via 0.3 μW (dotted line) and 0.5 μW (dashed line) to 0.8 μW (thick solid line). (b) Fit of $\Delta(\sigma_0/\sigma_{xx})$ $\times(B)$ at 0.8 μW to a combination (solid line) of a Gaussian line for the dip (dash) and a Lorentzian for the peak (dot). (c) Amplitude at the resonant magnetic field $B_c=1.58$ T for saturated density data in (a) (■) and (nonsaturated density) data at higher pressing field values (○). The lines are a linear and exponentional fit to the (■) data. All data were taken at $T=1.4$ K and $\nu_C=44.2$ GHz, $n=0.2$ $\times10^{12}$ m^{-2}.

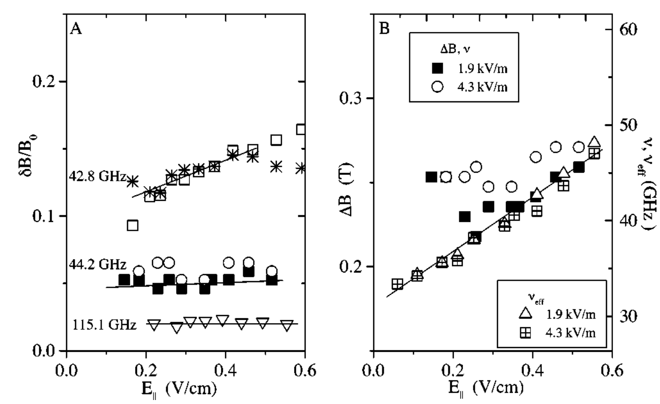

FIG. 3. (a) Normalized line-shift change $\delta B/B_0$ as a function of the driving field for three different microwave frequencies. Data points (▽) from (Ref. 7); (■,○), $n=0.2\times10^{12}$ m^{-2}, $E_\perp=1.9$ and 4.3 kV/m, respectively; (□,*), $n=0.3\times10^{12}$ m^{-2}, $E_\perp=2.9$ and 8.3 kV/m, respectively. (b) ΔB as a function of the driving-field $E_\parallel$ at 44.2 GHz. Datapoints (■,○) are taken from (a). On the right vertical axis the scattering frequency ν calculated according to Eq. (1) is given. Values for the effective scattering frequency ν_{eff} (⊞, △) were extracted from Eq. (2) using the values of σ_0/σ_{xx} in the minimum of the dip.

with increasing microwave frequency. For both the low-frequency data series (42.8 and 44.2 GHz) the line shift increases significantly with $E_{\parallel}$.

There exists no theory for CRIC effects in 2DES on liquid helium, but it can be expected that features like the magnetic field position of the resonance and its linewidth, which can be obtained from CR absorption measurements will also be reflected in the CRIC line form. Based on previous experiments and theory on CR absorption one would therefore expect a negative line shift, inversely proportional to the electron energy squared,[10] due to the presence of ripplons or a negative line shift due to the presence of an electron dimple.[11] However, they both do not coincide with the observed positive line shift in Fig. 3(a), though the frequency dependence of the effect is of the same order as in the ripplon case. Our experiments suggest that electron heating increases the effective electron mass and hence increases the coupling between the electrons. Such coupling may decrease at higher electron energies: a similar microwave frequency dependence as in the ripplon case.

Only one single (not explained) measurement[12] was reported in which a positive CR absorption line shift in the ripplon scattering temperature regime was observed in 2DES on liquid helium (at high driving field). CRIC has been frequently studied in semiconductors and Mordovets and Kotel'nikov[13] observed a positive shift of the CRIC signal in $GaAs/Al_xGa_{1-x}As$ heterostructures while the CR absorption line remained at its original position. They did not provide an explanation for this effect however, but the similarity with their result and ours deserves more investigation, for example by extended experiments with tilted magnetic field.

