RAPID COMMUNICATIONS

PHYSICAL REVIEW B VOLUME 44, NUMBER 15 15 OCTOBER 1991-I

Electron mobilities and quantum Hall effect in modulation-doped HgTe-CdTe superlattices

C. A. Hoffman, J. R. Meyer, and F. J. Bartoli
Naval Research Laboratory, Washington, D.C. 20375

Y. Lansari, J. W. Cook, Jr., and J. F. Schetzina
North Carolina State University, Raleigh, North Carolina 27695

(Received 20 June 1991; revised manuscript received 29 July 1991)

Photoassisted molecular-beam epitaxy and controlled modulation doping have been used to grow HgTe-CdTe superlattices with n-type carrier concentrations of up to 3×10^{17} cm^{-3}. It is found that in contrast to $Hg_{1-x}Cd_xTe$ alloys where the electron mobility decreases strongly with donor concentration, μ_n in the modulation-doped superlattices is nearly independent of N_D at large N_D. We also discuss an observation of the quantum Hall effect associated with carriers distributed throughout the interior of a HgTe-CdTe superlattice. Whereas previous reports of quantized steps in the Hall conductivity have involved a small number of conduction channels (hence a small fraction of the superlattice periods), we observe plateaus at multiples of $\approx 200e^2/h$ in a number of 200-period superlattices with high doping levels. This indicates participation by nearly all wells in the superlattice, and implies that the controlled doping is extremely uniform.

There have by now been numerous experimental investigations of free-carrier transport in HgTe-CdTe superlattices. These include studies of the electron and hole mobilities as a function of well and barrier thicknesses[1–4] as well as quantum transport effects.[5–9] A limiting feature of all of these previous experiments is that they were performed on unintentionally doped samples, which typically had net donor or acceptor densities between 2×10^{14} and 1×10^{16} cm^{-3}, with unknown degrees of compensation. Besides precluding studies of the scattering rates and mobilities as a function of ionized impurity concentration, the lack of control over unintentional doping raises questions concerning the uniformity of the carrier concentration along the growth axis. In particular, whereas both Ong *et al.*[8] and Woo, Rafol, and Faurie[9] reported observation of the quantum Hall effect in HgTe-CdTe superlattices, the magnitudes of the Hall-conductivity plateaus indicated relatively few conduction channels, i.e., in both cases only a small fraction of the wells in the superlattice contributed to the quantized conduction.

Here we report an experimental investigation of free carrier transport in HgTe-CdTe superlattices with controlled, modulation doping of the CdTe barriers. For donor concentrations of up to 3×10^{17} cm^{-3}, the doping dependence of the electron mobility has been systematically investigated, in order to determine whether modulation doping prevents the strong decrease of μ_n with N_D which occurs in $Hg_{1-x}Cd_xTe$ alloys. We also report an observation of the quantum Hall effect associated with carriers distributed throughout the interior of a HgTe-CdTe superlattice.

Twelve 200-period HgTe-$Hg_{0.15}Cd_{0.85}Te$ superlattices were grown by photoassisted molecular-beam epitaxy (MBE). Deposition was directly onto lattice-matched [100] $Cd_{1-x}Zn_xTe$ substrates with no buffer layers. Low substrate growth temperatures (140 °C) were employed to minimize layer interdiffusion effects. Modulation doping was achieved by incorporating indium donors or arsenic acceptors into the CdTe barriers of the superlattices. Well and barrier thicknesses were accurately determined from x-ray satellite peaks in conjunction with growth-rate data.[2]

In the magnetotransport experiments, diagonal (ρ_{xx}) and Hall (ρ_{xy}) resistivities were measured as a function of magnetic field (0–7 T) and temperature (1.5–300 K) by the Van der Pauw technique. A mixed-conduction analysis was then employed to extract densities and mobilities for the various electron and hole species contributing to transport in a given sample.[2] Data for two p-type samples and one lightly doped n-type sample showed evidence for an additional hole species (whose density and mobility was relatively independent of temperature) besides the superlattice majority and minority carriers. Such carriers have frequently been observed in HgTe-CdTe heterostructures, and are believed to correspond to a quasi-two-dimensional (2D) population which resides within the superlattice near either the ambient or substrate interface.[4,10] Whereas hole mobilities approaching 10^5 cm^2/V s were observed in lightly doped p-type samples, μ_p dropped significantly when higher doping levels were attempted.

