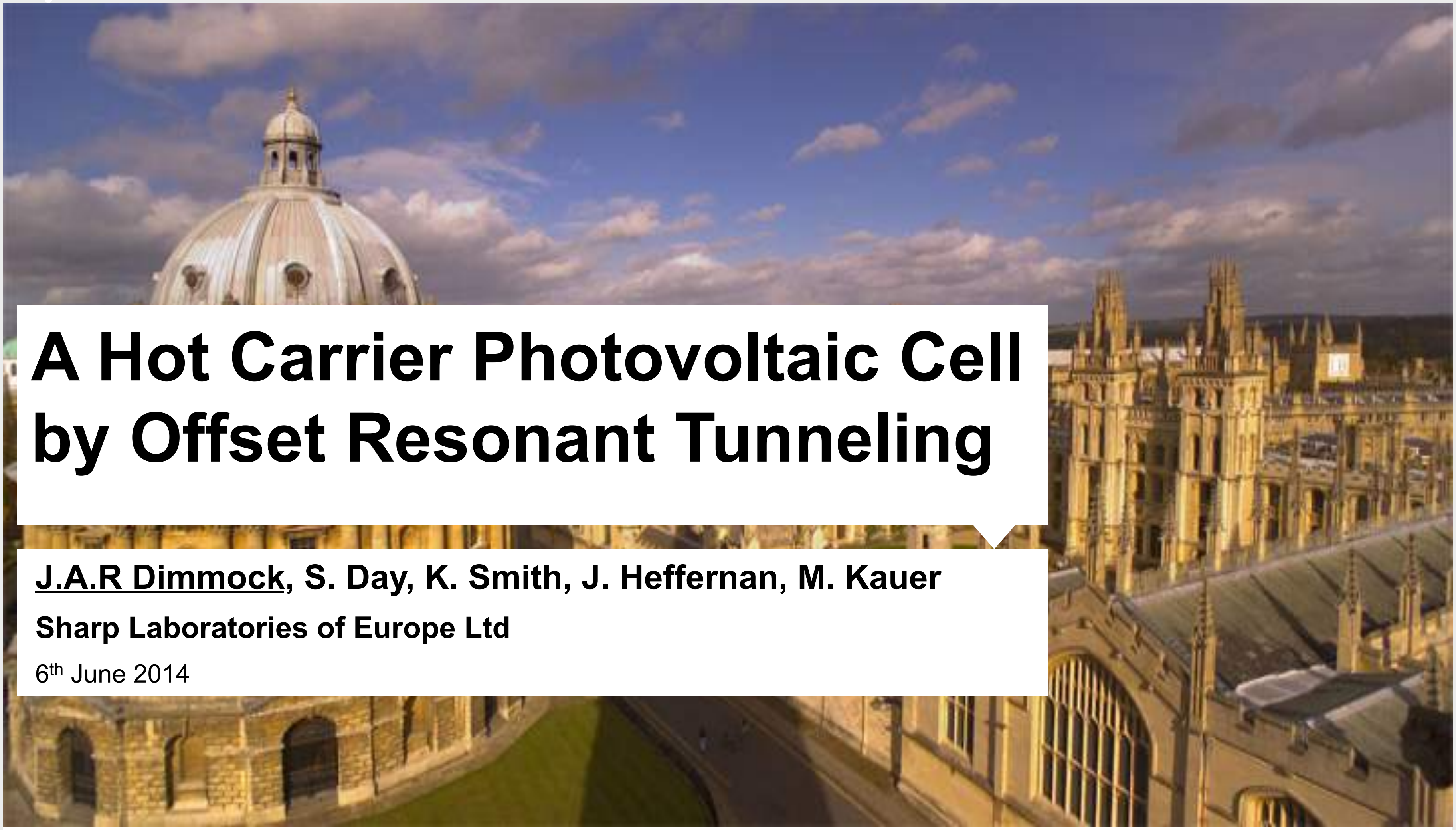
A Hot Carrier Photovoltaic Cell by Offset Resonant Tunneling



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Sharp Laboratories of Europe Ltd

6th June 2014

Oklahoma

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Talk Outline

- Who I am and who are Sharp?
- What motivates us to look at Hot Carrier cells?
- What progress have we made?
- What next?

About Sharp Corporation

Consumer/Information Products

Audio-Visual and Communication Equipment

Main Products
LCD color televisions, color televisions, projectors, DVD recorders, Blu-ray Disc recorders, Blu-ray Disc players, mobile phones, mobile communications handsets, electronic dictionaries, calculators, facsimiles, telephones

Health and Environmental Equipment

Main Products
Refrigerators, superheated steam ovens, microwave ovens, air conditioners, washing machines, vacuum cleaners, air purifiers, dehumidifiers, humidifiers, electric heaters, small cooking appliances, beauty appliances, Plasmacluster Ion generators, LED lights, solar-powered LED lights, network control units

Information Equipment

Main Products
POS systems, handy data terminals, electronic cash registers, information displays, digital MFPs (multi-function printers), options and consumables, software, FA equipment, ultrasonic cleaners

Electronic Components

LCDs

Main Products
TFT LCD modules, Duty LCD modules, System LCD modules

Solar Cells

Main Products
Crystalline solar cells, thin-film solar cells

Other Electronic Devices

Main Products
CCD/CMOS imagers, LSIs for LCDs, microprocessors, flash memory, analog ICs, components for satellite broadcasting, terrestrial digital tuners, RF modules, network components, laser diodes, LEDs, optical pickups, optical sensors, components for optical communications, regulators, switching power supplies

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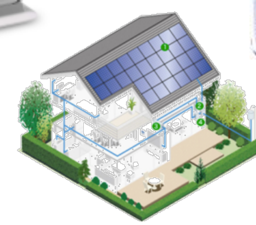
About Sharp Labs Europe

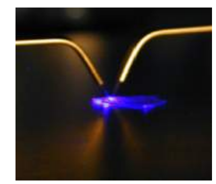
History and Mission

- Established in 1990 and was the first overseas R&D base of Sharp Corporation

- To provide SHARP Corporation with unique technologies and capabilities which match customer needs in order to create new business opportunities

- SLE is actively pursuing Global technology platforms and Local Fit (Europe-Middle-Africa) opportunities.





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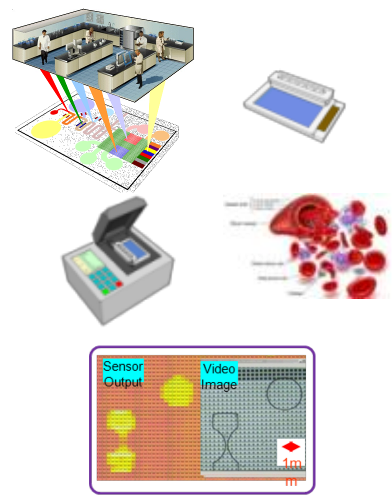
SLE's main R&D themes

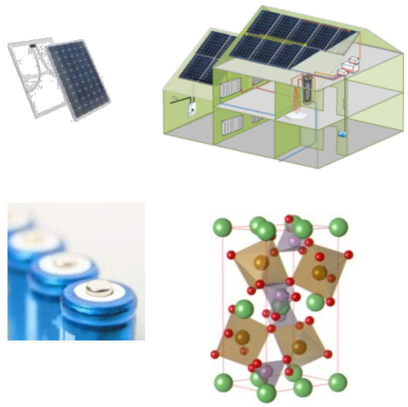
Health & Medical



Technologies to address health care challenges

•Point of care systems
•Sensors and detectors
•Imaging and diagnosis

Energy & Environment



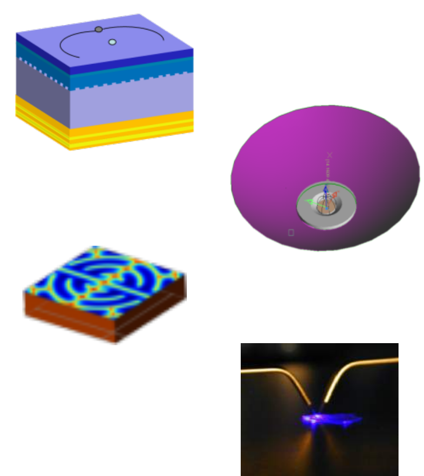
Energy solutions & materials beyond solar panels

