Extended Abstracts of the 1995 International Conference on Solid State Devices and Materials, Osaka, 1995, pp. 917-919 **PC-13-6**

Cyclotron Resonance Investigation of Multi-Quantum-Well Heterostructures $Ge/Ge_{1-x}Si_x$

V.Ya.Aleshkin, N.A.Bekin, I.V.Erofeeva, V.I.Gavrilenko, Z.F.Krasil'nik, O.A.Kuznetsov, M.D.Moldavskaya, V.V.Nikonorov, L.V.Paramonov and V.M.Tsvetkov

Institute for Physics of Microstructures of Russian Academy of Sciences
46, Uljanov St., 603600, Nizhny Novgorod, Russia

Cyclotron resonance spectra of 2D holes in strained MQW heterostructures $Ge/Ge_{1-x}Si_x$ were investigated. The hole cyclotron mass increase from $m_c \approx 0.07m_0$ in the undoped samples to $m_c \approx 0.2m_0$ in selectively doped heterostructures resulting from the strong nonparabolicity of the energy spectrum was observed. In strong electric fields up to $E \approx 300$ V/cm the enormous (up to 400%) shift of the absorption line to higher effective mass region was revealed that corresponds to the dynamical heating of the carrier up to $T_e \geq 200$ K.

1. INTRODUCTION

The paper deals with the cyclotron resonance (CR) investigation of both doped and undoped multi-quantum-well (MQW) heterostructures $Ge/Ge_{1-x}Si_x$ ($x \approx 0.1$, $d \leq 200$ A) grown by CVD technique on moderately doped Ge(111) substrates ($\rho_{300K} \approx 40 \div 45$ Ω·cm). In this heterosystem quantum wells in the valence band are realized in the pure germanium layers while the energy structure of the conductance band is not quite clear yet. The peculiarity of the heterostructures $Ge/Ge_{1-x}Si_x$ is the elastic deformation resulting from the mismatch of lattice periods of Ge and GeSi. The uniaxial part of the deformation which corresponds to the stretching tension P_{equiv} results in the valence band splitting. Earlier we have observed the CR absorption line of high mobility light 2D holes in the split valence band in Ge layers[1] and revealed the electric field effects on the hole system[2]. In this paper we report the first CR measure-ments in selectively doped MQW structures and the further investigation of hot hole CR. The results obtained are in a good agreement with the calculations of 2D hole energy spectra.

2. CYCLOTRON RESONANCE IN UNDOPED AND SELECTIVELY DOPED HETEROSTRUCTURES $Ge/Ge_{1-x}Si_x$

Typical CR spectra of photoexcited carriers in the undoped structures are presented in Fig.1 (sample #306). The position of the hole CR line corresponds to the effective mass $m_c \approx 0.07m_0$ ($\mu \approx 10^5$ cm^2/V·s); the electron CR lines were not observed in the spectra. Theoretical calculations of the energy spectra give the negligible value of the conductance band offset (it seems to be the reason of the absence of the electron CR lines) while in the valence band the depth of the quantum well is about 100 meV. The hole energy spectrum in the quantum well is given in Fig.2. The pronounced nonparabolicity of the energy-momentum law is clearly seen. The calculated effective mass value $m^* \approx 0.06m_0$ at the bottom of the lowest subband (Fig.3) is in a good agreement with the observed cyclotron mass of holes.

CR experiments with the selectively doped structure #123 with degenerated 2D hole gas ($n_s \approx 2 \cdot 10^{11}$ cm^{-2}, $\varepsilon_F \approx 8$ meV) showed the increase of the hole cyclotron mass up to $m_c \approx (0.09\text{-}0.1)m_0$ resulting from the above nonparabolicity of the energy-momentum law. The measurements were carried out both in millimeter (MM) wavelength range with the backward wave tube oscillator (Fig.4) and in submillimeter region with FT spectrometer BOMEM DA3.36 (Fig.5,6). It should be pointed out that the doping also results in some increase of the hole scattering rates up to υ = 1-1.5 THz in comparison with υ = 0.3 THz in the undoped sample at E = 0 (Fig.1). The increase of the hole concentration up to $n_s \approx 7 \cdot 10^{11}$ cm^{-2} leads to the further enhancement of the effective mass value (Fig.7,8, sample #355, $\varepsilon_F \approx 18$ meV, $m_c \approx 0.18\text{-}0.20m_0$). Though CR absorp-

