SpeckNET

Research Consortium in Speckled Computing

Towards III-V's on GoI

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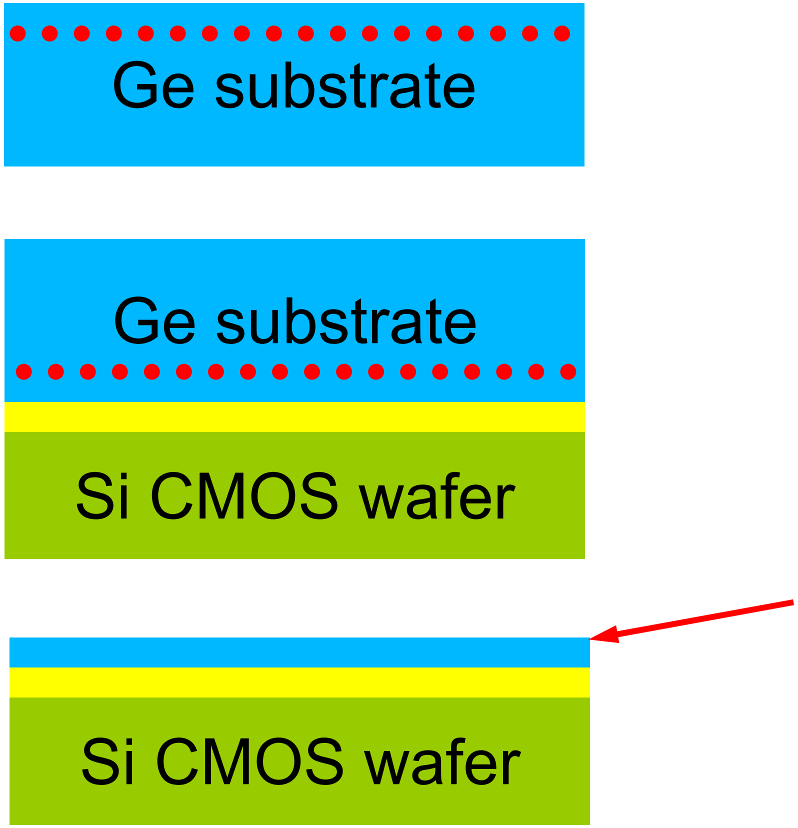
The long term vision

- Integration of functional electronic devices/ICs and photovoltaic power generators on a common platform.
- The common platform envisaged is Germanium-on-Insulator, or GoI for short.
  - Si wafer with CMOS processing circuitry embedded within it
  - Thin SiO_2 insulation layer over CMOS
  - Few microns thick, single crystal Ge template bonded to insulator-over-Si
  - Epitaxy of III-Vs on Ge

Germanium-on-Insulator



1. Implant hydrogen/helium ions to create plane of damage a few microns below the Ge wafer surface

2. Fuse Ge to Si (CMOS) wafer, with an intervening layer of SiO_2

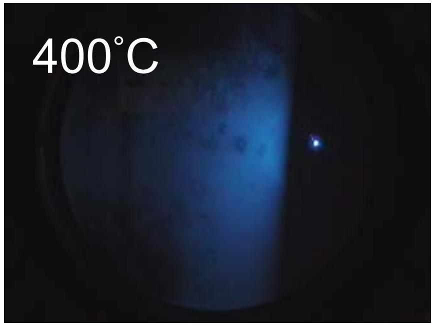
3. Separate, polish, anneal to leave a thin Ge template bonded to Si (remainder of Ge wafer re-used)

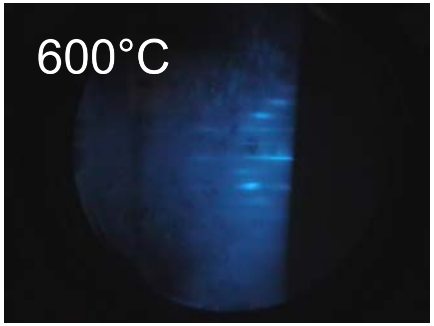
Epitaxy challenges

- Small mismatch in lattice constants of Ge and (Al,Ga)As.
- Out-diffusion of Ge into GaAs.
- In-diffusion of As into Ge.
- Ge is a non-polar semiconductor, whereas GaAs is polar.
  - High risk of anti-phase domains since either Ga or As can bond to Ge
- Ge substrates with a 6° off-cut of (001) orientation toward the in-plane [100] direction are widely used.
- Initial MBE growth studies at Glasgow have been on Ge substrates rather than GoI

