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**M.Sc. Course in Semiconductor Science & Tech.**

# LIGHT TRAPPING IN MQW SOLAR CELLS

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# Overview

1. Light Trapping
2. Optical Measurements
3. Growth on patterned Substrates
4. Patterning QWSC material
5. Summary

## 1. Light Trapping

- Light trapping can enhance the efficiency of MQW solar cells in particular.

- Based on work by M.A. Green the decision was made to employ geometrical structures which can be produced using anisotropic etching at the Toshiba Cambridge Research Centre Ltd.

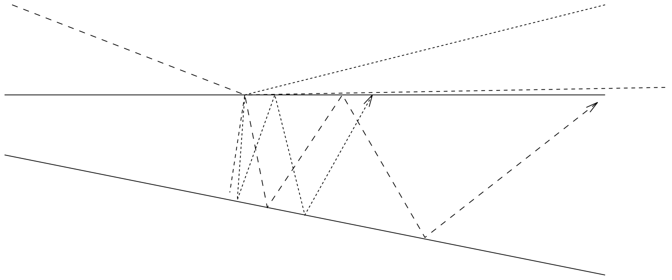
- Because of cell design relying on a thin p-region it was decided to pattern the back of the $p$-$i$-$n$ structures and make use of total reflection from a flat top surface.

# Reflection from the Back

- At the critical phase angle a material, changes its refractive behaviour to total internal reflection.

$$\phi_{ph}(GaAs/AlGaAs) = 16.6^\circ$$

- For the wedge structure shown below this means a beam of grazing incidence from the right will be refracted at $\phi_{ph}$ from the normal and beams of higher inclination at even lower angles.



- A back mirror tilted by $\phi_{ph}$ results in light being reflected back to the top surface at angles $> \phi_{ph}$. This remains true even more for incidence from the left.

# Conclusions for Light Trapping

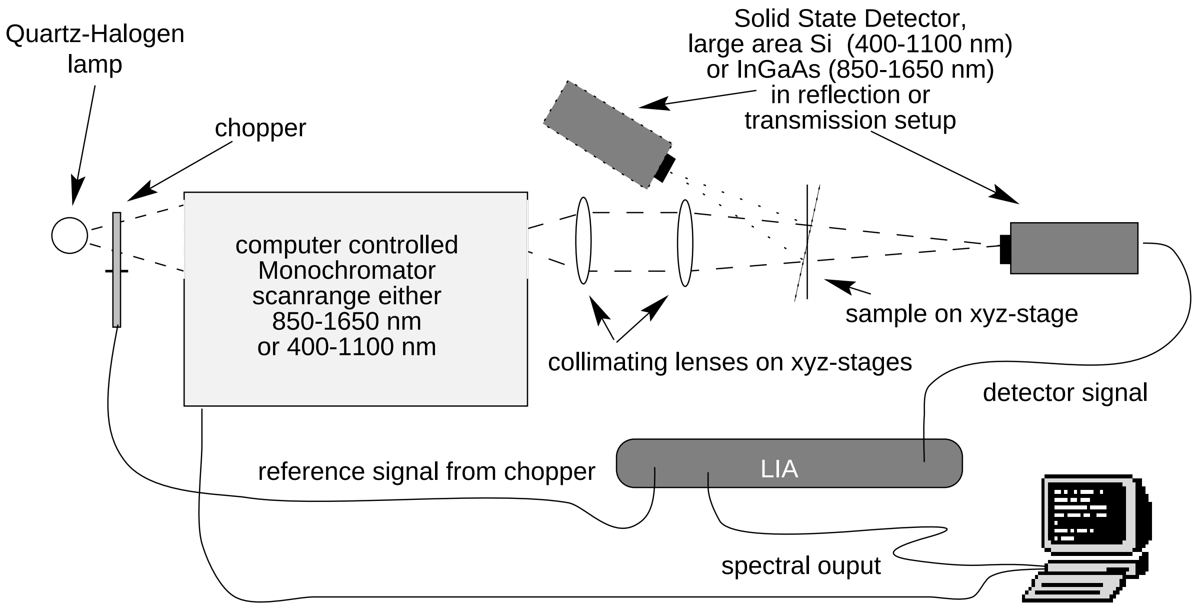
- This mirroring condition is fulfilled as for the back-surface all the light reaching the $AlGaAs$-air interface under angles $\phi_{inc} > \phi_{ph}$ will be reflected back into the material totally.

- Thus the side-angles for etching grooves and cones into substrate were chosen as $\sim 20^\circ$ to allow for $\pm 5^\circ$ errors arising from etchant composition.

- The pathological case of reflection to the opposite groove surface and directly out of the cell again won't occur for the dominant normal incidence. This leads to a minimum 4 passes of light through the cell.

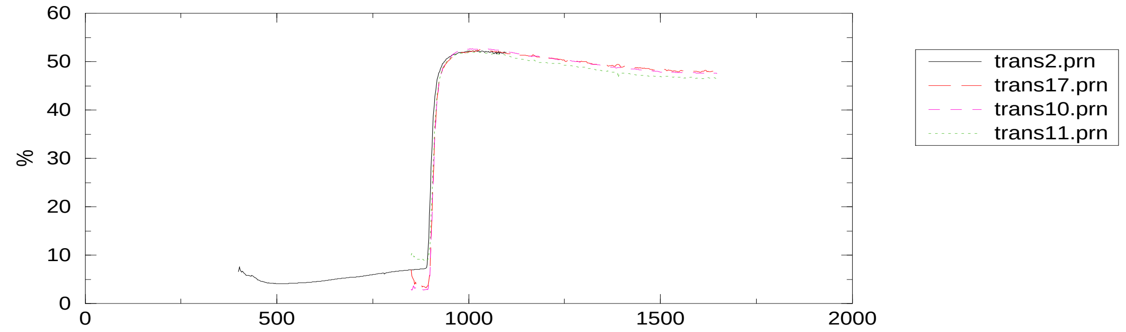
# 2. Optical Measurements

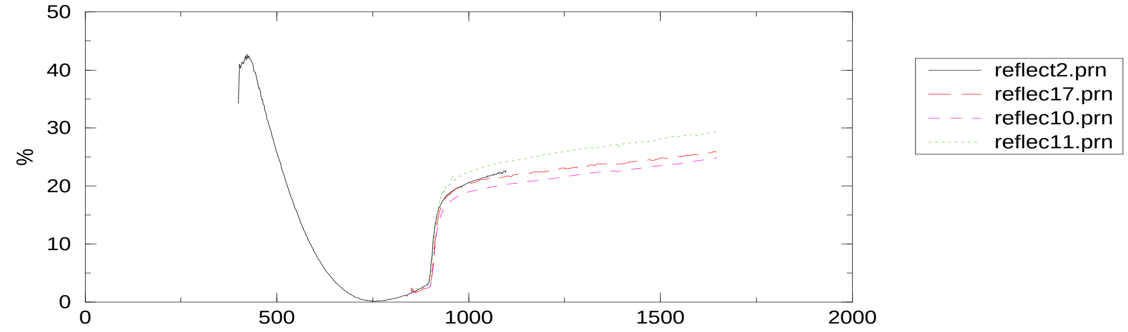
## Experimental setup:

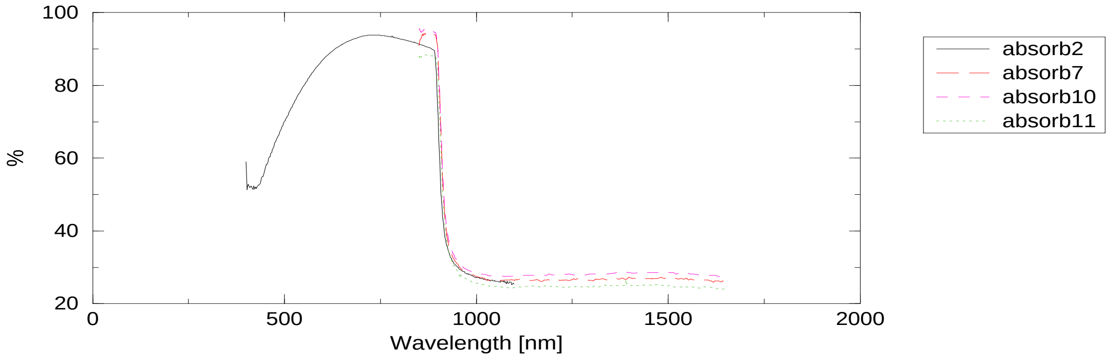


## Results

Transmission, reflection & resulting absorption ($\mathcal{R}+\mathcal{T}+\mathcal{A}=1$) of $n$-$GaAs$ are shown. The IR reflectivity shows large spread in the spectra due to the small area $InGaAs$ detector used.

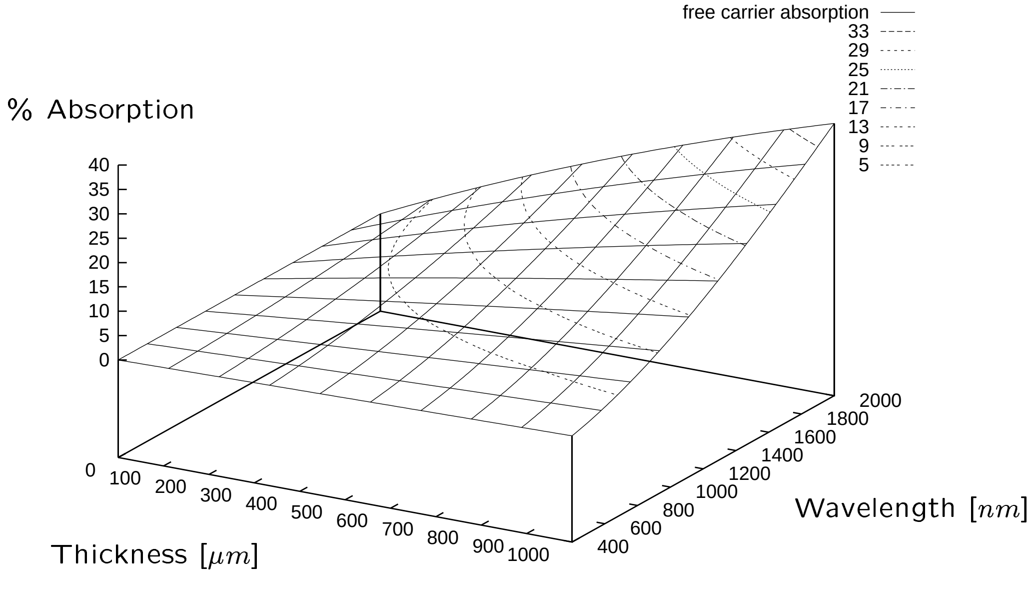

Transmission


Reflection

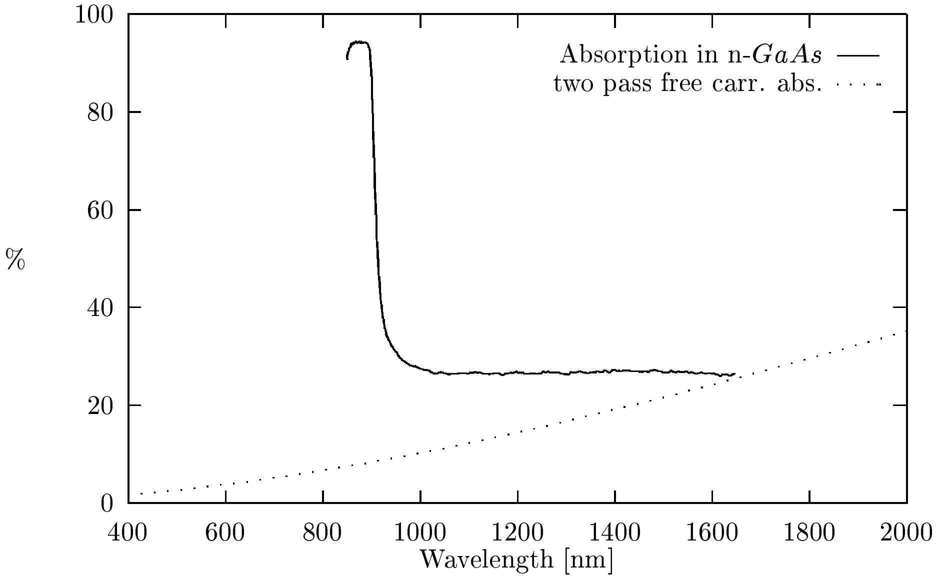

Absorption

# Substrate Absorption

- To explain the below bandgap absorption in $GaAs$ the Drude-Zener model for free carrier absorption was used.
- Remarkably the measured absorption in our substrate was much higher than predicted by the model and does not at all fit the spectral shape.



Drude-Zener absorption in n-$GaAs$ substrate for $\mu = 0.3\ m^2/(Vs)$, $N = 1.0 \times 10^{24}\ m^{-3}$ at varying thicknesses and wavelengths



Measured absorption in n-$GaAs$ substrate and theoretical free-carrier absorption for $\mu = 0.3\ m^2/(Vs)$, $N = 1.0 \times 10^{24}\ m^{-3}$, $d = 500\ \mu m$

- Another absorptive mechanism must be present which should roughly have inverse shape to account for the flat spectral shape of the measured absorption.

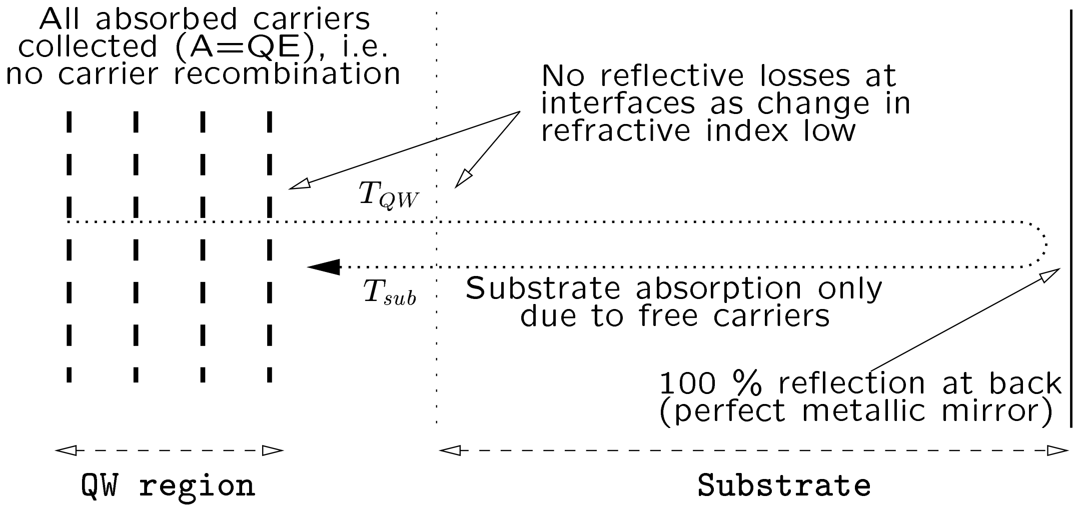
- Presumably inter-valley scattering of electrons into the next higher conduction band minimum with a spacing of $25 meV$ for $GaAs$ along $<111>$ takes place.

