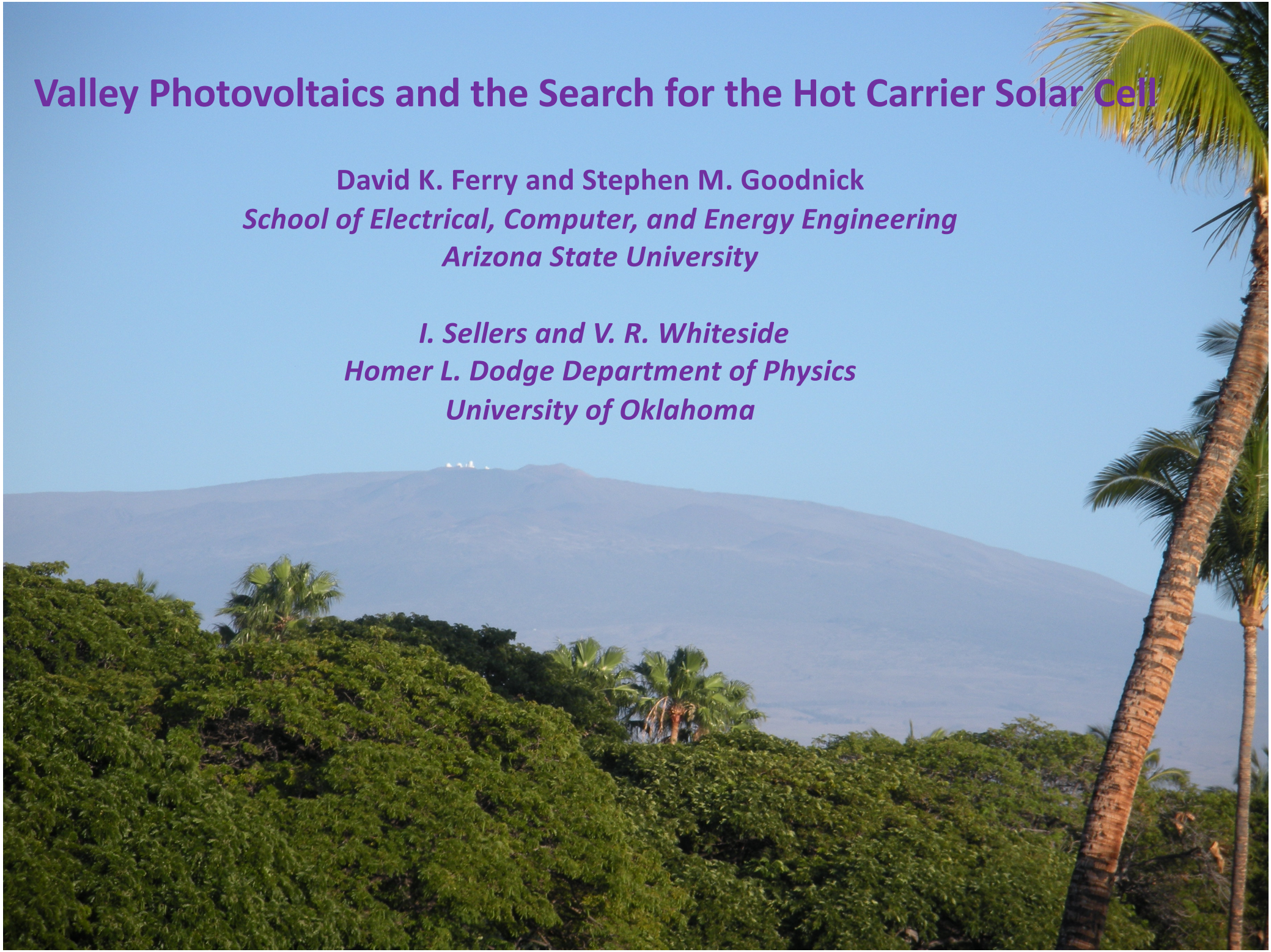
Valley Photovoltaics and the Search for the Hot Carrier Solar Cell

David K. Ferry and Stephen M. Goodnick
School of Electrical, Computer, and Energy Engineering
Arizona State University

I. Sellers and V. R. Whiteside
Homer L. Dodge Department of Physics
University of Oklahoma



Presented by David Ferry

The Hot Carrier Solar Cell was conceived in 1982 by Ross and Nozik

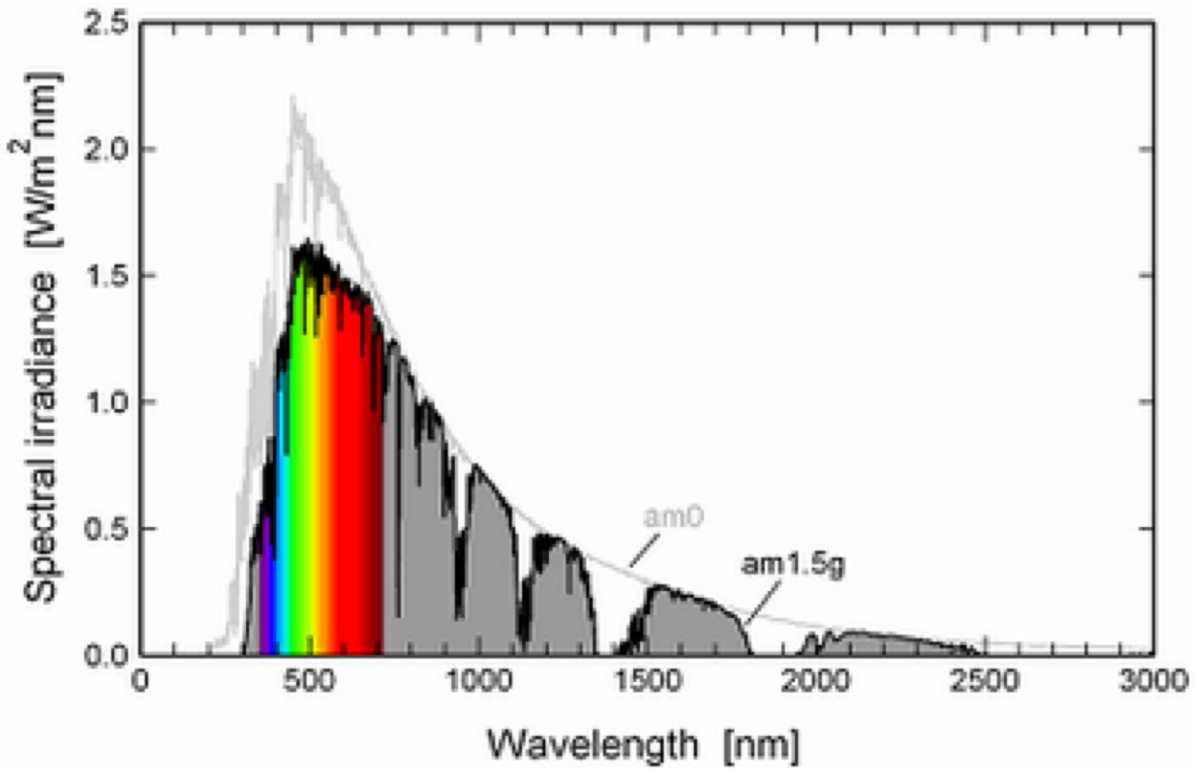
To establish such a cell, it was proposed that one needed to:

- Prevent the photo-generated carriers from thermalizing through the emission of phonons
- Extract only the hot carriers through an energy-selective contact

Since this time engineers have been hyper-ventilating over methods to cut down phonon emission by the photo-generated carriers and various superlattices for the energy-selective removal of the carriers

They have avoided the use of the known properties of hot carriers in semiconductors.

