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Quantum oscillations in strained-layer superlattices

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Large-amplitude quantum oscillations are observed in the magnetotransport in GaAs-$Ga_{0.8}In_{0.2}As$ strained-layer superlattices. These measurements demonstrate that single-crystal perfection and high mobilities at low temperatures can be achieved in a new class of semiconductor structures. The properties of these structures can be tailored easily over a wide range inaccessible to naturally occurring lattice-matched heterostructures.

There has been a very active interest recently in the properties of the two-dimensional electron gas (2D EG) formed in superlattices and at semiconducting heterostructure interfaces.[1] Intriguing quantum effects have been seen and the Hall effect has been utilized to measure precisely the fine-structure constant.[2] From a practical sense, the large mobilities (10^4–10^6 $cm^2/V\,sec$ at low temperatures) make such structures of potential importance for fast devices. To date, these effects have been observed only in the lattice-matched III-V materials such as $Al_{0.29}Ga_{0.71}As$-GaAs,[3] InAs-GaSb,[4] and most recently[5] $Ga_{0.47}In_{0.53}As$-InP, and in Si-metal-oxide-semiconductor field-effect transistors (MOSFET's).[2] The Si MOSFET's have higher–electron-effective-mass carriers and thus are intrinsically lower-mobility materials. The necessity for lattice matching in the III-V heterostructures severely limits the materials choices available and therefore flexibility with respect to band gap, lattice constant, and the attendant optical, magnetic, and electrical properties.

In this paper we report the first demonstration of these two-dimensional electron gas quantum effects in a new class of materials which promise important flexibility in tailoring electrical-optical-magnetic properties.[6,7] These materials are superlattices grown from lattice-*mis*matched semiconductors with layers sufficiently thin so that all of the mismatch is accommodated by uniform, elastic strains. Since misfit dislocations are not generated by the lattice mismatch, these strained-layer superlattices (SLS's) can have excellent crystalline quality. Without the constraint of using lattice-matched materials, SLS's can be grown from a wide variety of interesting semiconductors. The layer strains in SLS's also tend to prevent threading dislocations (originating in an underlying graded layer) from propagating into the SLS material.[8] This allows the growth of high-quality SLS material on poor-quality substrates, graded layers, and buffer layers.

The structure employed in this investigation consisted of an SLS grown from alternating 120-Å-thick layers of GaAs and $Ga_{0.8}In_{0.2}As$ (lattice mismatch $\sim 1.4\%$) atop a $Ga_{0.9}In_{0.1}As$ buffer layer structure with a lattice parameter corresponding to that of the SLS, on top of a semi-insulating [100] GaAs wafer. The entire superlattice was doped with Si which results in a uniformly doped device. The buffer layer was doped p type ($p \sim 1\times10^{18}$ cm^{-3}) to provide electrical (diode) isolation of the SLS from the buffer plus substrate. Tin contacts were diffused in the Van der Pauw geometry by annealing at $\sim 200\,°C$. The bulk of the measurements described here were taken in a rotatable 100-kG split superconducting solenoid with the sample mounted so that the field could be rotated continuously from perpendicular to parallel to the layers at temperatures from 1–4 K.

Figure 1 shows typical data for resistance versus magnetic field at ~ 1 K. Figure 1(a) is the Hall resistance and Fig. 1(b) is the transverse magnetoresistance both to a maximum field of about 105 kG. Shubnikov-de Haas (SdH) oscillations were observed in structures with carrier concentrations varying from 3.8×10^{16} to 6×10^{17} cm^{-3}. Data were also obtained at constant field by rotating the magnetic field. This mode gives an accurate measure of the angular dependence of the SdH frequency and therefore of the cross-sectional area of the Fermi surface. A two-dimensional electron gas (2D EG) has a cylindrical Fermi surface so that the SdH frequency varies as $(\cos\theta)^{-1}$, where θ is measured from the normal to the two-dimensional structure. Our SdH data for this series of structure follow very nearly a $(\cos\theta)^{-1}$ dependence, but consistently deviate slightly. This

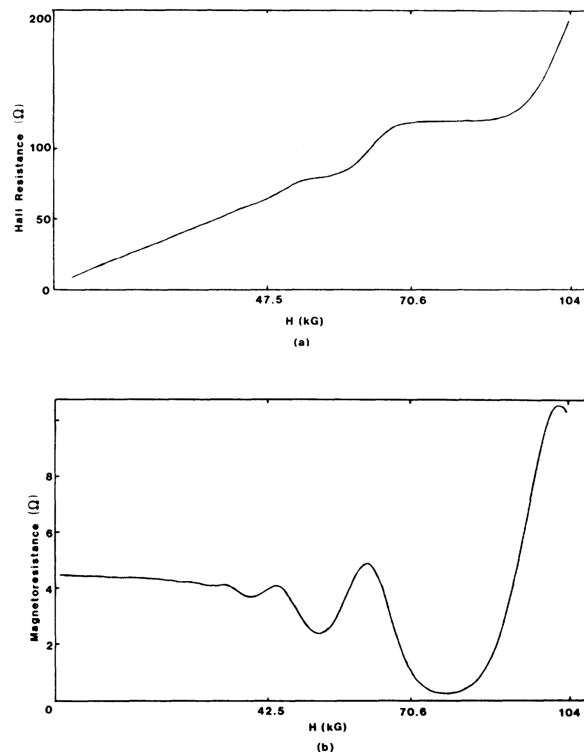

FIG. 1. (a) Hall resistance vs magnetic field at 1.1 K for a GaAs-$Ga_{0.8}In_{0.2}As$ superlattice with $n \cong 4\times10^{17}$ cm^{-3}. Current is 100 μA. (b) Transverse magnetoresistance for same structure as in (a) at 1.1 K with current 1 mA.