# Modelling

Free-carrier absorption was incorporated into a simple model aiming to understand why experimental data has not shown any enhancement in QE for the below bandgap region of a mirrored $GaAs/InGaAs$ QW cell.

*Idea:* Use QE data for an un-mirrored cell to make a modelled prediction whether free carrier absorption could cancel out the light reflected from a back mirror before reaching the QW region again.

*Assumptions:*



All absorbed carriers collected (A=QE), i.e. no carrier recombination

No reflective losses at interfaces as change in refractive index low

$T_{QW}$

$T_{sub}$

Substrate absorption only due to free carriers

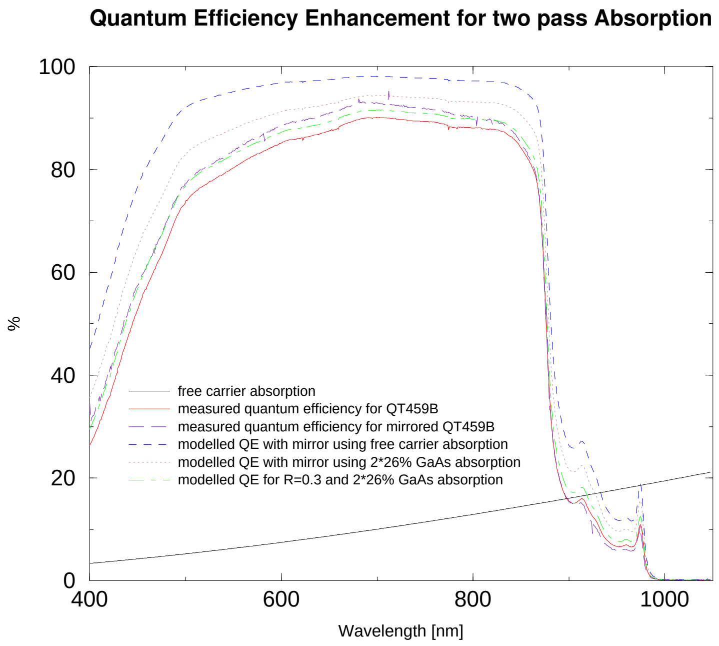
100 % reflection at back (perfect metallic mirror)

`QW region`

`Substrate`

*Calculations:* $T$ signifies the transmitted fraction of photons, $A$ the absorbed fraction:

$$T_{QW} + A_{QW} = 1 \text{ with } A_{QW} = QE$$
$$\Rightarrow \; T_{QW} = 1 - QE$$
$$T_{sub} = T_{QW} \cdot (1 - A_{fc}) \text{ and}$$
$$A_{enh} \doteq T_{sub} \cdot A_{QW}$$
$$\Rightarrow A_{QW}^{mir} = A_{QW} + A_{enh}$$
$$= QE + (1 - QE)(1 - A_{fc})A_{QW}$$



## *Results*

- The model is only applicable for the QW absorption as the assumption $A = QE$ only applies for the wells

- Initial model with free carrier absorption alone is too unsophisticated

- Use measured absorption to add intervalley scattering

- Realize that back reflectivity could be as low as 0.3.

# Conclusion for Optical Measurements

In any case it has to be concluded that the substrate thickness must be reduced to virtually zero, removing the substrate right down to the active region if most of the light not absorbed in the first pass is to be reflected back towards the quantum wells.

## 3. Growth on patterned Substrates

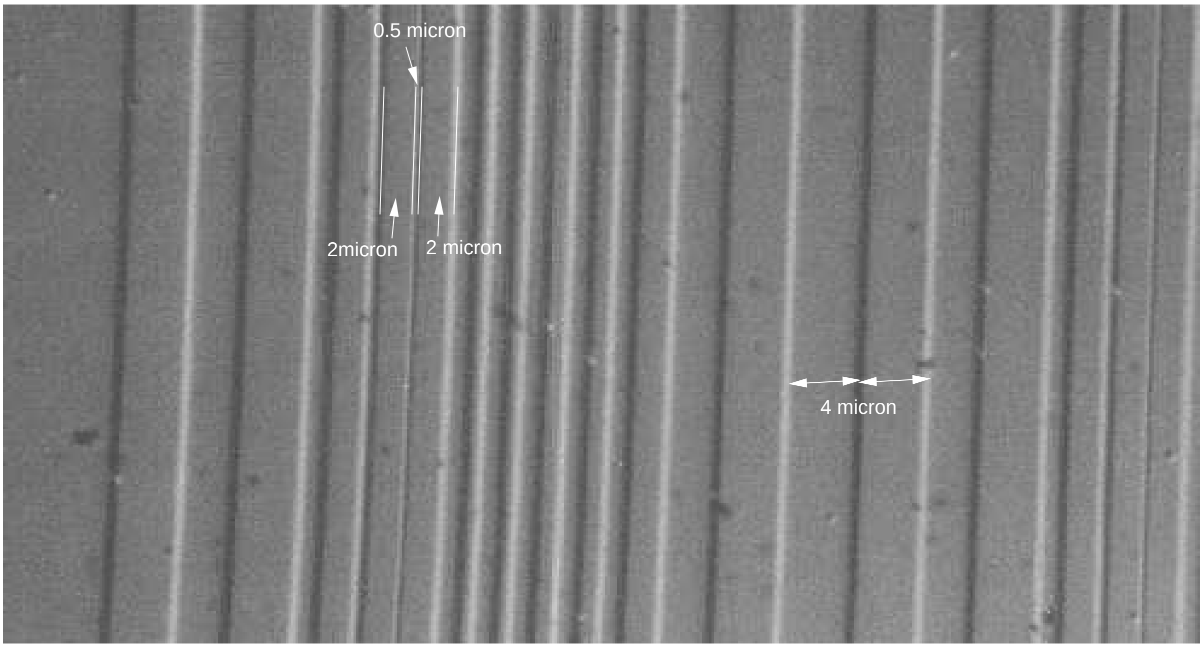
### Samples

- Wafers were patterned at TCRC using an anisotropic $HF$ etch with side wall control to ±5% and subsequently cleaned in an $O_2$ plasma.

