Raman studies of intrasubband plasmons in laterally modulated two-dimensional electron gases

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We report an inelastic light-scattering study of the intrasubband plasmons of a single two-dimensional electron gas (2DEG) at a $GaAs/Al_xGa_{1-x}As$ heterointerface under a grating Schottky gate with a period comparable to the plasmon wavelength. Gaps appear in the plasmon dispersion relation because of the spatially periodic screening by the gate, and these are successfully modeled using a scattering matrix calculation of the electromagnetic response of the system. Biasing the gate periodically modulates the 2DEG carrier density, and has a striking effect on the plasmon dispersion relation that cannot be fully explained within the existing theoretical framework.

I. INTRODUCTION

The excitations of two-dimensional electron gases (2DEG's) in Si-metal-oxide-semiconductor (Si-MOS) and $GaAs/Al_xGa_{1-x}As$ high-electron-mobility transistor (HEMT) structures have been the subject of very widespread interest for several years, and in particular the collective excitations—plasmons, both intersubband and intrasubband—have attracted much theoretical and experimental attention. The behavior of 2DEG's in structures with an overlaid Schottky gate is of particular interest since this allows the 2DEG density, and thus the plasmon energies, to be varied directly by applying a gate bias. An overlaid gate can also be laterally structured to form a grating which can act as a coupler for direct optical excitation of the plasmon modes. Biassing such gates can also modulate the 2DEG density, and at sufficiently strong biasses the 2DEG can be pinched off to form one-dimensional (1D) wires under a lamellar grating, or zero-dimensional (0D) dots under a 2D array of apertures in a gate.

We concentrate here on the intrasubband plasmons; the frequency ω of the intrasubband plasmon of a single, uniform 2DEG is expected[1] to disperse with wave vector k according to

$$\omega^2=\frac{N_s e^2}{2\bar{\varepsilon}\varepsilon_0 m^*}k \ , \qquad (1)$$

where N_s is the areal carrier density of the 2DEG, m^* is the electronic effective mass [taken here to be 0.070 m_e (Ref. 2)], and e is the electronic charge. The screening of the plasmons by the layers surrounding the 2DEG is accounted for in the effective dielectric constant $\bar{\varepsilon}$. For a HEMT structure without a gate—an open surface—the appropriate expression is[3]

$$\bar{\varepsilon}=\frac{(\varepsilon_{Al}+1)(\varepsilon_{Ga}+\varepsilon_{Al})+(\varepsilon_{Al}-1)(\varepsilon_{Ga}-\varepsilon_{Al})e^{-2kh}}{2(\varepsilon_{Al}+1+(\varepsilon_{Al}-1)e^{-2kh})} \ , \qquad (2)$$

where ε_{Ga} is the dielectric constant of GaAs, ε_{Al} is the dielectric constant of $Al_xGa_{1-x}As$, and h is the distance between the 2DEG and the sample surface. For a HEMT structure covered by a metallic gate—a closed surface—the corresponding expression is[4]

$$\bar{\varepsilon}=\frac{\varepsilon_{Ga}+\varepsilon_{Al}\coth(kh)}{2} \ . \qquad (3)$$

For systems with laterally structured gates—partly open surfaces—it is to be expected that the effective dielectric screening is intermediate between those given by Eqs. (2) and (3), and that gaps should appear in the dispersion relation of the modes because of the sample periodicity introduced. For a 2DEG having a carrier density periodically modulated by applying a bias to the grating, Krasheninnikov and Chaplik[5] and Chaplik and Govorov[6] have predicted gaps in the plasmon dispersion relation when the in-plane wave vector k is an integral multiple of π/d, where d is the period of the modulation; the calculations of Ager and co-workers[7,8] extended this work to include the periodic screening effects of a grating gate, and showed that this could itself induce similar gaps.

