Growth and Properties of Hg-Based Quantum Well Structures and Superlattices

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An overview of the properties of HgTe-CdTe quantum well structures and superlattices will be presented. These new quantum structures are candidates for use as new LWIR and VLWIR detectors, as well as for other optoelectronic applications. Much has been learned within the past two years about the physics of such structures. The valence band offset has been determined to be ~350 meV, independent of temperature. The occurrence of electron and hole mobilities in excess of $10^5$ cm$^2$/V·s is now understood on the basis of SL band structure calculations. The in-plane and out-of-plane electron and hole effective masses have been measured and interpreted theoretically for HgTe-CdTe superlattices. Controlled substitutional doping of superlattices has recently been achieved at NCSU, and modulation-doped SLs have now been successfully grown and studied. Most recently, a dramatic lowering of the growth temperature of Hg-based quantum well structures and SLs (to ~100 C) has been achieved by means of photoassisted MBE at NCSU. A number of new devices have been fabricated from these doped multilayers.

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GROWTH AND PROPERTIES OF Hg-BASED QUANTUM WELL STRUCTURES & SUPERLATTICES

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NCSU II-VI SEMICONDUCTOR MBE PROGRAM
Collaborators and Students at NCSU

- Research Associates
  N.C. Giles
  S. Hwang
  Z. Yang
  J. Yu

- Graduate Students
  D. Dreifus
  J. Han
  Y. Lansari
  R. Vaudo
  R. Reed

- Technicians
  J. Matthews
  B. Sneed
  K. Bowers

- Secretary
  T. Hockenberger

- Undergraduates (4)
OVERVIEW OF PRESENTATION

- **Photoassisted MBE at NCSU**
  - Experimental Procedures
  - Summary of Materials Properties

- **HgTe-CdTe Superlattices**
  - Growth of VLWIR Structures (18 - 22 μm)
  - Controlled Doping Studies
  - Low Temperature Processing at NCSU

- **Applications**
  - Sources & Detectors
  - Amplifiers & Modulators

ENERGY BAND GAP vs LATTICE CONSTANT OF SELECTED SEMICONDUCTORS
PHOTOASSISTED MOLECULAR BEAM EPITAXY
A New Approach to Controlled Substitutional Doping

R.N. Bicknell, N.C. Giles, and J.F. Schetzina

- A Form of Energy-Assisted Epitaxy
- Growth Temperatures of II-VI Compounds are Low (150 - 350 °C)
- Photons Provide a Source of High Energy, Low Momentum Particles that Bathe the Substrate Surface during Film Growth & Induce Photochemical Reactions
- "It's all done with MIRRORS!!!"

SUBSTITUTIONAL DOPING OF II-VI SEMICONDUCTORS
Major Long-Term Problems

- Poor Quality Bulk Crystals & Substrates
- Large Dislocation Densities
- Large Densities of Native Defects
- Low Percentage of Dopant Activation
- Compensation Effects Often Dominate
- Poor Electrical Properties - Low Mobilities
- Inferior Optical Properties - Deep Levels
PHOTOASSISTED MOLECULAR BEAM EPITAXY

Microscopic Mechanisms

- Conversion of Surface Molecules into Atoms
- Photochemical Changes in Atomic Bonding
- Enhancement of Surface Mobility of Atoms
- Photochemical Activation of Dopant Atoms
- Modification of Stoichiometry of Growth Surface

PHOTOASSISTED MOLECULAR BEAM EPITAXY
MBE Film Growth Systems at NCSU

SYSTEMS DESIGNED AND CONSTRUCTED AT NCSU
- Custom Features for II-VI Materials
  - Cost Effective

MBE FACILITIES
- Three Hg-Compatible Systems
- One System for Wide Gap II-VIs
- Special Hg Sources (NCSU)
- Two-Zoned Furnaces (NCSU)
- Computer-Controlled Shutters
- Spectra Physics Argon Ion Laser
PHOTOASSISTED MOLECULAR BEAM EPITAXY
WIDE-BAND-GAP & NARROW-BAND-GAP II-VIs

<table>
<thead>
<tr>
<th>MATERIALS GROWN</th>
<th>PROPERTIES</th>
</tr>
</thead>
<tbody>
<tr>
<td>CdTe:In</td>
<td>• Controlled Doping</td>
</tr>
<tr>
<td>CdTe:Sb</td>
<td>• High Carrier Mobilities</td>
</tr>
<tr>
<td>CdTe:As</td>
<td>• Narrow Rocking Curves</td>
</tr>
<tr>
<td>CdMnTe-CdTe Superlattices</td>
<td>• Bright Photoluminescence</td>
</tr>
<tr>
<td>HgTe-CdTe Superlattices</td>
<td>• p-n Junctions Fabricated</td>
</tr>
<tr>
<td>Modulation-Doped HgCdTe</td>
<td>• FETs Fabricated</td>
</tr>
</tbody>
</table>

HgTe-CdTe SUPERLATTICES
Growth Parameters

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>VALUE</th>
</tr>
</thead>
<tbody>
<tr>
<td>SUBSTRATE:</td>
<td>(100) CdZnTe</td>
</tr>
<tr>
<td>SUBSTRATE TEMPERATURE:</td>
<td>150 °C</td>
</tr>
<tr>
<td></td>
<td>140 °C (Photoassisted)</td>
</tr>
<tr>
<td>T_{In}</td>
<td>400-475 °C</td>
</tr>
<tr>
<td>T_{As}</td>
<td>220 °C</td>
</tr>
<tr>
<td>Hg FLUX:</td>
<td>1.5 \times 10^{-4} Torr</td>
</tr>
<tr>
<td>DEPOSITION RATE:</td>
<td>1-3 Å/sec</td>
</tr>
<tr>
<td>LAYER THICKNESSES:</td>
<td></td>
</tr>
<tr>
<td>HgTe</td>
<td>32-160 Å</td>
</tr>
<tr>
<td>CdTe</td>
<td>26-102 Å</td>
</tr>
</tbody>
</table>
Hg Te-CdTe SUPERLATTICES
Designation of Electronic Transitions