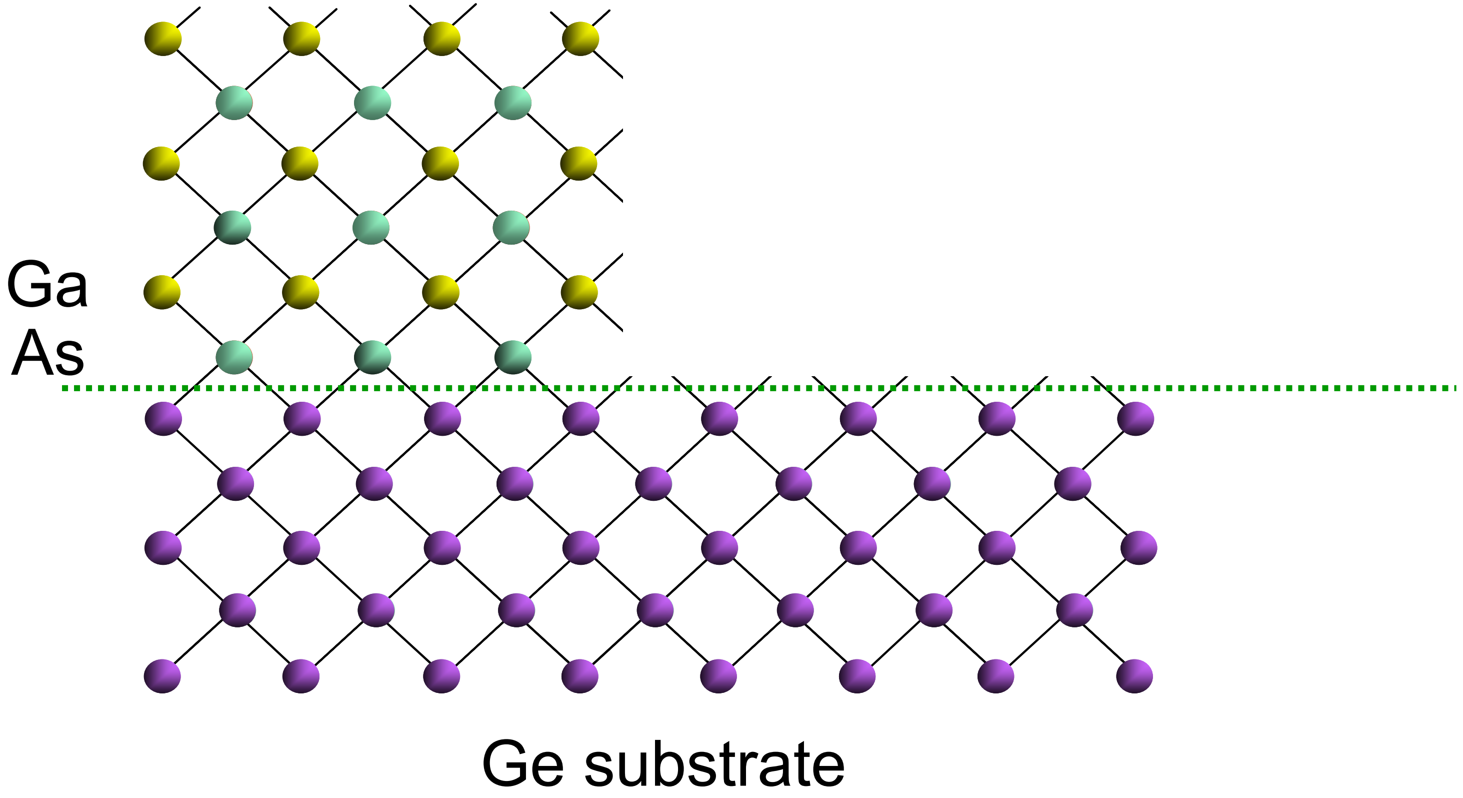
Nucleation layer - ideal

- Substrate degassed and Ge oxide(s) removed by a 20 min anneal at 640°C.
- Ideally, this should be followed by the deposition of an epitaxial Ge buffer layer prior to GaAs nucleation.
  - Ge source in MBE system produces a very low flux
  - Ge growth rate probably below 0.1μm/hr
  - Improvements to wafer surface as monitored by *in situ* RHEED have been inconclusive