In Fig. 3(b) the half width at half maximum ΔB of the dip is plotted versus $E_{\parallel}$ for two different pressing field values. In analogy with standard analysis of CR absorption data, the scattering frequency was extracted with[12]

$$\nu = \frac{e\Delta B}{m} \tag{1}$$

as is indicated by the right vertical axis in Fig. 3(b). For the same CRIC measurements the effective scattering frequency ν_{eff} was extracted from σ_0/σ_{xx} at the center of the dip by using:[14]

$$\sigma_{xx} = \frac{e^2 n_0}{m} \frac{\nu_{eff}}{\omega_c^2 + \nu_{eff}^2}, \tag{2}$$

where ν_{eff} is generally a function of the magnetic field. In Fig. 3(b) $\nu_{eff}(E_{\parallel})$ is plotted by using the right vertical scale in ν.

The resulting $\nu_{eff}(E_{\parallel})$ is in good quantitative agreement with the driving field dependent scattering time as was extracted from the width of the dip using ΔB and Eq. (1), which is valid for CR absorption lines. Extrapolation of ν_{eff} towards zero driving field as is indicated with the solid line gives an estimated ''nonheated'' value of order 30 GHz. The associated linewidth ΔB [Eq. (1)] is about 0.15 to 0.2 T, which is in quantitative agreement with the value of the Landau level width[14] $\Gamma = e\hbar/m\sqrt{2B/\pi\mu_G}$ (here, $\Gamma/\hbar\omega_c \approx 0.18$ T) where $\mu_G(\approx 13\ \mathrm{m^2/V\,s}$ at $T = 1.4$ K) is the zero-field mobility for gas scattering. It should be noted that the

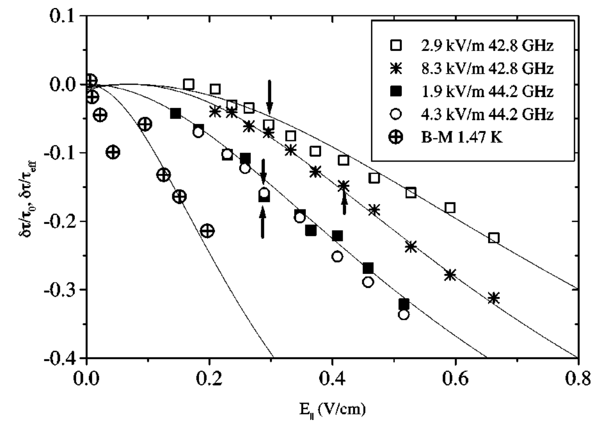

FIG. 4. Obtained normalized scattering time as a function of the driving-field for the (zero magnetic field) Bridges and McGill data (⊕) at 1.47 K, the 42.8 GHz data (□ and ∗, respectively) at $T = 1.44$ K and a density of $0.3 \times 10^{12}\ \mathrm{m}^{-2}$ and 44.2 GHz data (■ and ○, respectively) at $T = 1.4$ K and a density of $0.2 \times 10^{12}\ \mathrm{m}^{-2}$. The lines are fits according to the hot electron effects in a purely 3DES. The arrows mark the driving-field values where the peak starts to appear.

overall increase in line width with driving field is in agreement with the pioneering CR experiments by Brown and Grimes[1] in the same temperature region, where ''power broadened lines'' were observed due to the absorption of microwave radiation.

Bridges and McGill[15] (BM) performed time-of-flight measurements with low-density electron pulses on liquid helium in the gas-atom scattering temperature range from 1.17 to 2.7 K. They found that the electron mobility decreased with increasing dc electric drift field. It will be illustrative to compare the BM results with data extracted from the minimum in the observed negative change of the inverse normalized conductivity. It is clear from Fig. 3(b) that at CR $\tau_{eff} \equiv 1/\nu_{eff}$ decreases with increasing driving field. Data taken around $T = 1.4$ K show a qualitatively similar decrease with increasing $E_{\parallel}$ as the BM data. From the BM data at 1.47 K and CRIC measurements at 42.8 and 44.1 GHz, the normalized change in scattering time $\delta\tau/\tau_0$ (zero field for BM data) and $\delta\tau/\tau_{eff}$ (magnetic field dependent) has been calculated according to:

