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Persistent 2D states of δ-layer quantum well and resonant polaron in δ-GaAs/Al structures

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Abstract. The effect of time illumination by radiation $\hbar\omega > Eg$ on conductance between 2DEG and Al-electrode was investigated in tunnel structures Al/δ-GaAs at $T = 4.2$ K. Persistent tunneling photoconductivity (PTPC) and "thickening" 2D levels E_i to the ground state E_0 direction in the quantum well (QW) of the δ-layer was discovered. Subband energies were calculated from the tunneling spectra. PTPC achieved saturation as a function of illumination time t. The change of the tunneling conductivity $\Delta\sigma_S$ of the structures reaches 10%. There was a weak dependence E_0 on t, and its change at the saturation corresponded to 10–15% increase of 2D electron concentration. Shift of the energies E_i of the empty subbands of the QW amounts to 10–50 meV which leads to noticeable decrease of the intersubband energies. Persistent states' behaviour in the 2D-subband spectrum and the value of $\Delta\sigma_S$ indicates on broadening of the QW at fixed potential barrier between δ-layer and Al. It was observed that one of the terms $E_i(t)$ manifested the anticrossing and pinning to other one $E_j(t) + \hbar\omega_{\mathrm{LO}}$ ($\hbar\omega_{\mathrm{LO}}$ is LO-phonon energy in GaAs). These singularities could be associated with resonant intersubband polaron.

Introduction

Recently the intersubband resonant polaron in tunnel structure Al/δ-GaAs has been observed [1, 2]. In these experiments the diamagnetic shift of the 2D-subbunds was used. Subband energy positions in the δ-layer must also change due to persistent photoconductivity (PPC) effect. It is well known for "deep" δ-layers and filled subbands (see review [3] or more recent works [4, 5]). Models of increase of 2DEG concentration in the δ-structures due to the PPC (DX-centers [6], interface states [4], etc.) are still being discussed [5]. However, as far as we know, the spectra of the unoccupied subbands of the δ-layers in PPC regime have not been studied. Magnetotransport measurements allow to analyze only filled subbands of the 2DEG. The 2D subband features in the tunnel spectra (TS) of the junctions emerge irrespective to occupation of the 2D levels. Therefore the tunneling spectroscopy allow us to investigate experimentally the changes of the energy levels in the PPC regime for the near-surface δ-layers. It has been demonstrated first time in [7]. Moreover, we have the possibility to investigate resonant manybody effects by tuning the subband (or intersubband) energies by the PPC.

1. Samples and experiment

The tunnel structures Al/δ-GaAs were prepared in IRE RAS on semi-insulating (100) GaAs substrates by the method of molecular beam epitaxy (MBE) [2]. The δ-doped layer with the density of Si atoms 5.2×10^{12} cm^{-2} was formed at 570 °C and the distance of $L = 20$ nm from Al/GaAs interface. Deposition of Al from the Knudsen cell took place directly in the MBE chamber. The width of a semitransparent Al film was 80–100 nm. Al/δ-GaAs tunnel junctions were photolitographically defined and etched into samples. 2DEG concentration was in the range $0.5-1.5 \times 10^{12}$ cm^{-2}. The other samples parameters and measuring

technique see in [2]. The sample illumination was performed by LED with $\hbar\omega > E_g$, mounted in the cryostat.

2. Results and discussions

Figure 1 demonstrates TS of the Al/δ-GaAs junction with $n_{2D} \simeq 1 \times 10^{12}$ cm^{-2} at the temperature $T = 4.2$ K after cooling in dark (upper curve). Strong dips in TS are related with the bottoms E_i of the two-dimensional subbands in the δ-layer.

