Capacitance Oscillations in One-Dimensional Electron Systems

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We have made the first capacitance measurements of the density of states of quasi one-dimensional electronic systems. We observe oscillations reflecting the discrete energy levels of doubly confined electrons squeezed beneath submicron lines (0.2, 0.3, and 0.4 μm wide) patterned on the surface of GaAs-$Al_xGa_{1-x}As$ heterojunction capacitors. The spacings of the oscillations and their dependence on potential well width can be explained theoretically by quantum size effects and the quasi one-dimensional nature of our samples.

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Experimental studies of quasi one-dimensional (1D) electronic systems have been in progress for almost a decade. The first studies were done with the use of Si metal-oxide-semiconductor field-effect transistors (MOSFET's)[1-3] and, subsequently, GaAs heterostructures.[4] Some 1D effects [including density-of-states (DOS) effects] are more accessible in GaAs heterostructures because the effective mass is lighter (reducing the size requirements) and potential fluctuations are much smaller (reducing the broadening of 1D states). A variety of techniques have been employed to study 1D effects in Si[5-8] and III-V materials.[9-13]

In this Letter we report the results of capacitance measurements of quasi-1D electronic systems. Capacitance measurements have been widely used to study two-dimensional electronic systems (2DES),[14] and recently we showed that capacitance measurements could be used to determine the density of states of a 2DES in a quantizing magnetic field.[15] This is true only if parasitic resistance effects (long the bane of low-temperature capacitance measurements) can be avoided. One technique to avoid such effects to inject charge into an electronic system from an electrode in close proximity (see Fig. 1). If the series resistance is small compared with the capacitive impedance ($1/j\omega C$), then the DOS can be extracted from the measured capacitance. This is because the capacitance is sensitive to the filling of states in an electronic system. In this work we have exploited this technique to probe the energy spectra of quasi-1D electronic systems. There is good agreement between our experimental results and self-consistent calculations of the capacitance.

The samples used in our experiments are GaAs-$Al_xGa_{l-x}As$ heterostructure capacitors and a cross-sectional view is shown in Fig. 1. These samples are similar to those used by Hansen *et al.*,[16] except that the grating is produced by etching of the heterostructure rather than deposition of an insulator, and the sample has a conducting substrate. Because of the doped substrate, the mobility could not be measured directly. However, a sample grown to similar specifications had a low-temperature mobility of 5×10^5 cm^2/V-s. Grating capacitors with 0.2-, 0.3-, and 0.4-μm lines were fabricated with use of electron-beam lithography and reactive-ion etching. First, 250×250-μm^2 patterns (with periods approximately twice the width of the lines) were written into polymethylmethacrylate (PMMA) with a high-resolution electron-beam pattern generator.[17] An averaging process[18] was used to produce extremely smooth, regular lines. The PMMA was used as an etch mask and the GaAs cap layer was selectively etched in CCl_2F_2/He gas.[19] To reduce the damage to the surface of the $Al_xGa_{1-x}As$, the etching was terminated within 1 s after the $Al_xGa_{1-x}As$ surface was exposed. The PMMA was then removed and a 200×200-μm^2 metal gate was deposited.

The capacitance was measured with both a capacitance bridge and a lock-in amplifier at temperatures between 4.2 and 0.4 K. Data were taken only at voltages