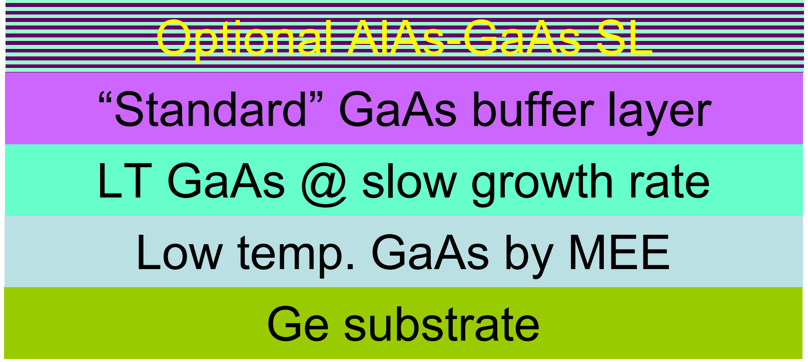


Anti-phase domains



Nucleation layer - practice

- Anti-phase domains (APDs) can be avoided by
  - **Migration Enhanced Epitaxy** of 10 monolayers (ML) GaAs at ~350°C and a growth rate of ~0.1 ML/s.
  - **~0.1μm of GaAs at ~500°C** and a growth rate of ~0.1μm/hr
  - **~0.5μm of GaAs at ~580°C** and a growth rate of ~1.0μm/hr
- An AlAs-GaAs superlattice may be required to provide electrical isolation of III-V device structure(s) from Ge.