While high-quality p-doping of MBE-grown CdTe remains difficult to achieve consistently, present procedures successfully produced a series of high-mobility n-type superlattices with donor densities systematically varying between 2×10^{15} and 3×10^{17} cm^{-3}. For eight n-type samples from the present investigation (solid circles) along with four unintentionally doped superlattices from previous studies[3,4] (open circles), Fig. 1 illustrates the dependence of the electron mobility at $T = 4.2$ K on net donor density, $N_D - N_A$.[11] The figure illustrates that whereas μ_n decreases with increasing impurity concentration in the lightly doped regime, there is little variation with N_D at higher doping levels. This sharply contrasts the case of the $\mathrm{Hg}_{1-x}\mathrm{Cd}_x\mathrm{Te}$ alloy (see the curve in the figure),[12] for which the low-temperature mobility strongly decreases with N_D over the entire range up to 10^{18} cm^{-3}.[13] We note that in both alloy and superlattice there are several competing factors which influence whether the mobility increases or decreases with increasing doping level. First, the higher Fermi energies at large n lead to an increase of the electron effective mass due to nonparabolicity, but also to a decrease of the energy-dependent scattering rate for ionized impurities. Second, larger N_D implies both a higher density of scattering centers and a higher density of free carriers that can screen the potentials. In the alloy the net variation of the mobility is dominated by the scattering-center density, and as a result μ_n decreases with increasing N_D. However, preliminary results from a new theory for electron and hole mobilities in HgTe-CdTe heterostructures[14] indicate that the situation is somewhat more complex when the doping profile is spatially modulated in the superlattice. As long as the screening length λ_s is longer than the superlattice period d, as it is at small N_D, the doping profile is relatively unimportant and the qualitative behavior for the superlattice is similar to that in the alloy. However, at high concentrations where $\lambda_s < d$, the scattering rate depends strongly on whether a given charged center is in a well or a barrier. When the impurities occupy only the barriers (as in the present experiments), all of the interactions become highly screened and increasing the density of scattering centers has a relatively smaller effect on the mobility. Theory predicts that at still higher modulation doping levels, μ_n in the superlattice should actually increase with N_D.

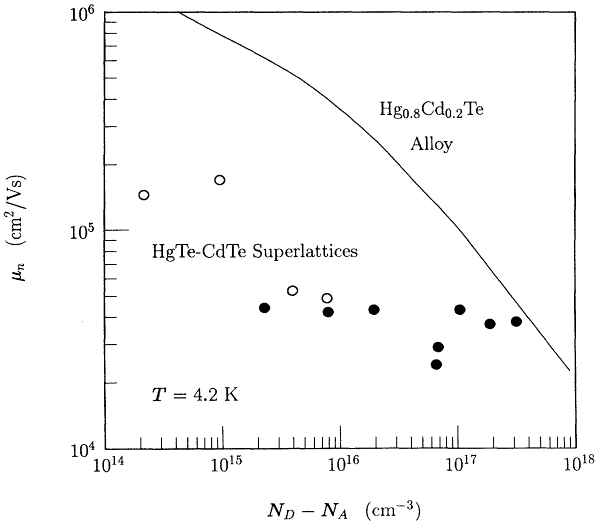

FIG. 1. Experimental electron mobilities (4.2 K) vs net donor concentration for n-type HgTe-CdTe superlattices. The filled circles are from the present work, while the open circles are from previous investigations (Refs. 3 and 4). The curve represents the corresponding dependence for electron mobilities in the $\mathrm{Hg}_{0.8}\mathrm{Cd}_{0.2}\mathrm{Te}$ alloy (Ref. 12).

Of the 12 superlattices studied, 1 of the 4 p-type samples and 7 of the 8 n-type samples (all but that with the lightest doping) displayed quantum Hall plateaus at low temperatures. While the quantum Hall effect is usually thought of as a two-dimensional phenomenon, Störmer *et al.* have demonstrated the possibility of observing it in a superlattice with 3D dispersion if the miniband width is smaller than the Landau level spacing.[15] Dimensionality considerations will be discussed further below.

