Indium Nitride: A potential material for hot carrier solar cells?

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- **Current Limitations in Solar Cell Efficiency**
- **Nitrides in Solar: Next Generation PV**
- **Hot Carrier Solar Cells *and* InN**

ukNC
UK Nitrides Consortium

Seminar, July 14th, 2021

@SellersPVGroup

RENEWABLE ENERGY

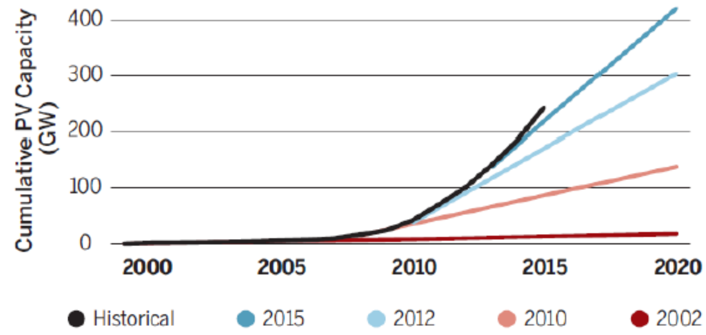
Terawatt-scale photovoltaics: Trajectories and challenges

Coordinating technology, policy, and business innovations

By **Nancy M. Haegel, Robert Margolis, Tonio Buonassisi, David Feldman, Armin Froitzheim, Raffi Garabedian, Martin Green, Stefan Glunz, Hans-Martin Henning, Burkhard Holder, Izumi Kaizuka, Benjamin Kroposki, Koji Matsubara, Shigeru Niki, Keiichiro Sakurai, Roland A. Schindler, William Tumas, Eicke R. Weber, Gregory Wilson, Michael Woodhouse, Sarah Kurtz**

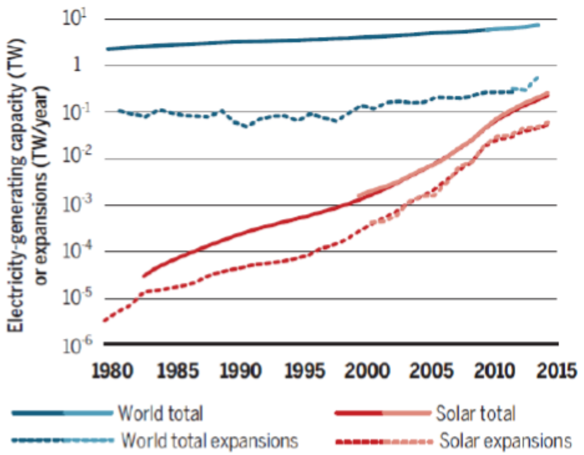
Cumulative PV installations

Projected (labeled by year of IEA publication) versus actual (labeled as "historical"). See supplementary materials for data sources and discussion.



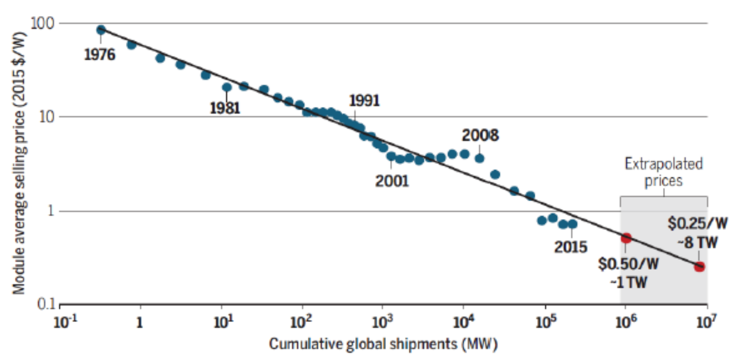
Global electricity-generating capacity

See supplementary materials for data sources.



PV module experience curve

Historically, module prices have decreased as a function of cumulative global shipments (blue dots reflect historical data, red dots reflect extrapolated prices for 1 TW and 8 TW based on the historical trend line). See supplementary materials for data sources.

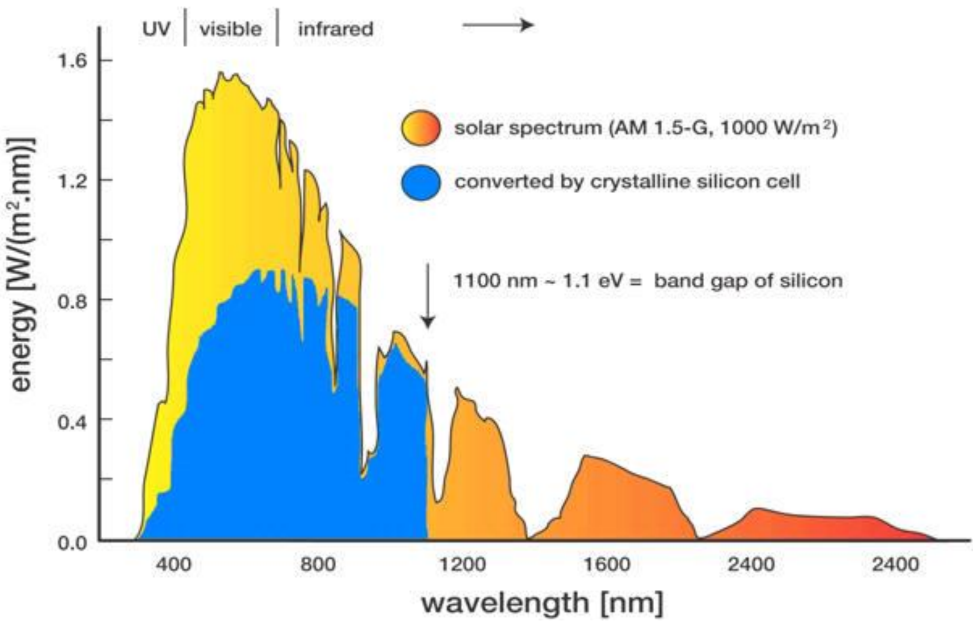


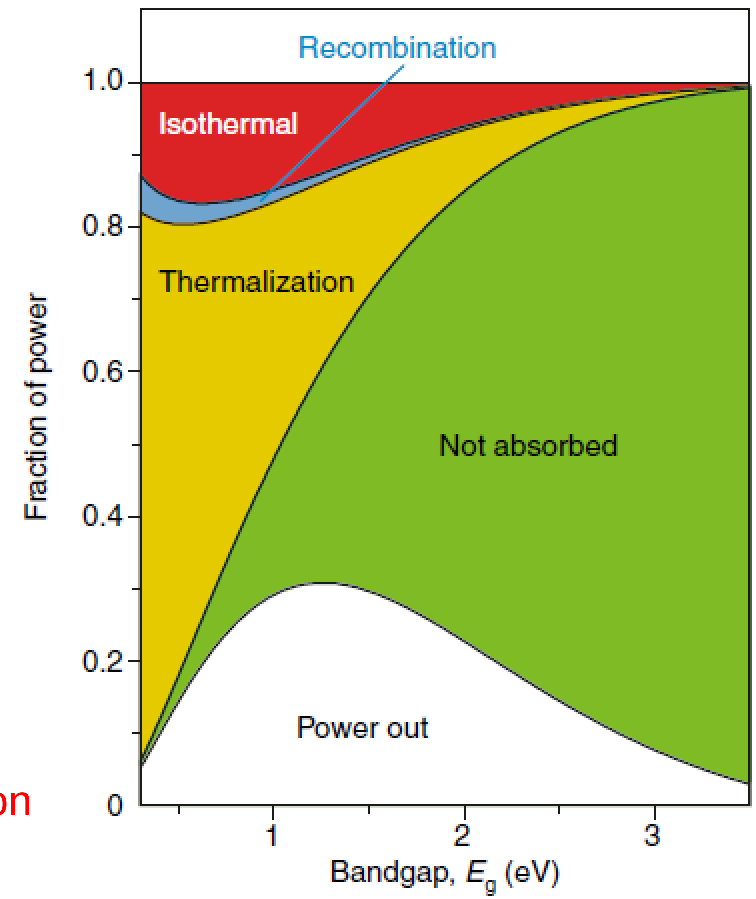
Science **356** (6334), 141-143.
DOI: 10.1126/science.aal1288

Photovoltaics Materials & Device Group, University of Oklahoma: http://www.nhn.ou.edu/~sellers/group/index.html

DoE SETO: "Net zero emissions no later 2050."

