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INTERSUBBAND SPECTROSCOPY OF TWO DIMENSIONAL ELECTRON GASES: COULOMB INTERACTIONS

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We have made a direct determination of resonant screening (the depolarization field effect) in the collective intersubband excitations of a dense two dimensional electron gas. The effect was observed, for both odd and even parity transitions, in polarized inelastic light scattering spectra of a modulation-doped GaAs-AlGaAs superlattice. We offer a quantitative interpretation in terms of the Coulomb matrix elements for the transitions. Final state, or exciton-like, many-body effects are considered briefly.

The spectroscopy of intersubband transitions has been very useful in the study of two dimensional electron gases, for carriers confined both at the helium-vacuum interface and at metal-oxide-semiconductor (MOS) structures. The ability to excite electrons from the ground subband to one or more excited states of the confining potential has lead to a considerable understanding of these systems.

The electrons at a helium surface constitute a dilute gas, its excitations adequately described within a single particle picture. In semiconductors, by contrast, densities are several orders of magnitude higher, and intersubband transitions are strongly affected by Coulomb interactions between the carriers. These interactions have consequences that are unique to two dimensional electron systems. We present here new experimental results which, together with our analysis, separate one of these effects (resonant screening) from the others.

In a dense two dimensional electron gas, the energies of intersubband excitations are understood to be shifted from subband spacings by two effects associated with electron-electron interactions. One is an upward shift by resonant screening,[1,2] also known as the depolarization field effect. The other is a downward shift caused by the final state or exciton-like interactions between the excited electron and the remaining "hole."[3,4] The independent evaluation of these two effects is the key problem of intersubband spectroscopy, expected to lead to a deeper understanding of the many-body interactions.

In the case of the silicon MOS system, a clear separation of the two effects has been elusive. Theoretical estimates by Ando,[4] supported by the experiments of Beinvogl and Koch,[5] suggest that a final state effect is large and almost completely cancels the depolarization field effect. In recent work, Ando and Mori[6] pointed out that exciton-like effects would be much smaller in semiconductors, like n-GaAs, which have a smaller effective mass.

In this paper we show that the depolarization field effect in a GaAs two dimensional electron gas can be determined by inelastic light scattering, from spectra of single-particle and collective intersubband excitations. This is possible because the polarization selection rules allow the observation of intersubband transitions which are either pure spin-density (spin-flip) or pure charge-density (non-spin-flip) excitations.[7] Because spin-density excitations are not subject to resonant screening,[8] they have single particle character with energies which may be shifted from subband spacings by final state interactions. The differences between the two types of spectra reveal directly the depolarization field effects.

The interpretation of previous inelastic light scattering work[9,10,11] was inconclusive about depolarization field effects and final-state interactions because a clean separation between spectra of single particle and collective intersubband excitations could not be achieved. In the results we present here, the collective character of the charge-density excitations is established by the observations of their coupling with LO phonons. This is the characteristic signature of the depolarization field effect in a polar semiconductor.[12] Furthermore, we give a quantitative interpretation of these results in terms of Coulomb interactions in the two dimensional electron gas.

We studied a GaAs-$Al_{0.18}Ga_{0.82}As$ heterojunction superlattice sample with layer thickness d_1 = 204Å and d_2 = 200Å. The AlGaAs layers were modulation-doped with Si donors. Shubnikov-de Haas measurements indicate that only one subband is occupied by carriers and yield a concentration of $n_s = 4.2\times10^{11}$ cm^{-2} in each GaAs layer. The Fermi energy is $E_F \simeq$ 14meV. Inelastic light scattering spectra were obtained with photon energies near the $E_0 + \Delta_0$ gap of GaAs. The magnitude of the scattering wavevector was $k \simeq 0.7\times10^6$ cm^{-1} and directed along $\hat{z}$, the (001) direction normal to the plane of the layers.

$z(y'x')\bar{z}$ and $z(x'x')\bar{z}$ spectra were recorded. $\hat{x}'$ and $\hat{y}'$ correspond to (110) and (1$\bar{1}$0). For these spectra, the polarization selection rules[10,11] predict spin-density and charge-density intersubband excitations respectively. The LO phonons of GaAs and AlGaAs are expected to occur in $z(x'x')\bar{z}$ spectra.

