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Raman probing of the magnetoresistance in doped GaAs/AlAs superlattices

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Abstract. The reaction of collective plasmon–longitudinal optical phonon excitations to a magnetic field in heavily doped GaAs/AlAs superlattices was studied. The influence of the magnetic field on both the spatial extent (the localization length) of the collective excitations and their damping constant was explored. The dependence of the damping constant, associated with the alternating-current conductivity, on the magnetic field was found to be in good agreement with the classical Drude theory. It was shown that the magnetic field influences the damping of the plasmon-like excitations much more strongly than their spatial extent.

As is well known, the localization properties of electrons are fundamental to the understanding of electrical resistance, one of the most frequently utilized properties of doped semiconductors. Therefore, the localization problem in the physics of disordered condensed matter which deals with the way in which localization occurs, how localization modifies the electron energy spectrum and how the localized wave functions decay in space has attracted much attention in the last few decades [1]. Most of the papers published in this area were devoted to study of the energy spectrum of the elementary excitations in the presence of disorder; however, they did not deal with their spatial extent (the coherence length of the excitations), although it contributes directly to the electrical resistance.

Additional information about the localization of electrons can be obtained when studying charge transfer in the presence of a magnetic field. One can distinguish the following contributions to the magnetoresistance: first, the magnetic field changes the symmetry of the electron wave function from one of plane-wave character to a central symmetry; second, an additional component of the quasimoment normal to the magnetic field appears; and third, the magnetic field influences electronic scattering processes. It is worth mentioning that the conventional magnetoresistance, being an integral effect, cannot separate these contributions, while, as will be shown in the following, Raman scattering provides us with a method for probing the spatial (the localization length) and the energy (the characteristic frequency and the damping constant) characteristics of the collective plasmon-like excitations.

Another important advantage of the investigation of the reaction of the plasmons to a magnetic field instead of that of electrons is that, in this case, the condition of a strong magnetic field ($\omega_c\tau \gg 1$, where ω_c and τ are the cyclotron frequency and the relaxation time respectively) can be much more easily achieved. This is because the relaxation time associated with the plasmons is usually much larger than that for the electrons. Thus, the reaction of the electron system to the magnetic field can be explored in heavily doped semiconductors under conditions different to those used in dc measurements.

In our recent papers we have already shown that Raman spectroscopy can serve as a uniquely useful tool for studying the spatial localization of the collective excitations in disordered doped semiconductors and in semiconductor superlattices [2, 3] and, thus, for obtaining direct information about the spatial extent of elementary excitations involved in Raman scattering. In this case of strong disorder induced by a random impurity potential, plasmons can be represented as a superposition of the plane waves with the wave vectors distributed in a finite interval $\delta \boldsymbol{q}$, which gives rise to their finite spatial extent (coherence length L_{c0}). As a consequence, the observed Raman line is actually caused by a superposition of a number of narrow Lorentz-type lines weighted according to the density of states of the plasmons. Therefore, the shape of the resulting Raman line is determined by the homogeneous broadening of the contributing individual Lorentz lines (plasmon damping) and by the spatial correlation of the plasmons. Thus, the Raman line acquires a specific asymmetry clearly seen in spectra of doped semiconductors and superlattices when the spatial correlation dominates [2]. The conductivity is responsible for the damping of the individual plasmon lines, while their spatial correlation determines the resulting Raman-line asymmetry. Therefore, when measuring Raman scattering by plasmons in the magnetic field, it is possible to separate the influence of the magnetic field on the spatial extent of the wave functions of the plasmons and on the conductivity.

In fact, the high-frequency ac conductivity is responsible for the homogeneous broadening of the spectral lines, while the low-frequency or dc conductivity determines the electric response when conventional electrical measurements are performed. The basic difference between the optical and electrical measurements of the conductivity is that in the first case the collective excitations (plasmons) are probed, while the single-particle excitations (electrons) contribute to the dc conductivity. In spite of the fundamental difference between a plasmon and a single electron, there are close similarities of their behaviours: both of them undergo localization when subjected to a random potential. Moreover, if one treats the plasmon as a plane wave, then in the magnetic field a modification of the plasmon motion similar to that of a single electron can be expected. Therefore, although the ac and dc conductivities are quantitatively different, they are expected to exhibit similar qualitative behaviours when one is studying the influence of disorder or magnetic field.

