EFFECT OF OCCUPATION OF THE EXCITED STATES AND PHONON BROADENING IN THE DETERMINATION OF THE HOT CARRIER TEMPERATURE

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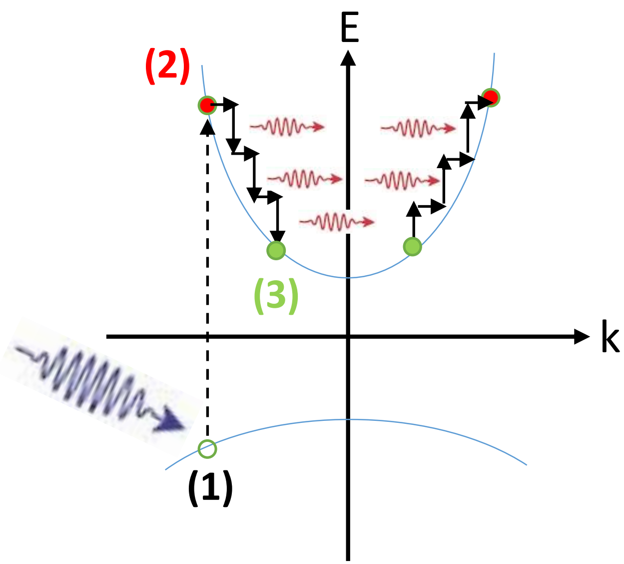
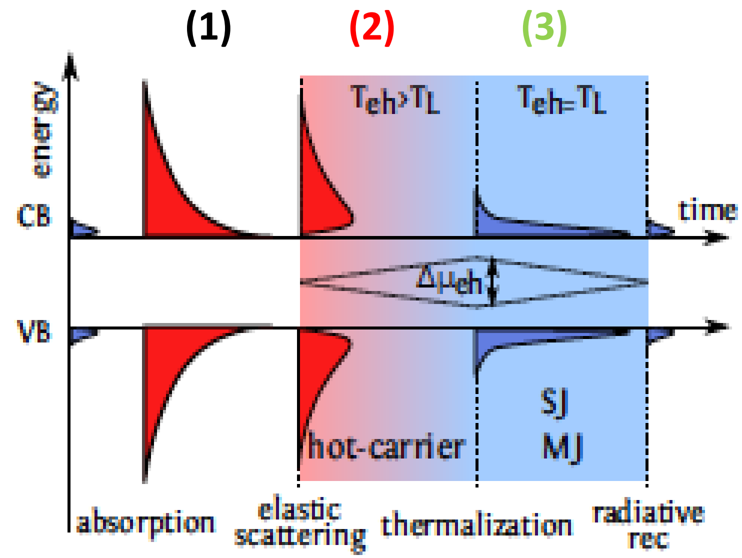
- Introduction: Hot Carrier solar cells
- Generalized Planck's radiation law
- Determination of carrier temperatures and chemical potentials
- Effect of occupation of excited state on carrier temperature determination
- Temperature dependent photoluminescence linewidth broadening

Introduction: Hot Carrier Solar cell

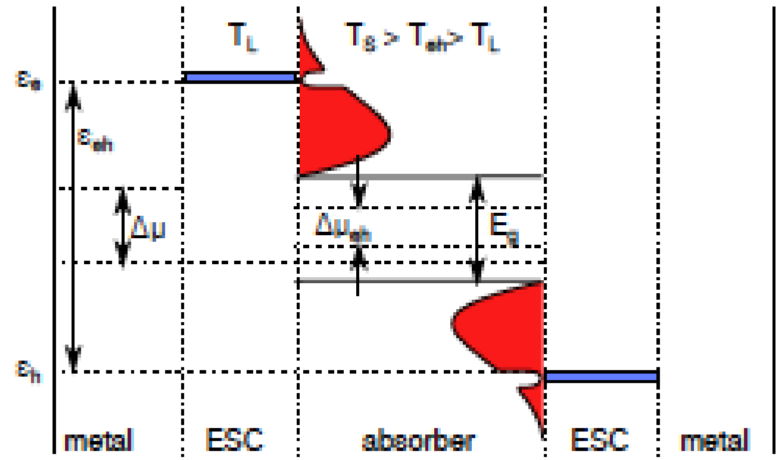




Green, Third generation photovoltaics, p.70, Springer (2006)

Energy selective contacts offer a potential route to efficient hot carrier extraction

- -Increase carrier lifetime
- -extract carriers before relaxation
- -Phonon bottleneck



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

Determination of carrier temperature

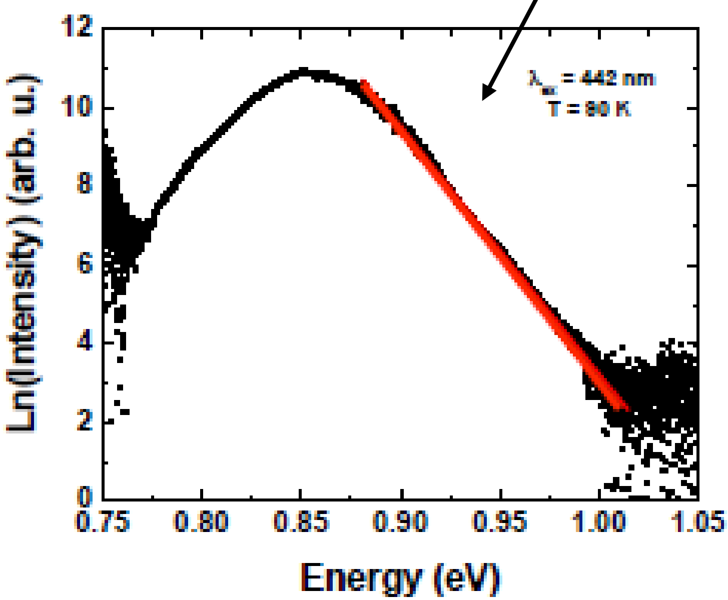
1. Linear fit

$$I_{PL}(h\omega) = \frac{A(h\omega)\,(h\omega)^2}{4\pi^2 h^3 c^2}\left[exp\left(\frac{h\omega - \Delta\mu}{k_B T}\right) - 1\right]^{-1}$$

