Acceptor-related terahertz and infrared photoconductivity in p-type GaAs/AlGaAs quantum wells

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Abstract. Photoconductivity in GaAs/AlGaAs quantum well nanostructures doped with acceptors was studied at low lattice temperatures in the infrared and terahertz spectral ranges. The photocurrent spectra revealed features that can be attributed to the hole transitions from the ground acceptor state to the excited acceptor states and size-quantized subbands.

1. Introduction

The use of optical transitions of charge carriers between impurity sublevels in doped semiconductor nanostructures is one of the promising ways for the creation of compact sources and detectors of terahertz (THz) radiation. This is due to the fact that the binding energies of shallow impurities correspond to the terahertz spectral range. The low-temperature terahertz emission associated with optical electron transitions involving donor states in n-GaAs/AlGaAs quantum wells under interband photoexcitation of electron-hole pairs was already observed [1-4]. The possibility to increase the donor-related THz emission intensity by effective depopulation of donor states in quantum wells with near-infrared stimulated emission or impurity compensation was demonstrated in [2-4]. The studies of low-temperature THz electroluminescence due to the acceptor-related hole transitions in p-GaAs/AlGaAs quantum wells under conditions of impurity breakdown in a strong lateral electric fields were also reported in [1]. The spectra of the acceptor-related THz emission experimentally obtained in [1] demonstrate both optical transitions of hot holes from the lowest subband to the excited acceptor states and intracenter optical transitions.

Investigation of semiconductor nanostructures with quantum wells doped with acceptors is of particular interest, since acceptors have a higher binding energy than donors, and for a certain width of GaAs/AlGaAs quantum wells, the binding energy of the acceptor impurity [5, 6] can even exceed the optical phonon energy in GaAs [7]. In this case, the probability of nonradiative capture of nonequilibrium holes, excited by optical or electrical pumping, from the valence subband to the ground acceptor state will be reduced, resulting in a more likely hole capture to the excited states. So, the subsequent transitions of nonequilibrium holes from the excited acceptor states to the ground state can be accompanied by emission of terahertz photons. The above described process of nonradiative capture of nonequilibrium holes on excited acceptor states from the valence subband can lead to an inversion of the hole population between the excited and ground acceptor levels, which is a necessary condition for the generation of stimulated THz radiation. The present paper focuses on the study of
photoconductivity of $p$-GaAs/AlGaAs quantum wells, which is one of the effective methods to investigate the contribution of impurity transitions to THz radiation.

2. Sample and experimental technique

The structure was MBE grown on a semi-insulating GaAs substrate and contained 200 GaAs/Al$_{0.4}$Ga$_{0.6}$As quantum wells. The quantum wells have a width of 3 nm; the barriers between them are 7 nm thick. Doping with beryllium was performed in the central part of each quantum well (~0.7 nm) with a surface concentration $N_A$ of about $10^{11}$ cm$^{-2}$.

The samples placed in a liquid nitrogen cryostat were characterized by interband photoluminescence studies using a Horiba Jobin Yvon FHR640 monochromator. A solid-state Nd:YAG CW laser with a 532 nm radiation wavelength was used for pumping. A liquid nitrogen cooled CCD-camera was used as a detector.

For photoconductivity studies, the Ohmic indium contacts were deposited on the sample surface. The contacts were annealed in nitrogen atmosphere at a temperature of 450°C during 5 minutes. The distance between contacts was about 5 mm. For the good heat dissipation, the sample was indium-soldered to a copper holder of a Janis PTCM-4-7 closed cycle optical cryostat with an operating temperature range of 4–320 K. The entrance window of the cryostat was made of KBr or TPX for mid-infrared and terahertz studies, respectively. The sample in the cryostat was shielded all around from external background radiation to prevent undesirable photoization of impurities. Infrared and terahertz radiation was directed to the sample through a cold polished stainless steel pipe of a 5 mm diameter.