In this paper we present a study of the coupled plasmon–LO phonon collective excitations by means of Raman scattering in heavily doped GaAs/AlAs superlattices in a magnetic field. The samples studied here were grown by molecular beam epitaxy: $(\mathrm{GaAs})_{17}(\mathrm{AlAs})_2$ superlattices (where the numbers denote the thicknesses of the respective layers expressed in monolayers) homogeneously doped with Si. The back-scattering configuration was used to perform the nonpolarized Raman scattering measurements using a Dilor XY triple monochromator equipped with a CCD detector. The 5145 Å line of an Ar^+-ion laser was used for the excitation. An Oxford Instruments optical helium cryostat with a superconducting magnet allowed us to realize measurements up to 7 T.

The Raman spectra reveal the plasmon–LO phonon modes arising due to the Coulomb interaction between the LO phonons and free electrons, as presented in [2]. Here, the high-frequency AlAs-like coupled mode was studied because, as has been shown in [3], this mode reveals mostly plasmon character and, therefore, it can be easily analysed. The Raman lines corresponding to this mode measured for one of the samples at different magnetic fields oriented parallel to the layers (the Voigt configuration) are shown in figure 1; the spectra were normalized with respect to the intensity of the GaAs-like unscreened LO phonon detected in the spectra due to the surface depletion layer. The full spectra obtained at $B = 0$ and $B = 7$ T, revealing

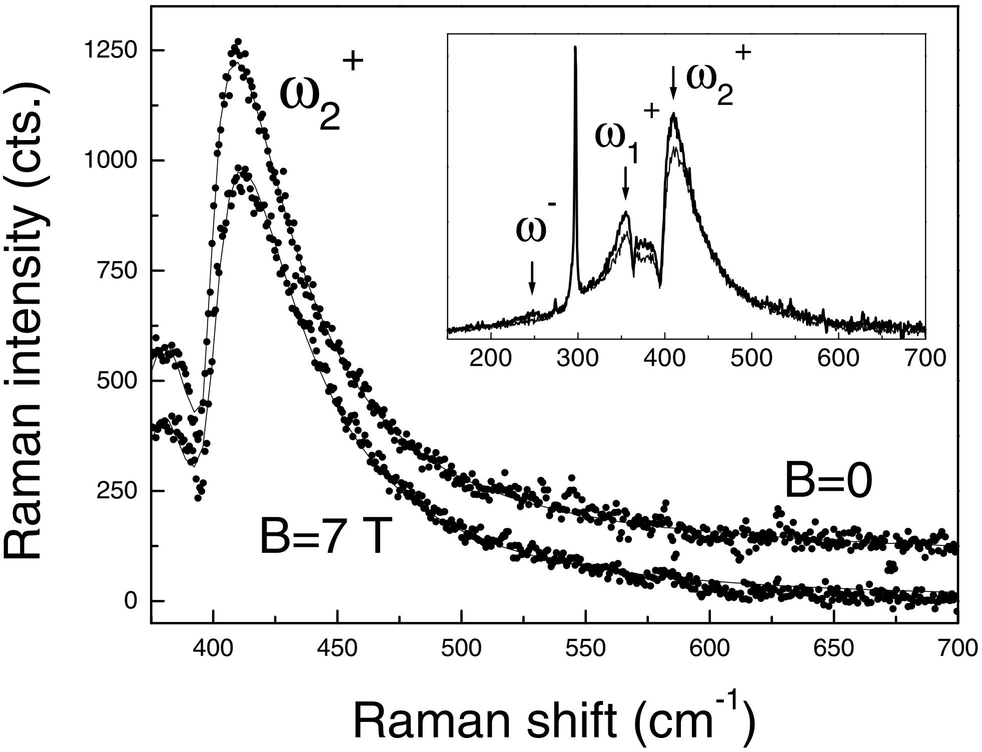


Figure 1. The experimental (points) and calculated (lines) Raman spectra of the AlAs-like coupled mode, normalized with respect to the intensity of the LO (GaAs) phonon, measured in the $(GaAs)_{17}(AlAs)_2$ superlattices with $N = 1.3 \times 10^{18}$ cm^{-3} at $T = 2.2$ K in the Voigt configuration at $B = 0$ (shifted up) and $B = 7$ T. The inset shows the full normalized spectra where the higher intensities were observed without a magnetic field.

all three expected coupled modes, are plotted in the inset; in addition, the TO phonons of GaAs measured at 274 cm^{-1} and the interface AlAs-like modes located around 380 cm^{-1} are seen in the spectra. The large signal-to-noise ratio allowed us to determine the shape of the relevant Raman lines with high precision. The intensity of the Raman line was calculated as in [2] according to

$$I(\omega) \sim \int f_{sc}(\vec{q}) \exp\left(-\frac{q^2 L_{c0}^2}{4}\right) \frac{\mathrm{d}^3 q}{[\omega - \omega(q)]^2 + (\Gamma/2)^2} \qquad (1)$$

where

$$f_{sc}(\vec{q}) = \left(\frac{4\pi}{q^2 + q_{TF}^2}\right)^2$$

is the screening correlation function with q_{TF} being a Thomas–Fermi wave vector; $\omega(q)$ is the dispersion of the relevant excitations contributing to the Raman scattering, calculated in the random-phase approximation as in [3], and Γ is the constant responsible for the line broadening.

