Hot Carrier cooling in Multiple Quantum Wells for Hot Carrier solar cells

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Outline

• Hot Carrier solar cells
• Slowed carrier cooling in MQWs
• Potential mechanisms – phonon bottleneck
  – Restricted hot carrier densities
  – Confined phonon modes
  – Resonant phonon mini-gaps
• GaAs/AlGaAs MQW by MBE
• Measure carrier temperatures and decay rates - TRPL
• Cooling rate trends – varying well or barrier thickness
• Initial device design and preliminary testing
• Summary
Hot Carrier cell

Extract hot carriers before they thermalise:
Need to slow carrier cooling
Collect carriers over narrow energy range

Max theoretical $\eta = 65\%$ (1 sun); 85\% (Concn.)

Carriers cool by emitting optical phonons

Hot Optical phonon population
“phonon bottleneck effect”
Slows further carrier cooling
Slowed carrier cooling in MQW

GaAs bulk cf. AlGaAs/GaAs MQW
[Guillemoles et al., PVSC, 2005] re-calc. from

Strain balanced MQW InGaAs/GaAsP
wider wells show higher carrier temperatures
[Hirst et al., JPV, 4 (2014) 244]
Phonon bottleneck in MQW

**Bulk – hot carrier diffusion enhanced**

**Reduced hot carrier diffusion**

**MQW – discrete wells**

Phonon reflection and confinement

**Phonon mini-gaps - resonant blocking of decay**

Spring constant calculation of folded phonon modes

Low wavenumber Raman measurement of GaAs/AlGaAs MQW

Phonon energies in AlAs/GaAs [Colvard, PRB 31 (1985) 2080]

Mini-gaps in phonon dispersion
## MQW - varying well or barrier thickness

MBE grown MQW samples GaAs/AlAs

<table>
<thead>
<tr>
<th>Sample</th>
<th>Well (GaAs)</th>
<th>Barrier (AlAs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6 nm</td>
<td>40 nm</td>
</tr>
<tr>
<td>2</td>
<td>8 nm</td>
<td>40 nm</td>
</tr>
<tr>
<td>3</td>
<td>12 nm</td>
<td>40 nm</td>
</tr>
<tr>
<td>4</td>
<td>30 nm</td>
<td>40 nm</td>
</tr>
<tr>
<td>5</td>
<td>30 nm</td>
<td>5 nm</td>
</tr>
<tr>
<td>6</td>
<td>30 nm</td>
<td>2 nm</td>
</tr>
</tbody>
</table>

- Increasing well width
- Decreasing barrier width

[Sample #2 TEM image]
TRPL - varying well thickness

![TRPL plots](image)

TRPL – carrier temp to high energy tail

![Carrier temperature graph](image)

**Single Exponential Fitting**

$L_B = 40 \text{nm}$

- $\tau_1 = 749 \pm 10 \text{ps}$, $T_o = 400 \pm 7 \text{K}$
- $\tau_2 = 1127 \pm 22 \text{ps}$, $T_o = 420 \pm 6 \text{K}$
- $\tau_3 = 800 \pm 10 \text{ps}$, $T_o = 385 \pm 7 \text{K}$
- $\tau_4 = 1109 \pm 17 \text{ps}$, $T_o = 380 \pm 2 \text{K}$

**Hot carrier lifetime (ps)**

<table>
<thead>
<tr>
<th>Well width (nm)</th>
<th>6</th>
<th>8</th>
<th>12</th>
<th>30</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barrier width (nm)</td>
<td>40</td>
<td>40</td>
<td>40</td>
<td>40</td>
</tr>
</tbody>
</table>
TRPL - varying barrier thickness

TRPL – carrier temp to high energy tail

- Sample #4, $L_B=40\text{nm}$
- Sample #5, $L_B=5\text{nm}$
- Sample #6, $L_B=2\text{nm}$
- Single Exponential Fitting $L_w=30\text{nm}$

$\tau_c=1109\pm17\text{ps}$, $T_0=380\pm2\text{K}$

$\tau_c=1100\pm15\text{ps}$, $T_0=450\pm4\text{K}$

$\tau_c=1567\pm20\text{ps}$, $T_0=580\pm7\text{K}$
TRPL – effect of well or barrier thickness

Resonant feature for 8nm wells – phonon mini-gaps block phonon decay?

Mini-gaps in phonon dispersion

Close to resonant for relevant lattice spacing for GaAs of 1.12 nm

Increasing lifetime with increasing quality

Decreasing temp with band gap

Lifetime and temp increase with decreasing barrier width – delocalisation of carriers, separation of e-h

Carrier temperature (K)

Well width (nm) 6 8 12 Increasing well width Barrier width (nm) 40 40 40 Decreasing barrier thickness

Carrier lifetime (ps)

30 30 30

40 5 2
MQW devices

GaAs/AlAs MQW by MBE at UNSW

MQW (30nm GaAs / 40nm AlAs)

in dark

- 0.5nm Al2O3
- 40nm AlAs

30 nm GaAs

0nm or 30nm GaAs

0nm AlAs

GaAs buffer

n-GaAs Sub

Au

- 300K
- 325K
- 350K
- 375K

MQW (8nm GaAs / 40nm AlAs)

in dark

- 300K
- 325K
- 350K
- 375K

MQW (30nm GaAs / 40nm AlAs)

Illuminated 0.8 suns

- 300K
- 325K
- 350K
- 375K

MQW (8nm GaAs / 40nm AlAs)

Illuminated 0.8 suns

- 300K
- 325K
- 350K
- 375K

Very little rectification

Rectification increases with temperature

Small thermoelectric effect

Power generation

Inverse temp coeff. V and esp. J increase with temp.

Photon enhanced thermoelectric effect
MQW devices

GaAs/AlAs MQW by MBE at UNSW
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MQW (30nm GaAs / 40nm AlAs) in dark

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Very little rectification
Rectification increases with temperature
Small thermoelectric effect

MQW (30nm GaAs / 40nm AlAs) Illuminated 0.8 suns

MQW (8nm GaAs / 40nm AlAs) Illuminated 0.8 suns

Power generation
Inverse temp coeff. V and esp. J increase with temp.
Photon enhanced thermoelectric effect

I (μA)

V (V)

I (μA)

V (V)
Conclusions

• Hot Carrier solar cell
  – Slowed Carrier cooling
• Carrier cooling: electron $\rightarrow$ Optical phonons
• Phonon bottleneck slows carrier cooling
• MQW have slowed cooling
  – phonon bottleneck or phonon localisation
• GaAs/AlGaAs MQW
  – Carrier temp increase as barrier decreases
  – High carrier temp for resonant well width
• Devices on GaAs/AlAs MQW
  – Power generation
  – Indirect evidence of hot carriers
• Outlook
  – Range of MQW parameters/materials
  – Comparison tr-PL with TA
  – Devices with selective contacts

\[ E_{\text{F}(p)} - E_{\text{F}(n)} = E_{\text{s}} \]

\[ E_{\text{s}} - E_{\text{f}} = E_{\text{g}} \]

\[ T_H \quad T_A \]

\[ I_{\text{illuminated 0.8 suns}} \]

\[ \text{Australian Research Council} \]
\[ \text{Australian Renewable Energy Agency} \]

Thank you for your attention