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Spin-density waves in a quasi-two-dimensional electron gas

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We report an inelastic-light-scattering study of the quasi-two-dimensional electron gas in $GaAs/Al_xGa_{1-x}As$ quantum-well structures. The spectra of the intersubband spin-density waves are measured as a function of wave vector. Detailed calculations are performed using self-consistent-field theory in which exchange and correlation are included through the local-spin-density approximation. We find good agreement between experiment and theory for both the energy of the spin-density wave at $k=0$ and the magnitude of the dispersion around $k=0$.

Intersubband spin-density waves (SDW) in a free-electron gas in microstructures exist through the exchange-correlation Coulomb interaction in a way similar to that by which charge-density waves (CDW), i.e., plasmons, exist through the direct Coulomb interaction. The energy shift of the SDW from the bare single-particle transition energy is a direct measure of exchange and correlation. In $GaAs/Al_xGa_{1-x}As$ structures, inelastic light scattering or Raman scattering can measure charge-density excitations (like inelastic electron scattering) and spin-density excitations.[1] In the latter case, this is possible because of spin-orbit coupling in the valence bands which are involved in the intermediate state of the Raman process.[1] Recently, Pinczuk *et al.*[2] demonstrated that collective SDW and intersubband single-particle excitations (SPE) of the quasi-two-dimensional (quasi-2D) electron gas could be measured with inelastic light scattering. In cases where the SPE are well separated from the collective excitations, the peak energy of the SPE gives a good measure of the bare intersubband transition energy and thus, Pinczuk *et al.*[2] were able to determine directly and precisely the strength of the exchange Coulomb field in this nonhomogeneous system. The intersubband excitation spectrum of the quasi-2D electron gas can be calculated using the self-consistent-field theory[3-5] in which exchange and correlation are included through the local-spin-density approximation (LSDA).[6,7] Therefore, inelastic light scattering on the quasi-2D electron gas presents a valuable opportunity to determine experimentally the applicability of LSDA to artificially structured semiconductors.

We report a study of the intersubband spin-density excitations of the quasi-2D electron gas in high-quality $GaAs/Al_xGa_{1-x}As$ quantum wells. Unlike the previous study,[2] the potential-energy profile of the structures are symmetric, and although our samples have broader spectral features (the SDW peak widths are approximately five times broader), well-defined CDW, SDW, and SPE are observed. We observe a strong dispersion of the SDW to lower energies with increasing wave vector in the layers. A detailed comparison of our Raman scattering measurements with a calculation employing the LSDA is presented. Exchange is included with and without correlation. In contrast to the previous study,[2] we find that the theoretical and experimental results are in good agreement for the energy of the SDW at $k=0$ and for the magnitude of the dispersion of this collective excitation around $k=0$.

Several $GaAs/Al_{0.25}Ga_{0.75}As$ multiple-quantum-well samples grown with conventional molecular-beam epitaxy were studied. All samples show similar behavior. In this paper we discuss the results from one, in particular, where the $Al_xGa_{1-x}As$ barriers were 600 Å thick with the center 30 Å doped with Si donors. The GaAs well widths and 2D densities are $L=260$ Å and $n_S=3.6\times10^{11}$ cm^{-2} per quantum well, respectively. Only one subband is occupied.

The inelastic-light-scattering spectra were obtained with a dye laser tuned to the $E_0+\Delta_0$ gap of the GaAs quantum wells. The data were taken at $T=6$ K and with laser power densities of 10–100 W/cm^2 using a cylindrical lens. The scattered light was collected with a f/1.2 lens. A backscattering geometry was employed and wave-vector transfer into the layers (perpendicular to the superlattice axis) was achieved by rotating the sample relative to the fixed incident wave vector of light. The charge-density and spin-density excitation spectra of the electron gas were obtained with the incident and scattered light polarized and depolarized, respectively. The excitations associated with the three subbands of lowest energy were studied.

