Infrared and Raman Spectroscopies of Plasmon Anisotropy in Heavily Doped GaAs/AlAs Superlattices

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We present infrared and Raman studies of the plasmon-LO phonon vibrational modes in heavily doped GaAs/AlAs superlattices. The experimental results reveal the dispersions of electrons normal and parallel to the layers which was found in good agreement with the miniband dispersions calculated in the envelope function approximation when both Γ and X conduction electron states were taken into account. We did not find any evidence of the contribution of the 2D electron states to the vertical transport.

Owing to the different periodicity in directions parallel and normal to the layers, the semiconductor superlattices (SL's) reveal properties of an anisotropic crystal with the axis normal to the plane of layers. The behavior of electrons in isolated quantum wells presents properties similar to those of the optical phonons - free propagation parallel to the layers and confinement in normal direction. With decrease of the barrier thickness, the electron wavefunctions in neighboring quantum wells become overlapping and the subband structure caused by the periodicity of a SL is formed. Now electrons can move through an entire SL like free particles with a new effective mass determined by the dispersion of a partially filled miniband.

Our interest in this paper is focused on the intrasubband plasmon in a partially filled miniband. We present the infrared and Raman study of the plasmon-LO phonon vibrational modes polarized normal and parallel to the layers in the GaAs/AlAs SL 's doped with Si donors. Two types of SL's were studied - those with thin barriers, penetrating for electrons and those with quantum wells isolated by thick enough barriers. The first type was realized with $(GaAs)_{17}(AlAs)_2$ SL's; as a second type $(GaAs)_5(AlAs)_5$ SL's were studied. According to the miniband calculations the lowest miniband in the (17,2) SL is formed by the Γ conduction band electron states, while in the (5,5) SL - by the longitudinal X_L valleys of GaAs and AlAs. In order to study the role of different electron states in the formation of a miniband structure we compared the frequencies of miniband plasmons measured in the samples with different electron densities with the ones computed using the envelope-function approximation when the direct $\Gamma-\Gamma$ and X-X and pseudodirect Γ-X electron transfers were taken into account.

The p-polarized reflection spectra of samples studied here are presented in Fig.1. The p-polarized infrared spectra reveal the lines originated from both transverse and longitudinal optical vibrational modes. Moreover, according to the Berreman effect, in this case only the longitudinal modes with an electric polarization parallel to the SL axis (z direction normal to the layers) are active. Thus we labeled the corresponding phonon lines observed in the reflection spectra as TO_x and LO_z modes. The fitting of the reflection spectra gave us the possibility to find the oscillator strengths of the observed optical modes and through them to obtain the values of the frequencies of the interface modes TO_z and LO_x. The calculated reflection spectra are shown in Fig.1 by broken lines.