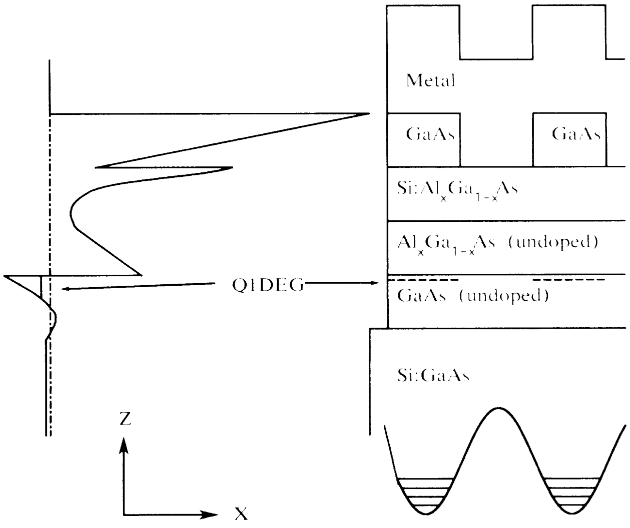

FIG. 1. Schematic drawing of the sample configuration and the resulting potential profiles. The electrons are confined in both the vertical ($\hat{z}$) and horizontal ($\hat{x}$) directions.

where the leakage current and series resistance were low enough that the signal was purely capacitive. Under these conditions the measured capacitance can be unambiguously related to the thermodynamic DOS. In addition, we worked at frequencies below 50 kHz, where there was no frequency dependence. The capacitance of the unpatterned sample is significantly different from that of the other samples. First, the capacitance of the control sample has a very sharp rise at turnon and, second, there is no structure in the capacitance after turnon. For the patterned samples the turnon is much more gradual. This is both a geometrical effect as well as an indication that the DOS is significantly different from that of unpatterned capacitors. Above turnon, there are weak oscillations in the capacitance.

Although the structure in the capacitance becomes stronger at low temperatures, it is still quite weak even at 0.4 K. To identify more clearly the positions of the peaks in the DOS we measured the first derivative of the capacitance (see Fig. 2). The main peak at the highest negative biases results from initial turnon of the capacitors. It is so large that it masks the presence of the lowest-lying 1D levels. Above turnon, we observe a well-resolved set of oscillations. These oscillations directly reflect the change in the DOS as the Fermi energy passes through successive 1D levels. Their spacing and magnitude are largest for the 0.2-μm lines. Both the amplitude and period of the oscillations decrease monotonically with increasing line size. This is consistent with the behavior of the DOS that one would expect for electrons confined to successively wider potential wells; i.e., the spacing of the energy levels and the variations in the DOS are largest for a narrow well. For all sizes of lines we are able to resolve a very large number of levels (at least fifteen in samples with 0.4-μm lines). It is surprising that the oscillations persist to such large positive biases and is indicative of a very well-defined potential, as well as relatively modest level broadening.

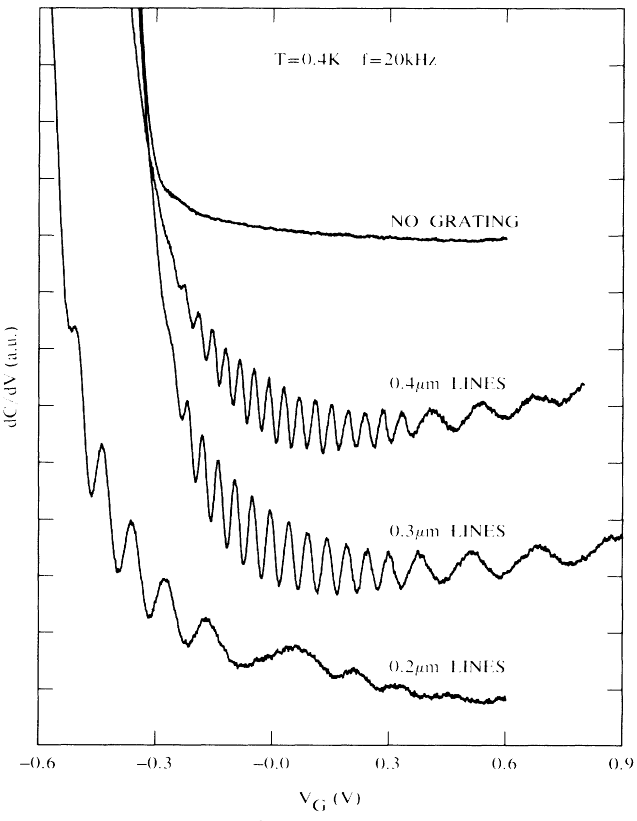

FIG. 2. Derivative of the capacitance vs gate voltage for four of the samples studied. The main peak in the derivative (due to turnon of the capacitors) has been excluded for clarity.