Optional AlAs-GaAs SL

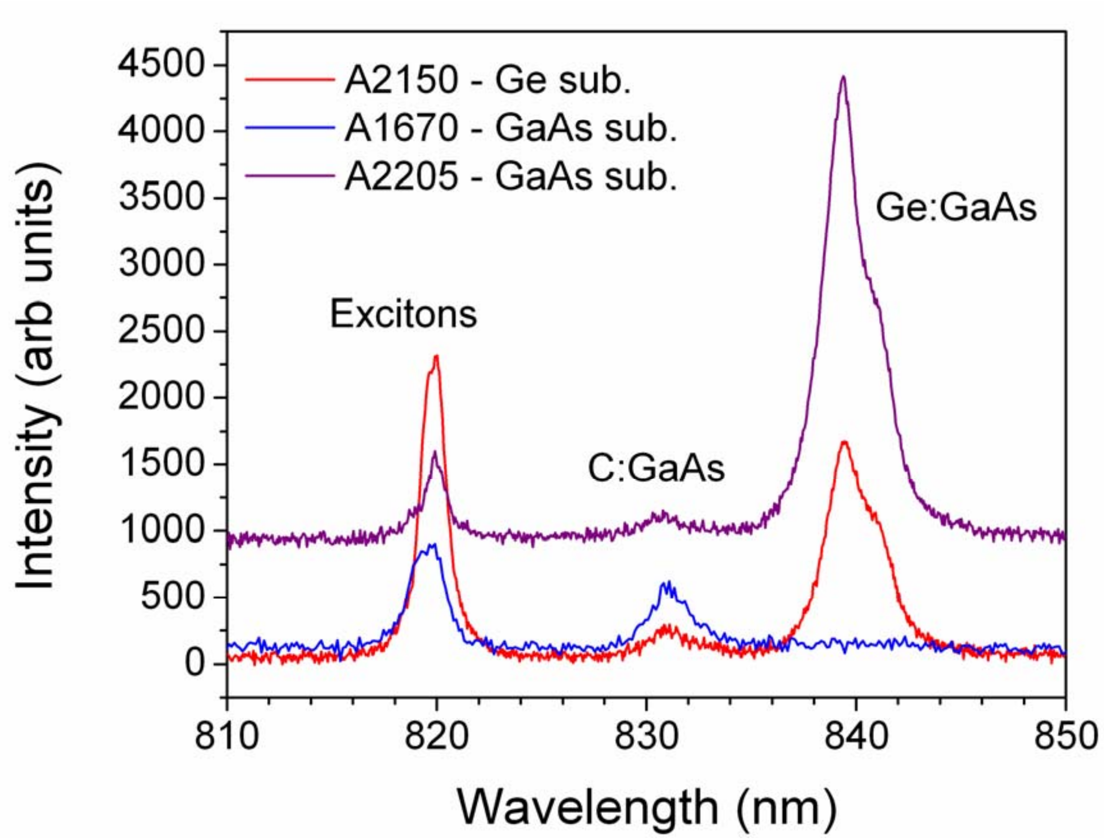
“Standard” GaAs buffer layer

LT GaAs @ slow growth rate

Low temp. GaAs by MEE

Ge substrate

PL for un-GaAs grown on Ge and SI-GaAs



AlGaAs-GaAs interface quality assessed by QW PL emission

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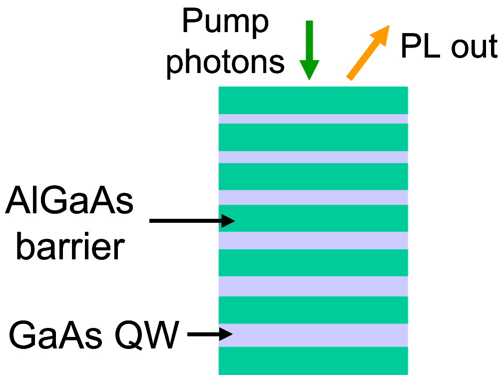
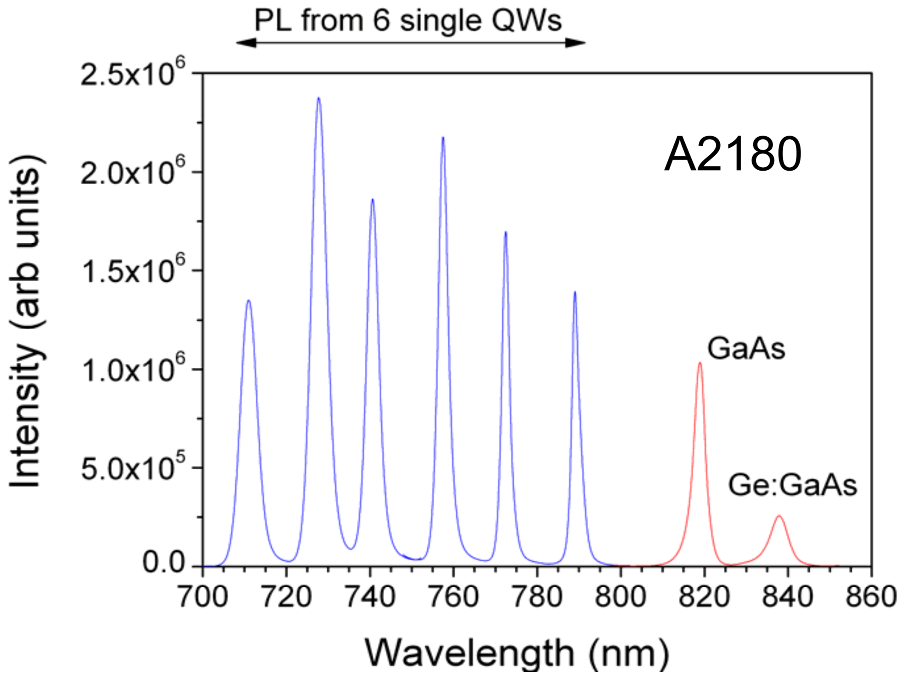


