

HgTe and CdTe epitaxial layers and HgTe–CdTe superlattices grown by laser molecular beam epitaxy

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CdTe and HgTe epilayers and HgTe/CdTe superlattices have been grown by laser molecular beam epitaxy (laser MBE) on CdTe substrates. The power density of the laser radiation used to evaporate source materials was found to be a very important growth parameter. The superlattice structures have been characterized by helium ion backscattering spectrometry, x-ray double crystal diffractometry, and low temperature electrical transport measurements. Results indicate good crystallinity and very strong 2D carrier confinement at low temperatures. At 77 K, electron mobilities in excess of $50\,000\text{ cm}^2/\text{V s}$ have been observed. Quantum Hall effect has been observed for the first time in this system.

I. INTRODUCTION

A recent surge of interest in the HgTe/CdTe superlattice as a promising candidate for detecting infrared radiation at wavelengths beyond $18\text{ }\mu\text{m}$ arises from the unique properties associated with this material such as the tunable band gap and long transverse tunneling length. Theoretical developments¹⁻⁴ on the band structure, optical properties, effects of interface states, and interdiffusion have been reported. Experimentally, it has been grown both by molecular beam epitaxy (MBE)⁵ and laser MBE.⁶

This paper reports recent progress on the studies of HgTe/CdTe superlattices grown by laser MBE. Results will include the growth conditions and physical properties of CdTe layers, HgTe layers, and HgTe/CdTe superlattices. The uniqueness of laser MBE will be reflected in the homoepitaxial growth of CdTe on (111)CdTe substrates. This will be followed by a description of the electrical properties of HgTe layers grown by laser MBE. Finally, the growth and characterization of HgTe/CdTe superlattices will be discussed. These superlattices show very high quality as evidenced by their high electron mobility and the observation of the quantum Hall effect for the first time in this system.

II. EXPERIMENTAL

Laser MBE, also known as laser assisted deposition and annealing, or LADA, is a technique in which a high power pulsed laser is used to induce source evaporation in a vacuum deposition system.

The growth apparatus is a two-chamber system consisting of a growth chamber and a sample load-lock. The growth chamber is lined with a liquid nitrogen cooled shroud in order to handle large Hg throughput for growing HgTe. The Hg beam is generated by a thermal effusive source. CdTe and tellurium polycrystalline pieces are placed in separate tantalum boats for evaporation. The sources are mounted to a rotatable platform. Superlattice structures are formed by al-

ternately exposing the two sources to the laser radiation. A calibrated quartz crystal thickness monitor is used to control the exposure time. The apparatus uses an acousto-optically Q-switched yttrium aluminum garnet (YAG) laser to induce evaporation. Typical operating conditions are: 3000 Hz repetition rate with an average power of 4.8 W (for CdTe) and 2.2 W (for tellurium). The beam is focused to a 0.03 cm diam spot and is rastered over the source surface at 0.5 Hz with a linear rate of 1.2 cm/s . Typical growth rate is about $1\text{ }\mu\text{m/h}$. Single crystal CdTe wafers were used as substrates. A $2000\text{ }\text{\AA}$ thick CdTe buffer layer was deposited before HgTe or HgTe/CdTe superlattice growth. The HgTe layers and HgTe/CdTe superlattices were grown at temperatures ranging from 160 to $210\text{ }^\circ\text{C}$.

III. RESULTS

A. CdTe

In laser MBE, the nucleation and growth kinetics are different from conventional MBE due to their different source temperatures. For regular MBE, the CdTe source is heated to about $650\text{ }^\circ\text{C}$. Under this condition, CdTe evaporates congruently into cadmium atoms and tellurium molecules. For laser MBE, the surface temperature is much higher than the melting point ($1098\text{ }^\circ\text{C}$) and the thermal cycle is very short. Under this condition, CdTe evaporates dissociatively and congruently into cadmium atoms and tellurium atoms.⁷ The different chemical states of tellurium play a very important role in nucleation kinetics. This is best exemplified by the homoepitaxial growth of CdTe on (111)CdTe substrates. Since (111) is a polar surface, it can have either a Cd terminated [i.e., (111)A] or a Te terminated [i.e., (111)B] surface. The surface polarity was identified by etching the substrate in a lactic acid, H_2O_2 and H_2O mixture.⁸ The (111)B face remained shiny while the (111)A resulted in a dull and dark appearance. By using effusive Knudsen cell as CdTe source and under the growth condition of $250\text{ }^\circ\text{C}$ growth

temperature and $1 \mu\text{m/h}$ growth rate, epitaxy can only be produced on the (111)B face. On (111)A, the CdTe film is polycrystalline.⁸