The oscillations in the measured capacitance are much smaller than those in the calculated capacitance. However, this is to be expected. The calculations are done for ideal structures and this is not the case experimentally. There are several factors which reduce the amplitude of the capacitance oscillations. First, the 1D levels are broadened by the presence of ionized impurities. Because of the high mobility of the electrons in unpatterned samples, potential variations due to ionized impurities are not a major factor. However, patterning of the samples produces defects on the sample surface. Although these defects are screened by the doped $Al_xGa_{1-x}As$ layer, they can produce potential fluctuations and broaden the quasi-1D states. In our experiments we sample many (250–500) lines in parallel; any variations in width of the lines or grating pitch will tend to shift the positions of the energy levels in each of the lines and average out the 1D effects. Although the uniformity of our lines is better than $\simeq 5\%$ and the etched GaAs lines are fairly distant from the electrons at the heterojunction, these variations can also reduce the size of the capacitance oscillations. The fact that we see any structure at all is an indication of the precision of the lithography. Finally, since the energy levels in our samples are separated by about 0.5–5 meV, the finite width of the Fermi function, even at 4.2 K ($kT = 0.35$ meV), will tend to reduce the structure in the capacitance. However, Fermi-function broadening should be negligible below about 0.5 K.

We have solved the Poisson and Schrödinger equations for our structures self-consistently. These calculations were performed with use of the same algorithms as previously described,[20] with appropriate modifications for GaAs heterostructures. In our data the oscillations in the capacitance of the 0.2-μm-line sample begin at a gate voltage (V_G) of 125 mV above the turnon or threshold voltage (V_Θ). The gate-voltage spacings of the first four oscillations are 70, 75, and 85 mV. This agrees very well with the calculated positions and spacings of the second, third, fourth, and fifth excited 1D subbands (labeled 02, 03, 04, and 05, respectively).[20] The Fermi level crosses the 02 level at $V_G - V_\Theta = 125$ mV and the V_G

spacings for the next four levels are 70, 79, and 85 mV, respectively. For the 0.3-μm lines, the agreement between the calculated and actual positions and spacings of the capacitance oscillations is fairly good. The first oscillation in the derivative of the capacitance occurs at 155 mV above V_Θ, and the spacing to the next level is 42 mV. These correspond to the Fermi energy's crossing the 03 and 04 levels in our calculations. However, the calculation places the 03 level 170 mV above V_Θ with the 04 level 58 mV higher in V_G. For the 0.4-μm lines, the first peak occurs at 220 mV above V_Θ, and the spacing to the next oscillation is 35 mV. The calculated position of the 05 level is 200 mV above V_Θ, and the 06 level is 40 mV above it. Although there are some discrepancies between the data and the calculations, the overall agreement is very good. These calculations also provide the energy spacing of the levels and the effective potential well widths. As the Fermi energy crosses the 02 level in the narrowest-line sample, the energy difference between the 01 and 02 levels is 5 meV. When the Fermi energy crosses the 03 level of the 0.3-μm line sample, the energy separation between the 02 and 03 levels is 4 meV. For the 0.4-μm-line sample, the energy difference between the 05 and 06 levels is 2.5 meV when the Fermi level crosses the 05 level. These energies are consistent with the temperature dependence of our measured oscillation amplitudes. If we define the effective width (L_{eff}) of the potential well as the width of the potential at the Fermi energy, then we find that L_{eff} is 900 Å for the narrowest lines at the 02-level crossing, 1150 Å for the 0.3-μm-line samples at the 03-level crossing, and 1760 Å for the narrowest- to widest-line samples at the 05-level crossing. A summary of the results for the three line sizes studied is given in Table I.