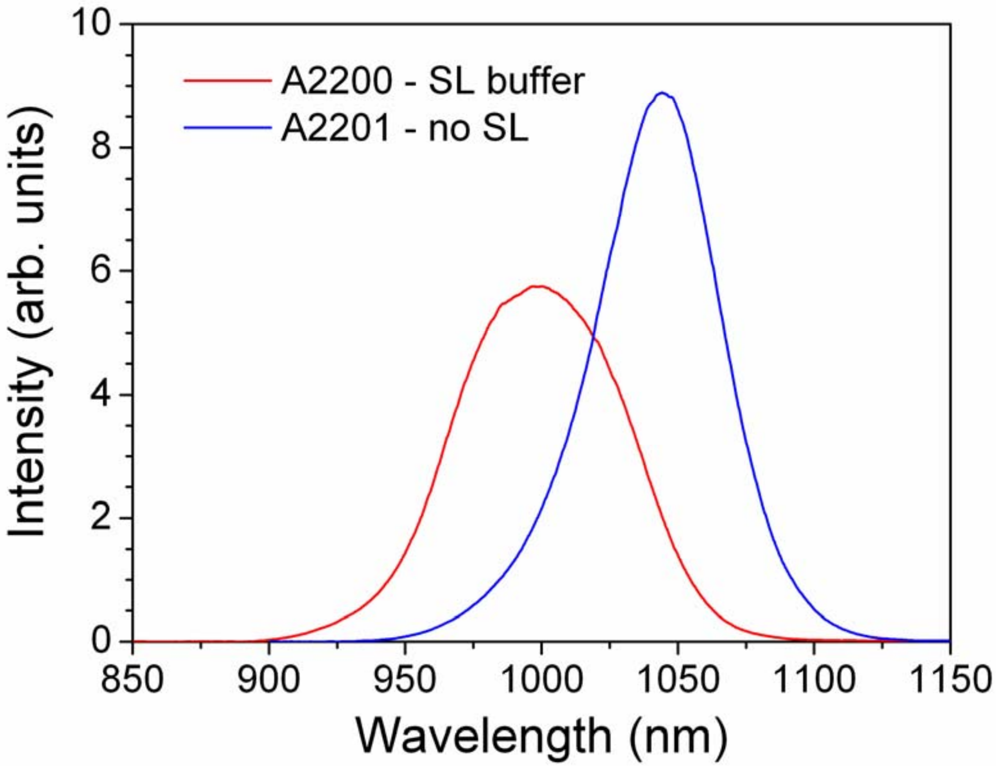
- SQWs grown on Ge (no Ge buffer)
  - 10ML of GaAs by MEE at 375°C)
  - 0.1µm GaAs buffer @ 0.1µm/hr at 500°C
  - Repeated annealing at 580°C
  - 5µm GaAs @ 1 µm/hr at 580°C
- SQWs on Ge buffer layer gave no measureable PL emission.