Fundamental Losses in Solar Cells



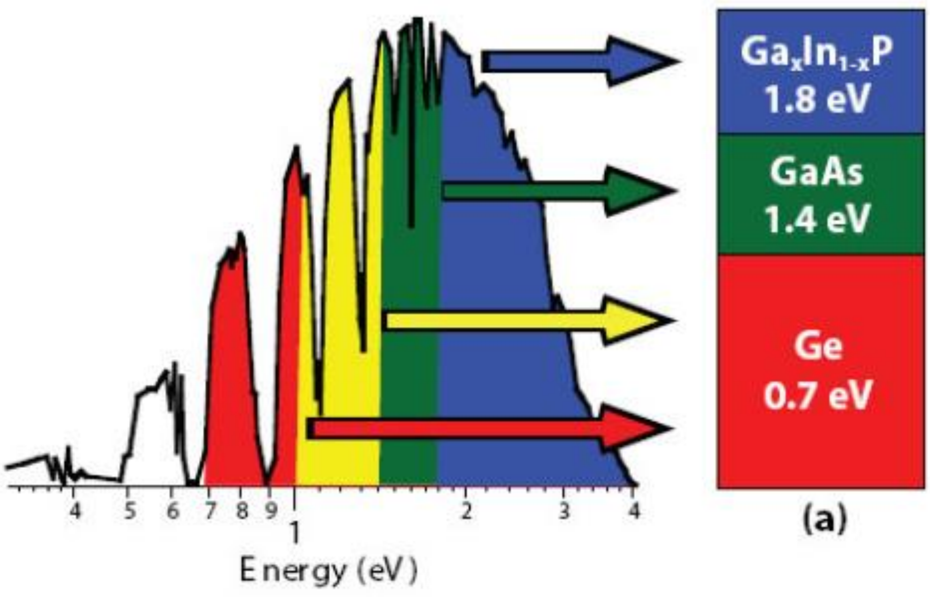


Guillemoles *et al.*, Nature 13, 501 (2019)

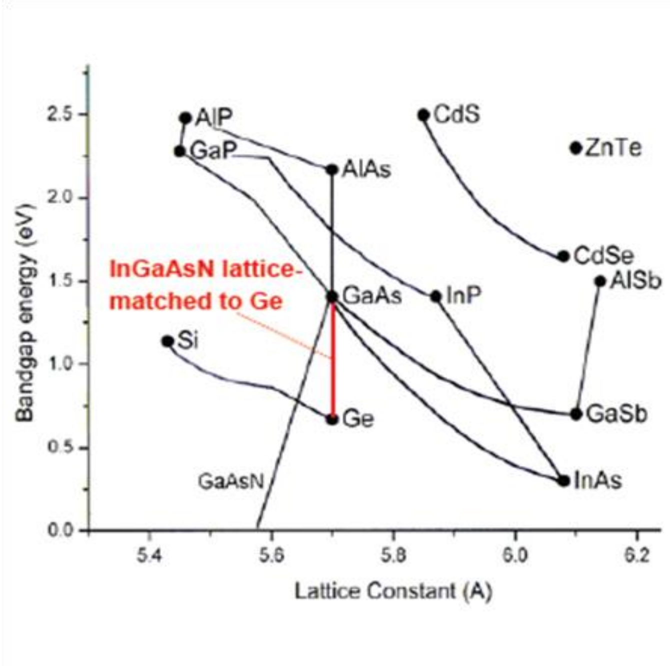
- Photocurrent determined by the photon absorption
- Photovoltage determined by the energy gap

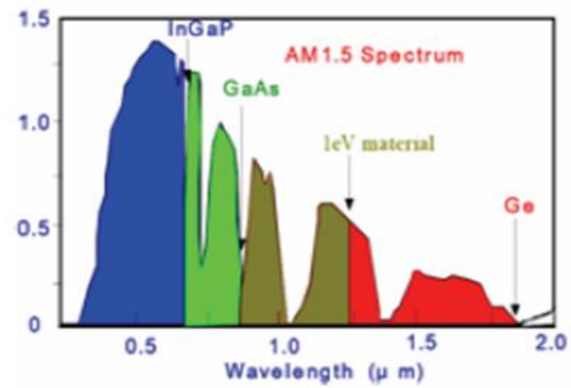
Shockley-Queisser limit predicted max efficiency ~ 30% (J. Appl. Phys. 1961)

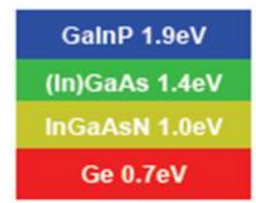
Multi-junction Solar Cells



GaInNAs: potential, but issues!







GaInNAs lattice matched to GaAs/Ge potential for > 50 %

Materials Quality Serious Problem

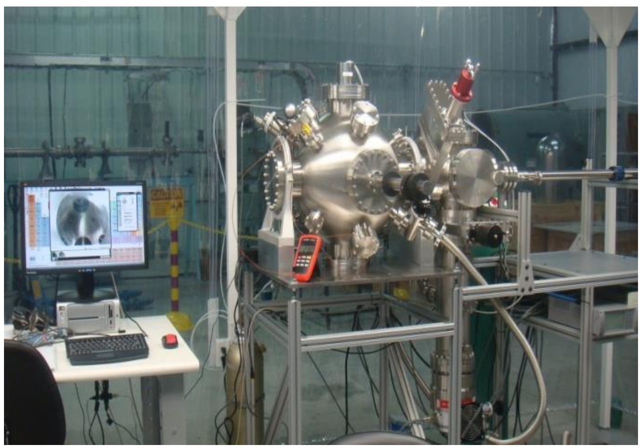
- **Low Nitrogen Solubility**
- **Phase Segregation**

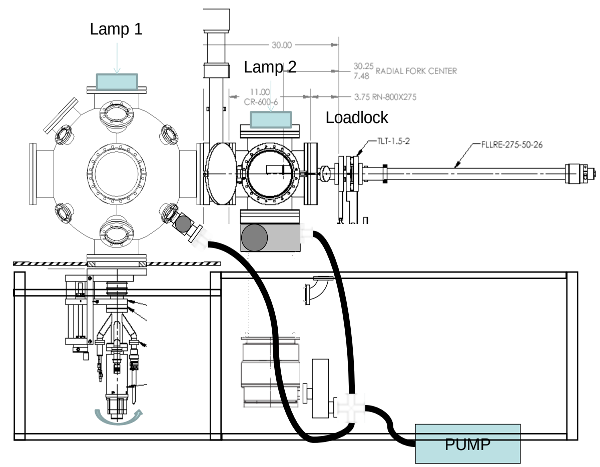
J. F. Geisz & D. J. Friedman. Semicond. Sci. Technol. 17 (2002) 769-777

Selective Defects Passivation in Solar Cell Materials

OCAST
Oklahoma Center for the Advancement of Science and Technology

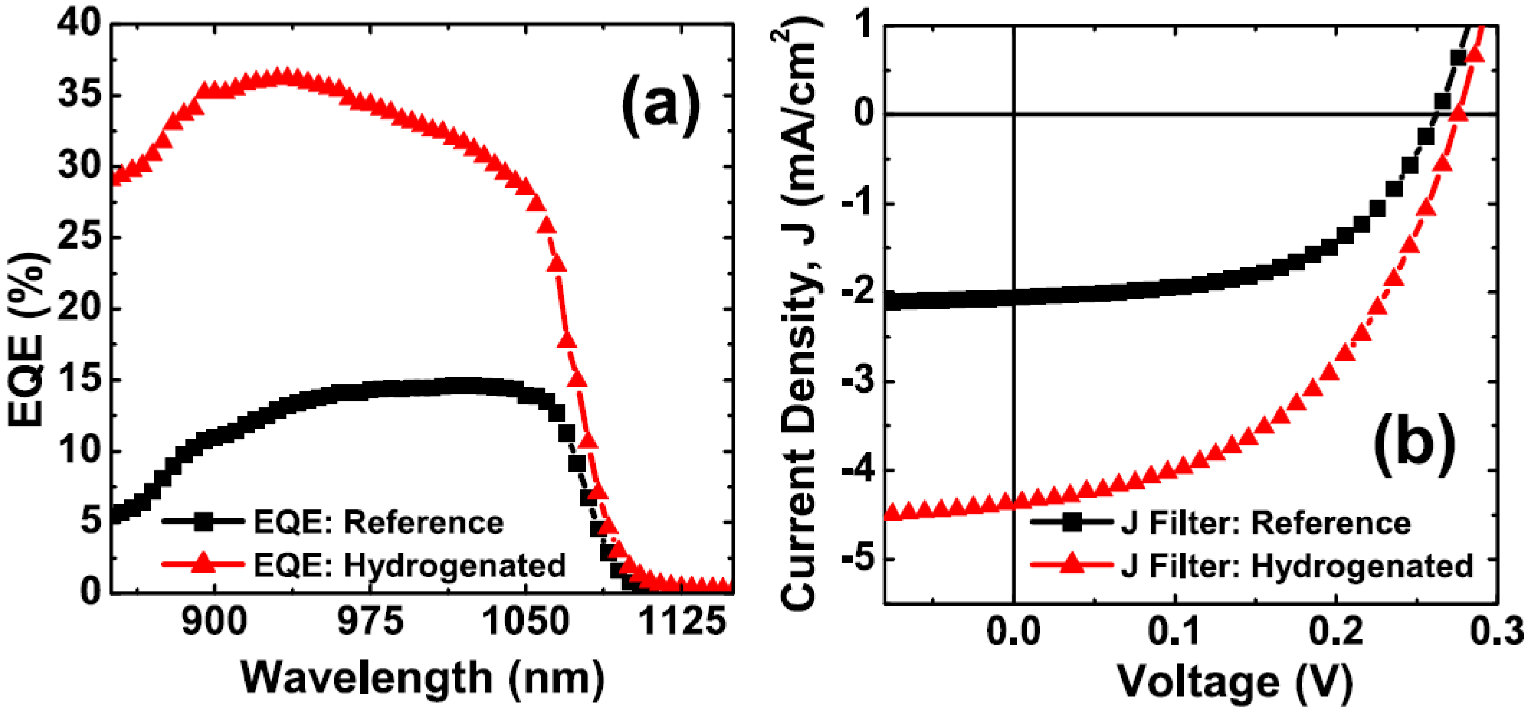
ARI
AMETHYST RESEARCH INCORPORATED





- UV-activated hydrogenation – Deuterium based
  - Typical 100 °C – 350 ° C
- Pressures ranging from 10^{-6} – 10^{5} Torr

