Progress in Hot Carrier Solar Cells

Martin Green, Gavin Conibeer, Santosh Shrestha, Dirk König, Nicholas Ekins Daukes, Eun-Chel Cho

ARC Photovoltaics Centre of Excellence
University of New South Wales, Sydney 2052 Australia
g.conibeer@unsw.edu.au

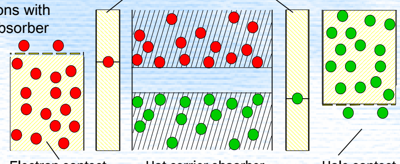
Concept of Hot Carrier cell [1,2]

Selective Energy Contacts

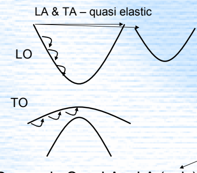
Carriers must be collected over narrow energy range:
- in conduction band for e^- and valence band for h^+;
- prevents loss of energy to cold carriers in contacts;
- minimises increase in entropy;

Replenishment of extracted energy by carrier-carrier scattering in hot carrier population.

Absorption of all solar photons with energies greater than the absorber threshold energy.
Collect carriers before they thermalise with lattice.
Requires:
Selective energy contacts
Slowing of carrier cooling



Hot Carrier cooling



Electrons carry most energy

Cool predominantly via small wave vector **optical** phonon emission - timescale of ps inelastic – energy relaxation

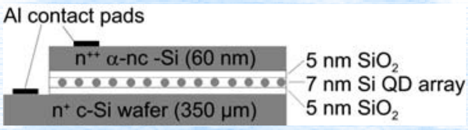
Hot Optical phonon population
"phonon bottleneck effect"

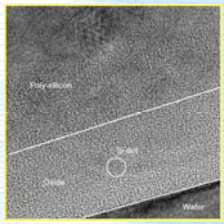
Decay via O → LA + LA (only)

Slows further carrier cooling

Selective Energy Contacts

Sample structure

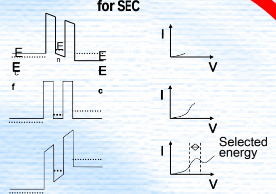




TEM showing the Si QD layer

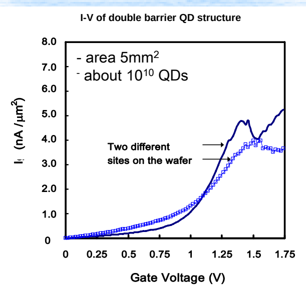
- Layers deposited by RF-sputtering
- On annealing at 1100°C- The Si rich layer (middle layer) crystallises to Si QD in a matrix of SiO_2

NDR using resonant tunnelling for SEC



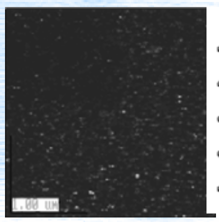
- Double barrier resonant tunnelling in a single layer QD structure used for SEC
- QD not QW required to give *Total* energy selection

I-V [3]

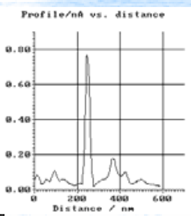


NDR at 300K- indicates SEC
To improve quality of peak need smaller area.

Conductive AFM [4]

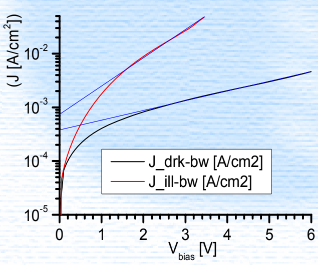


Current map over 10μm² - white dots are areas of higher conduction



The current profile at 10V across 2 spots

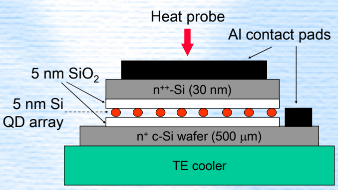
Optically assisted I-V [5]



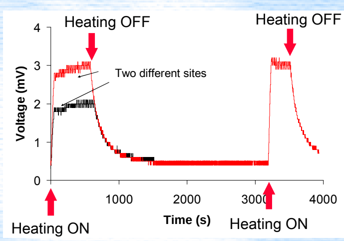
Dark and light I-V

Light I-V gives larger current- carriers excited to SEC level
Tentative evidence for resonance at ~ 3.5V for dark and ~ 2.1V under illumination- collection of hot carriers at lower bias with optical assistance.

