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Resonant magnetoconductance in a two-dimensional lateral-surface superlattice

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We have investigated magnetoconductance in a two-dimensional lateral-surface superlattice on modulation-doped GaAs/$Al_xGa_{1-x}As$ heterostructure, at 50 mK $< T <$ 1.5 K and $0 < B < 13.5$ T. The superlattice potential modulation is formed and controlled by a metal grid gate with 200-nm periodicity. This modulation can be made larger than the Fermi energy and cyclotron energy depending on the grid-gate bias. Conductance oscillations as a function of gate bias in the presence of a magnetic field have been observed. The magnetic-field dependence of the amplitude and position of the oscillations indicates that the effect of the magnetic field is to sharpen the superlattice potential modulation.

The transport of electrons in a periodically modulated two-dimensional electron gas (2D EG) (Ref. 1) has been extensively studied both theoretically and experimentally. Conductance modulation due to the superlattice effect was observed in one-dimensional (1D) (Refs. 2-4) and two-dimensional (2D) (Ref. 5) lateral-surface superlattice (LSSL) structures. Recently, a new oscillatory behavior in the presence of a weak magnetic field perpendicular to a 1D LSSL (Refs. 6 and 7) and 2D LSSL (Ref. 8) have been reported. These magnetoconductance oscillations are periodic in $1/B$ and are clearly distinguishable from the Shubnikov-de Haas (SdH) oscillations. The new periodicity is given by the condition that the cyclotron orbit diameter, $2Rc = 2mv_F/eB$, is an integer multiple of the modulation period. Magnetocapacitance measurements have also been performed on high-mobility 2D EG with a LSSL potential,[9-11] and Landau level splitting by the periodic LSSL potential has been observed.[10,11]

In this Rapid Communication, we extend those recent investigations to study the magnetoconductance in the presence of a 2D LSSL potential. The samples were fabricated in a similar way to a conventional modulation-doped field-effect transistor (MODFET), except for replacing the solid Schottky gate with a two-dimensional metal grid. The grid gate with 200-nm period and 60-nm nominal linewidth was defined by x-ray lithography, Ti/Au evaporation and liftoff. Details of the fabrication are described elsewhere.[12] The channel length and width are 10 and 20 μm, respectively. The gate voltage modulates the carrier density under the gate and creates a 2D LSSL potential in the 2D EG. Magnetoconductance was measured using standard ac lock-in techniques, at temperatures of 50 mK and 1.5 K. The ac drain bias was 100 μV at 1.5 K and 50 μV at 50 mK. The magnetic field was changed between 0 and 13.5 T.

We were interested in the negative gate bias regime near the threshold voltage V_{th} (V_{th}, defined by the gate bias corresponding to the first peak in the conductance at $B=0$, is about -0.5 V after illumination by a light-emitting diode for several minutes). The carrier density N_s is $(5\text{-}6)\times10^{11}$ cm^{-2} at $V_g=0$ V after illumination, corresponding to a Fermi energy of 17-21 meV. Near the modulating potential is relatively large (20-25 meV) and the Fermi wavelength λ_F is relatively long (150-200 nm), which make possible clear observation of the LSSL effect.

Figure 1 shows the change of channel conductance by sweeping the gate voltage from -0.5 to -0.3 V, at a fixed magnetic field B [(a) low field, (b) intermediate field, and (c) high field]. At $B=0$ [Fig. 1(a)], one can see the modulated conductance by the 2D LSSL potential. The oscillations are separated by 15-20 mV in gate bias, corresponding to a change of about 0.7-1 meV in electron Fermi energy underneath the gate. At low B, the conductance exhibits very complicated behavior, which is not very well understood. The amplitude of the first peak increases for $B < 2$ T [Fig. 1(a) inset]. This magnetic field, however, is high enough to rule out an explanation based upon two-dimensional weak localization effects. At $B > 2$ T, clear resonant structures are observed. The amplitude of the peaks in that case monotonically decreases with increasing B. We will focus upon both the gate bias position and the amplitude of these conductance peaks.