The photoconductivity spectra were obtained with a Bruker Vertex 80v vacuum Fourier transform spectrometer operating in a rapid scan mode with a spectral resolution less than 2 meV. The spectrometer was equipped with a Mylar, KBr and CaF$_2$ beamsplitters for the terahertz, mid-infrared and near-infrared studies, respectively. A globar was used as a source of broadband terahertz and infrared radiation. Photoconductivity measurements were carried out under 5 V bias voltage applied to the sample using a SR-570 current preamplifier.

3. Results and discussion

The theoretical calculation of the energy levels of electrons and holes in quantum wells of the nanostructure was performed in a parabolic model using material parameters taken from [8]. The calculation of the energy spectrum of the acceptor impurity located at the center of a quantum well is a separate complex problem. The energy $E_A$ of the ground acceptor state $A1$ was obtained from the temperature dependence of the conductivity (see below).

The measured spectra of interband photoluminescence of the sample at $T = 300$ K and $T = 77$ K are presented in figure 1. At room temperature, one can see the luminescence peaks associated with transitions between the first electron subband and the heavy and light hole subbands. The calculated photon energies related to direct interband recombination of electrons from the first electron subband $e1$ and holes from the first heavy $hh1$ and light $lh1$ hole subbands at room temperature are shown in figure 1 with red arrows $e1$-$hh1$ and $e1$-$lh1$. At liquid nitrogen temperature, only one peak associated with optical transitions $e1$-$hh1$ can be observed due to the lack of electrons in higher subbands. The temperature shift of the photoluminescence peaks is related to the bandgap $E_g$ change. The peak positions are in good agreement with the results of energy spectra calculations for the structure with the parameters stated above. One can see a shoulder on the longwave part of the luminescence spectra at $T = 77$ K marked with arrows $e1$-$A1$ in figure 1. We associate it with interband transitions of electrons from the first electron subband $e1$ to the ground acceptor state $A1$, which should be located at a distance $E_A$ of about 40-45 meV above the $hh1$ subband [5, 6].

In order to determine the value of $E_A$, we measured the temperature dependence of conductivity $\sigma$ presented in the inset to figure 2. We assumed that the hole mobility $\mu$ does not strongly depend on temperature, and used the proportionality of the conductivity and the free hole surface concentration $p$. We also used the well-known expression for the temperature dependence of the carrier concentration
in a bulk semiconductor with one type of uncompensated acceptors [9], replacing the effective density of states with the corresponding two-dimensional one:

\[
p \approx \left( \beta N_v N_A \right)^{1/2} \exp \left( \frac{-E_A}{2kT} \right),
\]

(1)

where \( \beta \) is the degeneracy factor of a ground acceptor state, \( N_v \) is the effective density of states in the heavy hole subband:

\[
N_v = \frac{mkT}{\pi\hbar^2}.
\]

(2)

Here, \( m \) is the heavy-hole effective mass, \( k \) and \( \hbar \) are the Boltzmann and Planck constants, respectively. Note that formula (1) is true for two-dimensional carriers only if the carrier gas is nondegenerate, i.e. \( p \ll N_v \). This fitting allowed us to obtain the impurity ionization energy \( E_A \approx 40 \) meV, which is in good agreement with a theoretical value of about 40-45 meV [5, 6].

Figure 1. Normalized near-infrared photoluminescence spectra of the sample, measured at a temperatures of 77 K (blue curve) and 300 K (red curve). The arrows mark the calculated energies of some interband transitions.

Figure 2. The near-infrared photoconductivity spectrum of the sample, measured at \( T = 7 \) K. The spectral resolution is less than 2 meV. The arrows show the calculated transitions (described in the text). Inset: the temperature dependence of conductivity (dots) and its fitting (line, described in the text).

