Effects of high optical injection levels in polycrystalline Si wafers on carrier transport

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Motivation

Concentrator photovoltaics:

- Explain efficiency degradation of poly-Si PV solar cells at high optical injection levels seen in previous experiments;

- Relate extended defect density to the observed electrooptical properties of poly-Si and to I-V characteristics of solar cells;

- Explain density-dependent (optical injection-dependent) recombination in polycrystalline Si**;**

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Broader impacts: developing electrical engineering research at Lincoln University (PA): Circuits, Electronics, Optoelectronics, Image Processing.

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Previous work - experiments

- **Reduced fill factors in multicrystalline silicon solar cells** due to injection-level were discussed in:

  D. Macdonald and Cuevas A., *Progress in Photovoltaics: Research and Applications*, **8**, pp. 363-375, 2000.

- **Intensity-dependent changes in equivalent circuit parameters of Si solar cells**:

  E. Connell, A. Semichaevsky, *43rd IEEE-PVSC*, June 8, 2016, Portland, OR.

  D. Nzonzolo, Lilonga-Boyenga, G. Sissoko, *Energy and Power Engineering*, **6**, 25-36, 2014.

- **Recombination lifetimes affected by transition metal impurities:**

  D. Macdonald, Applied Physics Letters, **85**, 4061-4063, 2004

Previous work-models and parameters

- **Injection-dependent recombination lifetimes in poly-Si** were measured, and the contributions of bulk trap, e.g., transition metal (Fe, Ti) interstitials, and surface recombination effects were studied in:

  D. McDonald, Sinton, R.A., Cuevas A., *Journal of Appl. Phys.,* **89**, 2772-2777, 2001,

  J. Schmidt, *Appl. Phys. Lett.*, **82**, pp. 2178, 2003.

- **Quantitative models for Auger recombination** in silicon were discussed in:

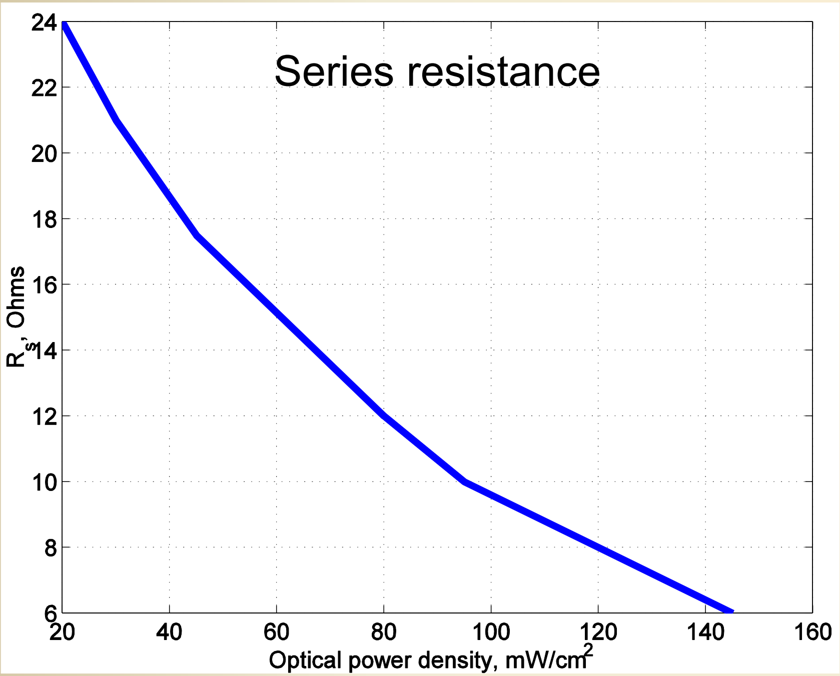
  A. Richter, A. Cuevas, et al., Phys. Rev. B, **86**, 165202, 2012.