Solar Cell Characterization

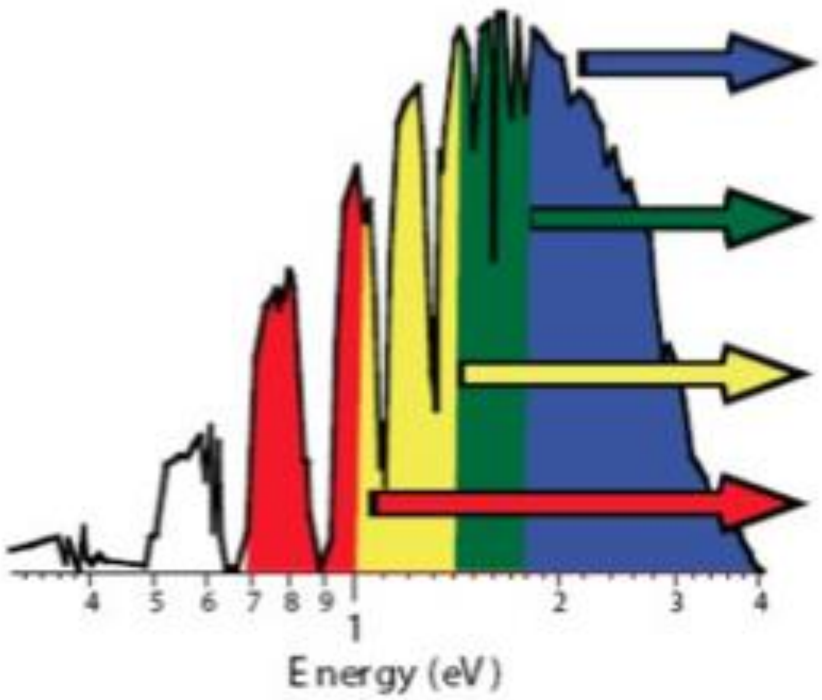


- **Increase in performance of the solar cell after hydrogenation**

- **No visible effect on the substitutional Nitrogen – *selective passivation***

Fukuda *et al*. *Applied Physics Letters* **106**, 141904 (2015)

3G PV: Harnessing the solar spectrum



Hot Carriers

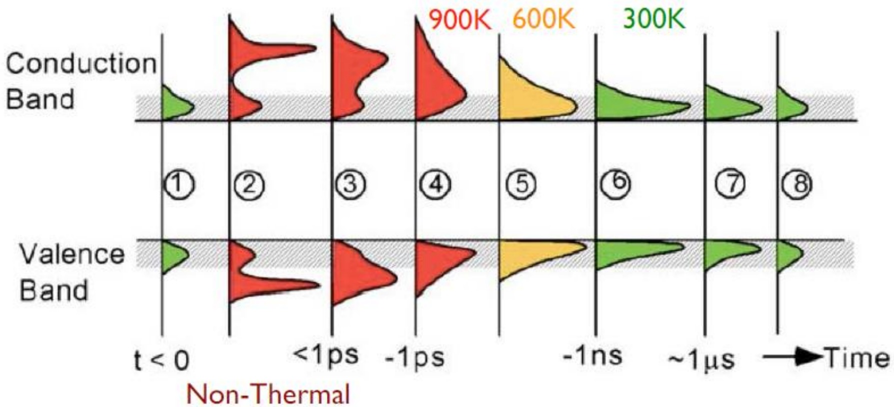
2, 3x Eg - MEG

ΔE_{IC} - IBSC

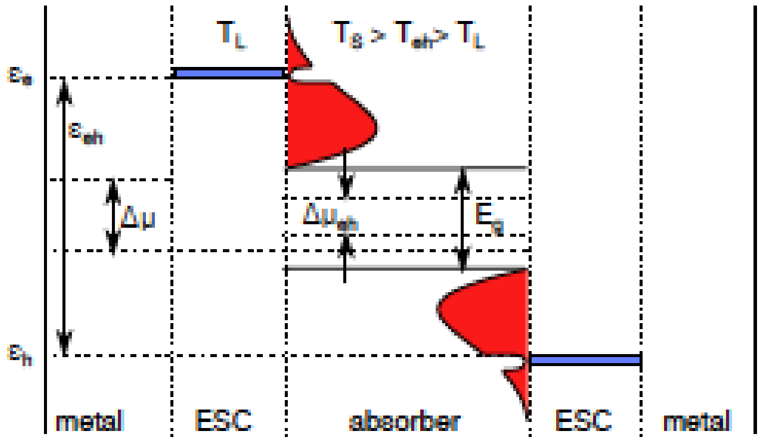
Fundamental Gap
~0.7eV

To harness the solar spectrum effectively Energy-gap is lowered slightly to ~0.7eV

Hot Carrier Losses and Solar Cells



Green, M.A., Third Generation Photovoltaics, Springer 2003



Wurfel, Sol. Energ. Mat. Sol. C., 46, p.43 (1997)

- "Hot carriers" rapidly transfer energy to the lattice – *thermalization*
- Rapid extraction of higher energy carriers via energy selective contacts has potential to increase power conversion:

- selective energy extraction
- inhibited electron-phonon relaxation pathways
- phonon bottleneck

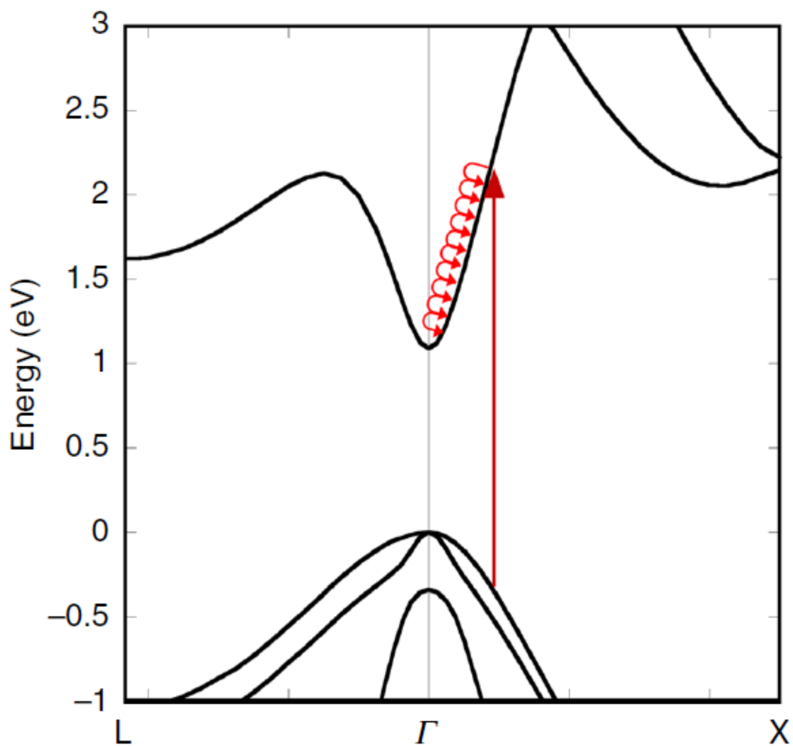
Hot Carrier Relaxation – Heat Generation

