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THz Spectroscopy of Extremely Shallow Acceptors States in Ge/GeSi Multiple-Quantum-Well Heterostructures

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New shallow acceptor magnetoabsorption lines in THz range have been discovered under bandgap photoexcitation in strained Ge/GeSi multiple-quantum-well heterostructures. It is shown, both theoretically and experimentally, that the resonant absorption results from the photoionization of A^+-centers and from $1s \rightarrow 2p_+$-type transitions from the ground state of the barrier-situated A^0-centers into excited states in the 1st and 2nd electronic subbands. The shallowest discovered ground acceptor states ($E_B \leq 0.5$ meV) are attributed to the "barrier-spaced" acceptors (a hole bound with an acceptor ion in the *neighboring* Ge quantum well).

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1. Introduction

Recent interest in the THz range has stimulated investigations of shallow impurities in strained Ge/Ge$_{1-x}$Si$_x$ quantum well (QW) heterostructures [1–3]. The strain-induced valence band splitting in Ge/GeSi structures decreases the effective masses of two-dimensional holes and the binding energies of confined acceptors compared with those in bulk Ge, in contrast to the donors whose binding energy is known to increase due to additional confinement of the wave function by the QW potential. In this paper, we employ the newly developed technique [3] to distinguish between different type shallow acceptor centers contributing to the magnetoabsorption in the THz range in Ge/GeSi heterostructures. The method is based on measuring the differential impurity magnetoabsorption in THz range at the modulated bandgap optical excitation. The absorption signal is due to free carriers capture by ionized impurities that are always present in a sample because of a partial impurity compensation (cf. [1]). This method allows us to reveal complicated features of confined acceptor spectra not detected by conventional techniques.

2. Experimental

The structures under study were grown on Ge(111) substrate by vapor-phase epitaxy. Sample parameters are given in the captions to Figs. 1 and 2. The total thickness of the structures exceeds the critical one, thus leading to the stress relaxation in the interface structure-substrate. As a result Ge layers are biaxially compressed while GeSi layers are biaxially stretched. The residual shallow acceptor concentration was estimated to be $\sim 10^{14}$ cm^{-3} [1]. Magnetoabsorption of THz radiation (0.3 to 1.25 THz) generated by backward wave tubes (BWT) has been measured in a swept magnetic field (normal to the plane of the sample) at $T =$ 4.2 K. Free carriers were excited by a modulated (usually 1 kHz meander) bandgap light ($\lambda \sim 0.9$ μm). The transmitted through the Ge/GeSi sample radiation has been detected by n-InSb crystal. To avoid the interference effects in the sample, the substrate has been polished to the wedge of 2°. A nearly circular polarization of the THz radiation has been employed to distinguish between the acceptor and donor absorption.

3. Results and discussions

Figure 1 shows the magnetoabsorption resonant line positions in sample #306 with narrow Ge QWs. Two spectral lines CH_1 and Ch_1 are known to result from cyclotron resonance (CR) transitions between the lowest hole Landau levels in Ge QWs, $0s_1 \rightarrow 1s_1$ and $3a_1 \rightarrow 4a_1$ correspondingly [4]. In contrast to the CR lines, the positions of two other lines, CI_1 and CI_2, do not extrapolate to the origin of coordinates. Earlier we have observed the CI_2 line in the impurity photoconductivity spectra [1, 5] (see open symbols in Fig. 1) and attributed this line either to the photoionization of the A$^+$-center (the A$^+$-center is the QW acceptor ion binding two holes) or to the $1s \rightarrow 2p_+$ transitions of the barrier situated neutral acceptors (A^0- centers). The acceptor (rather than the donor) nature of the lines CI_1 and CI_2 is confirmed by the results of the absorption measurements with nearly circular polarized radiation. For uniformly distributed residual acceptors, only QW-centered neutral impurities (with the maximal binding energy about 7 meV) and the barrier-centered ones (with the minimal binding energy about 2 meV) give rise to the resonant absorption (cf. [6]). The transitions for QW situated acceptors are out of the spectral range accessible to BWT (they have been observed earlier in the photoconductivity measurements with Fourier transform spectrometer [1]).

To distinguish between A$^+$-center and barrier situated A^0-center absorption in the "low-frequency" spectral range, we calculated the energies of $1s \rightarrow 2p_+$

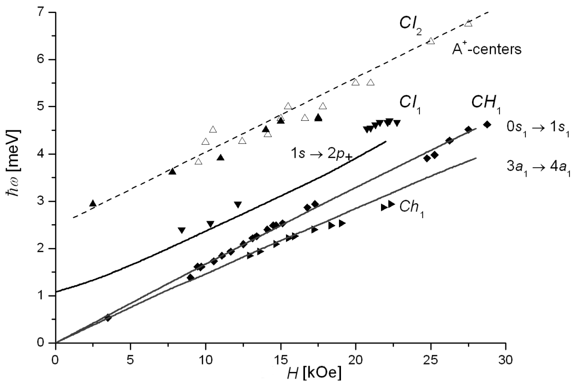

Fig. 1. Spectral positions of absorption (closed symbols) and photoconductivity (open symbols) [1, 5] resonances in the Ge/Ge$_{1-x}$Si$_x$ sample #306 ($x = 0.12$, $d_{\mathrm{Ge}} = 20$ nm, $d_{\mathrm{GeSi}} = 26$ nm, elastic deformation of Ge layers $\varepsilon_{xx} = 2.2 \times 10^{-3}$, $N_{\mathrm{period}} = 162$). Solid lines — calculated $\omega(H)$ dependences for hole CR lines CH_1 and Ch_1 and $1s \to 2p_+$ transitions for barrier-centered A^0 acceptors (CI_1). Dashed line — resonances attributed to photoionization of A$^+$-centers (CI_2).