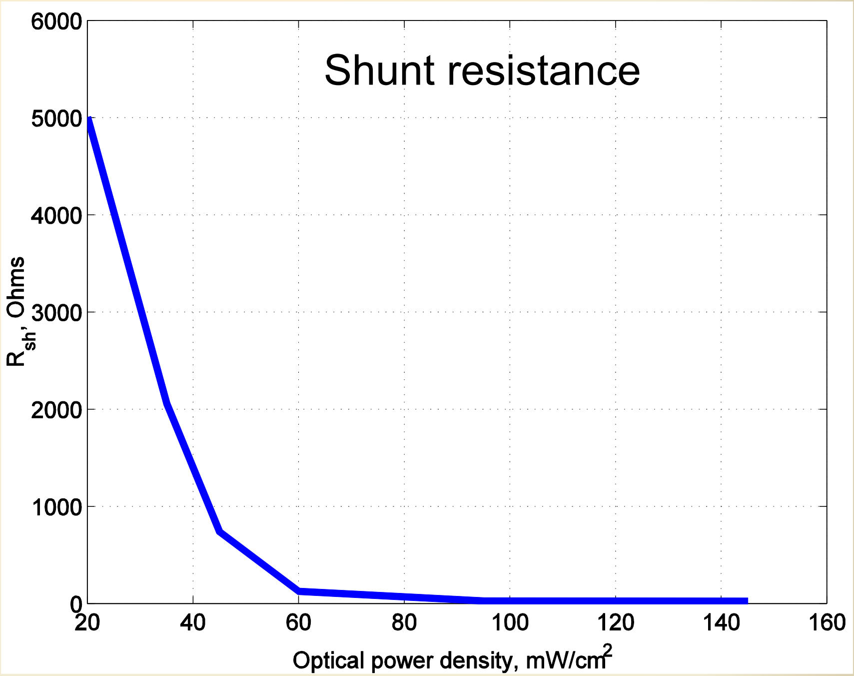
Our experiments

Transient photoconductance decay
at max. intensities of up to 65 Suns (ms- pulses)
Sinton WCT-120 lifetime tester

I-V curve and AC impedance spectroscopy
at intensities of up to 5 Suns (continuous)
Solar simulator, ABET, Inc.

Old experimental results for PV cells





$$R_s = 178.2 P_{opt}^{-0.6403} \Omega,$$

$$R^2 = 0.90$$

$$R_{sh} = 5.2 \times 10^7 P_{opt}^{-3.008} \Omega,$$

$$R^2 = 0.92$$

E. Connell, A. Semichaevsky, presented at 43rd IEEE-PVSC, Portland, OR, June 2016.

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Interpretation of old measurements

What is the meaning of $R_{sh} \sim (P_{opt})^{-3}$?

Steady-state 1-D transport of minority electrons by diffusion:

$$G - \frac{np}{\tau_n p + \tau_p n} - (C_n n + C_p p)np + \frac{\mu_p kT}{e}\frac{d^2 n}{dx^2} = 0$$

$$G - k_S \Delta n - k_a (\Delta n)^3 + D\frac{d^2(\Delta n)}{dx^2} = 0, \quad \mathrm{G} = kP_{opt}$$