Phonon Bottleneck: Klemens versus Ridley

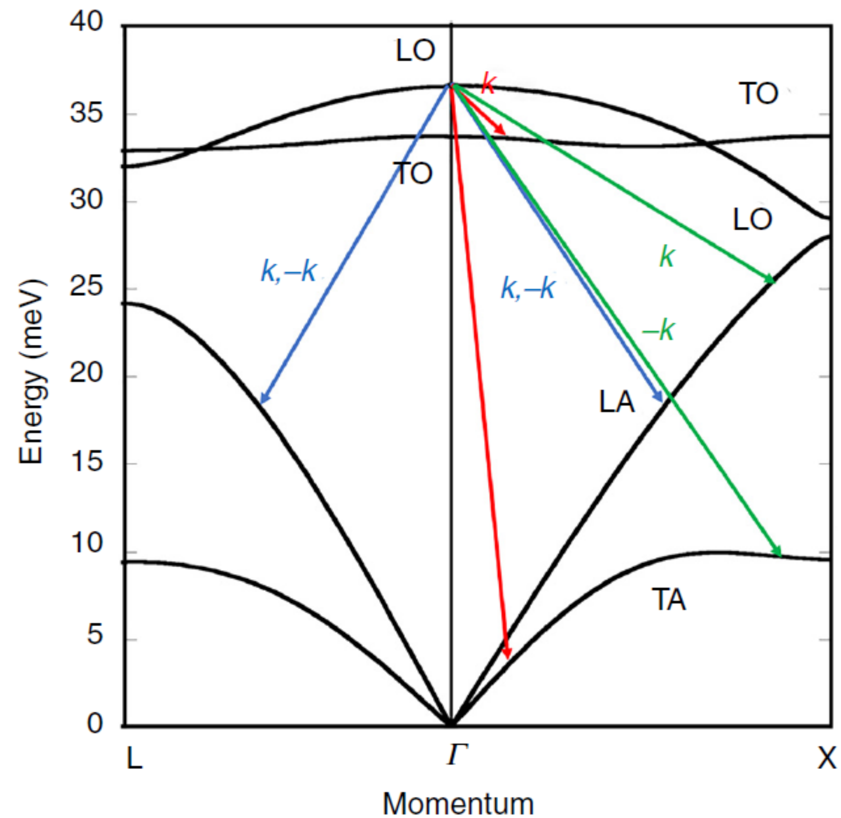
Non-equilibrium longitudinal optical phonons and their lifetimes

Cite as: Appl. Phys. Rev. **8**, 021324 (2021); https://doi.org/10.1063/5.0044374
Submitted: 15 January 2021 . Accepted: 21 May 2021 . Published Online: 29 June 2021

David K. Ferry



- **Klemens LO ➔ 2LA**
- **Ridley LO ➔TO + LA**



Hot-Carrier Effects in Semiconductor Devices

Several papers suggesting hot carriers are most robust in quantum confined systems:

J. F. Ryan *et al*. PRL **53**, 1841 (1984)
J. Shah *et al.* PRL **54**, 2045 (1985)
N. Balkan *et al*. Semi. Sci. Techn. **4**, 852 (1989)
K. Leo *et al*. PRB **38**, 1947 (1988)

Progress in PHOTOVOLTAICS

PROGRESS IN PHOTOVOLTAICS: RESEARCH AND APPLICATIONS
Prog. Photovolt: Res. Appl. 2016; **24**:591–599
Published online 26 February 2016 in Wiley Online Library (wileyonlinelibrary.com). DOI: 10.1002/pip.2763

ACCELERATED PUBLICATION

Suppression of phonon-mediated hot carrier relaxation in type-II InAs/AlAs$_x$Sb$_{1-x}$ quantum wells: a practical route to hot carrier solar cells

Hamidreza Esmaielpour[1], Vincent R. Whiteside[1], Jinfeng Tang[1], Sangeetha Vijeyaragunathan[1], Tetsuya D. Mishima[1], Shayne Cairns[1], Michael B. Santos[1], Bin Wang[2] and Ian R. Sellers[1]*

[1] Homer L. Dodge, Department of Physics & Astronomy, University of Oklahoma, 440 W. Brooks Street, Norman, OK 73019, USA
[2] School of Chemical, Biological and Materials Engineering, Sarkeys Energy Center, University of Oklahoma, East Boyd Street-T301, Norman, OK 73019, USA

Potential for Solar Cells:

Energy & Environmental Science

Dynamic Article Links

Cite this: DOI: 10.1039/c2ee02843c
www.rsc.org/ees

PAPER

Thermalisation rate study of GaSb-based heterostructures by continuous wave photoluminescence and their potential as hot carrier solar cell absorbers†

A. Le Bris,[*abc] L. Lombez,[abc] S. Laribi,[abc] G. Boissier,[d] P. Christol[d] and J.-F. Guillemoles[*abc]

Received 6th October 2011, Accepted 15th December 2011
DOI: 10.1039/c2ee02843c

Progress in PHOTOVOLTAICS

PROGRESS IN PHOTOVOLTAICS: RESEARCH AND APPLICATIONS
Prog. Photovolt: Res. Appl. (2013)
Published online in Wiley Online Library (wileyonlinelibrary.com). DOI: 10.1002/pip.2444

ACCELERATED PUBLICATION

Demonstration of a hot-carrier photovoltaic cell

James A. R. Dimmock*, Stephen Day, Matthias Kauer*, Katherine Smith and Jon Heffernan
Sharp Laboratories of Europe Ltd, Edmund Halley Road, Oxford Science Park, Oxford OX4 4GB, UK

IEEE JOURNAL OF PHOTOVOLTAICS 1

Enhanced Hot-Carrier Effects in InAlAs/InGaAs Quantum Wells

Louise C. Hirst, Michael K. Yakes, Christopher G. Bailey, Joseph G. Tischler, Matthew P. Lumb, María González, Markus F. Führer, N. J. Ekins-Daukes, and Robert J. Walters

Le Bris *et al*. APL 97, 113506 (2010)

Hirst *et al*. IEEE JPV 4, 244 (2014)

Hirst *et al.* APL 104, 231115 (2014)

Tang, IRS, *et al.* APL 106, 061902 (2015)

InAs/Al$_x$As$_{1-x}$Sb quantum wells: an interesting potential system for hot carriers solar cells

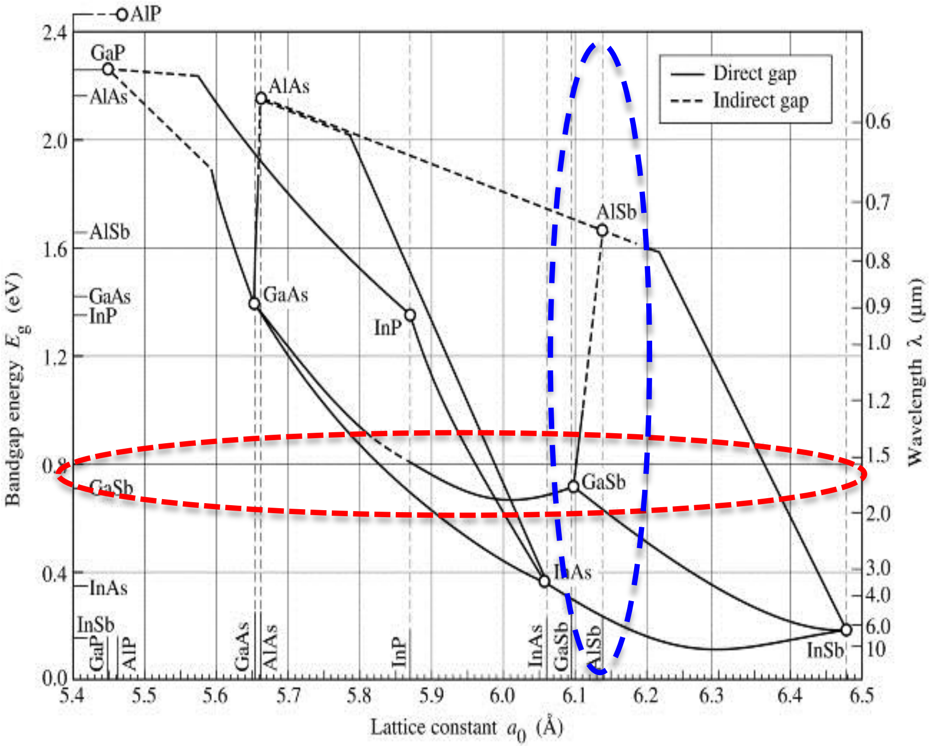
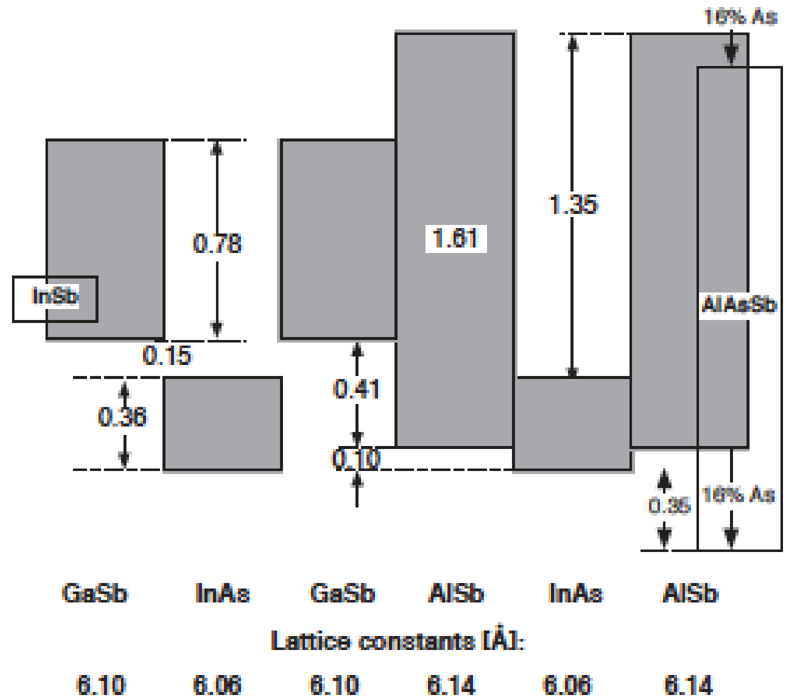


Fig. 7.6. Bandgap energy and lattice constant of various III-V semiconductors at room temperature (adopted from Tien, 1988).