Typical plasmon energies are in the range 10–100 cm^{-1}, suitable for investigation using far-infrared (FIR) radiation or Raman scattering. Such intrasubband plasmons have been observed with FIR emission and transmission spectroscopies,[9,10] and, for a 2DEG in a Si-MOS system with a carrier density spatially modulated by a Schottky grating gate,[11,12] gaps in the plasmon dispersion relation were indeed observed. Similar experiments[13,14] on 2DEG's in $GaAs/Al_xGa_{1-x}As$ systems showed that the modulation in carrier density significantly affected the behavior of the plasmons. Wilkinson *et al.*[14] also demonstrated the influence of the periodic screening by the grating gate. Unfortunately FIR absorption measurements are limited in that only values of k corresponding to the grating wave vector k_g, or a multiple thereof, can be probed. Raman measurements however can map out dispersion relations with good resolution over a wide range of values of in-plane wave vector k by changing the scattering geometry.[15,16] But Raman signals from these structures are weak, so most work has involved multiple quantum-well (and hence multiple 2DEG) systems;[15,16] for such systems with a grating gate[17,18] each 2DEG was separated from the grating gate by a different distance, so the screening effect, and any gate-bias-induced number-density modulation, was different for each 2DEG and no clear effect could be observed and interpreted.

So single 2DEG samples, especially with unstructured and grating gates, are of particular interest, but are experimentally more demanding. Apart from one early study of the single-particle excitations (SPE's) of a high-electron mobility transistor structure,[19] not until recently has there been much success using Raman spectroscopy to probe the intrasubband excitations of a single 2DEG; the k-dispersion relations of intrasubband plasmons of a single 2DEG have now been measured for a $GaAs/Al_xGa_{1-x}As$ quantum well[2,20] and for a $GaAs/Al_xGa_{1-x}As$ HEMT structure[21] using Raman spectroscopy, and more recently for single 2DEG samples with an unstructured gate,[22] and (together with the corresponding SPE's) in 1D wires formed from a single 2DEG (Ref. 23) as a function of the momentum transfer parallel to the wire direction.

Here we report Raman measurements on the plasmons of a single 2DEG in a HEMT structure with a surface Schottky grating gate—a conducting layer with an array of circular apertures; measurements have been made at several gate biasses, and permit a practical test of the theoretical approaches of Krasheninnikov and Chaplik[5] and of Ager and co-workers.[7,8]

II. EXPERIMENTAL DETAILS

The sample structure was similar to that of a standard HEMT, consisting of a GaAs substrate and buffer layer, followed by a superlattice (60×28 Å GaAs/28 Å AlAs), a GaAs active layer (1000 Å thick), an $Al_xGa_{1-x}As$ spacer layer (240 Å thick), a doped $Al_xGa_{1-x}As$ layer (480 Å thick), and a GaAs capping layer (100 Å thick); the Al mode fraction was 0.3 for all the $Al_xGa_{1-x}As$ layers. Also included was a δ-doped Be layer in the GaAs active layer, 250 Å from the active heterointerface to enhance the light scattering cross section of excitations of the 2DEG.[21,22] Hall-voltage measurements gave the 2DEG mobility and carrier density as 2.2×10^5 $cm^2\,V^{-1}\,s^{-1}$ and 2.1×10^{11} cm^{-2}, respectively, in the dark; the corresponding values after brief illumination by a red light-emitting diode were 3.0×10^5 $cm^2\,V^{-1}\,s^{-1}$ and 2.5×10^{11} cm^{-2}. The grating gate consisted of a 700 Å-thick metallic (nichrome) layer in which a regular square array (period $d=1.48$ μm) of circular apertures (diameter 0.87 μm) had been defined using electron-beam lithography over an area 400×200 μm^2.

The Raman spectra were obtained using a standard dye laser (pumped by a Kr ion laser) operating at a wavelength of about 780 nm (wave number $k_L=0.8\times10^5$ cm^{-1}) in combination with a Dilor triple spectrometer with multichannel detection. The sample was located in a liquid-helium cryostat and maintained at a temperature close to 10 K. The laser light entered and exited the cryostat in a back-scattering geometry. The momentum transfer parallel to the sample surface was determined by the angles of incidence (θ_L) and scattering ($\theta_R\approx\theta_L$), and varied as described elsewhere[16,22] up to a maximum of $2k_L$. The incident laser light was linearly polarized in a plane determined by a rotatable polarizer, while the scattered light was effectively linearly polarized by the (~95%) polarization selectivity of the optical-detection system. All the spectra presented here correspond to a configuration with incident and detected photons polarized parallel, which allows the observation of plasmons.[24] The polarization of the light and the momentum of the plasmons both lay parallel to one of the two principal axes of the square dot array. The laser power was 40 mW and the laser power density varied about 25 W cm^{-2} as the sample was rotated; the observed plasmon energies were constant over the range of power densities involved.

