

Intersubband resonant polaron in near-surface δ -doped GaAs

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Abstract. The many-body features of tunnel spectra of Al/ δ -GaAs are measured. The in-plane magnetic field shifts the 2D subband energies, with the diamagnetic shift of empty subband (E_1) is greater than that of the filled subband (E_0). The anticrossing of the terms $E_1(B) - \hbar\omega_{LO}$ and $E_0(B) + \hbar\omega_{LO}$ is observed (here $\hbar\omega_{LO}$ is the LO phonon energy; zero energy of the subband bottoms is at Fermi level E_F). The effect is attributed to the strong intersubband polaron interaction at double resonance conditions: $E_1 - E_F = \hbar\omega_{LO}$ and $E_1 - E_0 = 2\hbar\omega_{LO}$.

Introduction

The tunneling spectroscopy is extensively used for investigations of many-body effects. There are well-known polaron singularities in the tunnel spectra (TS) of 3D systems. For example, in n -GaAs Schottky-barrier tunnel junctions these features were found at the energies $E_F \pm \hbar\omega_{LO}$ [1], where $\hbar\omega_{LO} = 36.5$ meV. The singularities are weak in the 3D case.

We studied stronger LO-phonon singularities in TS of quasi-2D systems, namely, in δ -doped GaAs near Al/GaAs interface. In the system there are two 2D-subbands, the partly filled E_0 subband and the empty E_1 subband. The diamagnetic shift of subband energies induced by the in-plane magnetic field B [2] was used for the tuning of the intersubband energy $E_1(B) - E_0(B)$. The intersubband-resonance polaron effect was observed for the first time.

1 Samples and conditions of measurements

The tunnel structures Al/ δ -GaAs were prepared on semi-insulating (100) GaAs substrate by the method of molecular beam epitaxy (MBE). The δ -doped layer was formed at the distance of $L = 20$ nm from Al/GaAs interface at the temperature 570°C. The density of the Si atoms in the δ -layer was $5.2 \cdot 10^{12} \text{ cm}^{-2}$ and acceptor concentration in epitaxial layer was about 10^{15} cm^{-3} . Deposition of Al from the Knudsen cell took place directly in the MBE chamber after the cleaning procedure and cooling of the substrate down to 100°C. Al/ δ -GaAs tunnel junctions with the diameter of Al gate 0.7 mm were formed and Au-Ge-Ni ohmic contacts to the δ -layer were prepared. The 1st and 2nd derivatives of $I-U$ characteristic of the junction were measured. The magnetic field experiments were carried out in International Laboratory of High Magnetic Fields and Low Temperatures (Wroclaw, Poland) at $T = 1.6$ K and $T = 4.2$ K in $B \leq 15$ T. The Shubnikov-de Haas-like oscillations were observed in TS at $B \parallel I$ and $U = 0$ and the density $n = 1.1 \cdot 10^{12} \text{ cm}^{-2}$ of 2D electrons in the δ -layer under Al gate was determined from these data.

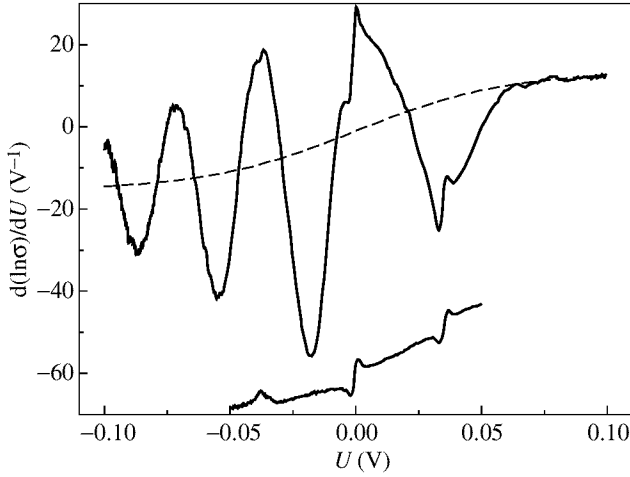


Fig. 1. The tunnel spectra of Al/ δ -GaAs (upper curve) and Al/n-GaAs (lower curve shifted on -50 V^{-1}) junctions at $T = 4.2 \text{ K}$ and $B = 0$. Dashed line is the background curve F . The positive bias U corresponds to electron tunneling from GaAs into Al electrode.

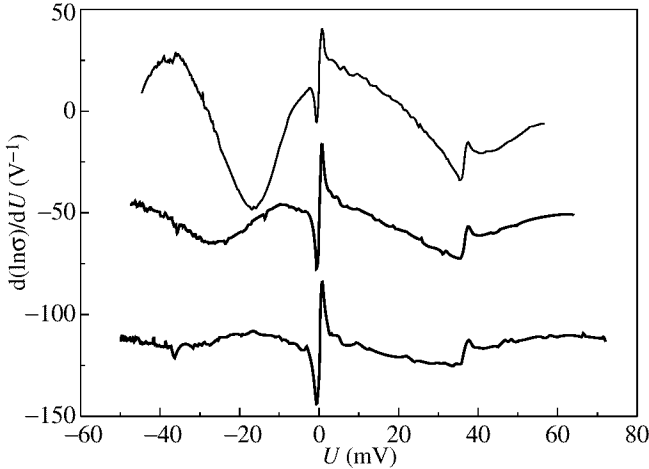


Fig. 2. The tunnel spectra with subtraction of the background curve $F(U)$. The upper curve corresponds to the magnetic field $B = 0$ (shift along Y-axis is equal to 0), for the middle curve $B = 7.8 \text{ T}$ (-50 V^{-1}), and for the lower curve $B = 10.7 \text{ T}$ (-110 V^{-1}).

