Light absorption related to hole transitions in quantum dots and impurity centers in quantum wells under external excitation

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Abstract. Optical absorption is studied in p-doped GaAs/AlGaAs quantum wells at lattice temperatures 4.2 - 300 K. Features in the absorption spectrum are associated to hole transitions from ground impurity level to resonant impurity states and subbands. Absorption modulation related to hole redistribution between impurity and subband states is studied. Spectra of intraband absorption are studied in Ge/Si quantum dots in equilibrium and under interband optical excitation. Filling the excited states with nonequilibrium holes leads to arising the additional peak in absorption spectrum related to hole transitions from the excited state.

1. Introduction
Optical transitions of charge carriers involving discrete energy states in nanostructures are very attractive in terms of the development of new light sources and detectors operating in mid-infrared and terahertz spectral ranges. Of particular interest are the resonant impurity states arising in quantum wells due to size quantization. Optical properties of resonant donor states in quantum wells have been studied rather extensively both theoretically [1] and experimentally [2]. The properties of resonant acceptor states are more poorly known and the first part of this paper is devoted to the influence of resonant acceptor states on intersubband light absorption. The acceptor state existence in quantum wells was experimentally confirmed with photoconductivity studies [3]. Optical phenomena related to the acceptors should be interesting because degeneracy of the valence band leads to lifting the polarization selection rules and both \( x,y \)- and \( z \)-polarized intersubband optical transitions become possible. Interest to the resonant acceptor states in quantum wells is also connected with the

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development of terahertz laser on stressed p-Ge [4] which is based on intracenter hole transitions with participation of the resonant acceptor states.

Quantum dots (QD) possessing the discrete energy spectrum are suitable for infrared photodetector applications including devices with normal light incidence. Usually, intraband light absorption is studied in doped quantum dot structures and carrier transitions from the ground state are considered. However, in some cases optical carrier transitions starting from excited state play the significant role in the device operation. For example, such transitions can determine the optical losses in light emitting cascade QD structures. Nevertheless no experimental studies of these transitions have been carried out. Intraband light absorption in p-doped quantum dots including transitions from excited states will be considered in the second part. Optical transitions from excited states can be studied in the structures with different doping providing the different occupation of the ground and excited levels. In our studies we changed the QD occupation using interband optical excitation.

In the present paper we report the results of the optical absorption studies in p-doped GaAs/AlGaAs quantum wells and Ge/Si quantum dots. Absorption studies can give valuable information about energy spectrum of impurity states and QD levels. Additional information can be collected in strongly nonequilibrium conditions, therefore we measured both equilibrium absorption spectra and spectra under strong longitudinal electric field in quantum wells and interband optical excitation in quantum dots.

2. Intersubband light absorption in p-GaAs/AlGaAs quantum wells

The GaAs/Al$_{0.4}$Ga$_{0.6}$As multi-quantum-well structure studied in the present work was grown by MBE. It contained 200 periods of 3.8 nm quantum wells separated with 7 nm barriers. Layer of 0.8 nm width in the center of each well was doped with Be to a concentration of 3.2·10$^{11}$cm$^{-2}$. The sample for optical investigations was prepared in multipass geometry with 12 light passes through QW layers. This sample configuration allowed to study the absorption of light polarized both in the plane of the structure (s-polarization) and at the angle of 45° to the growth axis (p-polarization). Indium contacts were deposited on a sample surface and annealed. Equilibrium absorption spectra was measured with VERTEX 80v Fourier transform infrared spectrometer at lattice temperature $T = 4.2 - 300$ K. Spectra of the absorption modulation at the longitudinal electric field were obtained at $T = 94$ K using tunable CO$_2$-laser. Reference sample was used in order to get the value of absorbance.

Spectra obtained at $T = 4.2$ K are of particular interest because at this conditions all the holes occupy the ground impurity state and features in the spectrum can be explained with hole transitions from this state only. Equilibrium absorption spectra measured at $T = 4.2$ K are shown in figures 1 and 2. Both spectra can be presented as a sum of Lorenz contours.