There are two key features which can be easily seen in Fig. 1. One is the fact that the gate bias, at which a peak in conductance is observed, slightly depends on the applied magnetic field. The other feature is that the amplitude of the peak monotonically decreases with magnetic field above 2 T. Figure 2 shows the relationship between the gate voltage corresponding to the conductance peak V_g^{peak} and the magnetic field B. The peak position increases slightly with increasing magnetic field, and the separation between two neighboring peaks is almost the same (15$\sim$20 mV), independent of magnetic field. V_g^{peak} can be described as $\gamma N + \alpha$, where N is the peak index and α is a constant (about -0.5 V). In the case of SdH oscillations $\gamma \sim B$, while $\gamma \sim B^2$ in the resonance effect between the cyclotron orbit diameter and the LSSL potential periodicity.[6-8] In our experiment, γ is roughly a constant ranging between 0.019 V at $B=3$ T and 0.016 V at $B=13$ T. This fact rules out an explanation based on the density-of-states change by a magnetic field as previously reported.[7,9] Magnetic flux commensurability effects[13] are also inconsistent with our observation, since the peak

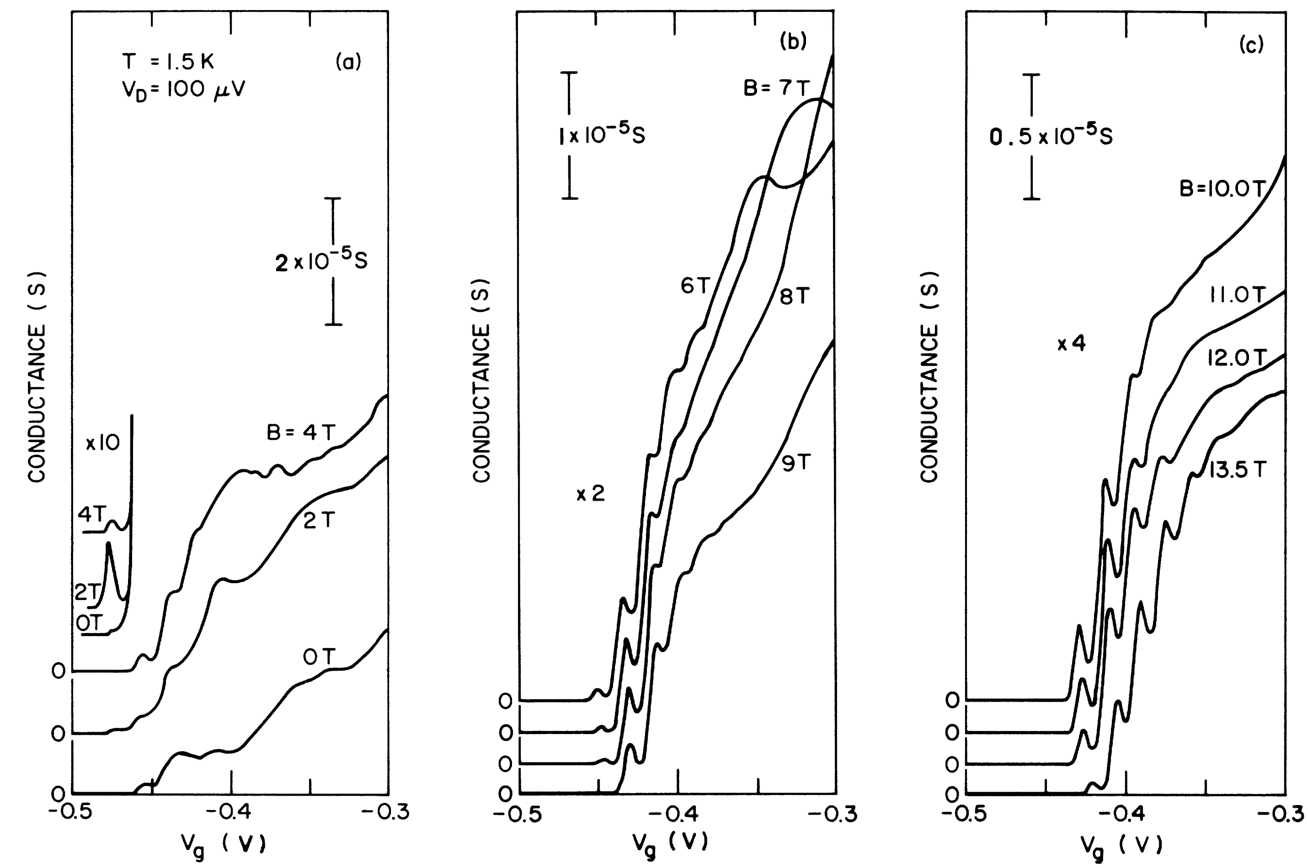

FIG. 1. The variation in conductance with gate voltage at 1.5 K, in the presence of (a) a low magnetic (0–4 T), (b) an intermediate magnetic field (6–9 T) (scale multiplied by two), and (c) a high magnetic-field (10–13.5 T) (scale multiplied by four).

structure becomes clearer and sharper at higher magnetic fields. This suggests that the conductance peaks in our experiment are caused by the resonant nature (tunneling from dot to dot) of the electron transport through the LSSL potential in the strong modulation regime under a magnetic field.