Technologies for environmental issues related to water, food, air

Displays & Embedded Systems

Building next generation technology in display systems

System Devices & Modules



Semiconductor based systems and devices

• LEDs and Lighting
• Power electronics
• Ultraviolet light
• Sensors and Systems

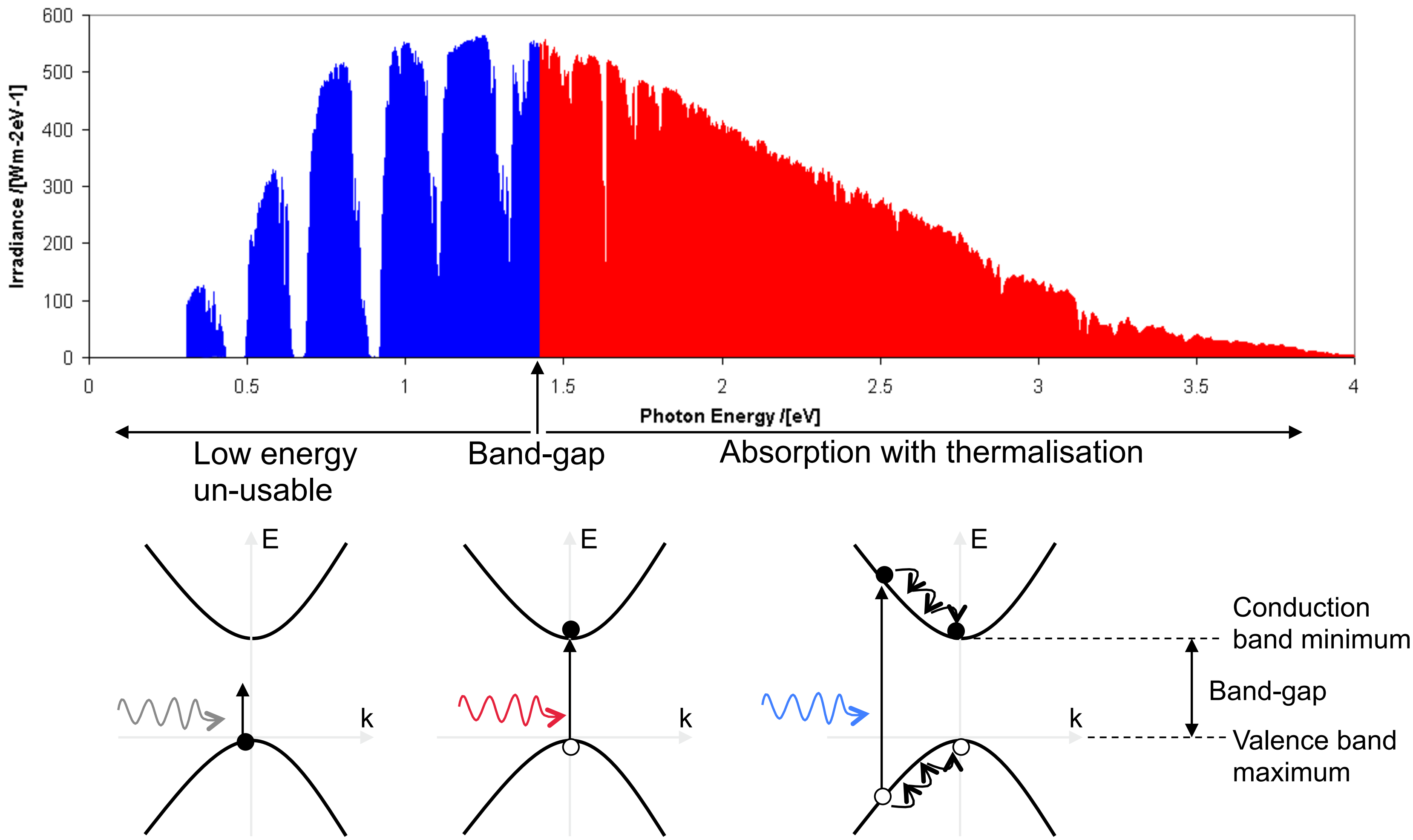
SLE's role in Sharp

"To provide Sharp Corporation with unique technologies and capabilities which match customer needs in order to create new business opportunities."

- SLE has a good track record in bringing major technology platforms to market, with Sharp partners.
- SLE is actively pursuing Global technology platforms and Local Fit opportunities in Energy & Environment, Health & Medical, Displays and System Devices & Modules.
- SLE is actively pursuing Open Innovation to leverage European expertise, reduce capital need, grow market opportunity and shorten time to market.

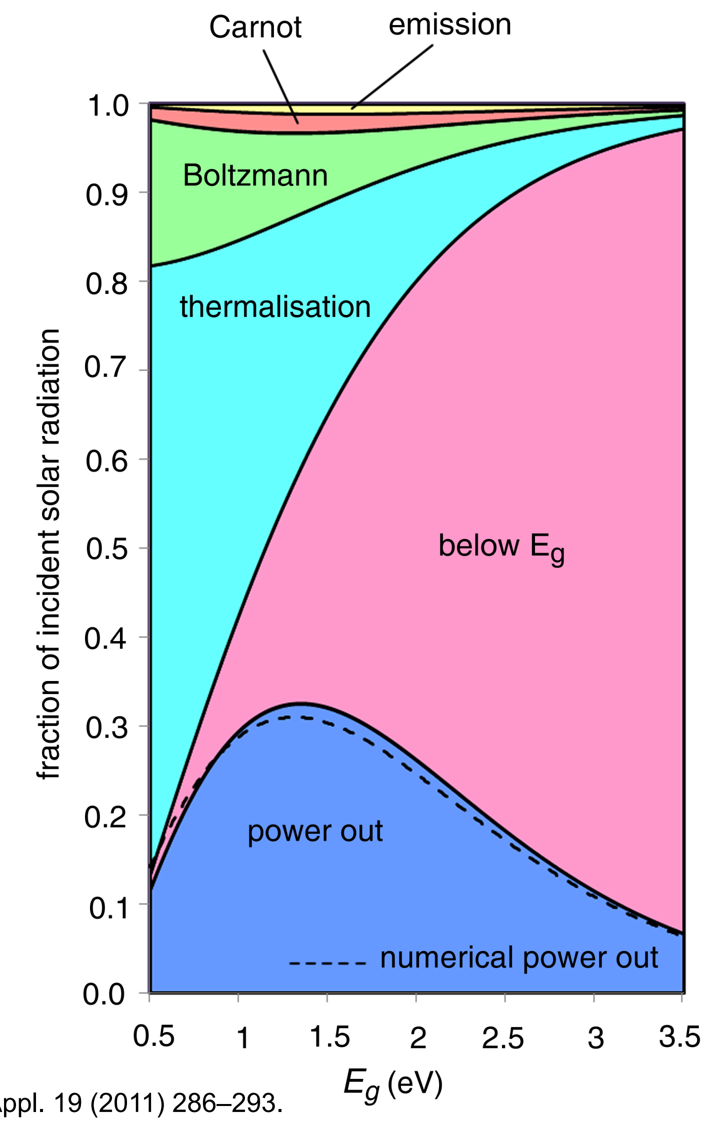
The limitations of First Generation PV

- Largest efficiency losses for a solar cell are spectral: 1.Inability to use photons with energy lower than its band gap 2.Thermalisation losses, when it absorbs photons with energy in excess of its band gap.