Solar Illumination

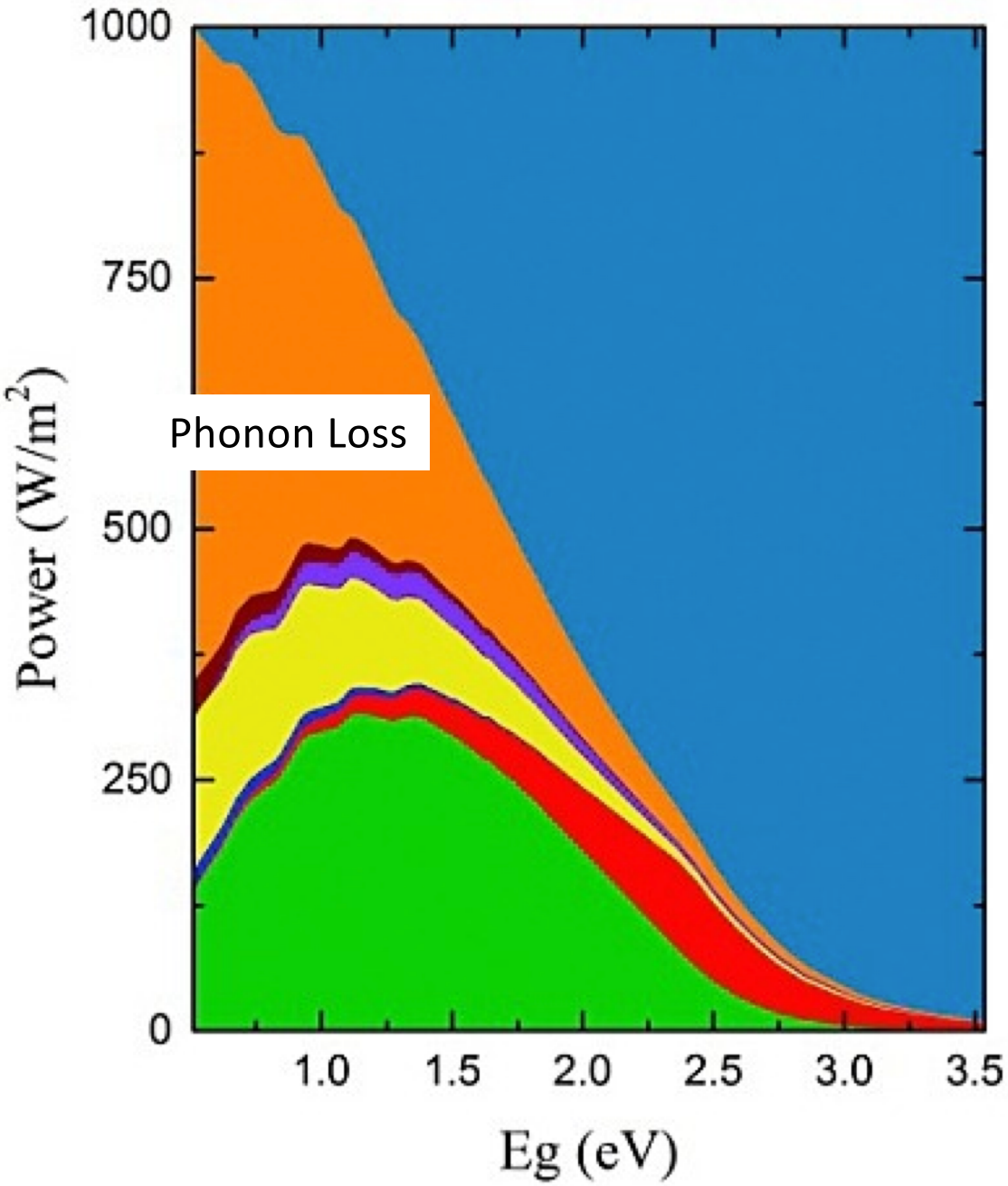


Hot Carrier Solar Cells:
Creating a True Hot Carrier Cell

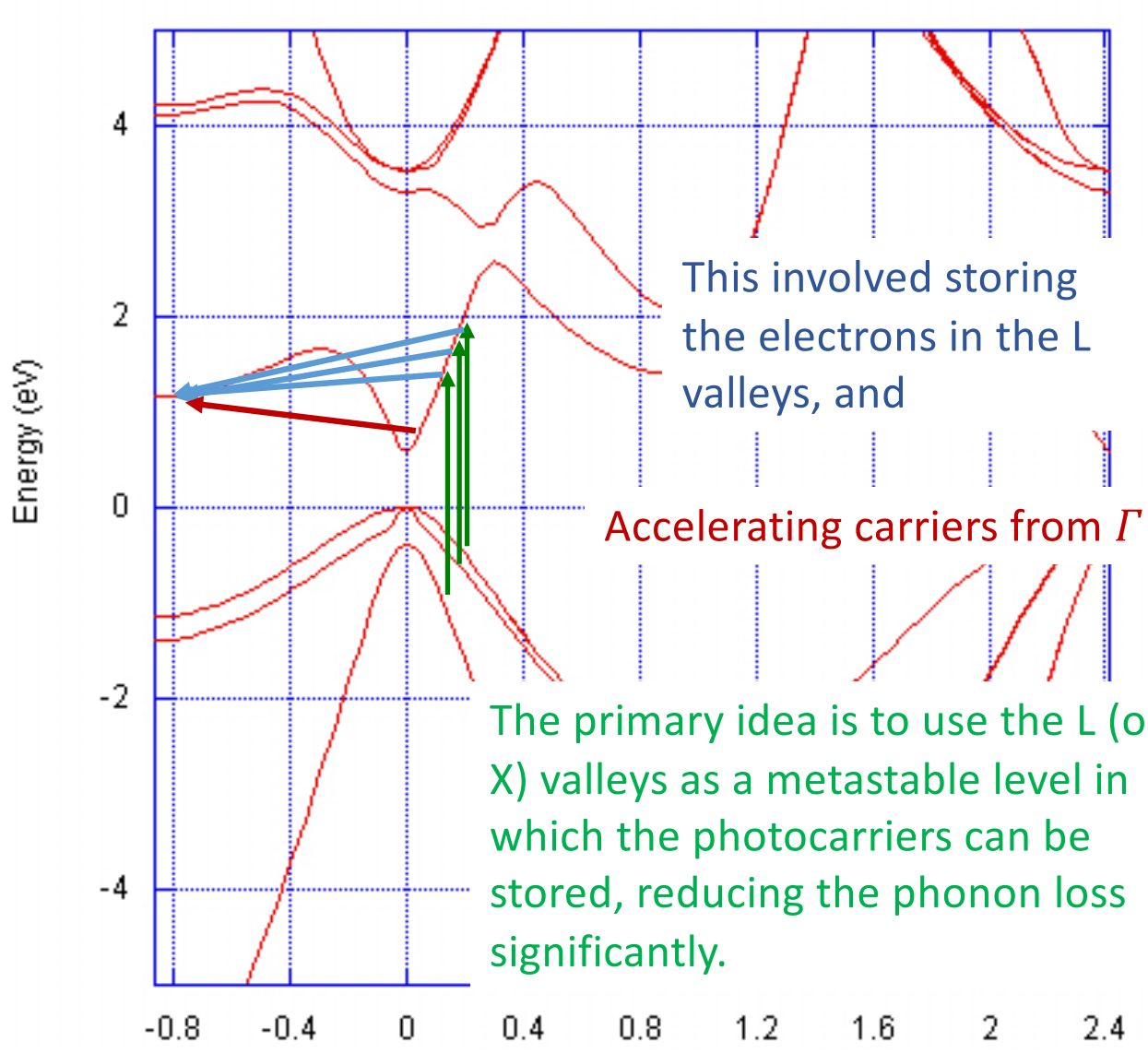
- **Park the carriers in the satellite valleys—the absorber layer must be thin so that carriers exit before decaying to the Γ valley**
- **Absorber layer should have high electric field to re-excite Γ carriers to satellite valleys—*p-n* junction should have "Mott barrier" configuration.**
- **ESC is not needed. Instead, wide band-gap layer is used as collector, allowing only carriers from the satellite valley out of the structure**

What is the governing physics that makes this better?

- We are going to effectively turn off radiative recombination
- We are going to dramatically reduce LO phonon emission
- This eliminates much of the known losses in the cell


1000
750
500
250
0
Power (W/m^2)
Phonon Loss
1.0
1.5
2.0
2.5
3.0
3.5
Eg (eV)

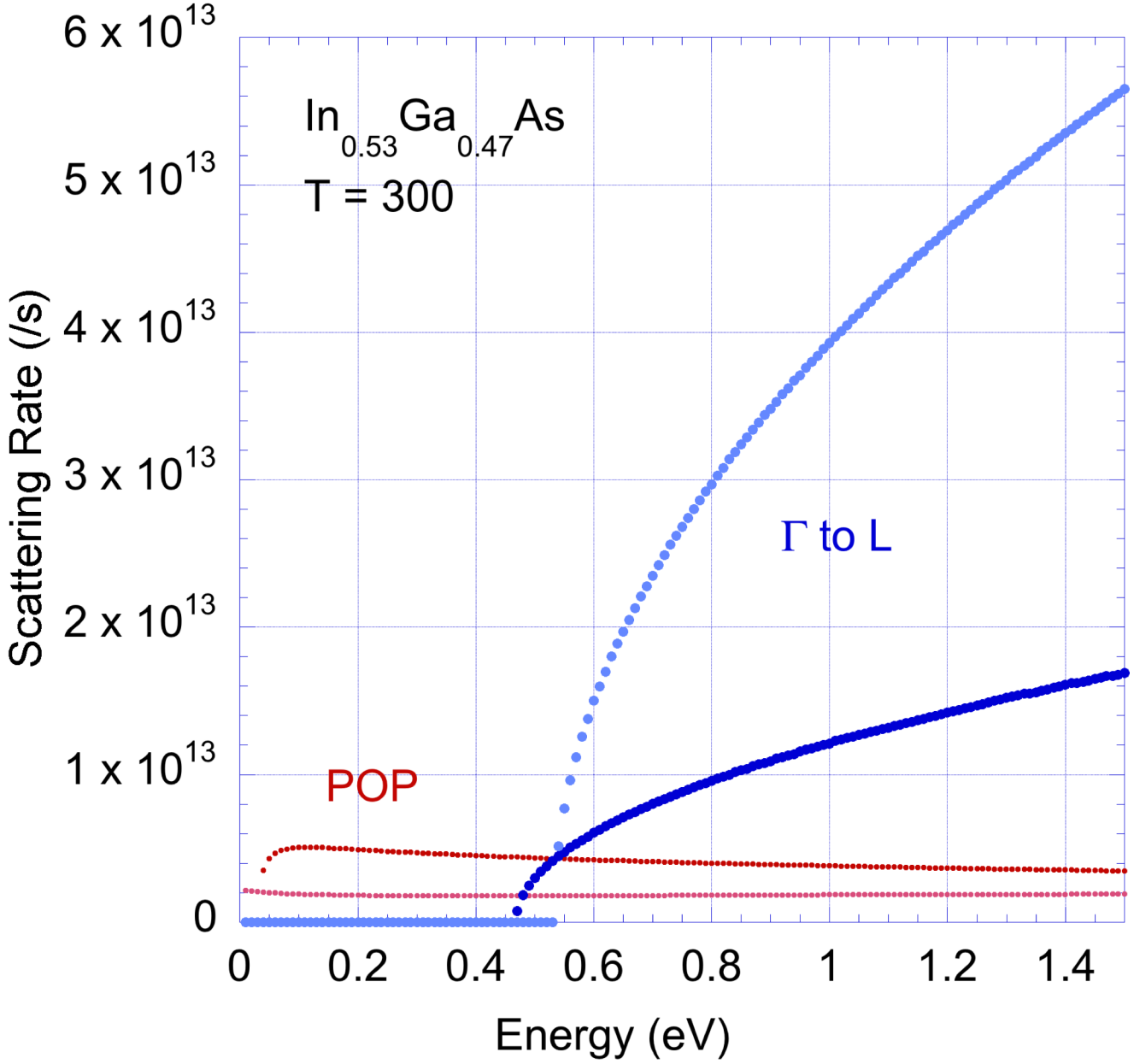
An approach to a *true* HCSC:



This involved storing the electrons in the L valleys, and

Accelerating carriers from Γ to L

The primary idea is to use the L (or X) valleys as a metastable level in which the photocarriers can be stored, reducing the phonon loss significantly.