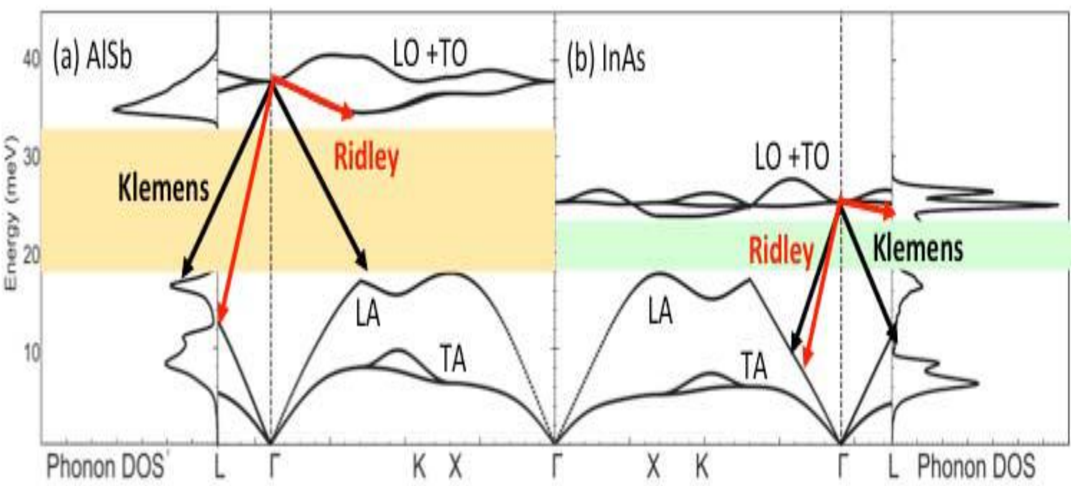


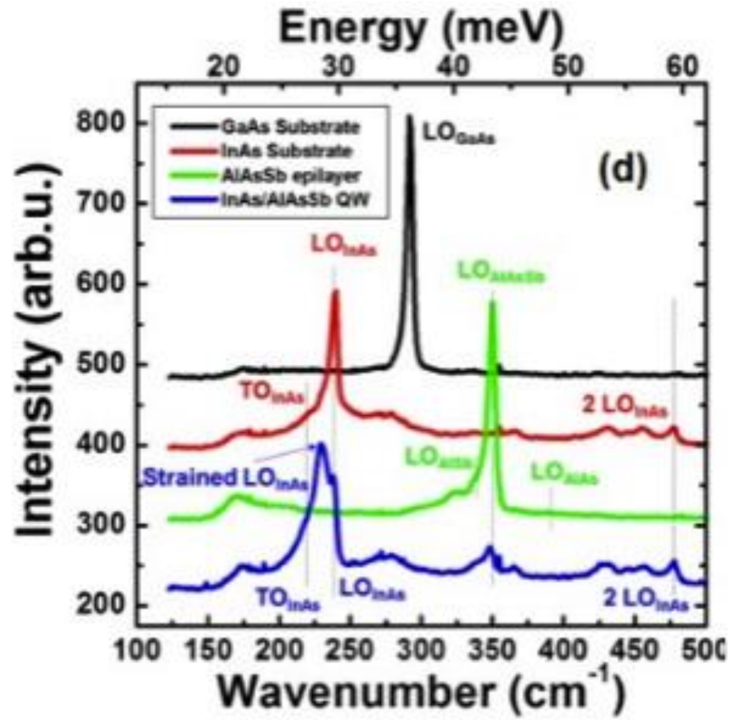
Kroemer *et al. Physica E* **20,** 196 (2004)

- **Potential to produce type-I, II or quasi-type-II structures**
- **Extremely deep confinement potential: large proportion of solar irradiance absorbed directly in QWs**

Inhibited hot carrier relaxation: phonon bottleneck

DFT Calculations: Bin Wang - OU

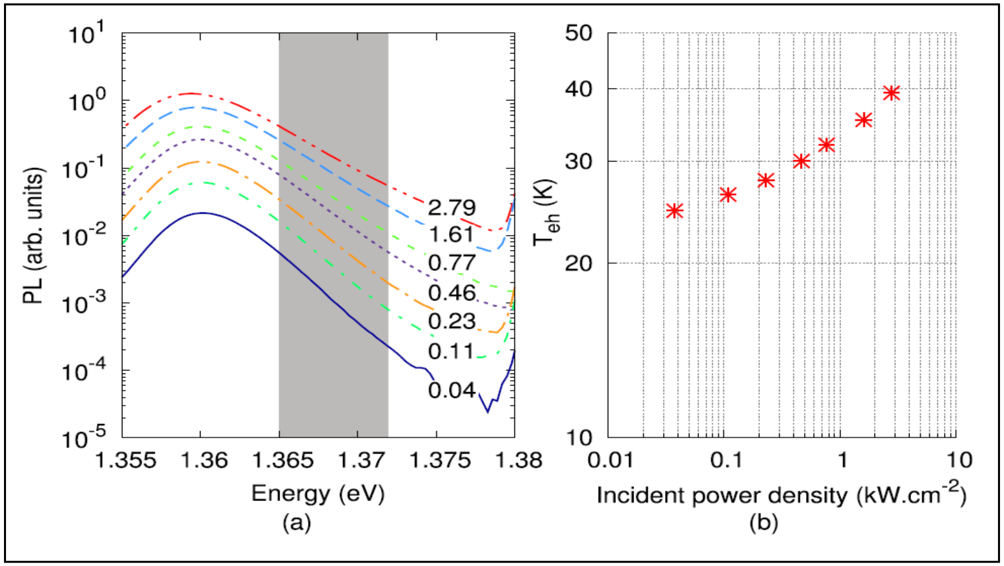




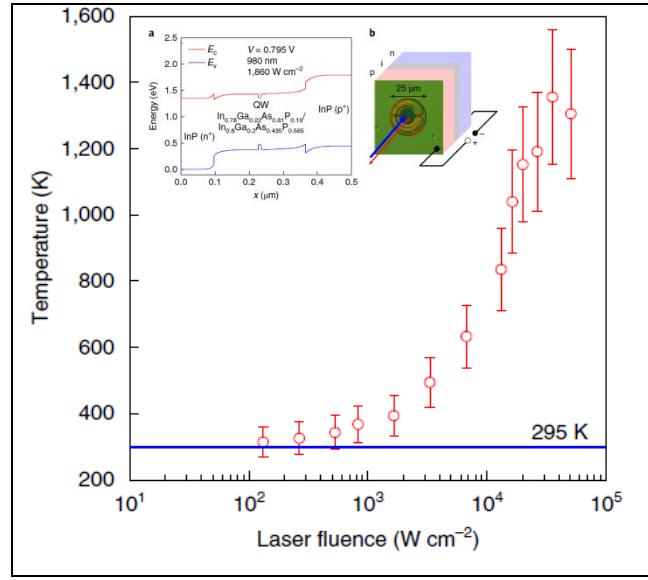
H. Esmaielpour *et al.* Scientific Reports 8, 12473 (2018)

- **Dominate relaxation processes: Klemens LO ➔ 2LA**
  Ridley LO ➔TO + LA
- **Large energy difference – *Reflections, poor thermal dissipation***
- ***Stable hot phonon bath***

Evidence of Hot-Carrier Effects in QWSC



Hirst & Ekins-Daukes. Appl. Phys. Lett. **104**, 231115 (2014)



Nguyen, Lombez, Guillemoles *et al.*
Nature Energy **3**, 231115 (2018)

Maxwell-Boltzmann like distribution of carriers:

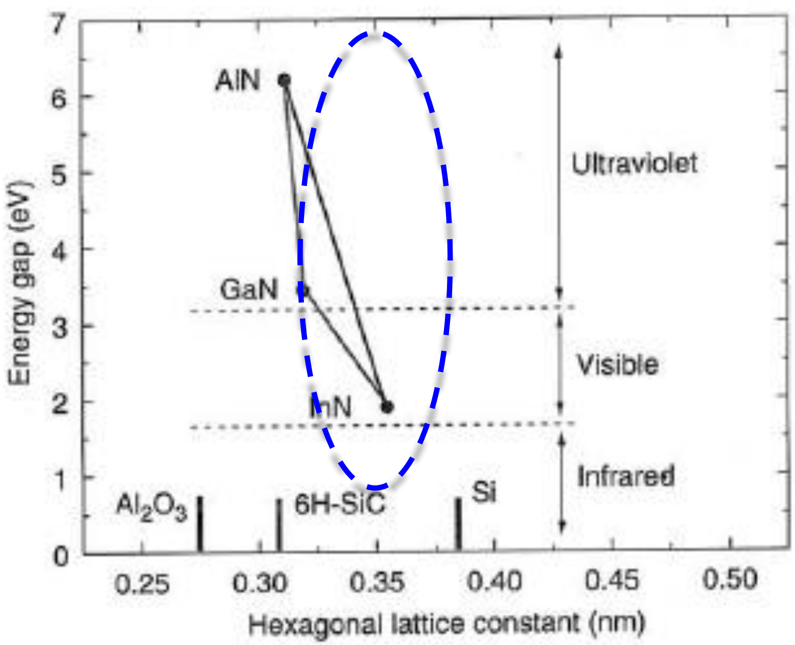
$$I(PL) \propto \exp\left(-\frac{h\nu}{k_B T_H}\right)$$

- Lasher & Stern, *Phys. Rev.* ***133**, A553 (1964)*
- De Vos & Pauwels, *Appl. Phys.* ***25**, 119 (1981)*
- P Wurfel, *J. Phys. C: Solid State Phys.* **15** 3967 (1982)

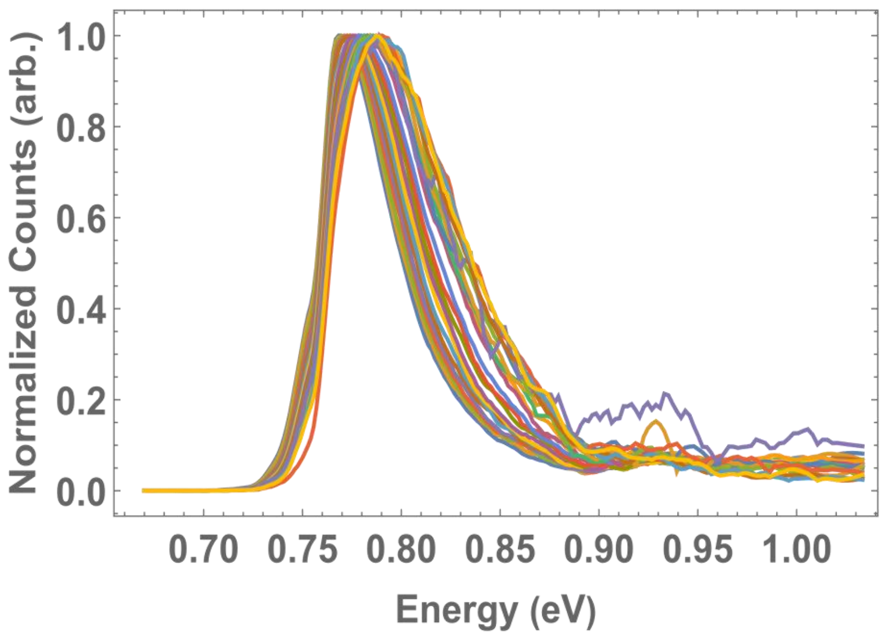
Proof of principle systems

- **Very high-power excitation**
- **Monochromatic illumination**
- **Non-optimum architecture**

Narrow-Gap Semiconductors



Y. S. Park, Optoelectronics Rev. **9**, 117 (2001)



Credit: Shashi Sourabh (OU)

InN has a favorable energy gap for Hot Carrier Solar Cells

Narrow-Gap Semiconductors: InN

Appl. Phys. Lett., Vol. 75, No. 21, 22 November 1999

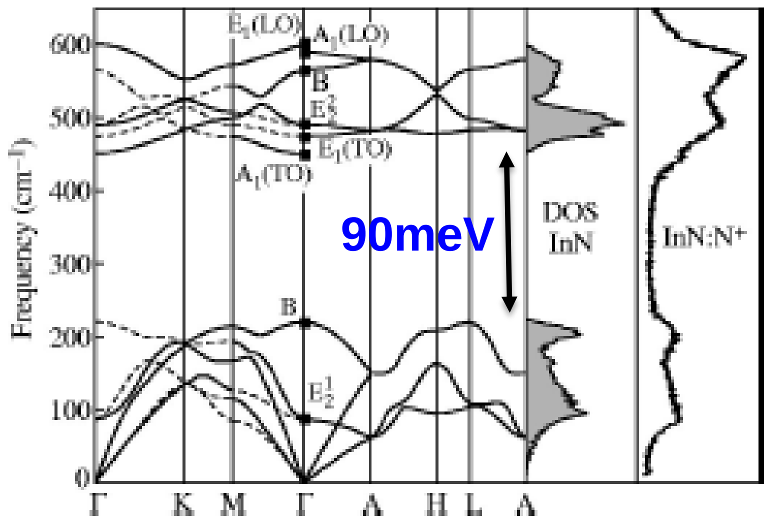
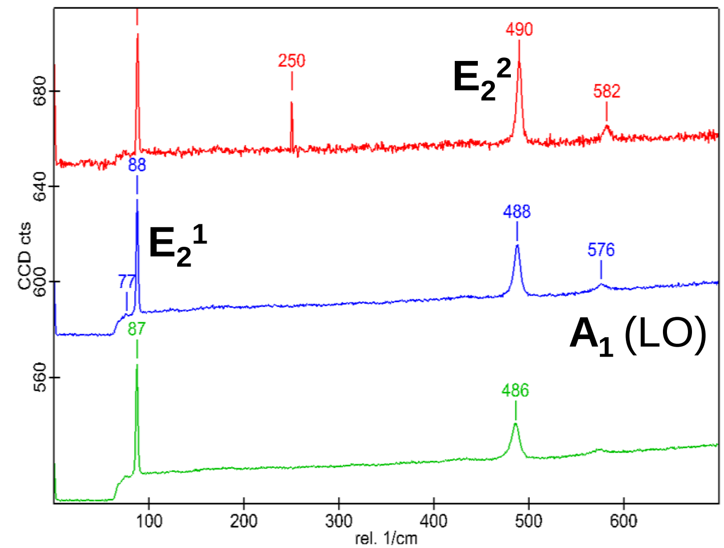


FIG. 4. Calculated phonon dispersion curves and phonon DOS function for hexagonal InN. The disorder-induced Raman spectrum obtained at 7 K for N^+-implanted InN is also shown.

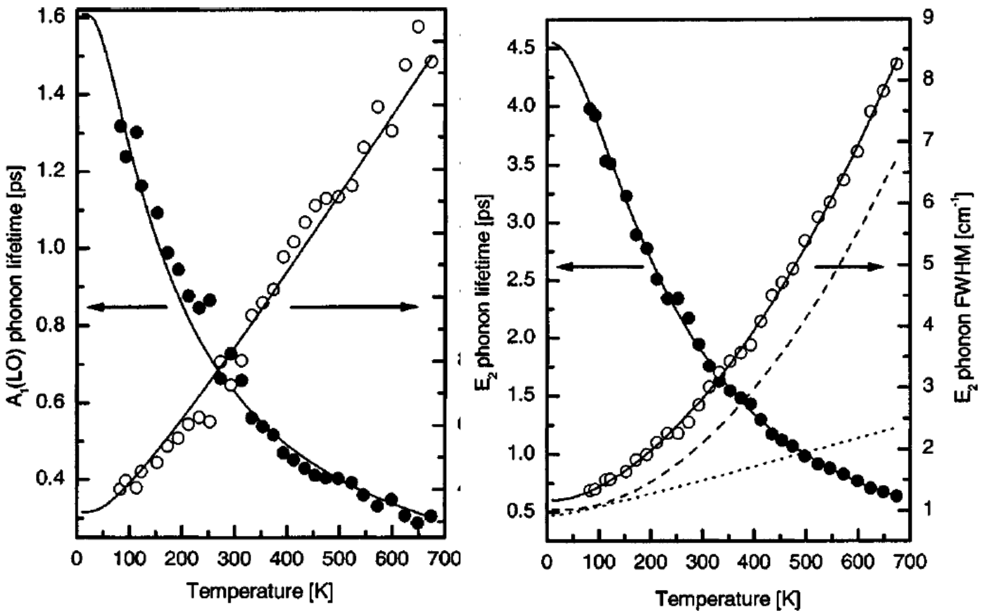
Davydov *et al* (1999)



Acknowledgement: Nazli Sarabi (OU)

Extremely attractive “phononic” properties optimum Energy gap!