The limitations of First Generation PV

- First generation photovoltaics fundamentally limited to ~31% at 1 sun due to a variety of loss mechanisms
- Hirst-Ekins-Daukes Plot*
- 30% of loss at the maximum power point attributed to thermalization losses
- Two options:
  1. Minimise initial excess energy generation by light (multi-junction, intermediate band…)
  2. Use excess energy to drive other processes (multiple excitons, hot carrier solar cell…)



* L.C. Hirst, N.J. Ekins-Daukes, Fundamental losses in solar cells, Prog. Photovolt. Res. Appl. 19 (2011) 286–293.

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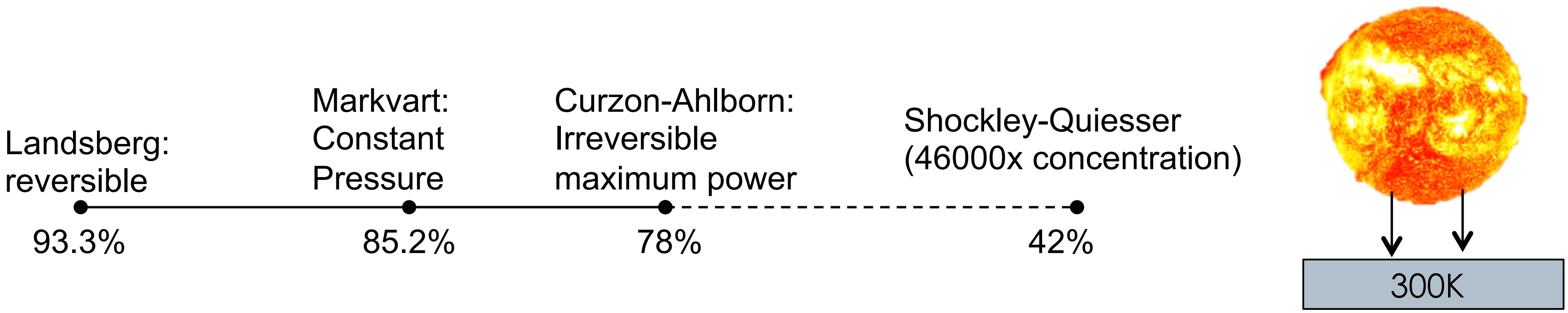
The Solar cell as a heat engine

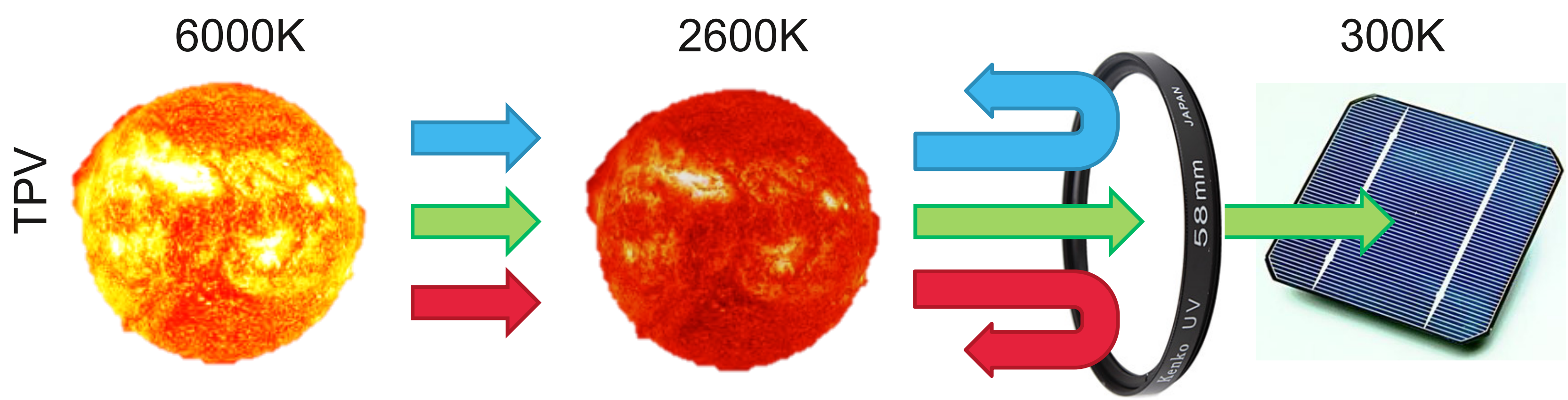
- Purpose of all solar driven heat engines (Photovoltaic and photothermal) is to do useful work with a temperature gradient: namely Sun→Earth
- By exploiting this temperature gradient directly we can achieve significantly higher efficiency than the Shockley-Quiesser limit
- Problem of limiting efficiency has been tackled many times, coming up with efficiency limits spanning 93.3%→78% depending on the nature of the process

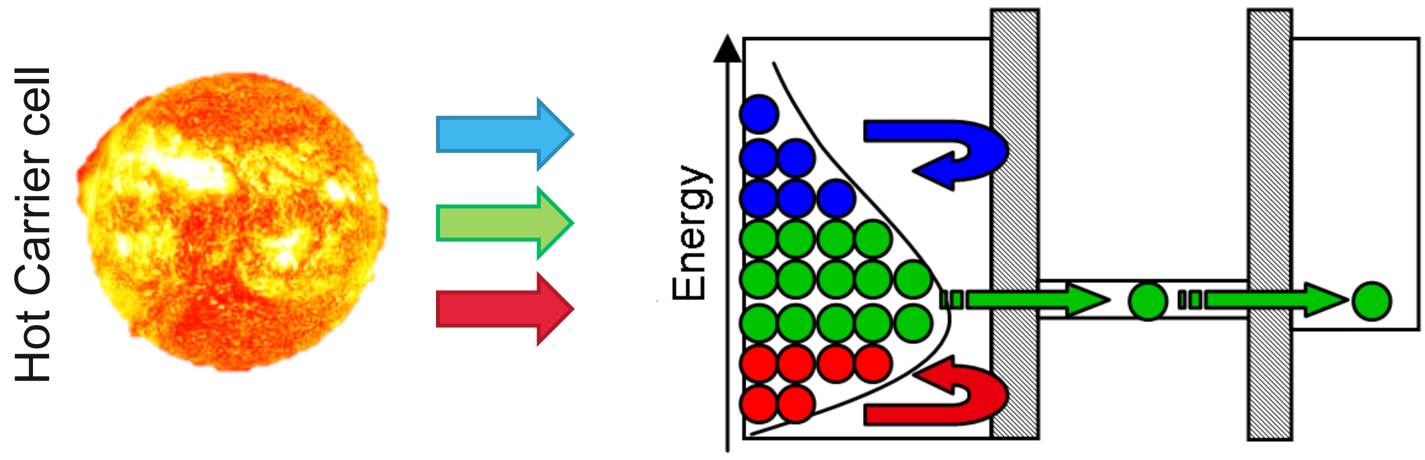


- Problem in realizing these efficiencies is in keeping one side of your heat engine at a high temperature and the other side at a low temperature – otherwise we just end up with the Shockley-Quiesser efficiency.
- We show a new approach to this and a proof of concept device demonstrating a temperature gradient driven PV cell

Why Hot Carrier Cells?

