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MAGNETIC FIELD ENHANCEMENT of RAMAN SCATTERING on FOLDED ACOUSTIC PHONONS in GaAs-AlGaAs SUPERLATTICE

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Drastic enhancement of the Raman scattering intensity of the folded longitudinal acoustic phonon in a GaAs/AlGaAs superlattice is observed in the presence of a perpendicular magnetic field.

A qualitative quasi-classical interpretation of this phenomenon is presented and a dependence of Raman scattering intensity on the magnetic field is obtained.

Raman scattering on folded acoustic phonons in superlattices (SL) has been widely studied (see, for instance, [1,2] and references cited therein). In this paper a very strong magnetic field enhancement of Raman scattering of a folded longitudinal acoustic (LA) phonon in a semiconductor SL has been observed.

1. The study was performed on a MBE-grown GaAs/$Al_xGa_{1-x}As$ SL which was not intentionally doped and consisted of 70 periods of 45Å wells and 42Å barriers with x=0.3. The characterization of the SL was made by x-ray diffraction and Raman scattering.

Raman spectra were taken on a spectrometer with double-monochromator in a back-scattering configuration. The sample was held inside a superconducting magnet in a He-cryostat. Magnetic fields, B, of up to 7T directed perpendicularly to the SL plane were used.

Fig.1 shows Raman spectra of a folded LA phonon at room temperature without a magnetic field. The sample was excited with the 488nm line of an Ar^+ laser with a pumping power of 200mW. In Fig.1 one can see the first folded acoustic (FA) doublet with the components at 15.2 and 20.7cm^{-1} and peak intensities of ≃ 80c/s (the measured ratio of FA and LO peak intensities was about 0.12)

At pumped He-temperatures the sample was excited at 1.647eV (7525Å) by a Kr^+ laser. This energy is slightly above the energy of the

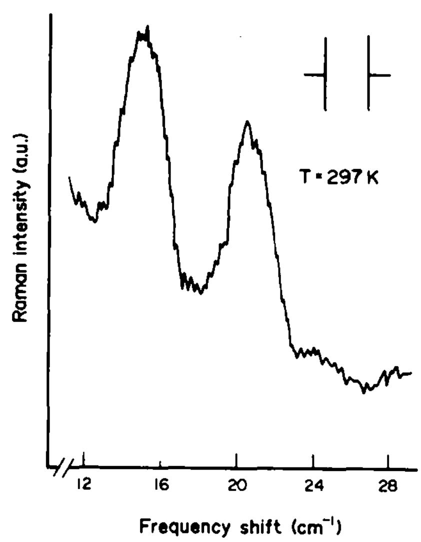

Fig.1. Raman spectrum of the folded LA phonon at T=297K without a magnetic field, configuration $z(x,y)\bar{z}$ ε_{exc}=2.54eV, power density $10^4 W/cm^2$, spectral slit width S=2cm^{-1}.

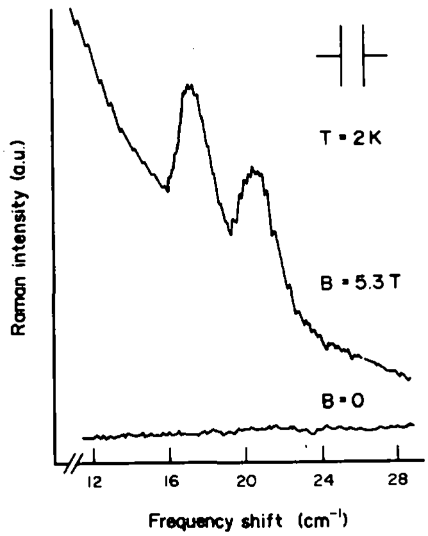

Fig.2. Raman spectra of the folded LA phonon at B=0 and B=5.3T $z(\sigma_-\sigma_-)\bar{z}$ configuration. $T\simeq 2K$, $\varepsilon_{exc}=1.647eV$, $S=1.5cm^{-1}$, power density $5W/cm^2$.