Generalized Planck's law

- 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)

$$\boldsymbol{ln\,(I_{pl}(hv)) \propto \left(-\frac{hv}{k_B T_{eh}}\right)}$$



- ✓ Simple and useful technique
- ✓ Applicable on PL spectra affected by non-idealities in the sample structure
- X Does not include occupation of excited states
- X **Does not exclude PL linewidth broadening**

Determination of carrier temperature

2. Generalized Planck's radiation law

$$I_{PL}(\hbar\omega) = \frac{A(\hbar\omega)\,(\hbar\omega)^2}{4\pi^2 h^3 c^2}\left[exp\left(\frac{\hbar\omega - \Delta\mu}{k_B T}\right) - 1\right]^{-1}$$

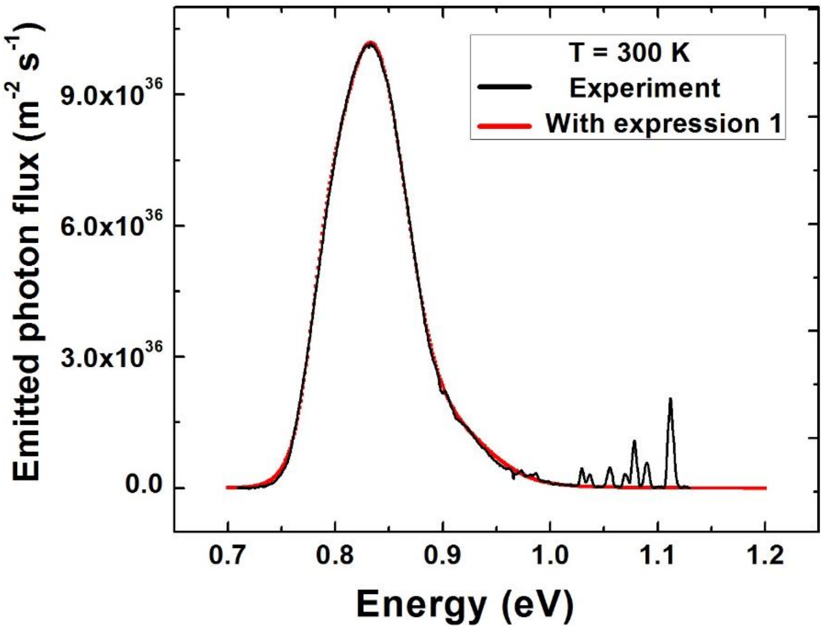
Generalized Planck's law

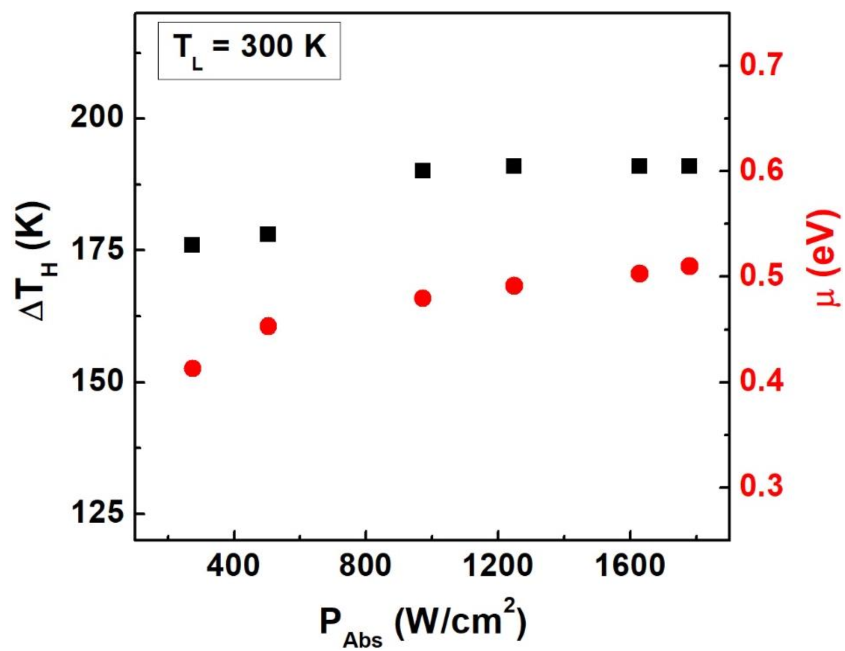
$$A(\hbar\omega) = 1 - \exp(-(A_{lh}\, exp\left(-\frac{(\hbar\omega - E_{lh})^2}{\Gamma_{lh}^2}\right) + A_{hh}\, exp\left(-\frac{(\hbar\omega - E_{hh})^2}{\Gamma_{hh}^2}\right) +$$

$$+ A_C \frac{1}{1 + exp\left(-\frac{(\hbar\omega - E_C)}{\Gamma_C}\right)} \frac{2}{1 + exp\left(-2\pi\sqrt{\frac{E_C - E_{lh}}{|\hbar\omega - E_C|}}\right)}) \, d\,(f_V^e - f_C^e)\,)$$

Absorptivity of the material

- Gibelli, F. et al., *Physica B: Condensed Matter* **498** (2016): 7-14.





