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Cyclotron Resonance of Two-Dimensional Holes in Strained MQW Ge/GeSi Heterostructures in Quantizing Magnetic Fields

V.Ya.Aleshkin, V.I.Gavrilenko, I.V.Erofeeva, O.A.Kuznetsov, M.D.Moldavskaya, V.L.Vaks, D.B.Veksler

Institute for Physics of Microstructures of Russian Academy of Sciences, GSP-105, Nizhny Novgorod, 603600, Russia
Phone: +7(8312) 675555 Fax: +7(8312) 675553 e-mail: gavr@ipm.sci-nnov.ru

1. 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 subbands and in decrease of hole mass at the bottom of the valence band while the confinement results in mixing of light and heavy hole states. Earlier in undoped $Ge/Ge_{1-x}Si_x(111)$ multi-quantum-well (MQW) heterostructures the cyclotron resonance (CR) of photoexcited 2D holes of low mass ($m_c = 0.07m_0$) and high mobility ($\mu \approx 10^5$ cm^2/V·s) has been observed in strain Ge layers in "semiclassical" case $\hbar\omega \approx k_BT$ (f =130 GHz, T = 4.2 K) [1]. In selectively doped Ge/GeSi heterostructures two CR lines were revealed in the spectra in quantizing magnetic fields up to 14 T using Fourier-transform spectrometer [2]; the lines were tentatively attributed to CR transitions from the two lowest hole Landau levels (cf. [3]). The present paper deals with high resolution hole CR investigation in *undoped* samples with more powerful monochromatic radiation sources, namely backward wave tube oscillators. The results are discussed on the base of the carried out Landau level calculations in strained QWs.

2. Experiment

MQW $Ge/Ge_{1-x}Si_x$ heterostructure (#306, x = 0.12, d_{Ge} = 200 A, d_{GeSi} = 260 A, number of periods N = 162) was grown by atmospheric pressure CVD technique on Ge(111) substrate. The whole width of the structure exceeds the critical value thus providing the stress relaxation between the substrate and the heterostructure and biaxial elastic deformation of Ge layers $\varepsilon = 2.2\cdot10^{-3}$. CR absorption was studied in Faraday geometry in the frequency range f = 350÷700 GHz at T = 4.2 K. Free holes were excited by band-gap illumination; *all spectra were measured at the modulation of photoexcitation.* Strip ohmic contacts were deposited on the sample surface to allow lateral d.c. electric field application.

The observed CR spectra are shown in Fig.1. Each experimental curve (solid line) is resolved into three or four Lorentzians (dashed lines), the Lorentzian positions being marked 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*. In contrast to CR in "semiclassical" case [1] d.c.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÷700 GHz are plotted in Fig.2. It is clearly seen that the linear extrapolation of line *1* position to H = 0 gives E = 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 [4] associated with two different Landau levels (cf. [5]). These states should become populated under the illumination. 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* ($m_c = 0.08m_0$) becomes discernible only at $f \geq 400$ GHz, its intensity being increased in comparison with that of the line 2 in d.c. fields. It indicates that line *3* is associated with CR transition of 2D hole from a higher Landau level.

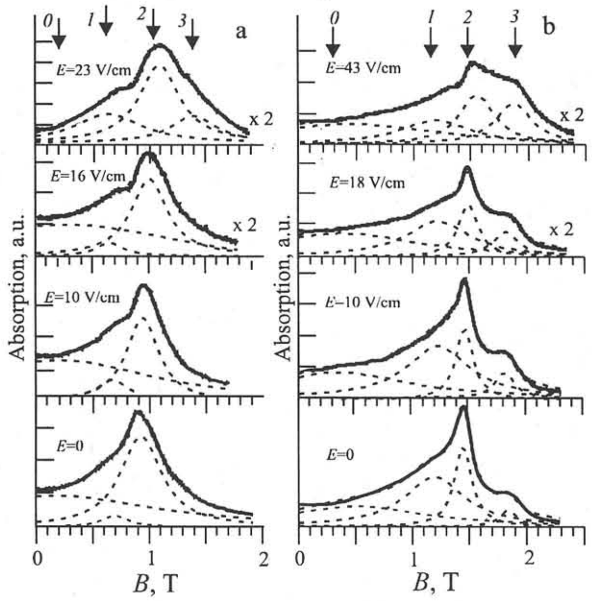

Fig 1. Cyclotron resonance absorption spectra of 2D photoexcited holes in $Ge/Ge_{0.88}Si_{0.12}$ heterostructure in d.c. lateral electric fields (solid lines). T = 4.2 K. a) f = 370 GHz, b) f = 600 GHz. Each absorption curve is resolved into three or four Lorentzians (dashed lines). Lorentzians positions are marked by arrows.

