Cyclotron resonance of charge carriers in strained $Ge/Ge_{1-x}Si_x$ heterostructures

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The cyclotron resonance of photogenerated carriers in a strained, multilayer, undoped $Ge/Ge_{1-x}Si_x$ heterostructure has been studied for the first time. The spectra of the absorption and the millimeter-range photoconductivity spectra have a line corresponding to a cyclotron resonance of carriers with an effective mass $m_c \simeq 0.07 m_0$. This value corresponds to the transverse mass of holes at the bottom of the deformed quantum wells in the Ge layers. A residual photoconductivity is observed. It results from holes which remain in Ge layers after the interband illumination is turned off.

The fabrication of selectively doped multilayer $Ge/Ge_{1-x}Si_x$:B heterostructures with quantum wells in the Ge layers by a vapor hydride method was reported in Refs. 1 and 2. The observation of an integer quantum Hall effect in those structures was also reported there. An important distinguishing feature of these heterostructures is an elastic deformation, which results from the mismatch of the lattice constants of Ge and $Ge_{1-x}Si_x$. As a result, the Ge layers are compressed in the plane of the heterostructure. This deformation can be thought of as the result of hydrostatic compression along with a uniaxial extension of the Ge along the axis of the heterostructure ($\mathbf{P} \| [111]$). By changing the symmetry of the crystal lattice, the uniaxial deformation splits the edge of the valence band; it also lifts the intervalley degeneracy in the conduction band.[3] Studies of selectively doped *p*-type heterostructures in strong magnetic fields have shown that the effective mass of the holes, found from the temperature dependence of the amplitude of the Shubnikov–de Haas oscillations [$m^* \simeq (0.10–0.14) m_0$], depends on the carrier concentration. It turns out to be much larger than the transverse mass (that in the plane of the layer) of the holes in uniaxially extended Ge ($m_\perp^* \simeq 0.053 m_0$; Ref. 4). In this connection, it is clearly of interest to directly determine the effective mass of the carriers in the Ge layers in strained quantum heterostructures by the cyclotron-resonance method.

In this letter we are reporting a study of the cyclotron resonance of carriers in undoped $Ge/Ge_{1-x}Si_x$ ($x \simeq 0.13$) multilayer heterostructures grown on a substrate of single-crystal Ge:Sb (111), of type GÉS-45 ($\rho_{300K} \simeq 45\ \Omega \cdot cm$). The substrate had a thickness of 0.3 mm. The heterostructure consisted of 243 $Ge/Ge_{1-x}Si_x$ periods, each 500 Å thick; the width of the quantum wells (the Ge layers) was about 180 Å. The

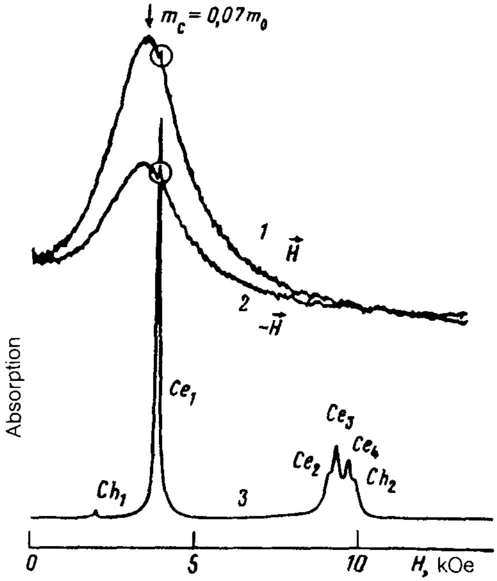

FIG. 1. Cyclotron resonance of photogenerated carriers in multilayer $Ge/Ge_{0.87}Si_{0.13}$ heterostructures (*1*—H‖[111]; *2*—H‖[$\bar{1}\bar{1}\bar{1}$]) and in the GÉS-45 substrate (*3*). $\lambda=2.3$ mm, $T=4.2$ K.