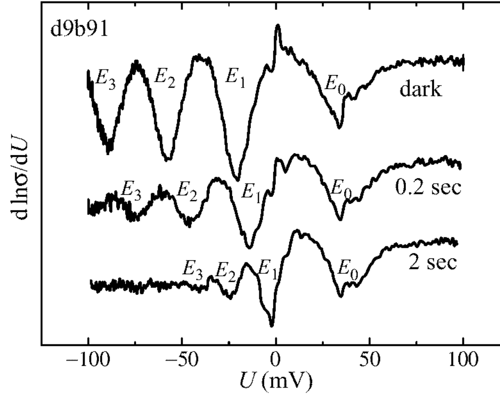

Fig. 1. Tunnel spectra at the dark (top curve) and different illuminations (bottom curves). Signs E_i show subband positions. Temperature is 4.2 K. Sample d9b91.

It is well known that the tunnel conductance in the i-subband is: $\sigma_i(U) \propto \rho_{\parallel i}(E_i - eU) \cdot D(E_i, E_F - eU)$, where $\rho_{\parallel i} = (m/\pi\hbar^2) \cdot \theta(E_i - eU)$ 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 this sample and the value of Fermi energy is $eU_0 = E_0 \simeq$ 40 meV. In all tested samples only E_0 subband was partially filled at the dark condition and the position U_0 in TS at different 2DEG concentrations was changed from 20 to 50 mV. Illumination of samples by LED at liquid helium temperatures in time t led to variation of the tunnel conductance and of the dips positions in TS [7]. Dips shifts are well seen in TS of Fig. 1. It is clear seen that unfilled levels “thicken”to the ground state E_0, changing their position on $\simeq 10-50$ meV. Variation of the E_0 value with t corresponds to $\simeq 10\%$ increase of 2DEG concentration. Observed PTPC and subband spectra variation reach saturation that corresponds to illumination time. Persistent state of the illuminated tunnel structure practically was not changed in several hours. Heating the sample to room temperature with following cooling in the dark returned the structures parameters to the initial (dark) values. Notice that at $T = 77$ K tunnel conductance $\Delta\sigma_S$ variation in saturation is about 1–2% (at $T = 4.2$ K $\Delta\sigma_S$ reach 10%), but all 2D subband levels shift to the bottom of conductance band of the GaAs on the same value $\simeq 1-2$ mV.

The data of the temperature dependence of $S_0 = d \ln \sigma/dU$ at $U = 0$ show (Fig. 2) the presence of two characteristic temperatures of the PTPC. At $T \simeq 40$ K main changes in S_0 vanished, and at $T \geq 120$ K curve $S_0(T)$ coincides with “dark” curve. The results obtained allow to suggest two mechanisms of PTPC in our samples. At $T = 77$ K the change of

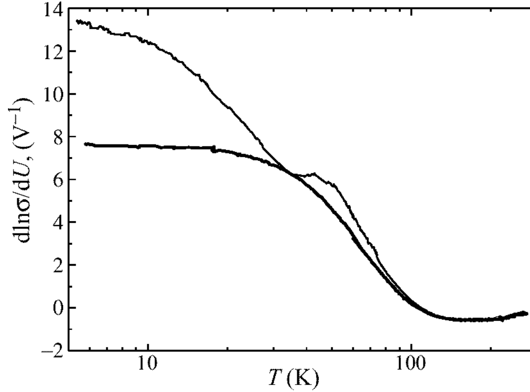

Fig. 2. $S_0 = d \ln \sigma / dU$ at $U = 0$ as a function of temperature: cooling in darkness (thick curve), reverse warming after illumination right up to saturation (thin curve). Sample d5b42.

the electrons concentration in QW occurs, possibly because of DX-centers ionization. At liquid helium temperatures, in addition, the broadening of the QW takes place. As the barrier hight at Al/GaAs interface is independent on illumination, such broadening can be associated with the change of the Fermi level position in the bulk of GaAs. This means that the photo-exited electrons are trapped in the impurity states beyond the δ-doped region.