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Generalized Planck's law

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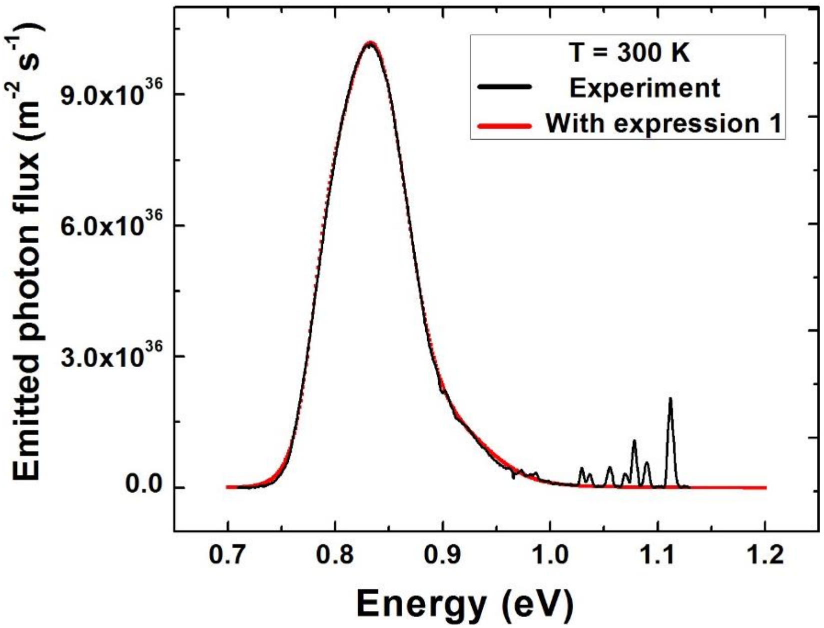


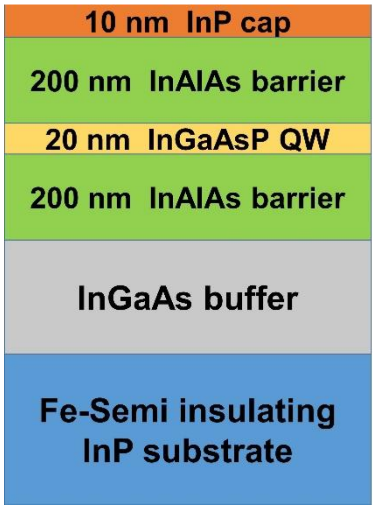
✓ Extraction of carrier temperature and chemical potentials

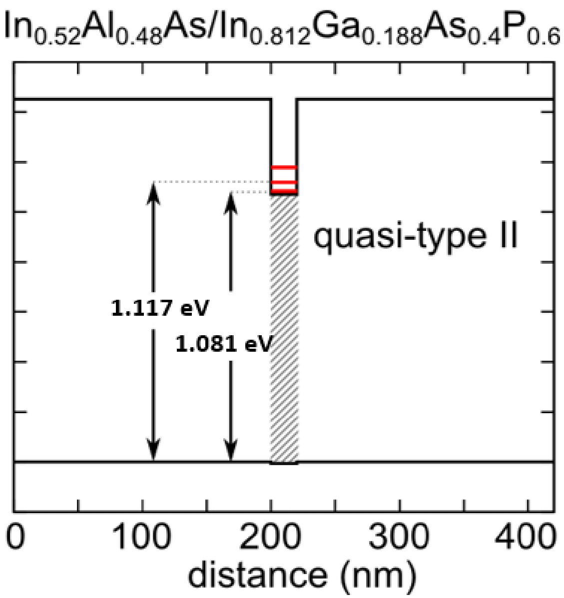
✓ **PL linewidth broadening is included**

X *Not a*pplicable on PL spectra affected by non-idealities in the sample structure

X Several fitting parameters

Quasi-type-II InGaAsP quantum well structure

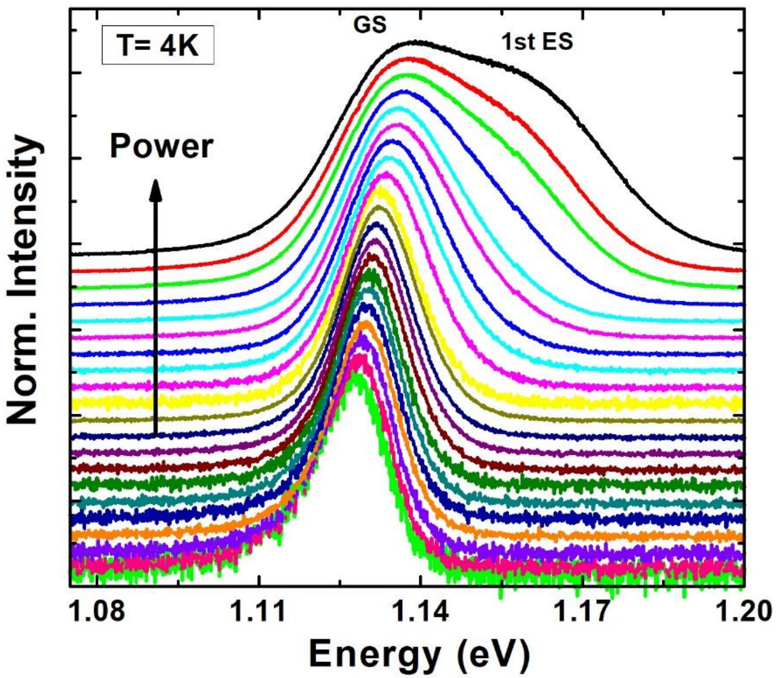




- ❖ Close energy levels in the conduction band: Possibility of occupation of excited states
- ❖ Quasi-type-II structure