By laser MBE, we have achieved epitaxy on both faces. We have grown CdTe films on CdTe (111)A and (111)B face at 250°C at $1 \mu\text{m/h}$ under different laser conditions. Under low power density (10^6 W/cm^2) irradiation, CdTe source is heated very gradually until it reaches a steady evaporation rate. Under this condition, which simulates thermal evaporation, epitaxy occurs only on the (111)B face as expected. A CdTe film grown on the (111)A face is polycrystalline with rough surface morphology. Its morphology can be improved by increasing the power density of the laser radiation used for evaporation. At 10^7 W/cm^2 , the morphology of the CdTe film grown on (111)A face becomes featureless. X-ray Laue diffraction was used to confirm it to be single crystal. We have also grown a $1 \mu\text{m}$ thick HgTe layer on top of the CdTe buffer layers grown under these various laser conditions. On CdTe buffer layer grown under high power laser radiation, the 77 K mobility of the HgTe layer exceeds $2 \times 10^4 \text{ cm}^2/\text{V s}$. On the other hand, for a HgTe layer grown on a CdTe buffer deposited with low power laser radiation, its mobility at 77 K is on $1000 \text{ cm}^2/\text{V s}$. This again proves that epitaxial nature of CdTe grown on (111)A substrate by using high power density laser radiation for evaporating the source material.

B. HgTe

HgTe was grown onto a CdTe substrate by laser evaporating tellurium in the presence of a high flux Hg beam. We have grown HgTe/CdTe heterostructures on (111)B, (110), and (100) oriented substrate at temperatures from 155 to 185°C . In each case, a 2000 \AA thick CdTe buffer layer was grown at 250°C prior to HgTe growth. Thickness of the HgTe layers varies from 0.7 to $2 \mu\text{m}$. Results indicate that the epilayer quality is strongly dependent on the substrate orientation. 77 K electron mobilities of the HgTe epilayers grown under various conditions are shown in Fig. 1. On (111)B substrate, the mobility increases as the growth temperature increases to a constant value in the range of $2 \times 10^4 \text{ cm}^2/\text{V s}$ to $3 \times 10^4 \text{ cm}^2/\text{V s}$ for films grown at 185°C . It agrees with the values reported for MBE grown HgTe on (111)B CdTe substrates.⁹ However, on a nonpolar substrate orientation such as (110) and (100), the HgTe epilayers show much higher mobilities. At 185°C growth temperatures, the 77 K carrier concentration and mobility are $7 \times 10^{16} \text{ cm}^{-3}$ and over $5 \times 10^4 \text{ cm}^2/\text{V s}$, respectively. These values are comparable to HgTe grown on CdTe(100)/GaAs(100) substrate by MBE⁹ and to bulk HgTe grown by the Bridgman technique.¹⁰

C. HgTe/CdTe superlattice

HgTe/CdTe superlattices have been grown by alternately evaporating CdTe and tellurium in the presence of a high flux density Hg beam.

Structural characterization was made by helium ion backscattering spectrometry (BSS), and x-ray double crystal diffractometry (DCD). Rutherford backscattering (RBS)

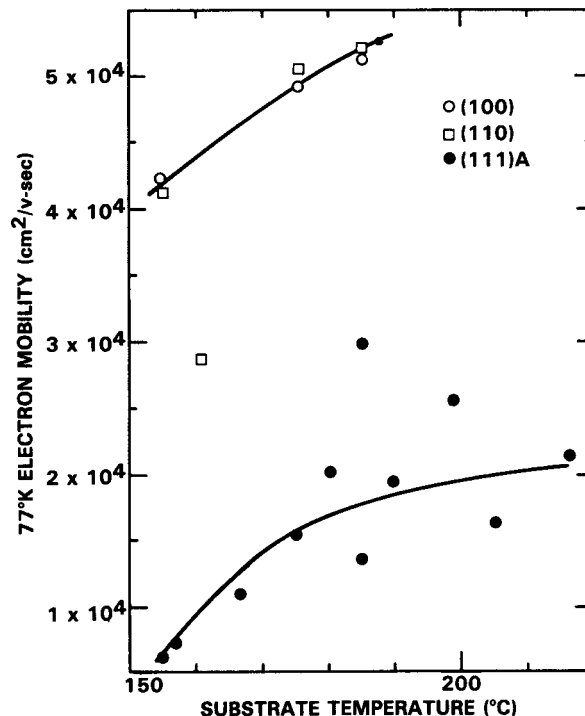


FIG. 1. Electron mobility at 77 K for HgTe layers grown on (111)B, (110), and (100) CdTe at different substrate temperatures by laser MBE.

