RAMAN SCATTERING AND PHOTOLUMINESCENCE STUDIES OF TWO-DIMENSIONAL ELECTRON SYSTEMS IN Ge/GaAs HETEROSTRUCTURES

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Resonant Raman scattering experiments on n-Ge/n-GaAs (100) heterostructures reveal transitions involving quasi-two-dimensional electron states in Ge-accumulation layers. The experiments were performed in the range of the E_1-gap of Ge. The electronic scattering transforms into E_1-luminescence as the laser energy is tuned above the resonance. Spectra obtained at higher excitation energies show luminescence bands associated with the E_1 and $E_1 + \Delta_1$-gap of Ge. The latter results are compared with recent data for bulk heavily-doped Ge.

The Ge/GaAs interface has received considerable theoretical[1-4] and experimental[5-11] attention in the past few years due to a nearly perfect lattice match and the different nature of the band gaps and bonding properties of the two materials. Interest in this heterojunction further stems from the possibility of building quasi-two-dimensional (2D) electron or hole systems associated with space-charge layers in Ge, using selectively-doped Ge/GaAs.[12] Discontinuities in the conduction (ΔE_c) and valence-band (ΔE_v) at the interface (at T=300K, ΔE_c~0.27 eV and ΔE_v~0.46 eV)[11] should lead to a transfer of carriers from the higher-gap GaAs into Ge, where they are expected to form accumulation or inversion layers. Recent photoemission experiments on Ge/GaAs (100), grown by molecular-beam epitaxy (MBE), indicate that defects at the interface do not play an important role in determining barrier heights.[11] The data discussed below and in a previous report[12] are also consistent with low interfacial densities for MBE-grown samples, as a large number of defect states should result in depletion regions at both sides of the junction contradicting our observation of Raman scattering (RS) from 2D-Ge-states.

The electronic properties of Ge space-charge layers have been previously investigated in works on metal-insulator-semiconductor structures, for (111) surfaces.[13] Inter-subband transitions of electrons have been observed using far-infrared absorption techniques.[13] In this communication we report the results of RS and photoluminescence (PL) experiments on n-Ge/n-GaAs (100) heterostructures. Raman spectra obtained under resonant conditions show features ascribed to transitions of electrons in Ge-accumulation layers. Photoluminescence data reveal broad bands associated with the E_1 and E_1+Δ_1-gaps of Ge, as in heavily-doped bulk samples.[14]

The samples used in this work were grown by MBE as indicated elsewhere.[7] They consist of a thin layer of Ge of thickness L (see Table I) on top of a ~1-2 μm (100) GaAs substrate. The Ge layers were unintentionally doped with As, with concentrations in the range 1-2 x 10^{18} cm^{-3}. The GaAs substrates are n-type (Ge-doped) with carrier densities (n) shown in Table I. From Hall measurements, we determine ~1-1.5 x 10^3 cm^2/V-s for the mobilities of the carriers in Ge at T=300K.

Table I: Sample parameters. The thickness of the Ge overlayer (L) and the carrier concentration in GaAs (n) are indicated

Sample	L (Å)	n (cm^{-3})
(1)	430	1.5 x 10^{18}
(2)	300	6.6 x 10^{15}
(3)	720	1.4 x 10^{17}

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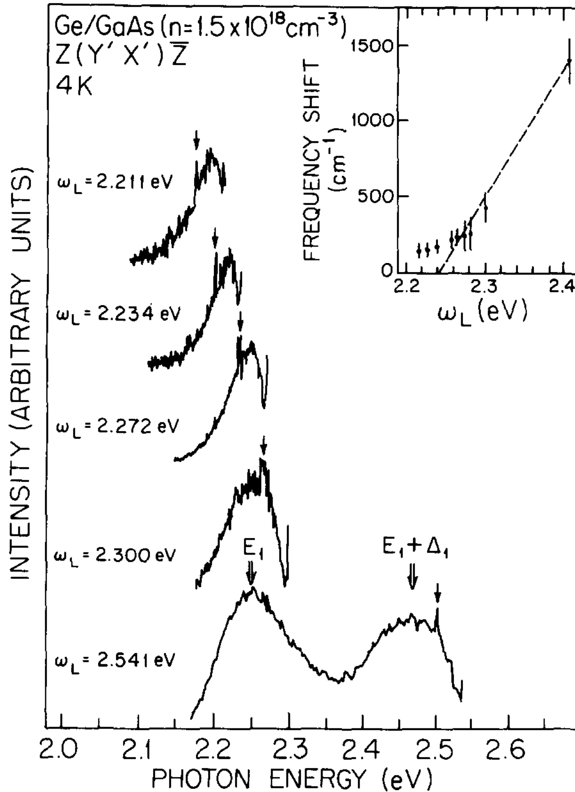