- Similar principle to thermophotovoltaics (TPV) to overcome losses:

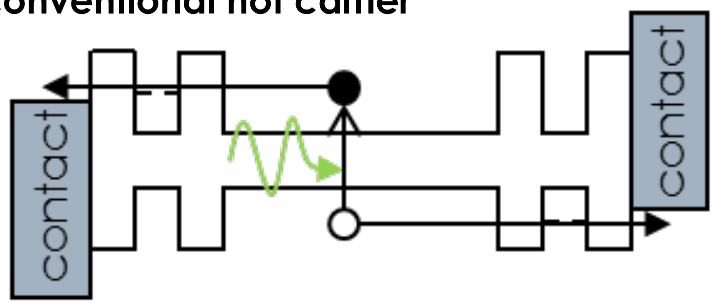




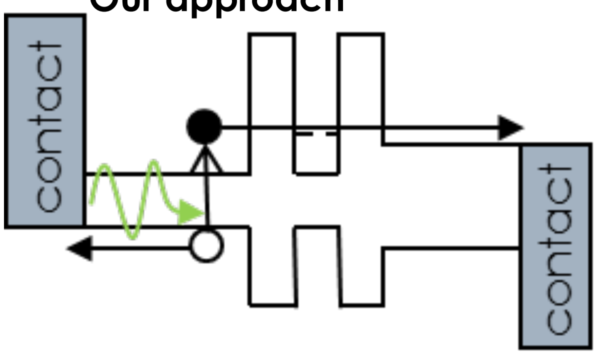
Hot Carrier Cells

- Hot carrier cells address the problem of thermalisation and high lattice temperature by decoupling temperature of electron distribution and the lattice
- P/N junction is not necessary – instead they are driven by temperature gradient between hot part and cold part of the cell
- So any hot carrier cell must meet two key criteria:
  1. Stop (or minimise) the loss of energy from photo-generated electrons to the lattice
  2. Keep photo-generated electrons at a different temperature to electrons in the rest of the cell while allowing them to be extracted

Conventional hot carrier

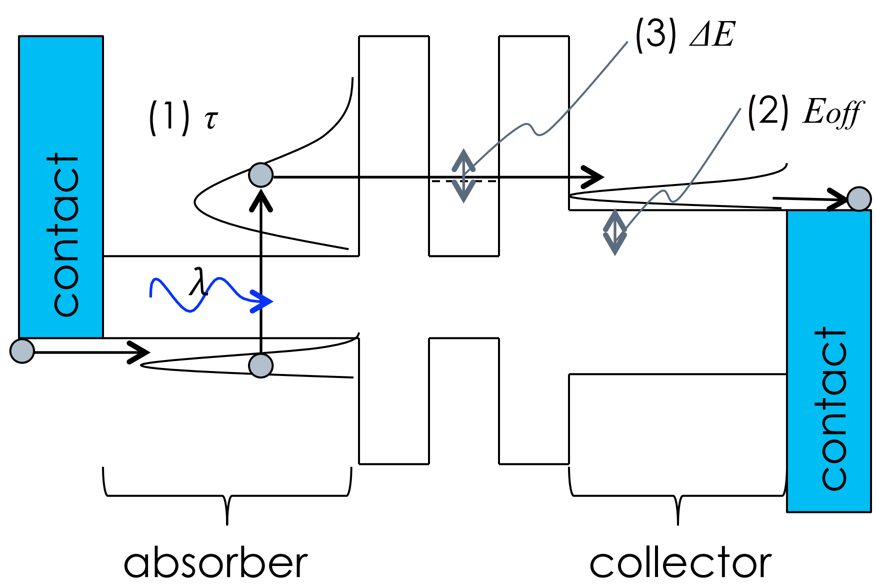


Our approach



Requirements of a Hot Carrier Cell

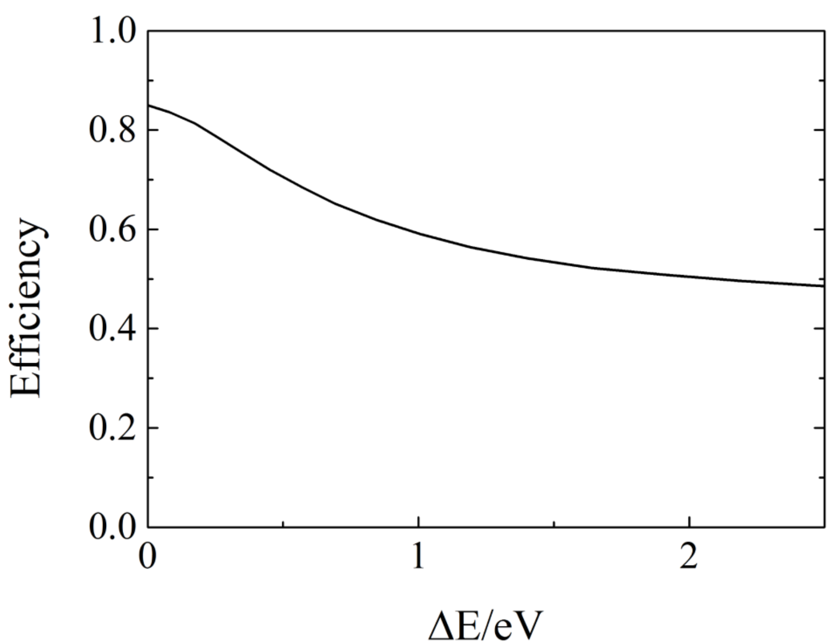
- How do we implement the two key criteria of a hot carrier solar cell?
- In three features:
  1. Slow Electron Cooling Rate
  2. Energy Offset
  3. Fast tunneling with Energy Filtering

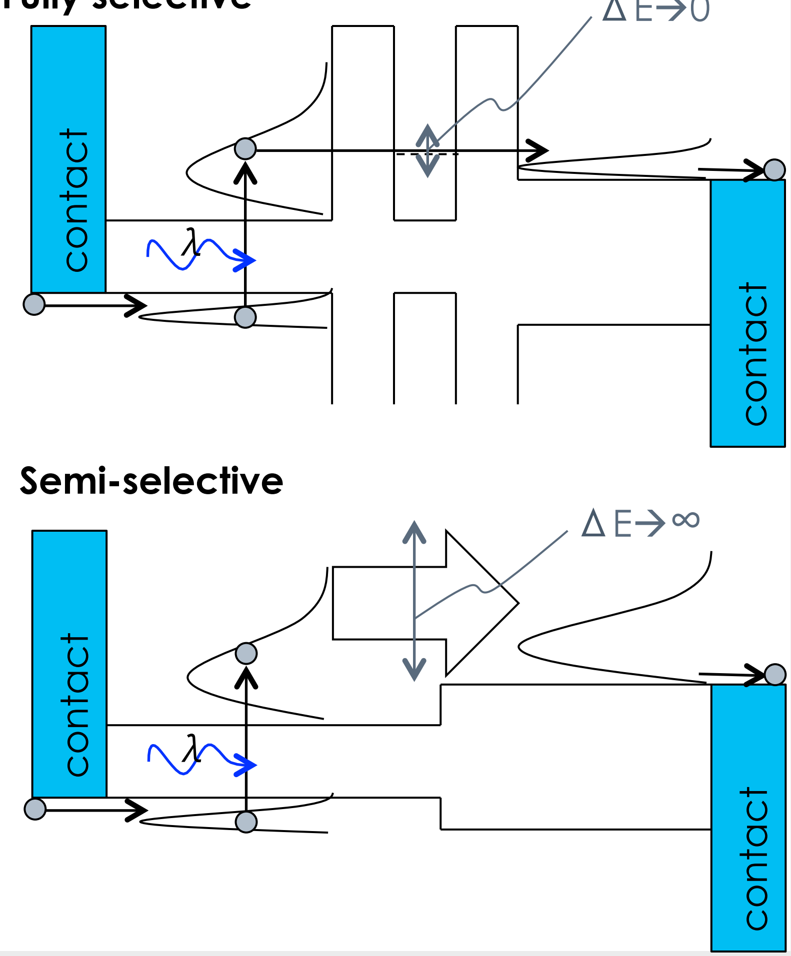


Why Do We Need Energy Selectivity?

