SLIVER Solar Cells
A technology development journey

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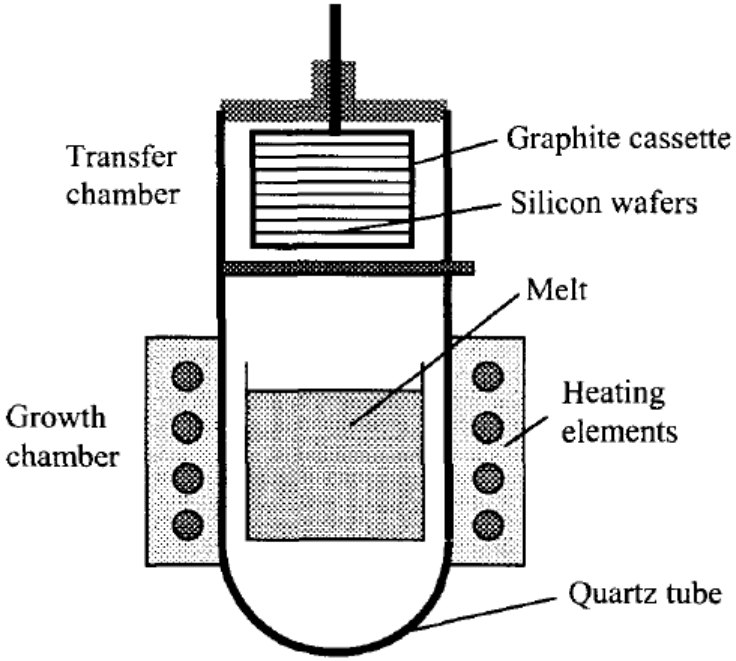
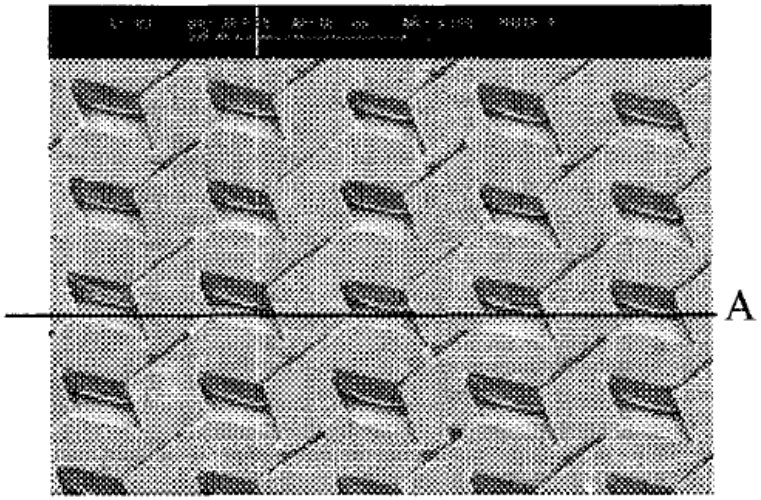
Who am I?

- Started at ANU in 1993 – new group
- 1994-1998 PhD in high efficiency multiX Si cells
- 1999-2003 Cell development for Epilift/SLIVER - ANU
- 2003-2009 Cell R&D Manager/ Chief Technologist
  - SLIVER Pilot Facility, Origin Energy Solar, Adelaide
- 2009-2013 Chief Technologist
  - SLIVER Manufacturing, Transform Solar, Boise Idaho
- 2013- Fellow, ANU

Epilift technology

- Liquid phase epitaxy
  - Dissolve silicon in melt
  - Cool on Si template
  - Process cell
  - Remove cell and re-use template

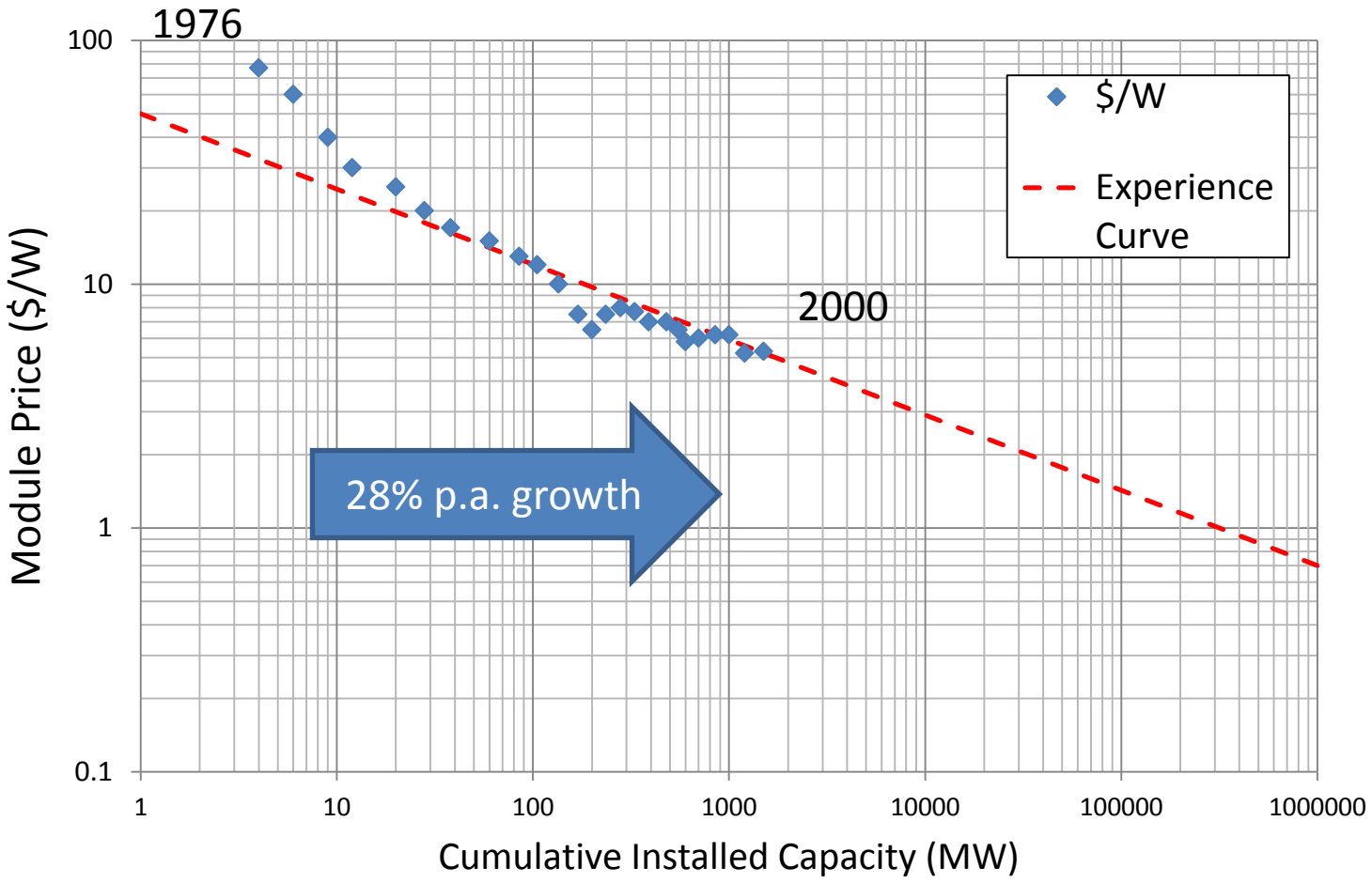




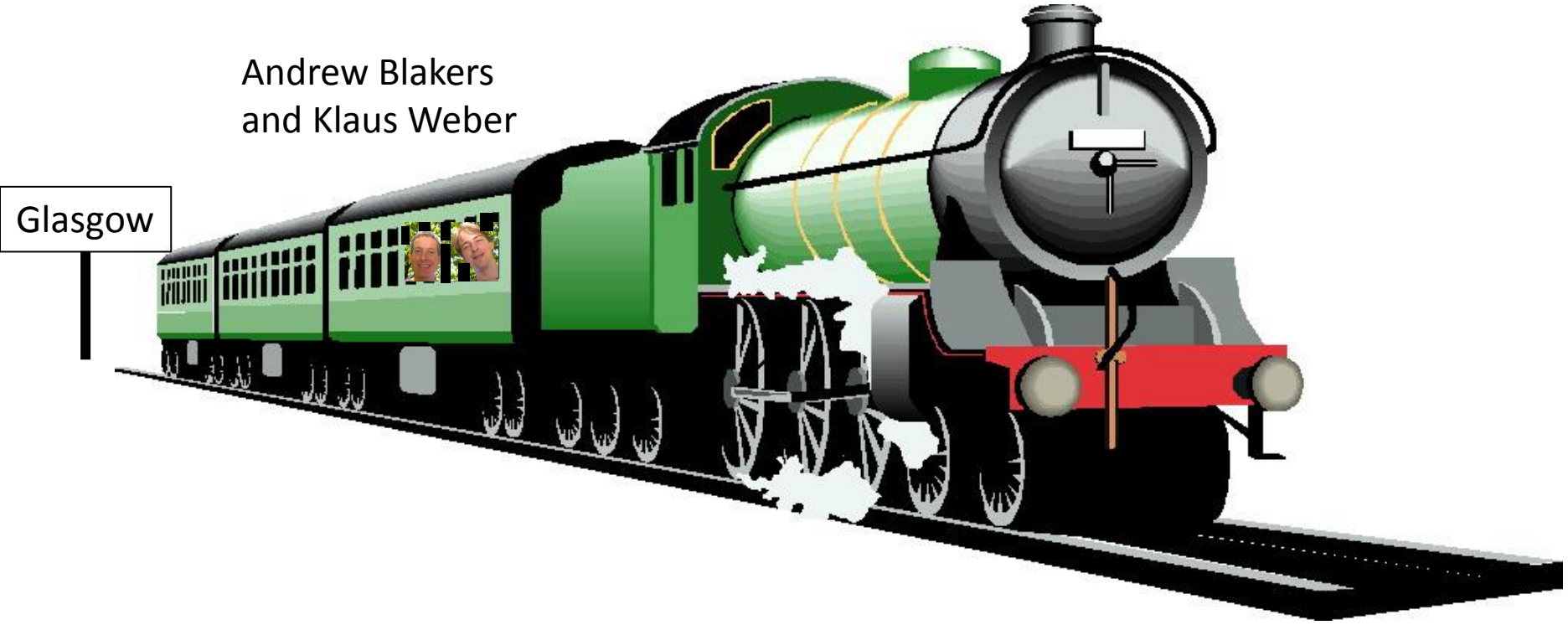
Origin Energy: Australia's largest Energy company

- $12B market cap
- H1 '09/10 EBITDAF $686M
- ASX top 20 by market cap
- $8.3B '08 revenue
- >3 million+ customers
- 4,000 employees
- Australia's largest retailer of PV & green energy
- 5,770 PJe oil & gas reserves
- $4.1B in cash, $6.4B in funding capability
- Spun out of Boral in 2000

Why Origin's interest?