Extraction of carrier temperature

- **Occupation of excited states**



❖ By increasing excitation power, a shoulder in the high energy side becomes clear indicative of occupation of 1st excited state.

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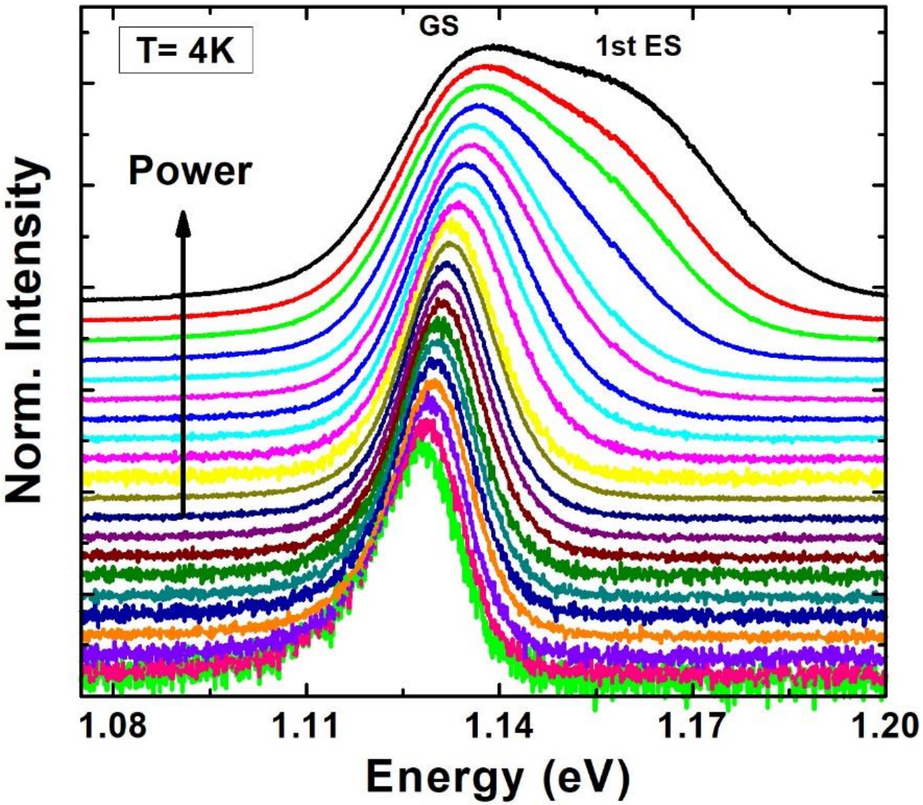
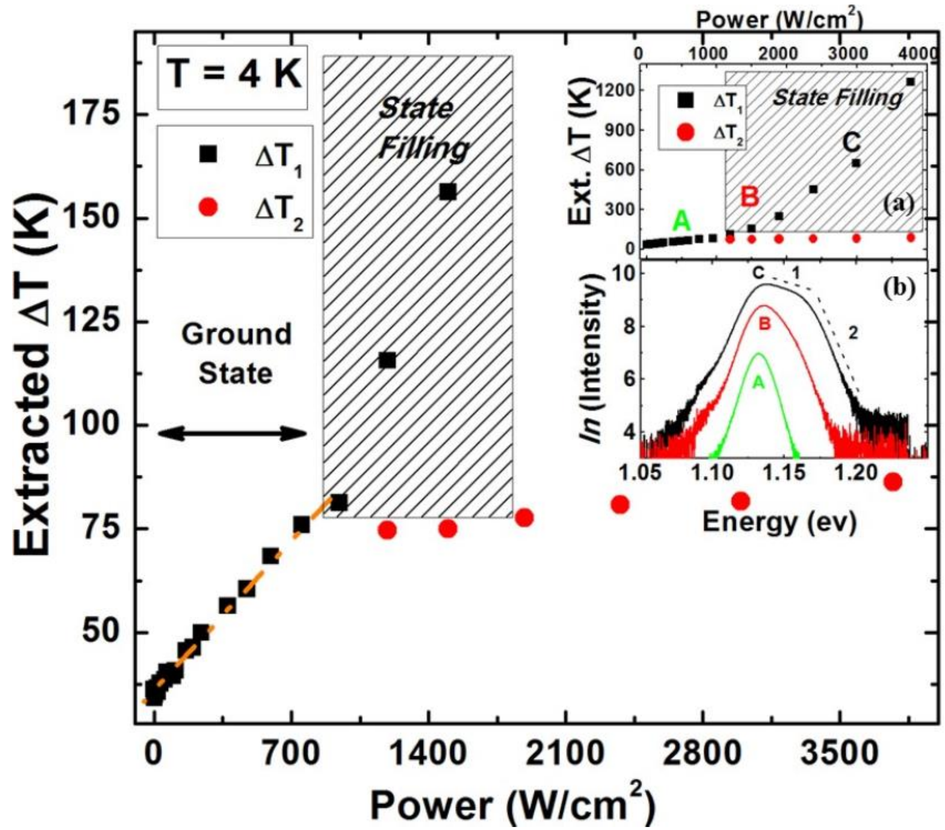
Extraction of carrier temperature

