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Magnetotransport properties of p-type HgTe-CdTe superlattices

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Magnetotransport measurements are reported on HgTe-CdTe and $Hg_{1-x}Cd_xTe$-CdTe superlattices. The Hall coefficients of these superlattices change from negative to positive as temperatures decrease and magnetic fields increase. Shubnikov–de Haas oscillations are observed and the temperature dependence of the amplitude of such oscillations indicates that the dominating carriers at low temperatures are the heavy holes. This is in agreement with band-structure calculations of these superlattices. The mobilities of these p-type superlattices are much higher than those of the best bulk p-type $Hg_{1-x}Cd_xTe$ layers. We speculate that this mobility enhancement is related to the interface states which only exist in type-III superlattices.

There has been a great deal of interest in HgTe-CdTe superlattices since the fabrication of such superlattices by Faurie, Millon, and Piaguet using the molecular-beam-epitaxial (MBE) technique.[1] These materials are not only excellent candidates for infrared detectors[2] but also provide excellent opportunities to study semiconductor superlattices because of their unique band structures. HgTe is a semimetal with a negative band overlap of 0.3 eV and CdTe is a semiconductor with a 1.6 eV band gap. The conduction band in CdTe becomes the light-hole band in HgTe. As a consequence of the matching up of bulk states belonging to the conduction band in HgTe with the light-hole valence band in CdTe in the HgTe-CdTe superlattice there exists a quasi-interface state.[3-5] Because of the peculiar character of this superlattice, it is expected that its properties are different from those of GaAs-AlAs (type I) and GaSb-InAs (type II) superlattices. Thus it constitutes a new type of superlattice system called a type-III superlattice.[6] A series of theoretical and experimental investigations have begun to study the electronic properties of this superlattice. The dependence of the band structure on layer thickness,[7,8] temperature,[9] interdiffusion,[10] optical absorption,[11] and interfacial stress[12] have been studied theoretically. Magneto-optical absorption,[13] magnetotransport,[14,15] light scattering,[16] Hall-effect,[17] infrared transmission,[17,18] and infrared luminescence[19] measurements have been made on these materials.

In spite of the large amount of work that has been done on HgTe-CdTe superlattices, there are still several unanswered questions. One such question is the existence of high hole mobilities in the p-type superlattices. Hole mobilities have been reported as high as 30 000 cm^2/V sec, but all are above 1000 cm^2/V sec.[20] The highest mobilities reported for bulk p-type $Hg_{1-x}Cd_xTe$ is about 1000 cm^2/V sec. Mixing of light and heavy holes has been suggested as an explanation for the enhancement of the hole mobilities.[17] Several theoretical investigations have been carried out to study this problem. The band-structure calculation has been refined using a multiband tight-binding model[21] and the effect of the lattice mismatch between HgTe and CdTe has been investigated.[7,21] These studies conclude that the light holes should not contribute to the in-plane transport properties. In this Rapid Communication .we present results from magnetotransport measurements to support such a conclusion.

We have made magnetotransport measurements on several HgTe-CdTe and $Hg_{1-x}Cd_xTe$-CdTe superlattices in magnetic fields up to 23 T and temperatures as low as 0.5 K. A Riber molecular-beam epitaxy 2300 machine that was specially designed to handle mercury was used to manufacture these superlattices. Details of the fabrication of these superlattices are reported elsewhere.[20,22] The mobility of these samples is between 2500 to 11 000 cm^2/V sec at 10 K. Samples were cut into Hall-bar and Van de Pauw geometries and Ohmic contacts were made by diffusing gold into the samples. Standard dc technique was used to measure ρ_{xx} and ρ_{xy}. Currents of less than 1 μA were used.

The uppermost layer of the superlattices is always a CdTe layer which keeps the HgTe layer from being oxidized. The n-type inversion layer formed at the surface of bulk p-type $Hg_{1-x}Cd_xTe$ layers has been a serious problem in studying those materials.[23] Such an n-type surface layer is not observed in our samples. All of our superlattices have negative Hall voltages at 300 K and change to positive Hall voltages as the temperature is lowered and the magnetic field is increased. At 10 K and 0.3 T, most of our samples are p type and by 0.5 K and 23 T, they all have positive Hall voltages (see Table I). This result is consistent with a positive valence-band offset between HgTe (or $Hg_{1-x}Cd_xTe$) and CdTe.[13] If the valence-band offset is negative, charge transfer would occur from CdTe to HgTe always leading to an n-type structure.