1e-1hh transition of the SL. Indeed, the exciton luminescence peak was observed at 1.615eV. Thus, the initial energy of the photocreated electron was about 15meV, i.e. lower than the LO-phonon energy (36.6meV).

Fig.2 shows the Raman spectrum at $T\simeq 2K$ (the sample was in the He-vapour) at B=0 and B=5.3T. The pumping power was 1.5mW. Such small pumping power was used to suppress the high-frequency tail of the exciton luminescence. While at B=0 FA-phonon could not be observed it was quite strong at B=5.3T in spite of low temperatures and very small pumping power. This is an evidence that a sharp enhancement of Raman scattering efficiency of a FA phonon occurs in a perpendicular magnetic field. We estimate the enhancement factor as, at least, 10^4 in a magnetic field of $\simeq$ 5T from the comparison with the room temperature data (note that Bose factor n+1 at room temperature is higher by an order of magnitude as compared with He-temperature).

The FA-phonon in Fig.2 is superimposed on a high structureless background caused by geminate radiative recombination which is also enhanced by a magnetic field [3]. Fig.3b shows the measured intensity of the low-frequency component of the FA-doublet as a function of magnetic field. A strong maximum is seen at B=5.3T and weaker oscillations

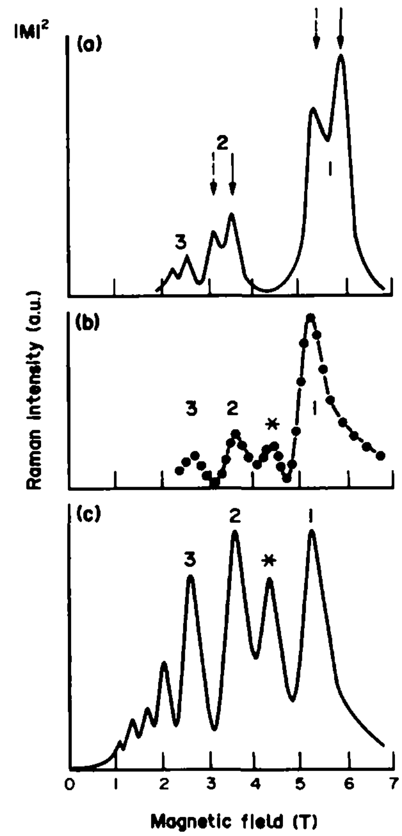

Fig.3 (a) $|M|^2$ as a function of the magnetic field calculated with the aid of Eq.(1) for ε=17meV, $\hbar\Omega$=2.15meV, $\tau=5\times10^{-13}$s $m_e=0.072m_o$, $m_{hh}=0.3m_o$. Numbers at the maxima are Landau level indices, solid arrows point to the incoming resonances, dashed arrows point to the outgoing ones.
(b) Raman intensity of the low-frequency component of the FA-doublet in configuration $(\sigma_-\sigma_-)$ as a function of the magnetic field.
(c) Total Raman intensity (LA phonon + background)at the same frequency.

at lower fields. The positions of the oscillations coincide with those of the total intensity (LA phonon + background) measured at the same frequency, Fig.3c.

The intensity of the peaks was maximal in the $(\sigma_-\sigma_-)$ and $(\sigma_+\sigma_+)$ configurations, where σ_- (σ_+) refers to the circular polarization of the incident and scattered light. In the configuration with crossed polarizations [for instance, $(\sigma_-\sigma_+)$] the FA phonon was not observed and the background intensity was about 4 times smaller. The resonances for $(\sigma_-\sigma_-)$ and $(\sigma_+\sigma_+)$ configurations occurred at slightly different values of the magnetic field. The experimental results will be discussed in section 3.

2. Let us first discuss qualitatively the cause of scattering enhancement in a magnetic field using a quasiclassical description of the carriers motion.

The inelastic light scattering is a result of three virtual transitions:
1. Creation of an electron and a hole by the exciting light.
2. Emission or absorption of phonons.
3. Recombination of the electron and the hole with the emission of a scattered photon.