We consider optical transitions from the localized impurity state, so the final state should have the

![Figure 1](image-url). Equilibrium absorption spectrum for $p$-polarized light and result of its deconvolution; $\alpha$ is absorption coefficient, $L$ is the optical path length. Diagram of hole transitions is shown on the right.
momentum near the center of Brillouin zone. Therefore we was able to estimate the energies of hole levels in QW using simple parabolic approximation without taking into account light and heavy hole mixing. We estimated energies for light (lh) and heavy (hh) hole subbands in meV: $E_{lh1} = 88$, $E_{hh1} = 134$. It should be noted that quantum well is near the resonant one, namely there is one more level $hh3$ located in close proximity of the well top (barrier height $E_B = 231$ meV). The binding energy of Be ground state in 3.8 nm GaAs/AlGaAs QW $E_{b1} = 43$ meV [5]. We see that the position of peak at 135 meV in figure 1 corresponds well to the calculated energy $E_{bb2} - E_{hh1} + E_{b1} = 142$ meV. Peak at 116 meV can be related to the transitions to resonant acceptor state attached to $hh2$ level. Analogously, peaks at 205 and 187 meV in figure 2 can be associated to the transitions in $hh3$ subband and resonant impurity state attached to this subband, respectively. Weak peak at 240 meV corresponds well to the transitions in 3D continuum above the well because the calculations give $E_{Barr} - E_{hh1} + E_{b1} = 239$ meV. The obtained results allow to estimate the binding energies of resonant states attached to $hh2$ and $hh3$ subbands as approximately $E_{b2} = 135 - 116 = 19$ meV, $E_{b3} = 205 - 187 = 18$ meV. It should be noted that strong absorption of $s$-polarized light at intersubband carrier transitions was observed in contrast to the case of n-doped QW. Depopulation of the ground state and filling the $hh1$ state with the temperature reveal themselves in spectra giving the corresponding features.

Spectra of absorption modulation at lateral electric field are shown in figure 3. These spectra present narrow peaks located in the region of the absorption of $p$-polarized light corresponding to the transitions from the ground localized impurity state to resonant one attached to $hh2$ subband. At $T = 94$ K impurity is partially ionized. Electric field leads to further impurity ionization decreasing the occupation of this state, so negative change of the absorption is observed.

Analyzing the field dependence of the absorption modulation and current-voltage characteristics one can determine the impurity ionization rate as a function of electric field.
3. Optically induced intraband light absorption in Ge/Si quantum dots

Samples under investigations contained 10 layers of Ge quantum dots separated with 55 nm Si layers and were grown on p-doped Si substrate. Structures were δ-doped with boron to $8 \times 10^{11}$ cm$^{-2}$. Doped layers were placed 5 nm below QD layers. The growth procedure and QD characteristics are similar to ones described elsewhere [6]. The sample also was prepared in multipass geometry. Equilibrium absorption spectra were measured with VERTEX 80v Fourier transform infrared spectrometer. Spectra of the absorption modulation were obtained using interband optical excitation from YAG laser with frequency doubling ($\lambda = 532$ nm). Experimental results are shown in figure 4.

![Figure 4](image)

**Figure 4.** Equilibrium absorption spectra (1) and absorption modulation under interband optical excitation (2) for $p$-polarized light. Dashed lines present the result of modulation spectrum deconvolution. No absorption of $s$-polarized light was observed in this spectral range.

The observed peak in equilibrium absorption spectrum is related to hole transitions from the ground state to continuum. Spectrum of the absorption modulation contains two peaks. Position of the main peak corresponds to hole transitions from the ground state. So, at equilibrium the ground level is not fully occupied due to doping and nonequilibrium holes arising after interband excitation fill this level increasing the appropriate absorption. They also begin to fill the first excited state and optical transitions from this state to continuum become possible (see the small peak shifted by 82 meV, this value corresponds to the energy distance between the ground and first excited states [6]). In principle, these results can serve as a basis for the development of two-color QD photodetector.

4. Conclusion

In conclusion, we studied optical absorption in quantum wells related to intersubband and intracenter hole transitions and experimentally proved the presence of resonant acceptor states in GaAs/AlGaAs quantum wells. For the first time the intraband light absorption related to hole transitions from the first excited state was studied in Ge/Si quantum dots.

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