Microwave radiation absorption by 2D-electrons in the type II composite InAs/GaSb/AlSb quantum wells in a magnetic field

I V Kochman¹, A I Veinger¹, M P Mikhailova¹, P V Semenikhin¹, K V Kalinina¹, R V Parfeniev¹, V A Berezovetz¹, A Hospodková², J Pangrác² and E Hulicius²

¹ Ioffe Physical-Technical Institute, 194021, Politkhnicheskaya, 26, St. Petersburg, Russia
² Institute of Physics CAS CR, v.v.i., Cukrovarnická 10, 162 00, Prague, Czech Republic

E-mail: kochman@mail.ioffe.ru

Abstract. Strong Shubnikov – de Haas (SdH) oscillations were observed in the derivative of microwave absorption (f = 10 GHz) in the InAs/GaSb/AlSb composite quantum wells (CQWs) using electron-paramagnetic-resonance spectroscopy at low temperatures (2.7–20 K) and in the magnetic field up to 14 kOe. CQWs were grown on the n-GaSb:Te(100) and n-InAs:Mn(100) substrates with various width of QWs by MOVPE. Predominance contribution of the bulk n-GaSb substrate in SdH oscillations was manifested. Two frequencies of the SdH oscillations were found from Fourier analysis, which is connected to warping of the Fermi surface of GaSb. Unusual angular indicatrix was observed in dependence on orientation of the samples in the magnetic field. Obtained results can be explained by inversion asymmetry, which is a feature of the substances with lack of inversion centres. For CQWs grown on n-InAs:Mn (n_s = 1.1 × 10¹⁷ cm⁻³) substrate, only several SdH oscillations with higher period were observed. Taking into account isotropic Fermi surface of bulk InAs, we succeeded to extract a contribution of the 2D carriers of InAs QW ~ H, from bulk substrate oscillations using special spline interpolation from angular dependence of SdH oscillatory amplitudes in the angle range 0–90°. 2D electron concentration in the InAs QW n_s ≈ 1 – 3 × 10¹¹ cm⁻² was evaluated from oscillatory period.

1. Introduction

Magnetotransport, spin-dependent and topological properties of the composite quantum wells (CQWs), based on the type II broken-gap InAs/GaSb/AlSb heterojunctions are actively studied in the last decades [1-6]. These structures are promising for spintronics and nanoelectronics side by side with HgTe [7] and graphene [8].

The unique properties of the type II broken-gap InAs/GaSb heterojunctions are due to the conduction band of InAs lying 150 meV lower than the valence band of GaSb [9, 10]. Electrons and holes are spatially separated, but they can tunnel between the wells. This allows the coexistence of closely separated electron (InAs) and hole (GaSb) two-dimensional gases. It gives the possibility to observe mixing conduction and valence band states and their hybridization under applied electric or magnetic fields [6]. In the narrow QWs (a_s < 85 Å), electron level E₁ is always higher than heavy hole level H₁ and we obtain normal semiconductor regime [2]. In wider well electron level E₁ will be lower than hole level H₁, so the band energy diagram of the QW will be inverted, i.e. E_g0 is negative [1, 2]. If
the QWs are undoped, there will be only electrons in such semimetal InAs QW due to their transfer from GaSb valence band which accounts for Coulomb interaction.

Previously magnetotransport, optical and spin-dependent phenomena were studied on the type II broken-gap GaInAsSb/p-InAs heterojunctions with self-consistent QWs grown by liquid-phase epitaxy (LPE) with sharp heterointerface and high mobility electron channel at the interface. At low temperatures, hybridization of the energy bands has been observed in the wide range of magnetic fields. For the first time the quantum Hall effect was observed and semimetal-insulator transition was obtained at $H_{\text{cont}} > 16$ T in such broken-gap structures [10-13].

We report here the absorption of microwave radiation power and the observation of Shubnikov-de Haas (SdH) oscillations using electron-paramagnetic resonance spectroscopy (EPR) on InAs/GaAs/AlSb CQWs grown by metalorganic vapor phase epitaxy (MOVPE) on the lattice-matched GaSb and InAs substrates.

2. Experimental

It is known that InAs, GaSb and AlSb belong to 6.1 Å family with near equal crystal lattices [14]. It allows growing up lattice-matched structures. The InAs/GaSb/AlSb CQWs were grown in Laytec EPIRAS 200TT equipped AIXTRON 200 machine by low-pressure MOVPE at 560 °C on n-GaSb:Te(100) ($n_t = 3 \times 10^{17}$ cm$^{-3}$) and on n-InAs:Mn(100) ($n_t = 1.1 \times 10^{17}$ cm$^{-3}$) substrates. Sb-rich interfaces between InAs and GaSb QWs were realized by special switching sequence of metalorganics [15, 16]. QW materials and thicknesses were chosen to create semimetal structures, according to [2]. Several structures with different QW widths were prepared. A buffer layer (30 nm) was grown on the substrate followed by undoped InAs QW ($a_e = 15$ nm or 12.5 nm) and GaSb QW ($a_h = 10$ nm or 8 nm) surrounded on both sides by AlSb barriers (30 nm). Thin GaSb cap layer (3 nm) was grown on the top of the structure to prevent AlSb oxidation. The growing processes were in-situ controlled by reflectance anisotropy spectroscopy (RAS) [16]. The InAs QWs widths were chosen to get an inverted band structures (figure 1).

