Investigation of semiconductor heterostructures HgTe/HgCdTe under magnetic fields up to 50 T

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Abstract. Our paper is devoted to a compact economic magnetic facility, which is equipped by a 300 kJ capacitor bank. The facility is designed for the exploration of magnetic and optical substance properties under magnetic fields up to 50 T and under cryogenic temperatures. The cyclotron resonance and quantum Hall effect measurement results are presented for semiconductor heterostructures HgTe/HgCdTe with quantum wells.

1. Introduction

High magnetic fields are an important instrument for a new material research and searching new effects. A majority of recent discoveries are connected with high magnetic fields. The generation of such fields is a difficult technical problem [1,2]. The pressure on a solenoid shell reaches the ultimate breaking strength of basic constructional materials at the magnetic induction of 50 T. This limit can be overcome by a pulse time reduction or by a load distribution in a compound sectional solenoid [1,3]. The increase of sections quantity leads to a solenoid size increase and magnetic energy growth. High-energy sources (50-100 MJ) are necessary, they are available for small amount of large magnetic laboratories [4]. Record magnetic fields up to 2800 T [5] can be generated in several laboratories with explosive techniques.

The majority of high magnetic fields experiments refer to solid state physics: investigation of upper critical magnetic field in high-temperature superconductors, magnetic phase transitions, magnetic resonance phenomena and etc. One of the most efficient methods of semiconductor zone structure research is a cyclotron resonance (CR). Its observation is possible when a cyclotron frequency exceeds a carrier scattering frequency. This demands high quality samples or high magnetic fields. A sample quality in new technologies is usually not high. Sample parameters measuring are important for the determination of the technology development prospect. That is why, higher magnetic fields allow samples of lower quality.

2. Experimental facility

A wire-wound coil with the internal diameter of 20 mm and external diameter of 80 mm is developed for the generation of magnetic fields up to 50 T. A small coil size leads to a high magnetic energy density and appearance of giant pressures on coil shell up to 1-1.2 GPa. Usual copper or steel wires fail
under such load. A microcomposite Cu-Nb wire with a cross-section of 2×3 mm² developed by VNIINM Bochvar was used for coil winding. The wire is characterized by a high elastic modulus and giant breaking strength more than 1.3 GPa.

Special technological equipment [6] is developed for a coil winding by a rigid wire. It allows winding with a gradual increase of the wire tension according to the layer radius increase. This leads to the production of the preliminary mechanical tension in a coil [7]. The wire is covered by a glasscloth isolation before winding. The wire coil is reinforced by a bandage of 20-30 mm from high-tensile fiber ARMOS. The coil is impregnated by an epoxy compound with a powdered quartz filler, and is dried layer-by-layer.

The electrical circuit of the facility is thoroughly described earlier [8]. One of the main component of the facility is a commutator based on the reversely connected dynistors. The advantage of semiconductor commutators is the absence of electric noise at the beginning of a pulse. The dynistors can endure high current overloads. At the nominal conditions the current is equal to 30 kA with 10 ms duration and can reach 90 kA with 2 ms duration of a pulse. Such overload ability is useful in a breakdown when the facility approaches a short circuit regime.

![Figure 1](image1.png)  **Figure 1.** Coil immersed into the plastic cryostat filled by the liquid nitrogen.

![Figure 2](image2.png)  **Figure 2.** Time dependence of the magnetic flux density for this coil.

The coil is preliminary cooled by the liquid nitrogen in the plastic cryostat (Figures 1, 2). The vacuum optical channel is placed along the coil axis and extends over the cryostat. The sample is attached to the heat-conducting ceramic holder in the coil center. On the holder a thermocouple and induction sensor are also mounted. The thermoregulator is used to set up a sample temperature in the range of 77-250 K. Optical windows are fixed at the ends of a vacuum channel, and they are used for optical measurements. They are carried out from a cooling region and provide a free transmission of the visible and infrared probing radiation. A different radiation sources and sensors can be used during the magnetic absorption investigation.

The sample cooling up to a liquid helium temperature is performed in a flow cryostat. The liquid helium is delivered under the pressure from the transport Dewar vessel. The sample is cooled by the helium vapor or by immersing into the liquid helium. The cryostat is used for measurements of the magnetoresistance and quantum Hall effect (QHE).

3. Experiment results and discussion

The results of the cyclotron resonance and QHE measurements are discussed for the semiconductor heterostructures HgTe/CdHg1-xTe. These structures have remarkable properties caused by the invert band and spin-orbital coupling [9]. The band-gap energy tends to zero for the heterostructures HgTe/CdHg1-xTe with a critical width of quantum well (QW) \( d_c = 6.3 \text{ nm}, x = 0.7 \) and the energy
dependence of the charge carrier on the wave vector becomes linear for the valence and conduction bands [9,10], similarly to the graphene spectrum.

![Figure 3. Magneoabsorption oscillograms for the samples under different temperatures.](image)

Dirac electrons with the linear dispersion law should be light with a high mobility. Consequently, CR and QHE should be observed at the higher temperatures than those for the common semiconductors. First liquid nitrogen temperature experiments have been carried out in Refs. [11,12]; and two lines of magnetoabsorption were observed with a wavelength of 10.6 μm. These lines survive till 200 K. The magnetoabsorption oscillograms for the samples with a different width of QW are presented in Fig. 3. Our samples were grown by a molecular beam epitaxy (MBE) on semi-insulating GaAs (013) substrates [13]. A CdTe buffer, ~ 40 nm lower Cd_{x}Hg_{1-x}Te barrier, HgTe QW, and ~ 40 nm Cd_{x}Hg_{1-x}Te top barrier were grown one by one. A 40 nm CdTe cap layer was also grown above the structure. The samples parameters are presented in the Table 1.

| №        | Quantum well-width, nm | Concentration of Cd | Carrier concentration, cm⁻² | Carrier mobility, cm²/V·s |
|----------|------------------------|---------------------|------------------------------|---------------------------|
| 091217   | 7                      | 0.72                | 2.2                          | 50000                     |
| 091223-1 | 8                      | 0.62                | 1.5-1.6                      | 20000                     |
| 101109   | 8                      | 0.77                | 4.5                          | 85000                     |
| 130212   | 8.3                    | 0.78                | 10.2                         | 69000                     |

The location of one of the lines is temperature independent. The location of another line has a strong temperature dependence. To interpret the experimental results, the temperature-dependent band structure and Landau level calculations based on the eight-band kp Hamiltonian for (013)-oriented heterostructures HgCdTe were performed in Ref. [14,15].

It can be assumed that one of the lines is associated with an interband transition, and its location is determined by a band-gap energy, which depends on the temperature. The second line is associated with an intraband transition, that is why, its temperature dependence is weak. The band structure of the heterostructure with QW ~8 nm changes from the invert to normal structure near T = 50 K, when the temperature rises. The detailed analysis of the temperature dependence of the magnetoabsorption lines is presented in Ref. [16].
Conclusions
The results of the magnetoabsorption investigation and CR of heterostructures HgTe/HgCdTe with QW in pulsed magnetic fields up to 40 T are presented for a wide temperature region. The intraband transition (cyclotron resonance) and interband transition (from the valence band Landau level to the conduction band) are observed. The quantum limit of the longitudinal resistance QHE is registrated (Figure 4). The transition from the invert band structure to the normal one is observed for the structures with QW ~8 nm.

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