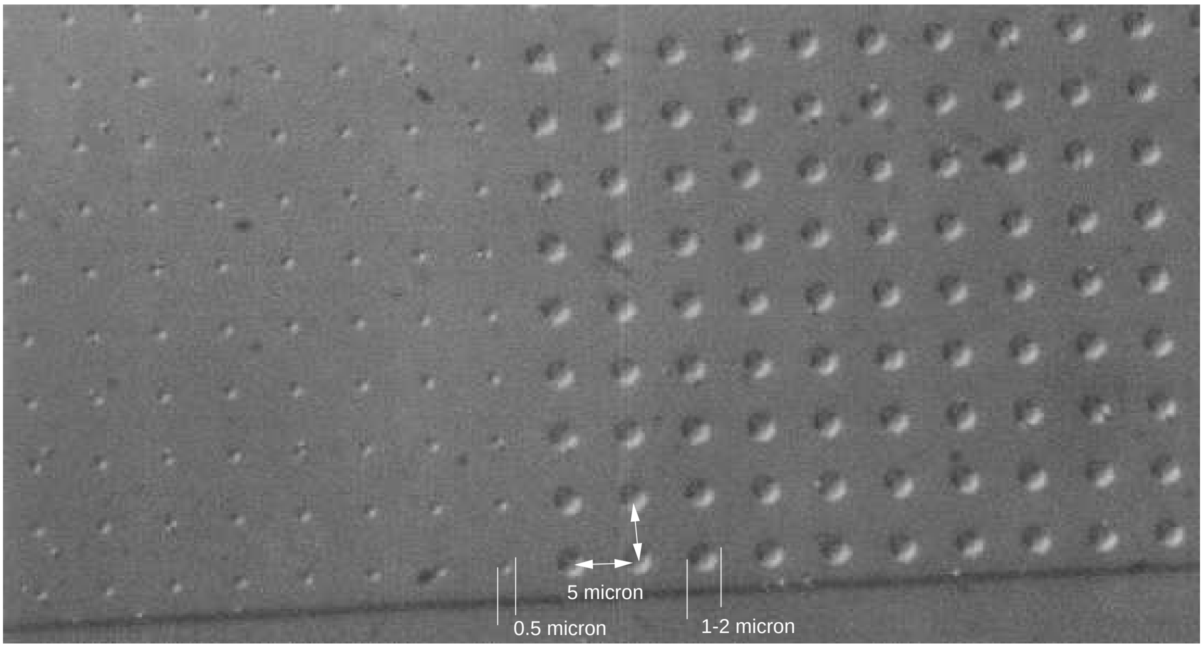
- IRC MBE Growth at 630 $^\circ C$ resulted in a 30 well $GaAs/Al_{0.3}Ga_{0.7}As$ MQW solar cell on top of a partially patterned wafer (U7113) and a control (U7114).

- The wafer was partially covered with AR-coating and devices defined on mesas using gold rings as contacts. Devices were first characterised with the substrate remaining and then with removed substrate enabling light trapping.

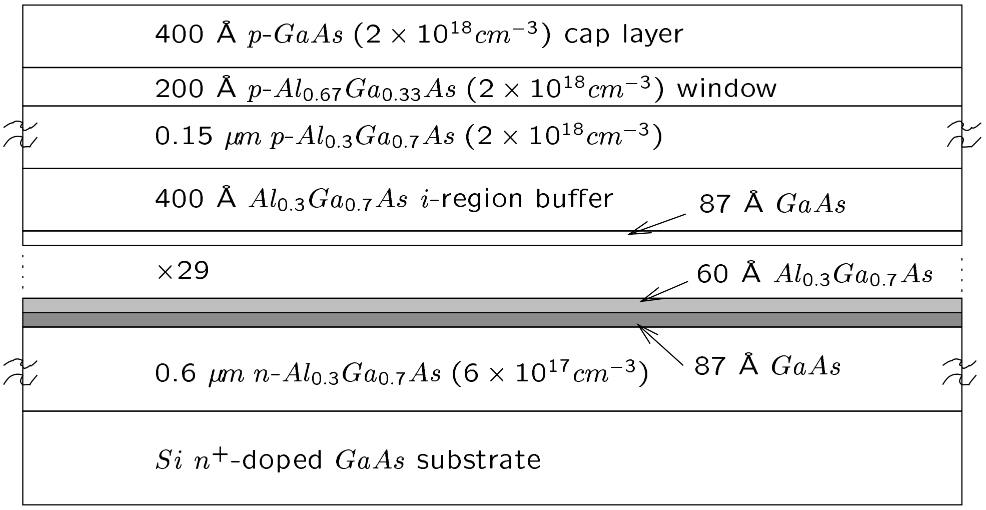
- After substrate removal part of the devices had a mirror evaporated on their back to check on internal reflection.



SEM micrograph of grooves etched into substrate



SEM micrograph of cones etched into substrate



400 Å $p$-$GaAs$ ($2 \times 10^{18} cm^{-3}$) cap layer

200 Å $p$-$Al_{0.67}Ga_{0.33}As$ ($2 \times 10^{18} cm^{-3}$) window

0.15 $\mu m$ $p$-$Al_{0.3}Ga_{0.7}As$ ($2 \times 10^{18} cm^{-3}$)

400 Å $Al_{0.3}Ga_{0.7}As$ $i$-region buffer

87 Å $GaAs$

×29

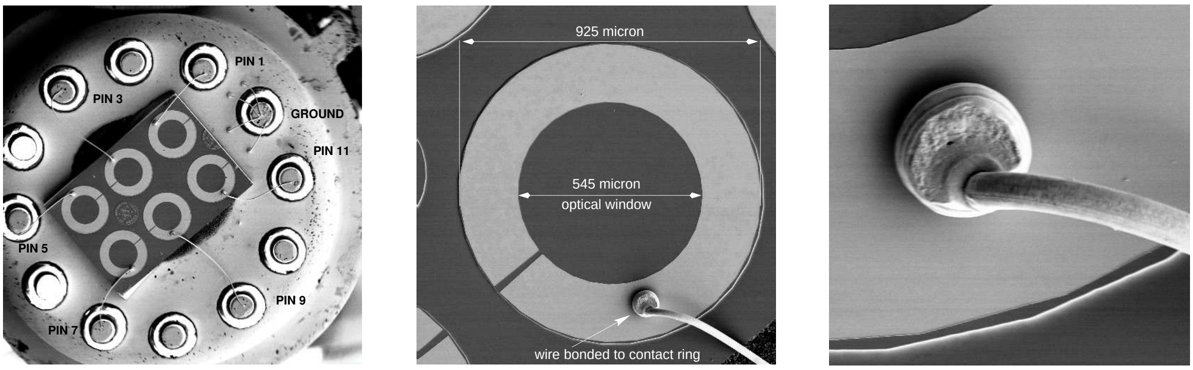
60 Å $Al_{0.3}Ga_{0.7}As$

87 Å $GaAs$

0.6 $\mu m$ $n$-$Al_{0.3}Ga_{0.7}As$ ($6 \times 10^{17} cm^{-3}$)