Superlattices displaying the quantum Hall effect may be subdivided according to whether the observed number of quantized conduction channels is of order unity or of order $\mathcal{N}_W$ (the number of superlattice periods). Of the present samples, the only representative of the first group was a p-type superlattice with low-temperature density $p_0 = 4.6 \times 10^{15}$ cm^{-3}, whose diagonal and Hall conductivities at $T = 2$ K are illustrated in Fig. 2. In quantized units (e^2/h), plateaus corresponding to $i = 3$–6 conduction channels are seen to be well resolved in σ_{xy}. Each of these plateaus is accompanied by a minimum (or inflection) in σ_{xx}, although parallel conduction by the second (quasi-2D) hole species in this sample apparently prevents σ_{xx} from closely approaching zero. Since the number of conduction channels represents a product of the number of quantum wells contributing and the number of occupied Landau levels in each well, observation of the $i = 3$ plateau implies that at most 3 of the 200 periods in the superlattice contribute to the quantized Hall conductivity. The obvious implication is that it is the quasi-2D population, p_s, which produces the effect rather than the holes residing in the interior of the superlattice. The same conclusion follows from the magnitudes of the

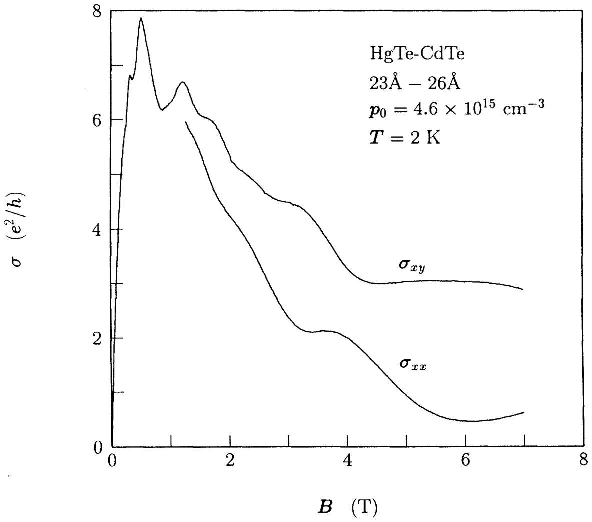

FIG. 2. Hall and diagonal conductivities vs magnetic field at $T = 2$ K, for a p-type superlattice with the indicated well and barrier thicknesses and low-temperature hole density.

fields at which plateaus are observed (up to 7 T). For a uniformly distributed hole population with the measured concentration, only the lowest Landau level should have been occupied at any magnetic field above 0.2 T. However, σ_{xx} due to a quasi-2D hole gas with the density p_s would continue to oscillate in a manner entirely consistent with the data in the figure.

We emphasize that all previous reports of the quantum Hall effect in HgTe-CdTe superlattices[8,9] have involved data similar to those shown in Fig. 2, in that the steps in σ_{xy} indicate a small number of conduction channels. For example, Ong *et al.* presented results showing plateaus at $i = 2$–12 in an n-type superlattice ($d_W = 90$ Å, $d_B = 40$ Å) with 12 periods. Although it was suggested by those authors that the observation of steps at $i \ll \mathcal{N}_W$ was related to a splitting of the growth-direction energy dispersion into $\mathcal{N}_W$ discrete levels, it was also noted that both their magneto-transport and their magneto-optical data showed evidence for at least two carrier species. It therefore seems likely that it is not the superlattice electron but the second species (presumably quasi-2D) which is responsible for the observation of quantum Hall plateaus at magnetic fields up to 29 T.[10]

In a similar study of a p-type $\mathrm{Hg_{0.92}Cd_{0.08}Te}$-CdTe superlattice with 100 periods ($d_W = 70$ Å, $d_B = 40$ Å), Woo, Rafol, and Faurie observed quantum Hall plateaus corresponding to $i = 9$ and 18 at $B = 5.5$ and 11 T.[9] The implication is clearly that only 9 of the 100 wells participated in the quantized Hall conduction. While those authors discussed the result in terms of only 9 layers being "contacted," it seems more likely that band bending near the top surface or near the interface of the superlattice with the substrate made it energetically favorable for the holes to populate only 9 wells.