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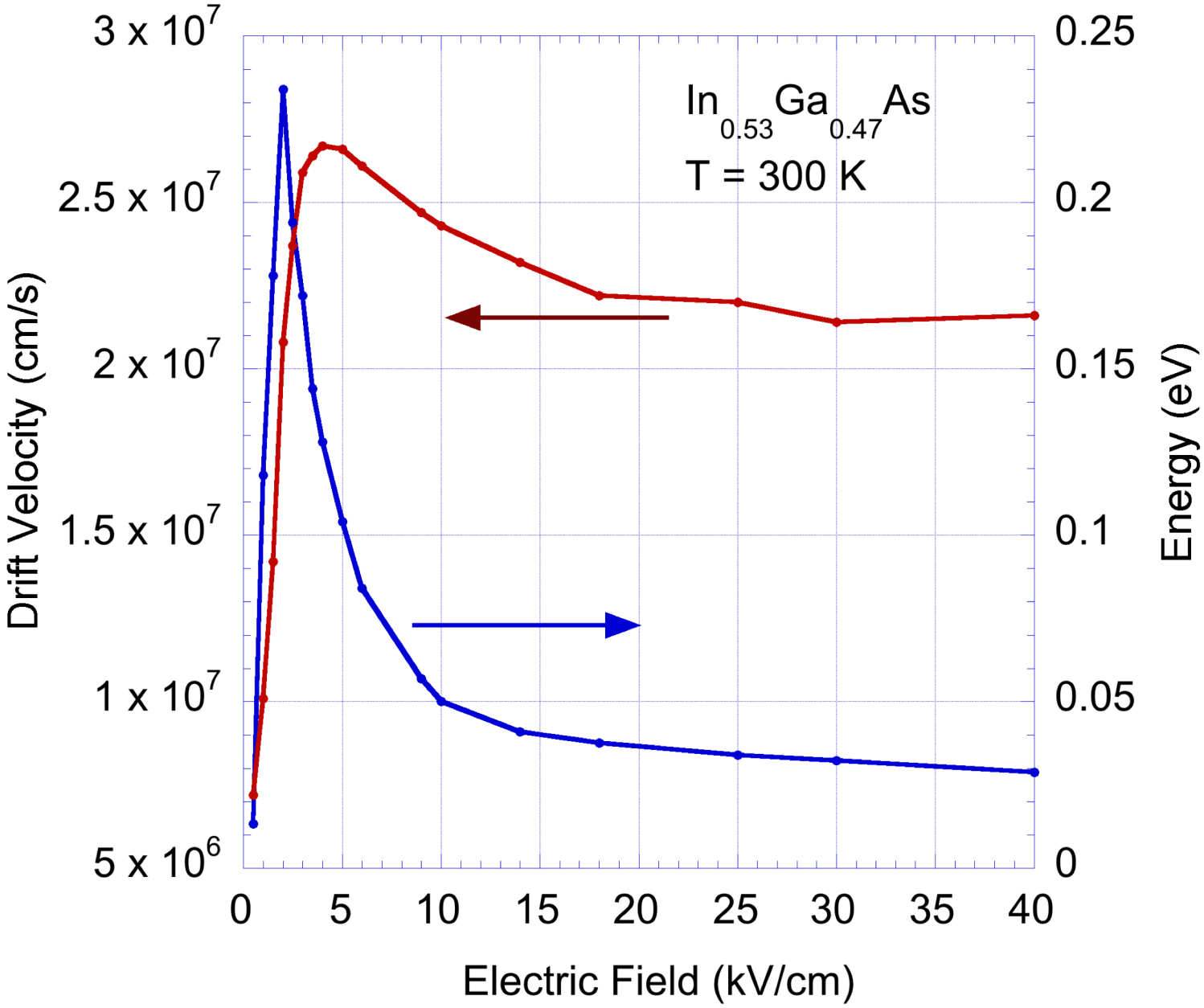

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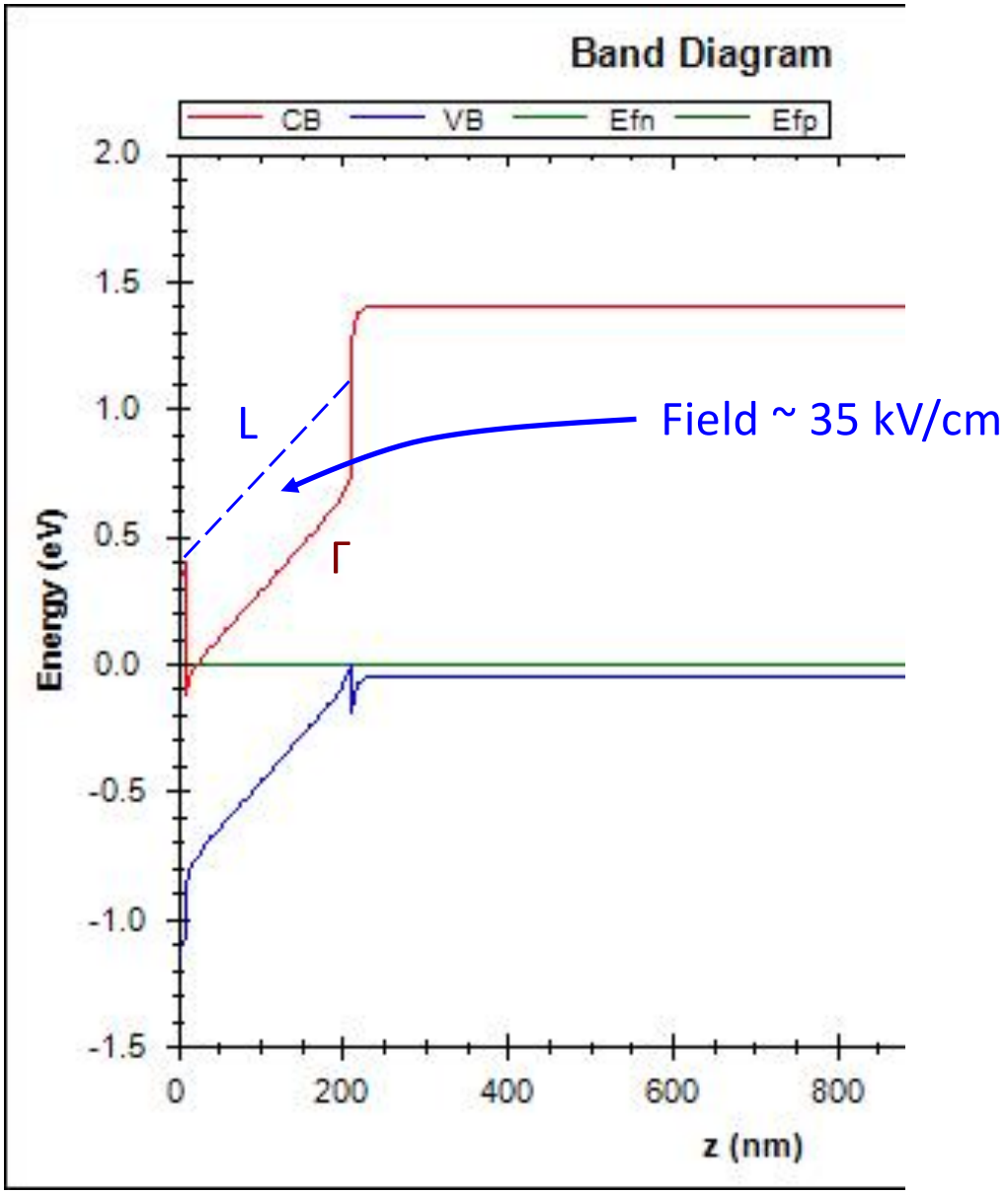
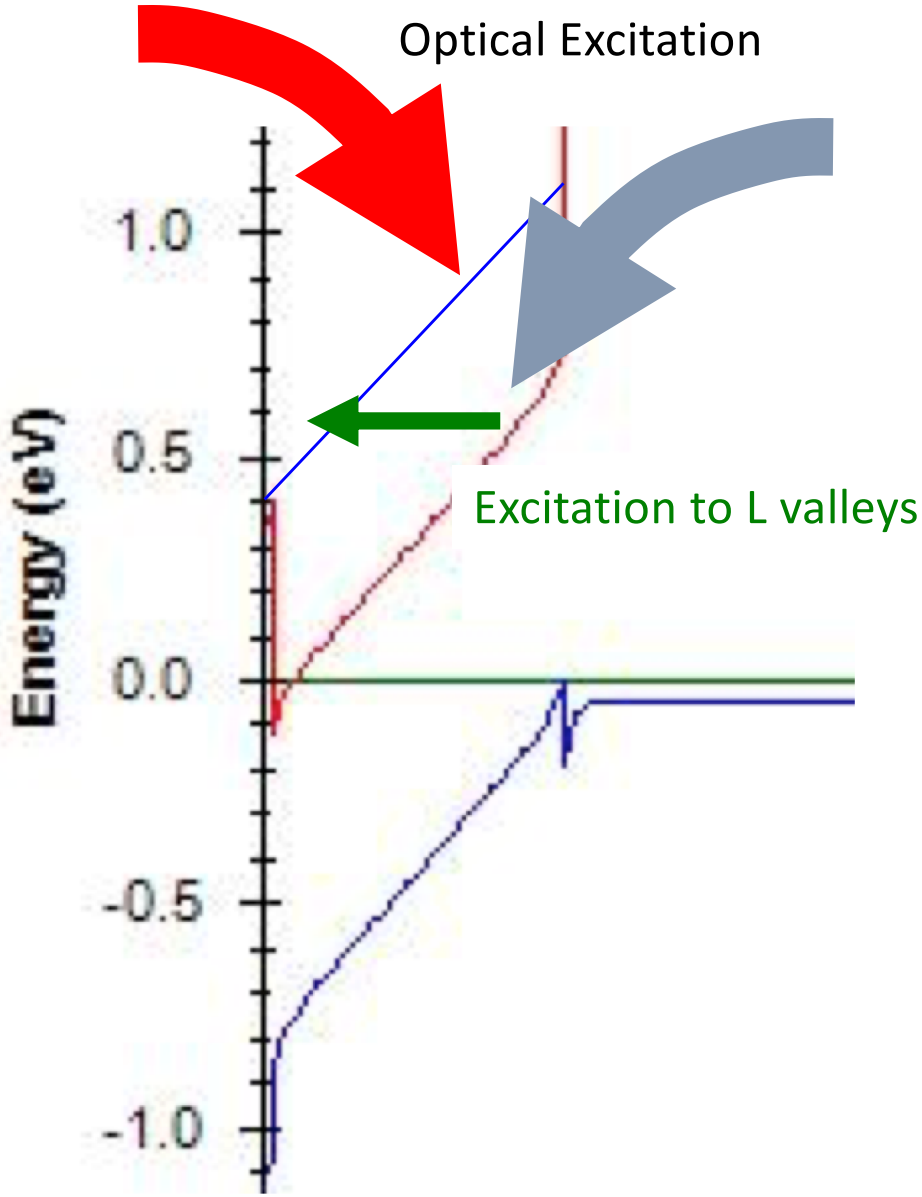
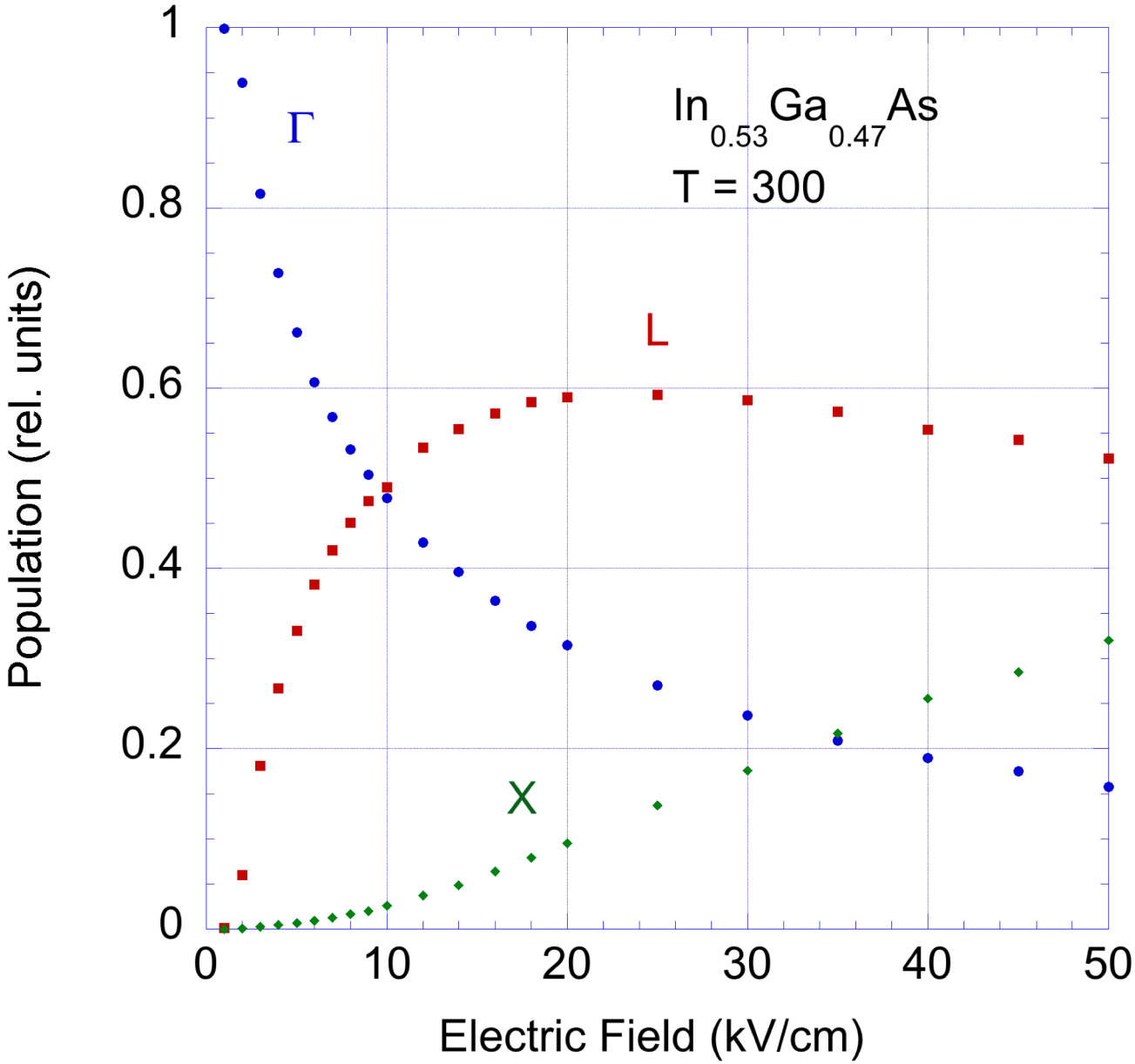