$Si$ $n^{+}$-doped $GaAs$ substrate

U7113/4: 30 well MQW cells grown by MBE at 630 $^{\circ}C$



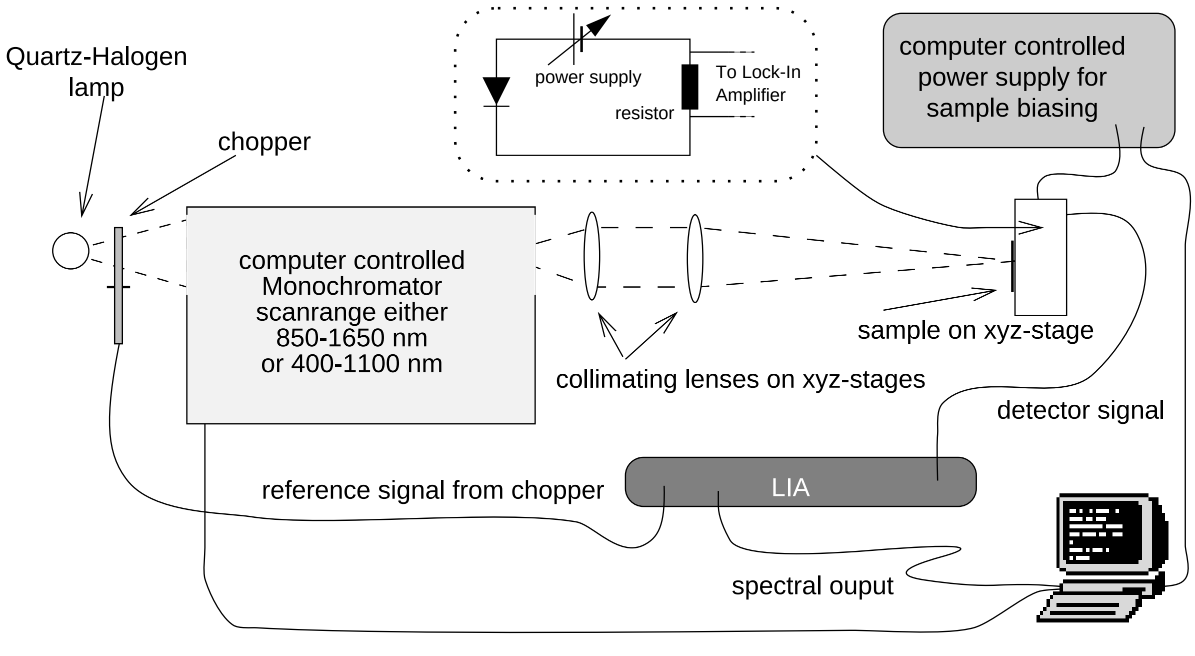
Six devices    Single device    Bonded wire

SEM micrographs of TO5 header Å

# Characterisation

- Devices were characterised by their dark and light I-V curves and monochromatic I-V and spectral response

- Electrical measurements were carried through on a SMU Unit with attached Tungsten lamp and the optical bench setup used before was altered as follows:



Experimental setup altered for SR measurements

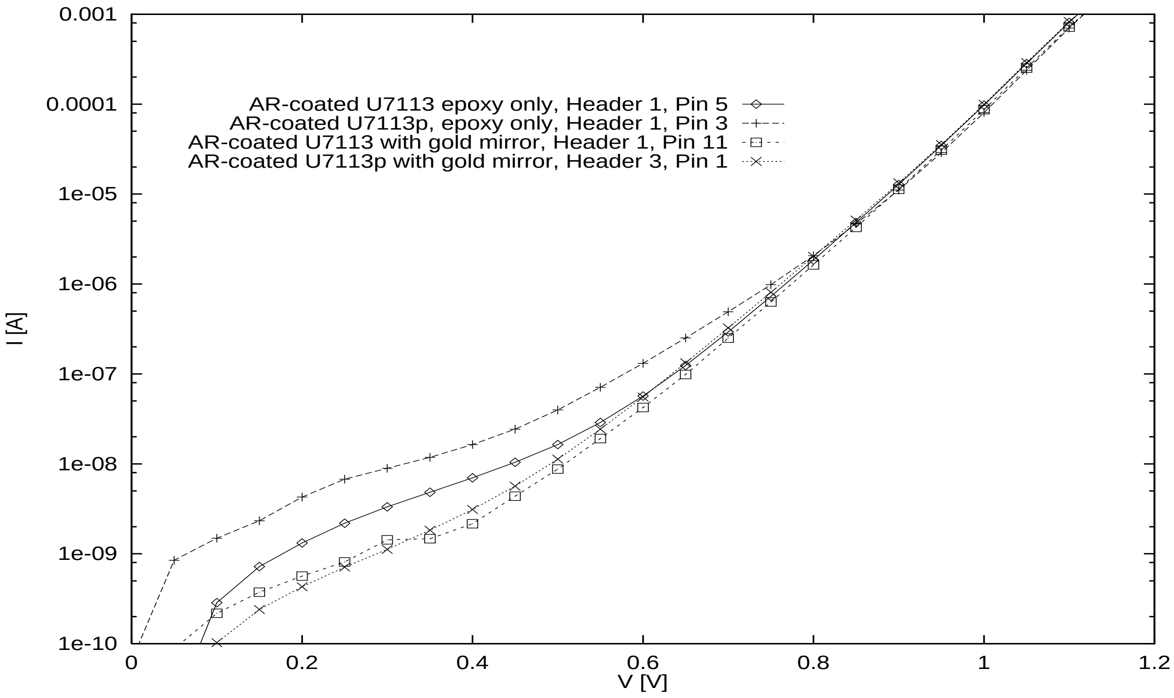
- The dark and light I-V curves show generally good device quality. Particularly the dark I-V characteristics are very good for all device types.

- Gradually decaying monochromatic I-V‘s suggest high background doping is present.

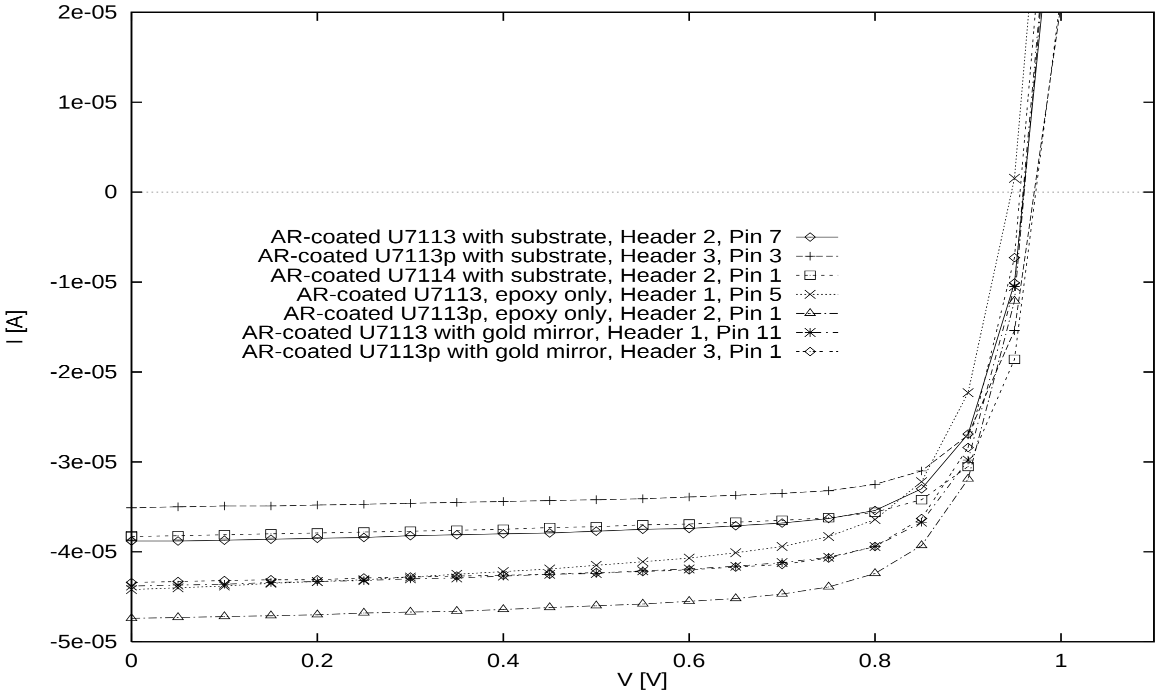
- Comparison of SR and light I-V for U7113 and U7114 before substrate removal might suggest lower device quality due to processing associated with patterning.