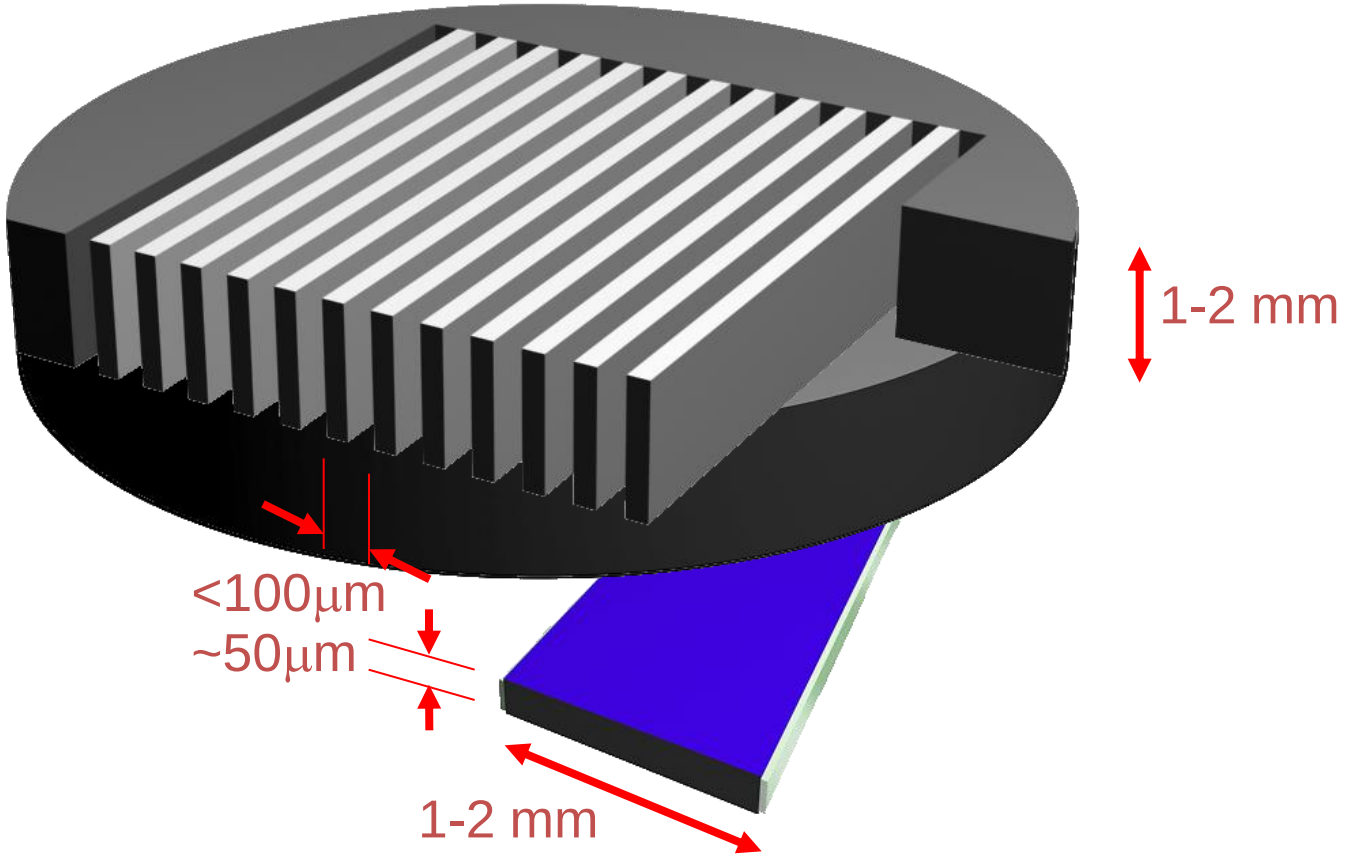


2000 – SLIVER idea conceived



What is SLIVER technology?

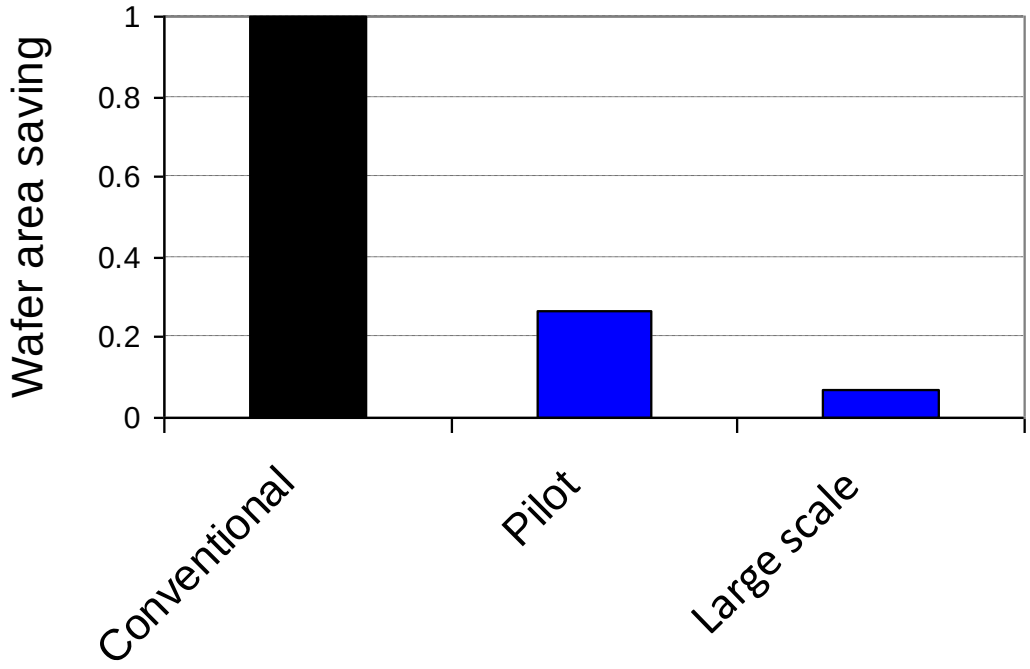
Wafer micromachined to form deep grooves through the wafer



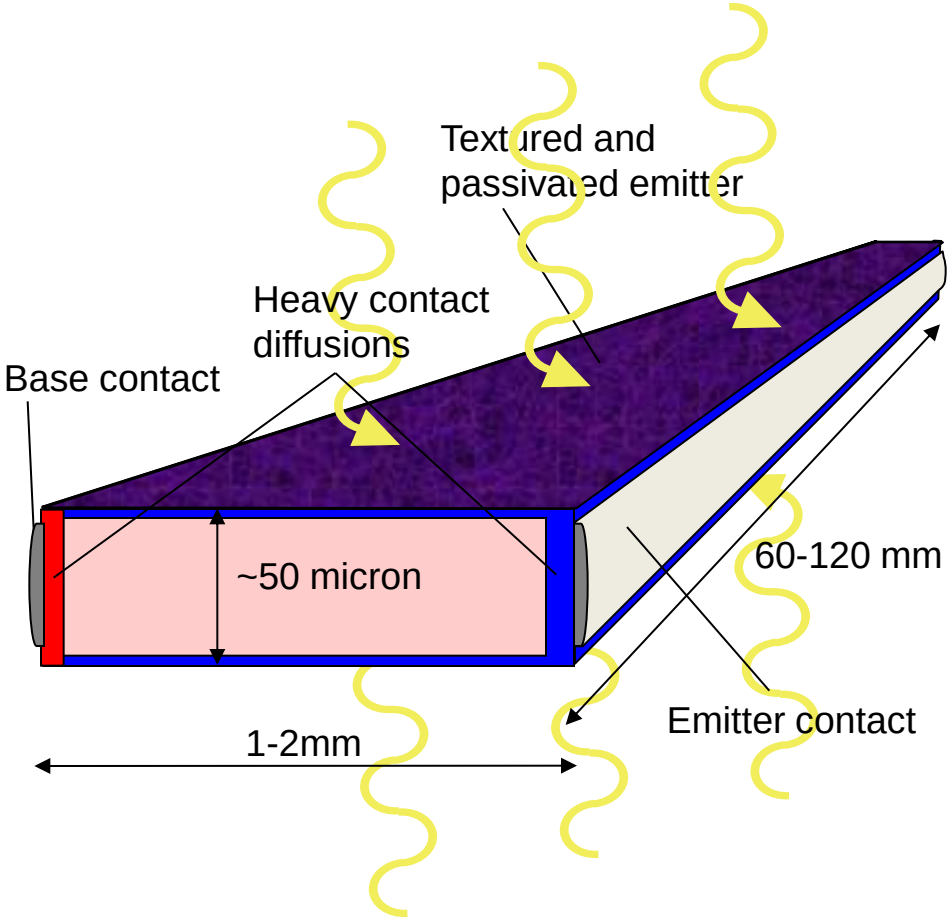
SLIVER technology dramatically reduces Si usage

- Micromachining increases the active area of solar cells from each wafer

- Actual saving depends on groove pitch, wafer utilisation and wafer thickness



High efficiency SLIVER cells



Monocrystalline silicon

- High voltage
  - Thin cell
  - Excellent surface passivation
- Good current
  - Front and rear collecting junctions
  - Excellent surface passivation
  - Lambertian light trapping

