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A study of the vertical transport of electrons in $(GaAs)_n(AlAs)_m$ superlattices by Fourier transform infrared spectroscopy

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Abstract. The longitudinal optical vibrational modes have been studied in $(GaAs)_n(AlAs)_m$ superlattices by means of FTIR spectroscopy. In the undoped samples, confined LO phonons have been observed; the dispersion of LO phonons obtained by FTIR spectroscopy was in good agreement with the Raman data. In the doped $(GaAs)_n(AlAs)_m$ superlattices, coupling of confined vibrational LO modes with superlattice plasmons has been found. Analysis of the experimental results showed that the frequency of superlattice plasmons in the superlattices studied is mostly determined by the population of the miniband formed by the Γ-like conduction band states. The fitting of the calculated reflection spectra to the experimental spectra allowed us to measure the population of the minibands, the effective mass and the vertical mobility of electrons.

1. Introduction

Since the first discussion of the new properties of electrons moving normal to the layers in a semiconductor superlattice (SL) by Keldysh [1] and Esaki and Tsu [2], only a few studies have demonstrated vertical electron motion through a Bloch-type miniband state [3,4]. In these papers, the drift of carriers under an electric field has been studied; the results presented no evidence for the formation on the miniband structure by X-like electron states and were explained in terms of Γ-like states associated with the Γ conduction band edges of GaAs and AlAs. However, a photoreflectance and photoluminescence study of the short-period $(GaAs)_n(AlAs)_m$ SLs revealed weak structures that arise because of the pseudo-direct transitions caused by the X_z-like states associated with the X_z conduction band minima of AlAs [5].

In the present paper for the first time the vertical transport of carriers has been investigated in doped $(GaAs)_n(AlAs)_m$ SLs (where n and m are the number of monolayers in the GaAs and AlAs layers, respectively) by means of Fourier transform infrared (FTIR) spectroscopy without application of an external electric field.

In recent years, FTIR spectroscopy has been intensively used to investigate the vibrational spectrum of SLs including the effect of quantization of optical phonons [6–9]. It was found that a study of the transverse optical (TO) and longitudinal optical (LO) vibrational modes as well as measurement of their oscillator strengths is possible in SLs by this method; the latter is not possible using Raman spectroscopy.

The use of FTIR spectroscopy with off-normal incidence of the light presents the possibility of studying LO confined phonons in SLs and coupling of these phonons with collective electron excitations, i.e. plasmons that occur in doped SLs. At the appropriate

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electric polarization of LO confined phonons (normal to the layers), their coupling with the SL plasmons can be studied. Such a coupling should occur in the case of a partly filled miniband when the excitation of SL plasmons is possible. This case may be quite easy realized in a SL with sufficiently thin barriers. In the case of a SL with thick barriers (isolated quantum wells), electrons are strongly localized in wells and do not couple with LO phonons polarized normal to the layers.

The electron–phonon coupling in a SL leads to the appearance of new coupled SL plasmons, i.e. LO confined phonon vibrational modes [7]. We measured the frequencies of these coupled modes which depend strongly on the value of the frequency ω_{pz} of SL plasmons in order to obtain the values of ω_{pz} for doped SLs. Such an analysis of the vibrational spectrum of plasmon–phonon excitations in a doped SL makes it possible to measure the density of electrons in minibands and mobilities normal to the layers.

2. Calculation procedures

The infrared spectra of a SL which reveal the optical properties of an anisotropic crystal with the axis normal to the planes of layers can be analysed by means of the dielectric response function tensor

$$\epsilon_{SL}(\omega) = \begin{vmatrix} \epsilon_x(\omega) & 0 & 0 \\ 0 & \epsilon_y(\omega) & 0 \\ 0 & 0 & \epsilon_z(\omega) \end{vmatrix} \tag{1}$$

where the SL axis is taken along the z direction.