In $z(y'x')\bar{z}$ spectra we observed three well separated bands at E_{01} = 21.7 meV, E_{02} = 63.7meV and $E_{03} \simeq$ 106meV. These excitations involve transitions from the lowest subband (of even parity) to consecutive higher subbands (of either parity), accompanied by the reversal of spin of the excited electron. The lowest of these bands is shown in Figure 1, along with the corresponding part of the $z(x'x')\bar{z}$ spectrum. This latter spectrum shows, in addition to the bands of the LO_1 and LO_2 phonons of the $Al_{0.18}Ga_{0.82}As$ layers, two bands labeled I_- and I_+ at energies E_- = 27.6meV and E_+ = 38.8meV. Their normalized intensities and that of the E_{01} band in the

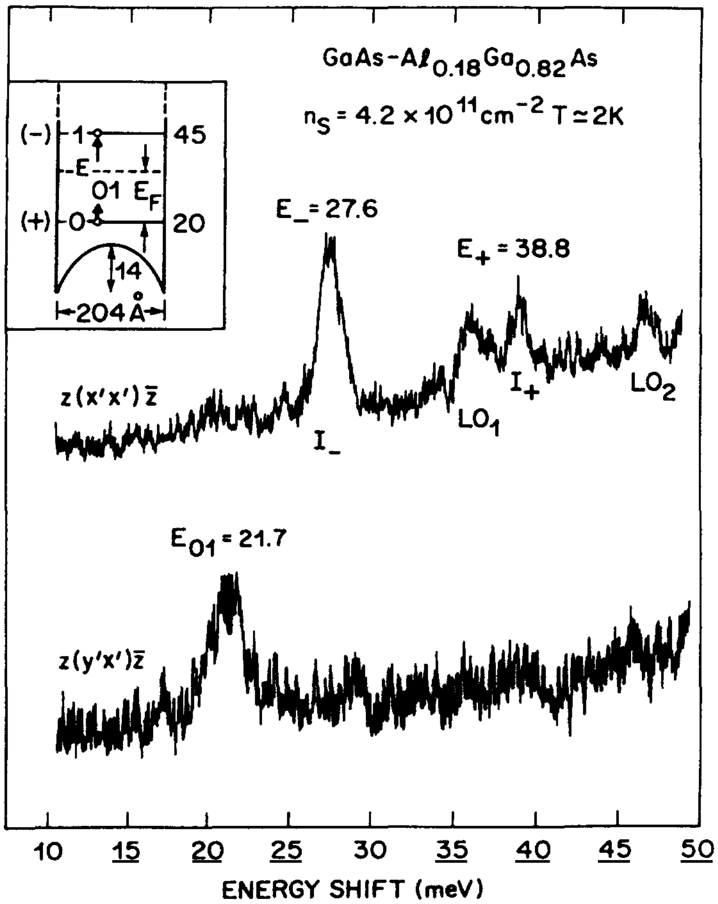

Fig. 1: Polarized light scattering spectra in the energy range of the lowest, odd parity, intersubband transition. $\hbar\omega_{laser}$ = 1935meV. The insert shows the calculated energies of the lowest subbands and the band bending. All the energies are in meV.

$z(y'x')\bar{z}$ spectrum have similar variation with incident photon energy. This indicates not only that they originate in the GaAs layers, but also that they are related to the same intersubband transition(0→1) shown in the insert to Figure 1.

We assign the I_- and I_+ bands to the two coupled collective modes of the charge density intersubband transition 0 → 1 and a GaAs LO phonon. The I_- mode, closer in energy to E_{01}, is mostly electronic in character. It is shifted upwards from E_{01} by its own resonant screening which is itself screened by the polar lattice. I_+ is the more phonon-like of the pair. We shall now justify this interpretation of the spectra in Figure 1 by a calculation of the coupled mode energies.

For $\vec{k}||\hat{z}$ the depolarization fields are also along $\hat{z}$ and are, therefore, contained within the layers. In order to calculate the energies of collective modes associated with the intersubband transitions, we may thus consider the case of a single layer and use the analysis of Dahl and Sham.[13] We neglect the coupling with transitions to other subbands, expected to be small because the E_{oi} are well separated. The coupled mode energies are then found to be the solutions of

$$1 - \frac{1}{\varepsilon_L(E_\pm)} \frac{E_{pl}^2}{E_\pm^2 - \hat{E}_{01}^2} = 0 \qquad (1)$$

where $\hat{E}_{01}$ is the intersubband energy in the absence of resonant screening. The "effective" plasma energy is

$$E_{pl} = \left[8\pi n_s e^2 L_{11} E_{01}/\varepsilon_\infty\right]^{1/2} \qquad (2)$$

where $\varepsilon_\infty = 11.1$. L_{11} is the matrix element of the direct Coulomb interaction in terms of a length given by[13]

$$L_{11} = \int_o^{d_1} dz \left(\int_o^z dz' \xi_o(z')\xi_1(z')\right)^2 \qquad (3)$$

where $\xi_o(z)$ and $\xi_1(z)$ represent the envelope functions of the two lowest subbands. In choosing the limits of integration we have assumed that the enevelope functions are completely within the GaAs layer.