Device Structures Grown on Ge

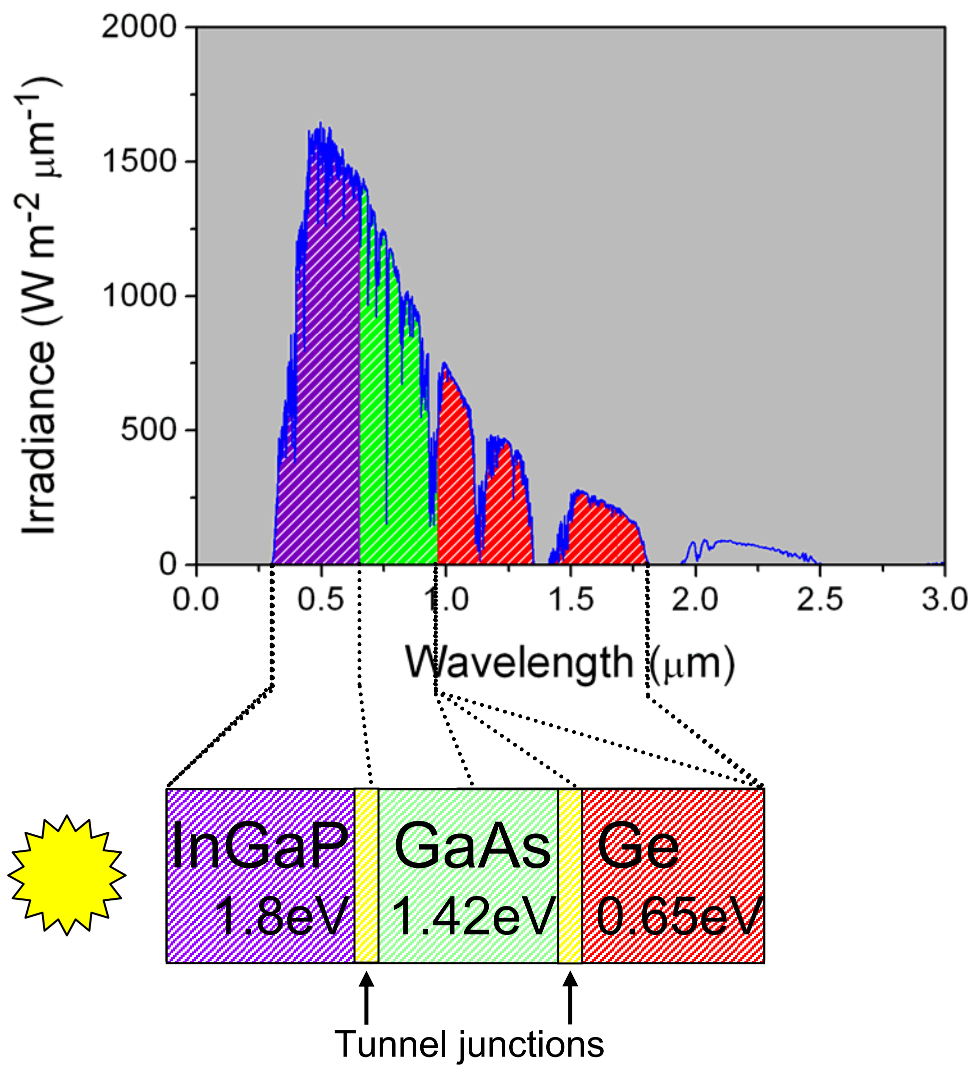
- “Standard” AlGaAs-GaAs HEMT for reference.
  - Bench-marks unintentional impurity concentration in GaAs and roughness of 2-DEG interface
- 53% InGaAs channel metamorphic HEMT.
  - Includes buffer layer with graded In-composition and InGaAs-InAlAs superlattice
- Standard GaAs-AlGaAs solar cell.
- InGaAs quantum dot stacks (1100-1300nm laser-type structure).

PL at 11 K from InGaAs QDs grown on Ge



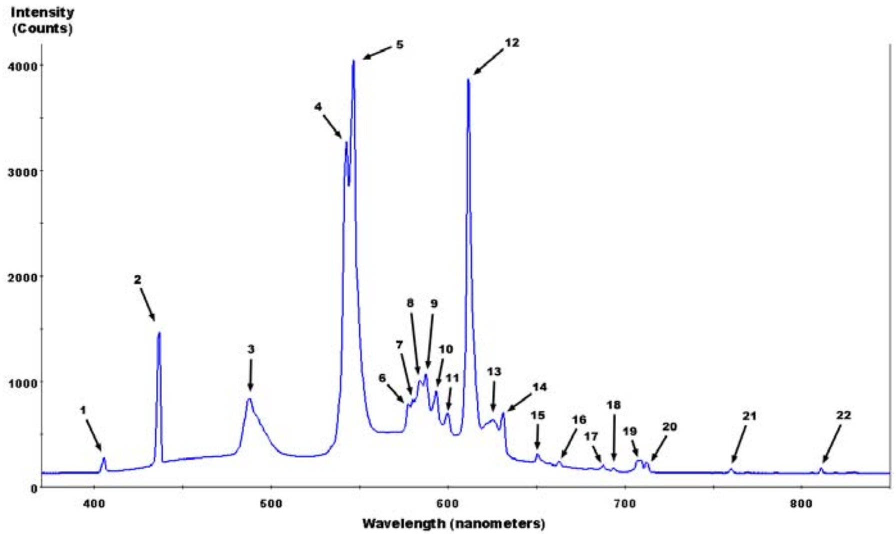
4 uncoupled layers of $In_{0.45}Ga_{0.55}As$ quantum dots