In a short-period SL when the effect of quantization of optical phonons is responsible for the vibrational spectrum of the SL the components of the tensor (1) should be taken from the microscopic theory [10]:

$$\epsilon_x(\omega) = \epsilon_y(\omega) = \epsilon_{\infty x}\left(1 - \sum_{\lambda,\mu} \frac{R_{T\mu}^{(\lambda)}}{\omega^2 - \omega_{T\mu}^{(\lambda)2} + i\Gamma_{x\mu}^{(\lambda)}\omega}\right) \tag{2}$$

$$\epsilon_z^{-1}(\omega) = \epsilon_{\infty z}^{-1}\left(1 + \sum_{\lambda,\mu} \frac{R_{L\mu}^{(\lambda)}}{\omega^2 - \omega_{L\mu}^{(\lambda)2} + i\Gamma_{z\mu}^{(\lambda)}\omega}\right) \tag{3}$$

where $\omega_{T\mu}^{(\lambda)}$ and $\omega_{L\mu}^{(\lambda)}$ are the frequencies of the confined TO and LO phonons in layer λ ($\lambda = 1$ for GaAs and $\lambda = 2$ for AlAs), μ is the index of the mode, $R_{T\mu}^{(\lambda)}$ and $R_{L\mu}^{(\lambda)}$ are their oscillator strengths, $\epsilon_{\infty x}$ and $\epsilon_{\infty z}$ are the principal components of the high-frequency dielectric function, and $\Gamma_{x\mu}^{(\lambda)}$ and $\Gamma_{z\mu}^{(\lambda)}$ are the damping constants for the corresponding modes.

In the case of high transparency of barriers the collective plasma vibrations of electrons in a partly filled miniband along the z axis can be taken into account in a quite straightforward manner by adding the term $-\omega_{pz}^2/(\omega^2 + i\gamma_p\omega)$ to (3) with the SL plasmon frequency $\omega_{pz} = (4\pi e^2 n/\epsilon_{\infty z} m_z)^{1/2}$ and its damping γ_{pz}, where n and m_z are the concentration and effective mass of free electrons in the miniband.

The reflection spectra of samples under investigation have been calculated by means of the dielectric function tensor (1) and the formulae for the reflection of an anisotropic film on an isotropic substrate given in [11]. The ratio n/m_z was obtained from fitting the calculated reflection spectra to the experimental spectra. Then the ratio determined in this way was compared with the same ratio calculated from the energy spectrum of the SL.

The miniband structure of the SLs has been computed using the envelope-function approximation when the boundary condition takes into account the difference between the effective masses in the well and in the barrier [12]. The effect of non-parabolicity was included in the dispersion relation following the Kane relation

$$\hbar^2k^2/2m = E(1 + E/E_g).$$

The effective mass which determines the plasma vibrations of electrons in the miniband was computed via the formula

$$m_z = \hbar^2 k/(\mathrm{d}E/\mathrm{d}k). \tag{4}$$

As it turned out, the minibands which can be filled by available doping in the SLs studied in this work can be formed by the Γ-like or X-like conduction band states of GaAs and AlAs. The influence of L valleys was neglected as they have a much higher energy.

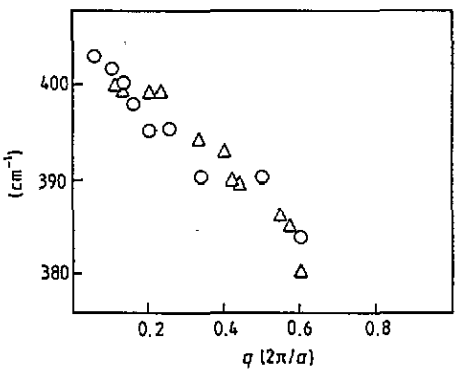

Figure 1. The dispersion of AlAs LO phonons measured at $T = 300$ K by infrared reflection spectra in the present work (○) and by Raman scattering (△) after [17].

In the following way we considered the minibands which arise owing to the Γ–Γ, X–X and Γ–X electron transfer (here the first Γ or X is associated with the GaAs, and the second with the AlAs). The Γ–Γ and X–X processes are direct electron transfers while the Γ–X process may occur either through a transverse X_T valley (indirect transfer) or through a longitudinal valley X_L (pseudo-direct transfer). We did not consider indirect electron transfer because this needs a large value of electron impulse transfer that must lead to disappearance of the miniband structure. In the case of pseudo-direct transfer the electron energy spectrum of the SL has been calculated using the treatment presented in [13], where the electron wavevector in the barrier is given by the complex value of $k_2 = k_{2r} + ik_{2i}$, where the real part k_{2r} is determined by the location of X_L minima (in the case of a SL axis parallel to the [100] direction, $k_{2r} = 2\pi/5.653$ Å^{-1}).