In all of the cases considered above (the data in Fig. 2 as well as the previous results of Ong *et al.* and Woo, Rafol, and Faurie), the observed number of conduction channels represented a small fraction of $\mathcal{N}_W$. In sharp contrast, Fig. 3 illustrates σ_{xx} and $|\sigma_{xy}|$ (the Hall conductivity is negative since the sample is n type) for a superlattice with a net donor concentration of 1.0×10^{17} cm^{-3} (the areal density per well is 1.9×10^{11} cm^{-2}). Note that instead of σ_{xy} plateaus at unit multiples of e^2/h, the data for $T = 1.5$ K (solid curves) show at least five steps varying by nearly $\mathcal{N}_W e^2/h$, where $\mathcal{N}_W = 200$. We also find that the minima in σ_{xx} are much broader and deeper than in Fig. 2, more closely approaching ideal behavior for the quantum Hall effect. Even at 15 K (dashed curves) the first three steps are easily resolvable, and the final plateau remains evident at temperatures as high as 90 K. The very light effective mass in HgTe-CdTe superlattices leads to this slow decay of the quantum oscillations with temperature.

These results represent the first observation of the quantum Hall effect associated with carriers distributed throughout the interior of a HgTe-CdTe superlattice. All seven of the modulation-doped n-type samples with $N_D \geq 8 \times 10^{15}$ cm^{-3} showed σ_{xy} quantized in steps corresponding to participation by 54–99% of the 200 superlattice periods. Defining $\mathcal{N}_W^{\mathrm{QHE}}$ to be the number of contributing wells obtained from the spacing of the plateaus for a given sample, $\mathcal{N}_W^{\mathrm{QHE}}/\mathcal{N}_W$ was found to decrease slightly with decreasing doping concentration. This implies that the background of unintentional dopants, whose concentration is known from previous work to be $\leq 1 \times 10^{16}$ cm^{-3}, may be somewhat nonuniform. In fact, magneto-transport results for the three samples with the lightest doping showed a conversion from n-type to p-type at the highest magnetic fields, implying that both electrons and holes were present in different regions of the sample.

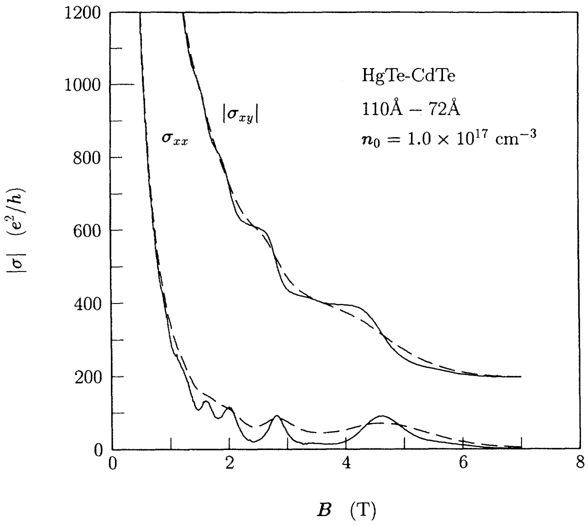

FIG. 3. Hall and diagonal conductivities vs magnetic field at $T = 1.5$ K (solid) and 15 K (dashed), for an n-type superlattice with the indicated d_W, d_B, and n_0.

Of the 12 superlattices studied, that shown in Fig. 3 had the thickest barriers (72 Å) and hence the narrowest miniband width (theory[4] predicts ≈ 2 meV). It is thus not surprising that the quantum Hall features in the figure are nearly as distinct as those one would expect for a single or multiple quantum well. Nonetheless, the σ_{xy} plateaus displayed by other samples with thinner barriers and much stronger three-dimensional dispersion were nearly as pronounced (in several cases the miniband width was in the 10–15-meV range). In fact, two of the moderately doped samples showed broad quantum Hall plateaus at magnetic fields for which the Fermi level is predicted to lie near the center of a miniband rather than in a gap between minibands (in one case it is questionable whether a gap even exists). These apparent anomalies will be discussed further in a future work.

