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LIGHT SCATTERING BY TWO DIMENSIONAL ELECTRON SYSTEMS IN SEMICONDUCTORS

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Résumé - Cette contribution présente une revue des expériences utilisant la diffusion inélastique de la lumière pour étudier les systèmes d'électrons bidimensionnels aux interfaces des semi-conducteurs. Les résultats obtenus sur des hétérostructures à modulation de dopage à base de GaAs-(AlGa)As sont également considérés.

Abstract - This contribution reviews resonant inelastic light scattering studies of two dimensional electron systems at semiconductor interfaces. The experimental results from modulation-doped GaAs-(AlGa)As heterostructures are considered.

1. INTRODUCTION

This paper is concerned with the spectroscopy of the elementary excitations of two dimensional electron gases that occur at interfaces of semiconductor micro-structures. In these systems, energy band discontinuities and space-charge electric fields quantize the electron motion normal to the interfaces into discrete energy levels. Since these electrons are free to move in a plane parallel to the interface, each of the discrete energy levels gives rise to a two dimensional subband. Electrons in subband states have many properties in common with those of an idealized 2D electron gas. Experimental and theoretical research of 2D electron systems at semiconductor interfaces has been extensive. The recent observations of the quantized Hall effect and the anomalous magneto - transport behavior in the extreme quantum limit (fractional quantization) are among the most exciting new developments in solid state physics.

In 1978 Burstein, et al., proposed resonant inelastic light scattering as a method for the investigation of the elementary excitations of 2D electron systems in semiconductors. It was pointed out that with the resonant enhancements of the light scattering cross-section the method has the sensitivity required to observe the elementary excitations of systems with areal densities n \( \geq 5 \times 10^{11} \text{cm}^{-2} \). It was also suggested that it should be possible to measure separate spectra of single particle and collective excitations. This feature was expected to lead to determinations of energy levels and collective electron - electron interactions. The proposal was almost immediately followed by the first observations of light scattering by intersubband excitations, between the discrete energy levels of electrons confined at GaAs-(AlGa)As heterostructures.

During the last four years light scattering by the 2D electron systems at GaAs-(AlGa)As heterostructures has been studied extensively. Intersubband spectroscopy has confirmed the predictions of Burstein.
et al. /6/ and gave considerable information on the behavior of free electrons in the heterostructures. They have revealed energy level structures and resonant enhancement of scattering intensities /7,8/, collective Coulomb interactions /9/, correlations with electron mobilities /10/ and the effects of photoexcitation at high intensities /11,12/. Excitations associated with in-plane motion, transitions between Landau level /13/ and plasma oscillations /14/, have also been observed in the GaAs-(AlGa)As heterostructures.

Resonant light scattering observations of excitations of 2D electron systems have been reported in several other semiconductor interfaces. Among them are the accumulation layers at MOS or MIS structures of InAs /15,16/, Si /17/ and InP /18/. Photoexcited systems have been studied in doping superlattices of GaAs /19/. Light scattering from electrons in doped Ge-GaAs heterostructures has also been reported /20/. In this review, I will consider only selected results from GaAs-(AlGa)As heterostructures. They represent examples of the physics of 2D electron systems of semiconductors that is accesible to investigation by light scattering. A more comprehensive review will soon become available /21/.

2. MECHANISMS, SELECTION RULES AND KINEMATICS

Within the effective-mass approximation the mechanisms and selection rules for resonant light scattering by a 2D semiconductor plasma are similar to those of 3D systems /6,22/. Resonant enhancements, essential to these experiments, are expected for photon energies near optical gaps that involve the free electrons. In the case of direct gap zincblende semiconductors the relevant resonances occur at the fundamental, $E_0$, and spin-orbit split-off, $E_0 + \Delta_0$, gaps near the $\Gamma$ point of the Brillouin zone. In n-type Ge the resonance occurs at the $L$ point, near the $E_l$ and $E_l + \Delta_1$ optical gaps. In p-type Si it is at the $E_0$ gap near the $\Gamma$ point.

Two types of spectra are measured. The polarized spectra, obtained with parallel incident and scattered polarizations, are assigned to collective charge density excitations of the electrons. Depolarized spectra, in which the two polarizations are orthogonal, are assigned to single-particle spin-density excitations. These assignments have explained the results obtained near the $E_0 + \Delta_0$ resonance /9,23/. Breakdown of these selection rules has been observed in spectra obtained with photon energies near the fundamental $E_0$ gaps /24/.