To characterize further the nature of the 1D confinement in our samples, we also studied the effects of a magnetic field applied in the $\hat{\mathbf{z}}$ direction. Figure 3 shows a plot of the minima in the magnetocapacitance as a function of magnetic field. Berggren *et al.* reported a deviation from the normal periodicity of the Shubnikov–de Haas effect as evidence of the presence of 1D levels.[9] We observe the same effect in our samples. Our data are plotted in a fan diagram similar to the one calculated by Kaplan and Warren[21] on the basis of the assumption that the confining potential is parabolic.[22] The shift in the positions of the minima in V_G for a given magnetic field should be smallest for the narrowest-line samples, and this is what we observe.

TABLE I. Energy-level spacings and well widths for the three types of samples studied. ΔE is the calculated energy-level spacing near the Fermi energy and at the gate voltage where the first clear oscillation is observed in dC/dV_G.

Nominal line size (μm)	Effective well width (μm)	ΔE (meV)
0.21	0.90	5.0
0.32	0.115	4
0.42	0.175	2.5

Returning to the oscillations observed at large positive biases (at $B=0$), we see a clear change in the period of the oscillations at about 0.6 to 0.9 V above threshold (depending on the sample). For the sample with 0.4-μm lines, the spacing changes by more than a factor of 2 in one period. However, as is the case for the oscillations at lower biases, the spacing is greatest for the narrowest lines and smallest for the widest lines. This indicates that they are also related to the potential wells formed by the gratings on the surfaces of the capacitors. From analysis of the magnetocapacitance oscillations we find a concomitant change in the V_G dependence of the two-dimensional carrier concentration (dN_s/dV_G). This indicates that charge is being induced in either the doped $\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As}$ layer or the GaAs cap layers (see Fig. 1). The change in the carrier density of the quasi-1D electronic system is smaller for a given ΔV_G and the structure due to the quasi-1D levels spreads out. Thus these oscillation are also reflective of the presence of quasi-1D levels.

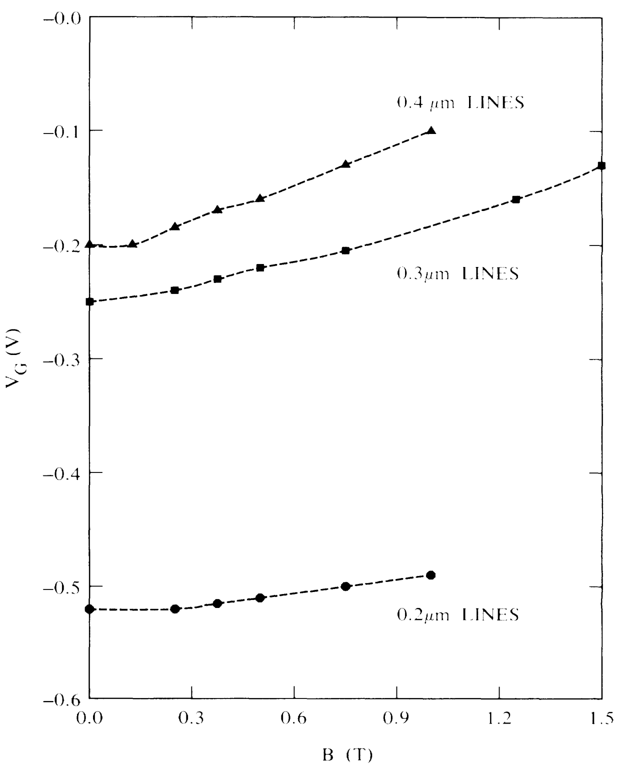

FIG. 3. Positions of the lowest-energy peaks in dC/dV_G vs magnetic field. As expected, the magnetic field most strongly perturbs the energy states of electrons in the widest potential wells.

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