Band Diagram
CB
VB
Efn
Efp
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
Energy (eV)
0
200
400
600
800
z (nm)
L
Γ
Field ~ 35 kV/cm


Optical Excitation
Excitation to L valleys
Energy (eV)
1.0
0.5
0.0
-0.5
-1.0



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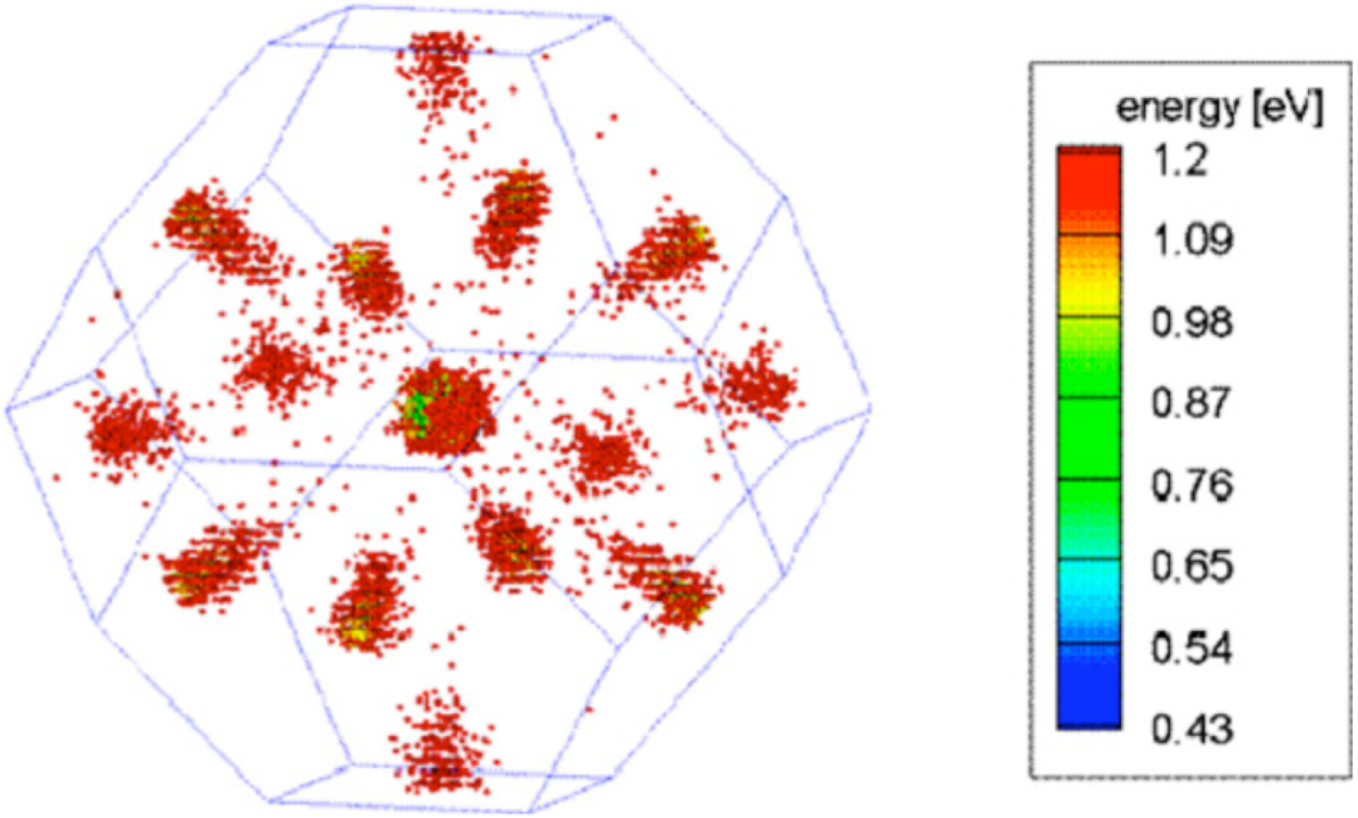
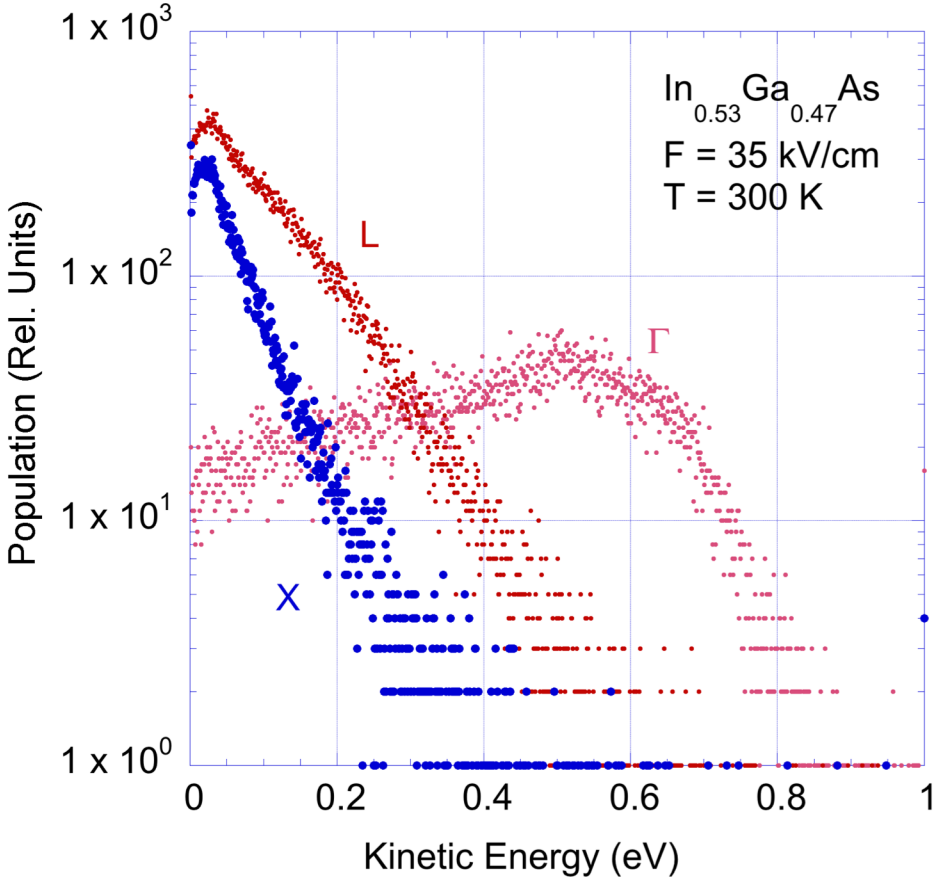
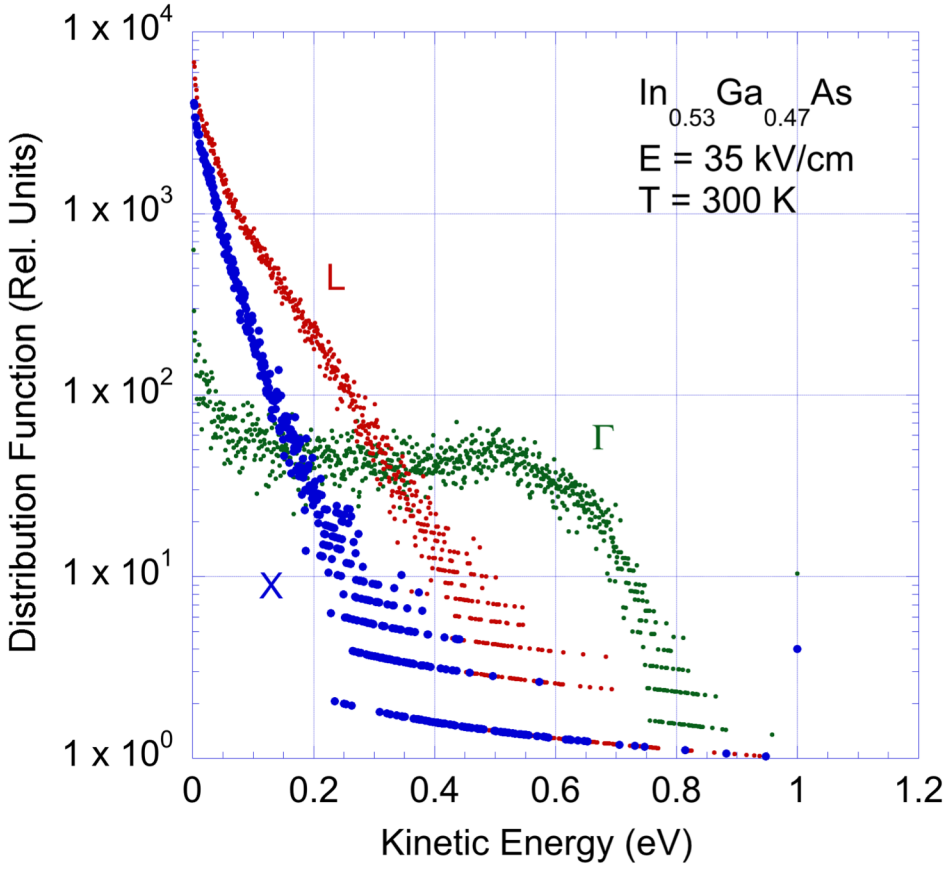