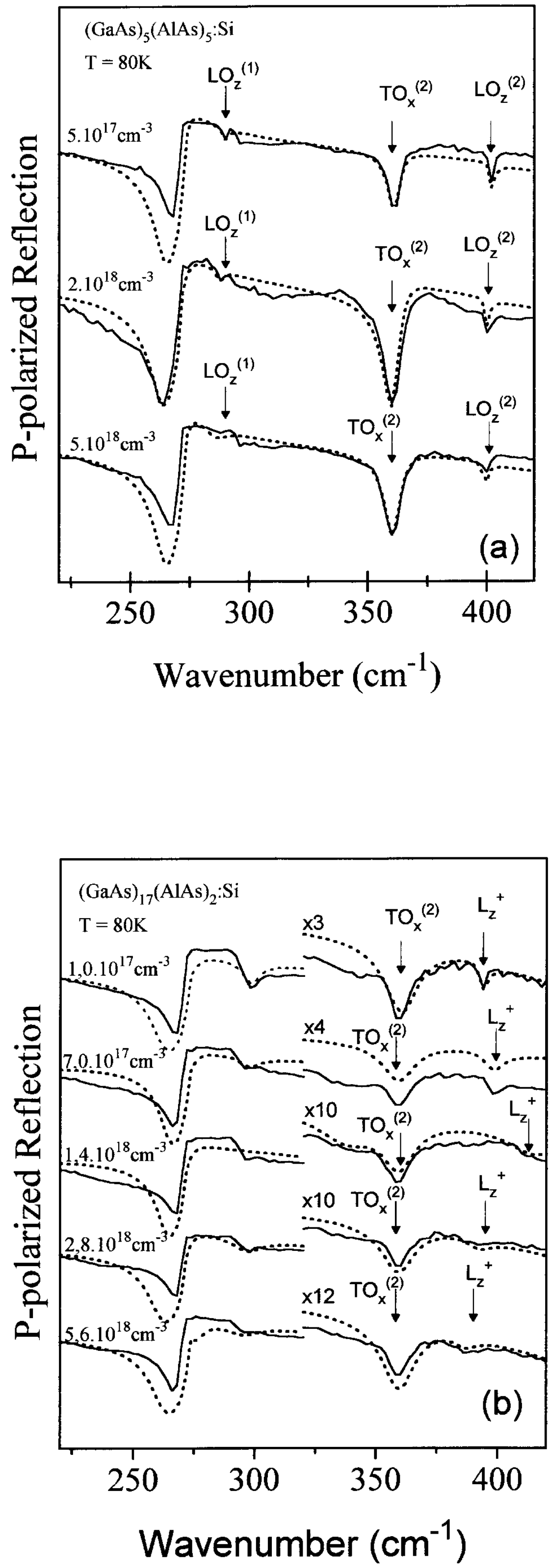

Figure 1. The p-polarized reflection spectra of the doped (GaAs)$_5$(AlAs)$_5$ superlattice (a) and of the doped (GaAs)$_{17}$(AlAs)$_2$ superlattice (b) measured at the temperature T=80 K. Dotted lines are the calculated spectra.