![Figure 1](image)

**Figure 1.** Energy band diagram of the inverted InAs/GaSb/AlSb structure. InAs well width $a_e = 125$ Å, GaSb well width $a_h = 80$ Å, band gap $E_{\phi} = 150$ meV.

The calculated positions of $E_1$ and $H_1$ quantum levels in the InAs/GaSb/AlSb QW for the InAs well width $a_e = 12.5$ nm and GaSb $a_h = 8$ nm were the following: $E_1 = h^2/8m_ea_e^2 = 100$ meV, $E_{H1} = E_{\phi} - h/8m_ea_h^2 = 136$ meV. Here $E_{\phi} = 150$ meV is inverted band gap, $m_e = 0.023m_0$ and $m_h = 0.41m_0$. So, $H_1$ level lies higher than $E_1$ level in QW. Figure 2 demonstrates schematic structures of both CQWs grown on n-GaSb and n-InAs substrates, respectively.

Microwave radiation power absorption with frequency ~10 GHz and SdH oscillations were studied in the QW grown on n-GaSb and n-InAs substrates by EPR technique at low temperatures ($T = 2.7$-20 K) in the magnetic fields up to 14 kOe. The EPR-spectrometer E-112 VARIAN with helium gas flow cryostat Oxford Instruments E-910 was used [17]. The EPR technique is contactless and the deposition of Ohmic contacts on samples is not required [18]. The samples of $5 \times 3 \times 0.3$ mm$^3$
were placed in the cavity and the outside magnetic field was applied. The microwave absorption power derivative \( \frac{dP}{dH} \) was registered in the experiments.

Magnetic field dependence of the cyclotron frequency \( \omega_c \), amplitudes of the SdH oscillations and their temperature dependence were studied. Angle indicatrix was determined by rotation of the samples in the magnetic field. Figure 3 demonstrates the position of the samples with regard to constant magnetic field \( H_{\text{const}} \) and alternate current \( I_{\text{alter}} \) which arises in the induction from microwave radiation field \( H_{\text{alter}} \). Microwave power \( P \sim 1 \text{ mW} \) (for \( H_{\text{alter}} \)).

3. Results and discussion

3.1. InAs/GaSb/AlSb CQWs grown on n-GaSb substrate

At first we are going to describe experimental results obtained for InAs/GaSb/AlSb CQW grown on n-GaSb:Te(100) substrate with carrier concentration \( n_s = 3 \times 10^{17} \text{ cm}^{-3} \). We observed strong SdH oscillations with small period at \( T = 2.7 \text{ K} \). In the range of 4-14 kOe, there were more than 20-50 of them which were attenuated at \( T \) near 15-20 K (figure 4). Microwave current induces in the the microwave field. Magnetoresistance changes from traverse one to longitudinal one. Usually, the last of them is much less than traverse magnetoresistance. Oscillations of the microwave power derivative correspond to the transverse magnetoresistance \( \Delta \rho / \rho_x \). Longitudinal magnetoresistance at \( H_{\text{const}} \) of the sample plain was not registered. The field of the cyclotron resonance \( H_c \) was evaluated from the dependence of filling factor on the reverse magnetic field. In our case we observed \( n = 25 \) to 60 Landau levels and \( H_c = 39 \text{ T} \) was obtained.

Fourier analysis of the SdH oscillations allows us to find 2 frequencies which can belong to the warping of the Fermi surface of the n-GaSb [19]. Rotation of the sample A (CQW on the n-GaSb:Te(100) substrate) in the magnetic field shows unusual angular dependence (figure 5). It is not corresponding to expected \( H_{\text{const}} \cos \Theta \) dependence which is a feature of 2D-carriers. Amplitude oscillations decay with the angle change from 0 to 60° (relates to [111] orientation) and then increase up to 90°. Then we can see new decay or nodes of the amplitude intensity at \( \Theta = 130° \) (orientation [110]) and amplitude increase at \( \Theta = 180° \). We can explain these results by the main contribution of n-GaSb substrate to the SdH oscillations. This effect may be connected with the bulk inversion asymmetry (BIA) which is inherent to III-V semiconductors with zinc-blende structure with the lack of the inversion centers [19-21]. Recently the effect of the inversion asymmetry was observed experimentally in n-GaSb with concentration of \( n_s > 10^{18} \text{ cm}^{-3} \), in n-HgSe [22] and n-InSb [23].

Figure 2. Schematic structure of the CQWs grown on n-GaSb:Te(100) substrate \((n_s = 3 \times 10^{17} \text{ cm}^{-3})\) and n-InAs:Mn(100) substrate \((n_s = 1.1 \times 10^{17} \text{ cm}^{-3})\).