III. RAMAN STUDIES FOR AN UNBIASED GRATING GATE

Some representative Raman spectra for the structure described in Sec. II are shown in Fig. 1 for various values of k, and with zero applied gate bias V_g. Previous Raman studies of a sample of the same wafer with an unstructured gate[22] showed a single plasmon peak, but here two peaks appear, an effect also seen in Raman studies of a $GaAs/Al_xGa_{1-x}As$ multiple quantum-well system with a lamellar grating gate.[18] We assume that the two peaks correspond to plasmons (i) with the wave vector supplied by the scattering configuration, $k_s=k_L(\sin\theta_R+\sin\theta_L)$, and (ii) to plasmons with wave vector $k_s\pm k_g$, where the grating lattice vector $k_g=2\pi/d$.

The energies of these features are plotted in Fig. 2 as functions of k, together with attempts to fit the observed dispersion with the expected dispersions for open and closed surfaces [Eqs. (2) and (3)]. It can be seen that by shifting the higher-energy set of peaks to higher k by k_g, the two theoretical dispersion relations thread both sets of points quite neatly; attempts to fit the data to the plasmon dispersion relations assuming that the modes correspond to other momentum transfers (e.g., k_s and k_s-k_g) were not satisfactory, and it appears that the two peaks indeed correspond to plasmons of wave vectors k_s and k_s+k_g. It is not understood why only these two plasmon modes should be observed, and not those corresponding to k_s-k_g, k_s-2k_g, $k+2k_g$, etc. Nor is it un-

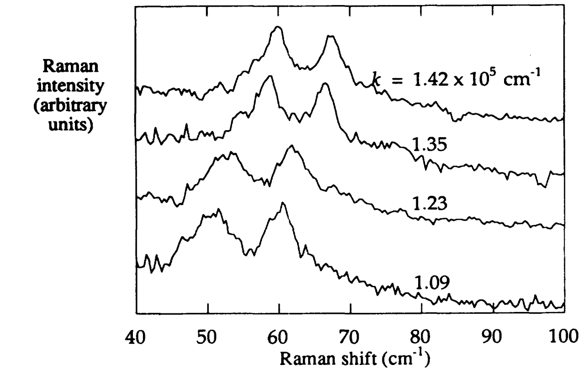

FIG. 1. Raman spectra for a 2DEG under-dot grating gate for various values of momentum transfer k, at $V_g = 0$ V.

derstood why peaks due to nonparallel folding of the plasmon modes are not observed. The range of k_s investigated had an upper bound given by the scattering geometry and momentum conservation ($k_s < 2k_L = 1.6\times10^5$ cm^{-1}), and a lower bound determined by the sharp decline in plasmon signal intensity below $k = 0.8\times10^5$ cm^{-1};[25] this range was coincidentally very close to k_g, so that the two sets of data points meet almost perfectly end-to-end when shifted as described above.

For the closed surface relation [Eq. (3)] the best fit corresponded to an electron density $N_s = 4.97\times10^{11}$ cm^{-2}, while for the open surface relation [Eq. (2)] $N_s = 4.24\times10^{11}$ cm^{-2}. Neither fits the data well, and an ideal fit must lie somewhere between the two, consistent with the fact that the surface is partly open and partly metallized.[8] Both of the numbers are considerably larger than the number extracted from Hall measurements, presumably because of the differing conditions of illumination.