- Substrate removal causes devices to exhibit higher SR with prominent Fabry-Perot features.

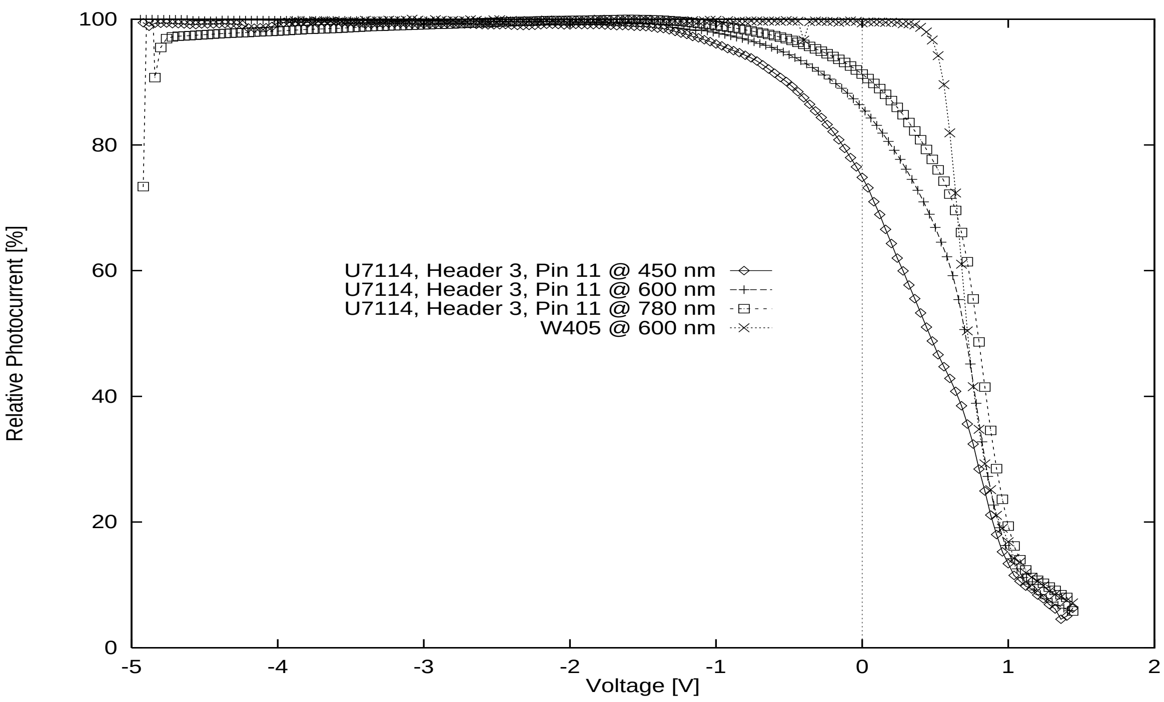
- Light Trapping indicated by lower amplitude of Fabry-Perot oscillations for patterned devices with and without mirror.



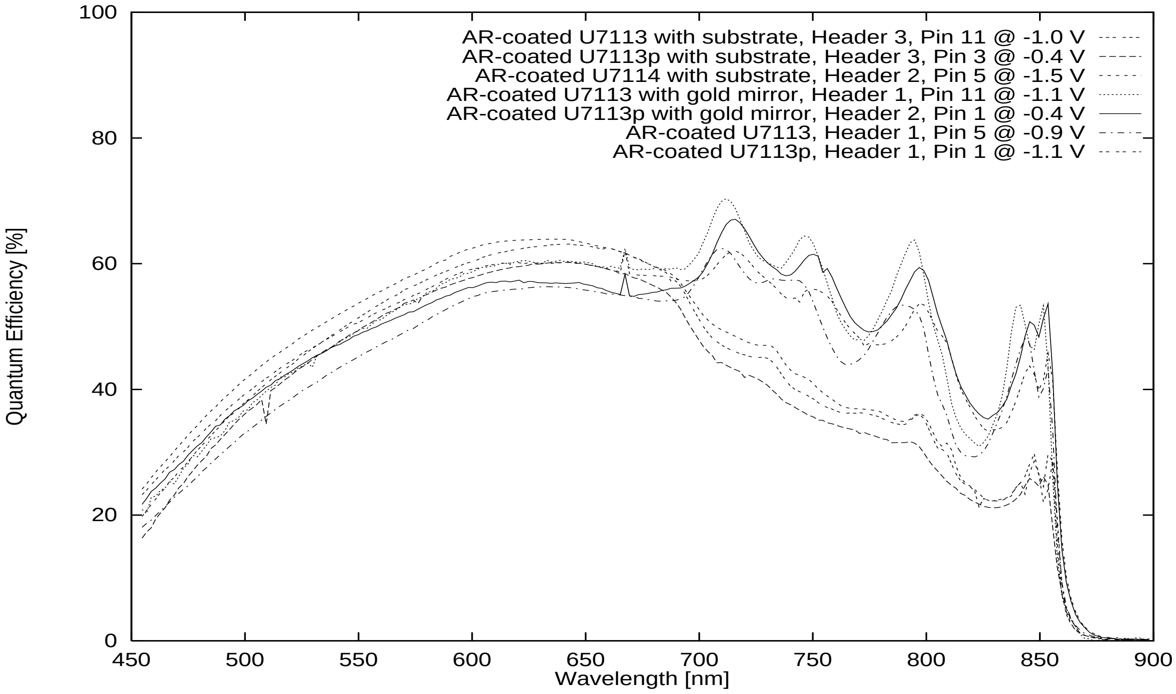
Dark I-V comparison for the four non-substrate sample types



Light I-V comparison for all seven AR-coated sample types



Monochromatic I-V curves at different wavelengths



SR comparison for all seven AR-coated sample types

# Results

- Device quality does not suffer substantially form patterning.
- For removed substrate two-pass light absorption from flat rear mirrors results in large enhancements in light I-V characteristic and SR already. As anticipated the latter is particularly true for the low absorption QW wavelengths.
- Light Trapping has not shown enhancement as mask set features are too widely spaced.
- An adapted mask set should allow production of cells exhibiting additional SR enhancement from light trapping.
- Efficiency enhancement can be as high as 2.5 % from flat mirror only.

| before substrate removal | | | | | |
|---|---|---|---|---|---|
| Sample | | u7113 | u7113p | u7114 | |
| Devices type | | AR coated | AR-coated, patterned | AR-coated | |
| | | | | | |
| Intensity | | 1e+03 | 1e+03 | 1e+03 | W/m$^2$ |
| $P_{in}$ | | 0.00023 | 0.00023 | 0.00023 | W |
| Area | | 2.3e-07 | 2.3e-07 | 2.3e-07 | m$^2$ |
| $V_{oc}$ | | 0.98 | 1.02 | 1.03 | V |
| $I_{sc}$ | | -3.88e-05 | -3.51e-05 | -3.83e-05 | A |
| $P_{max}$ | | 2.73e-05 | 2.61e-05 | 2.86e-05 | W |
| $V_{max}$ | | 0.819 | 0.831 | 0.84 | V |
| $I_{max}$ | | -3.46e-05 | -3.17e-05 | -3.46e-05 | A |
| FF | | 0.718 | 0.732 | 0.725 | |
| Efficiency | | 11.9 | 11.4 | 12.4 | % |
| Temperature | | 23.1 | 22.9 | 23.2 | °C |