Akis *et al*., J. Phys. Cond. Matter **20**, 384201 (2008)





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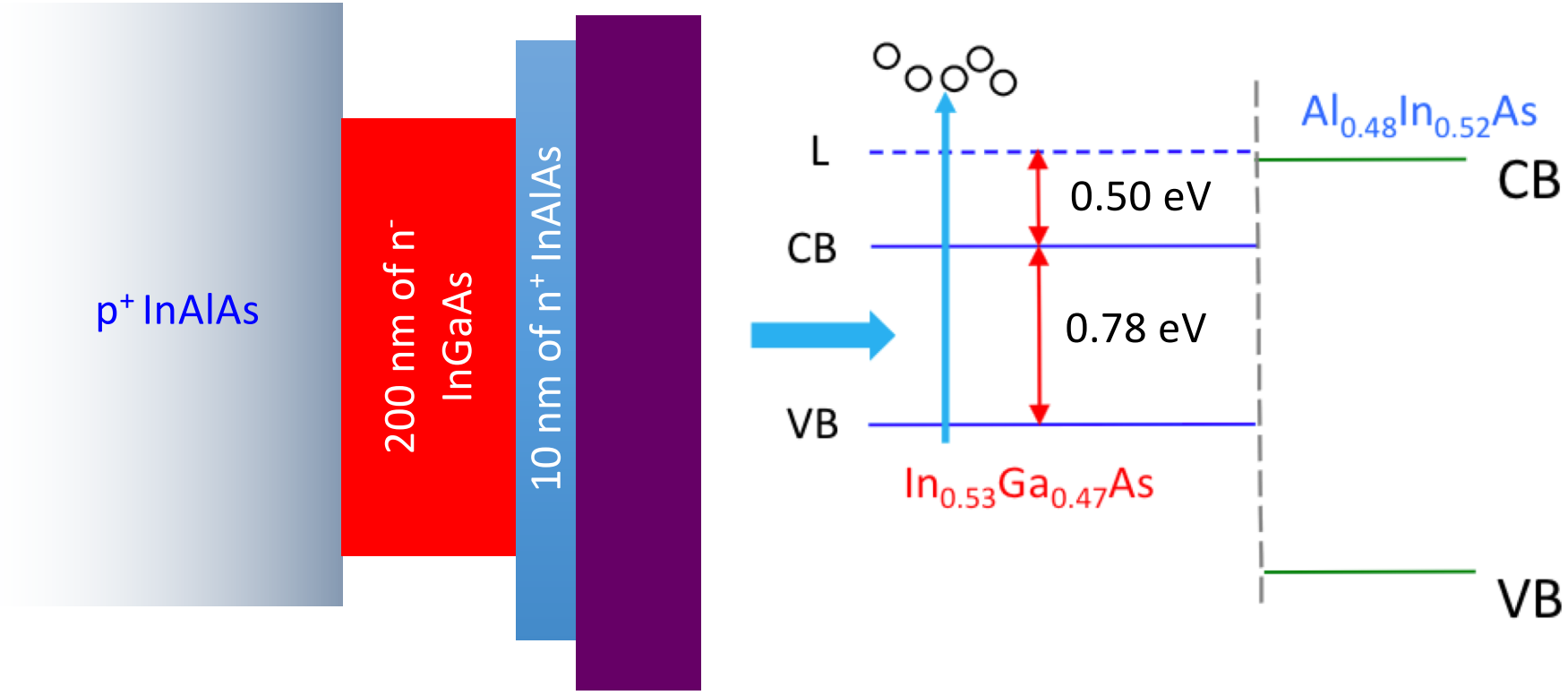
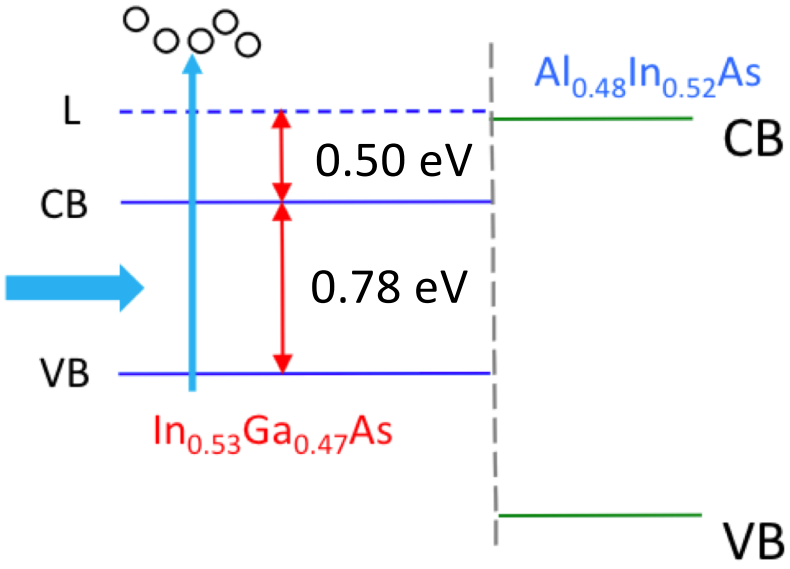
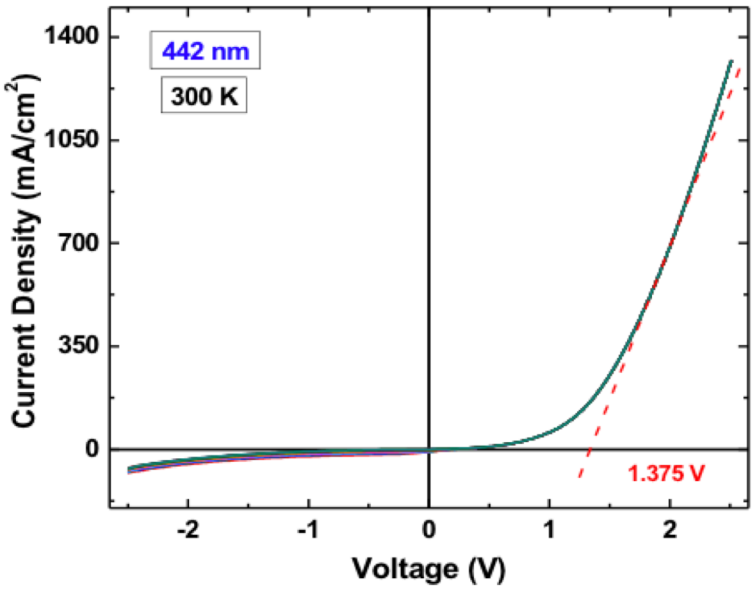
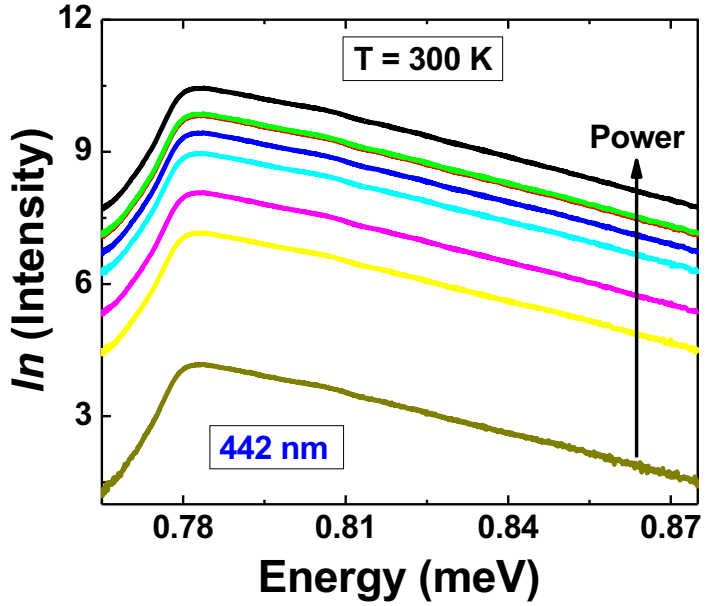
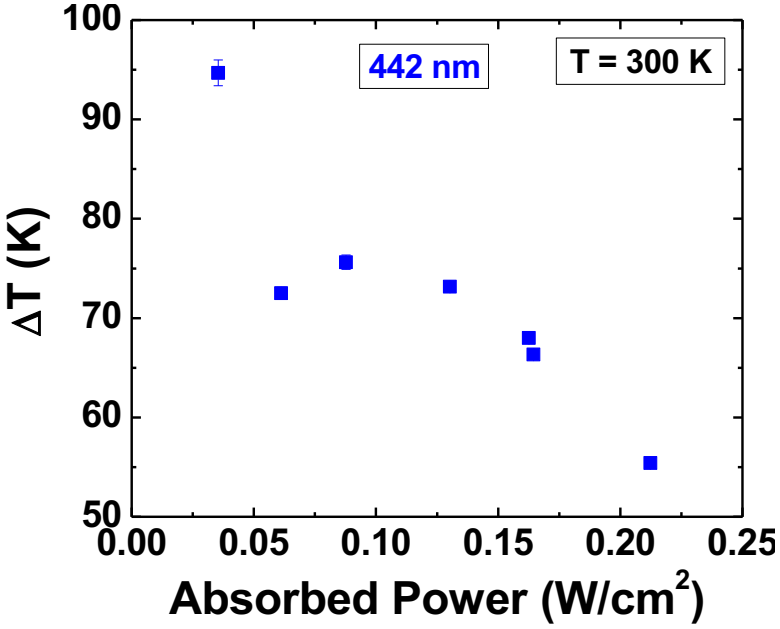

p+ InAlAs
200 nm of n- InGaAs
10 nm of n+ InAlAs
L
CB
VB
0.50 eV
0.78 eV
In0.53Ga0.47As
Al0.48In0.52As
CB
VB