Fig. 1. Spectra of sample (1) for different incident photon energies ω_L. The narrow Raman lines indicated by arrows are due to a 'leak' of the optical mode of Ge, which is forbidden in this geometry. The inset shows the shift of the E_1-luminescence/RS peak as a function of ω_L. The expected shift of the PL is given by the dashed line with unitary slope.

In the RS experiments, separate spectra originating from electrons in Ge and GaAs were obtained by tuning the laser energy ω_L to resonate with particular optical gaps of the corresponding material.[15] Electronic scattering associated with GaAs was observed in resonance with its $E_0+\Delta_0$-gap (at ~1.9 eV), using the 6471Å line of a Kr^+-laser. A Rhodamine 110-dye was used to overlap the range of the E_1-gap of Ge (at ~2.2 eV). Spectra were taken in the backscattering geometry with the polarization of the incident and scattered light along the x'≡[110] or the y'≡[1$\bar{1}$0] crystal axis. The PL data were obtained by using several lines of an Ar^+-laser as excitation sources.

For ω_L in resonance with the GaAs gap, the Raman spectra are essentially a superposition of those of bulk GaAs and Ge.[12] Sample (2) shows the longitudinal-optical (LO) phonon of GaAs and the optical mode of Ge in the z (x',x')$\bar{z}$ configuration. Single-particle excitations of the free carriers in the GaAs layer appear in the z(y',x')$\bar{z}$ spectra of samples (1) and (3); while the z(x',x')$\bar{z}$ geometry shows the Ge-phonon and coupled LO-plasma modes of GaAs.[15] Off the $E_0+\Delta_0$-resonance, the spectra did not exhibit features which might have been attributed to phonons or electronic excitations in GaAs. We believe that this is due to the strong attenuation of the GaAs signal caused by absorption in the Ge overlayer (the penetration depth for photons in Ge is ~1600Å at ω_L~$E_0+\Delta_0$, and ~370Å near E_1).[16]

Figure 1 shows z(y',x')$\bar{z}$ spectra of sample (1) near the E_1-resonance of Ge (four top traces), and at ω_L=2.541 eV. The broad bands in the bottom spectrum are due to PL associated with the E_1-gap and the spin-orbit-split $E_1+\Delta_1$-gap of Ge. Similar data were recently reported for bulk, heavily-doped n-Ge.[14] Undoped and p-type samples were found to exhibit no such luminescence.[14] Accordingly, we consider the observation of these bands in our samples to be an indication of the presence of free electrons in the Ge-layer. Effects due to carrier confinement are not apparent in the PL data in regard to the position and lineshape of the peaks. The intensity of the luminescence, however, appears to be much larger than what one could have expected for the relatively low bulk densities of our samples (see Ref. 14).

In the range $E_1<\omega_L<E_1+\Delta_1$, the spectra of sample (1) show E_1-luminescence. As ω_L approaches the maximum of the PL-peak from above, the band narrows and shifts to lower energies, and finally becomes a Raman feature at a shift of ~150 cm^{-1} (see Fig. 1). The position of the maximum of the PL/RS structure as a function of ω_L is shown in the inset of Fig. 1. Because of the large width of the bands, we were unable to discriminate between an actual PL→RS transformation taking place (as seen in other cases)[17] and the possibility of having a relatively narrower Raman-line undergoing resonant enhancement on top of the PL. The previously reported[12] ω_L-dependence of the scattering intensity at a constant frequency shift seems to support the latter interpretation.