$$\frac{\delta\tau}{\tau_0} = \frac{\tau_0(E_{\parallel}) - \tau_0}{\tau_0}, \quad \frac{\delta\tau}{\tau_{eff}} = \frac{\tau_{eff}(E_{\parallel}) - \tau_{eff}(0)}{\tau_{eff}(0)}, \tag{3}$$

where τ_0 is the towards zero driving field extrapolated value for τ in Fig. 2 of Ref. 16 at 1.47 K and $\tau_{eff}(0)$ is calculated with Eq. 2 from the experimental value for σ_{xx} at the resonant magnetic field in the absence of microwave radiation (heating). The results are plotted in Fig. 4.

The BM data have been successfully explained by Saitoh[16] who calculated the average scattering time of electrons occupying various sublevels where both inter and intralevel relaxation times were taken into account. Saitoh pointed out that in the limit of high driving field the zero-field gas-atom scattering time would decrease with $\tau_0 \propto 1/\sqrt{T_e}$, similar to the expected value for a purely 3D electron system (3DES).[17] From early calculations by Shikin and Monarkha[18] it follows that under CR conditions, the electron temperature $T_e(E_\parallel)\propto E_\parallel^2$. In analogy with Saitoh's explanation, we have fitted the data with

$$\frac{\delta\tau}{\tau_{0,eff}}=\sqrt{\frac{T}{T_e}}-1 \tag{4}$$

while $T_e(E_\parallel)\propto E_\parallel^2$. The fits of $\delta\tau/\tau_{0,eff}(E_\parallel)$ are denoted by the solid curves in Fig. 4 and give such good agreement with the experimental data that it is attractive to ascribe the whole negative change in the normalized inverse magnetoconductivity to heating in a 3DES. This would mean however, that 3D states are even occupied at $E_\parallel=0$. It follows from theoretical calculations[18,19] that the occupation over the sublevels in the one-dimensional quantum well formed by the surface of liquid helium, can be described with a Boltzmann distribution. At (nonzero) low temperatures, there will only be a small occupation of the high (quasi) 3D sublevels, but this occupation grows with T_e. Therefore, a realistic physical picture should also include the occupation ratio over the various sublevels including 2D states, in a similar way as was done by Saitoh. To apply a complete calculation of the kind Saitoh has performed to our case, information on the energy relaxation time as a function of the magnetic field is necessary. However, no experimental results on the study of the energetic relaxation time in the gas-atom scattering regime have been reported to date. In the ripplon regime, the energy relaxation time has been studied, though not in a large extent and magnetic field effects have never been included. With a wider understanding of the CRIC phenomena, it might be possible to extract the energy relaxation time directly from CRIC measurements. Therefore, a more complete understanding of CRIC and its features will probably contribute to the interesting subject of energy relaxation in 2DES.

In summary we have reported CRIC measurements in low density 2DES on liquid helium, in moderate magnetic fields by using a combination of CR absorption and magnetoconductivity measurements. After separation of the two resonances which build up the CRIC line shape, we have studied quantitatively the negative resonant change in σ_0/σ_{xx} or dip, which occurs at low electric driving fields. The first feature, the shift of the minimum to higher resonant magnetic field values with respect to the free electron position, cannot be explained. Secondly, the line width of the resonance reflects the scattering frequency in a magnetic field and is consistent with the effective scattering time that can be found from the dip's amplitude. Finally, we have found that the effective scattering time is in good agreement with results from dc time-of-flight measurements. Although a fit to the theoretical scattering time for 3D hot electrons gives an excellent agreement with the data over the whole $E_\parallel$ region, it is expected that this is not the right physical picture for the low driving field region. More extensive investigation of the 2D and 3D electron fractions due to electron heating in a magnetic field would be neccesary to resolve the present problem.

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