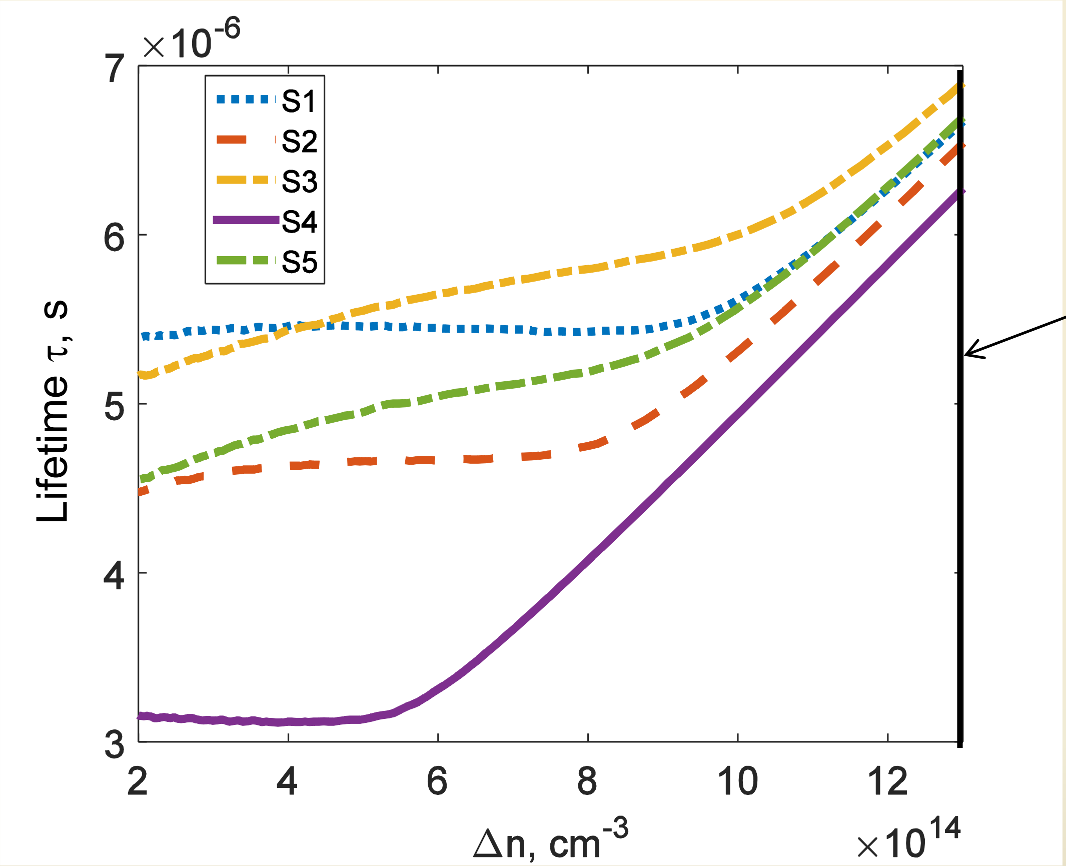
Diffusion current density: $J_d = -D\frac{d\Delta n}{dx} \approx J_S - J_R$

Equivalent shunt resistance: $R_{sh} \approx \frac{V_{oc}}{J_R A}$

Answer: yes, $R_{sh} \sim (P_{opt})^{-3}$ suggests higher-order recombination processes in finished Si PV cells.