Innovative SLIVER module designs

Unique SLIVER cell features open new module designs

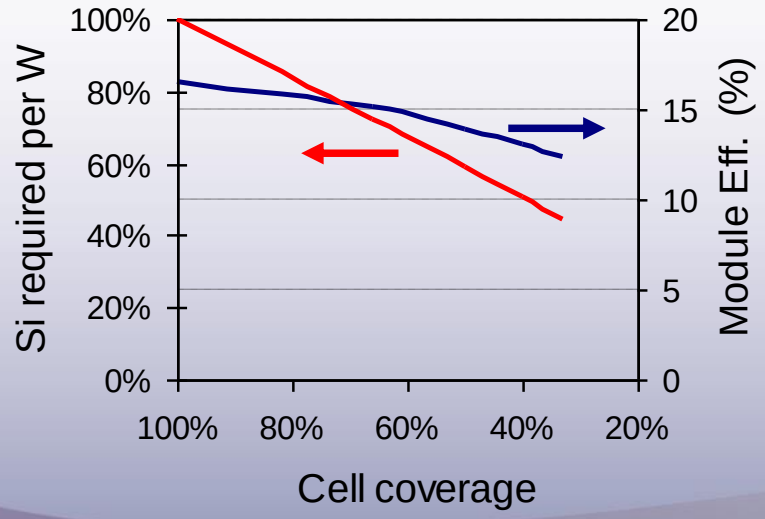
Cells narrow and bifacial

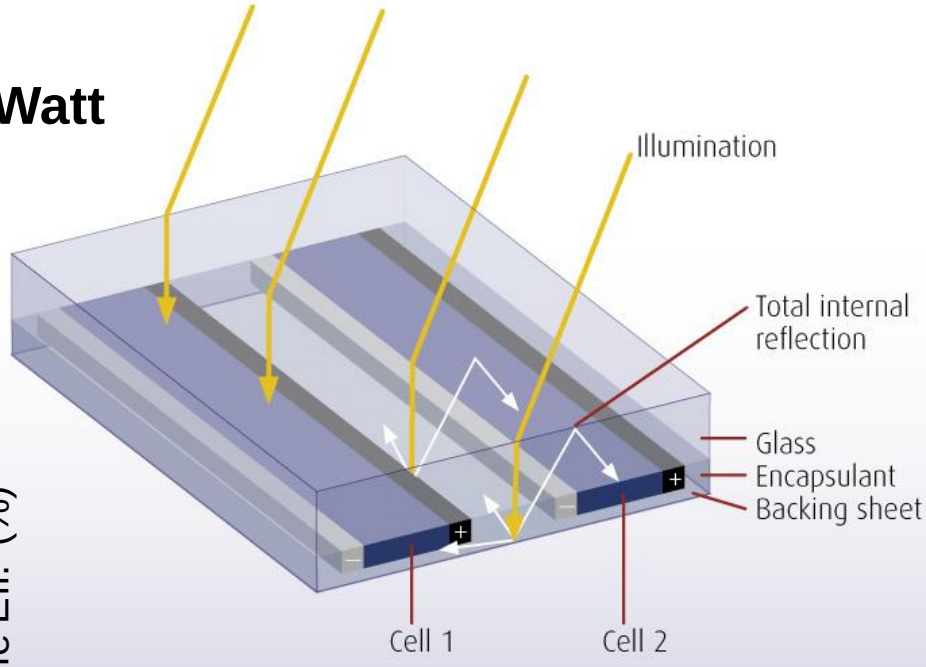
Spacing cells reduces Si per Watt

e.g. remove half the cells

84% of the module power

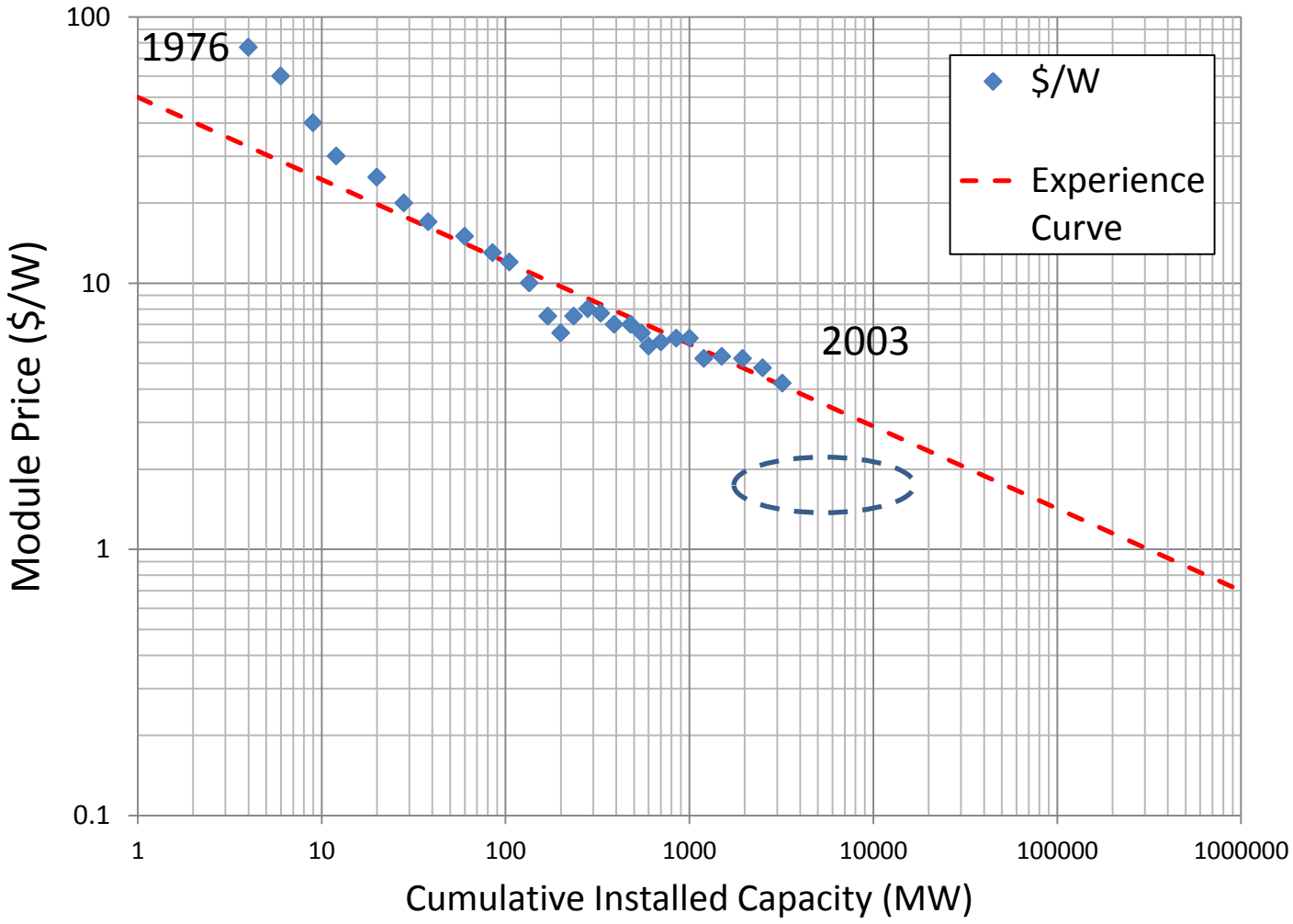
41% less silicon per Watt





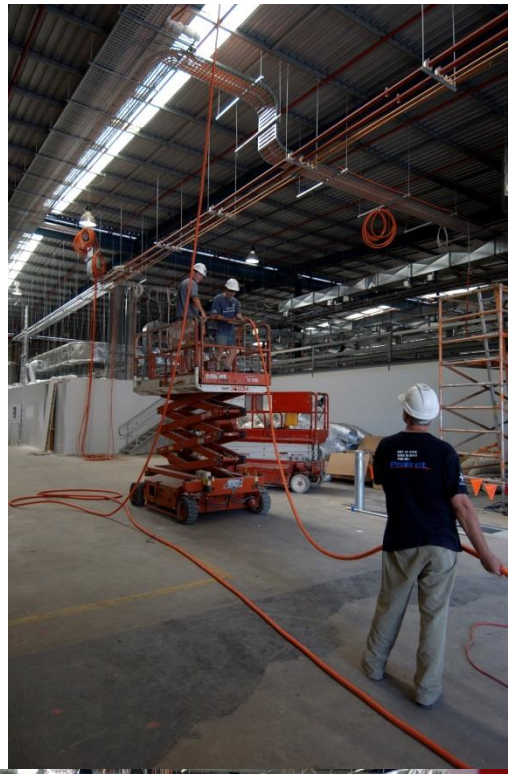
SLIVER TECHNOLOGY

2003 -Decision to build pilot facility



SLIVER Pilot facility Adelaide SA

- Why Adelaide?
  - Close to researchers at ANU? ☒
  - High quality water? ☒
  - Lots of high tech industry? ☒
  - Close to boss? ☑



Cleanrooms built from scratch within a paint warehouse

Nominally 20MW capacity

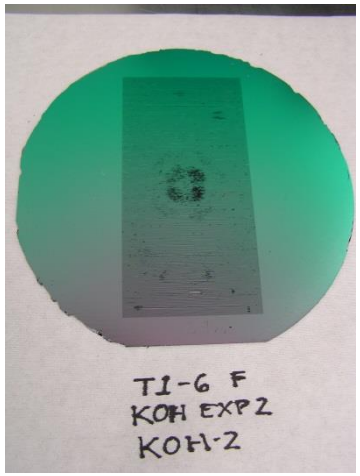
Cleanroom/Assembly areas complete

…and quickly produced first modules

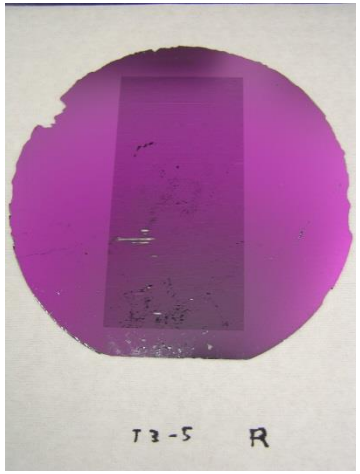

But the storm clouds were gathering

Sliver defects

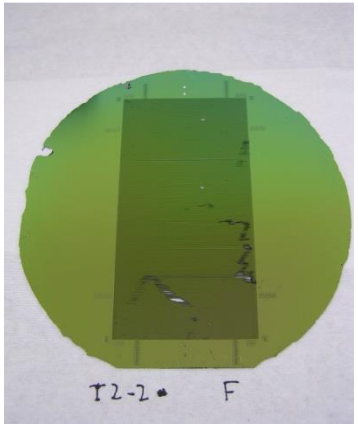
scanner



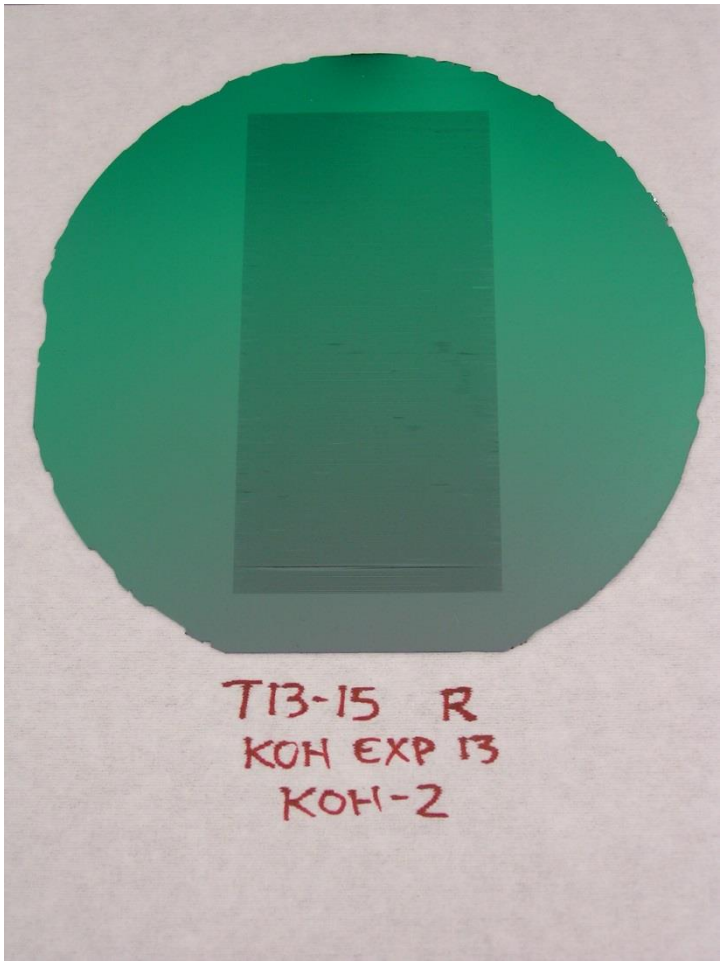
vacuum wand



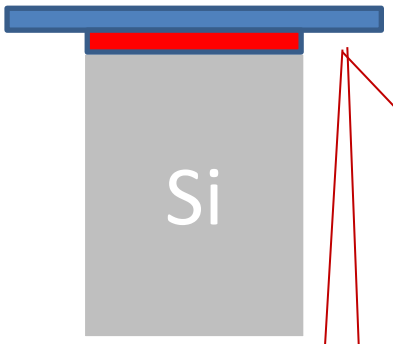
handling scratches



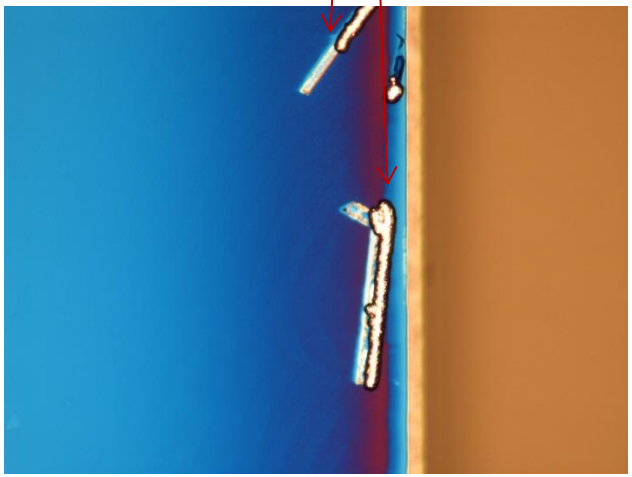
Edge damage



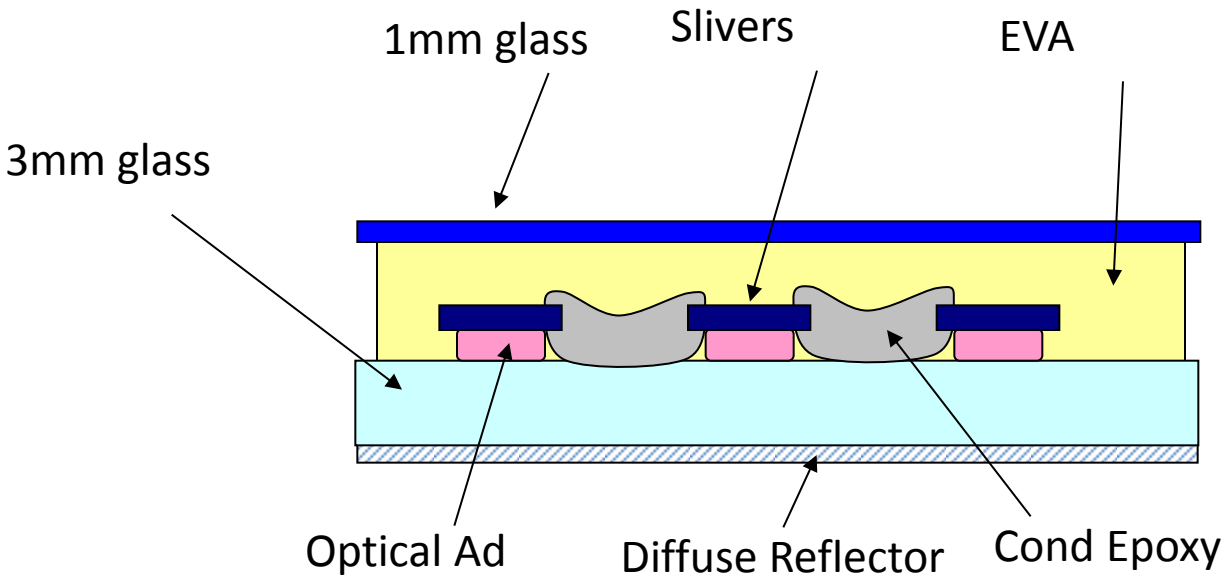
Poor cell design



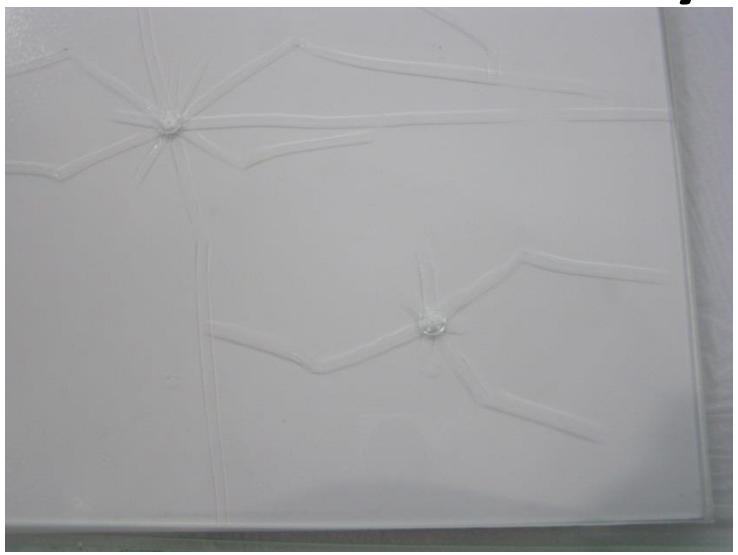
- Silicon nitride etch mask undercut by micromachining
- Broke uncontrollably blocking oxidation (LOCOS)
- Unwanted metal and shunting