- **Occupation of excited states**





- ❖ There is an increase in the extracted temperature as a function of power
- ❖ Above a certain excitation power (threshold power), there are two extracted temperatures associated with two slopes, as shown in the inset (b)

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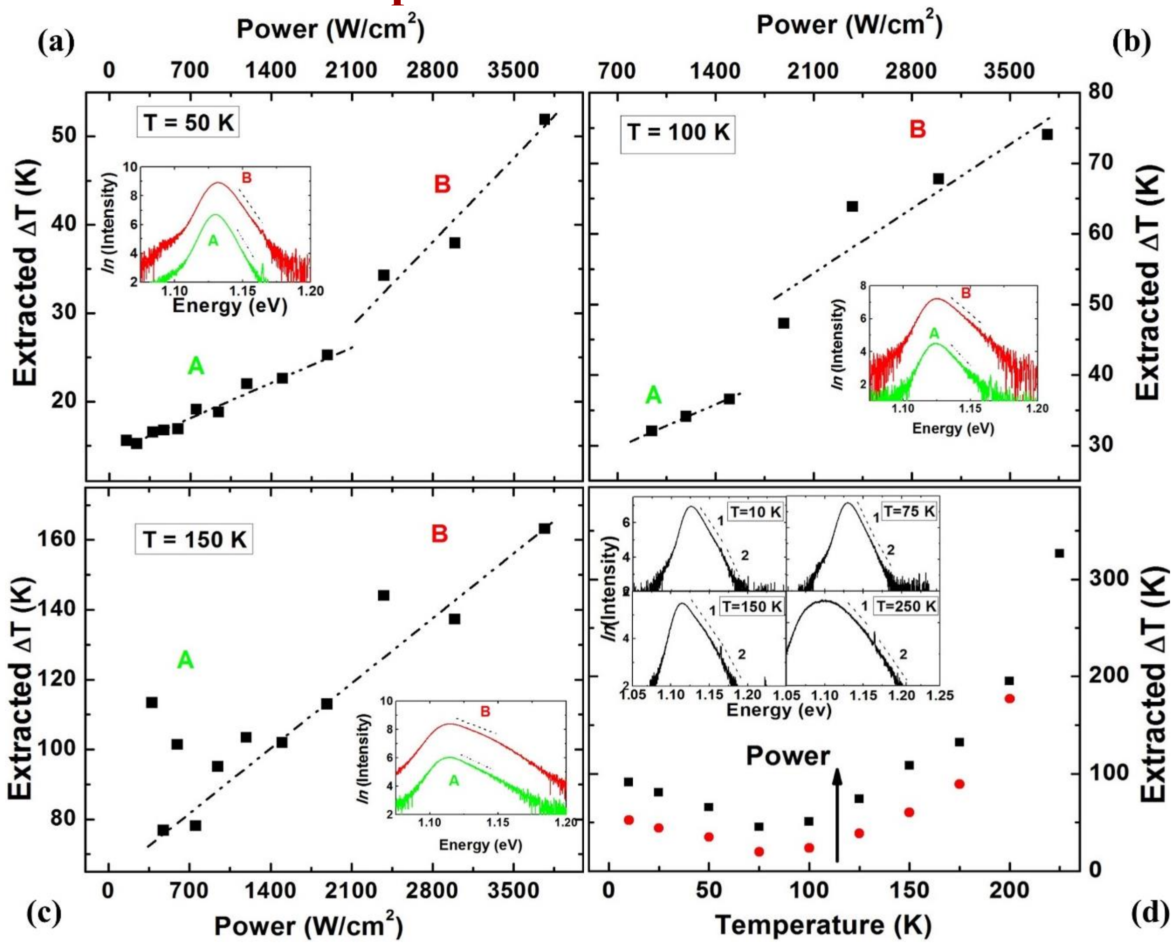
Extraction of carrier temperature

- **Occupation of excited states**



❖ By increasing excitation power, the threshold power shifts to lower values

❖ At elevated temperature (>150 K), electrons occupy 1st excited state even at very low power

