Hole Hall-mobility enhancement in $\text{HgTe-Hg}_{1-x}\text{Cd}_x\text{Te}$ heterojunctions

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The hole Hall mobilities of p -type $\text{HgTe-Hg}_{1-x}\text{Cd}_x\text{Te}$ structures are observed to be several times higher than the alloys. The $i=1$ plateau of the quantized Hall effect is observed and this indicates the two-dimensional holes at the $\text{HgTe-Hg}_{1-x}\text{Cd}_x\text{Te}$ interfaces are of high mobility. We speculate that the mobility enhancement is related to the interface states.

Hall mobility enhancement has been observed in several systems prepared by the molecular-beam epitaxial (MBE) technique. Superlattices and heterojunctions can have mobilities significantly higher than the bulk material. The MBE technique can control the growth of structures down to a single atomic layer and manufacture samples of very sharp interface. Such capabilities of the MBE technique allow the manufacture of several systems which exhibit mobility enhancement. In $\text{GaAs-Ga}_{1-x}\text{Al}_x\text{As}$ superlattices¹ and heterojunctions,² the mobility is increased because of the modulated doping technique. 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. Scattering at the interfaces due to the dopants is greatly reduced and this gives rise to a huge increase in mobility. In the strained layer superlattices³ the mobility is increased because of the mixing of the light and heavy holes. In the p -type $\text{HgTe-Cd}_x\text{Te}$ superlattices grown on CdTe substrate, mobility as high as $30000 \text{ cm}^2/\text{Vsec}$ has been reported.⁴ Bulk p -type $\text{Hg}_{1-x}\text{Cd}_x\text{Te}$ alloys have typical mobility of less than $500 \text{ cm}^2/\text{Vsec}$. The mobility enhancement is not due to modulation doping as in the $\text{GaAs-Ga}_{1-x}\text{Al}_x\text{As}$ system. In fact, modulation doping in the $\text{Hg}_{1-x}\text{Cd}_x\text{Te}$ system would be extremely difficult to achieve as the carriers of this system come from stoichiometry deviation. HgTe is a semimetal with a -0.3-eV band overlap and CdTe is a semiconductor with a 1.6-eV band gap. In the superlattices, the matching of the bulk states belonging to the HgTe conduction band which has positive mass and the CdTe light hole valence band which has negative mass gives rise to interface states.⁵⁻⁷ Such interface states do not exist in $\text{Hg}_{1-x}\text{Cd}_x\text{Te-CdTe}$ superlattice if $\text{Hg}_{1-x}\text{Cd}_x\text{Te}$ is a semiconductor. The mobility enhancement only occurs in a $\text{Hg}_{1-x}\text{Cd}_x\text{Te-CdTe}$ superlattice only if $\text{Hg}_{1-x}\text{Cd}_x\text{Te}$ is a semimetal. It has been suggested that the mobility enhancement of this system is related to the interface states.⁸ In this Rapid Communication we report for the first time hole mobility enhancement in $\text{HgTe-Hg}_{1-x}\text{Cd}_x\text{Te}$ heterojunctions where $\text{Hg}_{1-x}\text{Cd}_x\text{Te}$ is a p -type semiconductor.

The $\text{HgTe-Hg}_{1-x}\text{Cd}_x\text{Te}$ heterojunctions are grown in a Riber 2300 MBE machine which is designed to handle mercury. A $\text{Cr-doped [100]-oriented GaAs}$ substrate is preheated at 580°C for 5 min. A $2\text{--}2.5\text{-}\mu\text{m}$ CdTe buffer layer is then grown at 290°C . The preheated treatment assured the CdTe buffer layer would grow in the $[111]\text{B}$ orientation.⁹ The HgTe layers were grown using two cells

containing Hg and Te while the $\text{Hg}_{1-x}\text{Cd}_x\text{Te}$ layers were grown using three cells containing Hg , Te , and CdTe . The HgTe layers are $60\text{--}85 \text{ \AA}$ thick while the $\text{Hg}_{1-x}\text{Cd}_x\text{Te}$ layers are of $1.2\text{--}2.6 \mu\text{m}$. We have grown $\text{Hg}_{1-x}\text{Cd}_x\text{Te}$ layers with x values in the range of $0.2\text{--}0.33$. For comparison purpose, single $\text{Hg}_{1-x}\text{Cd}_x\text{Te}$ layers (without the HgTe layers) are also grown. Resistivities and Hall mobilities are determined using van der Pauw geometry between 30 and 300 K in magnetic fields up to 1.5 T . High magnetic field transport measurements were made between 0.5 and 4.2 K in superconducting and Bitter magnets using both van der Pauw and Hall bar geometries.

The Hall mobility at about 30 K of some p -type $\text{HgTe-Hg}_{1-x}\text{Cd}_x\text{Te}$ heterojunctions and $\text{Hg}_{1-x}\text{Cd}_x\text{Te}$ alloys are shown in Table I. The heterojunctions which contain a thin layer of HgTe between the $\text{Hg}_{1-x}\text{Cd}_x\text{Te}$ and the CdTe buffer layer have much higher mobilities than the $\text{Hg}_{1-x}\text{Cd}_x\text{Te}$ alloys which do not contain any HgTe layers.

Figure 1 shows the high magnetic field transport of one of the heterojunctions at 0.5 K . The quantized Hall effect is observed in these samples. ρ_{xx} is zero at about 9 T and ρ_{xy} shows a plateau of about $25 \text{ k}\Omega$ which corresponds to a Landau level index $i=1$. These results indicate that the carriers that have the high mobility are two-dimensional holes and the hole density is $2.1 \times 10^{11} \text{ cm}^{-2}$. Detailed interpretation of these data will be reported elsewhere.