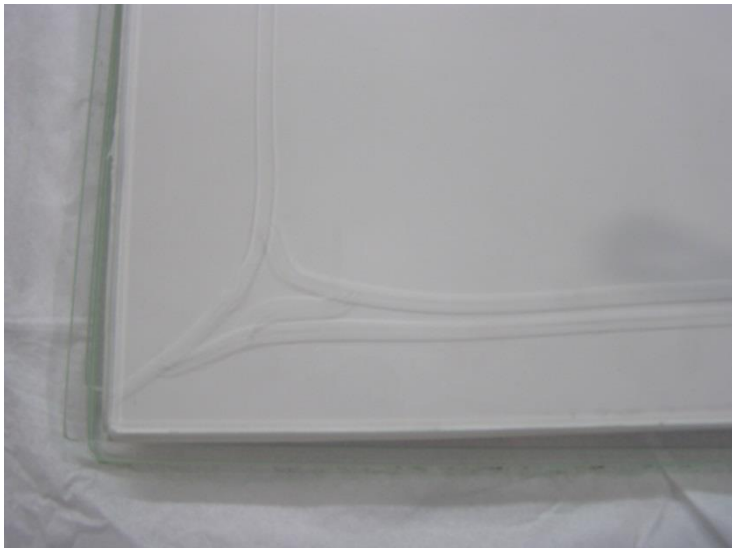


…and poor module design



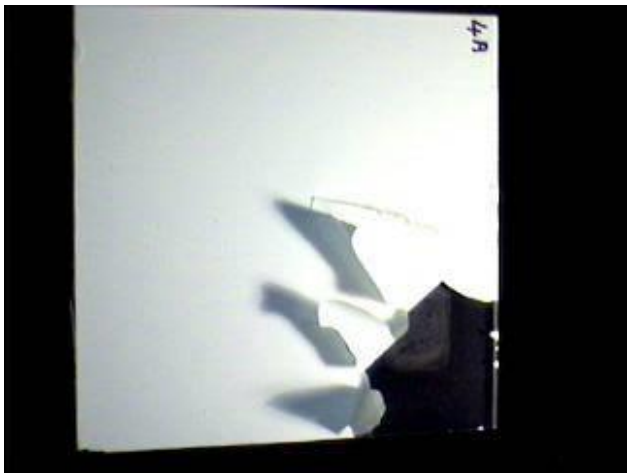
with… concerns over reliability

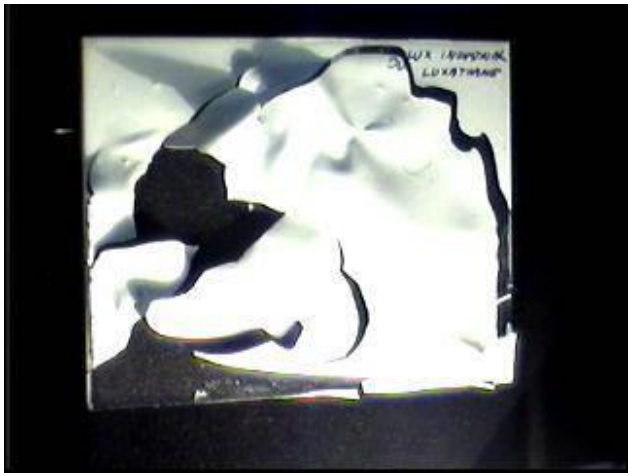




- Impact strength
- Thermal Cracking
- Freight (stress cracking)

and… concerns over reliability



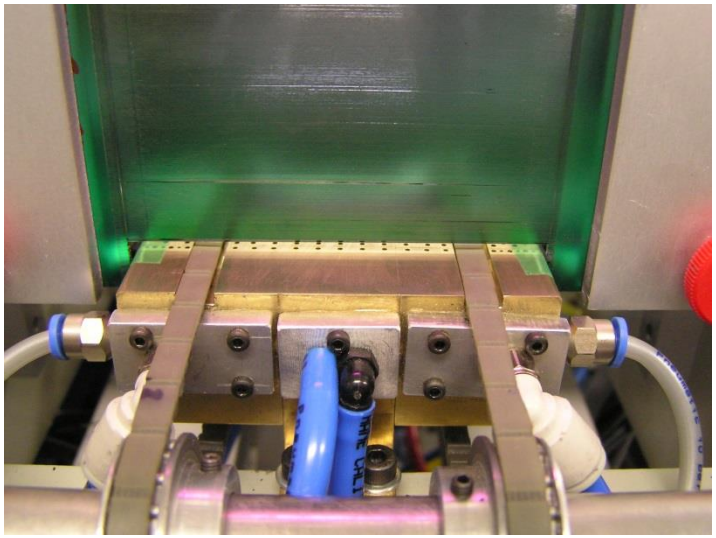


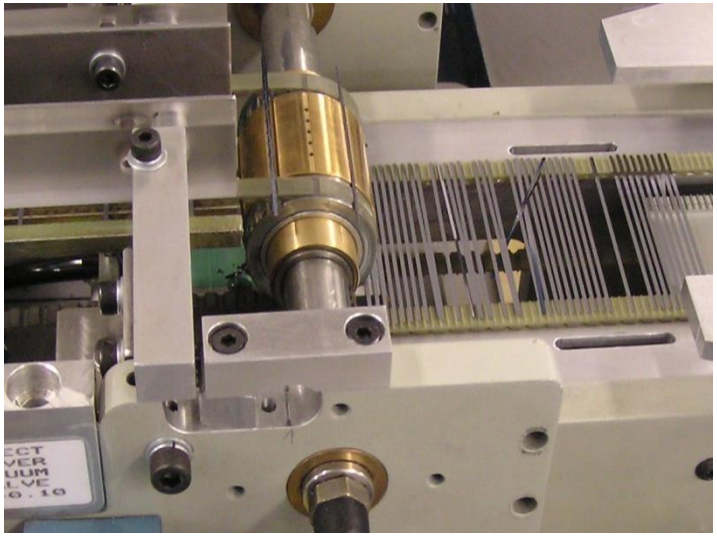
Automation

- Probably biggest challenge for commercialisation SLIVER technology
- Handle (very) large number of long thin parts
  - Initial approach
    - Throw dollars at the problem
    - Go to experts in handling and robotics
      - Custom automation companies

and… automation equipment needs improvement

Separation okay





Drum transfer is flawed

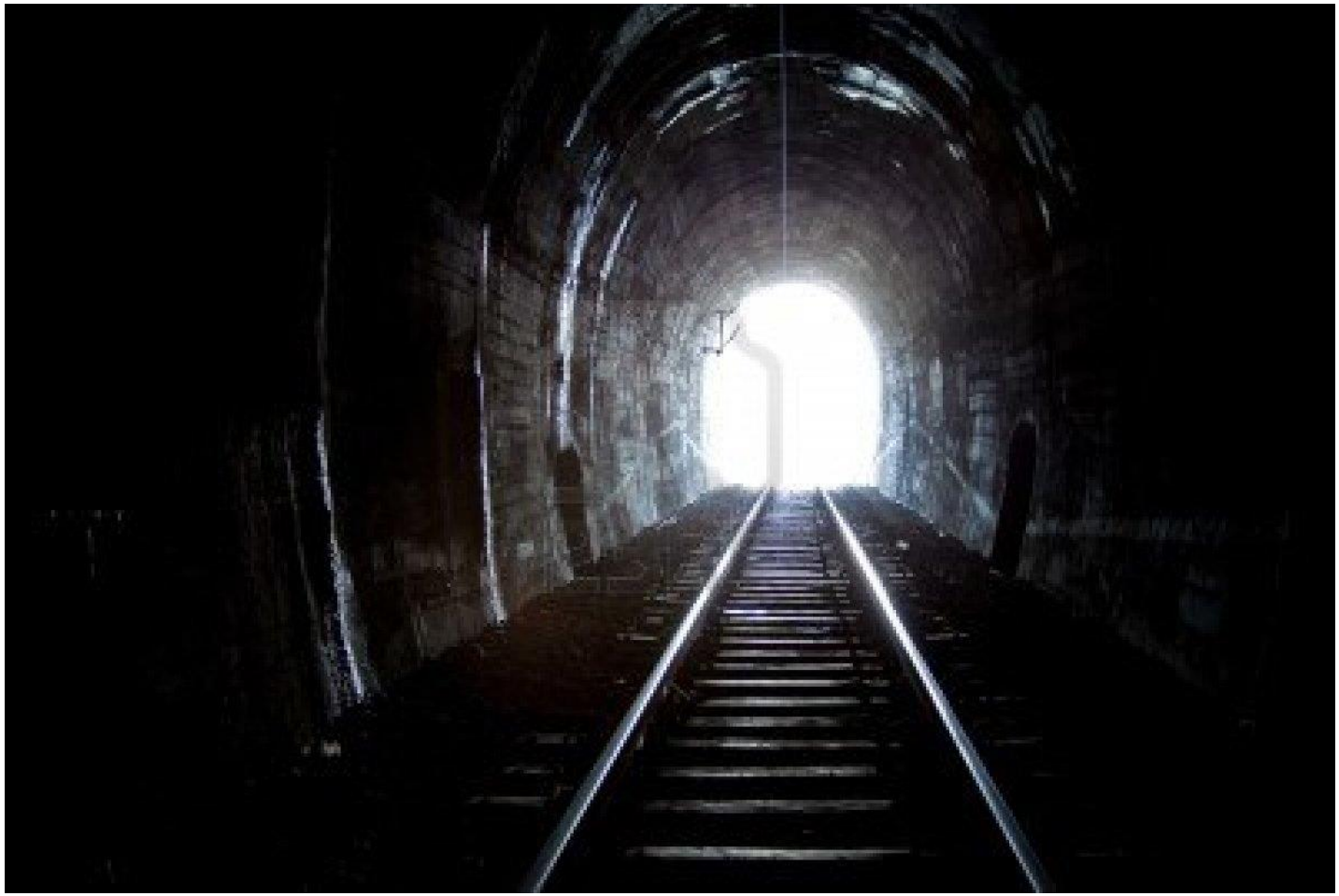
Back to basics

- Bring development back in house
- Cheap off the shelf SCARA robotic equipment
- Focus on design of head for interactions with SLIVER
- Slow down
  - Understand what works and what doesn't

To automation and back to in-house

- Gen 3 and 4 STP were back to automation companies
  - Issues again with understanding SLIVER cells
- Gen 5 back in house