Shubnikov–de Haas oscillations are observed at mag-

TABLE I. Characterization of $Hg_{1-x}Cd_xTe$-CdTe superlattices at 10 K with $B=0.3$ T. d_1 is the HgTe or $Hg_{1-x}Cd_xTe$ layer thickness, d_2 is the CdTe layer thickness, n the number of layers, μ_H the Hall mobility, in cm^2/V sec, and n_c the carrier density in cm^{-2}.

Sample	d_1 (Å)	d_2 (Å)	n	μ_H	n_c
1 HgTe-CdTe	40	20	250	11 000	2.65×10^{11}
2 $Hg_{0.92}Cd_{0.08}Te$-CdTe	70	40	100	2500	3.2×10^{11}

netic fields above 4 T at 4.2 K for a $Hg_{0.92}Cd_{0.08}Te$-CdTe superlattice (sample No. 2) Fig. 2(a). Shubnikov–de Haas oscillations are also observed in HgTe-CdTe superlattices. Furthermore, we have made measurements on some of the best p-type $Hg_{1-x}Cd_xTe$ epitaxial layers which have mobilities of about 1000 cm^2/Vsec and failed to observe any Shubnikov–de Haas oscillations. These results strongly indicate that p-type HgTe-CdTe and $Hg_{1-x}Cd_xTe$-CdTe superlattices have definitively higher mobilities than the bulk p-type $Hg_{1-x}Cd_xTe$ materials and therefore confirm the high hole mobilities observed in the Hall measurements.[17]

At $\omega_c\tau=1$ (or $\mu H=10^4$, where μ is the mobility in cm^2/Vsec and H is in tesla), the condition for observing quantum oscillations, the $Hg_{0.92}Cd_{0.08}Te$ sample should have a mobility of about 2500 cm^2/Vsec. With relatively strong oscillations above 5 T, it is surprising that no oscillation is detected below 5 T. Preliminary results of n-type heterojunctions show the expected gradual increase in the amplitude of the Shubnikov–de Haas oscillations and the sudden onset of the quantum oscillations in the p-type structures is a peculiar property of the system.

At low temperatures, the temperature dependence of the amplitude of the Shubnikov–de Haas oscillations is related to the effective mass of the carrier by the relation

$$A \propto T/\sinh(2kT/\hbar\omega_c) , \quad \omega_c = eH/m^*c , \tag{1}$$

where A is the amplitude of the oscillation, T is the temperature, ω_c is the cyclotron frequency, H is the magnetic field, m^* is the effective mass, $\hbar$ is Planck's constant, e is the electron charge, k is Boltzman's constant, and c is the velocity of light. Figure 1(b) shows the temperature dependence of Shubnikov–de Haas oscillations of the $Hg_{0.92}Cd_{0.08}Te$-CdTe superlattice (sample No. 2) between 1.5 and 4.2 K. Using Eq. (1), we obtained the effective mass of the carrier to be $0.36m_e$ at 5 T, where m_e is the mass of an electron. For HgTe-CdTe superlattices (sample No. 1), an effective mass of $0.30m_e$ is obtained. Depending on the experimental method used, the effective mass of the heavy hole of HgTe has been reported to be between $0.3m_e$ to $0.7m_e$.[24] The effective mass of the light hole is about the same as the effective mass of the electron which is $0.03m_e$. Our results indicate conclusively that the carriers showing Shubnikov–de Haas oscillations are the heavy holes. This is consistent with several band calculations.[13,21]

We determined the effective mass at 5 T; it is possible to have a different value at lower magnetic fields since we expect, from the band calculations, that the effective mass will have a magnetic field dependence.