All the parameters of GaAs and AlAs used in the calculation were taken from [14]; the values of conduction band discontinuity for X valleys were taken from [15].

3. Experimental details

The samples under investigation were grown by molecular beam epitaxy on doped (001) GaAs:Si substrates which caused an increase in the intensity of reflection as a result of the vibrational modes of the SL and eliminated interference due to the total thickness of sample.

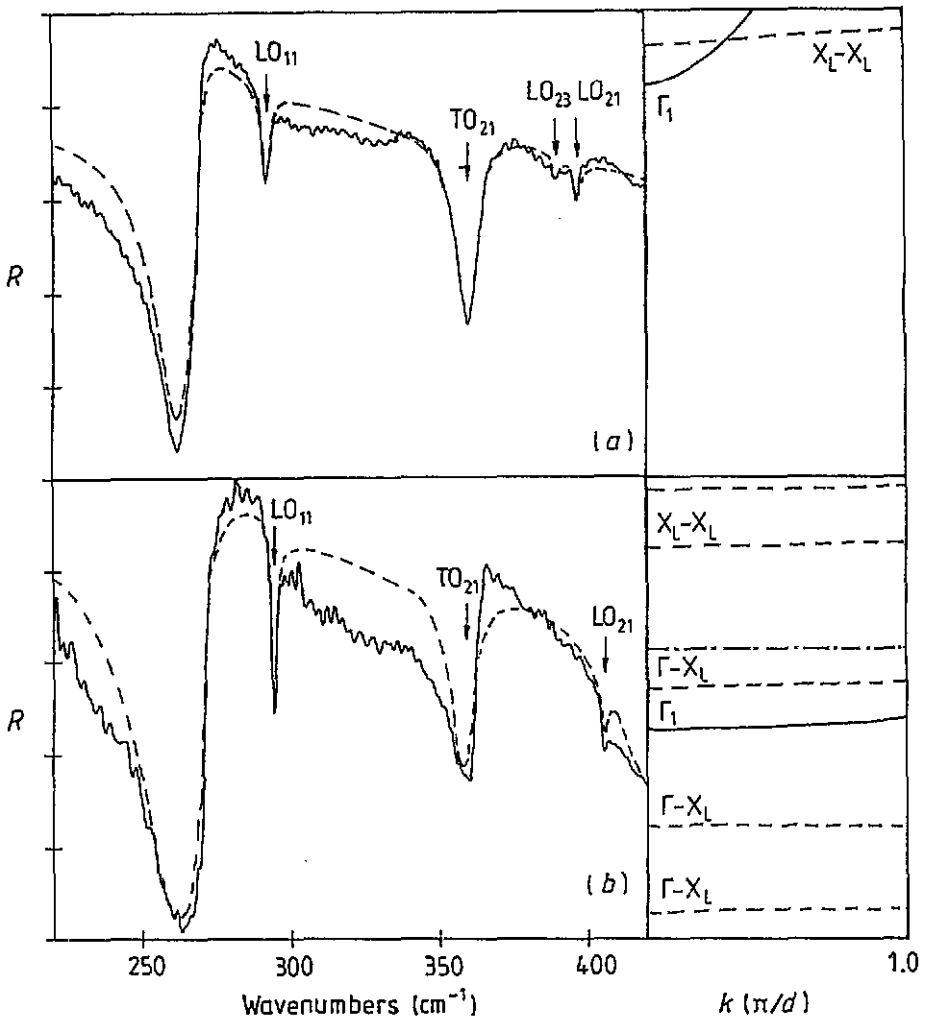

Figure 2. The reflection spectra measured at $T = 80$ K with p-polarized light for two samples: (*a*) undoped $(GaAs)_8(AlAs)_3$ and (*b*) doped $(GaAs)_{17}(AlAs)_{17}$ with $N = 5 \times 10^{17}$ cm^{-3}. The broken curves are the calculated spectra. The right-hand panels show the computed electron energy spectra in the corresponding SL (the full curves are the minibands formed by Γ-like states). The top of these panels corresponds to an energy of 0.25 eV. The chain lines denote the Fermi energy in the Γ–Γ miniband structure.