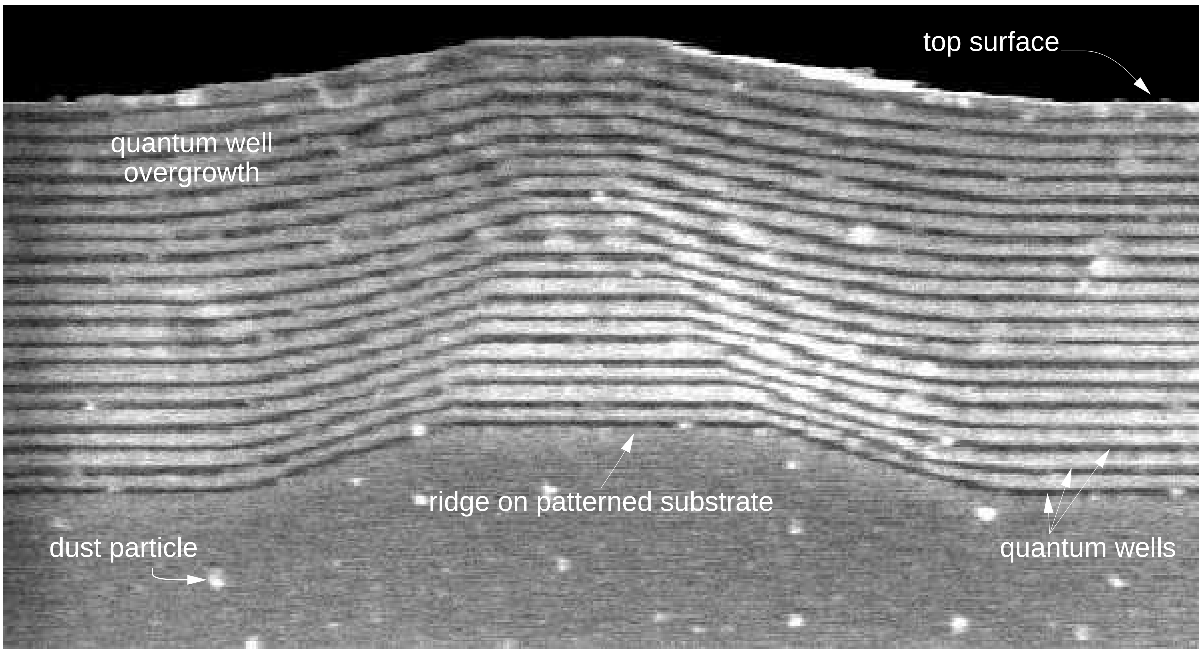
| after substrate removal | | | | | |
|---|---|---|---|---|---|
| Sample | u7113 | u7113 | u7113p | u7113p | |
| Device type | AR-coated, epoxy only | AR-coated, gold mirror | AR-coated, patterned, epoxy only | AR-coated, patterned, gold mirror | |
| | | | | | |
| Intensity | 1e+03 | 1e+03 | 1e+03 | 1e+03 | W/m$^2$ |
| $P_{in}$ | 0.000233 | 0.000233 | 0.000233 | 0.000233 | W |
| Area | 2.33e-07 | 2.33e-07 | 2.33e-07 | 2.33e-07 | m$^2$ |
| $V_{oc}$ | 1.01 | 0.977 | 0.981 | 0.967 | V |
| $I_{sc}$ | -4.42e-05 | -4.38e-05 | -4.74e-05 | -4.34e-05 | A |
| $P_{max}$ | 2.88e-05 | 3.05e-05 | 3.3e-05 | 3.06e-05 | W |
| $V_{max}$ | 0.784 | 0.816 | 0.811 | 0.808 | V |
| $I_{max}$ | -3.71e-05 | -3.86e-05 | -4.18e-05 | -3.9e-05 | A |
| FF | 0.644 | 0.712 | 0.709 | 0.729 | |
| Efficiency | 12.4 | 13.1 | 14.1 | 13.1 | % |
| Temperature | 26.6 | 27 | 26.9 | 27.1 | °C |

Comparison of efficiencies for all seven AR-coated sample types

## Unresolved Questions

- One peculiarity about the light I-V characteristics is that the gold mirrored U7113p devices exhibited very low short circuit current, while one would expect them to outperform the best I-V characteristics.
- This might be related to background doping due to problems with the MBE machine and has to be investigated.
- Why do un-mirrored cells without substrate also exhibit Fabry-Perot features ? The flat rear $AlGaAs$-epoxy interface is certainly no metallic mirror.
- Is there a problem with the $Au$ mirror ?

# Characterisation of Overgrowth:



TCRC study of overgrowth on patterned substrate

(dark lines are quantum wells)

- Cross-sectional SEM studies of the overgrowth on the pattern help identify whether imperfections have been introduced which degrade solar cell performance.
- Good overgrowth for our own samples has been suggested by the presence of excitonic features in SR.

## 4. Patterning of QWSC Material

- Instead of MBE growth on top of a patterned substrate subsequently etched down one can shift the patterning step to the end of the production sequence.

- Thus it is possible to upgrade a ready-grown cell to a light trapping structure by etching patterns into thinned down substrate on its back.

- The substrate thinning resulted in brittle 5 $\mu m$ thin wafer pieces

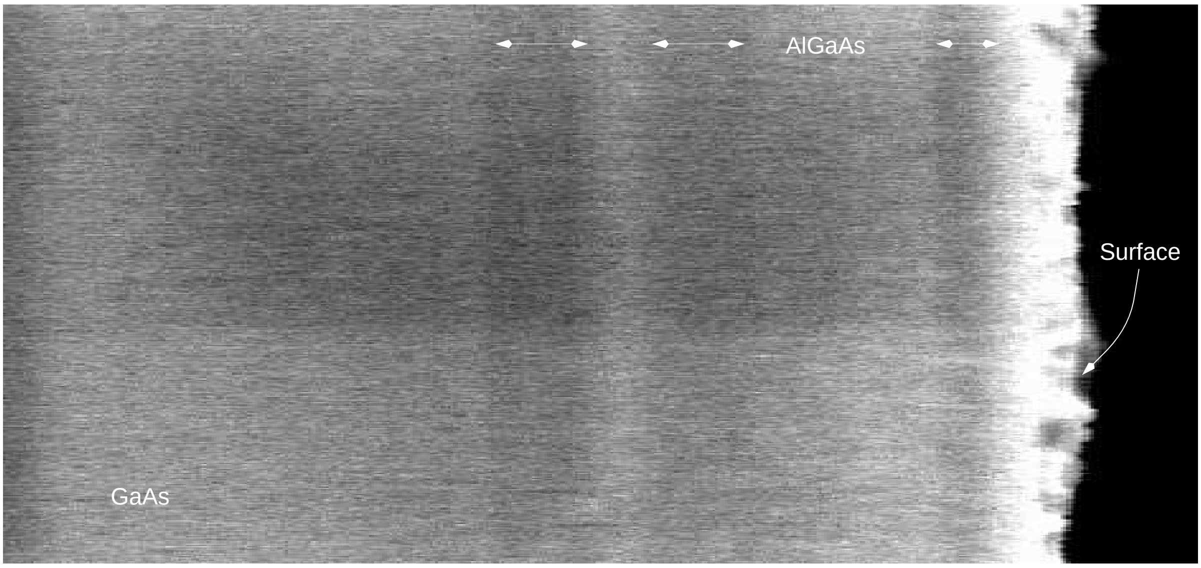
- Dental floss was used for transfer from etching bath to glass slides using wax for fixture.