Our results also indicate that carriers are in the HgTe or $Hg_{1-x}Cd_xTe$ layers of the superlattices. The lowest value for the effective mass of CdTe is about $0.7m_e$ (Ref. 25) which is larger than we observed. Furthermore, if the carriers are in the CdTe layer, the effective mass of the carriers should be the same for both HgTe-CdTe and $Hg_{0.92}Cd_{0.08}Te$-CdTe superlattices. Our results, determined under identical conditions, are $0.30m_e$ and $0.36m_e$, respectively, for the two superlattices which is consistent with the band-structure calculation that the heavy-hole effective mass increases as x decreases in $Hg_{1-x}Cd_xTe$.

The mobility enhancement in the $Hg_{1-x}Cd_xTe$-CdTe superlattices is different from that in the GaAs-$Ga_{1-x}Al_xAs$ system. In the GaAs-$Ga_{1-x}Al_xAs$ system, the mobility enhancement resulted from modulated doping. The dopants which are the sources of carriers at the interfaces or quantum wells are deliberately kept away from the interfaces during the growth process. In the $Hg_{1-x}Cd_xTe$-CdTe superlattice, the carriers come mainly from stoichiometry deviation. The growth conditions (e.g., temperature of cells and substrate) for the superlattice and the epitaxial layers are almost identical and yet the superlattices have mobilities significantly higher than those of the epitaxial layers. The enhancement of mobility in these p-type materials does not come from the growth conditions.

Since both HgTe-CdTe and $Hg_{1-x}Cd_xTe$-CdTe super-

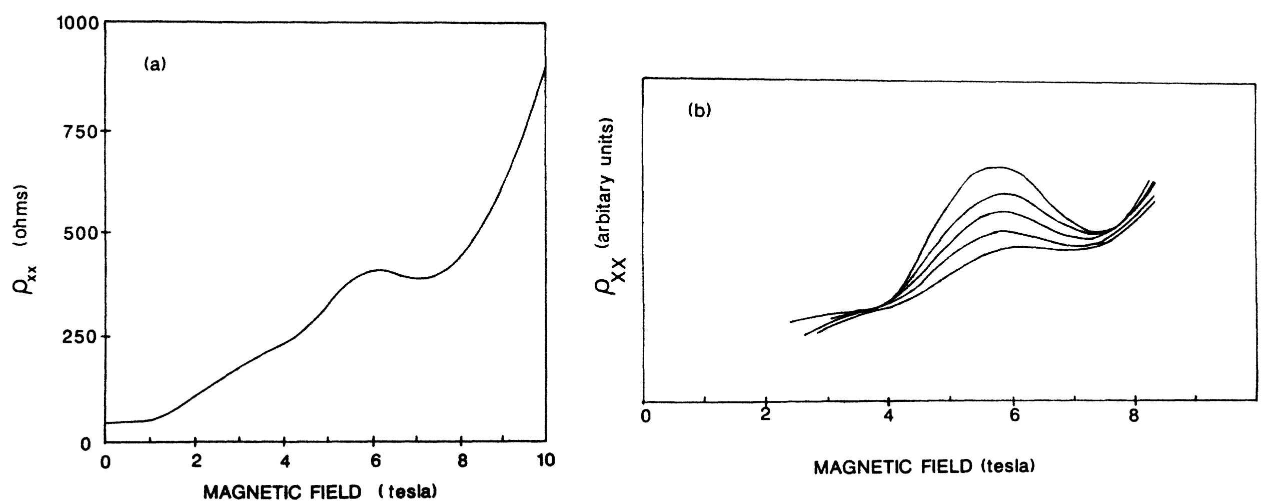

FIG. 1. (a) The magnetoresistance (ρ_{xx}) of a $Hg_{0.92}Cd_{0.08}Te$-CdTe superlattice (sample No. 2). (b) The temperature dependence of Shubnikov–de Haas oscillation between 1.5 and 4.2 K.