To study where the photocarriers are going, we probed with different light sources:
Esmaielpour *et al*., Nature Energy **5**, 336 (2020)









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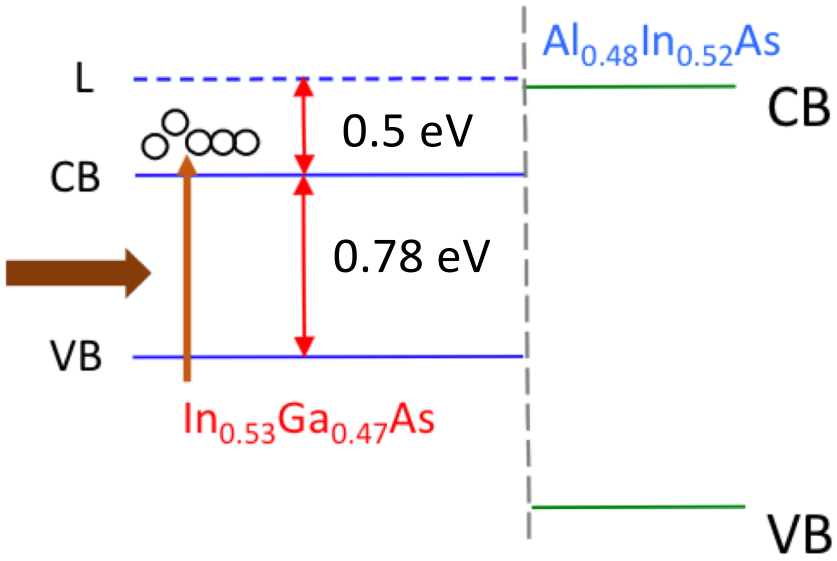
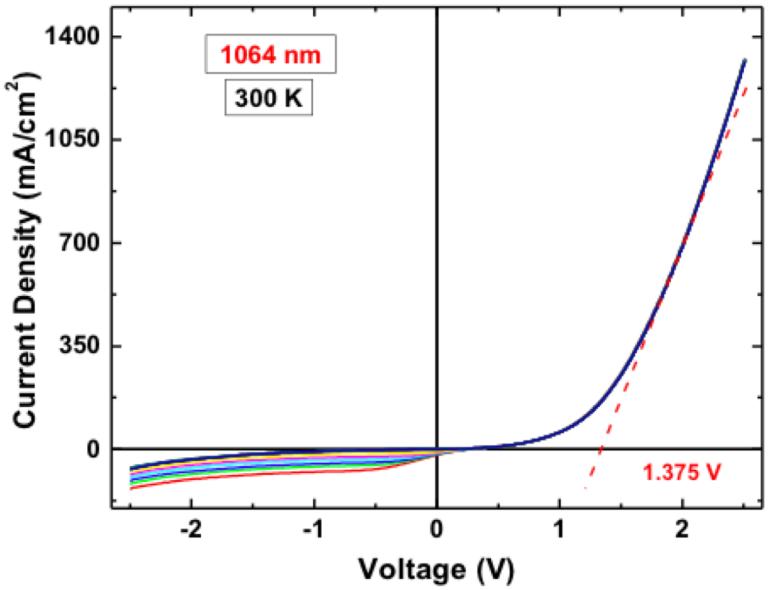
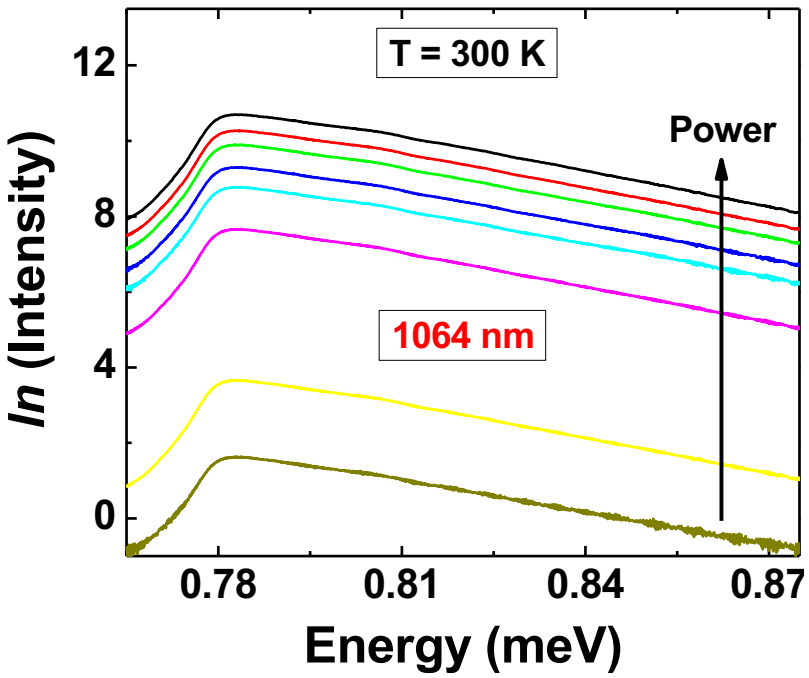
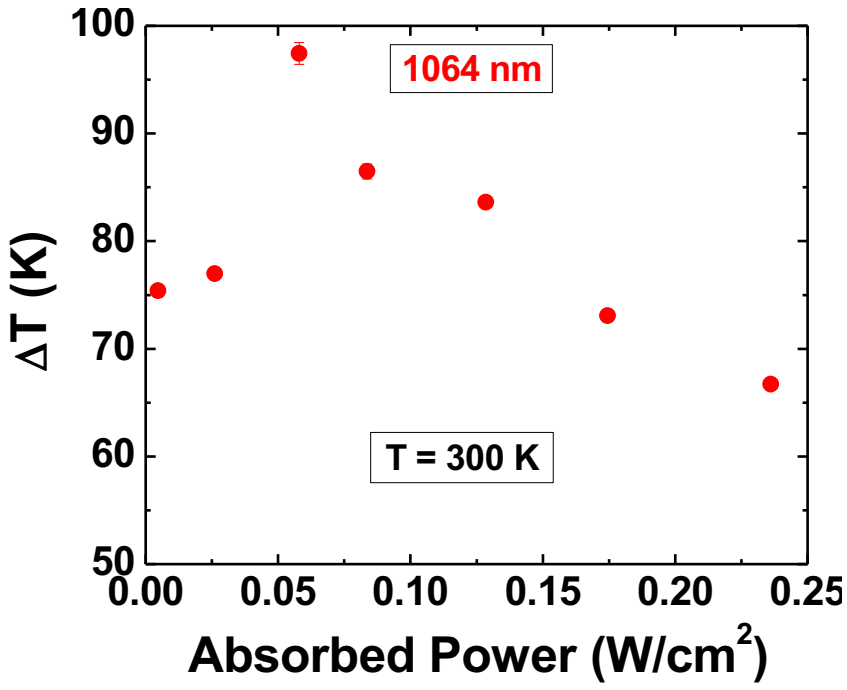


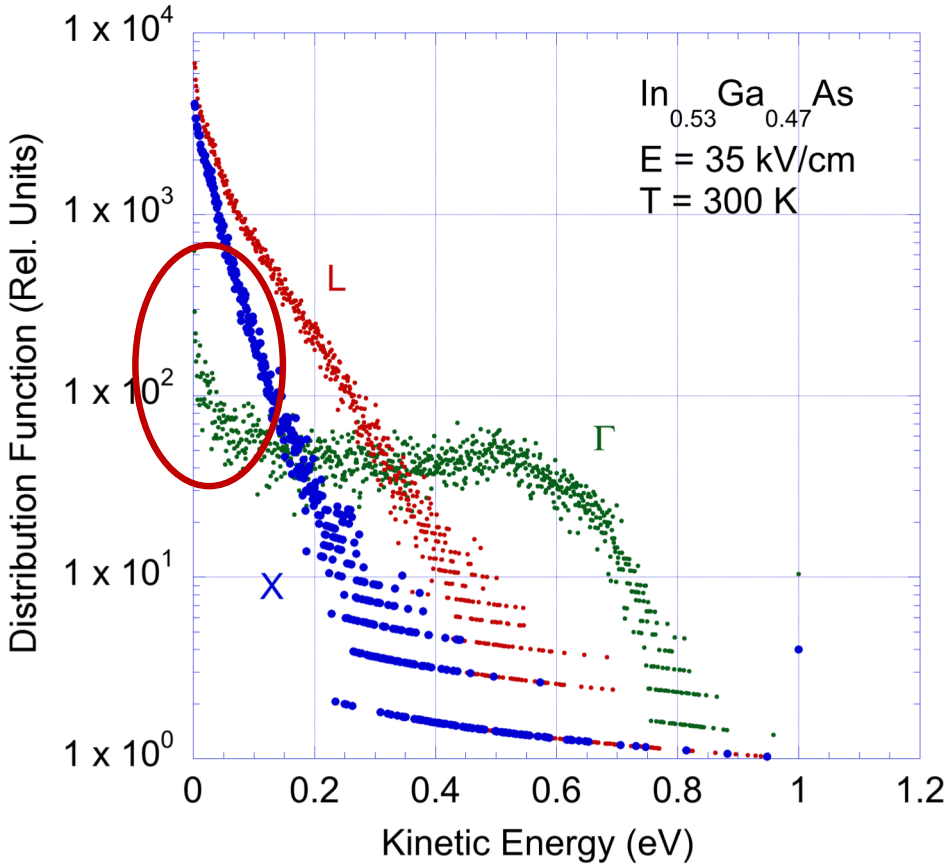






The excess temperature at low energies in the Γ valley (under solar illumination) shows only about 75 ± 25 K, comparable to the PL signals.

