Cyclotron resonance for 2D electrons on thin liquid helium films

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Abstract

An investigation of the microwave absorption for two-dimensional electron systems (2DES) on helium films and in the presence of acyclotron resonance (CR) magnetic field are presented. Measured data are explained by a recently proposed two-fraction model of the 2DES, which makes the general structure of the microwave absorption understandable. The fraction of localized and free electrons can be precisely determined and its dependence on the thickness of the helium film above the roughness of the underlying solid substrate is understood.

Key words: 2D electron systems; cyclotron resonance; thin helium films; surface roughness

A two-dimensional (2D) sheet of electrons on thin helium films forms an interesting field for studying low-dimensional systems. So there is, e.g., the "dimple" formation, the high level of stability (with respect to the bulk situation), the dipole-dipole crystallization, layering effect in the electron mobility and so on, see Ref. [1]. All these phenomena are developed under the assumption that the solid substrate is flat. However, in reality solid surfaces are not perfect and the level of roughness is usually not small (the roughness amplitude is comparable to the thickness of the helium film). So the question arises, how the 2D electron system on a thin helium film "feels" the random roughness of the substrate. A preliminary answer to this question is presented in Ref. [2]. Using quite general assumptions 2D electron layers on thin helium films are represented as a two-fraction system which leads to various consequences of the understanding of these electron layers [2]. In this paper the two-fraction scenario is used for the cyclotron resonance (CR) problem. We explain, how the free electron motion and localization phenomena can coexist in the presence of randomly rough solid substrates under CR conditions.

The experiments are done such that a thin liquid ^{4}He film is formed inside a microwave resonator, see inset in Fig. 1. This helium film is covering a high-ohmic Si-wafer on which a varying potential is applied and so building a holding electric field for the conservation of the 2DES. A magnetic field B is applied perpendicular to the the electron layer. The temperature of the system is ≈ 1.3K.

The total CR absorption Q^{-1} can be presented as a combination of two fractions, i.e.,

$$Q^{-1} = Q_e^{-1} + Q_l^{-1} \ , \tag{1}$$

where $$Q_e^{-1} \propto n_e p(\omega_o, \tau, \omega_c) \tag{2}$$

$$p(\omega_o, \tau, \omega_c) = \frac{1 + \omega_o^2\tau^2 + \omega_c^2\tau^2}{(1 - \omega_o^2\tau^2 + \omega_c^2\tau^2)^2 + 4\omega_o^2\tau^2} \ ,$$

and $$Q_l^{-1} \propto \ n_l \ q(\omega_c^2\tau^2, \omega_o^2\tau^2) \tag{3}$$

$$q(x,z) = \frac{\arctan\frac{\sqrt{z}}{1+x+\sqrt{xz}} + \arctan\frac{\sqrt{z}}{(1+x)\sqrt{z}-z\sqrt{x}} + \mathrm{c}(x,z)}{2\sqrt{z}} \ ,$$

with $x = \omega_c^2\tau^2 \ , \quad z = \omega_o^2\tau^2 \ ,$

and $$\mathrm{c}(x,z) = \frac{\pi}{2}(1 - \mathrm{sgn}((1+x)\sqrt{z} - z\sqrt{x})).$$

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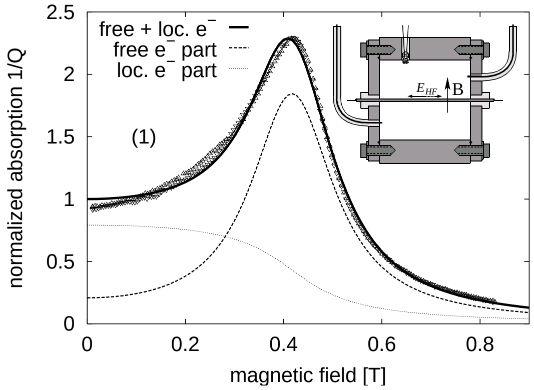

Fig. 1. Shown is the absorption Q^{-1} as function of magnetic field for up (△) and down (▽) sweeps. The dashed and dotted lines represent the free and localized electron fraction, the full line is the sum of both fitted to the data. Here $h \approx 6$ mm and $n_e \approx 60\%$. This data set (1) corresponds to the same labeled data point in Fig. 2. Inset: shown is the resonator as used in the experiment. In the center is the dielectric Si substrate, on which a thin helium film is adsorbed. $E_{\rm HF}$ indicates the microwave electric field which is parallel to the electron layer.