![Figure 1 - Typical nearly backscattering geometry used in the experiments described here.](image-url)
2 \text{ Tr } k_{ll} = (\sin \theta - \cos \theta) (11)

\[ k_{ll} = \frac{2\pi}{\lambda} (\sin \theta - \cos \theta) \]

\[ k_{\perp} = \frac{4\pi}{\lambda} \eta \left( 1 - \frac{1}{4\eta^2} \right) \]

where \( \lambda \) is the laser wavelength and \( \eta \) is the refractive index. \( k_{ll} \) can be varied from a small value of \( \sim 10^4 \text{cm}^{-1} \), at \( \theta \approx 45^\circ \), up to a maximum of \( \sim 10^5 \text{cm}^{-1} \). Typical values of \( k_{\perp} \) are \( k_{\perp} \approx 7 \times 10^5 \text{cm}^{-1} \) near the \( E_0 + \Delta_0 \) energy gap at \( \sim 1.9 \text{ eV} \), and \( k_{\perp} \approx 5 \times 10^5 \text{cm}^{-1} \) at the fundamental gaps \( (E_0 \approx 1.5 \text{ eV}) \).

3. INTERSUBBAND SPECTROSCOPY

The first light scattering experiments were carried out in doped GaAs-(AlGa)As heterostructures fabricated by molecular beam epitaxy. In this work the spectral features of intersubband excitations are broad, with line shapes that reflect the sample quality at the time. The most revealing studies of intersubband excitations have been carried out in modulation-doped \cite{25} quantum-wells. The heterojunctions have the structure shown in Fig. 2.

![Figure 2 - Sequence of layers and relative position of the conduction band edge in modulation-doped multiple quantum-well GaAs(AlGa)As heterostructures \cite{26}.](image)

The undoped \((AlGa)As\) spacer, with thickness \(d_3\), separates further the mobile electrons in the GaAs layers from the ionized donors. This results in a substantial enhancement of the electron mobility \cite{26}.

In the spectra of intersubband excitations shown in Fig. 3, \(z\) and \(\bar{z}\) are the propagation directions of the incident and scattered light. They are close to \(001\) and \(00\bar{1}\) crystal axes. \(x'\) and \(y'\) are \(110\) and \(1\bar{1}\bar{0}\) in-plane directions of polarization of light. These spectra, reported by Pinczuk et al. \cite{9}, are the first in which there is clear separation between single particle and collective excitations. The depolarized \(z(y'x')z\) spectrum shows a single band assigned to the lowest, single-particle, spin-density intersubband excitation. The spectra of Fig. 3 were obtained with \(\theta \approx 45^\circ\). Thus, \(k_{ll}\) is small and the intersubband transitions can be assumed to be vertical in the 2D wavevector space of the subbands. Therefore, \(E_{0l}\) represents an energy close to the spacing between the lowest conduction subbands. In the polarized \(z(x'x')z\) spectrum the peaks labeled \(I_+\) and \(I_-\), at \(E_+\) and \(E_-\), are assigned to the coupled collective intersubband -LO phonon excitations considered by Burstein et al. \cite{22}. Abstreiter et al. \cite{27} have observed similar spectra.
Single particle intersubband energies were measured in depolarized spectra from several samples /7,8,9,23,27/. In all cases there is good agreement with calculated subbands spacings /28,29/. The differences in energies of single particle and collective excitations are direct evidence of the macroscopic electric fields (or depolarization fields) due to resonant screening phenomena that are associated with intersubband transitions. The effects were first predicted by Chen et al. /30/, and were invoked in the interpretation of subband optical absorption /31,32/. The separate measurement of light scattering spectra by single particle and collective intersubband excitations have for the first time made possible simple determinations of depolarization field effects.