Figure 1 displays the spin-density and charge-density spectra at small k (3×10^4 cm^{-1}) for excitations involving the two lowest energy subbands. The narrow peaks that occur at 13 and 20 meV arise from SDW and CDW collective excitations, respectively. In addition, there is a broad feature that occurs between the SDW and CDW which we assign to intersubband single-particle scattering (SPE). It appears in both spectra, although there is a difference in line shape. Specifically, in the polarized spectrum it exhibits a well-defined peak, whereas in the depolarized spectrum it merges with the SDW. As discussed below we take the peak energy of the SPE in the charge-density spectrum at $k=0$ to be the bare intersubband transition energy. The spin-density spectra obtained in the depolarized scattering geometries for several k values are shown in Fig. 2. The SPE band broadens and increases in intensity relative to the collective excitations with increasing k. While this behavior is similar to that reported previously, the shift of the SDW to lower energies with increasing k with little increase in linewidth is

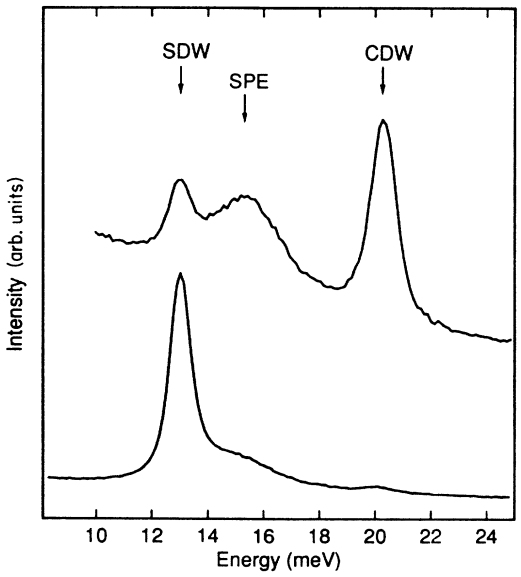

FIG. 1. Data of the first intersubband excitation spectra at $k=3\times10^4$ cm^{-1}. The top and bottom traces are the charge-density and spin-density spectra, respectively.

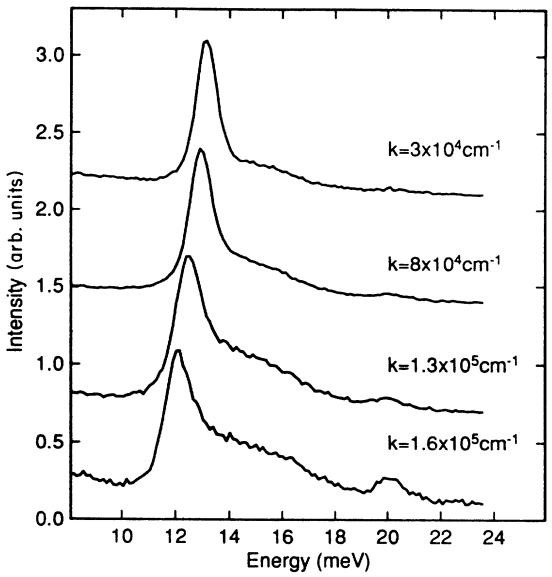

FIG. 2. The spin-density excitation spectra as a function of k.

different. Because of resonances involved in the scattering process,[1,8] the relative intensities of the SDW and SPE features change considerably when the laser energy is changed.

We determine the one-electron wave functions $\Psi_n(z)e^{i\mathbf{k}\cdot\mathbf{r}}$ and energies $\hbar\omega_n+\hbar^2k^2/(2m)$ of the quasi-2D electron gas from a self-consistent solution of the Kohn-Sham equation[9] in which exchange and correlation are included through the local-density approximation. The bare intersubband transition energies are given by $\hbar\omega_{nm}=\hbar\omega_m-\hbar\omega_n$. These wave functions and eigenenergies are used to determine the density-density correlation function, $\chi_i(k,\omega)$. The excitation spectra are proportional to the imaginary part of the density-density correlation functions

$$I_i(k,\omega)\propto -\mathrm{Im}\chi_i(k,\omega)\,, \tag{1}$$

where the subscript refers to the charge-density or spin-density response. In the absence of Coulomb interactions the response is that of the noninteracting electron gas. If there is no wave-function overlap between quantum wells, the spin-density excitations in different quantum wells are independent. This is also true for charge-density excitations at $k=0$. For a single quantum well in which couplings between excitations are negligible,[10] the noninteracting response function is given by[11]

$$\chi_0(k,\omega)=-\frac{m}{\pi\hbar^2}\left\{1+\frac{\omega_{01}}{\omega_k}-\left[\left(\frac{\omega+\omega_{01}}{2\omega_k}+\frac{1}{2}\right)^2-\frac{\omega_f}{\omega_k}\right]^{1/2}+\left[\left(\frac{\omega-\omega_{01}}{2\omega_k}-\frac{1}{2}\right)^2-\frac{\omega_f}{\omega_k}\right]^{1/2}\right\}, \tag{2}$$

where $\omega_f=\pi\hbar n_S/m$ and $\omega_k=\hbar k^2/2m$. This produces a single band of SPE peaked and centered at $\hbar\omega_{01}+\hbar^2k^2/2m$. When electron interactions are included through the LSDA, the response is modified,

$$\chi_i(k,\omega)=\frac{\chi_0(k,\omega)}{1-\gamma_i(k)\chi_0(k,\omega)}\,. \tag{3}$$