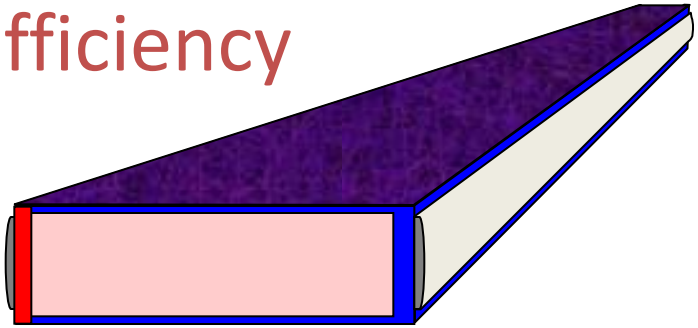
Gradually problems under control

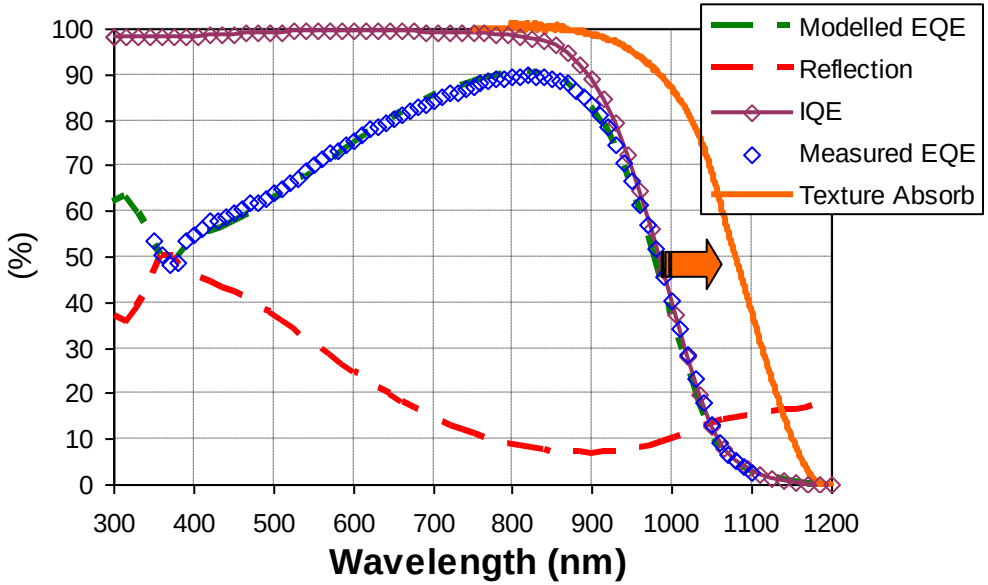


Production SLIVER cell results

Excellent internal quantum efficiency

- Thin cell
- Front and rear collecting junctions
- Excellent surface passivation
- Strong red response with texturing



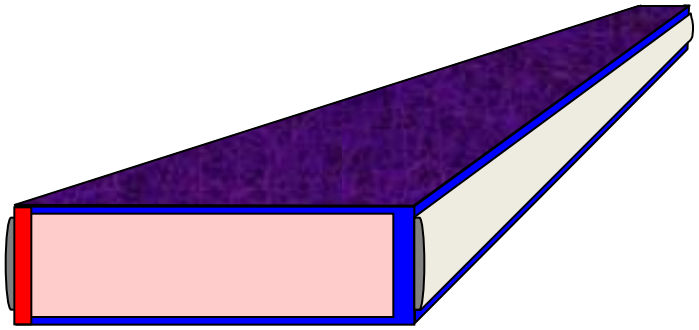


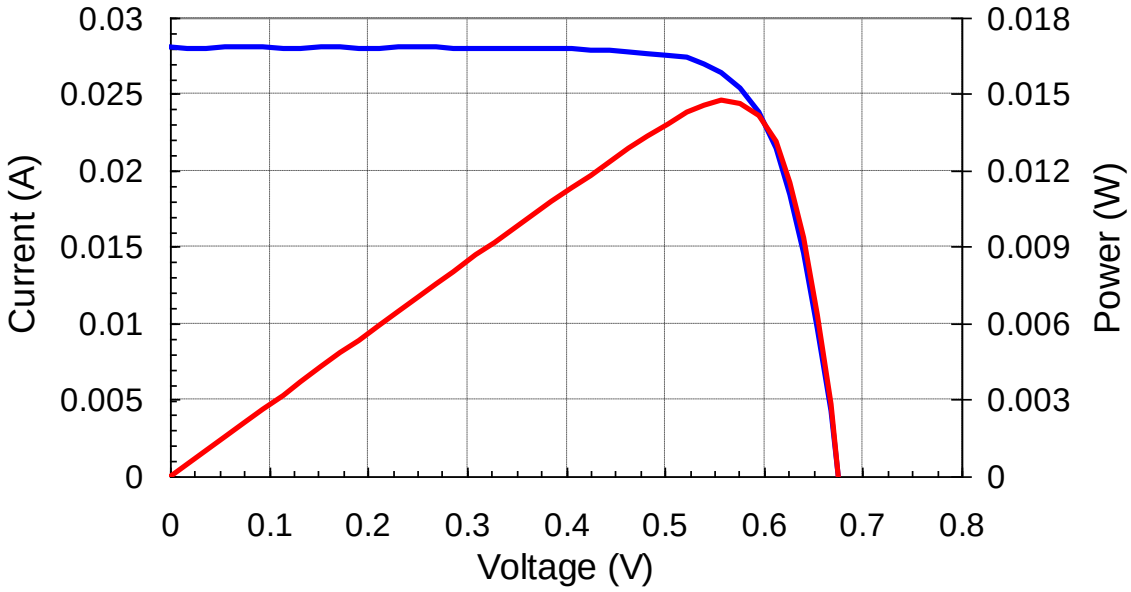
Production SLIVER cell results

Textured SLIVER cell

- Voc 675mV
- Jsc 36.4mA/cm^2 (0.77cm^2)
- FF 78.0%
- Efficiency 19.1%*

  *(not independently confirmed)





High voltage therefore low temperature coefficient (0.3%/°C)

Effect of lifetime on SLIVER cells

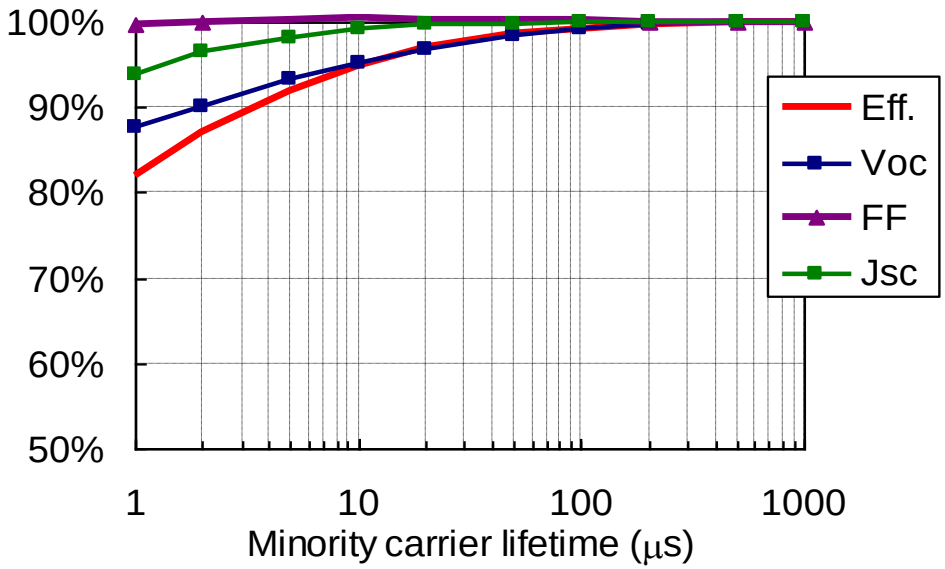
Voltage weakly dependent on bulk lifetime

>90% between 100μs and 1μs

Current almost independent of bulk lifetime

>95% from 5μs to 1μs

Excellent performance potential on moderate to good quality silicon (B Cz, Ga Cz, P Cz, FZ)



Normalised SLIVER cell performance

Modelled impact of variable lifetime

- 50μm 0.5 ohmcm p-type cell
- Max. Voc. 685mV, High lifetime eff. 19.6%

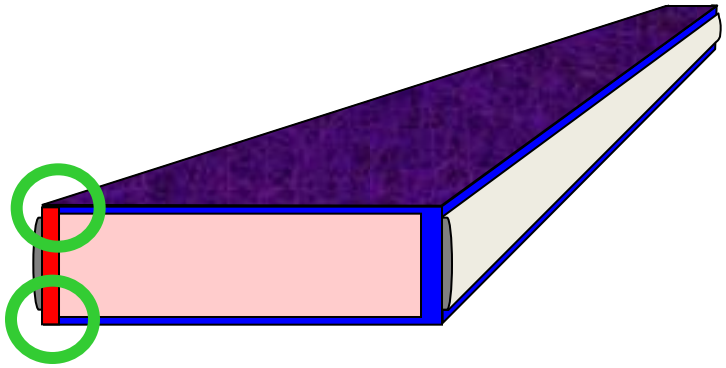
In-built Reverse Bias Protection of SLIVER cells

SLIVER cell design enables low voltage (~6V) controlled reverse breakdown along entire cell length