measurements were carried out with a 2 MeV He ion beam. Figure 2 shows a backscattering spectrum of a ten-period superlattice taken at random orientation. Oscillations due to composition modulation are well resolved and show excellent periodic thickness uniformity. However, the oscillatory amplitude decreases as the exposure time to the 2 MeV He ion beam increases. It suggests that the BSS technique is destructive to HgTe-CdTe superlattice structure, causing interdiffusion at the HgTe-CdTe interfaces.

A more powerful and nondestructive characterization technique is x-ray double crystal diffractometry (DCD) measurement. DCD experiments can be carried out either symmetrically or asymmetrically. In symmetrical diffraction, the incidence angle and the diffraction angle are symmetric about the axis perpendicular to the superlattice planes. Such a spectrum consists of diffraction peaks from

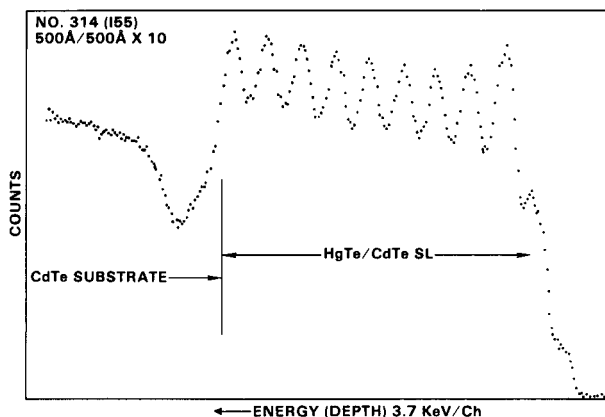


FIG. 2. BSS spectrum of a HgTe/CdTe superlattice taken at random orientation.

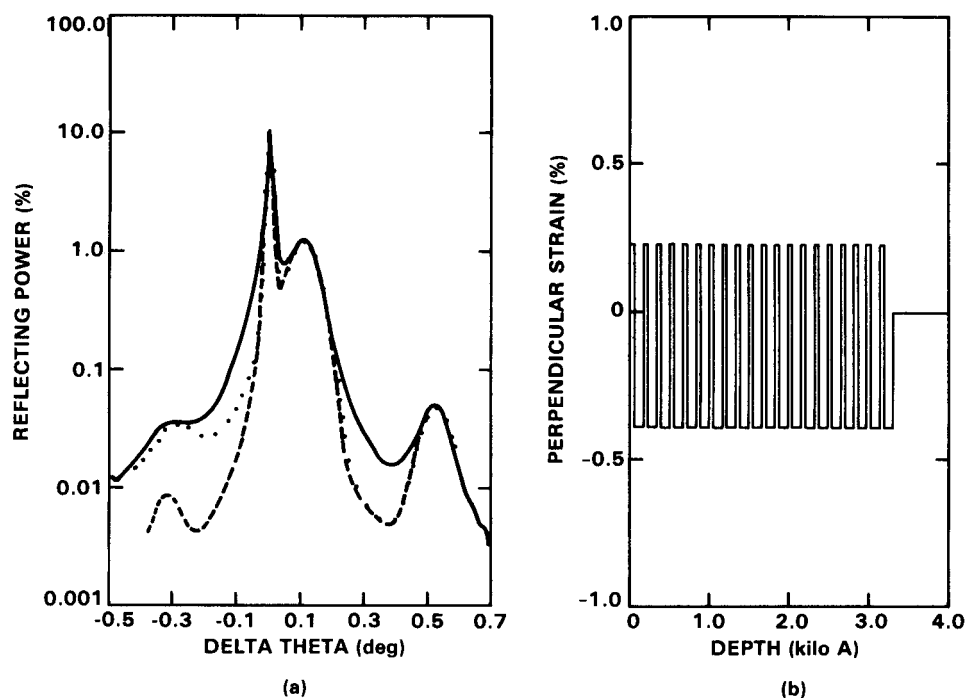


FIG. 3. (a) $\langle 400 \rangle$ diffraction from a HgTe–CdTe SL solid curve is the experimental value, dashed curve is the fitting by using the profile in (b), dotted curve is the fitting by using the profile in (b) and including a 1000 Å region with 1% strain.

the substrate, the superlattice structure, and a series of satellite peaks on both sides of the main peaks. These satellite peaks are due to the interference of the diffracted x-ray radiation from the crystal lattice spacing and the superlattice spacing. Information on perpendicular strain profile and composition modulation can be derived from their locations, widths, and relative intensities. In asymmetric diffraction, strain along a direction perpendicular to the layer normal axis can be determined since the rocking curve is affected by perpendicular as well as lateral strain. The perpendicular strain can be obtained directly from the symmetric strain; therefore, lateral strain can be calculated. Lateral strain arises when the coherence within the superlattice structure is lost.