We are convinced that the two-dimensional holes come from the HgTe layers. Samples that do not contain the HgTe layer do not exhibit the quantized Hall effect. We have also ruled out any possibility that a space charge

TABLE I. Mobilities of some $\text{HgTe-Hg}_{1-x}\text{Cd}_x\text{Te}$ heterojunctions and $\text{Hg}_{1-x}\text{Cd}_x\text{Te}$ alloys at about 30 K .

Sample	x	$d_{\text{HgTe}} (\text{\AA})$	$\mu_H (\text{cm}^2/\text{V sec})$
1	0.20	80	1000
2	0.21	60	1000
3	0.20	70	1200
4	0.28	75	1800
5	0.30	85	1100
6	0.33	70	1200
7	0.20	0	560
8	0.25	0	400
9	0.30	0	400

FIG. 1. The quantized Hall effect of a HgTe-*p*-type Hg_{0.28}Cd_{0.72}Te at 0.5 K.

layer is formed on an oxidized surface and contributes to the measurements. The measurements were made right after the samples are carefully etched so that the surface would not be oxidized. Reproducible results are obtained from several samples that are cut from the same wafer.

The $i = 1$ plateau implies that high mobility holes come from one sheet of two-dimensional hole gas. If there are two sheets of two-dimensional hole gas the 25-k Ω plateau would correspond to the fractional quantized Hall effect with an even fraction of $i = \frac{1}{2}$. This contradicts both experimental and theoretical results of the fractional quantized Hall effect that only odd fractions exist.¹⁰

In order to determine whether the HgTe-Hg_{1-x}Cd_xTe structure consists of a single quantum well or two heterojunctions of HgTe-CdTe and HgTe-Hg_{1-x}Cd_xTe, we manufacture a structure that consists of the CdTe buffer at the bottom, a thick Hg_{1-x}Cd_xTe layer in the middle, and a thin HgTe layer on the top. A similar result is obtained in this structure suggesting that the two-dimensional holes come from the HgTe-Hg_{1-x}Cd_xTe interface.

The Hg_{1-x}Cd_xTe alloys have higher mobilities if the Cd concentration is decreased. This is because the effective mass of the hole decreases and hence an increase of mobility. No such pattern is observed in the HgTe-Hg_{1-x}Cd_xTe structures indicating the holes are probably

in the HgTe side of the interface.

These experimental results suggest that two-dimensional hole gas at the HgTe-Hg_{1-x}Cd_xTe interface has significant higher mobility than the *p*-type bulk materials. The mobility enhancement observed in *p*-type Hg_{1-x}Cd_xTe-CdTe superlattice is somewhat related to the interface states. We speculate the mobility enhancement of these *p*-type heterojunctions is also related to the interface states. Presence of the interface states plays a role on the effective mass of the heavy hole. Interface states are also expected to exist in the HgTe-Hg_{1-x}Cd_xTe heterojunctions studied here as Hg_{1-x}Cd_xTe with $0.2 < x < 0.33$ is a semiconductor. The interface states are below the heavy hole bands. It should not affect the transport properties of the *n*-type heterojunction as the Fermi energy is in the conduction band. In this picture there should be no mobility enhancement in the *n*-type heterojunction. This is precisely what we observed. Our preliminary result of *n*-type heterojunctions (i.e., HgTe-*n*-type Hg_{1-x}Cd_xTe) show no mobility enhancement but the quantized Hall effect is observed indicating that the high mobility electrons are also two dimensional. All the samples presented in Table I are grown on GaAs substrates and the highest mobility is 1800 cm²/Vsec. This is not much different from 2500 cm²/Vsec, the highest mobility of the *p*-type Hg_{1-x}Cd_xTe-CdTe superlattices grown on GaAs substrates.¹¹

Cheung *et al.*¹² have reported that due to interfacial strain the CdTe-Hg_{1-x}Te layers closed to the buffer layers of HgTe-Cd_xTe superlattices have lower mobilities than those on the top of the superlattices. It is unclear whether interfacial strain is responsible for the discrepancy of the highest mobility observed for the heterojunctions and the superlattices. We have not found the optimized thickness of the HgTe layer for the mobility enhancement.

One of the differences between the two systems is that the Hg_{1-x}Cd_xTe in the heterojunctions studied here have a much smaller band gap than in CdTe. The valence-band offset in these heterojunctions should be much smaller than the superlattices. The energy of the interface states E_i , measured from the HgTe conduction-band minimum, depends on the mass of the electron of the HgTe, m_1 , the mass of the light hole in Hg_{1-x}Cd_xTe, m_2 , and the valence-band offset Λ ,

$$E_i = -\frac{m_1}{m_1 + |m_2|} \Lambda.$$

Thus the energy difference between the interface states and the heavy holes in these heterojunctions is smaller than that of the superlattices. A stronger mixing of the interface states and the heavy holes is expected. This stronger mixing could change the curvature of both bands and hence their effective masses. It is plausible that the mobility enhancement is stronger in these heterojunctions than in the superlattices. On the other hand, there would be less confinement of the carrier if the valence-band offset is too small. It is possible that there are several competing factors in the mobility enhancement in these heterojunctions.

In conclusion, hole mobility enhancement which could be related to interface states is observed in the two-

dimensional holes in the p -type $\text{HgTe-Hg}_{1-x}\text{Cd}_x\text{Te}$ heterojunctions. The quantized Hall effect is also observed in these structures.

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