An electron and a hole are created at one and the same point of space and at the instant of creation they have momenta equal in magnitude and opposite in direction. In order to undergo radiative recombination they must meet again at some point of space having there equal and oppositely directed momenta. The intensity of inelastic light scattering depends on the spacing in time of the stages 1 and 3. In the absence of a magnetic field there is a straight-line motion of the photocreated electron and hole in opposite directions. Therefore, the time interval during which the carriers can interact with the phonons is very short (of the order of $\hbar/\varepsilon$, where ε is the kinetic energy of the carriers at the instant of their photocreation).

In a magnetic field both carriers are moving on the same circular orbit in opposite directions and therefore they meet repeatedly after each cyclotron period. The barriers in the SL are assumed to be sufficiently broad, , so that one could ignore that the carriers can fly apart along the axis of the SL. The carriers may recombine at each of the meetings and thus have a considerably longer interaction time with the phonons (the time between the successive meetings which is of the order of $2\pi/\omega_c$,where ω_c is the sum of electron's and hole's cyclotron frequencies). Just this fact is the cause of the magnetic field enhancement of the inelastic light scattering.

The above considerations can be substantiated by a formal calculation of the matrix element of the transition related to the inelastic light scattering . It is assumed that the magnetic field, the exciting and the scattered light beams as well as the phonon momentum are perpendicular to the quantum well planes. For the sake of simplicity the complex nature of the GaAs valence band will be ignored. Under such approximation only the transitions between electron and hole Landau levels of equal indices are allowed.

The expression for the transition matrix element M of Raman scattering can be written in the form

$$M \propto \frac{F(\Omega)}{2\pi\lambda^2} \times \sum_{n=o}^{\infty} \frac{1}{(\varepsilon_o - n\hbar\omega_o + i\Gamma/2)(\varepsilon_o - n\hbar\omega_o - \hbar\Omega + i\Gamma/2)} \qquad (1)$$

where λ is the magnetic length, $\Gamma=\hbar/\tau$ is the width of the electron-hole pair Landau level due to the finite value of their outscattering time from this level, $\varepsilon_o=\varepsilon-\frac{1}{2}\hbar\omega_o$, $\varepsilon=\hbar\omega_{exc}-E_g$, where $\hbar\omega_{exc}$ is the excitation energy and E_g is 1e -1hh gap of the SL. The product of matrix elements corresponding to the afore-mentioned stages of the process of inelastic light scattering enters the function $F(\Omega)$, which depends on the energy $\hbar\Omega$ of the emitted phonon.

At the first glance this expression does not have any connection with the considerations outlined above. But using the Poisson's formula

$$\sum_{n=o}^{\infty} f(n) = \sum_{N=-\infty}^{\infty} \int_{o}^{\infty} f(x)\exp(+2\pi iNx)dx$$

we arrive at the following equation for M which allows us to get a more clear physical insight into the phenomenon of magnetic enhancement. Indeed,

$$M \propto \frac{F(\Omega)}{2\pi\lambda^2} \sum_{N=O}^{\infty} M_N$$

at $\varepsilon_o \gg \hbar\omega_o, \hbar\Omega$:

$$M_o = (\hbar/2\pi\varepsilon_o),$$

$$M_N = \frac{2\sin(\pi N\Omega/\omega_o)}{\Omega} \exp\left(-\frac{\pi\Gamma N}{\hbar\omega_o}\right) \times \exp\left(+\frac{2\pi iN}{\hbar\omega_o}(\varepsilon_o - \hbar\Omega/2)\right)$$

The term of number N describes the result of the corresponding electron-hole meeting.

The quantity $|M_N|^2$ is proportional to the probability of the phonon emission during the time $2\pi N/\omega_o$.

$$|M_N|^2 \propto \frac{\sin^2(\pi N\Omega/\omega_o)}{\Omega^2} \times \exp\left(-\frac{2\pi N\Gamma}{\hbar\omega_o}\right) \quad (2)$$

The main dependence of this quantity on a magnetic field is in the exponential factor $\exp(-2\pi N\Gamma/\hbar\omega_o)$, which gives the probability for the electron-hole pair to remain at the given energy level after N revolutions. Interference of the results of different meetings is leading to the oscillations in the scattering intensity due to Landau quantization.