Multi-junction solar cells for terrestrial power

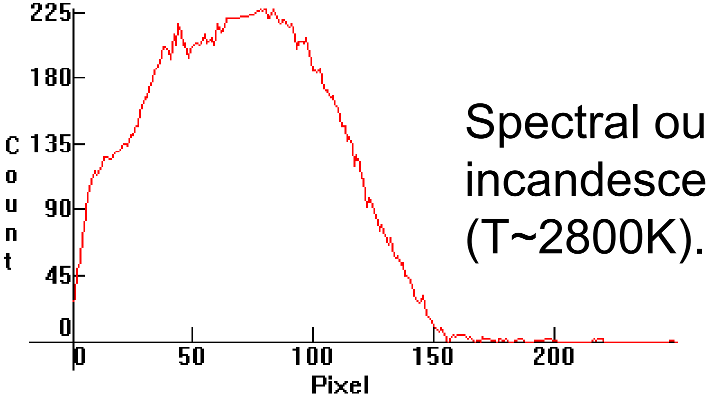


- Increase utilization of solar spectrum/reduce energy lost from thermalization of free carriers
  - Use a range of semiconductors to absorb segments of spectrum.
- PV cells connected in series
  - higher V_{oc} than single junction
  - reduced short circuit current, I_{sc}.
- Major difficulties;
  - tunnel junctions to interconnect cells.
  - careful design to ensure each cell generates the same current.
  - **sensitive to irradiance**

Spectral output of artificial light sources



A typical "cool white" fluorescent lamp utilizing two rare earth doped phosphors, Tb^{3+}, Ce^{3+}:$LaPO_4$ for green and blue emission and Eu:Y_2O_3 for red. Several of the spectral peaks are directly generated from the mercury discharge.



← Increasing wavelength

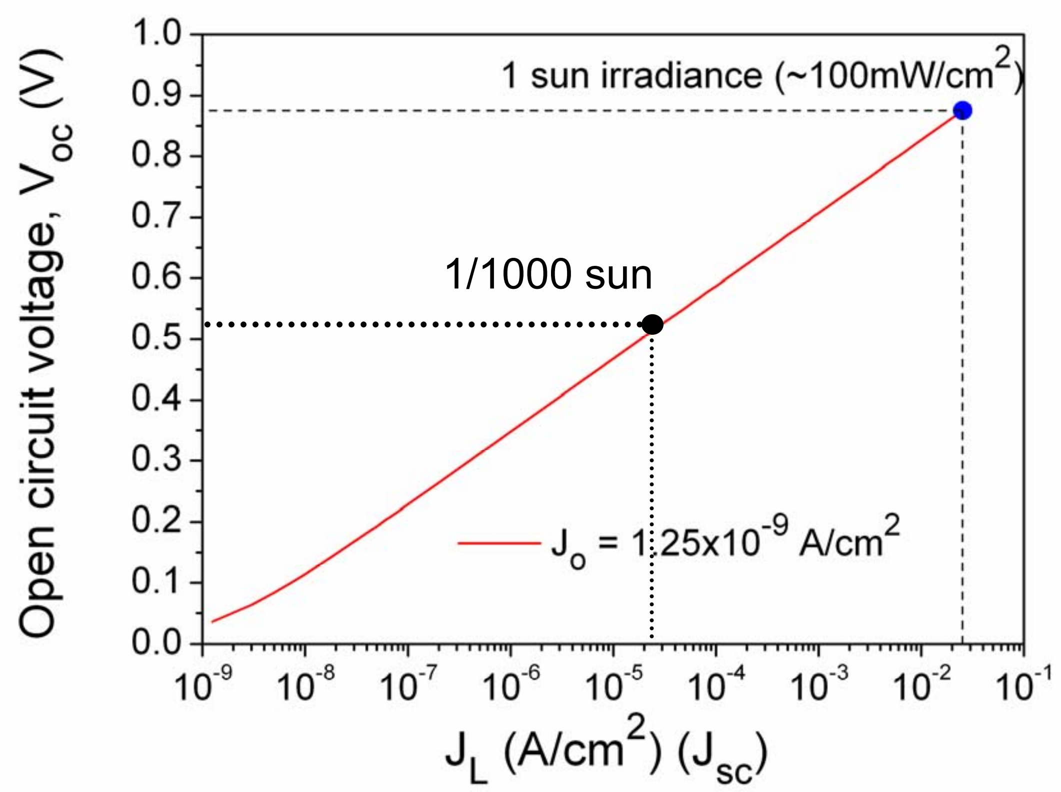
Spectral output of an incandescent light bulb (T~2800K).