- To prevent thermalization in the collector
- Reduces entropic loss of hot carriers from absorber thermalizing in cold collector

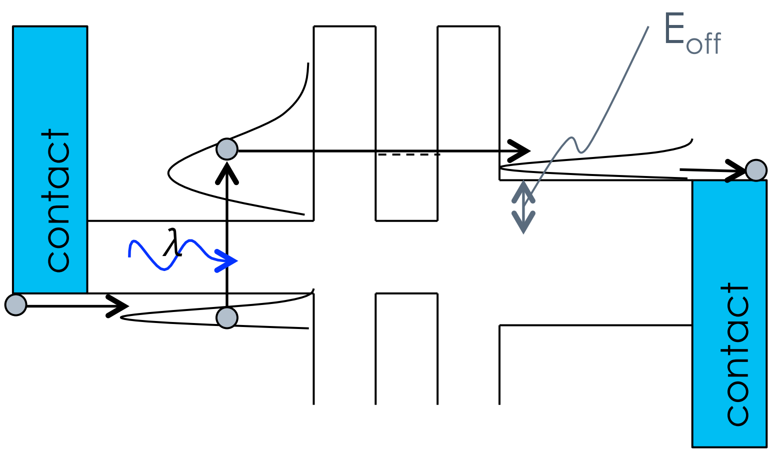
$$\dot{Q}_h = \frac{2N}{h}\int_{E_{off}}^{E_{off}+\Delta E} (E-\mu_h).(f_h(E) - f_c(E))dE$$

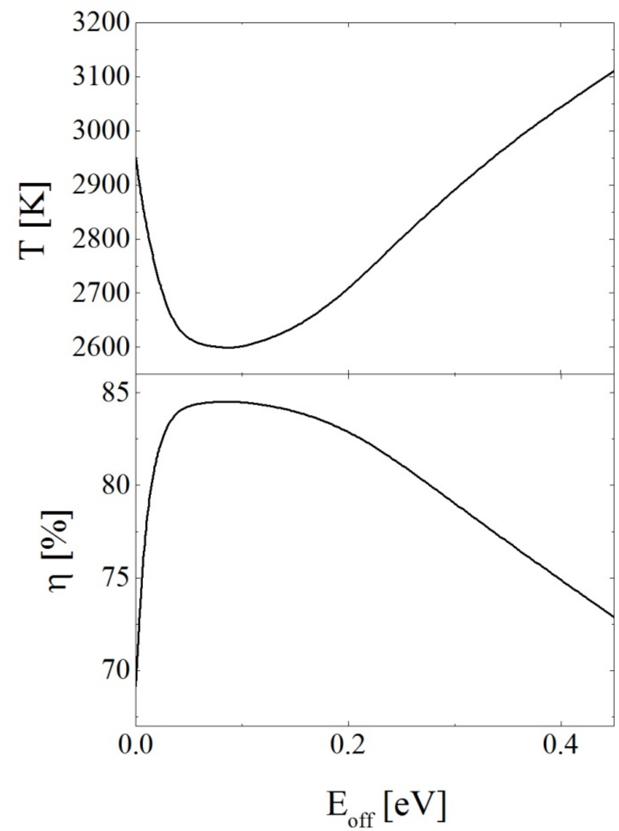




Why Do We Need an Offset?

- To prevent thermalization in the collector (again)
- Optimum offset acts to:
  1. Minimize width of energy selectivity
  2. Minimize temperature of electrons in absorber region

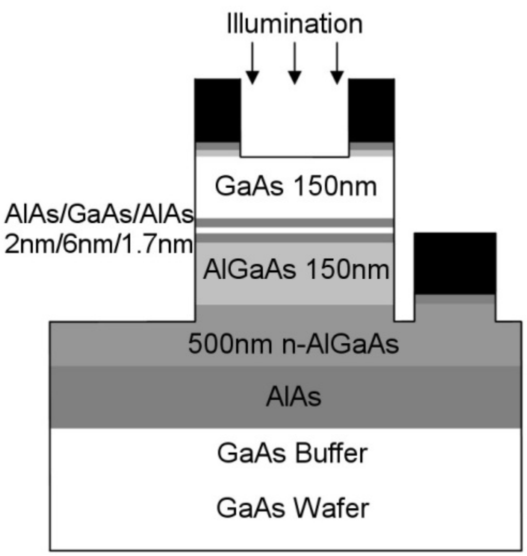


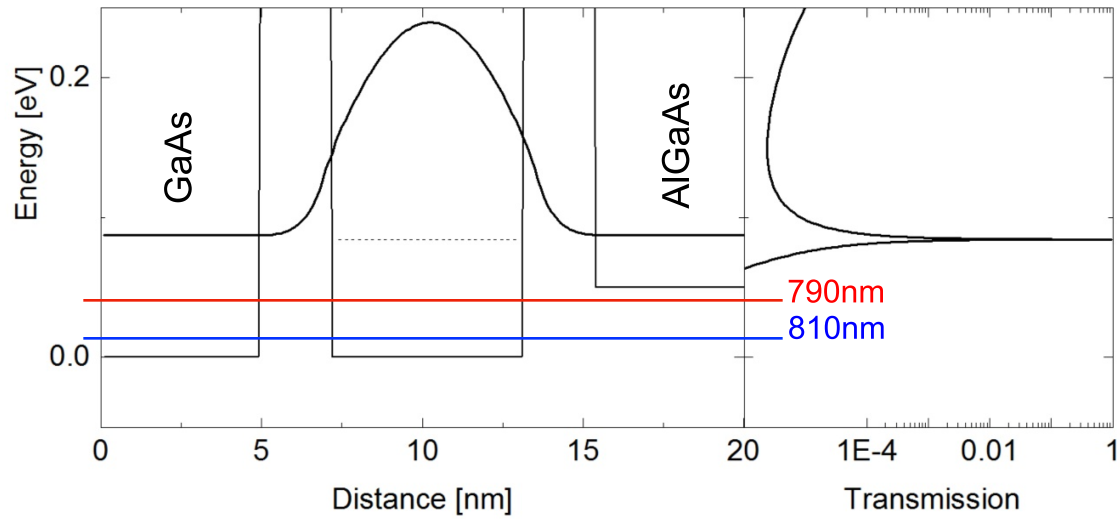


- N.B optimum operating temperature of the hot carrier cell same as optimum TPV

Device – the HOT Cell

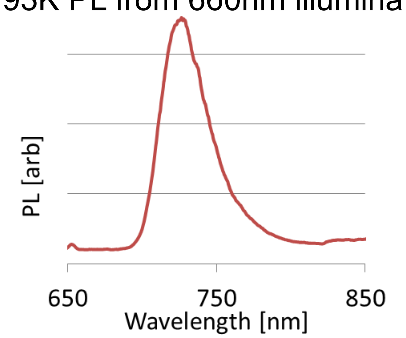
- Conduction band offset structure: Two undoped semiconductors (GaAs/AlGaAs) either side of a quantum well
- Device absorbs 790-810nm in the GaAs but not in AlGaAs or QW