Let's return to the persistent changes in 2D level positions at $T = 4.2$ K. In Fig. 3(a) we can see curves $E_i(t)$ obtained from TS measured for the junction with $n_{2D} \simeq 1.5 \times 10^{12}$ cm^{-2}. Displayed energies $E_i(t)$ are counted off from the GaAs Fermi level. The results seem to indicate that pinning of one of the unoccupated subband to the energy of the one of the filled subband plus LO-phonon takes place. Such pinning is typical for resonant intersubband polaron. This effect becomes more noticeable in Fig. 3(b), where levels E_1 and E_3 are in resonance with LO-phonon; moreover, an appreciable anticrossing of terms

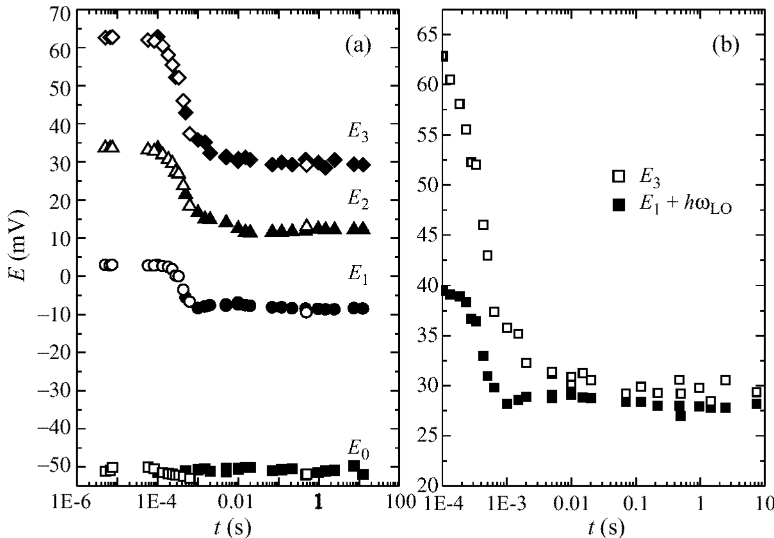

Fig. 3. Subband energies E_i of the sample d7c52 as functions of the illumination time t at $T = 4.2$ K.

occurs (see illumination time range 0.3–10 ms). Similar pinning and anticrossing effects are observed for the samples with other 2DEG concentrations, but for the other pair of terms. Note that in PTPC regime the anticrossing effect is localized by the parameter t, while in magnetic field B this effect increases with B [2].

The results obtained show that PTPC permits to provide the resonance conditions for detecting polaron effects in the QW of the near-surface δ-layer. In combination with the planned experiments being in parallel magnetic field, the PTPC effect allows to obtain new data on threshold interaction of 2D electrons with optical phonons. In our opinion, the significant value of the polaron effects in our structures is related to the self-consistent potential profile of δ-layer QW. Unfortunately, there is no theory of resonant intersubband polaron in such systems, which does not permit to compare observed effects with calculations.

Acknowledgements

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References

[1] I. N. Kotel’nikov and V. A. Volkov, *Proc. 7th Int. Symp. “’Nanostructures: Physisc and Technology”, St Petersburg* p 272, 1999.
[2] I. N. Kotel’nikov *et al*, *Pis’ma Zh. Eksper. Teor. Fiz.* **71**, 564 (2000).
[3] A. Ya. Shik, *Fiz. Tekh. Poluprov.* **26**, 1161 (1992).
[4] A. G. Oliveira *et al*, *J. Appl. Phys.* **78**(4), 2659 (1995).
[5] V. V. Valyaev *et al*, *Zh. Eksper. Teor. Fiz.* **113**, 693 (1998).
[6] P. M. Koenraad *et al*, *Semicond. Sci. Technol.* **6**, 143 (1991).
[7] S. E. Dizhur *et al*, *Abstr. 2nd All-Rus. Young Conf. on the Phys. of Semicond. and Semicond. Opto- and Nanoelectr. (in Russian), St. Petersburg.* p 48, 2000.