A HgTe–CdTe superlattice structure grown on $\langle 100 \rangle$ CdTe was analyzed by DCD. $\text{FeK}_{\alpha 1}$ radiation was used, and rocking curves were measured about both symmetric $\langle 400 \rangle$ and the asymmetric $\langle 440 \rangle$ Bragg angles. The symmetric diffraction is shown as the solid line in Fig. 3(a). In addition to the substrate peak at $\Delta\theta = 0$, a prominent peak and two lesser peaks from the epitaxial structure are also visible. The presence of the lower intensity “satellite” peaks shows clearly that a superlattice structure is present. Using the zero-order peaks in the $\langle 400 \rangle$ and $\langle 440 \rangle$ rocking curves, we find that the average lattice parameter of the superlattice in the direction parallel to the layer is less than that of the substrate by 0.17%. In other words, an effective -0.17% parallel strain is present relative to the substrate.

To obtain information about perpendicular strain distribution, we have used the kinematic model¹¹ and iterative technique to curve fit the $\langle 400 \rangle$ symmetric diffraction curve. Results are shown in Fig. 3(a). The solid curve is the experimental result, and the dashed curve is the calculated spectrum by using the perpendicular strain profile shown in Fig. 3(b). It corresponds to 20 periods of 127 Å HgTe layers and

38 Å CdTe layers. It was necessary to convolute the rocking curve calculated for perfect crystalline layers with a Gaussian function with standard deviation of 150 arc s. This accounts for lateral variation in strain, probably arising from extended defects and local inhomogeneities in composition. The fit is good for the zero-order and $n = -1$ order peak. The discrepancy at the angle midway between the peaks arises because the actual convolution function should have larger tails than a Gaussian function.

The position of the $+1$ peak is reproduced, but its intensity is low by a factor of about 8. This discrepancy can be accounted for by introducing a narrow region of approximately 1000 Å thick with 1% perpendicular strain. Curve fitting by taking into account this narrow but highly strained region is in good agreement with the experimental diffraction curve. X-ray diffraction is not sensitive to the location of this highly strained region. We have grown a number of single period structures with the thickness of the HgTe and CdTe layers the same as those in the superlattice. These samples exhibit very low electron mobilities only in the range between 5000 to 9000 $\text{cm}^2/\text{V s}$. This suggests that the first

TABLE I. Comparison of HgTe/CdTe SLS grown by MBE¹³ and by laser MBE.

SL parameter	Laser MBE		MBE		
	T_s (°C)	77 K Mobility ($\text{cm}^2/\text{V s}$)	SL parameter	77 K Mobility ($\text{cm}^2/\text{V s}$)	
280/180 × 14	210	5×10^2	180/44 × 100	200	8×10^4
100/75 × 15	160	1.4×10^4	100/40 × 102	185	4×10^4
127/38 × 20	185	2.7×10^4	400/150 × 13	160	1×10^4
200/100 × 6	160	5.5×10^4			
90/40 × 12	160	3.3×10^4			

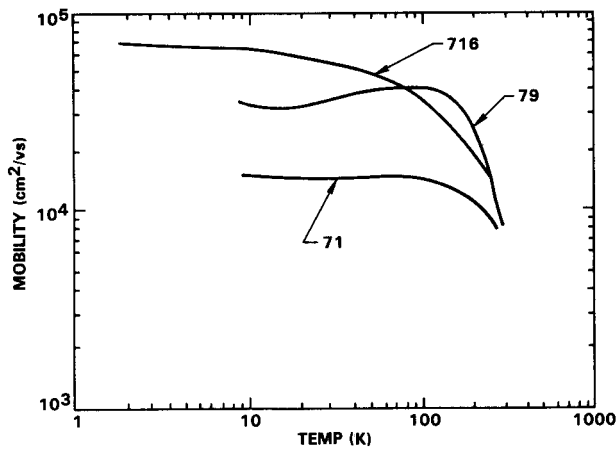


FIG. 4. Temperature dependence of electron mobility of several HgTe/CdTe superlattices.

few periods in the superlattice structure are highly strained, that the narrow but highly strained region is at the superlattice/buffer layer interface. Therefore, layers in this region have lower mobility. For this superlattice, a 1000 Å region corresponds to six periods or 30% of the entire structure.

