Intersubband resonant polaron in near-surface $\delta$-doped GaAs

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Abstract. The many-body features of tunnel spectra of Al/$\delta$-GaAs are measured. The in-plane magnetic field shifts the 2D subband energies, with the diamagnetic shift of empty subband ($E_1$) 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 $\delta$-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/$\delta$-GaAs were prepared on semi-insulating (100) GaAs substrate by the method of molecular beam epitaxy (MBE). The $\delta$-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 $\delta$-layer was $5.2 \cdot 10^{12} \text{cm}^{-2}$ and acceptor concentration in epitaxial layer was about $10^{15} \text{cm}^{-3}$. 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/$\delta$-GaAs tunnel junctions with the diameter of Al gate 0.7 mm were formed and Au-Ge-Ni ohmic contacts to the $\delta$-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 $\delta$-layer under Al gate was determined from these data.
The tunnel spectra of Al/δ-GaAs (upper curve) and Al/n-GaAs (lower curve shifted on −50 V⁻¹) junctions at $T = 4.2$ 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. 1.

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 $B = 7.8$ T (−50 V⁻¹), and for the lower curve $B = 10.7$ T (−110 V⁻¹).

Fig. 2.

2 Results and discussions

The typical tunnel spectrum of Al/δ-GaAs at $B = 0$ and $T = 4.2$ K is shown in Fig. 1. The many-body features are observed in TS: zero-bias anomaly (ZBA) and phonon lines at $eU = \pm \hbar \omega_Q$. 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
The magnetic field \((B \perp I)\) dependences of the subband energies \(E_0\) (‘s’ shift \(2\hbar\omega_{LO} = 73\) meV) and \(E_1\) (‘d’) for Al/\(\delta\)-GaAs tunnel junction. The Fermi energy of \(\delta\)-GaAs is accepted as zero of the energy scale.

\[
\rho_{ii} = \left(\frac{m}{\pi \hbar^2}\right) \Theta (E_F - eU - E_i) \text{ is the two-dimensional density of states and } D \text{ is the barrier transmission.}
\]
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 \(\simeq 1.2 \cdot 10^{12}\) cm\(^{-2}\) in agreement with our Shubnikov-de Haas tunneling measurements.

The magnetic field applied in the plane of the \(\delta\)-layer \((B \perp I)\) “pushes out” two-dimensional subbands from the quantum well of the \(\delta\)-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 \(\delta\)-layer. For our samples \(\Delta z_0\) and \(\Delta z_1\) 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 \(m = 0.07 m_0\). The energy \(E_1\) reaches the optical phonon energy at \(B = B_c \simeq 11\) 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:

\[
E_1(B) - E_0(B) = 2\hbar\omega_{LO}
\]
\[
E_1(B) - E_F = \hbar\omega_{LO}
\]

The effect can be interpreted as the observation of the intersubband resonant polaron.
The results are in semiqualitative 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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References