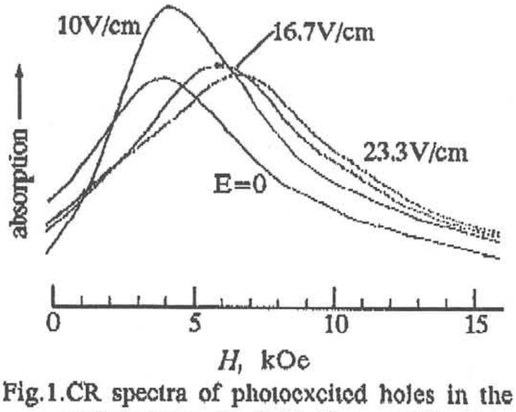


Fig.1.CR spectra of photoexcited holes in the undoped sample #306 (d_{QW}= 200 A) in d.c. electric fields; λ=2.11 mm, T=4.2 K.

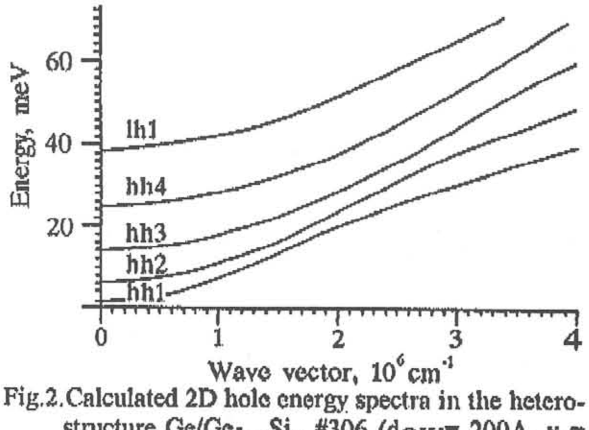


Fig.2.Calculated 2D hole energy spectra in the heterostructure $Ge/Ge_{1-x}Si_x$ #306 (d_{QW}= 200A, x = = 0.12, k || [112], $P_{equiv.}$= 4 kbar).

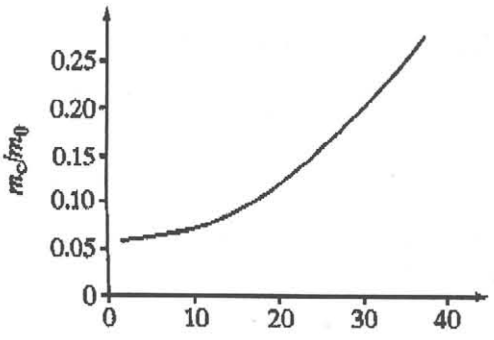


Fig.3. Energy dependence of hole cyclotron resonance mass in the lowest subband hh1 (Fig.2); sample #306.

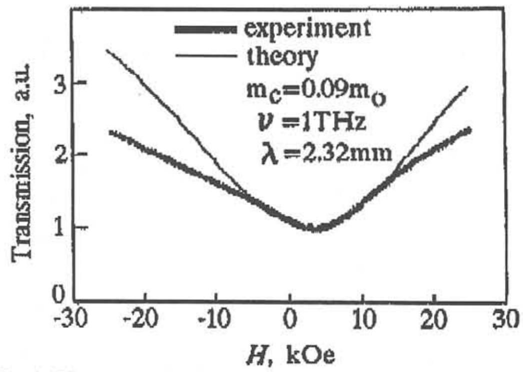


Fig.4. CR transmission spectra in selectively doped sample #123 (d_{QW}= =180 A, $n_s \approx 2 \cdot 10^{11}$ cm^{-2}) at nearly circular polarized MM radiation; T = 4.2K.

tion in Fig.4-8 is sufficiently "screened" by plasma reflection in the heterostructures (samples #123 and #355 "contain" 15 and 6 layers of 2D hole gas correspondingly) the remarkable increase of the effective hole mass with the energy is quite evident (to improve the accuracy of the mass measurements it is necessary to use the structures with 1-2 layers of degenerated 2D hole gas). The observed mass increase corresponds fairly well to the results of the theoretical calculations (see, for example Fig.2,3) thus allowing to predict the hole $\mathcal{E}$(k) dispersion law at different values of silicon content x and well width d_{QW} at least for the lowest subband.