Collective intersubband excitations were first considered by Dahl and Sham /33/. Burstein et al. /22/ have included the coupling to optical phonons that occurs in polar semiconductors. These treatments have been extended to incorporate the specific conditions that exist in quantum-well heterostructures /9,23/. The I+ and I- doublet seen in the spectrum of Fig. 3 can be interpreted in terms of simple coupled electron -LO phonon modes that are described by /9,23/

$$1 - \frac{E_{T0}^2 - E_{L0}^2}{E_{T0}^2 - E_{L0}^2} \times \frac{E_P^2}{E_P^2 - E_{01}^2} = 0$$

(3)

where $E_T = 33.6$ meV and $E_L = 36.7$ meV are the energies of T0 and L0 phonons of GaAs. $E_P$ is a plasma energy that describes depolarization field effects. It can be written as /23/

$$E_P = \left[ 8\pi ne^2 L_{01}/\epsilon_{\infty} \right]^{1/2}$$

(4)

Where $\epsilon_{\infty} = 11.1$ is the background dielectric constant and $L_{01}$ is the intersubband Coulomb matrix element given by

$$L_{01} = \int_{-\infty}^{\infty} dz \int_{-\infty}^{\infty} dz' \xi_1(z') \xi_0(z')$$

(5)
where $\xi_0(z)$ and $\xi_1(z)$ are the envelope functions of the ground and first excited subbands. The value of $L_{01}$ is the only adjustable parameter of the analysis. The values of $L_{01}$ determined from these experiments are in good agreement with the ones evaluated with sub-band envelope functions of simple model calculations /9,23,29/.

One of the intriguing questions in the spectroscopy of intersubband excitations is the relation to transport properties of the 2D electron system. Pinczuk et al. /10/ have identified a correlation between lineshapes in resonant light scattering spectra and the in-plane mobilities. These studies have been carried out in four similar modulation-doped quantum-well GaAs–(Al$_{0.12}$Ga$_{0.88}$)As heterostructures in which the electron mobilities are directly related to $d_3$, the thickness of the undoped (Al$_{0.12}$Ga$_{0.88}$)As spacer (see Fig. 2) /26/. Figure 4 shows spectra obtained from three of these samples. The spectral features are assigned to single particle intersubband transitions as indicated in the figure. The widths of the three bands can be seen to decrease dramatically with increasing Hall mobility and $d_3$. The correlation is also associated with an unexpected dependence of the spectral bandwidths on incident photon energy in the range of the $E_0 + \Delta_0$ optical gap /10,23/. This effect is striking in samples with electron mobilities lower than $\approx 25,000$ cm$^2$/Vsec.

In the interpretation of these results it was proposed /10/ that resonant inelastic light scattering is subject to wavevector relaxation processes related to those that limit the electron mobility. These processes, due to scattering of electrons by the Coulomb potential of the ionized donors, depend on $d_3$ in modulation-doped structures. Under these circumstances wavevector conservation breaks down for resonant light scattering. Thus, non-vertical intersubband, with an in-plane wavevector transfer $q \neq k|t|$ become active in the nearly backscattering spectra. The bands of non-vertical transitions have widths of $\approx h\nu v_F$ (where $v_F$ is the Fermi velocity). Therefore, as a consequence of breakdown of wavevector conservation the spectra are expected to show considerable width or even appear as a quasi-continuum. The stronger resonant behavior of light scattering with breakdown of wavevector conservation /21,34/ explains the dependence of spectral width on photon energy.
Measurements of resonant enhancements of light scattering by inter-subband excitations have been reported in single /7,35/ and multiple /8,36/ GaAs-AGaAs heterostructures. The results, obtained with photon energies across the $E_0 + \Delta_0$ optical gaps of the GaAs layers, display the general behavior anticipated by Burstein et al. /6,22/. The most recent work has been carried in the sample with the largest $d_3$ value of the group whose spectra are shown in Fig. 4 (unpublished results by the author). The integrated intensities of the even parity transition $E_0^2$ are much larger than those of the odd parity transition $E_0^1$. Scattering by the odd parity excitation, that breaks down the parity selection rule for quantum-wells /36/, has been assigned to the $k$-dependent contributions to the optical matrix element /21/.

Figure 5 - Depolarized light scattering spectrum of a modulation-doped quantum-well heterostructure under a magnetic field normal to the 2D electron system /13/. The inset shows the sample arrangement in the magnet.

4. LANDAU LEVEL EXCITATIONS

Resonant inelastic light scattering by the 2D electron systems in GaAs-AGaAs heterostructures under magnetic fields normal to the layers has been investigated /13,37/. For this orientation of magnetic field the electron motion in the plane of the layers is quantized into Landau levels and the energy spectrum of the 2D system is fully discrete /1/.