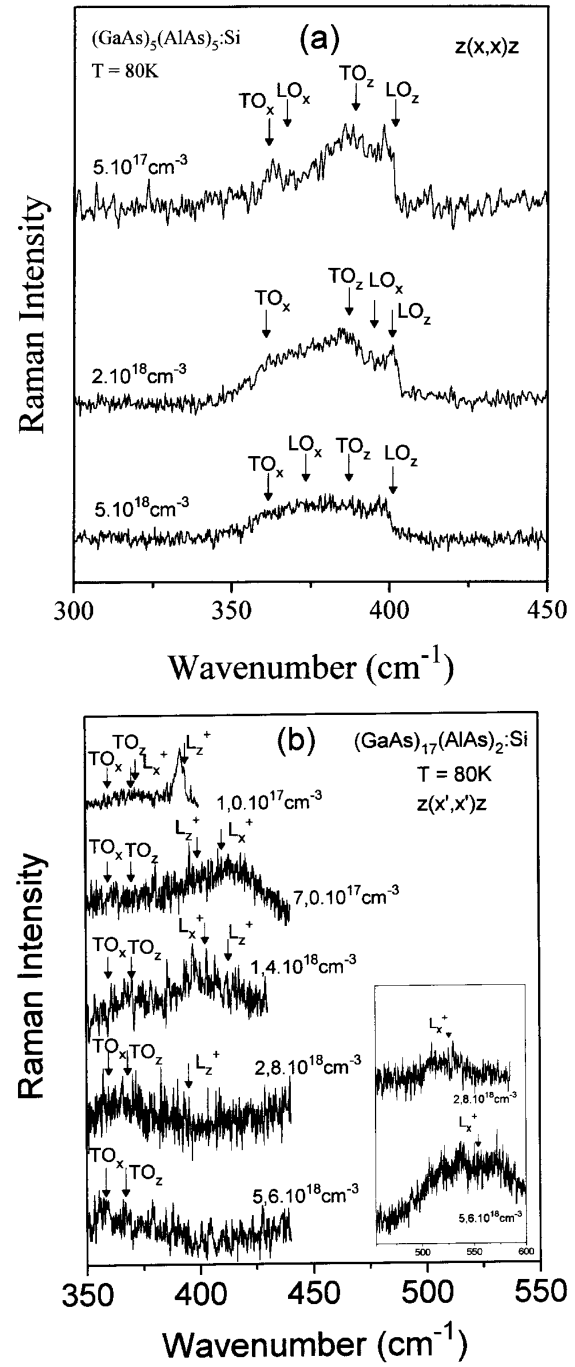

Figure 2. The Raman spectra of the doped (GaAs)$_5$(AlAs)$_5$ superlattice (a) and of the doped (GaAs)$_{17}$(AlAs)$_2$ superlattice (b) measured at the temperature T=80 K in the frequency range of the AlAs-like phonons; the spectra obtained with $x||[100]$ and $x'||[110]$ are presented in (b). The arrows indicate the frequencies of the optical modes obtained by reflection spectra.

In order to avoid any influence of the substrate we analyzed the AlAs-like vibrational modes. All the characteristic frequencies of the AlAs-like optical vibrational modes found by the reflection spectra are depicted by arrows in the Raman spectra of the corresponding samples shown in Fig. 2.

The positions of the lines in the Raman spectra corresponding to the transverse (confined and interface) optical modes were in good agreement with the frequencies obtained from the reflection spectra. The frequencies of the longitudinal vibrational modes in the $(GaAs)_5(AlAs)_5$ SL's with a dielectric behavior measured by FTIR and Raman are in good agreement as well. We did not find in these samples any shift neither of the confined LO_z modes nor the interface LO_x ones, which can be caused by their coupling with electrons. This happens because at any available doping the vertical motion of electrons is forbidden, while the acoustic-like behavior of the 2D plasmon (ω_{px}) in isolated quantum wells of the $(GaAs)_5(AlAs)_5$ SL's did not allow us to measure a significant shift of the interface LO_x modes.

A completely different behavior of the longitudinal modes has been found in the doped $(GaAs)_{17}(AlAs)_2$ SL's where the miniband structure should be formed because of the thin barriers. The different filling of the lowest Γ miniband causes a different shift of the longitudinal AlAs-like mode, labeled as L_z^+ coupled plasmon-LO phonon mode, which was clearly observed in the reflection spectra (Fig.1b). In the sample with the highest electron concentration ($n = 5.6 \cdot 10^{18}$ cm^{-3}) the position of the L^+ mode actually corresponds to the frequency of the first LO_{z1} confined AlAs-like mode in a nondoped sample. This is because at such an electron density the lowest Γ miniband is completely filled and electrons cannot move parallel to the SL-axis and, consequently, they cannot couple with the LO_z phonons. In such a case the SL reveals a dielectric character even at so high doping level.

The Raman spectra of the doped $(GaAs)_{17}(AlAs)_2$ SL's revealed a larger shift of the AlAslike longitudinal mode due to the plasmon-LO phonon coupling than it was observed in the infrared spectra. Only in the sample with the lowest concentration of electrons ($n = 1 \cdot 10^{17}$ cm^{-3}) we detected a line corresponding to the optical longitudinal vibration, which was in good agreement with the frequency of the L_z^+ mode measured by FTIR. In the other SL's we did not observe neither a tendency of the decrease of the plasma frequency with increasing electron density, nor the dielectric behavior as it was found in the infrared spectra. Due to these reasons we conclude that in the samples with high electron concentrations the plasmon with an in-plane electric polarization contributes to the Raman spectra. In this case, the larger shift of the plasmon-LO phonon mode relates to the higher frequency of the ω_{px} plasmon, comparatively to the ω_{pz} plasmon in the same sample; this is due to the smaller value of the mr electron effective mass with respect to the m_z one.