Temperature dependent Hall measurements were made on these samples by a four point Van der Pauw technique. Indium solder was used to form Ohmic contacts. All samples show *n*-type transport behavior from 4.2 K to room temperature. Their mobility values at 77 K are tabulated in Table I and are comparable to MBE grown HgTe/CdTe superlattices.¹²

Unlike the MBE grown superlattices, our samples do not show any *n* to *p* transition at low temperature. Figure 4 shows temperature dependence of the electron mobility. All samples show a similar trend. Namely, the mobility values increase with the decrease of temperature. As the tempera-

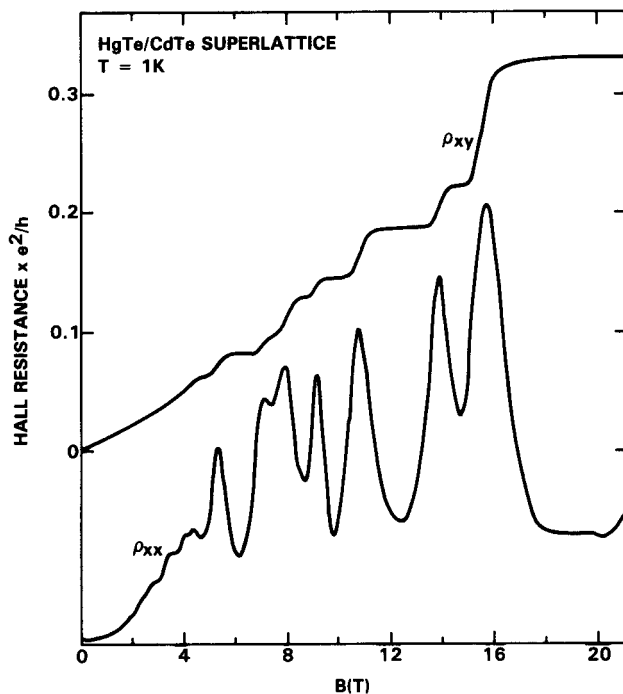


FIG. 5. Quantum Hall effect and magnetoresistance oscillation in a HgTe/CdTe superlattice.

ture further decreases, the mobility either increases slightly, stays near constant, or decreases very slightly.

We have also observed the quantum Hall effect (QHE) in the HgTe–CdTe superlattice system. This is again a proof of the high quality of laser MBE grown HgTe–CdTe superlattices. Thus far, quantum Hall effect has been observed in several two-dimensional electronic systems, namely, silicon inversion layers,¹³ and heterojunctions made from III–V compounds.¹⁴ The extension of QHE to HgTe–CdTe system is particularly interesting because of its interesting band structure and the large spin orbit scattering in HgTe. Measurements were made from 0.5 K to 4.2 K in a perpendicular magnetic field up to 21 T. The quantized Hall resistivity and strong oscillations in its magnetoresistance at 1 K are shown in Fig. 5. Clearly, the transport mechanism is far more complicated than those found in Si and other III–V systems. A detailed discussion on this subject will be published elsewhere.¹⁵ The result is consistent with an interpretation based on the coexistence of electrons and holes.

IV. SUMMARY

In this paper, we have given an overview of our progress on the studies of CdTe, HgTe epitaxial layers, and HgTe/CdTe superlattices grown by laser MBE. By varying the laser condition, this technique gives an added dimension in optimizing growth conditions. The uniqueness is best reflected in the homoepitaxial growth of CdTe/(111)A CdTe which can be achieved by increasing the power density of laser radiation used for evaporation. We have also demonstrated high quality HgTe layers grown on CdTe by laser MBE. Finally, we have measured the electronic and structural properties of HgTe/CdTe superlattices grown by laser MBE. HgTe–CdTe superlattice grown on (100) CdTe at 185 °C has an average lateral strain of -0.17% , and it has a narrow region with high strain at the superlattice buffer layer interface. The superlattice shows very high electron mobility. We have also observed the quantum Hall effect and very large oscillations in magnetoresistance. These observations confirm the quality of the HgTe/CdTe superlattice grown by laser MBE.

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