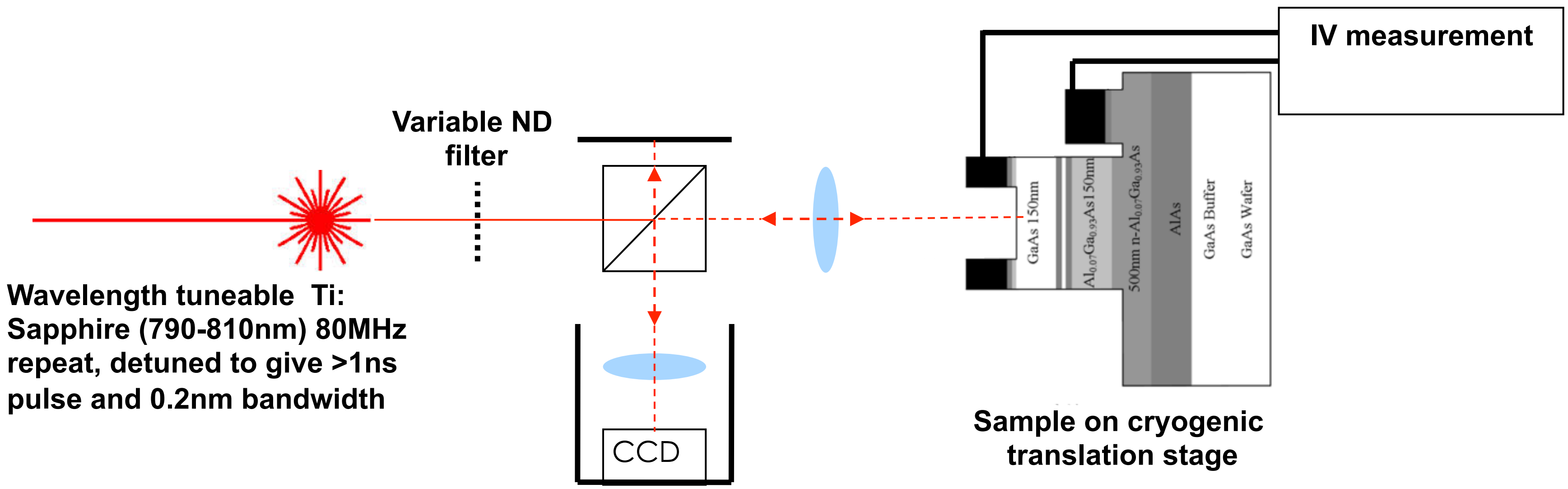
- Photoluminescence to confirm energy levels and a control structure to confirm no photocurrent from AlGaAs

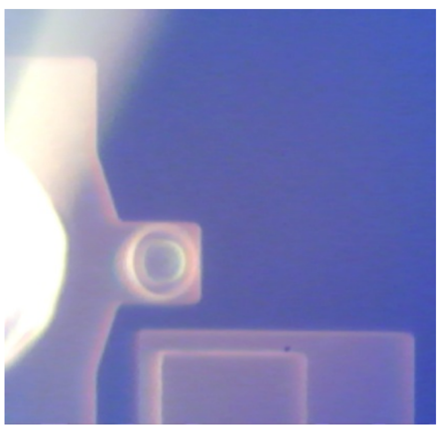
93K PL from 660nm illumination

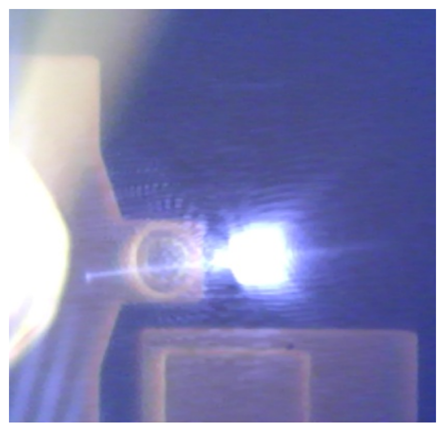


Experimental Setup

- Ti:Sapphire: wavelengths from 790nm-810nm, only exciting in the GaAs







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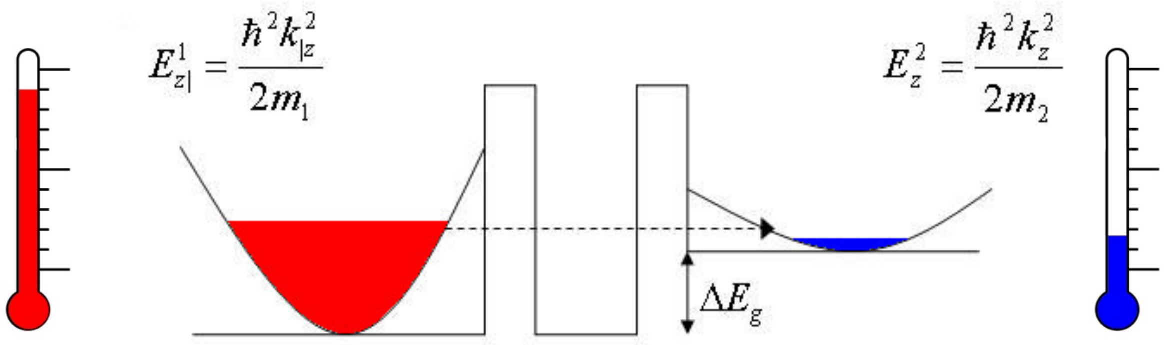
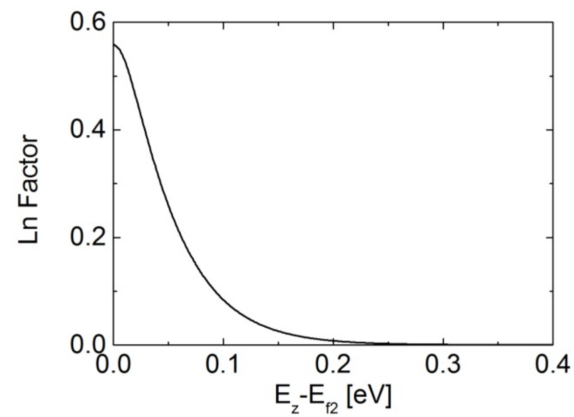
Theory of Offset Tunneling

- We have extended the theory of Esaki and Tsu* to calculate the current density from a narrow band gap material with a hot carrier distribution into a wider band gap material





The integrand as a function of electron energy in excess of Fermi energy for T1=477K, m1=0.063m0, T2=93K, m2=0.069m0, ΔEg=0.05eV at zero bias

$$J(V) = \frac{q}{4\pi^3}\int_0^\infty d^3k.v_z(k,E).T(E,V).\left[f_1^{Th}(k,E) - f_2^{Tc}(k,E-qV)\right]$$

$$J(V) \propto \int_0^\infty dE_z.T(E_z,V).\ln\left[F(E_z,T_h,T_c,V)\right]$$

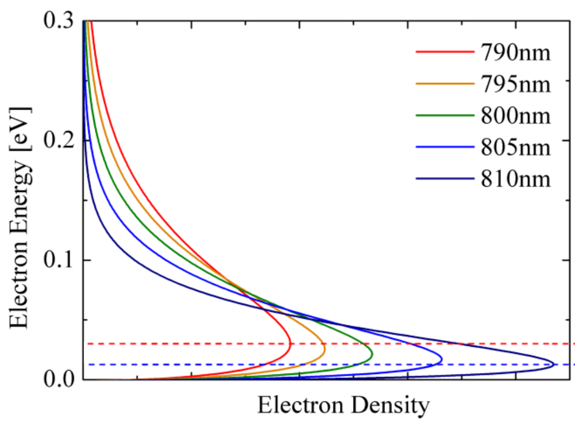
- The positive integrand for $T_h > T_c$ shows that there can be a tunnel current from the hotter distribution to the cooler one at zero bias

*Tsu R, Esaki L. Tunneling in a finite superlattice. Appl. Phys. Lett. 1973; 22: 562-564