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TABLE I. Measured quantities in strained-layer superlattices, GaAs-$Ga_{0.8}In_{0.2}As$.

Sample	n (4 K) (10^{17} cm^{-3})	μ (4 K) (cm^2/V sec)	N (4 K) (10^{11}cm^{-2})	F (kG)	m^*/m	X_D (K)
M-249	0.38	1680	1.26	26	0.06	9
M-251	0.90	3360	2.51	52	0.06	12
M-252	2.55	5860	6.19	128	0.063	18
M-261	2.95	6910	7.63	158	0.06	28
M-262	5.98	4100	15.00	310	0.06	21

deviation is in the direction of an ellipsoidal Fermi surface and is almost within experimental uncertainties. Thinner-layered structures will be required to ascertain when three-dimensional effects become important in this material system.

In Table I we list the measured quantities for this series of structures, all of which are ~ 240 Å/SLS period. We measured the carrier concentration and mobilities at 4 K using standard four-terminal techniques. The determinations were made at 6 kG for comparison with other higher-temperature studies.[9] The SdH frequencies were determined from both direct magnetoresistance versus field measurements as shown in Fig. 1 and by field-modulation techniques which enhanced the lower-field data. Effective masses and scattering temperatures (Dingle temperatures) were obtained from the temperature and field dependences of the oscillation amplitudes, respectively.

The relation[3] $N = 2eF/hc$, where e is the electronic charge, F the SdH frequency, h Planck's constant, and c the velocity of light, was used to calculate the two-dimensional carrier concentrations N. Division of this number by the SLS repeat thickness gives the three-dimensional carrier concentration which agrees with that determined from the transport measurements to well within experimental uncertainties. This again attests to the two-dimensional nature of the carriers in these structures.

The relation between the SdH frequency F and the carrier concentration is shown in Fig. 2, with F as the left-hand ordinate on the graph. Also plotted is the Dingle temperature (right-hand ordinate). The Dingle temperatures compare very favorably with those determined in high-quality bulk materials of similar doping levels. For example, Shaw and Hill[10] report a Dingle temperature of 13 K for n-type GaAs with a carrier concentration of 1.7×10^{17} cm^{-3}, while Stephens *et al.*[11] find $X_D \sim 16$ K for n-InAs at 1.4×10^{17} cm^{-3}. The SdH frequency is linear with carrier concentration as discussed above. There seems to be a correlation indicating that the scattering is due to the impurities associated with the doping although one sample appears to have an additional degree of scattering, perhaps due to growth imperfection in that particular sample. The effective-mass ratio m^*/m_0 is 0.063 (± 0.003) and is independent of carrier concentration as would be expected for a parabolic band. This compares well with the expected m^*/m_0 value of 0.06 based on the band-gap values of these SLS's.

There is no simple correspondence between the Dingle temperature and the mobility as can be seen by inspection of Table I. The low-temperature mobility for this series of structures decreases at high concentrations, probably due to increased scattering from the (neutral) donor ions. The mobility drops rapidly at low carrier concentrations also, which has been observed in lattice-matched, uniformly doped AlGaAs-GaAs superlattices.[12] This may be due to ionized impurity scattering which can occur when the separation of the Fermi energy and the donor levels is relatively small. Partial compensation due to residual acceptors in the InGaAs layers may enhance this effect. Separate measurements of mobility versus temperature (to be reported elsewhere[9]) have verified the dependence expected for ionized impurity scattering in the most lightly doped samples.

We anticipate that modulation doping[12] will greatly improve these structures as far as mobilities at low temperatures are concerned. In this procedure only the large band-gap layer of the superlattice is doped. The carriers then drop into the smaller band gap where there are no impurities to scatter them so that mobilities may increase to 10^6 cm^2/V sec and above at low temperature. Such structures will greatly facilitate study of quantum effects, particularly in the extreme quantum limit because of the enormous flexibility inherent in this fabrication scheme.

In summary, we have demonstrated that extremely high-quality long mean-free-path structures can be realized in strained-layer superlattices. Removal of the requirement to

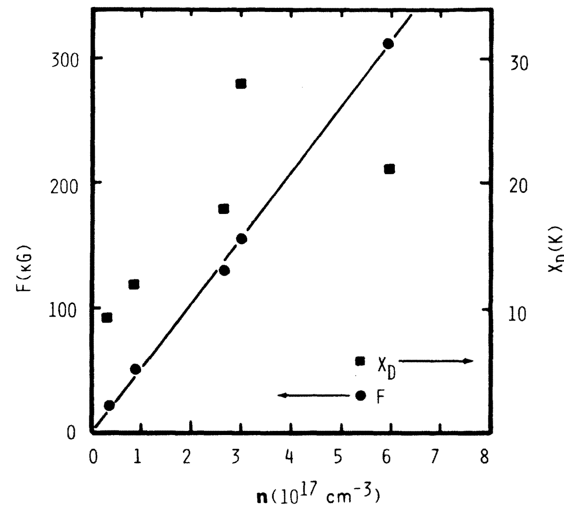

FIG. 2. Shubnikov–de Haas frequency, F (left-hand ordinate) in kG and Dingle temperature X_D in K (right-hand ordinate) vs carrier concentration in units of 10^{17} cm^{-3}.

find naturally occurring lattice-matched pairs opens up a myriad of possibilities for tailor making long mean-free-path, high-mobility materials ideal for the study of phenomena in the extreme quantum limit. Questions[13] concerning formation of collective ground states such as a Wigner solid or charge-density waves with triangular symmetry in the extreme quantum limit may be more easily addressed in these materials. Modulation doping promises to further increase the mobilities and decrease Dingle temperatures in these materials, making them even more attractive for both fundamental and device considerations.

ACKNOWLEDGMENTS

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