Terahertz luminescence and photoconductivity associated with the impurity electron transitions in GaAs/AlGaAs quantum wells

A D Kurnosova, I S Makhov and D A Firsov
Peter the Great St. Petersburg Polytechnic University, 195251 St. Petersburg, Russia

E-mail: ad-kurnosova@yandex.ru

Abstract. The photoconductivity and photoluminescence spectra of GaAs/AlGaAs quantum wells doped with shallow donors are studied at low lattice temperatures. The optical electron transitions between the first electron subband and donor ground states, as well as between the excited and ground donor states, are revealed in the terahertz photoluminescence and photoconductivity spectra. The temperature evolution of the impurity-related photocurrent in the terahertz spectral range is also studied.

1. Introduction
To date, interest in the research of terahertz radiation sources remains significantly high, because terahertz devices have a wide range of potential applications [1]. One of the ways to obtain terahertz radiation is to use optical transitions of nonequilibrium charge carriers involving shallow impurity states in nanostructures with quantum wells. Optical electron transitions between the first electron subband and donor ground states, as well as intracenter optical transitions, were observed in the terahertz photoluminescence spectra of laser nanostructures with GaAs/AlGaAs quantum wells doped with shallow donors under intense interband optical excitation [2]. Furthermore, impurity-related optical electron transitions should be observed in the terahertz photoconductivity spectra, which could confirm the participation of impurity-related optical electron transitions in the terahertz photoluminescence spectra. However, there are only a few studies of the impurity-assisted photoc conductivity in quantum wells in the terahertz spectral range. Thus, the recent paper is devoted to the comparative studies of the terahertz photoconductivity and photoluminescence in quantum wells doped with shallow donors.

2. Sample and experimental technique
The sample under study was molecular beam epitaxy grown on a semi-insulating GaAs substrate on a 0.5 µm thick GaAs buffer layer. It contained 50 periods of quantum wells (7.6 nm) and barriers (5 nm) formed by GaAs and Al$_{0.3}$Ga$_{0.7}$As epilayers, respectively. The quantum wells were doped with silicon up to a surface impurity concentration of $3 \times 10^{10}$ cm$^{-2}$ in a 2.6 nm-wide central region. The sample was mounted in a Janis PTCM-4-7 closed cycle optical cryostat aiming to cool the sample to liquid helium temperature.

The terahertz photoluminescence spectra were studied using a Bruker Vertex 80v vacuum Fourier transform infrared spectrometer operating in a step scan regime. A continuous wave Nd:YAG solid state laser ($\lambda = 532$ nm, 0.5 duty cycle, 80 Hz frequency) was used as a source of pumping radiation.
The spectrometer had a Mylar multilayer beamsplitter and a silicon bolometer cooled with liquid helium. The signal of the photodetector was measured with a SR830 lock-in amplifier at the modulation frequency of pumping radiation. The terahertz photoluminescence measurement technique is described in more detail in Ref. [3].

For the terahertz photoconductivity studies, the sample was soldered with indium by the substrate side to the copper holder of the closed cycle optical cryostat. The sample had indium electrical contacts on the surface, annealed at a temperature of 400°C in the nitrogen atmosphere. The distance between the contacts was about 5 mm.

The terahertz photoconductivity spectra were also studied using a Fourier spectrometer. A mercury lamp was used as a source of broadband terahertz radiation. Terahertz radiation of the lamp was modulated with a mechanical chopper at a frequency of 80 Hz and guided to the sample surface through a polished stainless steel pipe in order to prevent the equilibrium photoionization of impurities in quantum wells by external backlight. Photoconductivity measurements were carried out under a 5 V bias voltage applied to the sample using an SR-570 current preamplifier. The sample photocurrent was measured with a SR-830 lock-in amplifier.

3. Results and discussion
The terahertz photoluminescence spectrum of the investigated structure with donor doped quantum wells is shown in figure 1. Two emission bands can be observed in this photoluminescence spectrum. According to the energy spectrum calculation of the donor states in 7.6 nm-wide quantum wells, the donor binding energy is about 13 meV [4] (it is shown with the arrow $E_D$ in figure 1). So, we associate one of the terahertz photoluminescence bands located at the photon energies above 13 meV with optical electron transitions from the first electron subband $e1$ to the donor ground state $1s$. Moreover, according to Ref. [4], the energy distance between excited $2p_{x,y}$ and ground $1s$ donor states in 7.6 nm-wide quantum wells is about 10 meV. Thus, the second terahertz photoluminescence band presented in figure 1 should be connected with intracenter optical electron transitions between the excited $2p_{x,y}$ and $1s$ donor states. It should be noted that similar optical electron transitions were already observed in the terahertz photoluminescence spectra in laser nanostructures with similar quantum wells [2].