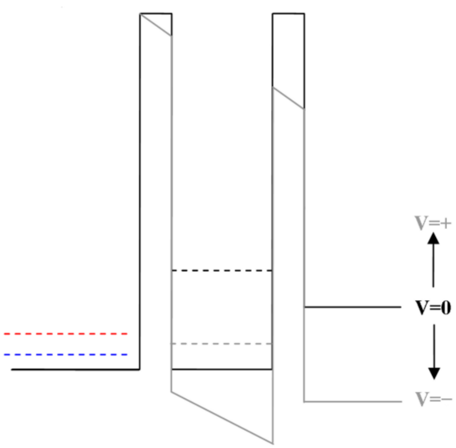
Outcome if Structure Extracts Hot Carriers

- From modelling the tunneling current 2 key features expected from the IV characteristics:
  1. Maximum power point shifts to higher voltage for shorter wavelength illumination (hotter electrons). [observed by Yagi* in symmetric structures]
  2. Decreasing peak to valley current ratio (PVR) with shorter illumination wavelength

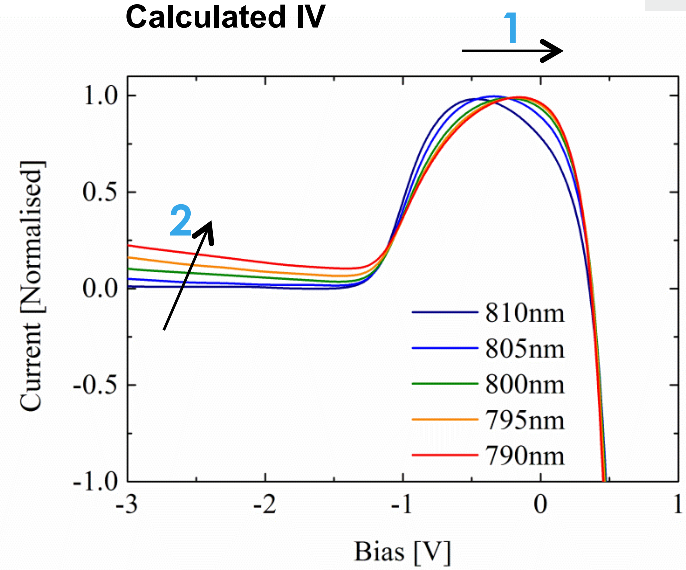
Electron density under illumination



Schematic band diagram



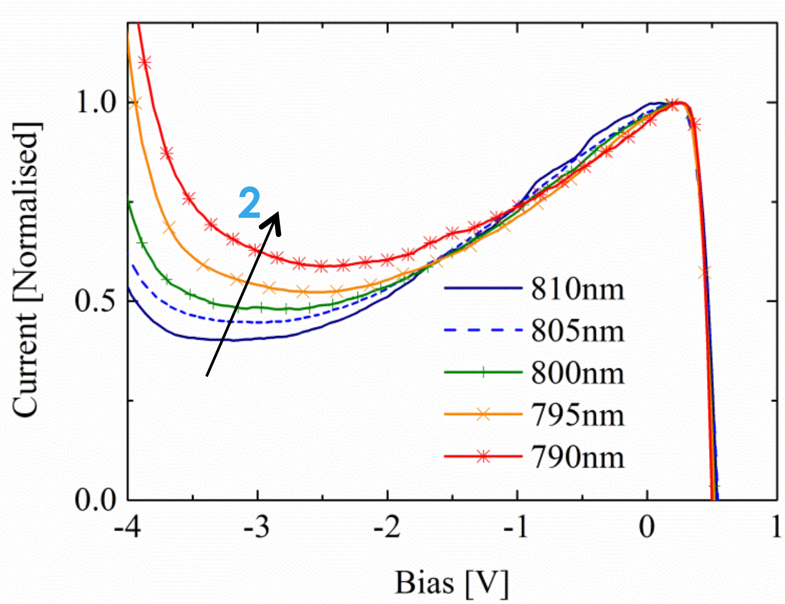
Calculated IV

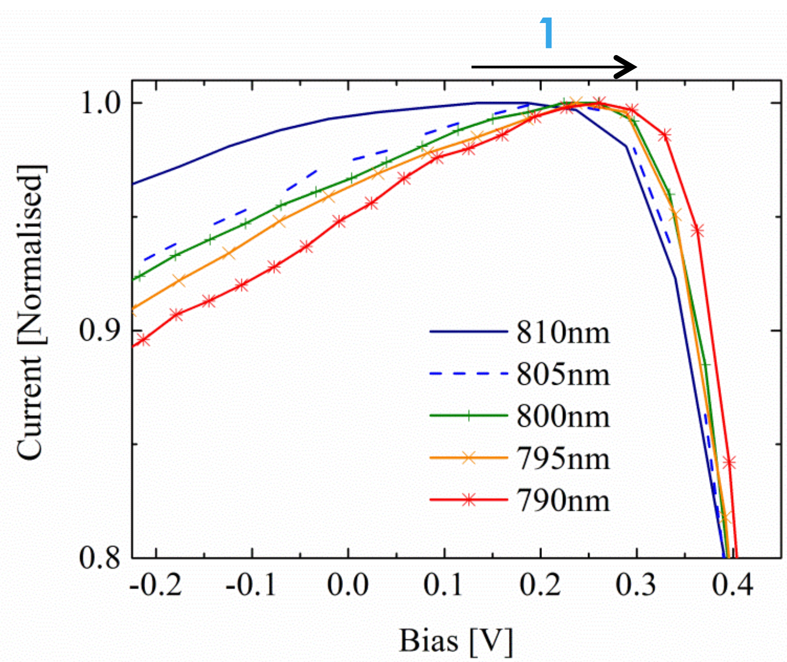


* Yagi S, Okada Y. Fabrication of resonant tunneling structures for selective energy contact of hot carrier solar cell based on III-V semiconductors. *Proceedings of the 35th IEEE Photovoltaic Specialists Conference 2010, Hawaii, USA*; 1213-1217

Observed Results

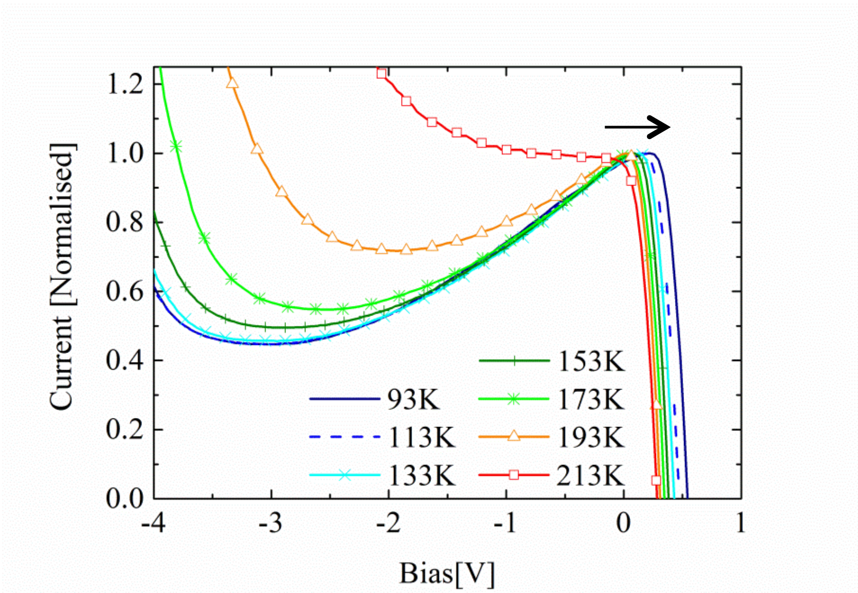
- Current at zero bias and forward bias demonstrating a photovoltaic response (Voc = 0.5V)
- Hot carrier extraction characteristics:
  1. 0.08V shift in current peak voltage
  2. PVR shift of 2.6→1.8 from illumination at 810→790nm

