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Terahertz Spectroscopy of Double CdTe/CdMgTe Quantum Wells

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Modulation doped CdTe/CdMgTe double quantum wells were studied at low temperatures and high magnetic fields. Transmission of THz monochromatic radiation from a molecular laser was studied as a function of magnetic field on samples with a grid processed on the surface either by evaporation of metallic stripes or by etching stripe-like trenches which cut only the well positioned closer to the surface. We compare dispersion relations of THz excitations in these samples and in an unprocessed one and we show that the strength of magnetoplasmon excitations in samples studied can be considered as a promising basis to construct magnetic-field tunable THz detectors.

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1. Introduction

Modulation doped heterostructures or quantum wells (QWs) with a two-dimensional electron gas (2DEG) have been intensively studied with THz spectroscopy techniques in the presence of magnetic field [1]. Two main reasons have been motivating this research. First, there have been an interest in basic studies of low-energy excitations of a 2DEG, particularly at very low temperatures and high magnetic fields [2, 3]. Second, such structures exhibit two types of excitations, i.e., a cyclotron resonance (CR) and a magnetoplasmons (MPs), which can serve as a basis for construction of magnetic-field tunable resonant detectors [4].

In theory, the CR is an exciton of a 2DEG in an infinite conducting plane, where two oscillating currents, shifted in phase by a quarter of period, flow in perpendicular directions. Then, a resonant response to a monochromatic excitation ω_L appears at magnetic field B which satisfies relation

$$\omega_L = \omega_c = eB/m,$$

with e and m being the charge and effective mass of electron, and ω_c — the cyclotron frequency. In experiments, to observe a CR transition one has to study an appropriately big sample. On the other hand, MP excitations appear in samples whose width or length is comparable to the MP wavelength. Then, MPs can be excited if the condition

$$\omega_L^2 = \omega_c^2 + \omega_p^2 \tag{1}$$

is satisfied, where

$$\omega_p^2 = \frac{Ne^2k}{2m\epsilon_0\epsilon_{\text{eff}}(k)} \tag{2}$$

describes the plasmon frequency at zero magnetic field. In the last formula, N is the 2DEG concentration, k is the MP wave vector, and $\epsilon_{\text{eff}}(k)$ is a k-dependent effective dielectric constant which describes the polarizability of media surrounding the 2DEG (see Ref. [1] for details).

In an essential difference with the cyclotron resonance, magnetoplasmons are propagating waves which carry a momentum $\hbar k$. This momentum cannot be transferred by an incident photon[†] and is given to the plasmon by the structure itself. Thus, k is quantized according to dimensions of the sample or is given by the period of a structure processed on the sample's surface. Typically, this structure takes the form of a grid (evaporated or etched) but other solutions are possible [5].

The semiconductor system most often used for studies of the CR and MPs is a modulation doped GaAs/AlGaAs heterostructure or a quantum well because of a high mobility of electrons. However, recently we have shown [1, 4, 6, 7] that magnetoplasmon spectroscopy at THz frequencies can be carried out also on

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[†]We consider here the case the most frequently realized in experiments, when k is high enough so that the group velocity of plasmon is smaller than the phase velocity of light propagating in the medium. This non-retarded limit can change to a retarded one if k is very small or the characteristic dimensions of the sample big enough.

CdTe/CdMgTe or GaN/AlGaN heterostructures. Interestingly, some phenomena that were not easily observed in GaAs/AlGaAs systems were shown in the case of other compounds, like an influence of the polaron effect on magnetoplasmon dispersion in CdTe/CdMgTe [7].

The main goal of the present paper was to study the CR and MP excitations in samples with a grid composed of stripes of a 2DEG. This idea originates from a paper by Mikhailov [8] who argues that the amplitude of MP resonances can be essentially increased if the plasmon frequency of the grid material is comparable to that of the 2DEG. Following this idea, a double CdTe/CdMgTe quantum well modulation doped was grown and etched in such a way that stripes of a 2DEG from one QW (closer to the surface) were left and formed a grid for a 2DEG residing in the other one (more distant from the surface). We compare results of magnetotransmission experiments which were carried out on etched sample, on a sample with a metallic grid and on an unprocessed sample. We also show that the strength of MP resonances observed on these samples make them good candidates for magnetic-field tunable detectors.

2. Experimental procedures and results

To make the description of the sample's structure simpler, we will refer to the QWs as "upper" and "lower" with the former residing closer to the surface. Both QW were 20 nm-thick and separated with a 84 nm-thick CdMgTe barrier. The upper QW was separated from the surface with a 74.5 nm-thick CdMgTe barrier and a 10 nm-thick CdMgTe cap layer. Both QW were modulation doped with iodine residing in twelve monolayers separated from the QW by a 20 nm-thick spacer. In both cases, the doping was "above" the QW, i.e., closer to the surface than the QW itself.

