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Interaction in the final state of the interface luminescence with delta-doped layers

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Abstract. We show that Coulomb interaction within a delta-layer of donors is governed by the neighbouring two-dimensional hole gas. It has been found experimentally that the interface luminescence band displays pronounced blue shift when the two-dimensional holes recombine with delta-donors. Our analysis confirms that uniform distribution of the delta-dopants provides adequate description of the energy shift versus excitation level.

Introduction

Atomic monolayers of dopants in close proximity of the two-dimensional electronic systems have formerly been used as effective optical probes in the Quantum Hall regime. Here we reverse the situation: the Coulomb interaction within a delta-layer of donors is probed by the neighbouring two-dimensional hole gas (2DHG). The latter is mainly responsible for low-dimensional screening of the electrostatic interaction between ionised delta-dopants.

In our photoluminescence experiments, an optical excitation above the bandgap produces electron-hole pairs with the photoelectrons successively captured by the delta-donors. Once a given fraction of the delta-donors has been neutralised, valence holes from the 2DHG may radiatively recombine with the donors. We show that energy of the outcoming photon depends on Coulomb interaction between delta-donors, which we refer to as an interaction in the final state.

Model

Experimentally this interaction in the final state translates into a spectral shift of the photoluminescence band towards the higher energy side of the spectrum as the density of the optical excitation increases. Under conditions of high optical pumping, all delta-donors are neutralised and the photon energy is at a maximum. The photon energy reaches its minimum when all donors are ionised. The total value of this blue shift is given by

$$\Delta = \frac{2e^2}{\epsilon}\left[\pi\left(2z_0 + q_s^{-1}\right)N\right], \tag{1}$$

where z_0 is the distance between 2DHG and the delta-layer, q_s^{-1} is the inverse screening radii, and N is a concentration of the delta-donors. Notice that without screening, $q_s = 0$, the energy shift would be infinitely large. However, in the case of the screening radii reduced to zero, the low-dimensional screening converts to induction of the image charge at the distance of $(-z_0)$ behind the 2DHG.

Experiments

In all our samples the 2DHG was formed within the potential notch at the modulation doped $Al_xGa_{1-x}As/GaAs$ heterojunctions. The samples were grown by molecular-beam epitaxy on CrO-doped (100) substrates. We used three different types of the layer sequences:
(*i*) The first structure contains a delta-layer of Si with concentration of $N = 4 \times 10^{10}$ cm^{-2}. The delta-layer was placed in GaAs at the distance of 350 Å from the heterointerface. This active layer of GaAs (700 Å) was terminated with a 30-period GaAs/AlAs superlattice buffer layer to prevent the diffusion of photocreated electrons away from the interface.
(*ii*) The second sample was a precise replica of the first one except that the GaAs layer was nominally undoped.
(*iii*) Finally, we also used an asymmetrically doped GaAs quantum well where the GaAs thickness was reduced down to 150 Å. In all structures we found that Hall measurements yield the 2DHG concentration of about 5×10^{11} cm^{-2}. During PL measurements, the samples were mounted in a He-flow cryostat. PL was excited by 5145 Å of Ar^+ laser line. The light was dispersed and subsequently detected by a liquid-nitrogen-cooled charge-coupled device detector array. All three types of the samples display an intensive interface PL band.

Results

The spectral shift of the interface luminescence in the delta-doped samples greatly exceeds that from the samples without delta-doping: We observe up to 30 meV of energy shift when the two-dimensional holes recombine with delta-donors as opposed to only 3 meV for the recombination with free electrons in the conduction band. To account for trivial band bending, the asymmetrical quantum wells were also studied.

We show that the large value of the blue shift, much in excess of the 2DHG Fermi energy, is explained by the electrostatic repulsion between ionised delta-donors. Our analysis confirms that uniform distribution of the delta-dopants provides adequate description of both the energy shift and the full width at a half maximum of the interface PL band. Taking into consideration also the concentration fluctuations within the delta-layer accounts for less than 10% of the total effect.

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