The data above correspond to $V_g = 0$ V, so the 2DEG carrier density should be uniform. Some density modulation arising from spatially periodic photoexcitation because of the shadowing of the incident laser light by the metal grating might be expected, but for a period of 1.5 μm this should be negligible because of lateral diffusion of the photoexcited carriers.[26] But though the density modulation is negligible, the system is still periodic because the screening influence of the gate is periodic, and gaps in the dispersion relation at values of k, which are integer multiples of $k_g/2$, are to be expected. In Fig. 3 the central part of Fig. 2 is magnified, and there are indeed gaps apparent in the plasmon dispersion curve close to $k = 3k_g$ and $4k_g$, although there is no noticeable gap at $k = 3.5k_g$. At these gaps, the plasmon dispersion relation is flat, giving rise to standing-wave modes with charge-density oscillation amplitudes which are symmetric and antisymmetric with respect to the center of the grating apertures. One of the two modes is better screened by the metal grating and has the lower energy, but a complicating factor in calculating the mode energies is that the charge-density oscillations are substantially distorted from sinusoidal by the presence of the grating itself.[27]

A fully two-dimensional calculation of the plasmon dispersion relation for this system would be very difficult, and is beyond the scope of this paper, necessitating the use of a more readily available alternative. Ager and Hughes[7] have developed a scattering-matrix computer code for the calculation of the electromagnetic response of multilayered systems including lamellar grating structures, and this also allows the calculation of the dispersion relation of any plasmon modes. Figure 4 shows the results of such a calculation for a sample structure identical to that studied experimentally, except that the grating is necessarily lamellar rather than dot grating. [The mark-space (metal to gap) ratio of the lamellar grating was arbitrarily set at 0.61/0.87 μm, 0.61 μm being the distance separating the edges of the dots and 0.87 μm the dot diameter.] Comparison with the data in Fig. 3 can therefore only be approximate, but there are nevertheless surprising similarities. Gaps are observed in the calculated dispersion relation at $k = 3k_g$, $3.5k_g$, and $4k_g$, and are

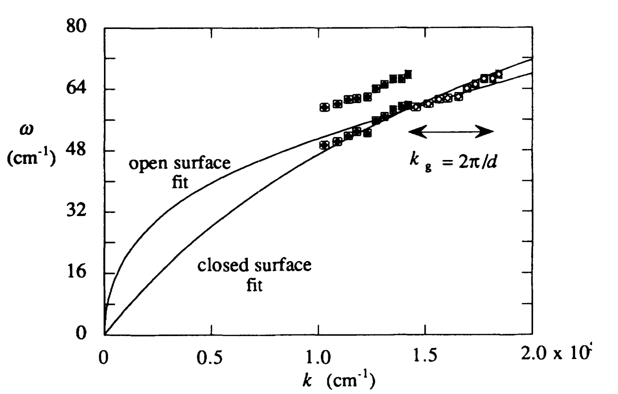

FIG. 2. Plasmon dispersion for the sample with a dot-grating gate with $V_g = 0$ V. ♦ denote the observed Raman peaks and ◊ denote higher-energy series of peaks shifted through $k_g = 2\pi/d$, where d is the grating period. The experimental errors are represented by the small boxes which surround each data point. Also shown are two fits to the data, one using the closed surface dielectric constant [Eq. (3)] and $N_s = 4.97\times10^{11}$ cm^{-2}, the other the open-surface expression [Eq. (2)] and $N_s = 4.24\times10^{11}$ cm^{-2}.

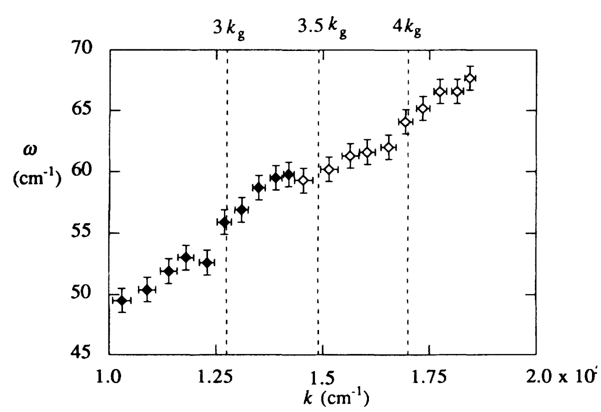

FIG. 3. A closeup of the central part of Fig. 2. Vertical dotted lines mark the positions $k = 3k_g$, $3.5k_g$, and $4k_g$.