The samples were processed with an electron lithography. A gold grid with the period and the geometrical aspect equal to 8 μm and 50%, respectively, was evaporated on one of them. Another one was subjected to etching which fabricated a grid with the same geometrical parameters. The third one was unprocessed.

The top part in Fig. 1 shows a photograph of the etched sample while the bottom one presents the etching profile measured with an atomic force microscope. As one can infer from Fig. 1, the maximum depth of etching was 100 nm which means that etching did not reach the lower QW which is positioned at a distance of almost 200 nm below the surface. On the other hand, etching was deep enough to remove partially the upper quantum well (bright stripes in Fig. 1) leaving the 2DEG in 4 μm-wide bars (dark stripes in Fig. 1).

Terahertz spectroscopy was carried out with the sample placed in a liquid helium cryostat at a temperature of 2 K (in a variable temperature insert) and in the magnetic field generated by a superconducting coil. A monochromatic radiation from a molecular laser was wave-guided to the sample. A carbon bolometer was placed behind the sample which allowed to measure transmission of the incident radiation as a function of magnetic field. A set of spectra obtained on three samples are shown in Fig. 2.

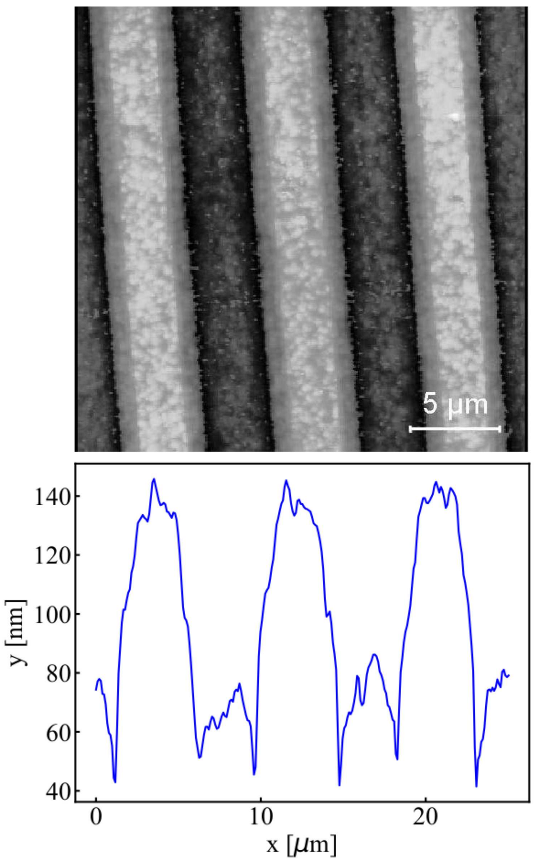

Fig. 1. A photograph of the etched grid (top) and the etching profile measured with an AFM (bootom). Brighter stripes correspond to trenches. Borders of trenches are darker than middle parts and reflect the presence of deep pits revealed in the etching profile.

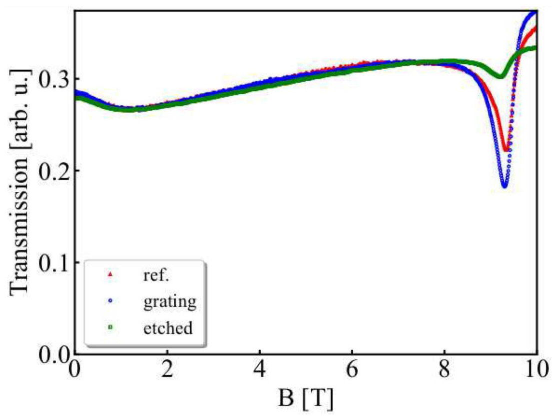

Fig. 2. Transmission spectra of radiation with the wavelength of 118.8 μm for three samples: with a gold grid, unprocessed and with an etched grid (bottom to top).

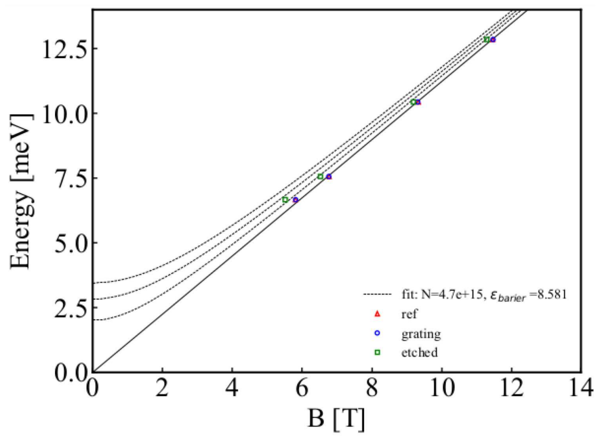

Fig. 3. Dispersion of excitations observed on samples studied.