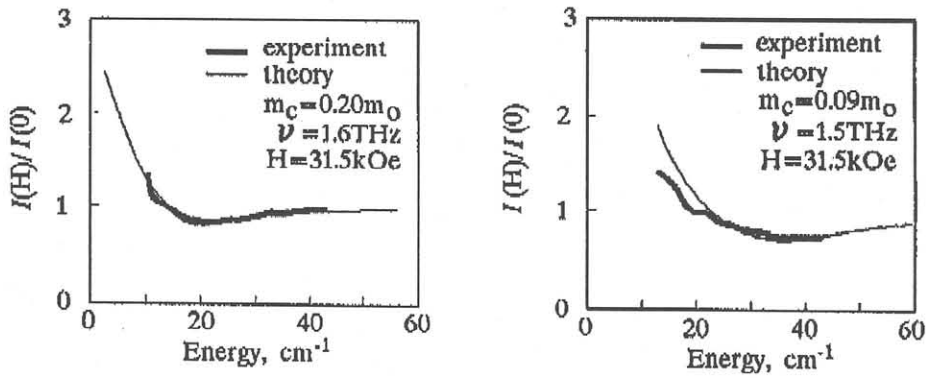


Fig.5,6. Normalized transmission spectra in selectively doped sample #123 (d_{QW}= 180 A, $n_s \approx 2 \cdot 10^{11}$ cm^{-2}); T = 4.2K.

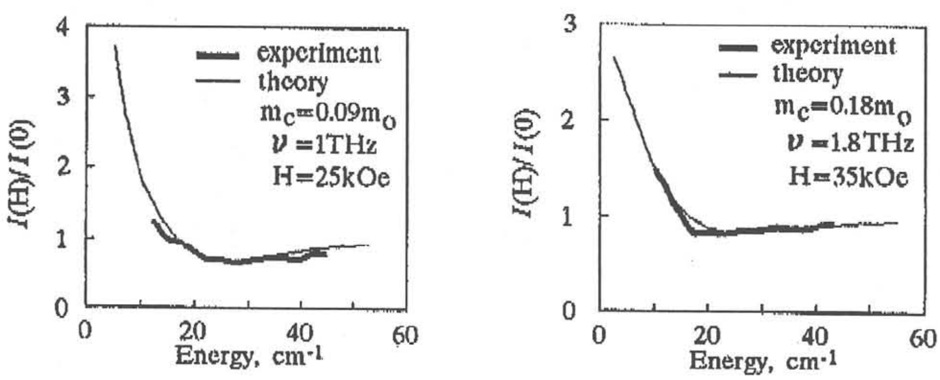


Fig.7,8. Normalized transmission spectra in selectively doped sample #355 (d_{QW}=130 A, $n_s \approx 7 \cdot 10^{11}$ cm^{-2}); T = 4.2K.

3. CYCLOTRON RESONANCE OF HOT HOLES IN STRONG ELECTRIC FIELDS

The enhancement of the effective mass with the rise of the hole energy was also revealed at the carrier heating in electric fields in the undoped sample #306. This effect is clearly seen even in d.c. fields about few V/cm for both the photoexcited holes (Fig.1) and holes produced by impact ionization of residual shallow acceptors (Fig.9). In higher electric fields the CR experiments were carried out using pulse technique (Fig.10,11). In the latter case free holes were also excited at the impact ionization of residual shallow acceptors in the heterostructure thus modulating the MM-wave absorption in the sample.

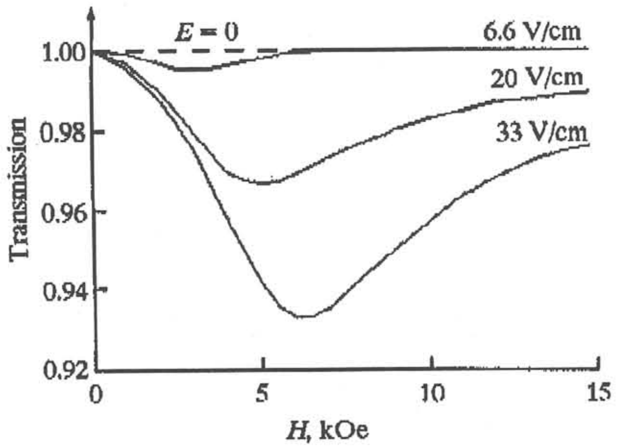
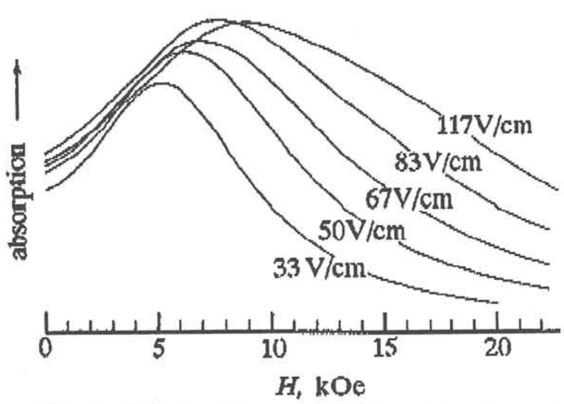