The function $c(x, z)$ is only needed to get the right branch of the arctan function.

The average total electron density n_s is given by

$$n_e + n_l = n_s \ , \tag{4}$$

where n_e and n_l corresponds to the free and localized electron densities.

The total absorption has now two fit parameters: τ and n_e/n_s. To extract these numbers from the experimental data it is convenient to fit the combination

$$\frac{Q^{-1}(\omega_c^{(max)})}{Q^{-1}(\omega_c = 0)} = \tag{5}$$

$$\frac{\nu_e \ p(\omega_o, \tau, \omega_c^{(max)}) + \nu_l \ q(\omega_o, \tau, \omega_c^{(max)})}{\nu_e \ p(\omega_o, \tau, 0) + \nu_l \ q(\omega_o, \tau, 0)}$$

where $\nu_e = \frac{n_e}{n_s}$, $\nu_l = \frac{n_l}{n_s}$ and $\nu_e + \nu_l = 1$,

together with the definition of $\omega_c^{(max)}$,

$$\left. \frac{\delta Q^{-1}}{\delta \omega_c} \right|_{max} = 0 \ . \tag{6}$$

The fits, based on definitions (1) – (6), for the data using the setup shown in the inset of Fig. 1, are presented in Fig. 1 together with the measured data. One can see that both Q_e (dashed line) and Q_l (dotted line) cannot separately fit the data. But their combination (solid line) with the flexible parameters τ and ν_e fits the data quite good. The dependence of $\omega\tau$ on h is shown in the inset of Fig. 2.

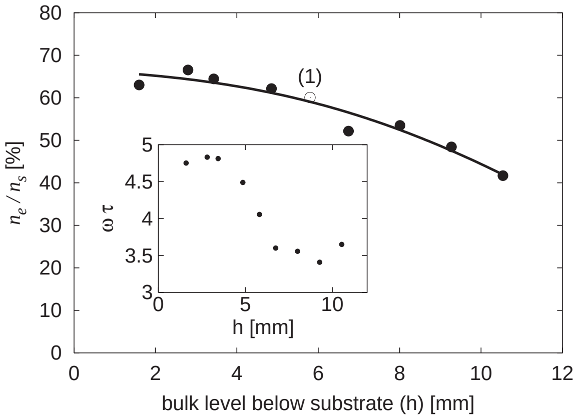

Fig. 2. Dependence of free electron fraction n_e as function of distance of bulk helium level below the substrate h. (•) and (∘) are from fitting to all measured data. The solid line presents the best fit to all measured fractions. The (∘), labeled (1), corresponds to the data-points shown in Fig. 1. Inset: the dependence of $\omega\tau$ as function of h is shown.

The results of fitting to CR data like in Fig. 1 but for a wide range of h are presented in Fig. 2. This shows clearly the influence of the substrate roughness (in the case of a regular corrugation such a dependence would not exist). Within the scenario of Ref. [2] for the gaussian roughness distribution, with Δ^2 as a mean-square roughness amplitude in vertical direction, and the same gaussian correlation in horizontal direction (the corresponding correlation length is equal to ζ, see Ref. [2]), we can fit the data (the solid line in Fig. 2) if $\Delta \approx 10$ nm and $\zeta \approx 6$ nm. These numbers are typical values for common solid substrates.

In conclusion we have shown that with the recently proposed two-fraction scenario of electrons on thin helium films, the measured CR-data can be understood. The asymmetry of the absorption line and its dependence on the thickness of the helium film is modelled. From this, the free and localized electron density is found and one can also obtain information about the roughness of the helium-covered substrate.

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