PL is coming from Γ valley, but the open-circuit voltage is set by the L valleys!



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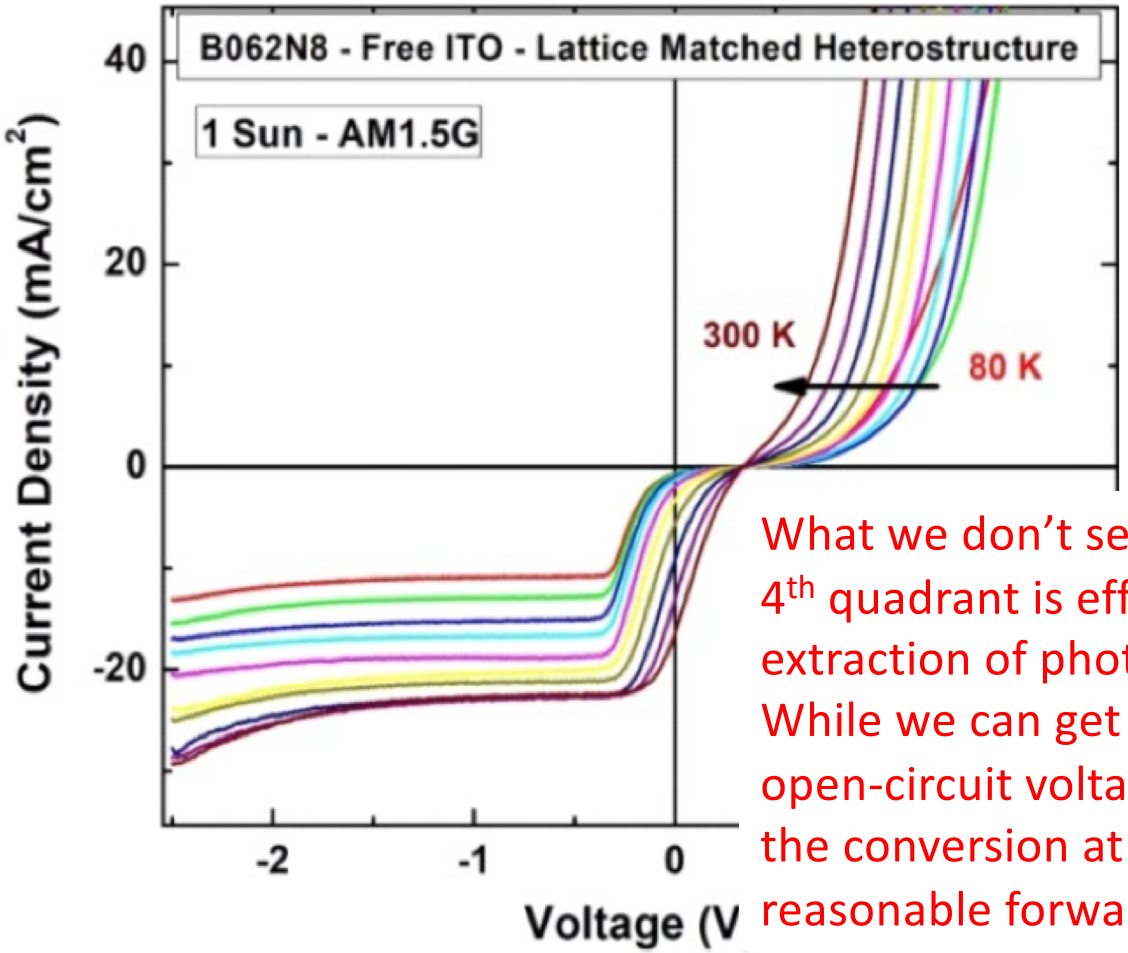

What we don't see in this 4th quadrant is efficient extraction of photo-current. While we can get a nice open-circuit voltage, we lose the conversion at any reasonable forward voltage.

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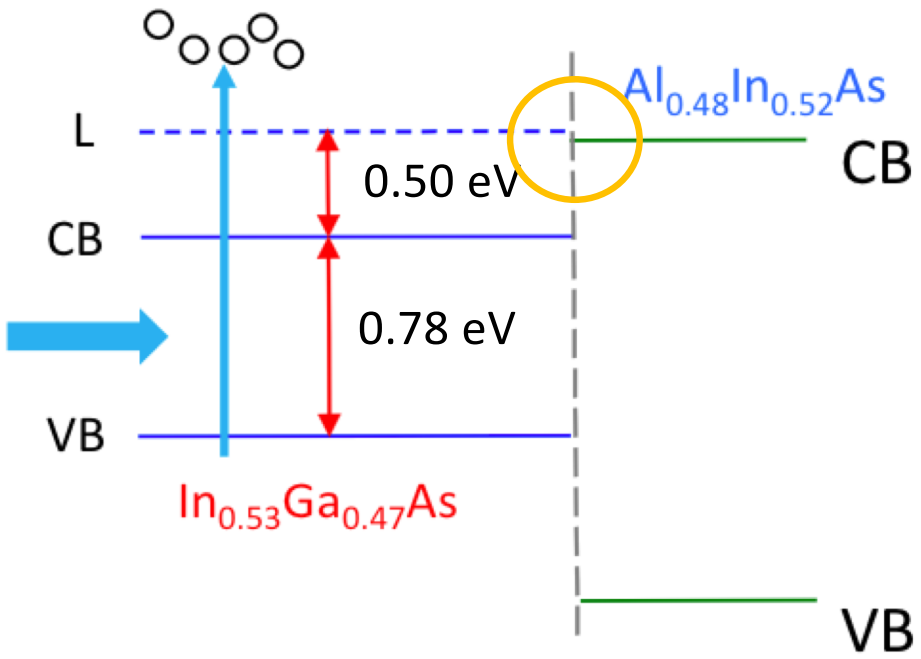
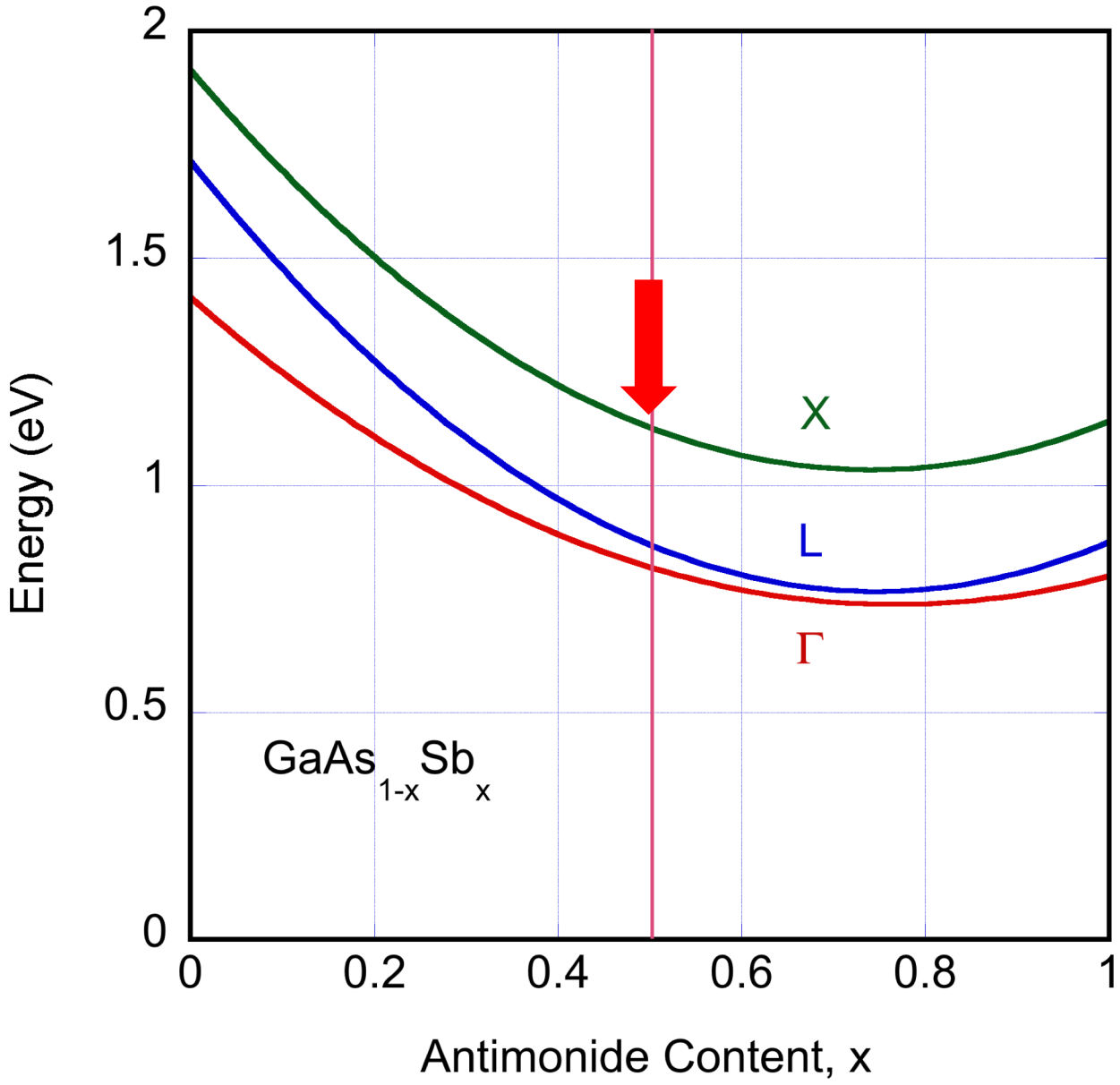
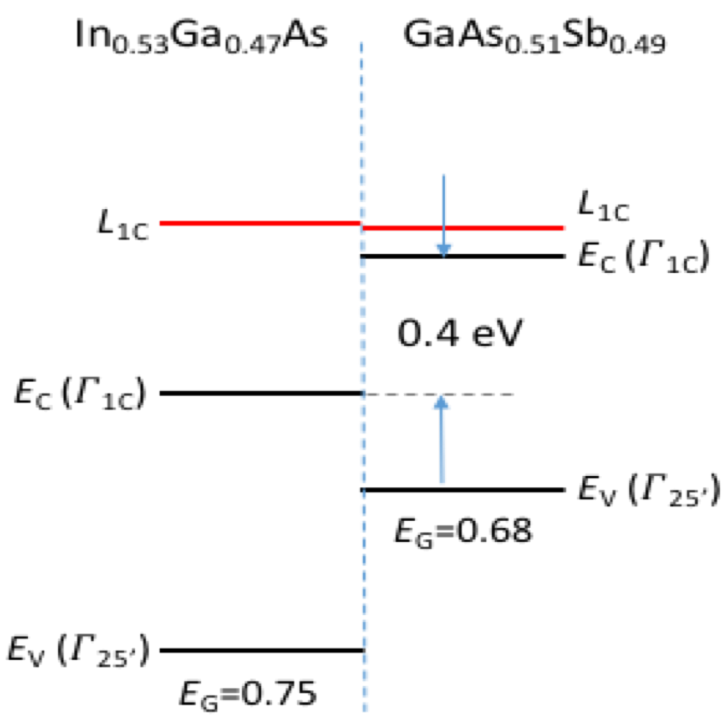