The near-infrared photoconductivity spectrum of the sample with QWs, measured at a temperature of about 7 K is shown in figure 2. One can see that photocurrent starts to increase at the photon energy corresponding to interband transitions in GaAs \( (E_g = 1.519 \) eV [8]). It is associated with the contribution to the photocurrent from the GaAs substrate and the \( p \)-GaAs cap layer of the nanostructure. At the same time, we observed the dips in the photocurrent spectrum at the photon energies corresponding to the calculated values of optical transitions related to the formation of heavy and light free excitons formed by charge carriers located in ground size-quantized subbands of quantum wells. They are marked in figure 2 with arrows \( hX \) and \( lX \) for free heavy and light excitons, respectively. The heavy and light exciton binding energies in 3 nm-wide GaAs/Al\(_{0.4}\)Ga\(_{0.6}\)As quantum wells were taken from [10]. The dips in the photoconductivity spectrum related to the formation of excitons in quantum wells are due to the fact that excitons cannot contribute to the photocurrent at such low crystal lattice temperatures. The exciton contribution to the photocurrent could be observed...
at higher lattice temperatures, when $kT$ is comparable with the exciton binding energy, which results in the appearance of nonequilibrium electrons and holes in the subbands of the conductive and valence bands due to thermal dissociation of excitons.

The impurity-related photoconductivity spectrum of quantum wells in the mid-infrared spectral range is shown in figure 3 for the temperature $T = 10$ K. The observed mid-infrared transitions of holes are shown by black arrows in figure 3 and in the optical transition scheme presented in the inset to this figure. We attribute the photocurrent peak observed near the photon energy of about 205 meV to the optical transitions of holes from the ground acceptor state $A1$ to continuum states above the QW. The high intensity of this peak should not be considered because the spectral dependence of the source of broadband mid-infrared radiation was not taken into account. The peak near the photon energy of 150 meV can be connected to the hole transitions from the ground impurity state $A1$ to the second heavy hole subband $hh2$. Finally, the long-wavelength peak at a photon energy close to 100 meV can be associated with optical hole transitions between $A1$ and the first light hole subband $lh1$. A slight discrepancy between theory and experiment can be explained by the incorrect value of the effective mass of light holes used in the calculation. Also it can be explained by the contribution of the hole transitions between the ground acceptor state $A1$ and the resonant acceptor state $A3$ located below the first light hole subband.

The terahertz impurity-related photoconductivity spectrum is shown in figure 4 for temperature $T = 10$ K. The observed terahertz transitions are shown by blue arrows in figure 4, as well as in the optical transition scheme presented in the inset to figure 3. We attribute the photocurrent peak observed near the photon energy of about 20 meV to the optical transitions of holes from the ground acceptor state $A1$ to the first excited acceptor state $A1^*$ associated with the first heavy hole subband $hh1$. The peak near the photon energy of about 40 meV can be connected to the hole transitions from $A1$ to the first heavy-hole subband $hh1$. Finally, the peak near the photon energy of 65 meV can be associated with intracenter optical transitions of holes between $A1$ and a lower impurity state of the first light hole subband $A2$.

![Figure 3](image1.png)
**Figure 3.** Mid-infrared photoconductivity spectrum of the sample, measured at $T = 10$ K. The inset shows a scheme of possible acceptor-related optical transitions in quantum wells in the mid-infrared and terahertz ranges.

![Figure 4](image2.png)
**Figure 4.** Terahertz photoconductivity spectrum measured at temperature $T = 10$ K. The arrow $A1$-$hh1$ shows the calculated hole transitions described in the text, while the other arrows simply indicate the peaks $A1$-$A1^*$ and $A1$-$A2$.

To clarify the obtained results, we investigated the photoconductivity spectra of the reference sample without QWs. In this case, we observed only the photocurrent peak associated with interband carrier transitions in GaAs. Thus, it confirms that all the features observed in the spectra of the sample with QWs are uniquely associated with impurity transitions.
Summary
The results of studies of low-temperature photoconductivity of acceptor-doped GaAs/AlGaAs quantum wells are presented. Impurity-assisted photoconductivity was studied in the terahertz, mid-infrared and near-infrared spectral ranges. The mid-infrared and terahertz photoconductivity is associated with hole transitions from the ground acceptor state to the excited states of the acceptor and to the size-quantized subbands of QWs. The spectral positions of the observed photocurrent and photoluminescence peaks are in good agreement with theoretical calculations.

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