- Slides sent to Toshiba Cambridge Research Centre for SEM study using their cathodoluminescence (CL) stage and patterning using $e$-beam lithography.

- Important to check surface topology to ensure successful anisotropic etching with good sidewall angle control.

- Problem: Charge buildup when using CL due to insulating glass slides and preparation for cross-sectional SEM destructive. $\Rightarrow$ Look at thick U7113 wafer instead.

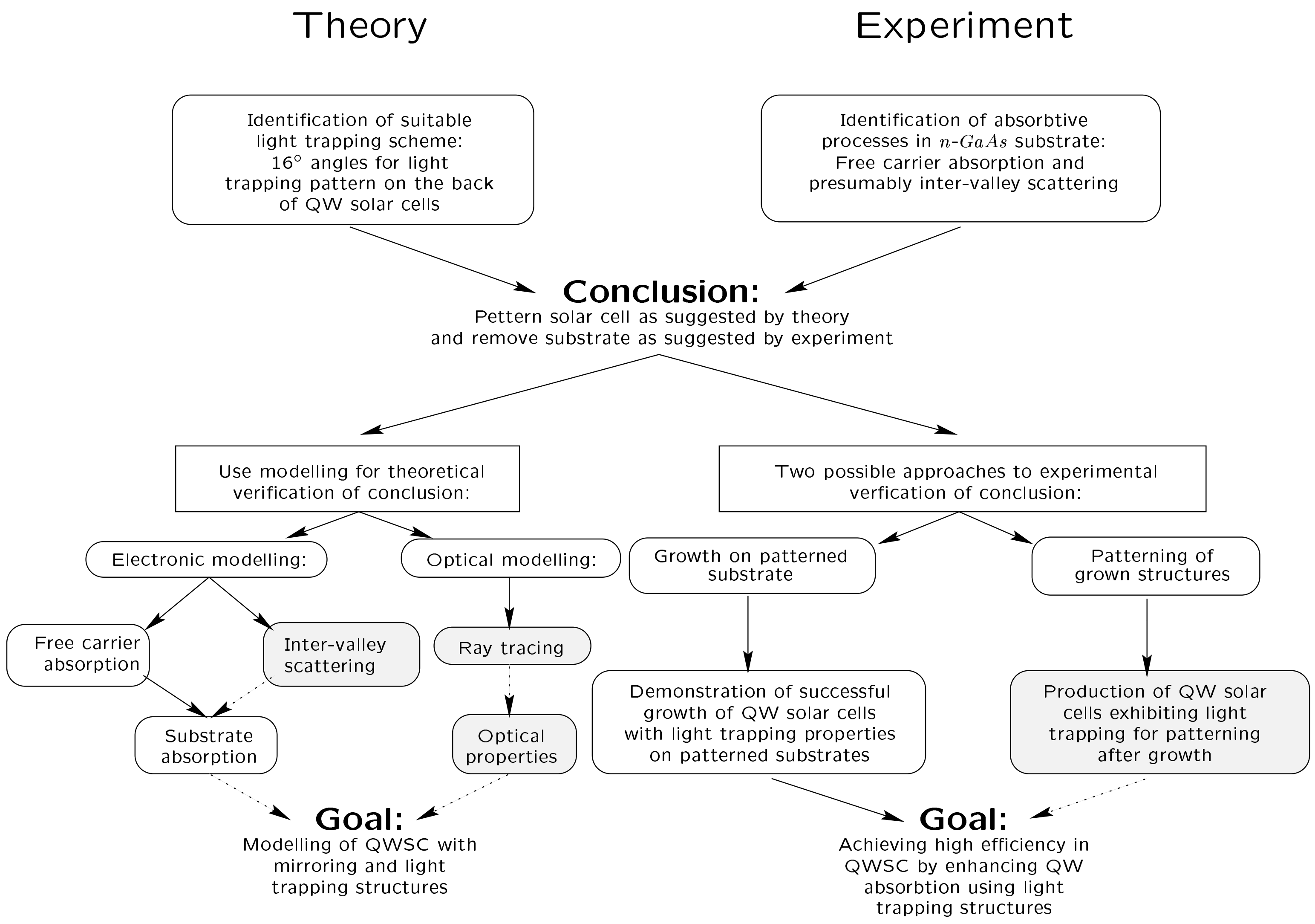
- U7113 shows a reasonably smooth surface in cross-section.



Cross-sectional SEM micrograph of U7113 wafer

# Conclusion

This approach to achieving light-trapping in QW solar cells is problem-ridden but with the skill displayed by the processors so far it's likely to succeed.



## Theory

## Experiment

Identification of suitable light trapping scheme: 16° angles for light trapping pattern on the back of QW solar cells

Identification of absorbtive processes in $n$-$GaAs$ substrate: Free carrier absorption and presumably inter-valley scattering

**Conclusion:**
Pettern solar cell as suggested by theory
and remove substrate as suggested by experiment

Use modelling for theoretical verification of conclusion:

Electronic modelling:

Free carrier absorption

Inter-valley scattering

Substrate absorption

Optical modelling:

Ray tracing

Optical properties

**Goal:**
Modelling of QWSC with
mirroring and light
trapping structures

Two possible approaches to experimental verfication of conclusion:

Growth on patterned substrate

Demonstration of successful growth of QW solar cells with light trapping properties on patterned substrates

Patterning of grown structures

Production of QW solar cells exhibiting light trapping for patterning after growth

**Goal:**
Achieving high efficiency in
QWSC by enhancing QW
absorbtion using light
trapping structures

## 5. Summary

1.
    - From investigation of Geometrical light trapping in a solar cell the optimum angle of inclination for mesas or grooves at the rear of a solar cell with a plane top was identified as 16°.
    - The average optical path-length enhancement exceeds the factor 4.

2.
    - Measurements showed that absorptive processes in doped $GaAs$ substrate will inhibit light trapping and mirroring.
    - Modelling showed that a second absorptive process must be present.
    - This process is most likely to be attributed to inter-valley scattering.
    - As much substrate as possible has to be removed.

3.
- Undisrupted QW overgrowth on top of patterned substrate is possible and shows little deterioration in material quality comapred to controls.

- The SR without substrate exhibits prominent Fabry-Perot oscillations which suggests very plane-parallel top and back surfaces.

- Loss in oscillation amplitude for patterned devices might indicate a possible light trapping effect in comparison to the controls.

- Adapted mask set with a pattern resulting in less plane area has to be designed for future measurements.

- How has a Fabry-Perot cavity been established for the cells with a plain $AlGaAs$-epoxy interface at the back ?

- The $i$-region background doping is high. Problems with the MBE machine ?
- Substantial enhancement in SR from the QW region and efficiency has been achieved using plain mirroring already.

4.
- Producing a solar cell exhibiting light-trapping by defining the pattern in thinned down substrate might be possible.
- Still, handling of these cells will be extremely challenging for processors.