The calculation of the sum gives

$$|M|^2 \propto |F(\Omega)|^2 \times \exp(-2\pi/\omega_o\tau)\frac{\sin^2(\pi\Omega/\omega_o)}{\Omega^2\varphi(\varepsilon_o)\varphi(\varepsilon_o-\hbar\Omega)} \quad (3)$$

where

$$\varphi(\varepsilon)=(1-\exp(-\pi/\omega_o\tau))^2 + 4\exp(-\pi/\omega_o\tau)\sin^2(\pi\varepsilon/\hbar\omega_o)$$

In this expression the exponent describes the enhancement of the scattering in a magnetic field and the functions $\varphi(\varepsilon_o)$ and $\varphi(\varepsilon_o-\hbar\Omega)$ at strong magnetic fields ($\omega_o\tau>1$) describe the in- and out-resonances. Close to the resonance

$$\varphi(\varepsilon_o) = \frac{4\pi^2}{(\hbar\omega_o)^2}\left[\frac{\Gamma^2}{4} + (\varepsilon_o-n\hbar\omega_o)^2\right]$$

The spectrum of the scattered light is mainly defined by the function $|F(\Omega)|^2$. For a single quantum well and scattering by acoustic phonons the width of the spectrum is of the order of $s\cdot 2\pi/L_w$, where L_w is the well width and s is the sound velocity. In a case of a superlattice superposition of the contributions of different wells leads to the peaks in the Raman spectrum which correspond to the scattering on the so called folded acoustic phonons, $\omega=s(\frac{2\pi m}{L}\pm 2æ)$, where L is the SL period, æ is the wave vector of light and m is an integer.

3. Let us compare the experimental results with the calculation. Fig.3a presents $|M|^2$ as a function of the magnetic field calculated with the aid of Eq.(1), which does not require the fulfillment of the condition $\varepsilon \gg \hbar\omega_o$. The calculation was performed for the transitions between the Landau levels of electrons and heavy holes and with the following parameters:

ε=17meV, $\hbar\Omega$=2.15meV and $\tau=5\times10^{-13}$s .The full and dashed arrows point to the incoming and outgoing resonances,respectively, and the numbers are the Landau level indices.

Comparison of the experimental (Fig.'s 3b and 3c) and theoretical results shows a qualitative agreement. One must keep in mind that the developed theory does not take into account the real band structure (nonparabolicity and warping) as well as spin splitting and light absorption. The latter must be essential in the region of strong peaks in the density of states corresponding to Landau levels with small indices.

Incoming and outgoing resonances were not resolved in the experimental spectra (except maybe for n=1 in the total intensity spectrum for configuration $(\sigma_+\sigma_+)$ where the out-resonance was much stronger than the incoming one).

As was mentioned above the resonances for $(\sigma_-\sigma_-)$ and $(\sigma_+\sigma_+)$ configurations occur at slightly different values of magnetic fields.Apparently this is due to the spin splitting of electron and hole levels.We estimate the spin splitting for n=1at B=5T as ≃1.4meV.

An additional peak (marked by an asterisk) shows up in Fig.3b and 3c at B=4.5T. it is due to the resonance with some unidentified Landau level transition.

The described mechanism of magnetic enhancement can be used in the interpretation of magnetic enhancement of LO-phonon scattering which was observed in [4] and of geminate recombination observed in [3].

The magnetic enhancement of Raman scattering on LO-phonons was also observed in bulk samples [5,6]. The appropriate calculation which took into account the real band structure is presented in[7]. The qualitative interpretation given above can be applied to the magnetic enhancement in bulk samples too. But in this case one must take into consideration the possibility for the carriers to fly apart along the magnetic field.

In conclusion, we have observed strong magnetic enhancement of Raman scattering on folded longitudinal acoustic phonons in a SL. This enhancement has been interpreted within the frame of a quasiclassical model.

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