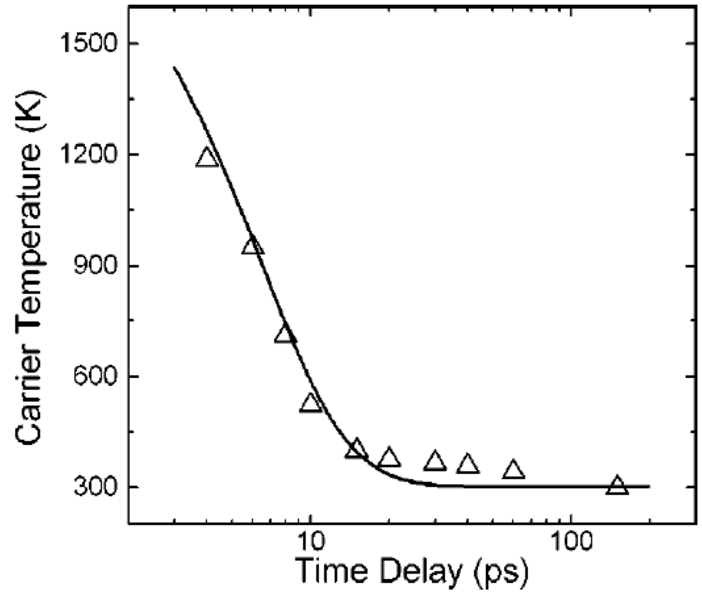
InN: Evidence of Carriers



Phonon lifetimes and phonon decay in InN

Cite as: Appl. Phys. Lett. **86**, 223501 (2005); https://doi.org/10.1063/1.1940124
Submitted: 18 January 2005 . Accepted: 21 April 2005 . Published Online: 24 May 2005

J. W. Pomeroy, M. Kuball, H. Lu, W. J. Schaff, X. Wang, and A. Yoshikawa



APPLIED PHYSICS LETTERS VOLUME 83, NUMBER 24 15 DECEMBER 2003

Time-resolved spectroscopy of recombination and relaxation dynamics in InN

Fei Chen and A. N. Cartwright[a)]
Department of Electrical Engineering, University at Buffalo, State University of New York, Buffalo, New York 14260

Hai Lu and William J. Schaff
Department of Electrical and Computer Engineering, Cornell University, Ithaca, New York 14853

(Received 18 June 2003; accepted 22 October 2003)

Early prediction *and* data suggested strong potential

Not the whole story…..

Acknowledgement: Gavin Conibeer (UNSW)

Phonon Bottleneck: Klemens versus Ridley

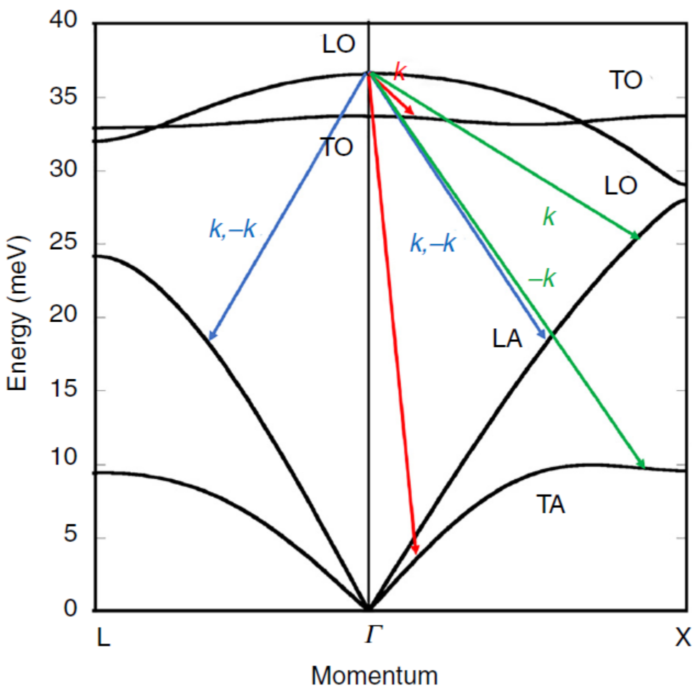


FIG. 13. The decay mechanisms suggested by Klemens[73] are shown in blue, Ridley-Gupta in red, and Vallée-Bogani in green. The indicated momenta are discussed in the text.

D. K. Ferry, Appl. Phys. Rev. 8, 021324 (2021)

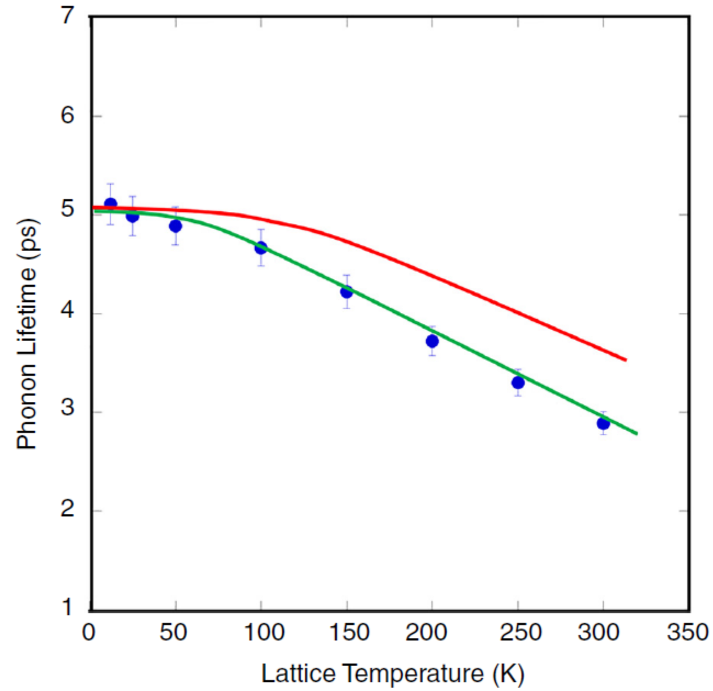


FIG. 14. The phonon lifetime, as deduced from Raman scattering, as given as a function of temperature for wurtzite GaN. The blue curve is the Klemens[99] channel while the green curve is the Ridley-Gupta[102] channel. The data are adapted from K. T. Tsen *et al.*[105]

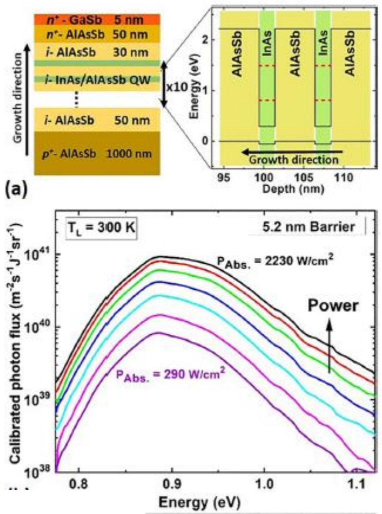
Ridley channel is very effective in nitrides (in all III-V's)

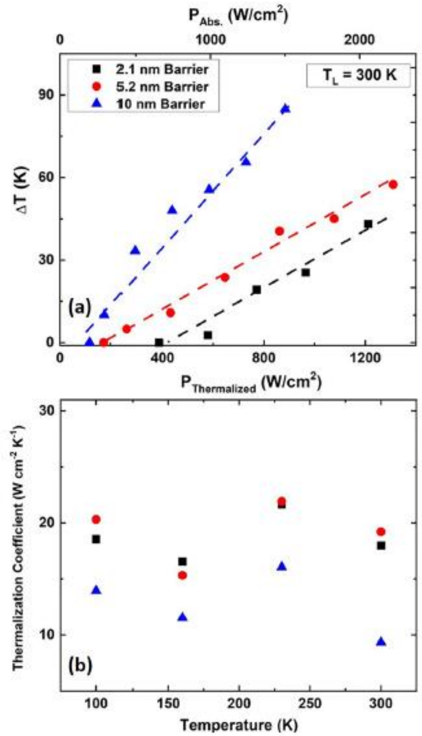
Strain and piezoelectric fields also facilitate hot carrier relaxation