The frequency positions of the coupled plasmon-like excitations can be obtained if one knows the dielectric function, which in the case of a SL has the form of a tensor. For the plasmon propagating along the superlattice axis (in the z-direction) and for the magnetic field applied perpendicular to this axis, the corresponding component of the dielectric function tensor is [4]

$$\epsilon_z(\omega) = \epsilon_{zL}(\omega) - \frac{\omega_p^2}{(\omega^2 - \omega_c^2 + \mathrm{i}\omega/\tau)} \qquad (2)$$

where $\epsilon_{zL}(\omega)$ is the lattice contribution to the dielectric function of the SL, ω_p is the plasma frequency, $\omega_c^2 = eB/mc$ is the cyclotron frequency which was incorporated into the dielectric function according to [5] and τ is the plasmon relaxation time. As was mentioned above, the conductivity is responsible for the broadening of the Raman lines which can therefore be qualitatively estimated as the imaginary part of the dielectric function. In the case of mostly plasmon character of the mode of interest,

$$\sigma(\omega) \sim \mathrm{Im}\,\epsilon_z(\omega) = \frac{\omega_p^2\omega\gamma}{(\omega^2 - \omega_c^2)^2 + \omega^2/\tau^2}. \qquad (3)$$

The dependence of the conductivity on the cyclotron frequency calculated according to (3) is plotted in the inset of figure 2(b). As can be seen, the conductivity reveals different behaviours depending on the relative strength of the magnetic field and the value of the relaxation time.

Meanwhile, the alteration of the spatial extent of the plasmon in the magnetic field which contributes to the Raman scattering according to (1) can be estimated following the theory developed for a quasi-one-dimensional electron system in a magnetic field in the presence of localization [6]:

$$\frac{1}{L_c^4} = \frac{1}{L_{c0}^4} + \frac{1}{L_B^4} \qquad (4)$$

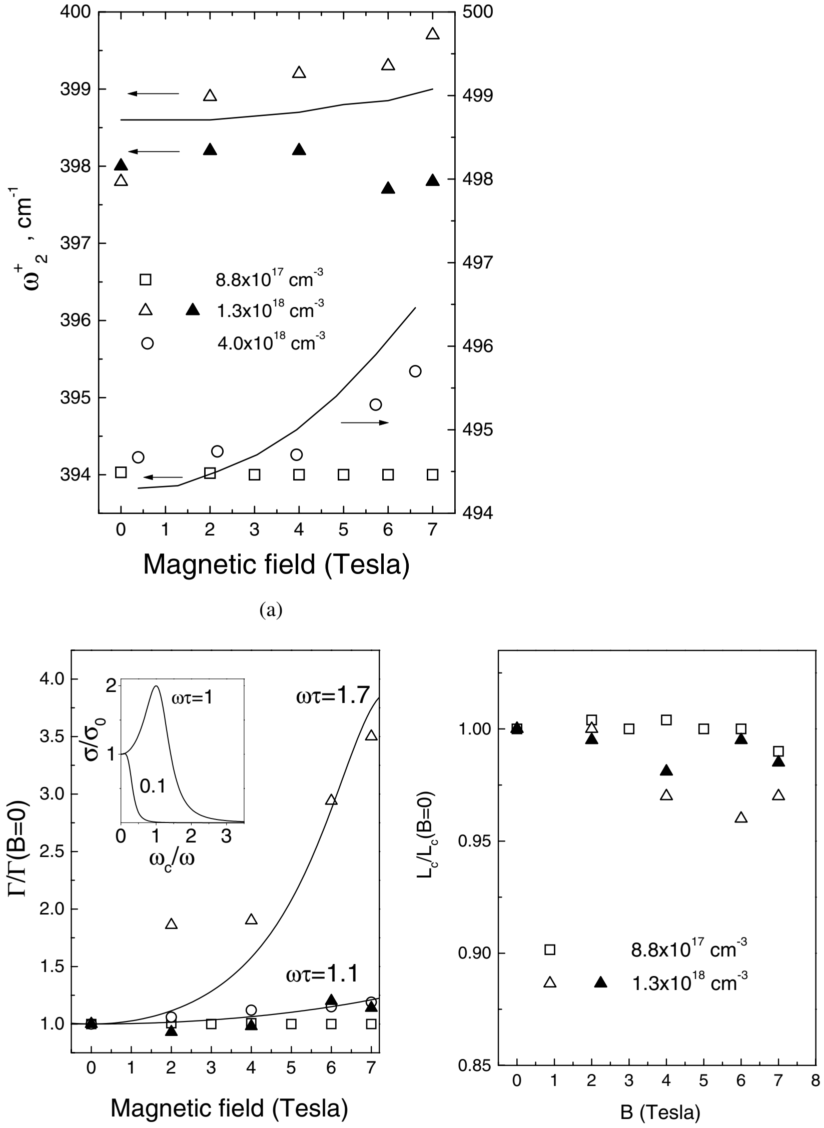
where L_{c0} is the coherence length of the plasmon without the magnetic field, $L_B = \sqrt{\hbar/m\omega_c}$ is the magnetic length.