Summarizing, modulation-doped HgTe-CdTe superlattices have been grown by photo-assisted MBE. While p-type doping with As was not fully reproducible, n-type doping with In produced a series of high-quality structures with donor concentrations varying between 2×10^{15} and 3×10^{17} cm^{-3}. Electron mobilities in the n-type superlattices displayed a weak dependence on doping level, in contrast to the strong decrease of μ_n with increasing N_D in the $\mathrm{Hg_{1-x}Cd_xTe}$ alloy system. Low-temperature magneto-transport measurements on the n-type samples have yielded the first observation of the quantum Hall effect due to carriers populating the interior of a HgTe-CdTe superlattice. In heavily doped superlattices with 200 periods, multiple plateaus in σ_{xy} at steps varying by $\geq 196e^2/h$ confirm that at least 98% of the wells in the superlattice participated in the quantized conduction. On the other hand, any inhomogeneities in the carrier concentration significantly affect the magnetotransport results. For this reason, quantum Hall plateaus at much closer spacing were observed in previous studies of HgTe-CdTe superlattices,[8,9] as well as in a p-type sample from the present study (Fig. 2). The broad, well-defined plateaus in Fig. 3 imply high-quality superlattices with uniform modulation doping.

We thank L. R. Ram-Mohan for the use of his superlattice-band-structure software. This research was supported in part by the Strategic Defense Initiative office of Innovative Science and Technology, and in part by ONR.

---

[1] J. P. Faurie, S. Sivananthan, and J. Reno, J. Vac. Sci. Technol. A **4**, 2096 (1986).

[2] C. A. Hoffman, J. R. Meyer, F. J. Bartoli, J. W. Han, J. W. Cook, Jr., J. F. Schetzina, and J. N. Schulman, Phys. Rev. B **39**, 5208 (1989).

[3] C. A. Hoffman, J. R. Meyer, F. J. Bartoli, J. W. Han, J. W. Cook, Jr., and J. F. Schetzina, Phys. Rev. B **40**, 3867 (1989).

[4] C. A. Hoffman, J. R. Meyer, R. J. Wagner, F. J. Bartoli, X. Chu, J. P. Faurie, L. R. Ram-Mohan, and H. Xie, J. Vac. Sci. Technol. A **8**, 1200 (1990).

[5] M. W. Goodwin, M. A. Kinch, R. J. Koestner, M. C. Chen, D. G. Seiler, and R. J. Justice, J. Vac. Sci. Technol. A **5**, 3110 (1987).

[6] D. G. Seiler, G. B. Ward, R. J. Justice, R. J. Koestner, M. W. Goodwin, M. A. Kinch, and J. R. Meyer, J. Appl. Phys. **66**, 303 (1989).

[7] L. Ghenim, R. G. Mani, J. R. Anderson, and J. T. Cheung, Phys. Rev. B **39**, 1419 (1989).

[8] N. P. Ong, J. K. Moyle, J. Bajaj, and J. T. Cheung, J. Vac. Sci. Technol. A **5**, 3079 (1987).

[9] K. C. Woo, S. Rafol, and J. P. Faurie, J. Vac. Sci. Technol. A **5**, 3093 (1987).

[10] J. R. Meyer, C. A. Hoffman, R. J. Wagner, and F. J. Bartoli, Phys. Rev. B **43**, 14 715 (1991).

[11] Although the figure compares superlattices with well thicknesses varying between 61 and 110 Å, these variations do not greatly influence the electron effective mass at high n where nonparabolicity effects dominate (the Fermi level can be as much as 70 meV above the bottom of the band). For moderate to heavy doping, the present results show no apparent correlation between μ_n and d_W.

[12] J. J. Dubowski, T. Dietl, W. Szymanska, and R. R. Galazka, J. Phys. Chem. Solids **42**, 351 (1981).

[13] Interface roughness scattering (see Ref. 14) may account in part for the observation of lower mobilities in the superlattice than in the alloy at light doping levels. Compensation may also be a factor.

[14] J. R. Meyer, D. J. Arnold, C. A. Hoffman, and F. J. Bartoli, Appl. Phys. Lett. **58**, 2523 (1991).

[15] H. L. Störmer, J. P. Eisenstein, A. C. Gossard, W. Wiegmann, and K. Baldwin, Phys. Rev. Lett. **56**, 85 (1986).