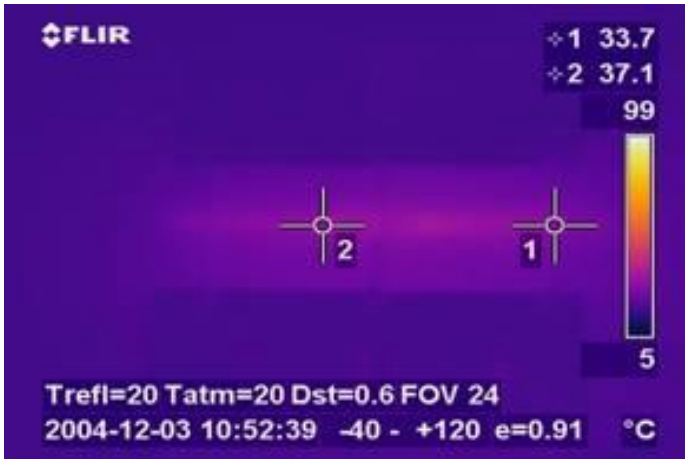
⇒ No bypass diode requirements

⇒ Simplify module construction

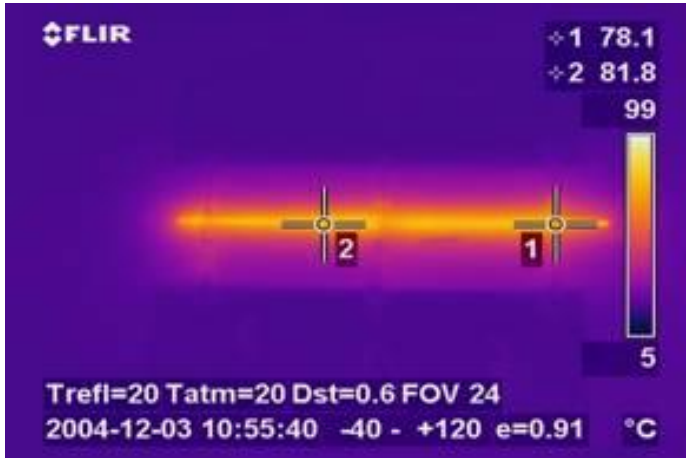
⇒ More reliable module



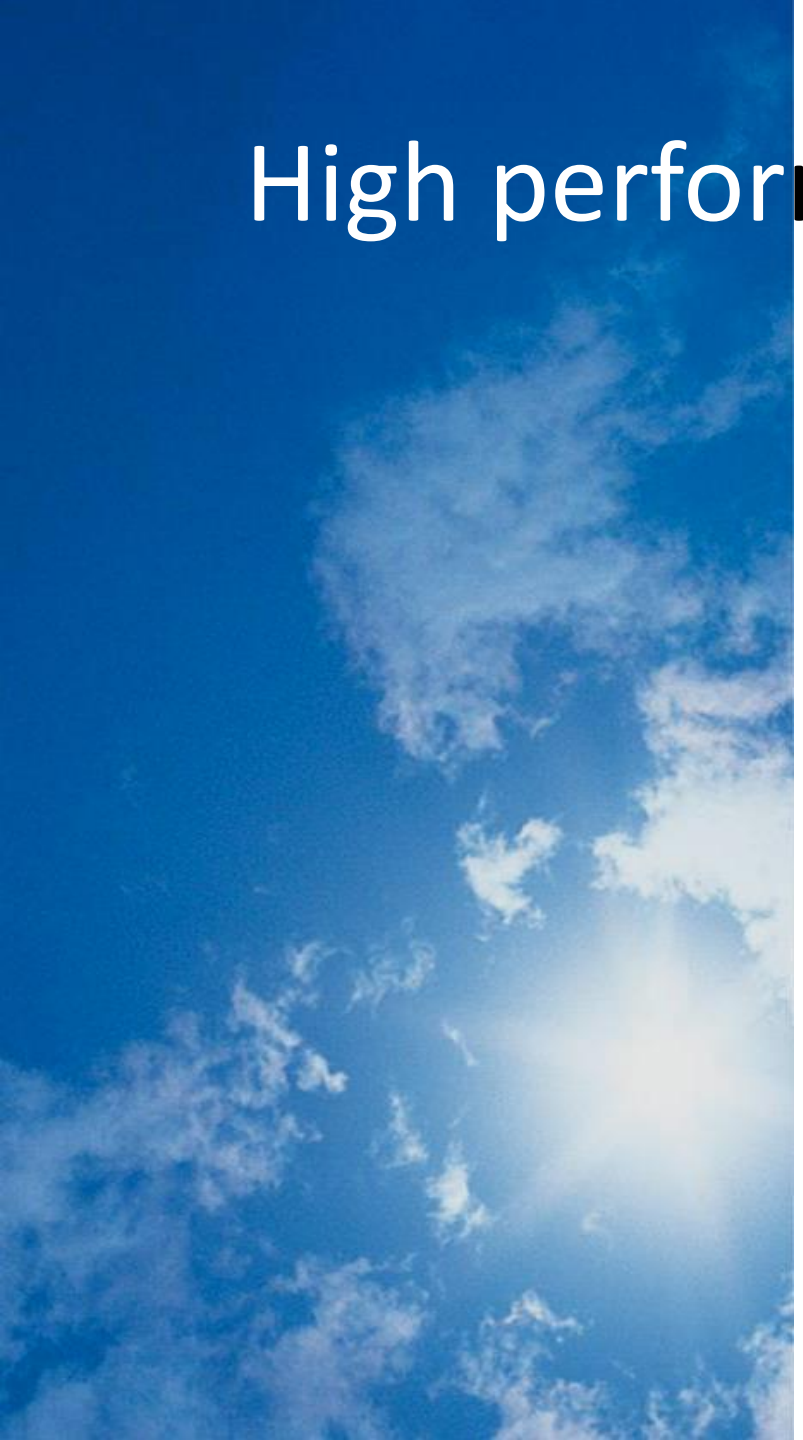
<40°C @ 3x Isc (0.1A)



~80°C @ 15x Isc (0.5A)

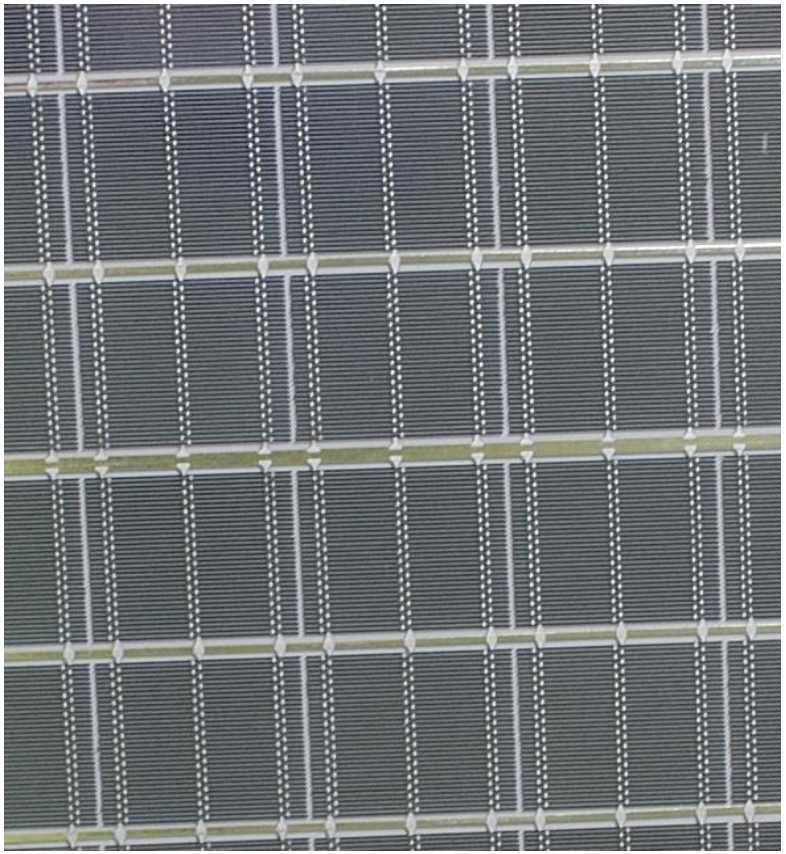


High performance features



- High cell efficiency (>19%)
- High open circuit voltage (up to 685mV)
- Low temperature coefficients (0.3%/°C)
- Excellent internal quantum efficiency
- Negligible shading with edge contacts
- Perfect bifacial response
- Low reverse breakdown voltages – no bypass diodes
- Excellent near lambertian light trapping

SLIVER module design



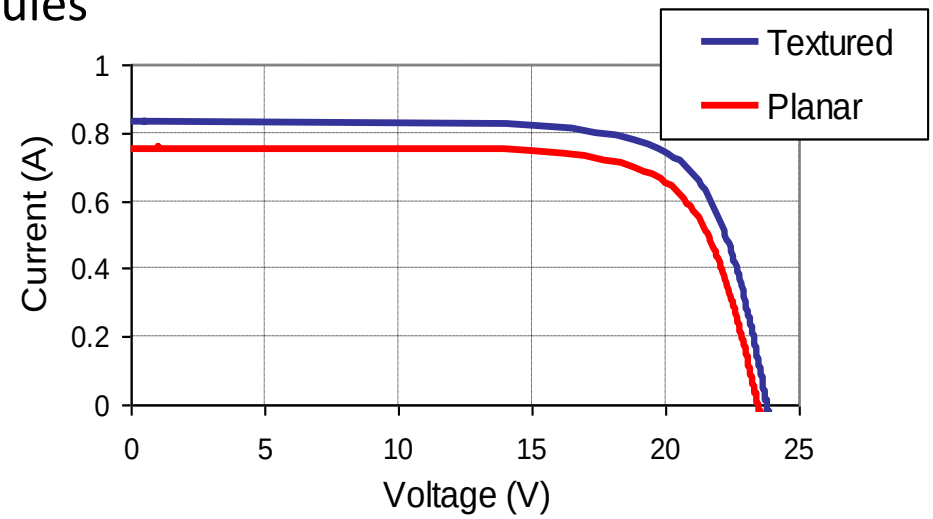
- Series/Parallel architecture
  - Longer banks more voltage
  - More banks more current
- SLIVER modules very robust
  - >500 thermal cycles
  - >1600 hours damp heat
  - >2x IEC UV test requirement

SLIVER modules surpass the reliability standard

SLIVER module performance

1st generation small area biglass modules

- 50% cell coverage
- 23.8V Voc (680mV/cell)
- 75% fill factor
- 14.9W (13% boost from texture)
- 9.5% framed - 12.2% active area

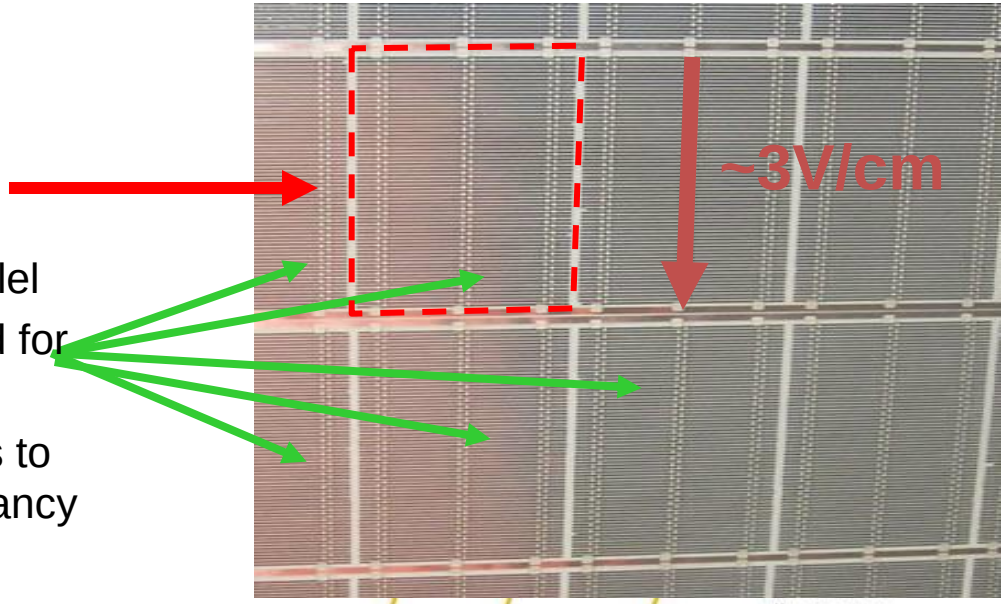


Preproduction modules

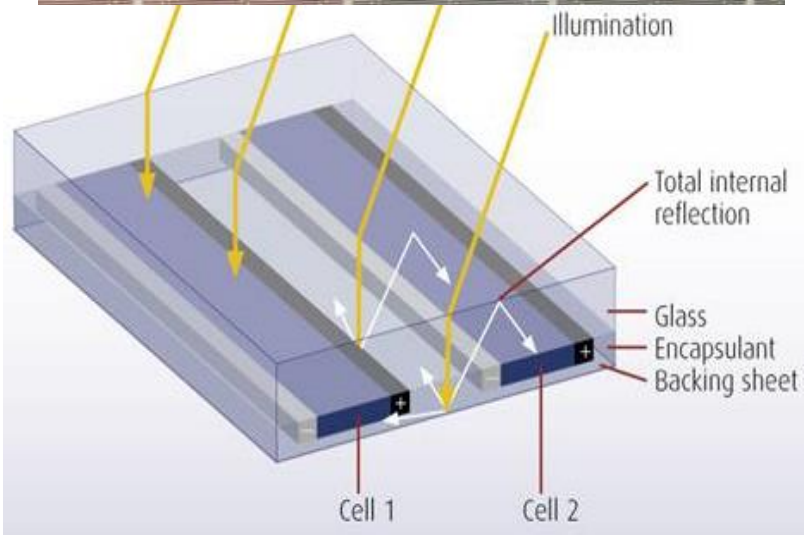
Textured cells	Isc (A)	Voc (V)	Pmp (W)	FF (%)
Yes	0.83	23.8	14.9	75.1
No	2.13	22.3	35.3	74.2
No	4.06	23.6	70.6	73.8

SLIVER module architecture

- Series/parallel architecture:
  - Based on *banks* of cells
  - Build voltage within a bank
  - Build current with banks in parallel
  - Current and voltage easily tuned for given application
  - Multiple cell to cell interconnects to improve FF and provide redundancy



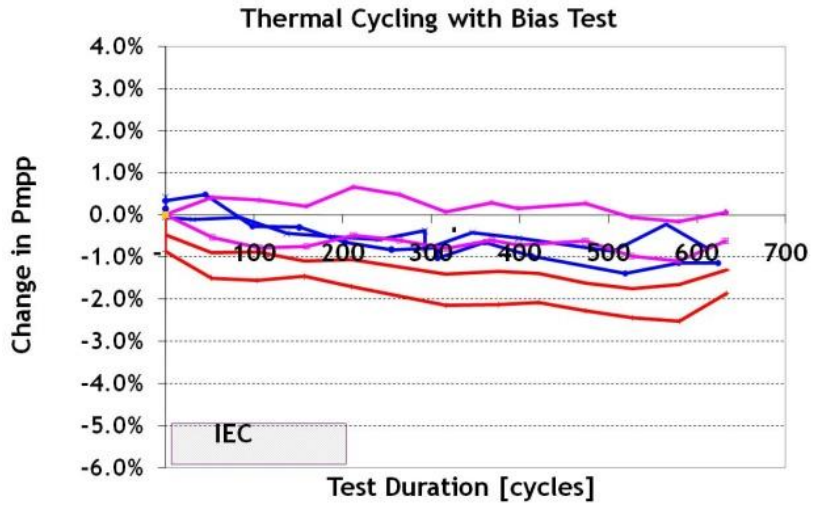
- Conventional monoglass module structure
- SLIVER cells are narrow and perfectly bifacial
- Spacing cells reduces Si per Watt and modules can be semi-transparent
- Light entering a gap between cells can be efficiently collected:
  - Scattering from backsheet and absorbed by rear of cells
  - TIR from front surface (glass) to trap the light