Output truncated above ~1000nm due to response of Si detector

Photovoltaic cells for energy-neutral systems

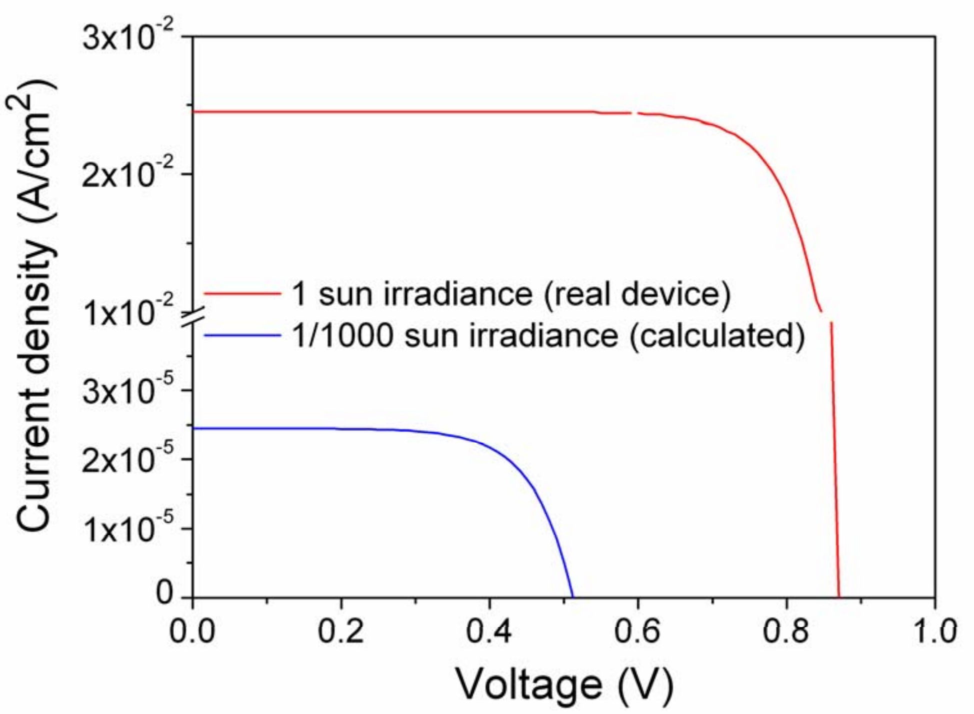
- Spectrum of artificial illumination important.
- Cells needs to be designed around the source for maximum power out.
- Single (Al)GaAs p-n junction might be the simplest implementation
  - Practical conversion efficiency ~25%, compared with ~40% for triple-junction terrestrial cells under concentrated sunlight
  - Max. open circuit voltage, V_{oc} of ~1.0 V, but this depends on the current created by illumination (I_L)
  - Short circuit current (max I), $I_{sc} = -I_L$

Photovoltaic cells – V_{oc} considerations



$$\boxed{V_{oc} = \frac{nk_BT}{q}\ell n\left[\frac{I_L}{I_o}+1\right]}$$

Photovoltaic cells – effect of irradiance



- These curves are based on 1 sun irradiance.
- I_{sc} scales with linearly irradiance.
- The output under illumination with artificial light will depend on the spectral content of the source.

Under 1/1000 sun illumination, the voltage at maximum output power is ~0.4V, with a current ~20 μA/cm^2

Configuration of PV cells

- Connect cells in series to achieve output voltage.
  - Wider band-gap PV cell for fluorescent lights? Higher V_{oc}
- Connect strings of series-connected cells in parallel, to achieve desired output current.
- V~4-4.2 volts with I~10-20 μA can potentially be generated by an 10x10 array of single junction GaAs PV cells covering an area of ~1cm^2.