QUANTUM TRANSITIONS IN MULTILAYERS

Optical Properties

ORIGINAL PAGE IS OF POOR QUALITY
HgTe-CdTe SUPERLATTICES

Optical Properties

HgTe-Hg$_{0.85}$Cd$_{0.15}$Te Superlattice (SL3)
- 200 Double-Layers
- $L_z = 51.7$ Å
- $L_b = 51.8$ Å
- Substrate: (100) CdTe
- $T_s = 175$ °C

HgTe-Hg$_{0.15}$Cd$_{0.85}$Te Superlattice (SL21S)
- 200 Double-Layers
- $L_z = 54.9$ Å
- $L_b = 42.1$ Å
- Substrate: (100) CdTe
- $T_s = 175$ °C

Optical Properties: VLWIR Structures

HgTe-Hg$_{0.85}$Cd$_{0.15}$Te Superlattice (A66B)
- 200 Double-Layers
- $L_z = 77.8$ Å
- $L_b = 51.8$ Å

HgTe-Hg$_{0.85}$Cd$_{0.15}$Te Superlattice (A67B)
- 200 Double-Layers
- $L_z = 81.0$ Å
- $L_b = 51.8$ Å
HgTe-CdTe SUPERLATTICES
Optical Properties: VLWIR Structures

HgTe-Hg$_{0.85}$Cd$_{0.15}$Te Superlattice
200 Double-Layers
$L_z = 77.8$ Å
$L_b = 48.6$ Å

HgTe-Hg$_{0.85}$Cd$_{0.15}$Te Superlattice
200 Double-Layers
$L_z = 58.4$ Å
$L_b = 48.6$ Å

HgTe-CdTe SUPERLATTICE BAND GAP

$T = 77$ K
SL Band Gaps in 2-5 μm Regime
For All Possible SL Layer Combinations

WAVELENGTH (μm)
SL Band Gaps in 8-14 $\mu$m Regime
For All Possible SL Layer Combinations

SL Band Gaps in 18-32 $\mu$m Regime
For All Possible SL Layer Combinations
HgTe-CdTe SUPERLATTICE BAND GAP

T = 77 K

All SL Band Gaps
For All Possible SL Layer Combinations

Vertical Cross-Section TEM Photo
of Modulation Doped HgCdTe

N. Otsuka, Purdue University
HgTe-CdTe SUPERLATTICES

Structural Properties: X-Ray Diffraction

Substitutional Doping: n-Type (Indium)
HgTe-CdTe SUPERLATTICES

Substitutional Doping: n-Type (Indium)

HgTe-\text{Hg}_{0.15}\text{Cd}_{0.85}\text{Te} Superlattice (A68A)
\begin{align*}
L_z &= 77.8 \text{ Å} \\
L_b &= 48.6 \text{ Å} \\
T_{1n} &= 450° \text{ C}
\end{align*}

HgTe-\text{Hg}_{0.15}\text{Cd}_{0.85}\text{Te} Superlattice (A69A)
\begin{align*}
L_z &= 58.4 \text{ Å} \\
L_b &= 48.6 \text{ Å} \\
T_{1n} &= 475° \text{ C}
\end{align*}

Substitutional Doping: p-Type (Arsenic)

HgTe-\text{Hg}_{0.3}\text{Cd}_{0.7}\text{Te} Superlattice (A74) 200 Double-Layers p-type As-Doped Barriers
\begin{align*}
L_z &= 25.9 \text{ Å} \\
L_b &= 35.6 \text{ Å}
\end{align*}

HgTe-\text{Hg}_{0.3}\text{Cd}_{0.7}\text{Te} Superlattice (A76) 200 Double-Layers p-type As-Doped Barriers
\begin{align*}
L_z &= 22.7 \text{ Å} \\
L_b &= 25.9 \text{ Å}
\end{align*}
HgCdTe-CdTe SUPERLATTICES
Stimulated Emission

HgCdTe Double Heterojunction

Substrate: CdZnTe (100)

DARPA Selective-Area Epitaxy of HgTe-CdTe Superlattices

NCSU
Selective-Area Epitaxy of HgTe-CdTe Superlattices

Growth Parameters: CdZnTe Substrates, Ts = 150 °C,

Applications: Multicolored Sources and/or Detectors; Optical Waveguides; Light Modulators
$T = 300 \text{ K} \quad 2.630 \text{ eV}$

FWHM = 54 meV

$T = 77 \text{ K} \quad 2.699 \text{ eV}$

$T = 4.2 \text{ K} \quad 2.786 \text{ eV}$

$2.700 \text{ eV}$

ENERGY (eV)
### HgTe-CdTe SUPERLATTICES

**Summary of Properties**

- An interesting infrared quantum structure
- Superlattice has many different states which exhibit very different properties
- A variable band gap structure as predicted
- Exhibits large absorption in infrared region
- Excellent electrical properties
- Excellent structural properties
- Short minority carrier lifetimes (10 - 20 ns )
- Detector applications: VLWIR region (18 - 24 μm)