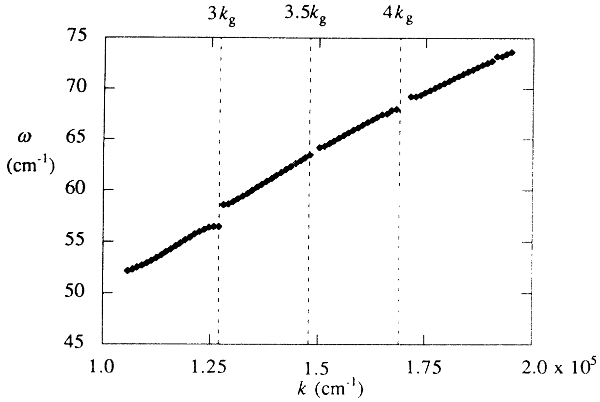

FIG. 4. Scattering matrix calculation of the plasmon dispersion relation in a 2DEG (of carrier density 5×10^{11} cm^{-2}) under the periodic screening effect of a linear grating gate of period 1.48 μm and mark-space ratio 0.61/0.87 μm.

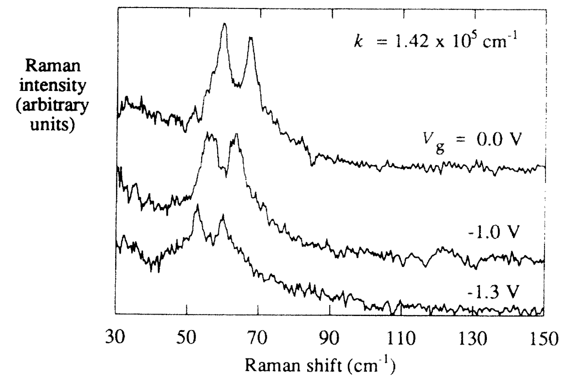

FIG. 5. Intrasubband plasmon spectra for different gate voltages applied to the dot-grating gate. The spectra are spaced vertically for clarity.

very similar in magnitude to those in the experimental dispersion relation, i.e., ~2.5 cm^{-1} at $k=3k_g$ and ~1.5 cm^{-1} at $k=4k_g$. The experimental data show no clear gap at $k=3.5k_g$ (though this region of the experimental dispersion curve may be difficult to interpret because $k=3.5k_g$ coincides with the stitching point between two sets of data) and any gap here must certainly be much smaller than those at $3k_g$ and $4k_g$. The gap calculated at $k=3.5k_g$ is also much smaller than the others, and the fact that both experiment and theory indicate that the gaps do not decrease monotonically with increasing order is contrary to previous expectation.[11] The surprisingly good agreement between experiment and theory, given that the calculation is for a lamellar grating with a somewhat arbitrary mark-space ratio, can in part be accounted for by noting that the gaps in the dispersion relation must be zero for mark-space ratios of either zero or infinity, and reach a maximum value for some intermediate mark-space ratio. A peak in the gap's size as a function of mark-space ratio corresponds to a slow variation in gap size as a function of mark-space ratio. Ager, Wilkinson, and Hughes[8] showed that the magnitudes of gaps in the dispersion relation should be constant (to within $\pm15\%$) for lamellar grating mark-space ratios in the range 0.4–2.5; this embraces the value of 0.7 used for Fig. 4 and the largest reasonable value of 2.7 corresponding to the ratio of the metallized and open areas. That the calculated plasmon energies are a little larger than those experimentally determined reflects the fact that the 2DEG carrier density used in the calculation (5×10^{11} cm^{-2}) is slightly higher than those (4.24 and 4.97×10^{11} cm^{-2}) obtained from the experimental fits shown in Fig. 2.

IV. RAMAN STUDIES FOR A BIASED GRATING GATE

Applying a negative voltage V_g between the gate and the 2DEG reduces the carrier density under the metallized areas of the gate, and so modulates the carrier density. Figure 5 shows representative Raman spectra taken at different gate biases, and in Fig. 6 the corresponding dispersion relations obtained from many such spectra are plotted. The initial effect of making the gate bias more negative is simply to shift the dispersion relation down a little in energy, corresponding to a lower average charge density. Increasing the bias, and correspondingly the amplitude of the charge-density modulation, has dramatic consequences for the dispersion relation; this corresponds to the situation where the 2DEG is substantially depleted under the metallized areas of the gate, and the 2DEG dots are separated by areas of low-carrier density and low mobility. The dispersion relation differs considerably between a gate bias of -1.0 and -1.3 V, despite the fact that the carrier density for a similar sample with a continuous gate hardly changes over the same bias range;[22] this is because higher biases are required to influence the 2DEG density under the apertures in the structured gate used here. The dispersion relation for $V_g=-1.3$ V oscil-