transitions for the barrier situated A^0-centers in the magnetic fields using the expansion of the acceptor wave function in terms of the hole wave functions in the Ge QW at $H = 0$ (see Ref. [7] for details). Comparing the calculation results with the experimental data (see Fig. 1), we attributed the CI_1 line to the $1s \to 2p_+$ transitions. The minor discrepancy (the experimental data for CI_1 line are slightly higher than the calculated magnetic field dependence for $1s \to 2p_+$ transitions) seems to be caused by dispersion of the transition energy for the uniformly distributed residual impurities. The CI_2 line seems to result from the photoionization of the A$^+$-centers. We estimated that the corresponding binding energy is $E_+ \approx 2$ meV at $H = 0$ [8] that is a little bit smaller than the value that CI_2 line cuts on the ordinate axis in Fig. 1. It is reasonable to assume that A$^+$-center, just as a D$^-$-center, has no excited states [9], so the observed optical transitions should take place at $\hbar\omega > E_+$.

Figure 2 presents a typical magnetoabsorption spectrum in the sample #308 with broader Ge QW where three acceptor related lines CI_1–CI_3 are observed [2, 3] (CE_{1L} is CR line of 1L-electrons in GeSi layers [10]). The overall data on the spectral line positions are given in Fig. 3. Time-resolved measurements with pulsed bandgap optical excitation show that typical relaxation times for all impurity lines are as high as 10^{-4} s (Fig. 2). Therefore, these lines result from the optical transitions from the *ground* state of shallow acceptors rather than from their excited states (cf. [11]). Just as for sample #306, the highest frequency line (CI_3) can be attributed to the photoionization of the A$^+$-centers. The calculation results for the sample #308 with broad QWs predict two optical transitions of comparable intensity from the ground $1s$ state of barrier-situated A^0-center into

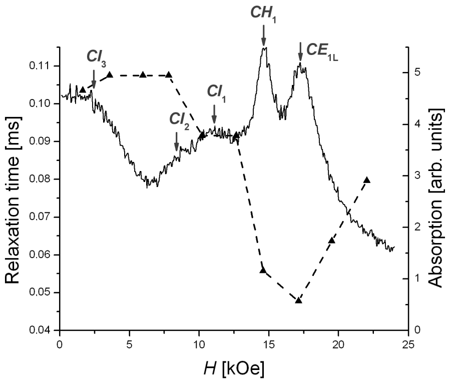

Fig. 2. Absorption (solid line) and signal decay time (symbols connected by a broken line) versus the magnetic field in the Ge/Ge$_{1-x}$Si$_x$ sample #308 ($x = 0.09$, $d_{\mathrm{Ge}} = 35$ nm, $d_{\mathrm{GeSi}} = 16$ nm, $\varepsilon_{xx} = 4.4 \times 10^{-4}$, $N_{\mathrm{period}} = 162$) at the pulsed optical excitation ($\tau_{\mathrm{pulse}} = 330$ μs, repetition rate $f = 100$ Hz). $\hbar\omega = 2.43$ meV.

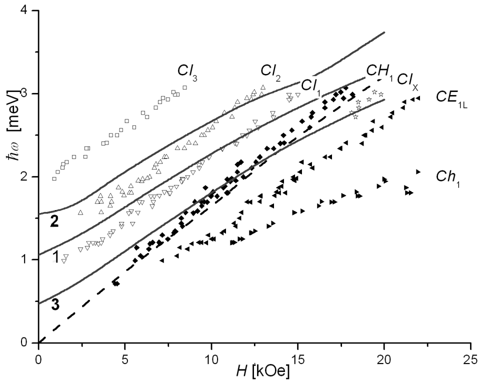

Fig. 3. Spectral positions of the observed absorption resonances in the sample #308 (symbols). Dashed line — calculated $\omega(H)$ dependence for the hole CR line CH_1. Solid lines 1 and 2 — calculated $\omega(H)$ dependences for transitions from $1s$ state to $2p_+$ states pertained to the 1st and the 2nd electric hole subband in the QW (CI_1 & CI_2) correspondingly. Black solid line 3 — calculated dependence for $1s \rightarrow 2p_+$ transition for "barrier spaced" A^0-center (CI_x).

$2p_+$ states related to the 1st and the 2nd hole electronic subbands (Fig. 3). This results from a lower (compared to sample #306) energy of the size quantization and from the state mixing in the 1st and the 2nd subbands.

In conclusion, we discovered a new acceptor related to magnetoabsorption line CI_x that becomes discernible on a higher H side of the main hole CR line CH_1 when the frequency increased (see Fig. 3). We speculate that this line results from $1s \rightarrow 2p_+$ transitions for very shallow "barrier-spaced" A^0-center consisting of the hole bound with an acceptor ion in the *neighboring* Ge QW. According to our calculations (see Fig. 3), the energy of such transition only slightly exceeds that of the main hole CR transition in the magnetic fields up to 1 T, and this line is typically masked by the powerful absorption line CH_1. However, at $H > 17$ kOe, this transition becomes distinguishable.

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