In magnetotransport measurements, one has to consider effects of both the density-of-states modulation and the scattering events, which partially reflect the tunneling probability through the LSSL potential in the device operated near V_{th}. The density-of-states modulation by the periodic LSSL potential has been studied in magnetocapacitance measurements in a similar structure under weak potential modulation.[10] The key point in that study is that the high degeneracy of the original Landau levels is removed by the LSSL potential, and instead, small structures in the density-of-states are formed. On the other hand, one can also take discrete energy levels in a quantum box under a magnetic field as a starting point, especially near V_{th}. In that case, a hybridization between electrical confinement and magnetic confinement can take place in a 2D EG.[14] The independence of γ on B in our experimental results suggests that a subband producing a conductance peak does not come from orbit degeneracy by the magnetic field, but rather from a *miniband* induced by the superlattice effect. This hybridized miniband picture could be responsible for the resonant nature of the G vs V_g relationship. A slight increase in V_g^{peak} vs B for each resonant peak, and the weaker dependence of the peak position on the magnetic field for higher index in Fig. 2, are both qualitatively consistent with the simple energy-level calculation in a quantum box. However, more rigorous calculation is needed to quantitatively explain our results. In fact, the manifestation of the LSSL in our experiment is observed between the two extreme cases described above, that is, between the weak perturbation regime and the isolated quantum dot regime.

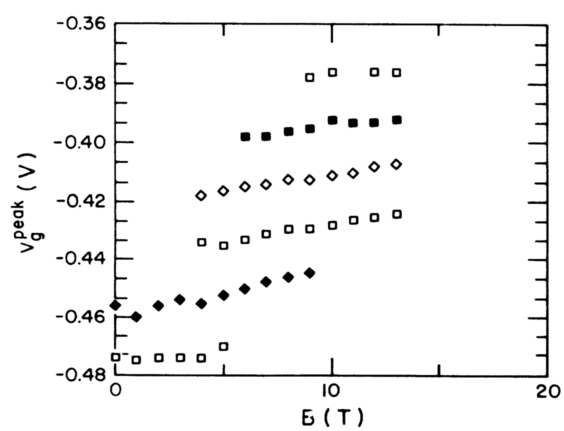

FIG. 2. Resonance peak position in gate voltage as a function of magnetic field.

The peak voltage separation corresponds to the modulation energy width. Experimentally, we observed that $\delta V_g = 15\text{–}20$ mV, which is about a 1-meV change in electron Fermi energy underneath the gate. According to our numerical calculation, this value is quite reasonable for the modulating potential and the periodicity in our structure, in the absence of a magnetic field.

Next, we discuss the variation in the amplitude of the peak conductance as a function of B. The magnetic field enhances the effective tunneling barrier, because the potential energy can be described by a harmonic potential which creates an effective energy barrier. According to the WKB approximation in a one-barrier problem under a magnetic field, which is assumed to influence only the barrier region,[15] the conductance decreases with the field for small voltages as follows.

$$G(B)/G(0) \sim \exp[-C_N(l_b,k_F)B^2] , \quad (1)$$

where l_b is the barrier thickness in the confining potential. Although this is a theoretically oversimplified picture, we found that the amplitude changes with the field as $\exp(-CB^2)$ in a wide range of magnetic field, as shown in Fig. 3. It should be noticed that a clear manifestation of the superlattice effect, as shown in Fig. 1, rules out the possibility that one particular barrier limits the electron conduction in the present device. The decrease in the peak amplitude is probably due to the decrease of the tunneling probability through the magnetic potential induced barriers. This means that the magnetic field localizes the electrons effectively within the grid potential, so one can see clear resonances in the conductance as a function of gate voltage. $C_N(l_b,k_F)$, which can be determined from the slope in Fig. 3(a), is shown in Fig. 3(b) against the peak index. The value of C_N increases with decreasing index number. This is due to the combined effect of widening of the tunneling barrier caused by the gate fringing fields, in addition to a decrease in k_F caused by the reduction in carrier density. The conductance peak with higher index may partly include a component of unmodulated electron conduction in the 2D EG.