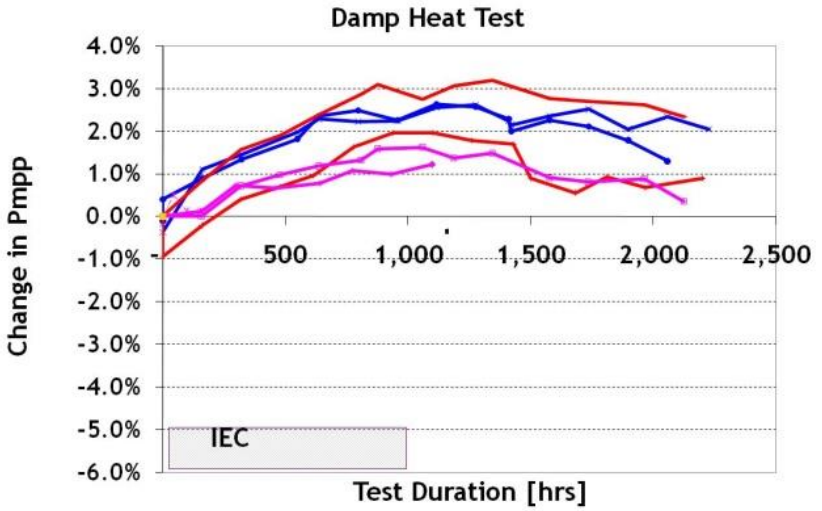


Reliability

Modules built to comfortably exceed IEC standards

- Standard module architecture
  - Glass/pottant/cell/pottant/back sheet
- Cells with in-built reverse breakdown protection
- Series/parallel connections
- Multiple cell to cell connections
- Low current cell to cell connections
- Bulk current carried only by busbars





Series II SLIVER modules

- Product as of Q1 2008
- 92Wp panels
  - 6 sub-assemblies
  - Convenient size to demonstrate manufacturability of multi subassembly panel
  - Representative performance testing
  - Similar architecture used for larger modules
  - Certified Nov ’08 TUV IEC 61215 + 61730

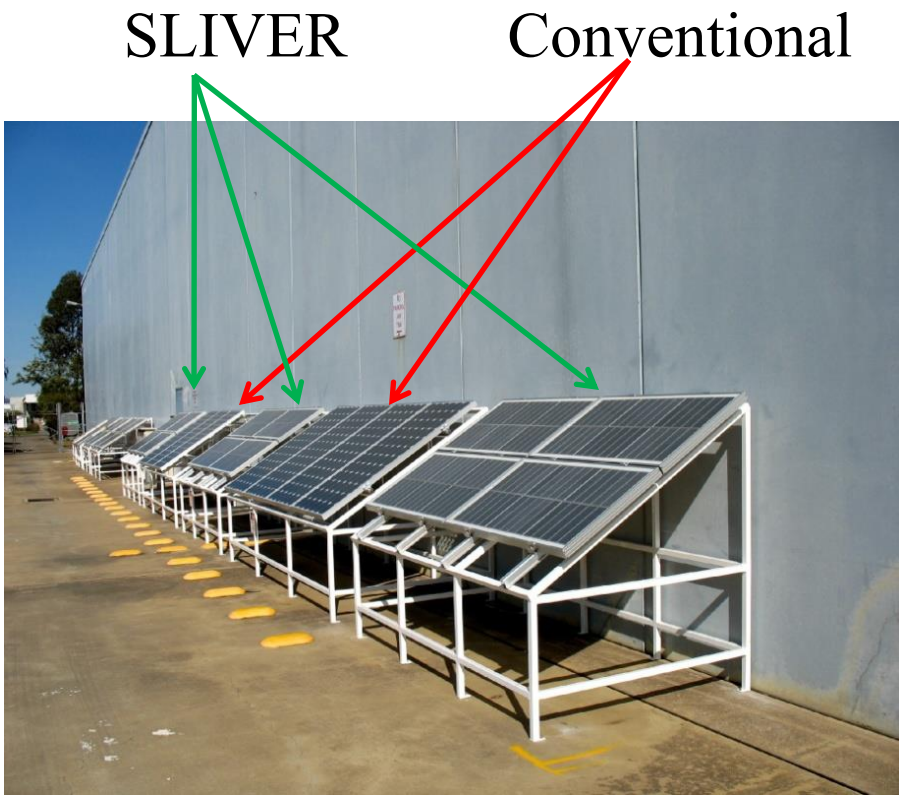
Outdoor testing

Outdoor test bed for comparison of SLIVER and convention c-Si Systems performance

- Two ~1kW systems
- Leading Japanese c-Si supplier
- Identical power electronics
- Modules measured at STC after light degradation

Data collected for

- AC & DC characteristics
- Incident illumination
- Temperature (module and ambient)
- Monitoring at 5 minute intervals

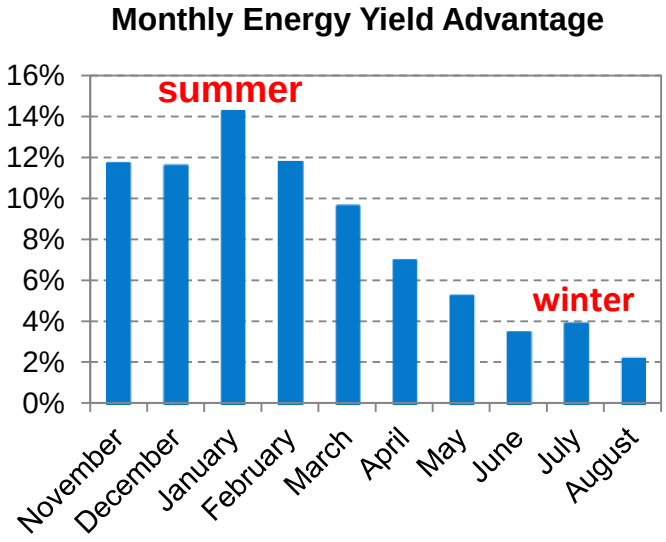


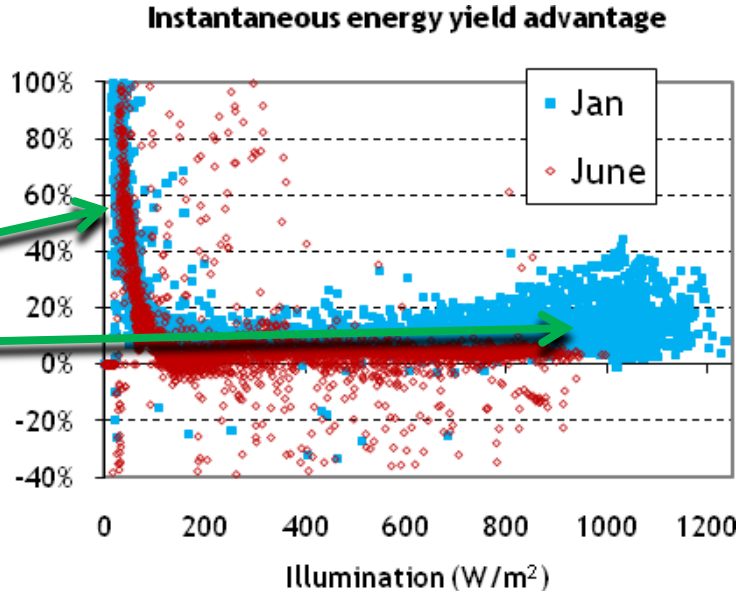
Energy Yield (kWh/kWp)

The SLIVER system delivered 8.6% better yield (harvest) than the conventional system over the first 10 months of testing to date

SLIVER modules outperformed the conventional modules most times, especially

- At low levels of illumination
- At high illumination on warmer days (summer)



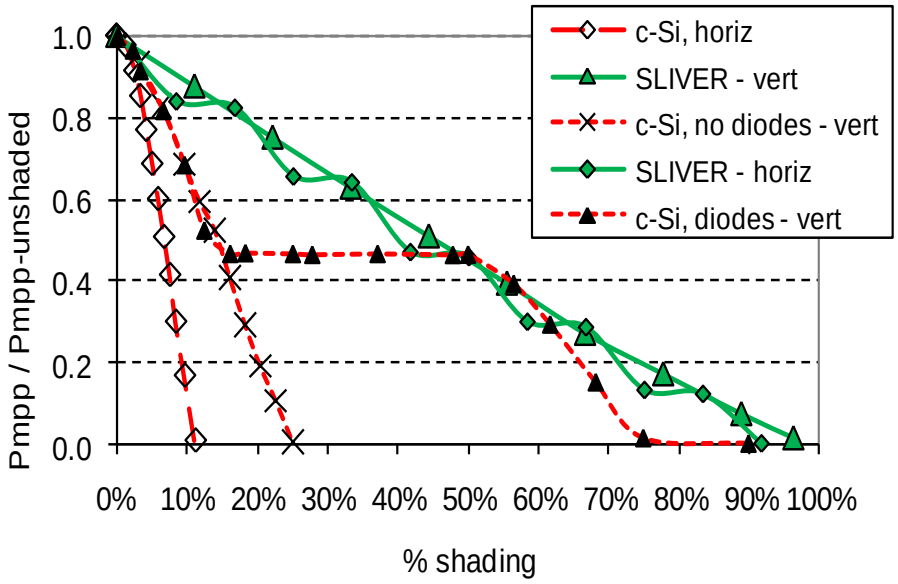


Partial Shading

SLIVER modules more tolerant than conventional modules to partial shading.

- Shading of parallel banks has little impact on SLIVER module without any need for diodes
- Shading of cells in conventional module affects the entire string

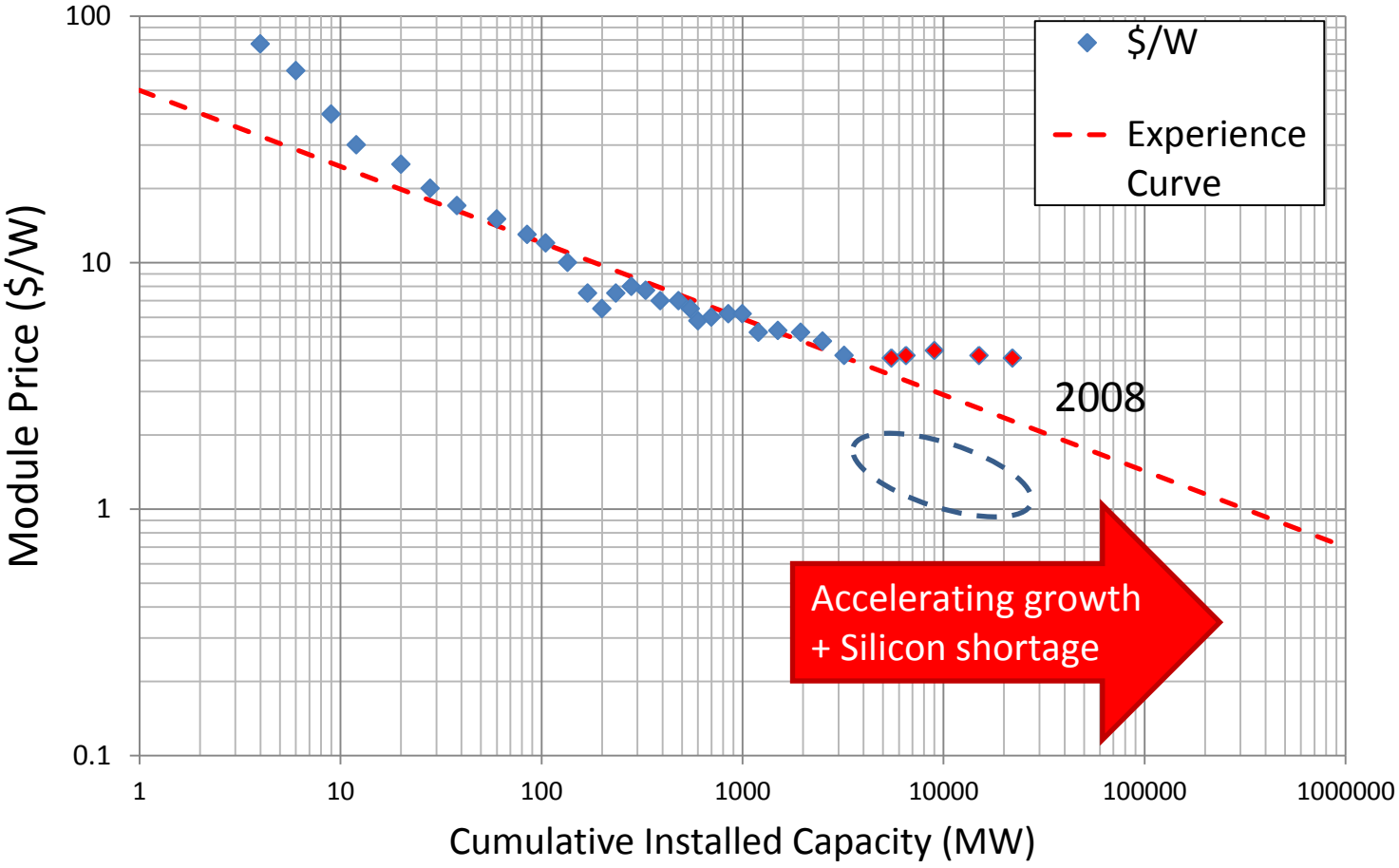
Part of energy yield advantage probably due to tolerance to partial shading (soiling)