The middle curve was obtained on the unprocessed sample and shows a cyclotron resonance transition. The curve with the strongest absorption, even stronger than that of the CR, comes from the sample with the gold grid. The smallest absorption was obtained on the sample with the etched grid.

Repeating experiments with a few laser lines, we arrived at plasmon dispersions shown in Fig. 3. The straight line corresponds to the CR with $m = 0.101m_0$ (m_0 is the electron mass). Plasmonic dispersion for three modes are calculated according to Eq. (2) with $N = 4.7 \times 10^{11}$ cm^{-2} and a dielectric constant of the CdMgTe barrier equal to 8.581. In calculations, we assumed that plasmon wave vectors are defined as $k_n = 2\pi n/\Lambda$, where $n = 1, 2, 3...$ is the number of the mode, and $\Lambda = 8$ μm is the period of the grid. Also, the effective dielectric constant was assumed to be that for ungated plasmons. We observe an overall agreement between the model and experimental data.

3. Discussion

The results presented show that the strongest magnetoplasmon response is obtained in the case of a gold grid (see Fig. 2). This result is the opposite to expectations based on Ref. [8]. However, a more detailed studies (not presented in this paper) show that the amplitude of the MP resonance in etched samples depend both on the depth of trenches as well as on the geometrical aspect ratio of the grid. This suggests that etching decreases the concentration of 2DEG both in the upper QW (which is obvious, because a part of it is removed) and in the lower QW due to creation of edge states in trenches which are populated with electrons from the 2DEG.

On the other hand, the concentration of 2DEG in a sample with the gold grid is not perturbed which leads to a strong MP resonance. Looking through the literature devoted to magnetoplasmons we note that such a strong MP signal is rather an exceptional case because MP features typically are much weaker than these related to the CR. This observation requires confirmation on metallic grids with different aspect ratio.

An interesting feature of the present study is a difference in the shift (in magnetic field) between the CR and MP in two samples with a grid. This shift is much smaller in the case of the gold grid than the etched grid. Analyzing Eq. (1) and (2) one finds that the bigger is the shift, the higher is ω_p. Taking into account that in the case of grids with the same period, k vector is the same, and the concentration N is smaller in the etched sample, one concludes that in the case of etching, the effective dielectric constant, entering Eq. (2), must be essentially smaller than in the case of the gold grid. This opens a possibility to introduce another technological parameter (next to the geometry of the grid) which defines the frequency of MP modes.

4. Conclusion

We carried out THz transmission experiments at cryogenic temperatures and high magnetic fields on CdTe/CdMgTe double quantum wells. The samples were equipped with a gold grid or an etched grid. We show that both types of grids can be used to observe magnetoplasmon resonances but etched grids introduce an additional flexibility in controlling their frequency. Also, the amplitude of resonances are comparable to that of the cyclotron resonance which shows that one can construct THz detectors based on magnetoplasmon excitations.

Acknowledgments

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References

[1] J. Łusakowski, *Semicond. Sci. Technol.* **32**, 013004 (2017).

[2] M.S. Kushwaha, *Surf. Sci. Rep.* **41**, 1 (2001).

[3] I.A. Dmitriev, A.D. Mirlin, D.G. Polyakov, M.A. Zudov, *Rev. Mod. Phys.* **84**, 1709 (2012).

[4] M. Białek, M. Czapkiewicz, J. Wróbel, V. Umansky, J. Lusakowski, *Appl. Phys. Lett.* **104**, 263514 (2014).

[5] R. Krahne, M. Hochgräfe, Ch. Heyn, D. Heitmann, M. Hauser, K. Eberl, *Phys. Rev. B* **62**, 15345 (2000).

[6] K. Nogajewski, J. Lusakowski, W. Knap, V.V. Popov, F. Teppe, S.L. Rumyantsev, M.S. Shur, *Appl. Phys. Lett.* **99**, 213501 (2011).

[7] I. Grigelionis, K. Nogajewski, G. Karczewski, T. Wojtowicz, M. Czapkiewicz, J. Wróbel, H. Boukari, H. Mariette, J. Łusakowski, *Phys. Rev. B* **91**, 075424 (2015).

[8] S.A. Mikhailov, *Phys. Rev. B* **58**, 1517 (1998).