7th Int. Symp. "Nanostructures: Physics and Technology"
St Petersburg, Russia, June 14–18, 1999

Intersubband resonant polaron in near-surface δ-doped GaAs

I. N. Kotel'nikov†‡ and V. A. Volkov†

† Institute of Radioengineering and Electronics of the RAS, Moscow 103907, Russia
‡ International Laboratory of High Magnetic Fields and Low Temperatures, Wroclaw, Poland

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 $E_1(B) - \hbar\omega_{\mathrm{LO}}$ and $E_0(B) + \hbar\omega_{\mathrm{LO}}$ is observed (here $\hbar\omega_{\mathrm{LO}}$ 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: $E_1 - E_{\mathrm{F}} = \hbar\omega_{\mathrm{LO}}$ and $E_1 - E_0 = 2\hbar\omega_{\mathrm{LO}}$.

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 $E_{\mathrm{F}} \pm \hbar\omega_{\mathrm{LO}}$ [1], where $\hbar\omega_{\mathrm{LO}} = 36.5$ 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 $5.2 \cdot 10^{12}$ 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 $n = 1.1 \cdot 10^{12}$ cm^{-2} of 2D electrons in the δ-layer under Al gate was determined from these data.

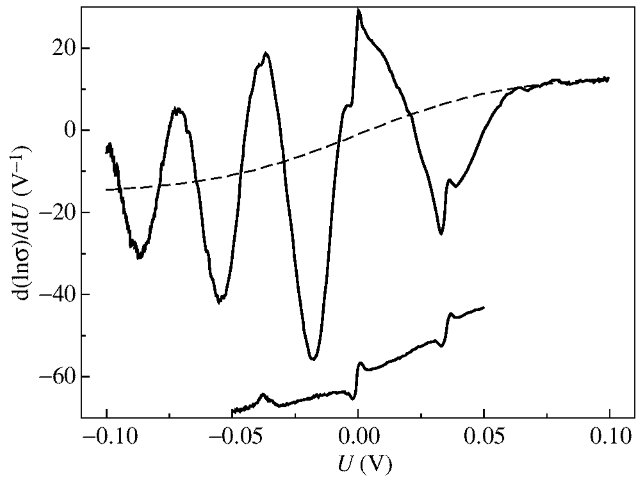

Fig. 1. The tunnel spectra of Al/δ-GaAs (upper curve) and Al/n-GaAs (lower curve shifted on $-50\,\mathrm{V}^{-1}$) junctions at $T = 4.2$ K and $B = 0$. Dashed line is the background curve F. The positive bias U corresponds to electron tunneling from GaAs into Al electrode.

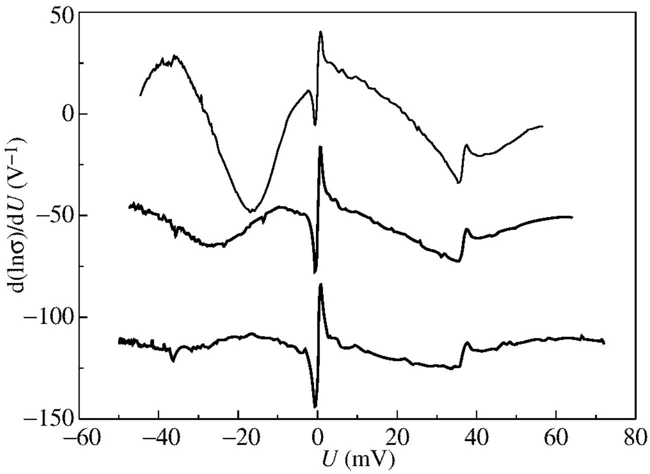

Fig. 2. The tunnel spectra with subtraction of the background curve $F(U)$. The upper curve corresponds to the magnetic field $B = 0$ (shift along Y-axis is equal to 0), for the middle curve $B = 7.8$ T ($-50\,\mathrm{V}^{-1}$), and for the lower curve $B = 10.7$ T ($-110\,\mathrm{V}^{-1}$).

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 $eU = \pm\hbar\omega_{\mathrm{LO}}$. 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 $\sigma_i(U) \propto \rho_{\|i}(E_i, U) \cdot D(E_i, E_{\mathrm{F}} - eU)$, where

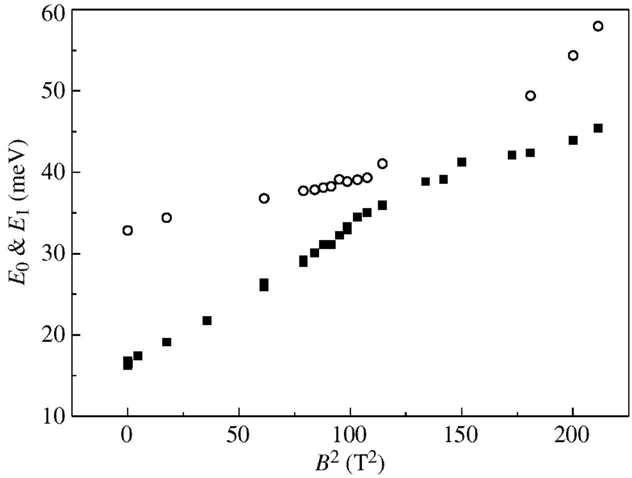

Fig. 3. The magnetic field ($B \perp I$) dependences of the subband energies E_0 ('○', shift $2\hbar\omega_{LO} = 73$ meV) and E_1 ('■') for Al/δ-GaAs tunnel junction. The Fermi energy of δ-GaAs is accepted as zero of the energy scale.

$\rho_{||i} = \left(m/\pi\hbar^2\right)\Theta\left(E_F - eU - E_i\right)$ 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 $E_0\left(B^2\right)$ and $E_1\left(B^2\right)$ 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 $\Delta z_i = \left(\langle z_i^2\rangle - \langle z_i\rangle^2\right)^{0.5}$ 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:

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

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].

We are grateful to Yu. V. Fedorov and A. V. Hook for preparation of the samples in MBE chamber, A. Ya. Shul'man for helpful discussions and V. G. Mokerov for support of this work. The work has been partly supported by INTAS-RFBR (Project No 97-11475) and RFBR (No 97-02-17750 and No 99-02-17592).

References

[1] J. W. Conley and G. D. Mahan, *Phys.Rev.* **161** 681 (1967).
[2] A. Zrenner, H. Reisinger, F. Koch, K. Ploog and J. C. Maan, *Phys. Rev.* **B33** 5607 (1986).
[3] D. J. BenDaniel and C. B. Duke, *Phys. Rev.* **160** 679 (1967).
[4] D. C. Tsui, *Solid State Commun.* **9** 1789 (1971).
[5] F. Stern and W. E. Howard, *Phys. Rev.* **163** 816 (1967).
[6] I. B. Levinson and E. I. Rashba, *Usp. Fiz. Nauk* **111** 683 (1973) [in Russian].
[7] A. Petrou and B. D. McCombe, in: *Landau Level Spectroscopy*, ed. Landwehr G. and Rashba E.I. Elsevier Science Publishers B.V., 1991, Chapter 12.