Figure 3. Position of the QW plane relative to magnetic field \( H_{\text{const}} \) at various angles \( \Theta \) of the sample rotation. a — \( \Theta = 0° \), b — \( \Theta = 90° \).
Inversion asymmetry obeys the spin-splitting of the conduction band in semiconductors with warping of Fermi surfaces and was theoretically calculated in [20-22]. A value of the spin-splitting of the conduction band is very small, less than ~1% and it is about $C_2E_F = 0.005$ meV (as it was found in [24]) for n-GaSb with concentration of $n_s > 10^{18}$ cm$^{-3}$ and $E_F = 0.095$ eV, where parameter $C_2$ is equal to 0.005. For n-GaSb with $n_s \approx 3 \times 10^{17}$ cm$^{-3}$ and $E_F = 125$ meV, the value of the conduction band spin-splitting can be evaluated as $C_2E_F = 0.006$ meV.

3.2 InAs/GaSb/AlSb CQWs grown on n-InAs substrate

The microwave radiation absorption and SdH oscillations were measured for the sample B with semimetal InAs/GaSb/AlSb QW (figure 1, 2), grown on the n-InAs:Mn(100) substrate. In this case, only several wide SdH oscillations were observed (about seven) which corresponded to this sample in the magnetic field range of 4-14 kOe (figure 6).
The angular dependence of the SdH oscillations amplitude was obtained by rotation of the sample in magnetic field in the angle range of 0-90°. As the Fermi surface of n-InAs is isotropic [22], we tried to extract the contribution of 2D-InAs QW from complete pictures of the SdH oscillations with high period at $T = 2.7$ K and at $H_{\text{const}} = 4$-14 kOe, with taken into account a typical angular dependence for 2D-carriers which has to be proportional to $H_{\text{const}}\cos \Theta$.

We calculated angular indicatrices of the amplitude oscillations that belong to 2D-InAs QW by the subtraction the oscillation pictures at 90° from the whole picture oscillations at the other angles 0° – 75° (figure 7). End-point result is presented on figure 8, where angular dependences of the SdH oscillations for microwave absorption of the inverse magnetic fields is shown. As one can see, a position of the amplitude oscillation minimum at $1/\hbar \approx 0.12$ kOe$^{-1}$ shift to higher fields according to $\sim H_{\text{const}}\cos \Theta$. 2D electron concentration in the InAs QW $n_s = 3 \times 10^{11}$ cm$^{-2}$ was evaluated from oscillation period [25].

4. Conclusion
The type II broken-gap InAs/GaSb/AlSb CQWs heterojunctions were for the first time grown by MOVPE on the lattice-matched n-GaSb:Te(100) (structure A) and n-InAs:Mn(100) (structure B) substrates with QWs width InAs 12.5 nm, for GaSb 8 nm to get inverted band structure.

Strong SdH oscillations at derivate microwave radiation absorption ($f = 10$ GHz) were observed at low temperatures $T = 2.7$-20 K by using the electron-paramagnetic resonance spectrometer in the magnetic fields up to 14 kOe for both types of the CQWs grown on n-GaSb:Te(100) and on n-InAs:Mn(100).

Predominance contribution to SdD oscillations amplitudes relates to bulk electrons of n-GaSb:Te substrate as was established by rotation of sample A in the magnetic field. That was demonstrated by Fourier analysis and by measurement of the angular dependence on rotation of the substrate in the magnetic field. Two frequencies of SdH oscillations were found.

Observed unusual angular indicatrix of the amplitude for different orientation of $H_{\text{const}}$ in dependence on the crystal orientation can be explained by inversion asymmetry, which is inherent to III-V semiconductors with zinc-blende structure without the inversion center. This effect obeys spin-orbit splitting of the conduction band spectrum and agrees to warping of the n-GaSb Fermi surface at high concentration. A small value of the spin-splitting parameter was evaluated according to Seiler, Becker and Roth and may be about $C_2E_F = 0.006$ meV for n-GaSb:Te(100) substrate with the concentration of $n = 3 \times 10^{17}$cm$^{-3}$.

Taking into account isotropic Fermi surface of n-InAs, we succeeded to extract a contribution of the 2D-carriers of InAs QW to SdH oscillation amplitudes. Angle dependence of SdH oscillation positions of amplitudes $\sim H_{\text{const}}\cos \Theta$ was observed in the magnetic field range of 10-14 kOe at $T = 2.7$ K.
Further growing of the InAs/GaSb/AlSb QW structures on the semi-insulating substrates (GaAs, p-GaSb or p-InAs:Mn with lower concentration) allows us to study quantum phenomena in these unique and interesting QW structures more in detail. Investigation of the magnetotransport at higher magnetic fields and studying a conductivity and hybridization of electron-hole bands by the gating CQW samples under applied electric and magnetic fields at low temperatures are also in the project.

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