strain was determined by x-ray diffraction; it corresponded to a uniaxial extension of the Ge layers by a stress $P\simeq 6.0$ kbar along the axis of the heterostructure. The cyclotron resonance was studied in the 2-mm wavelength range. The source of the radiation was a G4-161 signal generator, which uses a backward-wave tube. The radiation from this source propagated along a quasioptical line into a cryomagnetic insert in a portable STG-40 helium Dewar. The test sample was in this Dewar, at the center of a superconducting solenoid. The microwave radiation transmitted through the sample was detected by an *n*-InSb photoresistance outside the solenoid. Nonequilibrium carriers were excited by interband illumination from an AL319A gallium arsenide LED ($\lambda \simeq 0.9\ \mu$m) mounted on a wall of the quasioptical line, directly above the test sample. The light from the LED was modulated at a frequency of 1 kHz. A standard lock-in detection system was used to detect the signal representing the absorption of the microwave radiation by the photogenerated carriers. The cyclotron resonance of the carriers was also studied by the method of millimeter-range photoconductivity. In this case the radiation detector was the heterostructure itself, which had two ohmic contacts attached to its surface. We used the same lock-in detection system, but, in contrast with the absorption experiments, the LED was fed a direct current, and the radiation from the G4-161 source was modulated.

Figure 1 shows a cyclotron-resonance spectrum of the carriers in the sample, recorded through modulation of the interband illumination. Spectra *1* and *2* were recorded for opposite directions of the magnetic field. The substantial changes in the magnitude of the signal in these two cases are evidence that the polarization of the electric field of the millimeter-range radiation in the sample was elliptical.[1)] The spectrum is dominated by a broad absorption line peaking at $H\simeq 3.5$ kOe. Against the background of this line we see a small, narrow peak at $H\simeq 3.9$ kOe. The position of this narrow peak coincides with the electron line Ce_1 ($m_c=0.082m_0$) in the cyclotron-resonance spectrum of single-crystal Ge (spectrum 3 in Fig. 1), which was recorded on the same sample, rotated 180° to a substrate-up orientation. The narrow peak in spectra 1 and 2 in Fig. 1 is thus due to the cyclotron resonance of electrons in Ge, in a valley in the magnetic-field direction, (111). The width of this peak corresponds to a pulse relaxation frequency $\nu \simeq 10^{10}$ s^{-1}, which is characteristic of the scattering of photogenerated carriers by acoustic phonons and neutral impurities in moderately doped Ge. It is thus natural to suggest that the narrow peak observed here is due to a cyclotron resonance of electrons in the Ge substrate, in which the electrons are generated by the light from the LED, which is greatly attenuated as it passes through the heterostructure.

It can be seen from Fig. 1 that the intensity of the broad absorption line, peaking at $H \simeq 3.5$ kOe, is higher when the magnetic field is directed in accordance with spectrum 1, while the amplitude of the narrow peak is higher when **H** is in the opposite direction (spectrum 2). Since these measurements were carried out with elliptically polarized, millimeter-range radiation, and this polarization was evidently closer to a circular polarization in the "electron" direction in the second case (the "resonant" situation for the Ce_1 line), and closer to a circular polarization in the "hole" direction in the first case, it can be concluded that the broad absorption line is due to a cyclotron resonance of carriers with a positive charge, i.e., holes. The position of the line corresponds to an effective mass $m_c^* \simeq (0.07–0.075)m_0$, which is quite different from the mass of light holes ($m_{1l} \simeq 0.042m_0$) and also quite different from the mass of heavy holes ($m_{1h} \simeq 0.39m_0$) in undeformed Ge. The width of this line corresponds to a relaxation frequency[2)] $\nu \simeq 3 \times 10^{11}$ s^{-1} [$\mu \simeq 10^5$ cm^2/($V \cdot$s)] and, as is evident in Fig. 1, is noticeably greater than the characteristic linewidths in single-crystal Ge. Putting all these pieces of evidence together, we conclude that the absorption line seen here is due to a cyclotron resonance of holes in the Ge/$Ge_{1-x}Si_x$ heterostructure.

Figure 2 illustrates the observation of the cyclotron-resonance line of holes in the heterostructure in the spectra of the millimeter-range photoconductivity. The absorption of the millimeter-range radiation resulted in an increase in the static conductivity of the sample, apparently because of a decrease in the collision rate as a result of the heating of free carriers. It was found that the hole cyclotron-resonance line which arises in the photoconductivity spectra during interband illumination persists after the illumination is cut off, for several hours, until the sample is warmed up. Furthermore, this line arose a few tens of minutes after the sample was cooled even in the absence of the interband illumination, apparently because of carrier generation by background radiation from the warm part of the cryostat. The residual photoconductivity observed here is evidence of a spatial separation of the holes and electrons in the heterostructure. The latter are apparently trapped by trapping centers of some sort; the same mechanism would explain the absence of electron lines from the cyclotron-resonance spectra.