Results for carrier lifetimes

Density-dependent lifetimes, p-type Si

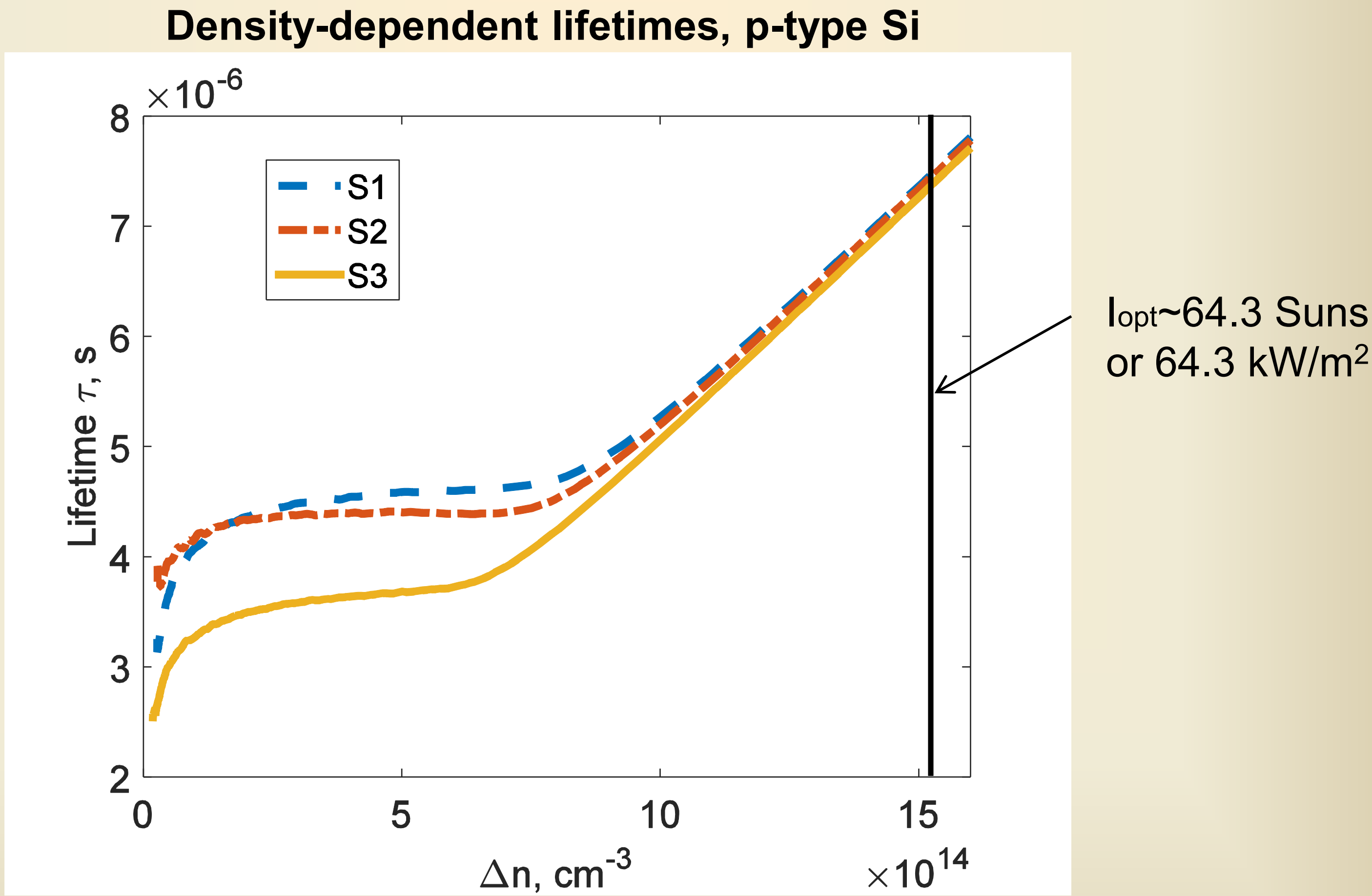


I_{opt}~61.6 Suns or 61.6 kW/m^2

We observed significant variability in lifetime dependences on injection level among the samples that come from different batches.

U. Anyanwu, C. Harris, A. Semichaevsky, submitted to *44th IEEE-PVSC*, Washington, DC, June 2017 and *to IEEE Journal of Photovoltaics*, 2017.

Results for carrier lifetimes



Lifetime dependences on optical injection converge at high intensities for the samples that come from the same batch.

Contribution of Auger recombination

- Using the model described in A. Richter, A. Cuevas, et al., Phys. Rev. B, **86**, 165202, 2012.

$$C_{\mathrm{n}} = 2.8\times10^{-31}\,\frac{cm^6}{s}, C_{\mathrm{p}} = 9.9\times10^{-32}\,\frac{cm^6}{s}$$

the **relative contribution of Auger recombination is expected to be small**. $I_{opt} = 0...65 Suns,\ \Delta n_{\max} \approx 2\times10^{15}\,cm^{-3}$

For

$$\tau_{Auger} = \frac{1}{(C_n + C_p)\Delta n^2} \approx 0.65s >> \tau_{eff} \approx 10^{-5}\,s$$

Theory

- Transport modeling

$$\frac{\partial n}{\partial t} = G(t) - R(n, p) + \nabla \cdot [-\mu_n n \nabla \Phi + \frac{\mu_n kT}{e} \nabla n],$$

