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Hole cyclotron resonance in MQW Ge/GeSi heterostructures in quantizing magnetic fields

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Abstract. "Quantum" cyclotron resonance of 2D holes in strained Ge/GeSi heterostructures has been investigated in frequency range $\nu = 370 \div 700$ GHz. Calculations of hole Landau levels in rectangular quantum well in strained heterostructures have been performed allowed to interpret the observed far infrared magnetoabsorption spectra.

Introduction

The two-dimensional (2D) holes in strained SiGe-based heterostructures have been found to be sensitive to band structure engineering "tools": built-in deformation and quantum confinement. The deformation results in decoupling of light and heavy hole energy subbands and in decrease of hole mass at the bottom of valence band while confinement results in mixing of light and heavy hole states. Energy-momentum law of 2D holes in strained Ge/GeSi(111) heterostructures were studied earlier [1] both theoretically and experimentally (by means cyclotron resonance (CR) at $\nu = 130$ GHz, $T = 4.2$ K, i.e. in "semiclassical" case $\hbar\omega \approx k_B T$). In undoped samples spectra the CR line of photoexcited 2D holes in Ge quantum wells (QWs) was observed corresponded to the small mass value $m_c = 0.07m_0$. The application of lateral electric field was shown to result in the remarkable shift of the hole CR line to higher magnetic fields (up to 400%) due to the strong nonparabolicity of 2D hole dispersion.

In the first study of "quantum" CR in strained Ge/GeSi(111) system [2] selectively doped heterostructures were investigated using Fourier-transform spectrometer (cf. [3, 4]). Two CR lines were observed in the spectra in magnetic fields up to 14 T which was tentatively attributed to CR transitions from the first and the second lowest hole Landau levels. In this paper we present the study of "quantum" CR absorption in *undoped* samples that becomes possible due to the usage the more powerful radiation source: backward wave tube oscillators. The results were interpreted on the base of Landau level calculations in strained QWs.

1 Experimental

MQW Ge/Ge$_{1-x}$Si$_x$ heterostructure (#306, $x = 0.12$, $d_{\mathrm{Ge}} = 200$ Å, $d_{\mathrm{GeSi}} = 260$ Å, number of periods $N = 162$) was grown by CVD technique on Ge(111) substrate. The whole width of the structure exceeds the critical value thus providing stress relaxation between the substrate and the heterostructure and biaxial elastic deformation of Ge layers $\epsilon = 2.18 \times 10^{-3}$. The CR absorption spectra of the sample were studied in Faraday geometry at $T = 4.2$ K in the frequency range $\nu = 350 \div 700$ GHz using n-InSb detector. The sample was illuminated by LED ($\lambda \approx 0.9\ \mu$m) that was triggered at $f = 1$ kHz; thus

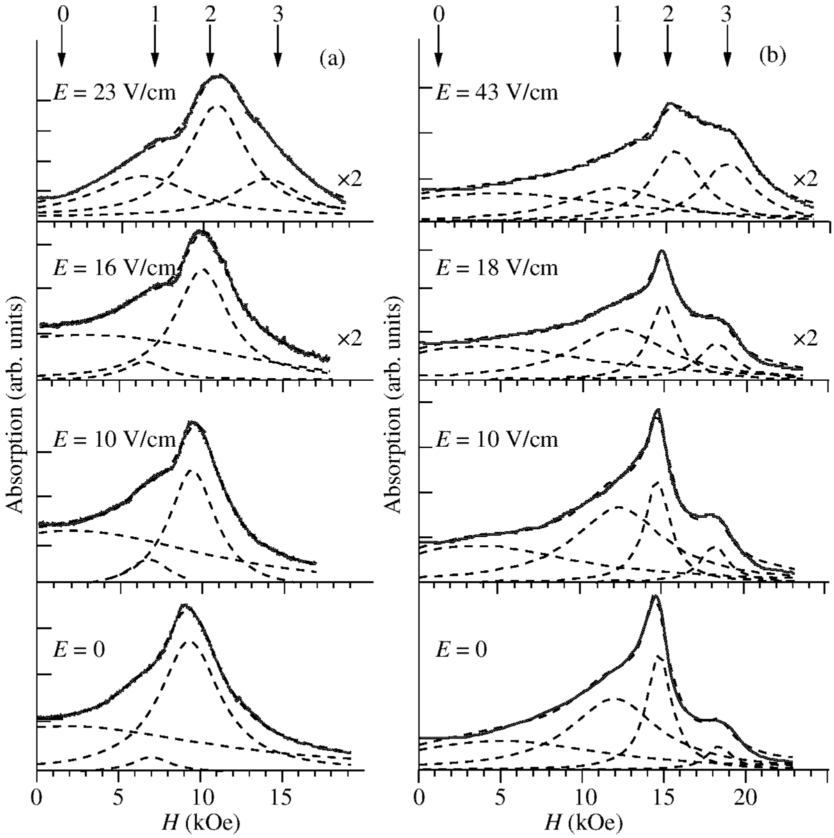

Fig. 1. CR spectra of photoexcited holes in Ge/GeSi heterostructure #306 at dc electric fields; $T = 4.2$ K; (a) $\nu = 370$ GHz, (b) $\nu = 600$ GHz. Each experimental curve (solid line) is resolved into three or four Lorentzians (dashed lines). The Lorentzians positions are marked by arrows.

all spectra were measured at the modulation of photoexcitation. Strip ohmic contacts were deposited on the sample surface to allow lateral electric field application.