Finally, we discuss the low-temperature behavior of the conductance, measured in a dilution refrigerator. The G vs V_g relationship at 50 mK is shown in Fig. 4 for three different magnetic fields. At $V_g \sim -0.41$ V, we estimate the potential barrier height ($B = 0$ T) to be about 5 meV higher than the electron Fermi energy from numerical calculation. This means that the tunneling ($N = 1$ peak) in our LSSL is through a bound state in the quantum box. With application of a magnetic field, this state shifts to higher energy with respect to E_F. It also splits into two peaks, which is observed at all B. This peak splitting may be due to higher-order perturbation of the density of states by the LSSL potential. On the other hand, on the higher index peaks (where tunneling might be taking place through virtual states) we could not detect the splitting at any magnetic field. Instead, a new periodic conductance oscillation ($\delta V_g \sim 1.5$ mV) was observed in addition to the same resonant behavior as that in Fig. 1. It is distinguishable from the universal conductance fluctuation, since it is perfectly periodic within a limited range of the gate voltage. Independence of the periodicity on mag-

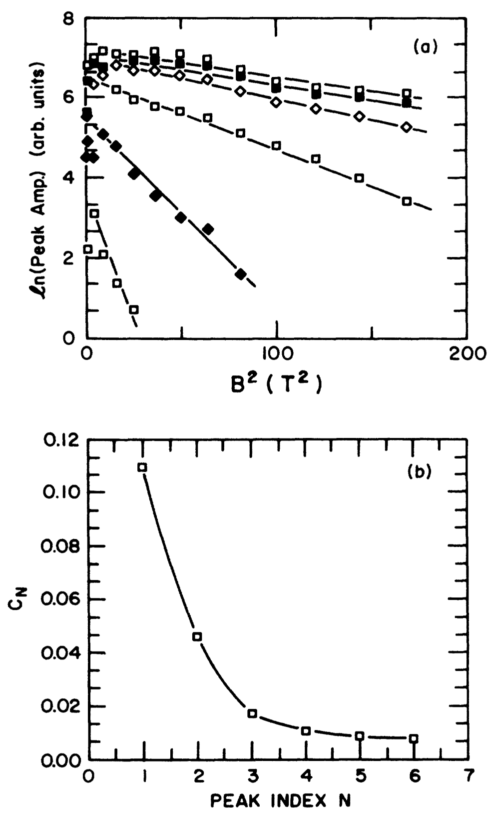

FIG. 3. (a) Resonance peak amplitude vs B^2. The solid lines merely serve as a guide to the eye. (b) Attenuation coefficient of the peak amplitude C_N vs peak index. See Eq. (1) in the text.

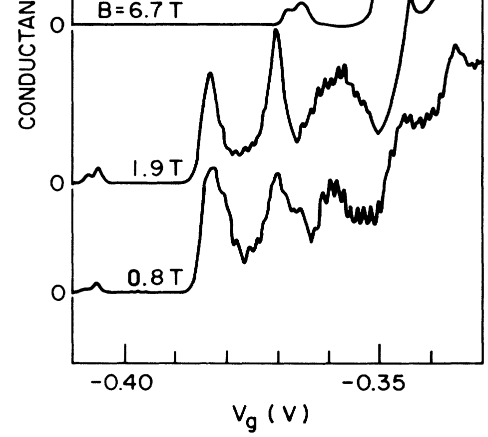

FIG. 4. Conductance vs gate voltage at 50 mK at three different magnetic fields. The splitting in the first resonance peak and the additional fine oscillations can be clearly seen.

netic field suggests that this oscillation is neither due to Aharonov-Bohm effect nor magnetic breakdown, but that it is due to an electrostatic effect. Although we have been unable to explain this oscillation clearly, we would like to note that the elementary charging energy $e^2/2C$ in each well could be larger than $k_B T$, because of the very small capacitance between neighboring wells. The actual capacitance, however, is difficult to evaluate. The fact that we cannot see this oscillation at 1.5 K implies that the capacitance involved in this system may be on the order of 10^{-15} F (the gate capacitance in each dot is an order of magnitude less than this value). This effect could lead to an oscillatory conductance[16] corresponding to the addition of one electron per unit cell of the LSSL. In fact, $\delta V_g \sim 1.5$ mV corresponds to a change in density of 2×10^9 cm^{-2}, which, in turn, is nearly equivalent to changing one electron per unit cell. We also believe that our structure is very similar to an array of ultrasmall tunnel junctions, where the conductance is partially dominated by the formation of single electron solitons.[17] This oscillatory feature apparently requires much more investigation.

In summary, we observed new resonant structures in the G vs V_g relationship as a function of magnetic field in a two-dimensional lateral-surface superlattice. These are attributed to a modulated density-of-states in superlattice minibands in the presence of a magnetic field, and to a change of energy barrier height by the magnetic potential. A clear manifestation of the LSSL effect under magnetic field was demonstrated. Furthermore, a new periodic oscillation in G vs V_g was observed at 50 mK, together with a splitting in the lowest resonant peak.

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