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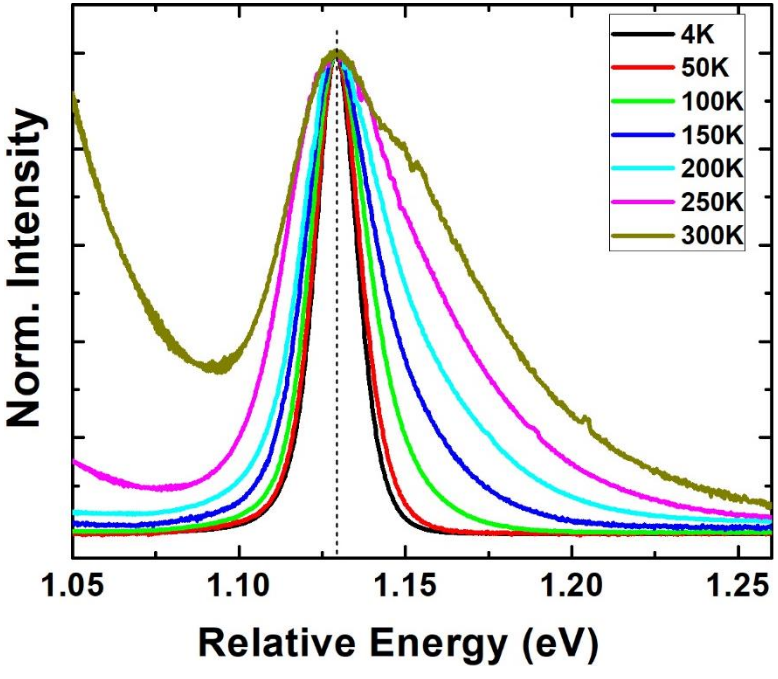
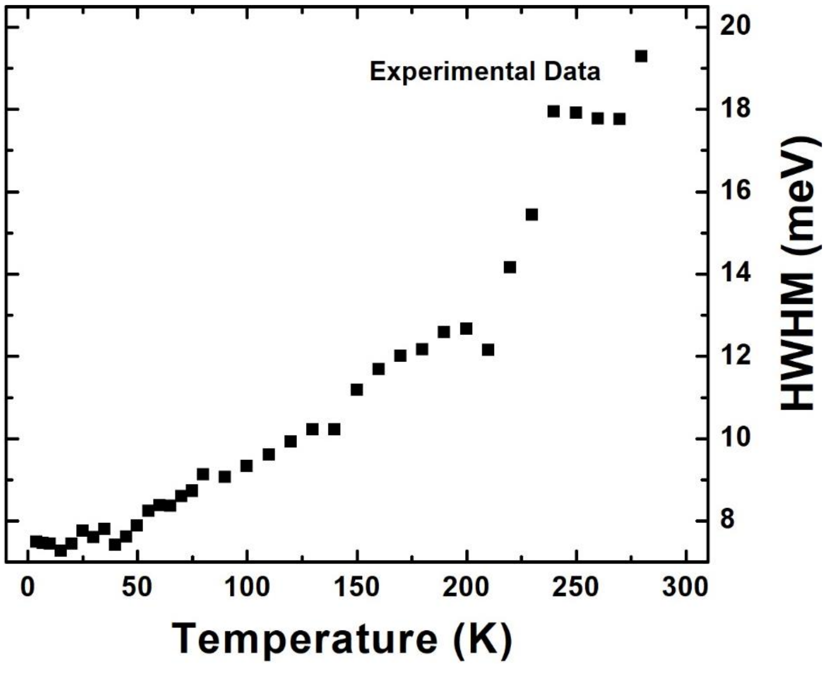
Photoluminescence linewidth broadening

$$\Gamma_{tot}(T) = \Gamma_0 + \Gamma_{LA}\,T + \frac{\Gamma_{LO}}{\left[\exp\left(\frac{h\omega_{LO}}{k_B T}\right) - 1\right]} + \Gamma_{Imp.}\,exp\left(-\frac{E_b}{k_B T}\right)$$

Temperature dependent PL linewidth broadening

E_b : **Ionized impurity binding energy**
$h\omega_{LO}$: **Longitudinal optical (LO) phonon energy**





H. Esmaielpour, V. R. Whiteside, I. R. Sellers et al., *Progress in PV Res. Appl.* ***25****, 782 (2017)*
H. Esmaielpour, V. R. Whiteside, I. R. Sellers et al., *Journal of Applied Physics* **121**, 235301 (2017)

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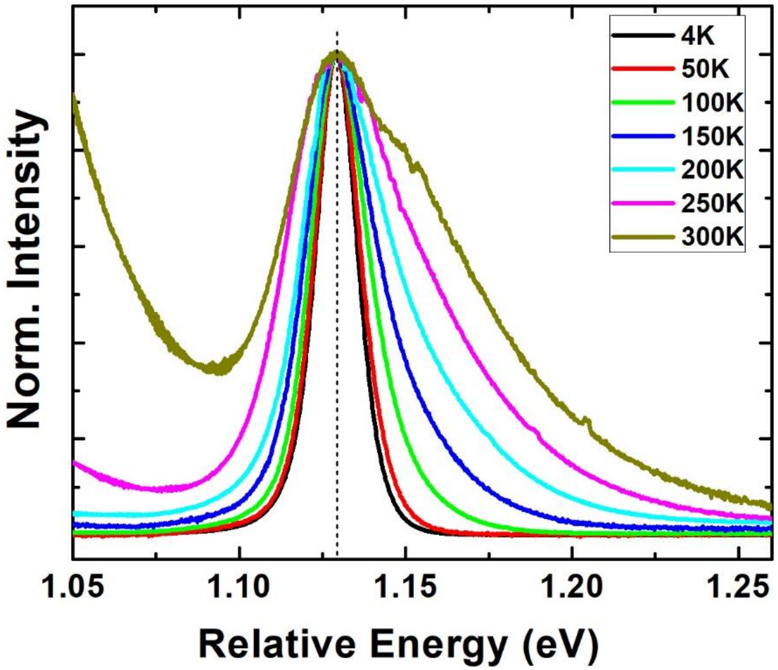