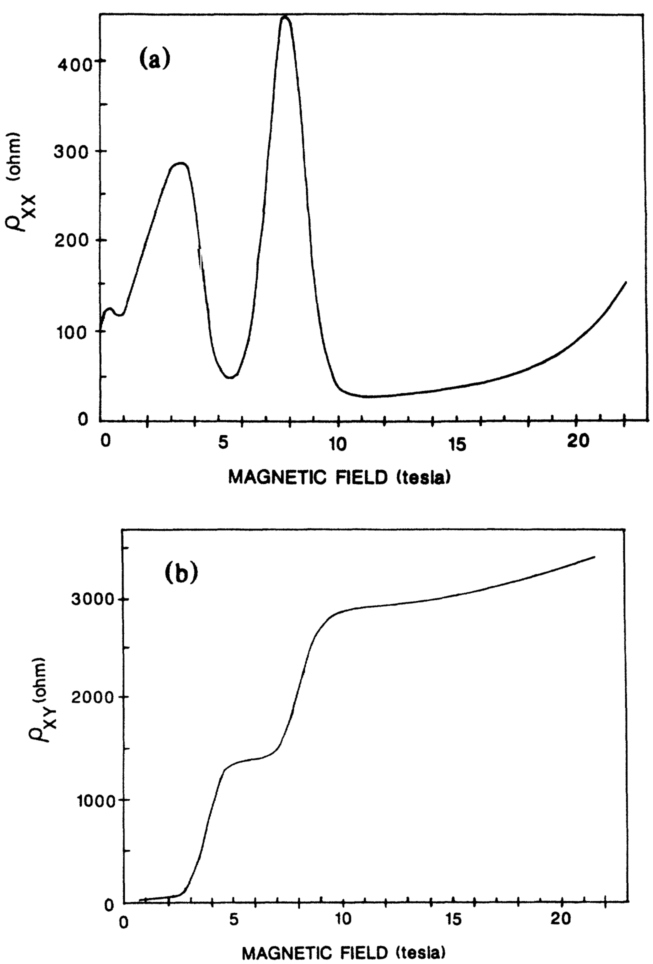

FIG. 2. The (a) ρ_{xx} and (b) ρ_{xy} of a $Hg_{0.92}Cd_{0.08}Te$-CdTe superlattice at 0.5 K.

lattices have mobility enhancement, alloy scattering is ruled out as the reason for the mobility difference between HgTe-CdTe superlattices and $Hg_{1-x}Cd_xTe$ bulk materials.

Interestingly, the mobility enhancement ceases when the $Hg_{1-x}Cd_xTe$ in the $Hg_{1-x}Cd_xTe$-CdTe superlattices changed from a semimetal to semiconductor.[22] $Hg_{1-x}Cd_xTe$-CdTe superlattices with $x = 0$, 0.01, 0.08, 0.16, 0.23, 0.27 have been manufactured and the Hall mobilities determined. If $Hg_{1-x}Cd_xTe$ is a semimetal, the mobilities are above 1800 $cm^2/V sec$. If $Hg_{1-x}Cd_xTe$ is a semiconductor, the mobilities are 350 $cm^2/V sec$ or less. This strongly suggests that mobility enhancement only occurs for the type-III superlattices (semimetal-semiconductor) and not type-I superlattices (semiconductor-semiconductor) in the $Hg_{1-x}Cd_xTe$-CdTe system. The interfacial strain and the valence-band offset in all these samples should be the same. One of the differences between type-III and type-I superlattices is the existence of interface states in the type-III superlattice but not in the type-I superlattices.[3] It is possible that the drastic difference in mobility in these superlattices is related to these interfacial states.

Figure 2 shows ρ_{xx} and ρ_{xy} of a $Hg_{0.92}Cd_{0.08}Te$-CdTe superlattice. The quantized Hall effect is observed in ρ_{xy}. Since the observation of the quantized Hall effect in silicon inversion layers, most of the systems found to exhibit such an effect are mainly n-type III-V semiconductor heterojunctions. There has only been one p-type system reported to exhibit the quantized Hall effect.[26] The HgTe-CdTe system represents the second p-type system that shows such an effect. A detailed report of this effect in HgTe-CdTe and $Hg_{1-x}Cd_xTe$-CdTe will be published elsewhere.

In conclusion, we have determined from effective-mass measurements at 5 T that the dominating carriers of $Hg_{1-x}Cd_xTe$-CdTe superlattices are the heavy holes. We speculate that the mobility enhancement in the type-III superlattices is related to the interface states.

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