![Figure 1. Terahertz photoluminescence spectrum of the sample measured at the temperature $T = 8$ K and a pumping power of about 0.25 W/cm$^2$. The spectral resolution is about 1.5 meV.](image1)

![Figure 2. Terahertz photoconductivity spectrum of the sample measured at the temperature $T = 4$ K. The spectral resolution is about 0.4 meV. The inset shows the current-voltage characteristic of the sample (the dashed line shows a linear dependence).](image2)
In order to confirm the nature of the terahertz photoluminescence bands presented in figure 1, the impurity-related photoconductivity in quantum wells was investigated. The photoconductivity spectrum of the nanostructure is shown in figure 2. It consists of a broad photocurrent band with a few peculiarities. The photocurrent peak observed near the photon energy of about 10 meV should probably be connected with the optical transitions of electrons from the ground donor state 1s to the excited donor states 2p_x,y (it is shown by the arrow 1s-2p_x,y in figure 2). The contribution to the photocurrent due to these intracenter optical electron transitions between localized impurity states is related to the thermal ejection of photoexcited electrons from the 2p_x,y donor states to the first electron subband e1. The high-energy part of the photoconductivity spectrum presented in figure 2 corresponds to the photoionization of electrons from the donor ground states 1s to the first electron subband e1 (it is shown by the arrow 1s-e1 in figure 2). Finally, the long-wavelength edge of the photoconductivity spectrum can be associated with optical electron transitions between other excited donor states in quantum wells or with optical transitions involving impurity states in the donor-doped GaAs cap epilayer of the nanostructure. The shallow donor binding energy in bulk GaAs is about 5.8 meV [5].

It should be noted that the spectral positions of the photocurrent and photoluminescence intensity maxima related to the optical transitions of electrons involving the donor ground states 1s and the first electron subband e1 do not coincide. This difference is associated with different spectral dependencies of the cross-section for the photodeionization and photoionization of shallow impurities in semiconductors [6].

The presence of shallow donors in quantum wells was also confirmed by an investigation of the current–voltage characteristic measured at low temperature and presented in the inset of figure 2. The initial part of the characteristic is linear (the linear dependence is shown with a dashed line in the inset of figure 2), which corresponds to the Ohm's law. When the electric field exceeds the value of about 20 V/cm, a superlinear dependence of the current density on the electric field is observed. It is related to the impurity breakdown that results in the ionization of neutral shallow donors in quantum wells. The observed electric field value of the impurity breakdown (about 20 V/cm) is in a good agreement with similar studies of current-voltage characteristics in the 30 nm wide donor-doped GaAs/AlGaAs quantum wells [7]. The donor binding energy in 30 nm quantum wells is about 8.8 meV and the value of impurity breakdown field is about 10 V/cm [7].

Also, we have investigated the temperature dependence of the integrated photocurrent in quantum wells. It is presented in figure 3 with dots and exhibits a nonmonotonic dependence of the photocurrent on the crystal lattice temperature of the nanostructure. As it was shown above, the main contribution to

![Figure 3](image-url)

**Figure 3.** Temperature dependence of the integrated photocurrent of the sample (dots) and the approximation of the experimental data with equation (1) (black solid curve) and equation (2) (red solid curve). The parameters ΔE and ED used in the calculation are 2 meV and 13 meV, respectively.
the photoconductivity spectrum (see figure 2) is made by the optical electron transitions from the donor ground state $1s$ to the excited $2p_{x,y}$ donor states and to the first electron subband $e1$. The temperature dependence of the intensity of transitions $1s$-$2p_{x,y}$ should depend on the temperature dependencies of the concentration of neutral donors and the probability of thermal ejection of electrons from excited $2p_{x,y}$ donor states to the first electron subband $e1$. At the same time, the temperature dependence of the intensity of $1s$-$e1$ optical electron transitions should depend only on the temperature dependence of the concentration of neutral donors.

In the actual temperature range, the Fermi level almost does not shift with temperature and remains located in the middle between the donor ground state $1s$ and the first electron subband $e1$. In this case, the temperature dependence of the neutral donor concentration $N_D^0(T)$ in quantum wells should be described by the following expression:

$$N_D^0(T) \sim N_D - \left( \frac{N_C \cdot N_D}{g_D} \right)^{1/2} \cdot \exp \left( -\frac{E_D}{(2 \cdot k_B \cdot T)} \right),$$

(1)

where $N_D$ is the full concentration of donors, $N_C$ is the effective density of states in quantum wells (it linearly depends on the temperature), $E_D$ is the donor binding energy, $k_B$ is the Boltzmann constant, $g_D$ is the degeneracy factor for the donor ground state. The temperature dependence of the probability of thermal ejection $\gamma(T)$ of electrons from the excited $2p_{x,y}$ donor states to the first electron subband $e1$ is described as follows:

$$\gamma(T) \sim \exp \left( -\frac{\Delta E}{(k_B \cdot T)} \right),$$

(2)

where $\Delta E$ is the value of the energy barrier for thermal ejection of electrons from the excited $2p_{x,y}$ donor state to the first electron subband $e1$.

We assume that at low crystal lattice temperatures, the initial growth of the photocurrent with temperature (see figure 3) is associated with an increase in the contribution of the $1s$-$2p_{x,y}$ optical transitions with increasing temperature. The low-temperature part of the experimental data presented in figure 3 is well approximated by equation (2) (it is shown by the red solid curve in figure 3). The decline in the temperature dependence of the integrated photocurrent at high crystal lattice temperatures is caused by a decrease in the neutral donor concentration due to thermal ionization of donor impurities. The high-temperature part of the experimental data presented in figure 3 is well approximated by equation (1) (it is shown by the black solid curve in figure 3).

**Conclusion**

The comparative studies of terahertz photoluminescence and photoconductivity involving the shallow impurity states in GaAs/AlGaAs quantum wells are conducted. The spectral positions of the impurity-related photocurrent and emission bands observed in the photoconductivity and photoluminescence spectra of the donor doped quantum wells are in good agreement with each other and with theoretical calculations.

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