During uniaxial extension of the Ge, the splitting of the subbands at the $\mathbf{k} = 0$ point amounts to about 4 meV/kbar, so the holes in the test sample ($P \simeq 6.0$ kbar) at liquid-helium temperature fill only the lower subband (corresponding to the heavy-hole subband in undeformed Ge). The effective mass in the plane of the layers, $m_{\parallel} \simeq 0.053m_0$, at the bottom of the band turns out to be much smaller than the mass

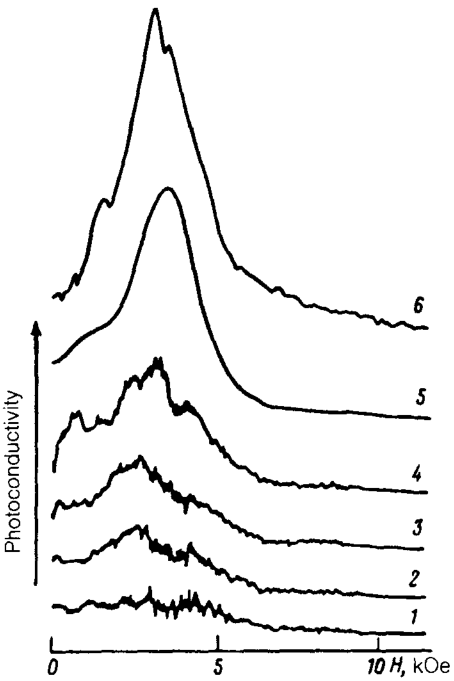

FIG. 2. Millimeter-photoconductivity spectra of a multilayer $Ge/Ge_{0.87}Si_{0.13}$ heterostructure ($\lambda=2.3$ mm, $T=4.2$ K, H||[111]). Curves *1–4*—Recorded in succession over the course of several minutes after the sample was cooled to liquid-helium temperature; *5*—recorded during interband illumination; *6*—recorded after the illumination was turned off.

along the growth axis of the heterostructure,[3)] $m_\perp \simeq 0.49 m_0$. To evaluate the influence of the quantum size effect on the energy spectrum of the holes in the plane of the heterostructure, we can substitute the transverse momentum found from the uncertainty principle into the dispersion relation for uniaxially extended bulk Ge: $p_\perp \simeq \hbar a^{-1}$, where a is the width of a quantum well. The value found for the transverse mass at the bottom of the first quantum-well subband, $m_\perp \simeq 0.08 m_0$, agrees satisfactorily with the value found from the position of the cyclotron-resonance line. A study of the position of the observed cyclotron-resonance line in the heterostructure as a function of the angle (θ) between the magnetic field and the plane of the heterostructure revealed a direct proportionality between $H_{\rm res}$ and $(\cos\theta)^{-1}$. This result cannot, however, be taken as direct proof that the hole gas is two-dimensional, since the large ratio $m_\parallel/m_\perp \simeq 9$ means that approximately the same dependence should be observed in uniaxial extended bulk Ge. Preliminary studies of the hot-hole cyclotron resonance in the heterostructure show that the heating of the carriers by the electric field results in a further increase in the effective mass, to $m_c \simeq 0.1 m_0$, as a result of the very nonparabolic nature of the dispersion relation.

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[1)]The polarization of the electromagnetic radiation was not monitored in this experiment. It was shaped in a random way by rereflections in the quasioptical line.

[2)]This value should be considered an upper limit, since the width of the observed absorption line may also be due to a dispersion of the hole cyclotron frequencies. In order to clarify the contributions of various factors to the broadening of the cyclotron-resonance line, it will be necessary to carry out measurements of this type over a wide frequency range.

[3)] We observed the cyclotron-resonance line of holes with an effective mass $mc \simeq 0.053m0$ in a comparatively thick ($d \simeq 700$ Å) strained epitaxial layer of Ge, grown on a buffer layer of a $Ge_{0.9x}Si_{0.1}$ solid solution, with a thickness of 1.4 μm.

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