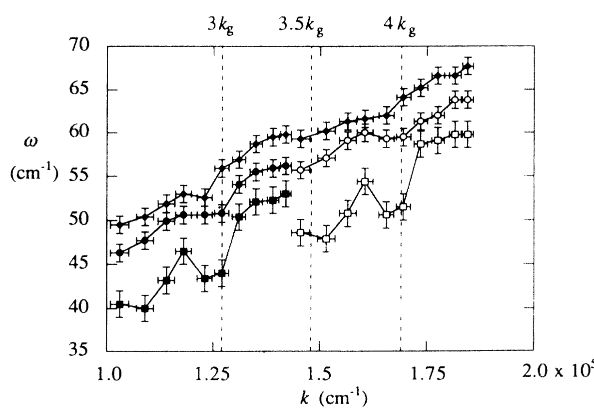

FIG. 6. Dispersion relations of intrasubband plasmons of a 2DEG under a dot-grating gate for different gate voltages: 0.0 V (diamonds), -1.0 eV (circles), and -1.3 V (squares). The filled data points correspond to the lower energy of each pair of peaks, while the open points are derived by shifting the higher-energy peak of each pair upwards in k by k_g as in Fig. 2. Vertical dotted lines mark the positions $k=3k_g$, $3.5k_g$, and $4k_g$.

lates with k with a large ($\sim 20\%$) amplitude, and period $0.5k_g$

While the plasmon energies of a 2DEG with a periodically modulated carrier density have been investigated for both strong and weak modulation (Eliasson *et al.*[28]), plasmons in periodically modulated 2DEG's with grating-induced periodic screening have received limited theoretical attention. Ager and Hughes[7] found that the screening influence of the grating modified considerably the plasmon energies from those predicted for a modulated 2DEG without periodic screening by Krasheninnikov and Chaplik;[5] this latter approach allows the calculation, for weak modulation amplitudes and ignoring the periodic screening of the grating, of any gap in the dispersion relation, and gives the gap at $k = nk_g/2$ as $N_n \omega_0 / N_0$, where ω_0 is the plasmon energy for the unmodulated 2DEG (with the average carrier density N_0) and N_n is the amplitude of the nth Fourier component in the expansion of the periodic charge-density profile.[6] For the lower two curves in Fig. 6 the carrier density is expected to be about 1.5×10^{11} cm^{-2} under the metal (from work on a sample of the same wafer with a uniform gate[22]) while for the dots the density should be about 5×10^{11} cm^{-2} (Sec. III). Although the latter figure may have been somewhat lower because of fringing effects from the electric field between the metal gate and the 2DEG, it is clear that the overall density modulation is strong and it is extremely unlikely that the approach of Krasheninnikov and Chaplik is applicable here.

The situation under investigation here is complex, with three competing length scales—the periodicity of the dot array, the dot diameter, and the plasmon wavelength—all of which are comparable in magnitude. Clearly a sophisticated numerical simulation of the system is required to model the observed behavior adequately. A more accurate experimental determination of the dispersion relation would also be desirable, but the k spacing in Fig. 6 is already close to the limit of resolution of the optical system.

V. CONCLUSION

In summary, the presence of a Schottky grating gate on the surface of a modulation-doped HEMT structure with a single 2DEG was found to induce an extra intrasubband plasmon peak derived from the transfer of momentum corresponding to the grating periodicity. The periodic screening of the 2DEG by the grating was also found to induce energy gaps in the plasmon dispersion relation at the corresponding zone boundaries, in accordance with theoretical predictions. The magnitudes of the gaps agree with the results of a calculation using the scattering matrix technique. Strong spatial periodic modulation of carrier density by a Schottky grating gate, with a period of the same order of magnitude as the plasmon wavelengths, also has a striking effect, introducing quasioscillatory behavior into the dispersion relation; this cannot be explained within the existing theoretical framework.

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