M. D. Yang *et* al., J. Appl. Phys. 105, 013526 (2009)

What now for InN? *Bulk versus low-Dimensional*

Phonon management in QWs

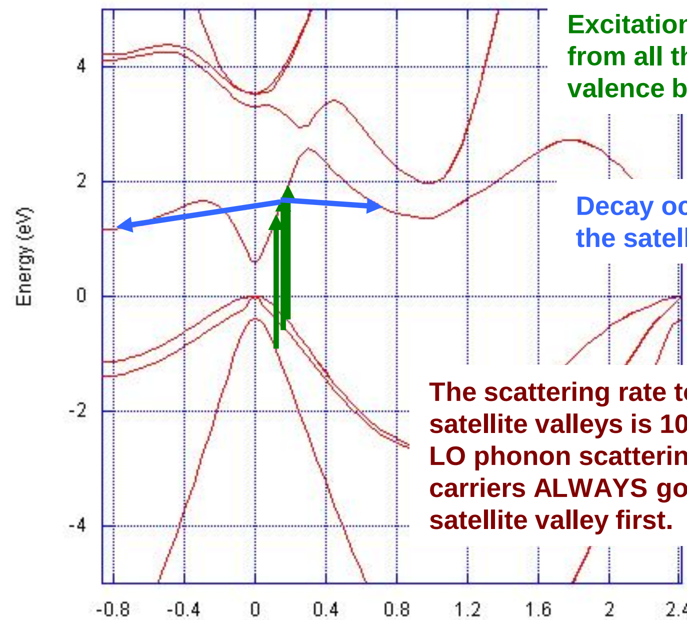




H. Esmaielpour *et al*.
Appl. Phys. Lett. 118, 213902 (2021)

Valley Photovoltaics

Consider a typical direct gap III-V



D. K. Ferry Semi. Sci. Techn. 34, 044001 (2019)
H. Esmaielpour *et al*. Nature Energy 5, 336 (2020)
D. K. Ferry *et al*., J. Appl. Phys. 128, 220903 (2020)

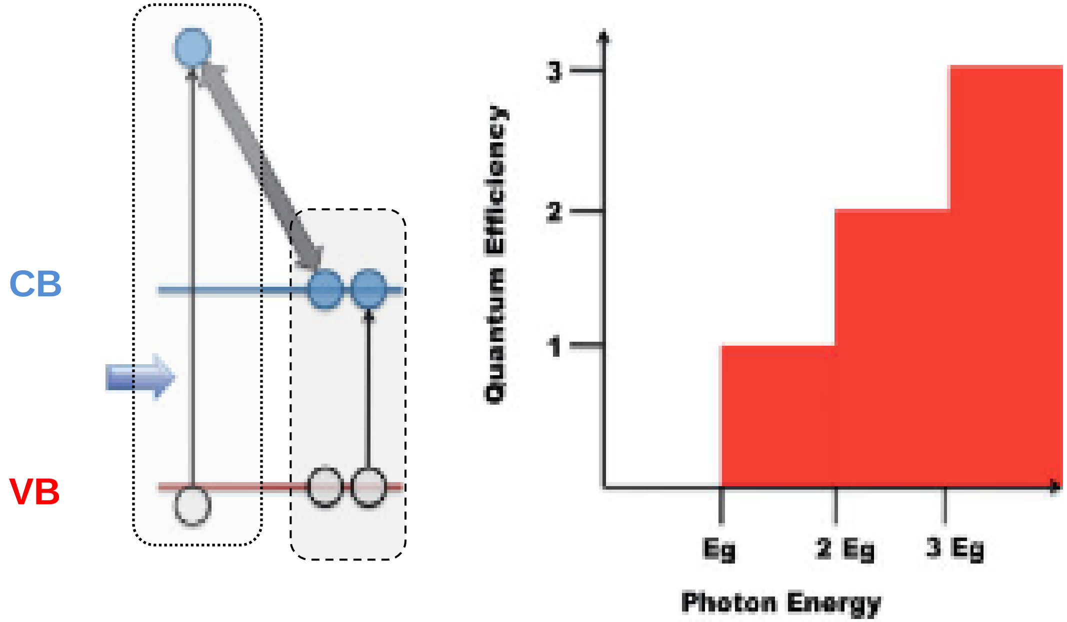
It is well established that thermalization can be inhibited in quantum wells

Intervalley scattering is now being considered at a method for HCSCs

Multi-Exciton Generation or Carrier Multiplication

Initial photon absorbed one electron – hole pair

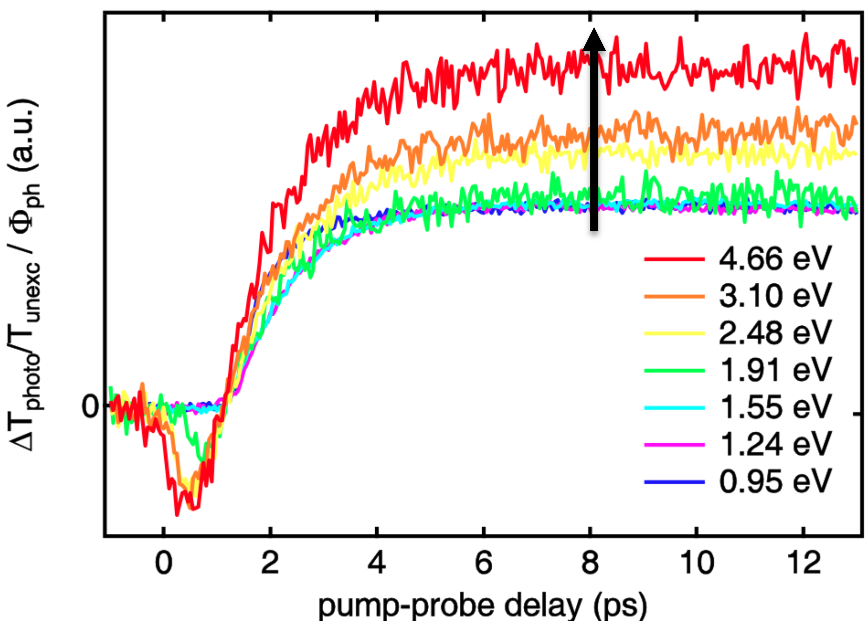
Energy relaxation with second photon absorbed: two electron – hole pairs

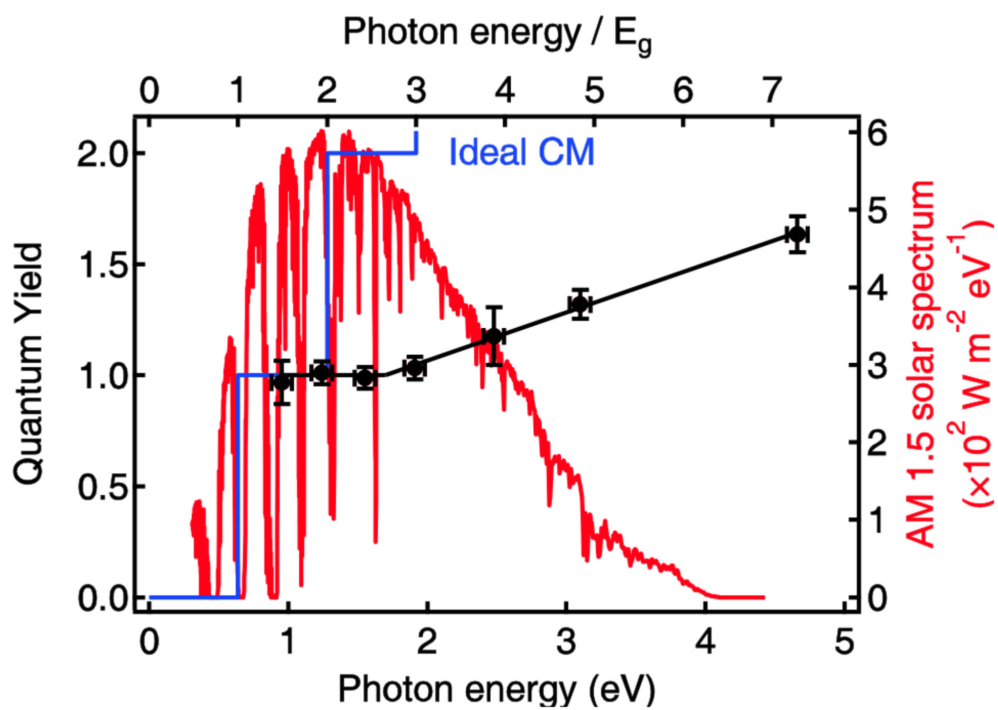


Brown & Wu. Laser & Photon Rev. ***3****, 394 (2009)*

Impact Ionization seen in InSb, Si, PbS, and PbSe, and now InN!

InN: multi-exciton generation





$$\sigma(\omega) = N \times e \times \mu(\omega) = N \times \frac{e^2 \tau_s}{m^*} \times \frac{1}{1 - i\omega\tau_s}$$

*Jensen, Sellers, Bonn et al, APL **101,** 222113 2012*

Summary and Acknowledgements

- **While the performance and cost of solar cells has improved considerably TW implementation require further improvements and *all* and *new* technologies**
- **Stable high efficiency single junction solar cells in excess of 30% likely require III-Vs!**
- **Hot carrier solar cells have potential to exceed the single gap limit but innovation and cost-effective approaches are required**
- **The phonons in InN suggest it has the potential to inhibit thermalization – *much more work needed!***

U.S. DEPARTMENT OF ENERGY

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NSF ECCS # 1610062

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The Oklahoma Photovoltaic Research Institute
http://okpvri.okstate.edu/

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