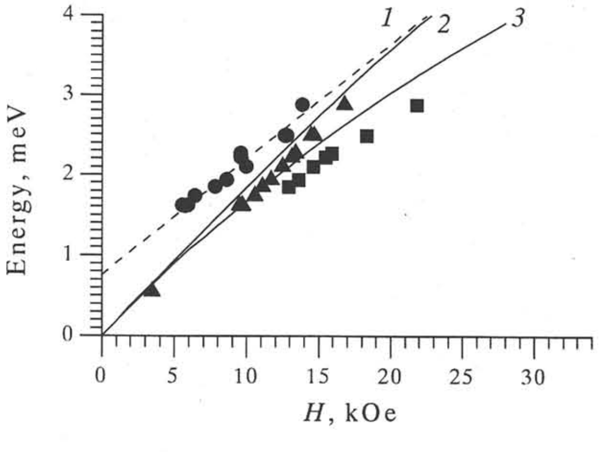

Fig.2. Spectral positions of the observed absorption lines *1, 2, 3* (see Fig.1) versus magnetic field. The dashed line shows the extrapolation of the line *1* to $H = 0$. The solid lines show calculated hole cyclotron transitions corresponding to the observed lines *2, 3*.

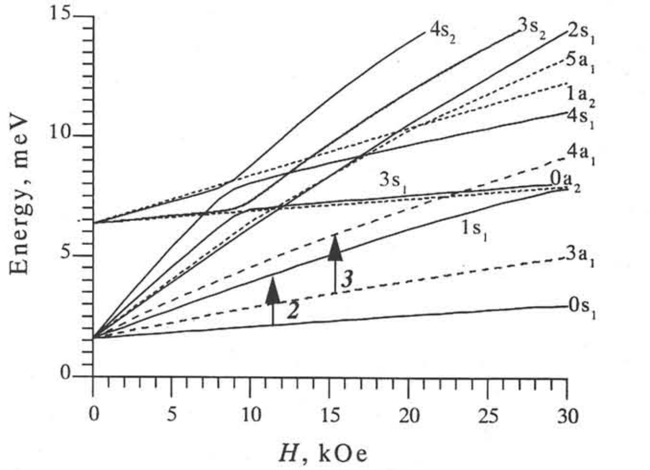

Fig. 3. Fan chart of calculated Landau levels in rectangular quantum well in $Ge/Ge_{0.88}Si_{0.12}$ heterostructure. Arrows *2, 3* correspond to the lines *2, 3* in Fig.2.

3. Calculations and Comparison with Experiment

The above interpretation is supported by the results of the calculation of hole Landau levels in rectangular quantum well in strained Ge/GeSi heterostructure performed using 4x4 **k·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. Thus each state could be classified by eigenvalue $n = M_j+3/2$ ($n = 0,1,2,...$), and should be either symmetric (s) or antisymmetric (a). 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. The correction resulted from nondiagonal warping term in Hamiltonian was found to be of 3÷5% for several Landau levels. (the results shown in Fig.3 include this correction). In Faraday configuration dipole transitions are allowed between two states of the same parity if $\Delta n = \pm 1$. The most of photoexcited holes at $T = 4.2$ K populate the lowest Landau level $0s_1$. The allowed CR transition $0s_1 \rightarrow 1s_1$ corresponds to the cyclotron mass $m_c= 0.064m_0$ that is a little bit less than observed mass for the line 2 of $0.07m_0$. The allowed CR transition from the next Landau level $3a_1 \rightarrow 4a_1$ corresponds to heavier calculated effective mass $m_c= 0.073m_0$; it seems to be responsible for the line *3* observed to the right of the line *2* on Fig.1 ($m_c= 0.08m_0$). It is clearly seen from Fig.1 that the relative intensity of the line *3* goes up with the increases of the heating d.c. 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 discrepancy 8% between the calculated and the observed effective mass values can be explained by the neglecting split-off hole subband. This corrections seems to be less than 1% for the Landau levels under consideration. The reasonable origin of the discrepancy may be a nonrectangular form of the well potential due to Si profile blurring during the growth.

Thus CR of 2D hole in undoped strained MQW Ge/GeSi (111) heterostructures were investigated in wide frequency range 130÷700 GHz. Effects of built-in deformation and confinement on 2D hole energy spectra were demonstrated. Calculations of 2D hole Landau levels and investigation of hole heating allowed to interpret the observed evolution of the CR spectrum from "classical" to "quantum" range.

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