In Equation (1), $\varepsilon_L(E_\pm)$ accounts for the screening of the Coulomb interaction by the polar lattice. $\varepsilon_L(E_\pm) = (E_L{}^2-E_\pm{}^2)/(E_T{}^2-E_\pm{}^2)$, where $E_T = 33.6$meV and $E_L = 36.7$meV are the energies of TO and LO phonons in GaAs. Equation (1) describes the coupling of collective intersubband excitations to LO phonons. It is similar to that obtained with the anisotropic dielectric slab model in which E_{pl} is a phenomenological parameter.[12]

In the following analysis we are going to take $\hat{E}_{01} = E_{01}$. This means that final state interactions are assumed to be the same for spin-flip and non-spin-flip intersubband transitions. We then treat E_p as an adjustable parameter in Equation (1) to fit the energies of the $E_\pm$ modes. With $E_{pl} = 21.1$meV we obtain $E_- = 27.5$meV and $E_+ = 38.9$meV, in excellent agreement with the measured energies. We go one step further and insert this fitted value of E_{pl} in Equation (2), to obtain $L_{11} = 15$Å. This is the first determination from experiment of an intersubband Coulomb matrix element in a two dimensional electron system. The relatively large value of L_{11}[2,13] is consistent with the properties of the lowest subband states in our sample. This we established by estimating the matrix element in Equation (3). For that purpose we used the envelope functions of an infinite square well potential of width $d_1 = 204$Å. This is a reasonable approximation since the band bending in these particular GaAs layers is small. We calculated $L_{11} = 11.5$Å. We note that finite band bending will tend to increase the overlap between envelope functions of the ground and first excited state, so this model calculation should, as it does, give a somewhat smaller value for L_{11}.

Even parity transitions, although inactive in optical absorption,[6] may and do have large depolarization fields giving rise to resonant screening effects that can be observed in light scattering spectra (see Equation 3). In the case of the 0 → 2 intersubband transition of our sample the depolarization fields can be thought of as arising from a quadrupolar distribution of induced charge density. Such an effect is described by a Coulomb interaction length L_{22} similar to that in Equation (3) but with $\xi_1(z)$ replaced by $\xi_2(z)$. In $z(x'x')\bar{z}$ spectra we found that the band of the 0 → 2 transition occurs at an energy higher by 1.1 ± 0.4meV than its corresponding band at $E_{02} = 63.7$meV in $z(y'x')\bar{z}$ spectra. This relatively small but measurable shift actually corresponds to a sizable "effective" plasma energy of $E_{p2} = 12$meV. This value of E_{p2} yields $L_{22} = 1.7$Å. Again using the envelope functions of the infinite square-well potential, we calculated $L_{22} = 3.3$Å. As in the case of L_{11}, the discrepancy is consistent with the expected distortion of the square well envelope functions due to band bending effects.

We would like to stress the fact that the results reported here show that light scattering spectra contain information about many-body interactions. Final state effects can be investigated by comparing the single particle energies of spin-density intersubband excitations with calculated subband spacings. In fact, we find that measured single particle energies are systematically lower than the subband spacings calculated either by outselves (see insert to Figure 1) or by Ando and Mori.[6] This could indicate that exciton-like shifts in GaAs, although most likely smaller than in Si,[6] may not be negligible. We, therefore, encourage theoretical investigations of the differences between final state interactions for spin-density and charge-density intersubband excitations of the two dimensional electron gas, the two types of excitations observed in light scattering spectra. Theoretical studies might also investigate the possibility that final state interactions can contribute to the observed bandwidths. For example, in Figure 1, the width of the band due to spin-density excitations is about twice as large as those of the collective coupled modes.

In summary we have used inelastic light scattering spectroscopy to make the first direct observation and evaluation of resonant screening associated with interband transitions of a dense two dimensional electron gas. Such a depolarization field affect exists for even parity as well as odd parity transitions. In addition, we have discussed more speculatively the possible observation of exciton-like or final state effects. We believe, finally, that the light scattering technique can be applied to other dense two dimensional electron systems (e.g., the silicon MOS structure) with the aim of elucidating the many-body interactions in two dimensions.

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