In order to cross this interface, the carriers in the L valleys have to emit/absorb an L phonon to reach the Γ valley of the InAlAs. The L valleys of the latter lie at much higher energy, and the carriers come out either by tunneling or by involving the phonon—*Not good!!*

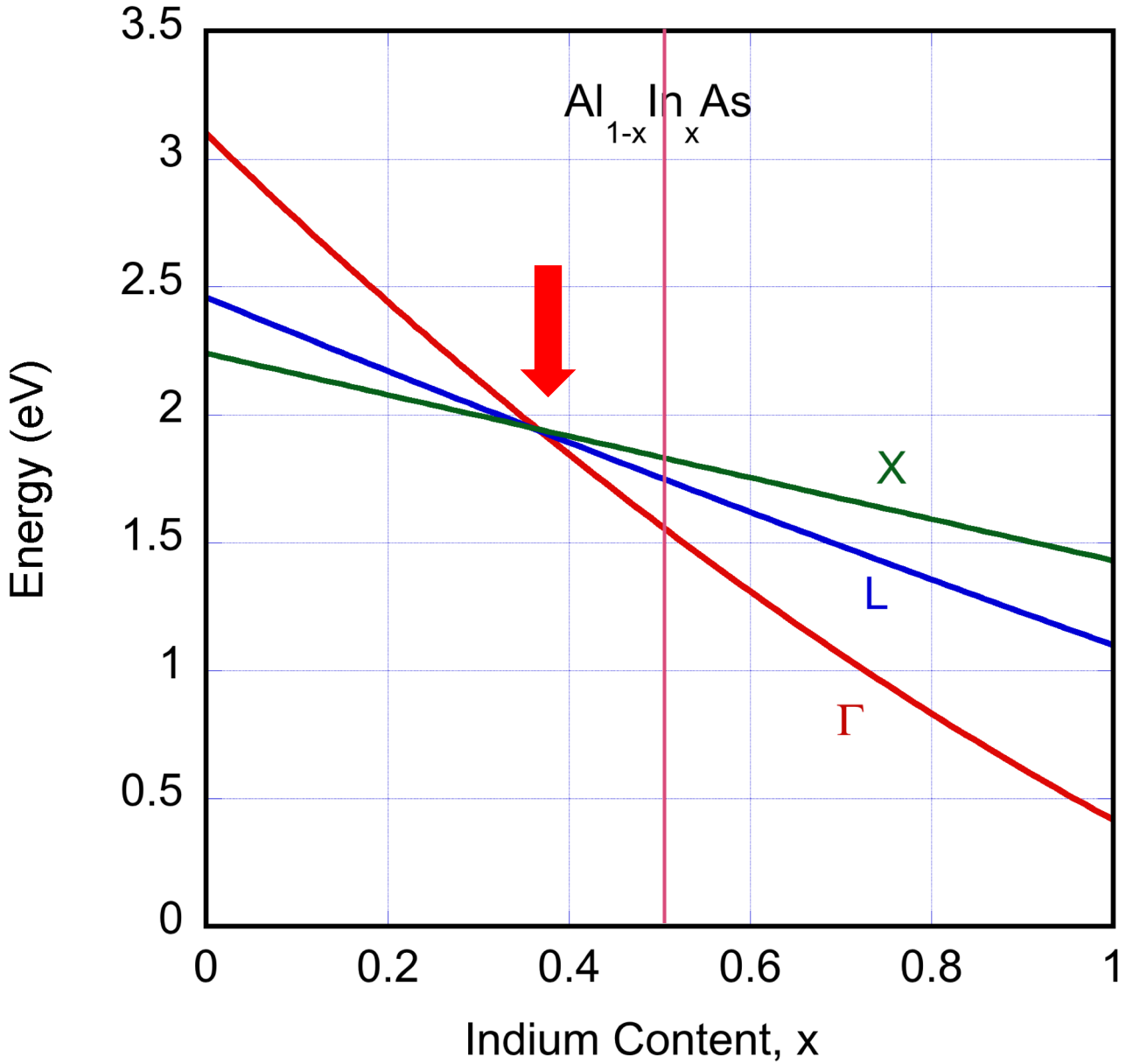
We need a better extraction layer.

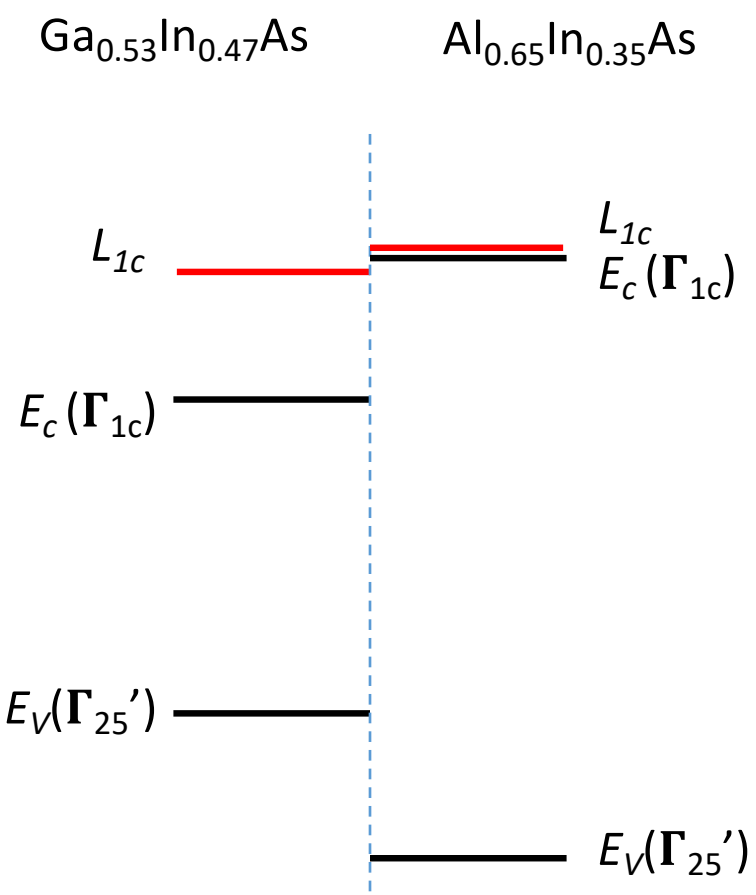
Possible Solutions




$In_{0.53}Ga_{0.47}As$
$GaAs_{0.51}Sb_{0.49}$
L_{1C}
L_{1C}
$E_C\,(\Gamma_{1C})$
0.4 eV
$E_C\,(\Gamma_{1C})$
$E_V\,(\Gamma_{25'})$
E_G=0.68
$E_V\,(\Gamma_{25'})$
E_G=0.75

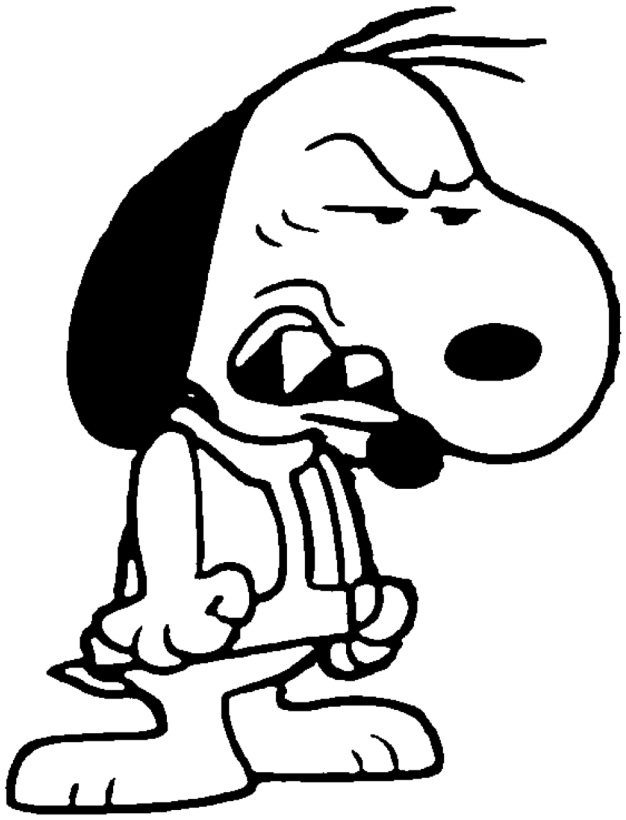
Possible Solutions




$Ga_{0.53}In_{0.47}As$
$Al_{0.65}In_{0.35}As$
L_{1c}
L_{1c}
$E_c(\Gamma_{1c})$
$E_c(\Gamma_{1c})$
$E_V(\Gamma_{25}')$
$E_V(\Gamma_{25}')$

So, the ideas have been supported by some experimental data in cells using an InGaAs absorber layer and a lattice matched AlInAs extraction layer.

We are seeing an open circuit voltage well above the band gap, which suggests the upper valley metastable level is working.



But, we have an extraction barrier, which gives vanishingly small efficiencies in the cell.

We obviously need to do some materials research to find a better extraction layer.

Nevertheless, we are agonizingly close ….


Thanks for your attention!