

Hot Carrier Solar Cells – structures for slowed carrier cooling

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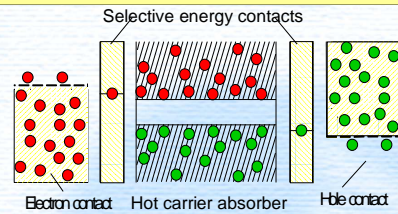
Hot Carrier cell requirements

- Absorption of all solar photons with energies greater than the absorber threshold energy.
- Collect carriers before they thermalise.

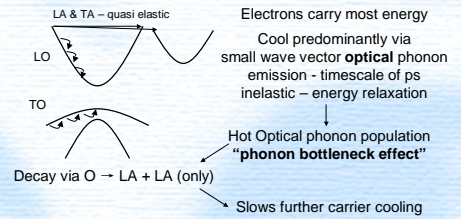
Requires:

- Selective energy contacts -
- Slowing of carrier cooling -

Concept of the Hot Carrier cell 1,2,1



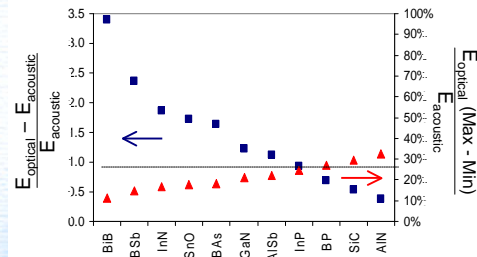
Hot Carrier cooling



Phononic band gaps in bulk materials

Simple force constant model derived from the equation of motion gives phonon frequency, ω , as:

$$\omega_{acoustic} = \sqrt{\frac{2T}{aM}} \quad \omega_{optical} = \sqrt{\frac{2T}{am}} \quad \text{and} \quad \sqrt{\frac{2T}{a} \left[\frac{1}{m} + \frac{1}{M} \right]}$$

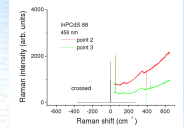


Acoustic max. and optical min. & max. phonon energies [M' (heavy), m' (light) atomic masses; T/a = force constant]

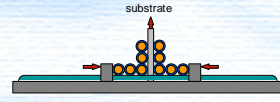
Deposition of nanocrystal superstructures

Langmuir-Blodgett deposition to fabricate ordered arrays of nanoparticles (NP)

- Initial work on Si & Au NPs of uniform size
- Functionalise to give close packing
- Langmuir-Blodgett deposition in layers
- Characterise periodicity
- Later work on NPs with $M_{QD} \gg m_{matrix}$



Raman spectra of InP/CdS NPs (crossed polarization) Displaying LO & TO modes

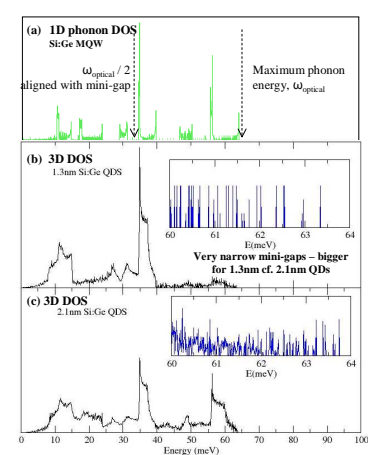


Langmuir-Blodgett deposition of a monolayer of encapsulated NPs

InP/CdS core-shell NPs:

1. Synthesis
2. Characterization
3. Test of phonon engineering concepts (Planned)

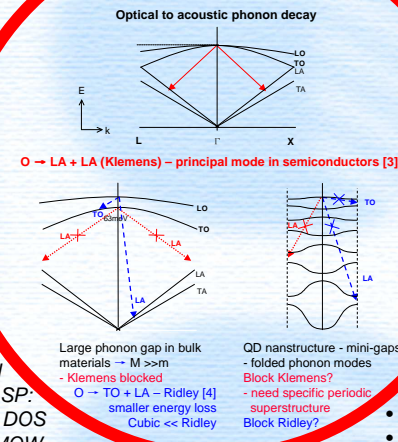
Phonon mini-gaps in nanostructures



Ab-initio model of Si:Ge by VASP:

- (a) 1D phonon DOS for Si:Ge MQW.
- 3D DOS for QD arrays, Si dots of (b) 1.3 nm and (c) 2.1 nm.
- Insets show detail over 60-64 meV, indicating very small mini-gaps in 3D.

Blocking Optical Phonon decay



Large phonon gap in bulk materials - $M \gg m$
 - Klemens blocked
 O -> TO + LA - Ridley [4]
 smaller energy loss
 Cubic << Ridley

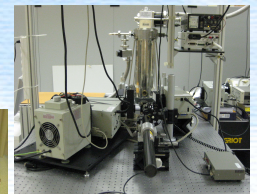
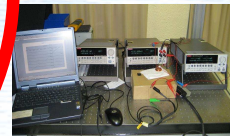
QD nanostructure - mini-gaps - folded phonon modes
 Block Klemens?
 - need specific periodic superstructure
 Block Ridley?

Characterisation for Hot Carrier Solar Cells

Four characterisation techniques for HCSC:

- Low temperature current-voltage
- Low temperature quantum efficiency (QE)
- Photoreflectance for band diagram analysis
- Time resolved PL - measure carrier cooling

Low temperature I-V high I and very low I

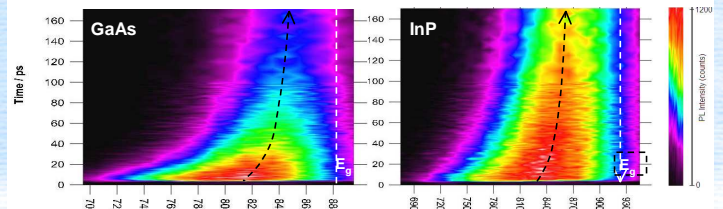


Low temperature QE adapted for the UV

Time resolved PL - results

- InP has large phonon band gap - should block Klemens decay
- GaAs has no phonon gap - but similar E_g

Time resolved PL spectra for bulk GaAs and InP
 730 nm excitation - carrier density - $8.5 \times 10^{19} \text{ cm}^{-3}$



- Peak intensities (black arrows) shift closer to the band gap (white lines) with time
- InP stays further above the band gap for longer times than GaAs
- Slower cooling in InP due to suppression of Klemens' decay

References:

1. P. Würfel, SOLMAT. 46 (1997) 43-47.
2. M.A. Green, Third Generation Photovoltaics (2003).
3. P. Klemens, Phys Rev 148 (1966) 845; 4. J.W. Pomeroy et al., AAPL. 86 (2005) 223501.

Conclusions

- Carriers cool by emission of phonons - restricting Optical to Acoustic phonon decay can slow cooling
- Binary semiconductors can have large band gaps between O and A modes, e.g. InP: phonon gap large enough to block Klemens decay - from TRPL
- Ridley mode allowed but this has lower energy loss
- Cubic materials restrict Ridley loss through narrow optical dispersion

- Folding of Brillouin zone in QD nanostructures gives gaps in phonon DOS
- These can prevent Klemens decay if tuned correctly
- Modelling in 1D and 3D - Group IV and hypothetical superlattices
- Complete gaps in reciprocal space can block Klemens decay
- Langmuir Blodgett deposition of ordered arrays of NP superstructures