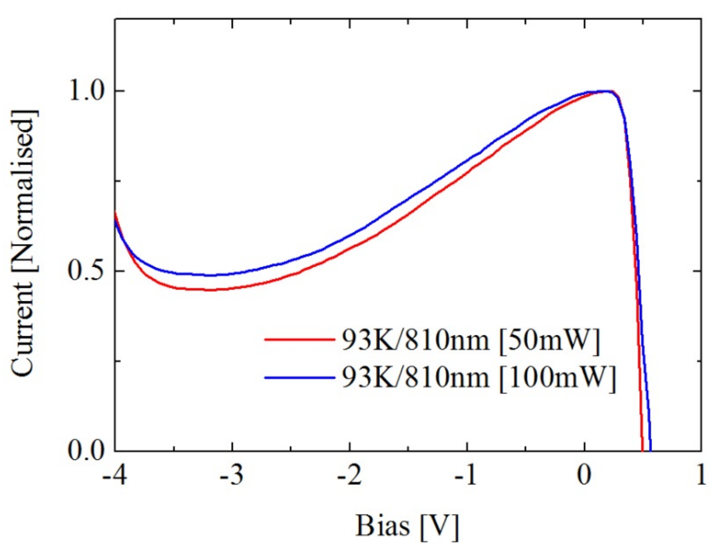




Observed Results - controls

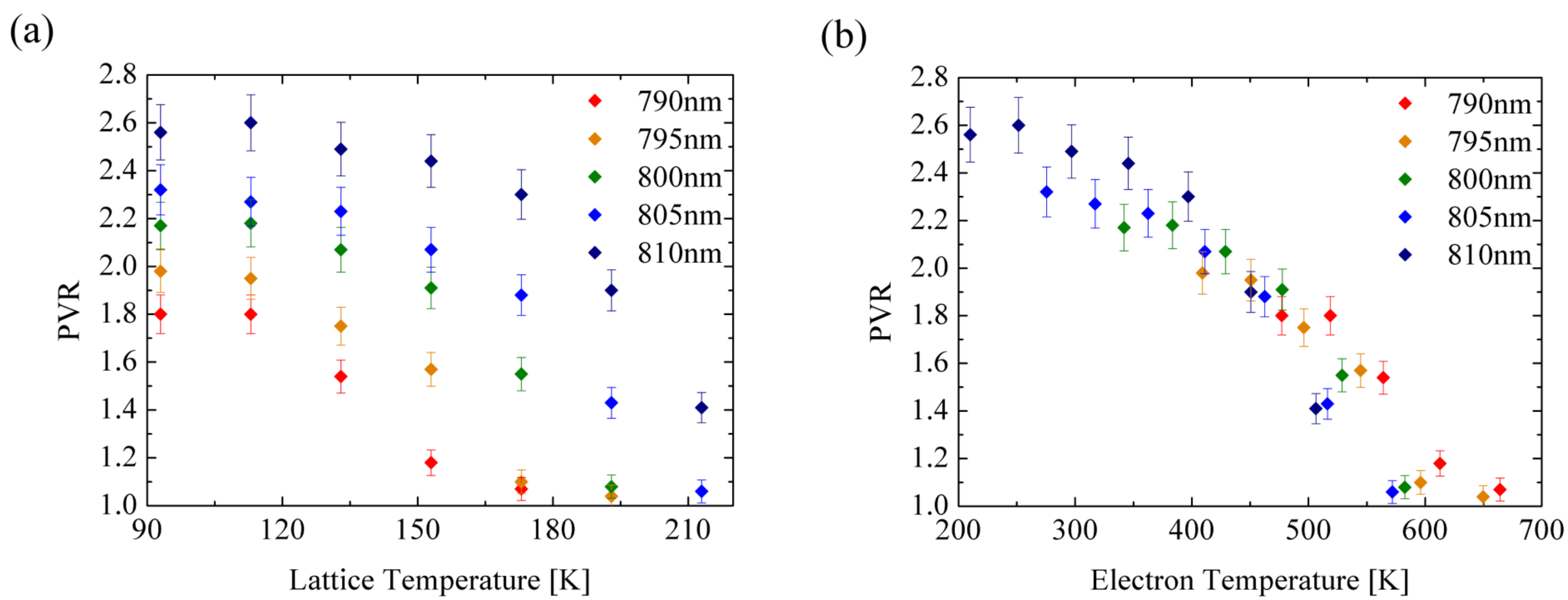
- Not a carrier density phenomenon – carrier density kept constant (to within ±5%)
  - If carrier density is doubled we do not see the large changes observed under wavelength changes (change in peak position is negligible and PVR only changes very slightly)
- Not a lattice heating phenomenon
  - Increasing lattice temperature causes shift in V_{mpp} to lower voltages (shift to higher voltages observed when increasing electron temperature)





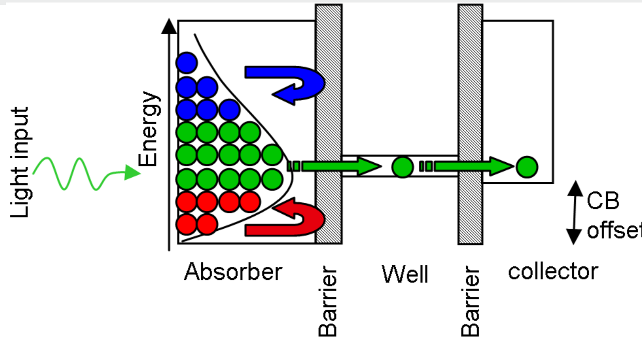
PVR Shift in Observed Results

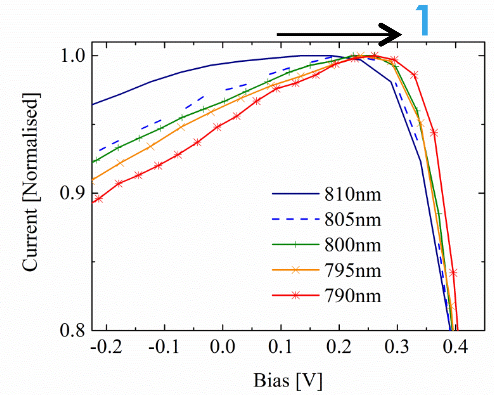
- PVR shift in observed results over all wavelengths and temperatures plotted as a function of measured lattice temperature and calculated electron temperature
- PVR is dependent on electron temperature, not lattice temperature → further evidence that tunneling is from a population of carriers which are not thermalized with the lattice

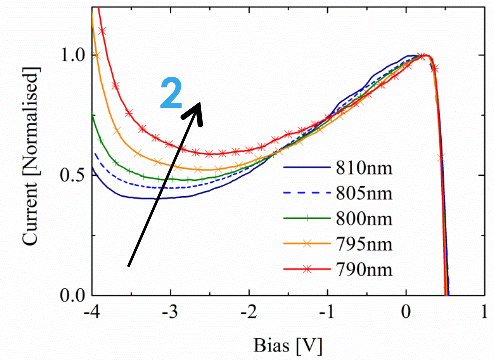


Conclusions

- Developed a hot carrier PV cell using offset tunneling between undoped semiconductors
- Shown a photovoltaic response under monochromatic illumination
- Demonstrated two wavelength dependent features in the IV consistent with hot carrier extraction:
  1. A shift in peak current voltage
  2. A reduction in peak to valley ratio
- Next steps, extend proof of concept device to:
  1. Higher operating temperatures
  2. Broadband illumination
  3. Improve absorption







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Acknowledgments

- Sharp Laboratories of Europe
- Royal Commission for the Exhibition of 1851
- T. Takamoto and K. Miyata, Solar Systems Group, Sharp Corporation
- N. J. Ekins-Daukes

Questions?

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