Fig.9. Absolute measurements of CR transmission spectra; sample #306, $\lambda = 2.1$ mm, $T = 4.2$ K.

The obtained absolute values of CR transmission (Fig.9) together with the relative increase of the integral intensity of CR line with the rise of pulsed electric fields up to its saturation at $E \geq 200$ V/cm (Fig.10,11) corresponding to the complete ionization of shallow acceptors allow to estimate the total concentration of residual impurities in the heterostructure: $n_s \approx 2 \cdot 10^{11}$ cm^{-2} (per 162 layers of the structure) that roughly corresponds to the volume concentration $n \approx 3 \cdot 10^{14}$ cm^{-3}. The technique used makes it possible to estimate the binding energy $\mathcal{E}_B$ of acceptor centers in quantum-well heterostructures Ge/$Ge_{1-x}Si_x$. Because of adiabatic heating of the sample (together with the substrate) during the strong electric field pulse its temperature increases significantly over 4.2K that results in the thermoionization of shallow acceptors behind the trailing edge of the pulse[3]. Measuring the intensity of CR absorption line just after the electric field pulse as a function of the dissipated Joule energy and taking into account the temperature dependence of the specific heat of the germanium substrate we obtain the temperature dependence of the concentration and estimate $\mathcal{E}_B \approx$ 2-4 meV that is sufficiently smaller than in bulk Ge because of the strain induced valence band splitting.

In strong electric fields a marked CR line shift to higher effective mass region up to $m_c \approx 0.3 m_0$ at $E \approx 300$ V/cm (Fig.10,11) was revealed that corresponds to the carrier heating up to $T_e \gtrsim 200$ K. The latter proves the realization of the streaming motion of the carriers and indicates the possibility of the population inversions of 2D holes in E⊥H fields just similar to those in bulk p-Ge[4].



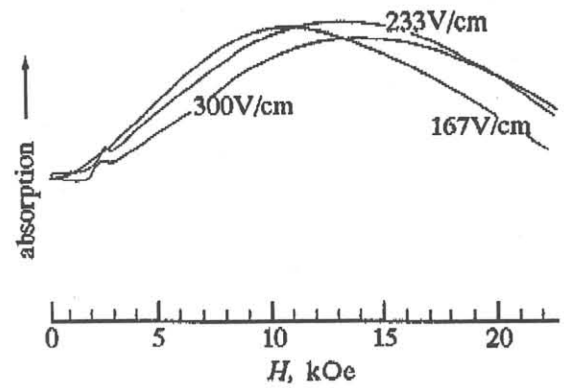


Fig.10,11. Hole CR spectra in the undoped sample #306 in pulsed electric fields; $\lambda = 2.32$ mm, $T = 4.2$ K.

The research described in this publication was made possible in part by Grants ## 93-02-14721, 94-02-05445 from Russian Foundation for Fundamental Investigations, Grant #R8H000 from the International Science Foundation and Grant #R8H300 from the International Science Foundation and Russian Government.

References

1. V.I.Gavrilenko, I.N.Kozlov, O.A.Kuznetsov, M.D.Moldavskaya, V.V.Nikonorov, L.K.Orlov, and A.L.Chernov, JETP Lett. **59** (1994) 348; Jpn.J.Appl.Phys. **33** (1994) 2386.
2. V.I.Gavrilenko, I.N.Kozlov, O.A.Kuznetsov, M.D.Moldavskaya and V.V.Nikonorov. 1994 Intern. Conf. Solid State Devices and Materials (Yokohama, Japan). Extended Abstracts, p.503
3. V.I.Gavrilenko, A.L.Korotkov, Z.F.Krasil'nik and V.V.Nikonorov. Opt. Quantum Electron. **23** (1991) S163.
4. Opt. Quantum Electron. **23**, N2 (1991), Special Issue on Far-infrared Semiconductor Lasers.