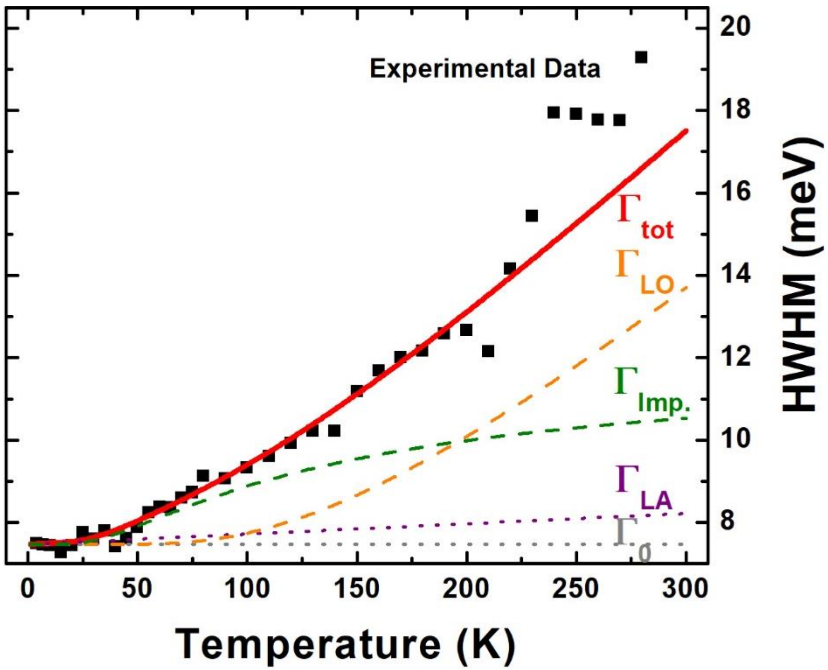

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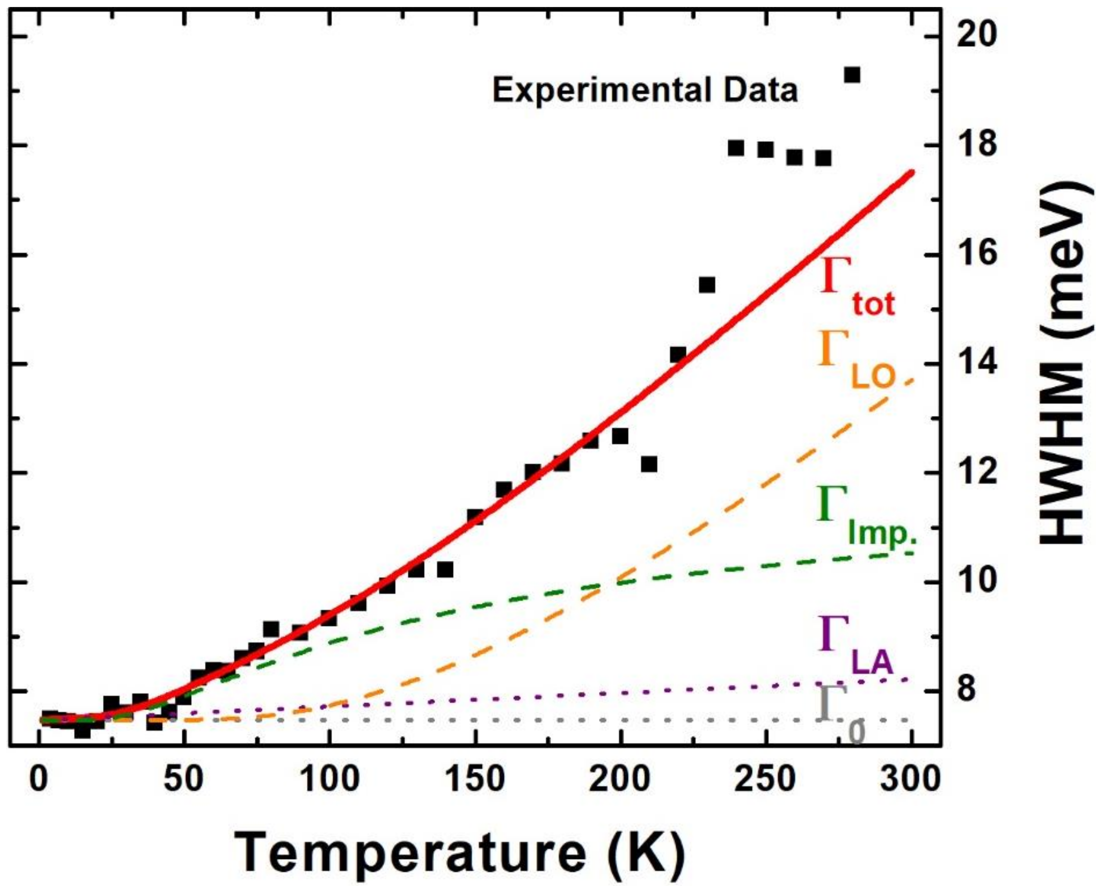
Temperature dependent PL linewidth broadening

E_b : **Ionized impurity binding energy**
$h\omega_{LO}$: **Longitudinal optical (LO) phonon energy**

❖ Linewidth broadening due to LO phonon scattering is dominant above 100 K

- Half-width-at-half-maximum (HWHM) diverges above 200 K due to the effect of occupation of excited states