Collective excitations occur at the poles of χ_i,

$$1-\mathrm{Re}\gamma_i(k)\chi_0(k,\omega)=0,\ \mathrm{Im}\gamma_i(k)\chi_0(k,\omega)=0\,, \tag{4}$$

and the SPE are partly screened. The Coulomb interaction is written in terms of the direct term, $\alpha(k)$ and exchange and correlation terms, β_i:

$$\gamma_{\mathrm{CD}}(k)=\alpha(k)/\tilde{\epsilon}(\omega)-\beta_{\mathrm{CD}} \tag{5}$$

and

$$\gamma_{\mathrm{SD}}(k)=-\beta_{\mathrm{SD}}\,. \tag{6}$$

The direct term is given by[9,12]

$$\alpha(k)=\frac{2\pi e^2}{\epsilon_\infty k}\int dz\int dz'\,\Psi_0(z)\Psi_1(z)\times e^{-k|z-z'|}\Psi_0(z')\Psi_1(z')\,. \tag{7}$$

In the above equations we follow the conventions of Pinczuk *et al.*[2] and separate out the resonant LO phonon contribution to the background dielectric constant $\epsilon(\omega)=\epsilon_\infty\tilde{\epsilon}(\omega)$,

$$\tilde{\epsilon}(\omega)=\frac{\omega^2-\omega_{\mathrm{LO}}^2}{\omega^2-\omega_{\mathrm{TO}}^2}\,, \tag{8}$$

where ω_{LO} and ω_{TO} are the phonon energies. The exchange and correlation contribution to the interaction in the response function is given by

$$\beta_i=-\int dz\,U_i(z)\Psi_0^2(z)\Psi_1^2(z)\,. \tag{9}$$

$U_i(z)$ is given by

$$U_i(z)=\left.\frac{\partial V_i}{\partial \rho_i}\right|_{\rho_{CD}=n_S\Psi_0^2(z),\rho_{SD}=0}, \tag{10}$$

where V_i are the exchange and correlation potentials and ρ_i is either the 3D charge density, $\rho_{CD}=\rho_\uparrow+\rho_\downarrow$, or spin density, $\rho_{SD}=\rho_\uparrow-\rho_\downarrow$, and $\rho_\uparrow$ and $\rho_\downarrow$ are the number densities with spin up and down, respectively. This interaction has different forms for the spin-density and charge-density excitations. Using V_i from Ref. (6) we find

$$U_{CD}(z)=(-1.706a_B^3r_S^2)\left(1+\frac{0.6213r_S}{11.4+r_S}\right)(\mathrm{Ry}_{GaAs}) \tag{11}$$

and

$$U_{SD}(z)=(-1.706a_B^3r_S^2)\left(1-0.036r_S+\frac{1.36r_S}{1+10r_S}\right)(\mathrm{Ry}_{GaAs}), \tag{12}$$

where $r_S(z)=[4\pi a_B^3 n(z)/3]^{-1/3}$, $n(z)=n_S\Psi_0^2(z)$, a_B is the Bohr radius in GaAs (104 Å), and Ry_{GaAs} is the effective Rydberg for GaAs. The first term in Eqs. (11) and (12) is identical and arises from the exchange interaction. The remaining terms are a consequence of electron correlations. At $k=0$ the energies of the collective excitations from Eq. (4) are given by

$$\frac{\omega_{01}^2-\omega_{SD}^2}{\omega_{01}}=\frac{2n_S}{\hbar}\beta_{SD} \tag{13}$$

and

$$\frac{\omega_{CD}^2-\omega_{SD}^2}{\omega_{01}}=\frac{2n_S}{\hbar}[\alpha(0)/\tilde{\epsilon}(\omega_{CD})-\beta_{CD}+\beta_{SD}]. \tag{14}$$