2 Results and discussions

The typical tunnel spectrum of Al/ δ -GaAs at $B = 0$ and $T = 4.2 \text{ K}$ is shown in Fig. 1. The many-body features are observed in TS: zero-bias anomaly (ZBA) and phonon lines at $eU = \pm \hbar\omega_{\text{LO}}$. The latter were associated with electron-optical phonon self-energy (polaron) effects as was first suggested for 3D GaAs in [1]. The TS of the Al/n-GaAs junction (see the lowest curve in Fig. 1) shows that the many-body singularities in 3D and 2D tunnel junctions are qualitatively the same. The strong dips in TS are related with the bottoms E_i of the two-dimensional subbands in the δ -layer. It is well known [3] that the tunnel conductance in i -subband $\sigma_i(U) \propto \rho_{||i}(E_i, U) \cdot D(E_i, E_F - eU)$, where

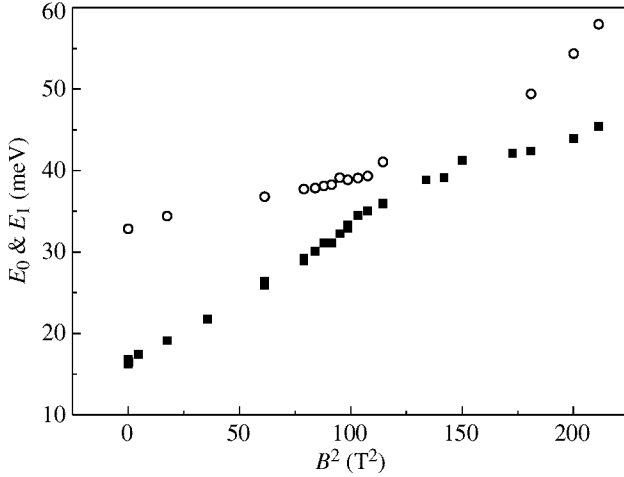


Fig. 3. The magnetic field ($B \perp I$) dependences of the subband energies E_0 (‘○’, shift $2\hbar\omega_{LO} = 73$ meV) and E_1 (‘■’) for Al/ δ -GaAs tunnel junction. The Fermi energy of δ -GaAs is accepted as zero of the energy scale.

$\rho_{||i} = (m/\pi\hbar^2) \Theta(E_F - eU - E_i)$ is the two-dimensional density of states and D is the barrier transmission. Thus, the positions U_i of dips in TS $d(\ln \sigma)/dU$ can be used to determine the subband energies E_i in 2DEG. The dips at $U > 0$ and $U < 0$ correspond to full and empty subbands, respectively. According to Fig. 1, only one subband E_0 is occupied in our samples and the value of Fermi energy is $\simeq 40$ meV. This value gives 2DEG density $\simeq 1.2 \cdot 10^{12} \text{ cm}^{-2}$ in agreement with our Shubnikov–de Haas tunneling measurements.

The magnetic field applied in the plane of the δ -layer ($B \perp I$) “pushes out” two-dimensional subbands from the quantum well of the δ -layer (diamagnetic shift [4]) and reduces the magnitude of the dips in TS. Fig. 2 shows this behavior of TS for subbands E_0 and E_1 where the background curve $F(U)$ was subtracted. The curve $F(U)$ can be seen in Fig. 1 (dashed line). This background curve does not depend on magnetic field B as it results from our experiments. We used the curves $d(\ln \sigma)/dU - F$ in the data treatment to obtain the dependence of the minimum position of the dips $eU_i = -E_i$ on the magnetic field.

The dependencies $E_0(B^2)$ and $E_1(B^2)$ are shown in Fig. 3 where E_0 is shifted up on 73 meV. In the low field range the usual diamagnetic shift [4, 5] is observed: $\Delta E_i = e^2 \Delta z_i^2 B^2 / 2m$. Here $\Delta z_i = (\langle z_i^2 \rangle - \langle z_i \rangle^2)^{0.5}$ is the spread of i -subband wave function at $B = 0$ in the direction z perpendicular to δ -layer. For our samples Δz_0 and Δz_1 are determined from the slope of the curves in Fig. 3 near the $B = 0$ region and are equal to 6.4 and 11 nm, respectively. These values are obtained for GaAs electron effective mass $m = 0.07m_0$. The energy E_1 reaches the optical phonon energy at $B = B_c \cong 11$ T.

At $B > B_c$, when $E_1(B) \geq \hbar\omega_{LO}$, the slopes of E_0 and E_1 are drastically changed. That means the renormalization of the 2DEG spectrum above the threshold field B_c . The anti-crossing of terms in Fig. 3 corresponds to the double resonance:

$$\begin{aligned} E_1(B) - E_0(B) &= 2\hbar\omega_{LO} \\ E_1(B) - E_F &= \hbar\omega_{LO} \end{aligned}$$

The effect can be interpreted as the observation of the intersubband resonant polaron.

The results are in semiquantitative agreement with the model of the resonant polaron interaction in two-level electron 3D system [6]. The corresponding 2D theory is absent, but we expect that the 2D polaron resonance could be stronger than that in 3D case [7].

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