Thermal characterisation

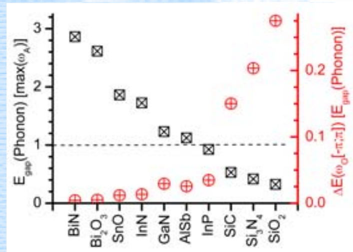


Sample structure

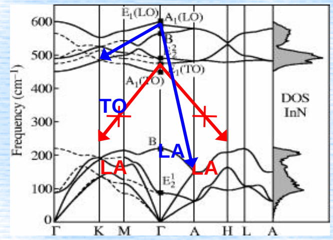


Thermoelectric voltage generation- evidence of tunnelling through QD structure

Phononic band gaps in nanostructures

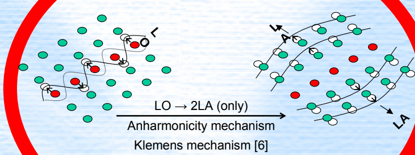


Phononic band gap ratios for binary compounds:
⊕ energy gap between acoustic and optical modes;
⊠ energy dispersion of optical modes.
Data normalised to max. acoustic phonon energy.

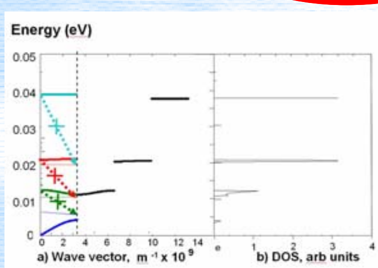


Phonon energy vs. momentum and DOS for InN from [7].
Klemens mechanism LO → 2LA is forbidden, because $E_{LO}>2E_{LA}$;
Ridley mechanism LO → TO+LA can occur, involves smaller energy loss [8].

LO phonon decay - selection rule



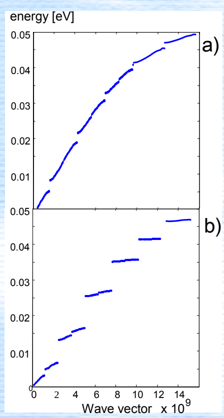
In addition to Energy and Momentum conservation, LO decay obeys this selection rule.
Hence reduction in available LA modes will reduce chances of LO decay

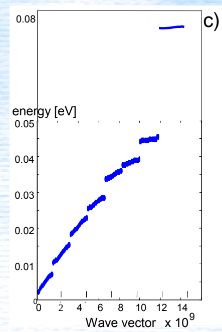


Acoustic phonon dispersion for 1D periodic structure (Linear chain model)
- Bi-layer periodicity of two.
- Ratio of acoustic impedances of seven.

Shows a folded dispersion with mini-gaps in all directions in real and reciprocal space.
DOS for a 3D structure with the phonon dispersion shown in (a).

Interface modes





Dispersion curves of acoustic phonons with:
a) intermediate; b) very soft;
c) very stiff; interface modes

References:
1. P. Würfel, Sol. Energy Mats. and Sol. Cells. 46 (1997) 43-47.
2. M.A. Green, Third Generation Photovoltaics (Springer-Verlag, 2003).
3. C-W. Jiang, et al., Proc. 19th Euro PVSEC (Paris, 2004) 80-83.
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5. D. König, et al. 21st Euro PVSEC (Dresden, 2006) 124.
6. P. Klemens, Phys Rev 148 (1966) 845
7. V. Davydov et al., Appl Phys Lett, 75 (1999) 3297.
8. J.W. Pomeroy et al., Appl. Phys. Lett. 86 (2005) 223501.

Conclusions

- Hot carrier cells require carrier collection over a narrow energy range;
- We are using resonant tunnelling through confined levels in Si QDs for this;
- I-V data, at room temperature, indicates energy selective NDR type behaviour;
- I-V of small areas under AFM gives tentative evidence for steps in current;
- Small resonance in the dark increases in magnitude but at lower bias in light; - further indication of creation of a non-equilibrium 'hot' carrier population;
- Further work will improve this resolution and combine C-AFM with optical I-V.

- Carriers cool by emission of phonons - restricting O to A decay can slow cooling.
- Binary compounds can have large band gaps between O and A modes,
  e.g. InN: gap larger than max. Acoustic energy – Klemens mode forbidden;
  Ridley mode allowed but this has lower energy loss.
- Folding of Brillouin zone in QD nanostructures gives gaps in phonon DOS.
- These can prevent Klemens decay if tuned correctly.
- Gaps are increased by either very soft or very stiff interface modes.
- A core shell QD nanostructure, with soft or ahrd shells, should slow cooling.

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