The behavior of z(x',x')$\bar{z}$ spectra is qualitatively similar to that of z(y',x')$\bar{z}$. For ω_L~E_1, however, differences in the position and lineshape of the peaks in the two configurations were noticeable. This is shown in Fig. 2 for an excitation energy in the region of RS behavior.

A clearly identifiable PL→RS transition was not observed in sample (2). This sample shows PL-structures analogous to those in Fig. 1, but weaker by a factor of ~10. The E_1-luminescence in sample (2) could be followed down to ω_L~2.28 eV; below this value it became too weak to be detected.

Spectra of sample (3) for different ω_L's are shown in Fig. 3. The spectrum at ω_L=2.541 eV differs from the corresponding data on sample (1) in regard to the positions of the maxima. This difference may be accounted for by the presence in sample (3) of a broad structure behaving as a Raman feature (at a shift of ~0.2 eV), clearly shown in the trace for ω_L=2.345 eV. An alternative explanation involves shifts of the PL-peaks due to different sample quality. As for sample (1), we observe a somewhat broader and weaker Raman band at ~350 cm^{-1} when $\omega_L \lesssim E_1$ (see top spectrum in Fig. 3). This band was found roughly at the same position in the two configurations. The transformation from RS to PL is not very well defined. The strongest

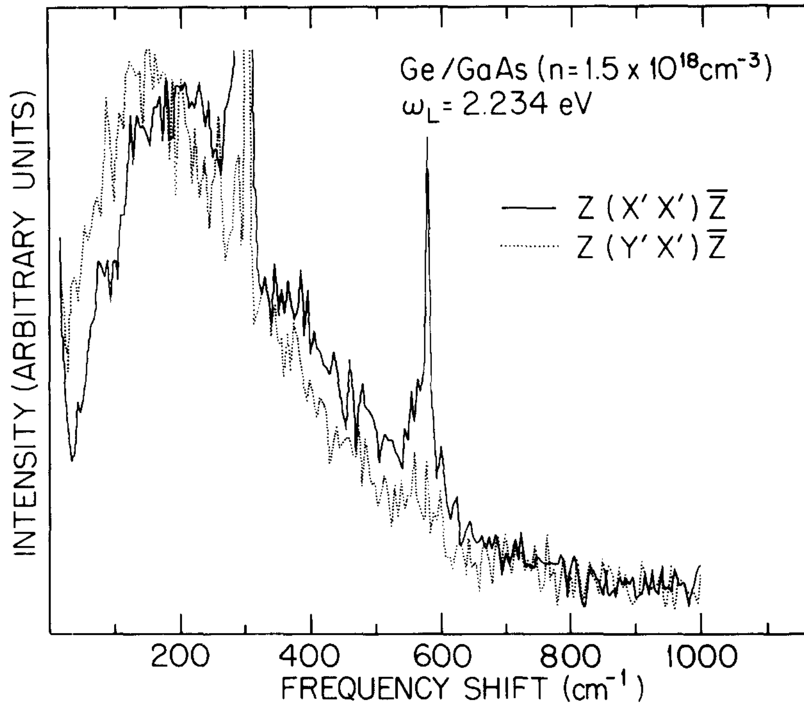

Fig. 2. Raman spectra of sample (1) at T=4K showing different positions of the maxima in the two configurations. The narrow features at ~305 and ~578 cm^{-1} correspond, respectively, to the optical mode of Ge and second-order phonon scattering.

feature in the spectra shows a behavior intermediate between RS and PL up to ω_L~2.4 eV.

The ω_L-dependence of the Raman peaks at ~150 cm^{-1} and ~350 cm^{-1} in samples (1) and (3) identifies the scattering as associated with the Ge layer (see also Ref. 12). The position and lineshape of the lines further point to the electronic origin of the scattering, as they do not correspond to any known feature of vibrational-RS in Ge.[18] A question arises as to the 2D-or 3D-nature of the carriers. The 3D case implies an assignment in terms of single-particle excitations[19] considering that plasmon scattering, as recently observed in n-type Ge,[20] is forbidden in the $z(y',x')\bar{z}$ configuration. Such an interpretation, however, is inconsistent with the bulk carrier densities of the samples corresponding to qV_F~100 cm^{-1} (q is the magnitude of an effective wave vector transfer and V_F an average Fermi velocity).[21] This value is considerably lower than the positions of the lines. Moreover, for our low-mobility samples, the single-particle spectrum is not expected to exhibit peaks but tails, as for intervalley-density fluctuations in n-type Si.[22]