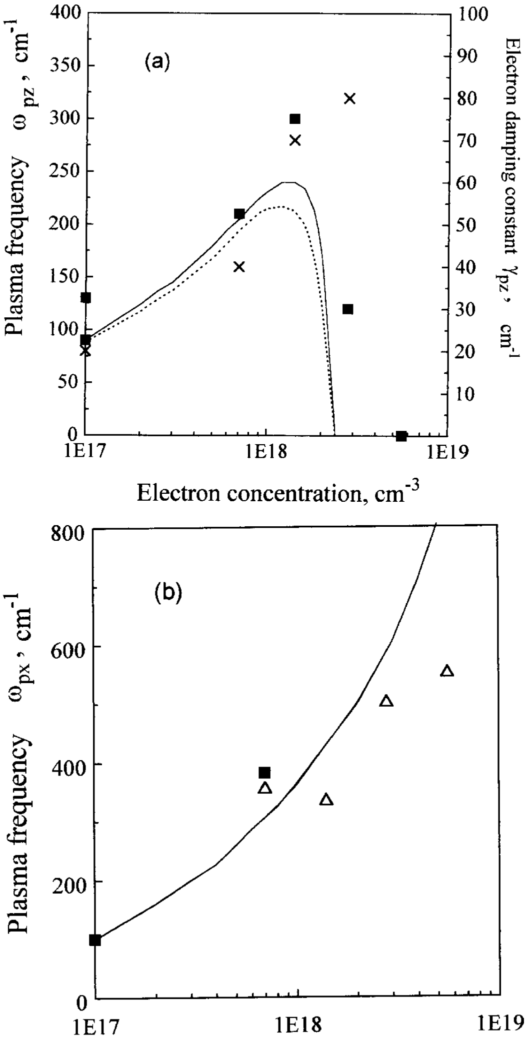

Figure 3. Dependence of the superlattice plasmon (ω_{pz}) (a) and the in-plane plasmon (ω_{px}) (b) on an electron concentration in the $(GaAs)_{17}(AlAs)_2$ superlattice. Crosses show the values of the electron damping constant (γ_{pz}); the squares and triangles in (b) relate to the in-plane electric polarization of the incoming light parallel to the [100] and [110] respectively.

The frequency dependencies of the ω_{px} and ω_{pz} plasmons on the electron density obtained from the Raman and reflection spectra respectively of the doped $(GaAs)_{17}(AlAs)_2$ SL's are shown in Fig.3. The dependence of the superlattice plasmon ω_{pz} on the electron density directly relates to the miniband dispersion. The $\omega_{pz}(n)$ curves calculated in the envelope-function approximation are depicted by full and broken lines. The full line corresponds to the nominal compositional profile of the $(GaAs)_{17}(AlAs)_2$ SL with a rectangular potential while the broken line was calculated for the broad $Al_{0.5}Ga_{0.5}As$ barrier with the thickness of 4 monolayers. Such an alteration of the compositional profile is expected due to the smoothing of the interfaces which has been already studied in two-monolayer wide AlAs barriers in [1]. As it turned out, this broadening of the AlAs barrier is almost completely compensated by the decrease of its height and an electron effective mass, giving the same miniband dispersion as in the nominal barrier, which explains our experimental results quite well. The values of the electron damping constant pz obtained from the fitting of the reflection spectra are also plotted in Fig.3a.

As it has been established theoretically in [2], when the Fermi level is located in the minigap between two minibands, 2D electron states should contribute to the vertical transport (along the superlattice axis) giving rise to the conductivity. Hence, the nonzero vertical conductivity, and as a consequence the nonzero plasma frequency ω_{pz}, are expected even in the SL's with completely filled minibands. As it follows from Fig.3a, our experiments do not present any evidence of such contributions due to the 2D electrons.

The frequency of the in-plane plasmon w_{pl} versus the electron density is shown in Fig.3b. The full line was calculated with an effective mass at the bottom of the 2D Γ subband equal to $m_x = 0.067 m_0$.Thus, the dependencies of the ω_{pz} and ω_{px} plasmons on the electron density, which directly reflect the miniband dispersions of the electrons normal and parallel to the layers respectively, were found in reasonable agreements with the miniband calculations.

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