To compare the experimental values of energy on the left-hand side of Eq. (13) with β_{SD} obtained from LSDA theory on the right-hand side we need accurate values for the density (n_S) and well width (L). These are found from the Raman data. We use our result that $(\beta_{CD}-\beta_{SD})\tilde{\epsilon}(\omega_{CD})/\alpha(0)<0.05$ to neglect the last two terms on the right-hand side of Eq. (14). Since $\alpha(0)$ from Eq. (7) is a function of n_S and L, the right-hand side of Eq. (14) is a function of n_S and L. The value of this function is given by the measured energies on the left-hand side of Eq. (14). We also have the constraint that $\hbar\omega_{01}$ as calculated for a given pair of values for n_S and L must be fixed at the value measured in the charge-density spectrum of Fig. 1. This allows us to calculate n_S and L self-consistently. In fact, because we also have data for the excitations associated with $\hbar\omega_{02}$ and $\hbar\omega_{12}$, and also for the phononlike modes associated with $\hbar\omega_{01}$ and $\hbar\omega_{02}$, the problem is overspecified. We find that all values that we calculate for n_S and L agree to within 20%. The difference between experimental and calculated values of β_{SD} is found to be less than 15%. In addition the values of $\beta_{SD}/\alpha(0)$ agree to within 5%. In Fig. 3 the solutions to Eq. (4) as a function of k are shown with and without the correlation terms in Eq. (12). The edge of the single-particle continuum is also shown $(\hbar\omega_{01}\pm v_f\hbar k+\hbar^2k^2/2m)$, where $v_f=(\hbar/m)(2\pi n_S)^{1/2}$ and the experimental value for $\hbar\omega_{01}$ is employed. The peak energies of the SDW from Fig. 2 are also plotted for comparison. Correlation makes a relatively small improvement in the agreement between the calculated and experimental results. In addition, the magnitudes of the dispersion from theory and experiment are in good agreement. Because the data points do not overlap with the SPE continuum, the SDW should not be Landau damped. This is consistent with the lack of significant broadening of the SDW peak in Fig. 2 with increasing k.

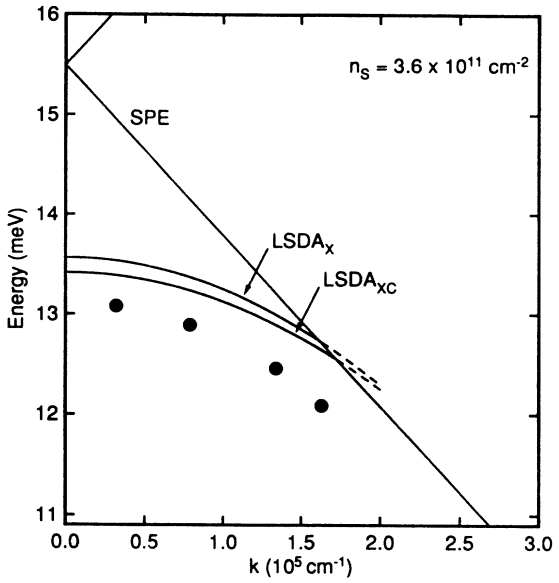

FIG. 3. The dispersion of the measured SDW energy (dots), the calculation results with and without correlation ($\mathrm{LSDA_{xc}}$ and $\mathrm{LSDA_x}$), and the SPE continuum.

We have also performed the calculation using the given n_S and well width for the asymmetric quantum well of one of the samples studied by Pinczuk *et al.*[2] The asymmetry in the quantum-well potential arises because the quantum well is doped only on one side. The experimental and calculated values agree to within 10% for β_{SD} and 20% for $\beta_{SD}/\alpha(0)$. However, from our calculation we would also expect a measurable dispersion which they do not observe. A possible explanation involves the asymmetry of their quantum well. Because of this asymmetry there is a coupling between the intersubband and intrasubband transitions which would tend to decrease the dispersion. However, from our calculations this coupling is about 2 orders of magnitude too small to flatten out the dispersion curve.

Finally, we discuss the intensities of our spectra. The line shape of the calculated SPE given by Eq. (1) agrees with the data. In particular, the SPE band in the spin-density spectra is not peaked at $\hbar\omega_{01}$, but is stronger closer to the SDW energy. This is due to the screening factor $[1-\beta_{SD}\chi_0(k,\omega)]^{-1}$ which enhances the SPE band in the region of $\hbar\omega_{SD}$. This is in contrast to the charge-density spectrum in Fig. 1 which, because $\hbar\omega_{CD}$ is well away from it, shows a peaked symmetrical band. A comparison between the relative intensities of the SDW, CDW, and SPE features is difficult because of the resonant nature of the Raman process. The spectra show large resonant enhancements which change the relative intensity of the peaks as the laser energy is changed. In

addition, several scattering mechanisms may be present which could affect the excitations differently.

In conclusion, the energies and line shapes of the single particle and collective-spin-density excitations of the quasi-2D electron gas as a function of k are well described by a generalized self-consistent-field theory in which exchange and correlation are included through a static local-spin-density approximation.

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