SLIVER Module Advantages

- Monocrystalline silicon based
- High energy yield (kWh/kWp)
  - Low temperature coefficient
  - Low operating temperature
  - Low shunt resistance
  - High tolerance to partial shading
- Designed and constructed for excellent reliability
  - TUV 61215 + 61730 certified
  - Conventional module packaging materials used
  - In excess of 600TC and 2000h DH with no power loss

Partnership phase



Silicon shortage

- Strong PV growth and silicon shortage paradoxically hurt SLIVER technology
- Ingot growers were
  - Short on polysilicon
    - Focused on supplying core customers
  - Interested in bigger volumes of standard PV
    - Sell more wafers
  - Sensitive to non-standard material (110)
    - No-one to sell to if SLIVER failed

Why partner?

- Understanding and mitigating risk
- Origin very willing to take risks
  - Every exploration/ drilling project has good chance of failure
  - Typically shared with partners
  - No feel for manufacturing
    - Therefore risk averse
- Criteria
  - Semiconductor/ solar/ technology company
  - Manufacturing experience
    - Origin is an energy company
  - Similar scale to Origin
    - Genuine partnership
    - Neither side too big to bully the other
  - Lower cost access materials
    - Particularly module

2007-2008

- Detailed negotiations with 3 technology companies
  - Two large solar companies
- Novel technology
  - Extensive discussions to understand technology
  - Significant investment time and effort
- Every partnership deal fell over very late in the process
  - Ultimately, companies believed their own roadmap to cost and silicon savings
  - Less risk averse with own technologies

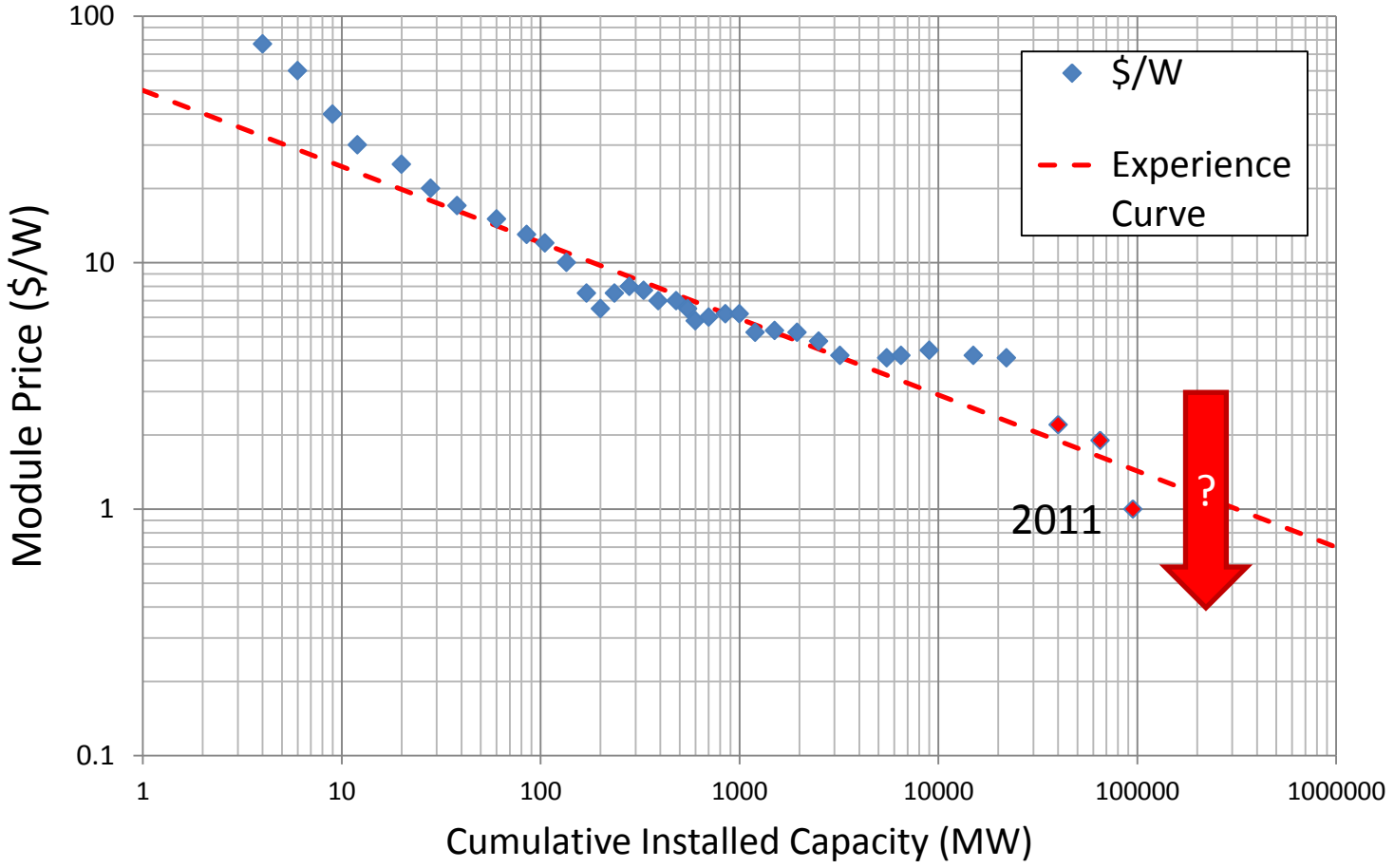
Plan B - expand then find partner

- Decision to manufacture outside Australia
- Demonstrated 200mm SLIVER manufacture with contract Fab
  - show there are no show stoppers
- Identified 200mm facilities to lease/but
  - Semiconductor facilities largely 300mm
  - Large number (~100) idle 200mm Fabs around world
  - 200mm Fabs available at cents in the dollar

- Serendipity hit

Micron – Boise Idaho

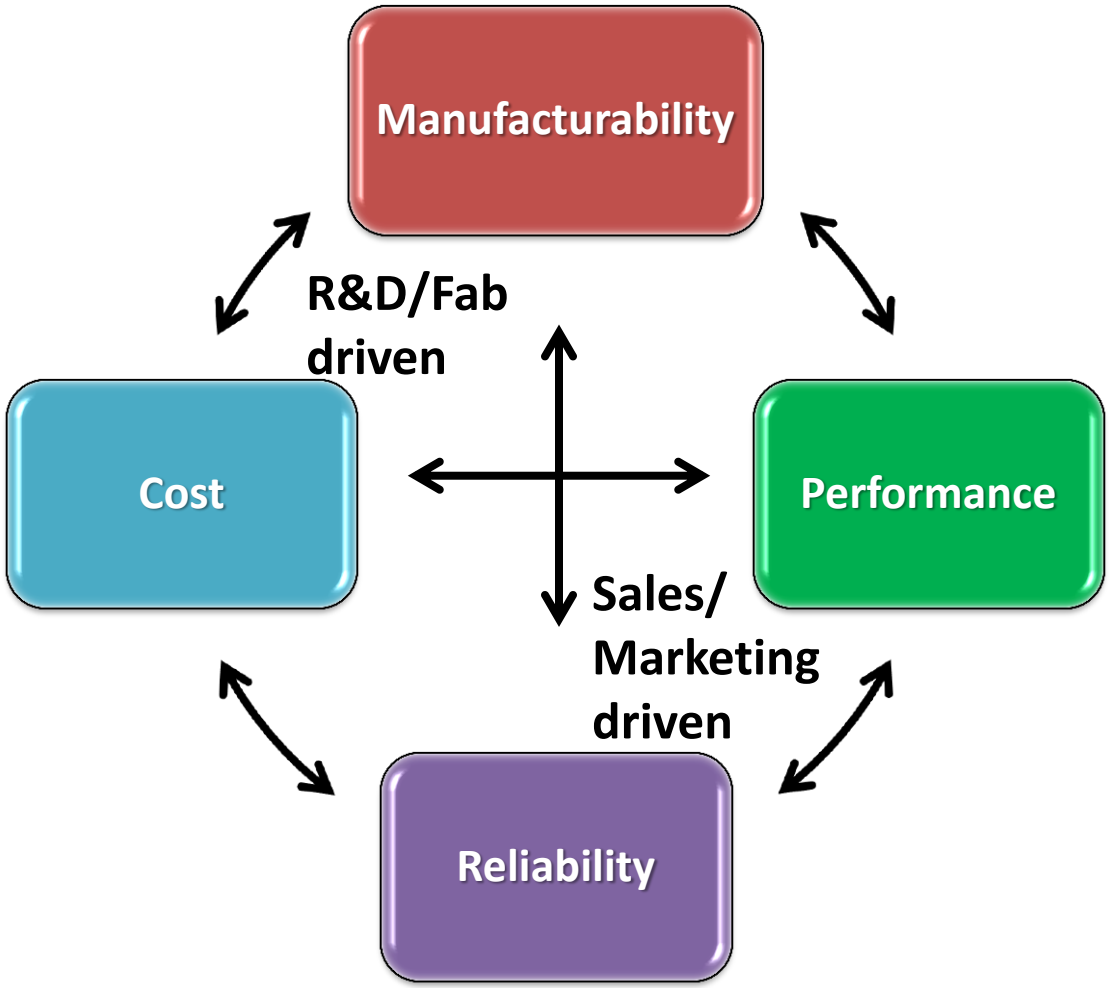
The perfect storm



SLIVER dollars

- Total investment
  - $19M in capital in original pilot facility
  - $240 million across Origin and Micron to final closure
- Returns to ANU
  - >$11 million in royalties
  - ~ $18 million in R&D funding

Solar Technology Design Tensions



- Increase wafer utilisation
  - Decrease etching pitch
  - Two cell lengths
- Reduced yield
  - Higher stiction
  - More stress points
- Need to recertify
  - 10% change in cell thickness
- Lower efficiency
  - Thinner cell

Goal alignment (or be careful of walls)

Poor goals can drive bad behaviours

Total = Wafer x Separation x SA x Module

Yield   

Cell team goal is to maximise wafer yield

Assembly team goal is to maximise separation and SA yield

Module team goal is to maximise module yield

What are the motivators?

- Upstream – soften criteria and push poor product!
- Downstream - toughen criteria and reject ok product!

Better goals

- Focus on best for business
- Agree metrics at handover/boundaries

Start Up vs Big Business

- Cash poor
  - Motivated to be fast
- Risk takers
  - Good enough
- Everything from scratch
  - Need to invent it all
- Strong team ethos
  - Us against the world

- Deep pockets
- Risk averse
  - Slow to move
- Systems in place
  - E.g. safety
- Door opener
  - access to suppliers, etc

Don’t underestimate need for champions

Biggest satisfaction

- Solving technical challenges to move from lab to manufacturing
  - Deepest, narrowest micromachining
  - Vastly simplified cell process
  - STP
  - Sub assembly development
  - Demo of >190W wafer
  - Reliable module product
  - Building good R&D teams

Biggest disappointment

- Focus on commodity product
  - Tried to go head to head with Chinese Tier 1 and failed
- Missed opportunity with SLIVER enabling products
  - Recognised benefits too late