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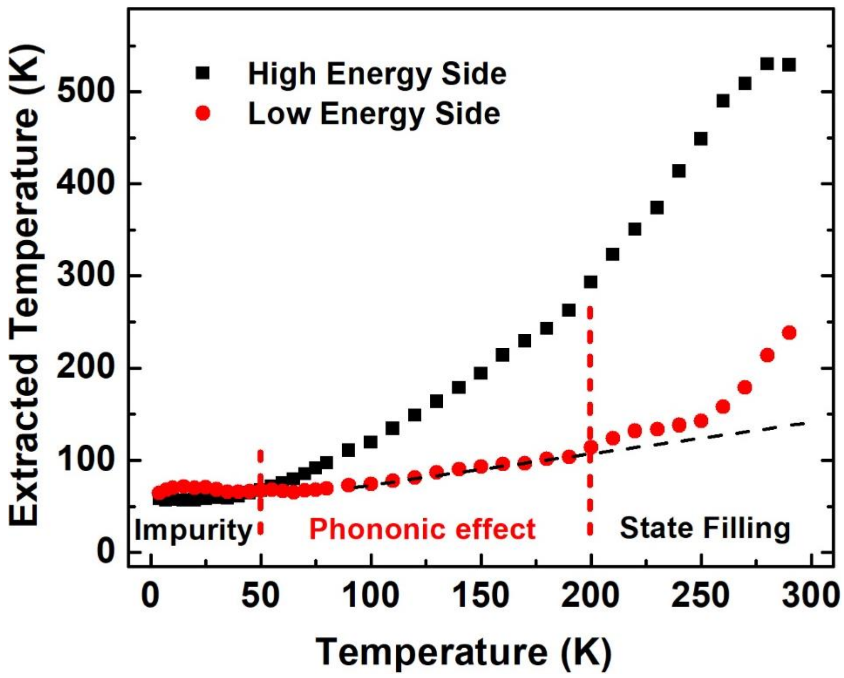
Determination of carrier temperature



- There is a linear regime for the extracted temperature and lattice temperature (50 K < T_L < 200 K)

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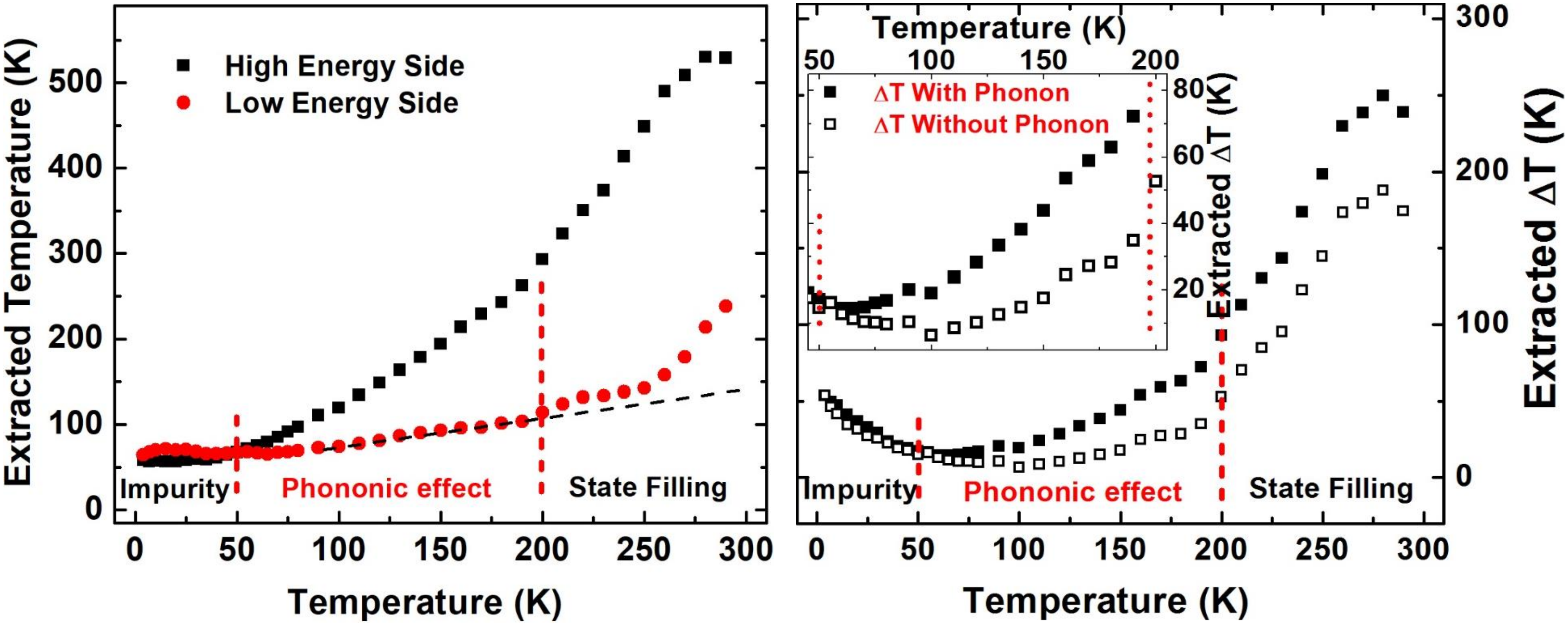
Determination of carrier temperature



❖ Extracted temperature is adjusted by subtracting the contribution of PL linewidth broadening

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Summary

- The effect of occupation of excited states was studied in the InGaAsP QW structure
- PL linewidth broadening of the sample was investigated to evaluate the contribution of each scattering mechanism
- Extracted temperature was adjusted by subtracting the contribution of phonon broadening

Publications

- H. Esmaielpour, V. R. Whiteside, I. R. Sellers et al., *Progress in PV Res. Appl.* ***25****, 782 (2017)*
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