The doping of the SLs was achieved with Si donors. The p- and s-polarized reflection spectra were recorded using a Bruker IFS–113V Fourier transform spectrometer equipped with an Oxford Instruments cryostat.

Owing to the Berreman [16] effect at off-normal incidence, the resonance interaction of light with optical vibrational modes of layered structures such as a SL occurs at the frequencies of both TO and LO phonons. In p-polarized spectra, the TO and LO phonons are revealed while, in s-polarized spectra, only TO modes can be observed.

Initially we studied the LO vibrational modes in the undoped samples with different thicknesses of layers. This made it possible to measure the dispersion of LO phonons in the $(GaAs)_n(AlAs)_m$ SLs; the results for AlAs are displayed in figure 1 together with the data

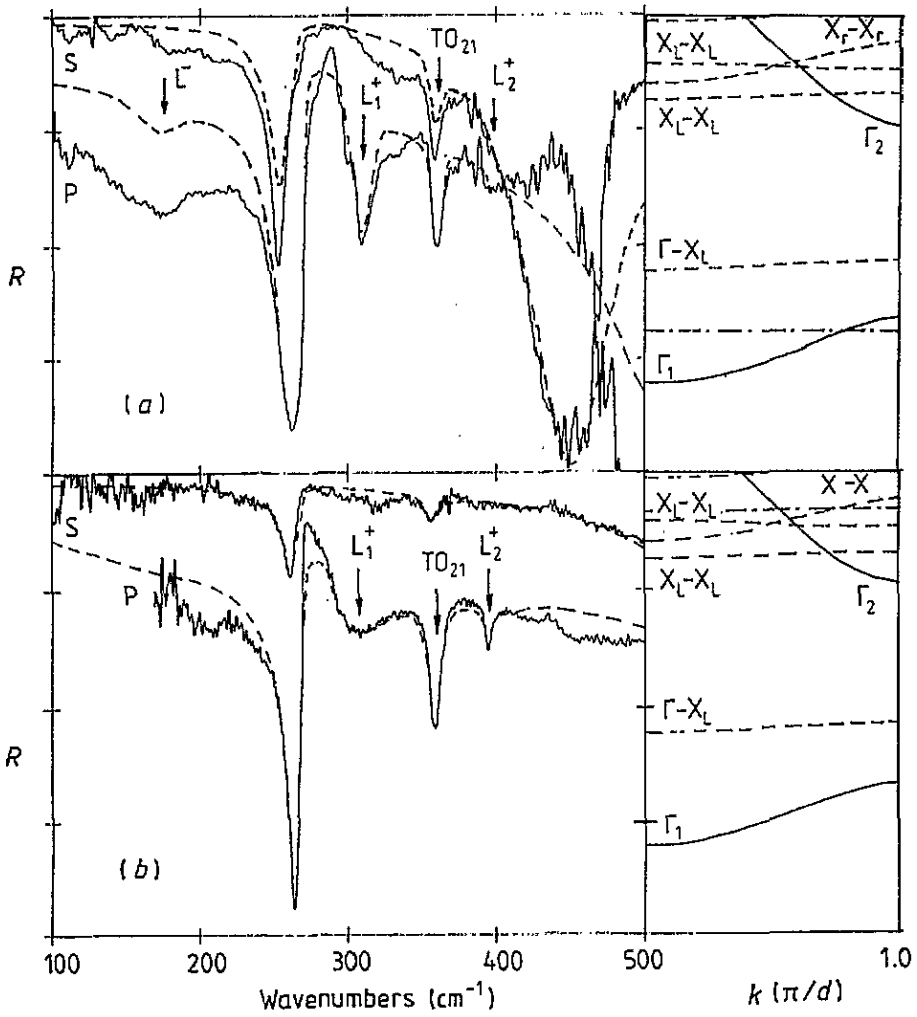

Figure 3. The reflection spectra measured at $T = 80$ K at s- and p-polarized light for two doped samples $(GaAs)_{25}(AlAs)_2$ with (*a*) $N = 4 \times 10^{17}$ cm^{-3} and (*b*) $N = 5 \times 10^{18}$ cm^{-3}. The right-hand panels are the same as in figure 2 with a top energy of 0.25 eV.

obtained by Raman scattering [17]. The comparison shows good agreement between the data obtained by FTIR spectroscopy and those from Raman scattering. In the following we used these results to determine the frequencies of LO modes confined in the layers of doped SLs.