The observed CR spectra are shown in Fig. 1. The lowest curves represent the spectra at zero electric field while the upper ones are obtained at some dc voltages applied to the sample. To distinguish the spectral features each curve was resolved into three or four Lorentzians; the feature positions being marked in Fig. 1 by arrows. The broad line 0 seems to results from nonresonant tails (polarization of radiation was nearly linear) of the other lines 1, 2, 3. Note that in contrast to CR in "semiclassical" case [1] dc electric field does not shift the lines but changes the relative magnitudes of lines 2 and 3. The line positions $\hbar\omega(H)$ in wide frequency range $130 \div 700$ GHz are plotted in Fig. 2. It is clearly seen that the linear extrapolation of line 1 position to $H = 0$ gives $\varepsilon = 0.85$ meV; hence this line cannot be attributed to CR of free carriers. It is natural to attribute the line 1 to transitions between excited residual shallow acceptor or A^+-center states [5] (which become populated under LED illumination) associated with two different Landau levels (cf. [6]). The line 2 corresponds to the same cyclotron mass $m_c = 0.07m_0$ both in "semiclassical" and in quantizing magnetic fields and results from CR of 2D holes occupying the lowest Landau level. At last the line 3 becomes discernible only at $\nu \geq 400$ GHz, its intensity

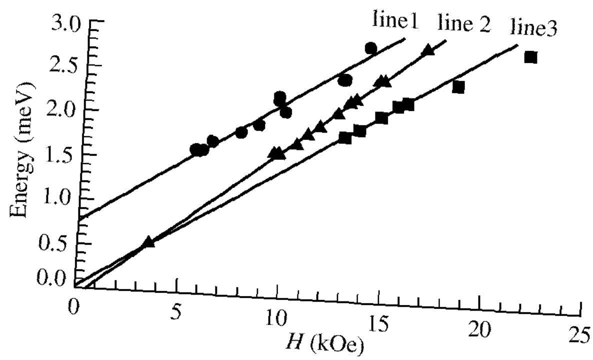

Fig. 2. Spectral positions of the absorption lines 1, 2, 3 versus magnetic field.

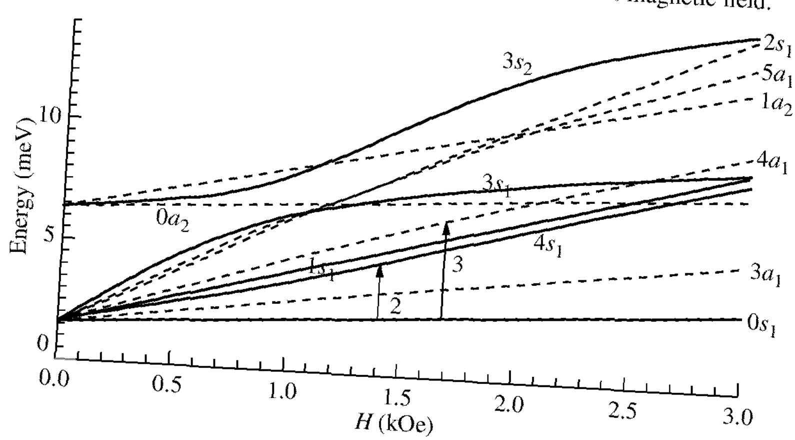

Fig. 3. Fan chart of calculated Landau levels in Ge QW for Ge/GeSi heterostructure #306. Arrows 2, 3 correspond to lines 2, 3 on Fig. 2.

being increased in comparison with that of the line 2 in dc fields. It indicates that the line 3 is associated with CR transitions of 2D holes occupying the higher Landau level (cf. [2]).

2 Calculations and comparison with the experiment

Calculations of Landau levels of 2D holes in rectangular quantum well in strained Ge/GeSi heterostructures were performed using 4×4 $\boldsymbol{k}\cdot\boldsymbol{p}$ Hamiltonian in axial approximation. The symmetry results in the conservation of the total angular momentum projection on the magnetic field direction M_j and the parity of the wave function with respect to the reflection in the plane $z = 0$ that goes through the QW center. Thus each state could be classified by eigenvalue $n = M_j + 3/2$ $(n = 0, 1, 2, \ldots)$, and should be either symmetric (s) or antisymmetric (a) with respect to the plane $z = 0$. This notation is used in Fig. 3 where fan chart of lower Landau levels is plotted. The index in notation indicates the subband from which the given Landau level originates from. In Faraday geometry dipole transitions are allowed between two states of the same parity if $\Delta n = \pm 1$. As it is seen from Fig. 3 the lower Landau levels are weakly interacting and their energies depend linearly on the magnetic field up to 30 kOe. The most of photoexcited holes in our experiments populate the lowest Landau level $0s_1$. The allowed CR transition $0s_1 \to 1s_1$ corresponds to the cyclotron mass $m_c = 0.06m_0$ that is a little bit less than observed mass for the line 2 of $0.07m_0$. Similarly the calculated mass for the allowed transition from the next Landau level $3a_1 \to 4a_1$ $m_c = 0.065m_0$ is less than the observed one for the line 3 ($0.08m_0$). It is cleally seen from Fig. 1 that the relative intensity of the line 3 increases with the heating dc electric field resulting in the populating of the upper laying Landau level $3a_1$ at the expense of devastating of the lowest one $0s_1$. The 15% discrepancy between the calculated and the observed effective mass values probably results from the neglecting of the split-off hole subband in the calculations.

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