The spectra calculated using the formula (1) reproduced the observed shape of the Raman lines well; taken together with the well pronounced spectral line asymmetry, this implied a high precision in the determination of the fitting parameters (the frequency of the collective mode, the coherence length and the damping constant).

The values of the characteristic frequencies of the coupled modes (ω_2^+), the coherence lengths (L_c) that are associated with the spatial extent of the collective excitations and the values of the broadening constants (Γ) measured for the superlattices with different electron concentrations at different magnetic fields are plotted in figures 2(a), 2(b), 2(c).

In the superlattices with low electron concentrations (smaller than 10^{18} cm^{17}) there were not enough electrons to produce a significant response to the magnetic field. As a result, all of the parameters characterizing the collective excitations remain unchanged until rather high magnetic fields are reached. On the other hand, for the samples with higher doping levels the Raman lines associated with the coupled AlAs-like excitations reveal in the magnetic field both a weak blue-shift of the frequency found in accordance with (2) and a modification of their shape.

As the fitting obtained with expression (1) showed, the line-broadening constant Γ associated with the conductivity is mostly responsible for the observed modification of the shape of the Raman lines. This is because, in the sample which revealed the alteration of the line shape with the magnetic field, the coherence length measured without the magnetic field ($L_{c0} = 27$ Å) was smaller than the calculated magnetic length (at $B = 7$ T, $L_B = 97$ Å) and, therefore, according to (4), a significant renormalization of L_c is not expected. At the same time, the broadening constant Γ, being proportional to the conductivity, increased with the magnetic field which is expected at $\omega_c < \omega$ as in our case. The dependencies of



(a)

(b)

(c)

Figure 2. The frequencies (a), the broadening constants (b) and the coherence lengths (c) of the AlAs-like coupled mode measured in the $(GaAs)_{17}(AlAs)_2$ superlattices with different dopings at $T = 2.2$ K in the Voigt configuration (open symbols) and in the Faraday configuration in the superlattice with $N = 1.3 \times 10^{18}$ cm^{-3} (full triangles) . The solid lines show the dependencies calculated as explained in the text.

the damping constants on the magnetic field calculated in accordance with (3) reveal good qualitative agreement with the experimental data obtained on the SLs with electron densities $N = 1.3 \times 10^{18}$ cm^{-3} and $N = 4.0 \times 10^{18}$ cm^{-3}.

In the superlattices with electron concentrations higher than 4.0×10^{18} cm^{-3}, the low electron mobilities significantly decreased the response of the electrons to the magnetic field and, as a consequence, a weaker dependence of Γ on the magnetic field was observed.

It is clear that, unlike the transverse magnetic field, the longitudinal one (oriented normal to the layers) will not influence the collective excitations with the wave vectors perpendicular to the layers if a scattering process does not provide the collective excitations with a significant impulse transfer along the layers. The results obtained with the longitudinal magnetic field (in the Faraday configuration) depicted in figures 2(a), 2(b), 2(c) do indeed show no influence of the longitudinal magnetic field on the collective excitations.

To conclude, the reaction of the collective excitations to a magnetic field in heavily doped GaAs/AlAs superlattices was studied by means of Raman scattering. As a consequence, an analogue of the magnetoresistance was measured through optical spectroscopy and the separate influences of the magnetic field on the spatial extent and on the damping of the collective plasmon-like excitations were explored. The results obtained were found to be in good agreement with the theoretical predictions.

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