Figure 6 - Plot of the energies of $\Delta \ell = 1$ Landau level transitions as a function of magnetic field. Results from six different modulation doped quantum well heterostructures are shown /13/.
These experiments were also carried out in, n-type, modulation-doped quantum wells. Typical depolarized $\chi(y'x')\chi$ spectra can be seen in Fig. 5. The photon energies are close to the $E_0 + \Delta_0$ optical gaps of the GaAs layers. The band labeled $\hbar\omega_c$ has been assigned to $\Delta l = 1$ Landau level excitations of single particle character. Similar spectra have been obtained from several samples having a range of free electron densities and layer thicknesses. Figure 6 shows the values of $\hbar\omega_c$ as a function of magnetic field. The linear behavior of $\hbar\omega_c$ supports the assignment as $\Delta l = 1$ Landau level transitions. The slope of the straight line gives an electron effective mass of $m^* = 0.068 \pm 0.003$. Light scattering by the $\Delta l = 1$ excitations, having odd parity, is forbidden in the dipole approximation. Breakdown of this approximation has been invoked to explain these experiments /38/.

5. PLASMA OSCILLATIONS

Light scattering by plasma oscillations in multiple quantum well GaAs-(AlGa)As heterostructures has been observed by Olego et al. /14/. These oscillations are collective modes associated with the 2D in-plane motion of electrons confined in the GaAs layers. The experiments were carried out in modulation-doped samples with the structure shown in Fig. 2. The photon energies ($\sim 1.58$ eV) are relatively close to the fundamental optical gap. This allowed relatively large penetration depths while retaining the benefits of resonant enhancements and relatively low luminescence.

$$\omega^2_P = \omega^2_{2D}(k||)S(k||, k_L, d)$$

(6)

where

$$\omega_{2D}(k||) = \left[ \frac{2\pi ne^2}{\epsilon_0 m^*} k|| \right]^{1/2}$$

(7)

The charge density oscillation of semiconductor superlattices have been described /39,40/ as plasmons of an idealized layered 2D electron gas /41/. Such modes have large dispersive effects of the form /39,41/
is the 2D plasma frequency associated with the free charge in each layer and $\varepsilon_M$ is the background dielectric constant. The structure factor of the superlattice is given by

$$S(k||,k_\perp,d) = \frac{\sinh k||d}{\cosh k||d - \cos k_\perp d}$$

(8)

where $d = d_1 + d_2 + d_3$. For $k||d < 1$, Eqs. (6) - (8) predict the acoustic-like behavior

$$\omega_p \approx v k||$$

(9)

where

$$v = \left[\frac{2\pi e^2 d}{\varepsilon_M^*} \frac{1}{1 - \cos k_\perp d}\right]^{1/2}$$

(10)

An important feature of the plasmon described by Eqs. (9) and (10) is the absence of Landau damping since $v > v_F$.

Figure 7(a) shows a spectrum from a GaAs-(Al$_{0.5}$Ga$_{0.5}$)As sample with $d_1 = 262\AA$, $d_2 = 317\AA$, $d_3 = 163\AA$, and $n = 7.3 \times 10^{11} \text{cm}^{-2}$. The $E_{01}$ and $E_{11}$ bands are associated with single particle and collective intersubband excitations. There is also a lower energy peak at 3.5 meV. Its most remarkable characteristic, displayed in Fig. 7(b), is its dependence on the angle of incidence. It follows from Eq. (1) that this indicates a dependence on $k||$. This dispersive behavior led Olego, et al. /14/ to assign the lower energy peak to a plasma oscillation of the free carriers in the quantum wells.

Figure 8 shows the plasma dispersion measured in two samples. These results were interpreted with Eqs. (6) - (10). The full lines are the evaluations with the structure factors of the superlattices, while the dashed lines are the extrapolations of the linear behavior. The agreement between measured and calculated dispersion is very good.
The small differences can be explained by uncertainties in the values of the sample parameters. The observation of the plasma oscillations and determination of its dispersion are an example of the application of the light scattering method to studies of the in-plane motion of 2D electron gases.

6. CONCLUDING REMARKS

The intense activity of the last four years has shown that inelastic light scattering is one of the most resourceful methods for the spectroscopy of elementary excitations of 2D electron systems at semiconductor interfaces. Further interest can be anticipated, with emphasis in heterostructures, spectroscopy of in-plane motion and lower dimensionality phenomena in general.

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