The considerations above, and also the absence of an analogous feature in the spectra of sample (2), suggest that the Raman peaks found in samples (1) and (3) are associated with excitations of 2D electron systems in the Ge-layers. The fact that the lines occur only in samples for which the GaAs layer is heavily n-type (see Table I) is an indication that the electrons involved in the scattering have transferred from GaAs. As previously discussed, such a transfer of charge with the consequent formation of accumulation layers at the Ge side of the interface is expected in our samples. Accordingly, we ascribe the 150 cm^{-1}-and 350 cm^{-1}-peak to excitations associated with Ge-accumulation layers. A crude estimate of the amount of charge transferred into Ge is given by $\lambda_{FT}N_D$, where λ_{FT} is the Fermi-Thomas screening length of the carriers and N_D the donor concentration in GaAs. This indicates that the interface carrier density for samples (1) and (3) should be a factor of ~10^2 and ~15 larger than the corresponding density in sample (2). We believe that this is the reason why sample (2) does not show evidence of electronic scattering.

According to the known mechanisms of scattering and similar data obtained in other semiconductor structures,[15] the $z(x',x')\bar{z}$ and $z(y',x')\bar{z}$ spectra are assigned to charge-density and spin-density fluctuations of the 2D-system. In the backscattering geometry, the motion probed is along the direction perpendicular to the layers, i.e., the Raman lines correspond to intersubband (or possibly 2D→3D-band)[12] transitions. The bare transition energy can be determined from $z(y',x')\bar{z}$ spectra, as spin-density fluctuations are unscreened.[15] A shift of the intersubband-peak to higher energies is expected in $z(x',x')\bar{z}$ due to depolarization field effects increasing with the magnitude of the interfacial charge density.[15]

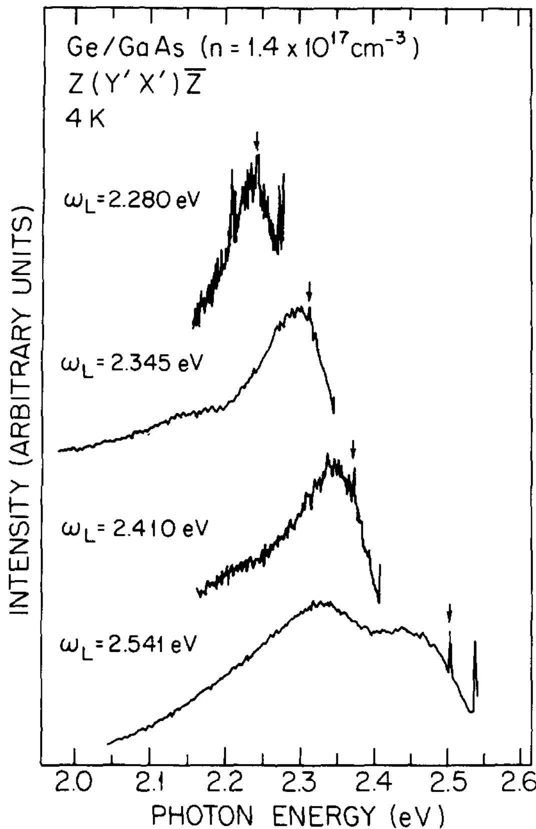

Fig. 3. Spectra of sample (3) for different excitation energies ω_L. The arrows denote the 'leak' of the Raman line associated with the optical phonon of Ge.

This is consistent with our data showing almost no shift for sample (3), but a clear shift in the right direction for sample (1) (see Fig. 2).

The origin of the ~0.2 eV Raman band in the spectra of Fig. (3) is not clear. Possibilities are that it is due to layering-induced transitions between subbands derived from the L-point and higher conduction-states in Ge, or excitations into the continuum of states above the barrier at the interface. Sample (1), however, does not show any related feature. This suggests that the 0.2 eV-structure may be the result of a lower sample quality leading to wave vector non-conservation.

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