4. Results and discussion

The reflection spectra of some of the samples studied are shown in figures 2 and 3. The right-hand panels display the computed electron energy spectra. The p-polarized reflection spectrum of undoped SLs (figure 2(*a*)) reveals the lines caused by the $LO_{\lambda\mu}$ and $TO_{\lambda\mu}$ vibrational modes confined in both layers.

Table 1. The parameters of doped $(GaAs)_n(AlAs)_m$ superlattices.

	Experimental results				Calculated with Γ–Γ transfer			
Sample	N (cm^{-3})	ω_{pz} (cm^{-1})	γ_{pz} (cm^{-1})	nm_0/m_z (cm^{-3})	E_F (eV)	nm_0/m_z (cm^{-3})	m_z/m_0	μ_z ($cm^2\ V^{-1}\ s^{-1}$)
$(GaAs)_{25}(AlAs)_2$	5×10^{18}	200	150	4.4×10^{18}	0.23	6.2×10^{18}	0.053	1.2×10^3
$(GaAs)_{25}(AlAs)_2$	4×10^{17}	200	30	4.4×10^{18}	0.07	1.5×10^{18}	0.24	1.3×10^3
$(GaAs)_5(AlAs)_5$	2×10^{18}	230	50	5.8×10^{18}	0.42	4.8×10^{18}	0.49	3.8×10^2
$(GaAs)_5(AlAs)_5$	1×10^{17}	100	1.5	1.1×10^{18}	0.36	5.7×10^{17}	0.28	2.2×10^4

The reflection spectra of doped SLs are plotted in figure 2(*b*) and figure 3. The fundamental confined longitudinal modes LO_{11} and LO_{21} have been observed in the sample with thick barriers ($m = 17$). As follows from the calculated electron spectrum of this sample the electrons are located in completely filled narrow minibands and thus cannot couple with LO modes polarized in the z direction.

It should be mentioned that the intersubband splitting in all SLs studied here was much larger than the frequencies of phonon vibrations and therefore the coupling of LO phonons with the collective intersubband electron excitations can be neglected

The reflection spectra of doped SLs with thin barriers are displayed in figure 3. The spectrum with a low density of electrons presents all three coupled plasmon–phonon modes: one low-frequency L^- mode and two high-frequency L_1^+ and L_2^+ modes originating from GaAs and AlAs layers, respectively. In a heavily doped sample, only two broad high-frequency L^+ modes were found.

The total concentration of electrons in the sample was used to determine the Fermi energy and thus the effective mass m_z of electrons in the relevant miniband. Finally the vertical mobility μ_z of carriers in the SLs studied was calculated using this effective mass and the damping γ_{pz} of plasmons. It turned out that the best agreement between the measured and calculated ratios n/m_z was obtained in the case when only Γ–Γ electron transfer was taken into account. If other types of electron transfer were taken into account, the discrepancy with experiment was much larger.

The parameters of the doped SLs studied that were obtained in this way are collected in table 1.

Thus in this paper we found that the frequency ω_{pz} of SL plasmons and as a consequence the vertical mobility of electrons in doped $(GaAs)_n(AlAs)_m$ SLs is mostly determined by the population of minibands originating from Γ-like conduction band states. We did not find any significant influence of other types of electron state.

5. Conclusion

Coupled SL plasmon–LO phonon vibrational modes in doped $(GaAs)_n(AlAs)_m$ SLs have been studied. This made it possible to study the vertical transport properties of electrons in the SLs under investigation. The transition between isolated and coupled quantum wells was observed. Analysis of the experimental results shows that the frequencies of SL plasmons is mostly determined by the population of minibands formed by Γ-like electron states.

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