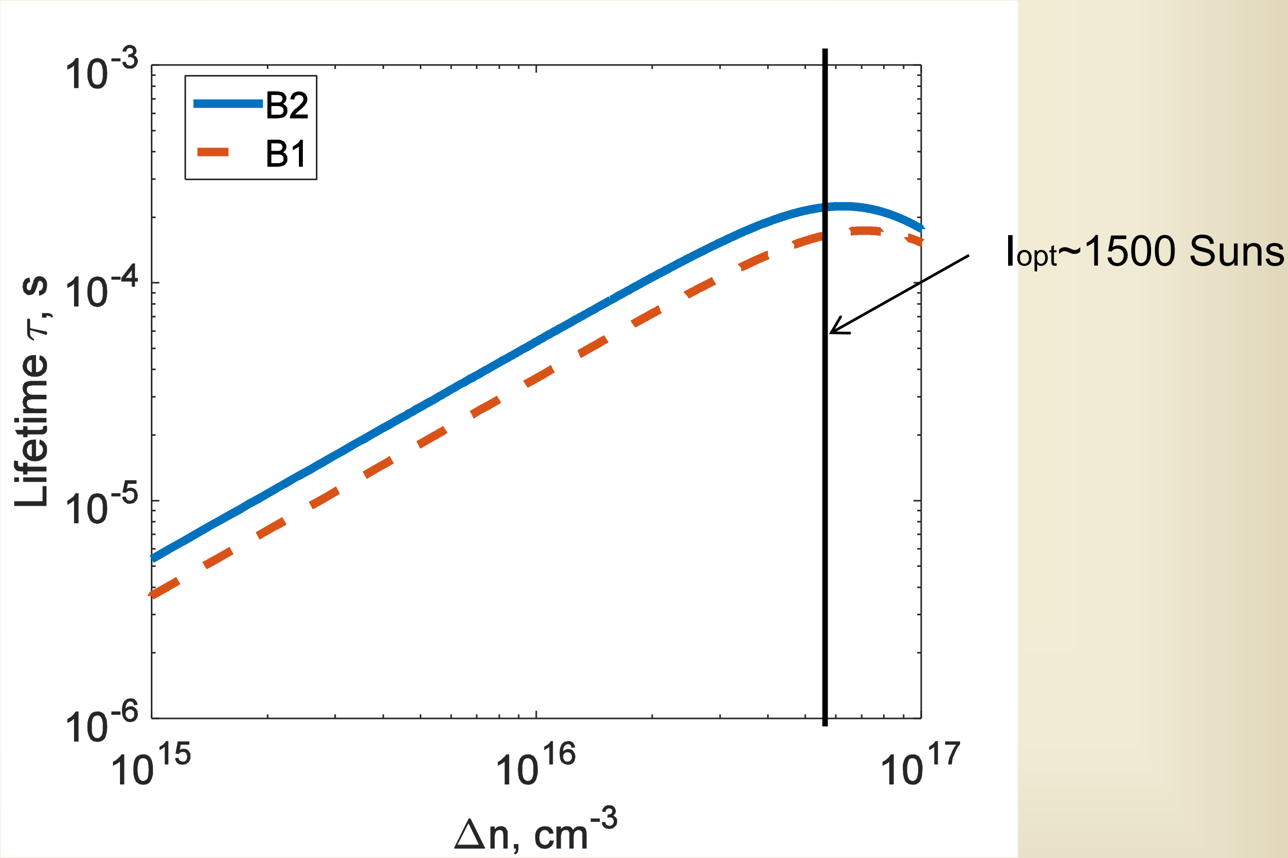
$$\frac{\partial p}{\partial t} = G(t) - R(n, p) - \nabla \cdot [-\mu_p p \nabla \Phi - \frac{\mu_p kT}{e} \nabla p]$$

- Measurements of injection-dependent lifetimes/recombination rates (Sinton, Inc.)

$$R_{SRH} = \frac{np}{\tau_n p + \tau_p n}, \quad R_{Auger} = (C_n n + C_p p)np$$

$$\frac{1}{\tau(n)} = \frac{1}{\tau_{SRH}(n)} + \frac{1}{\tau_{rad}(n)} + \frac{1}{\tau_{Auger}(n)} \approx An^3 + Bn^2 + Cn + D$$

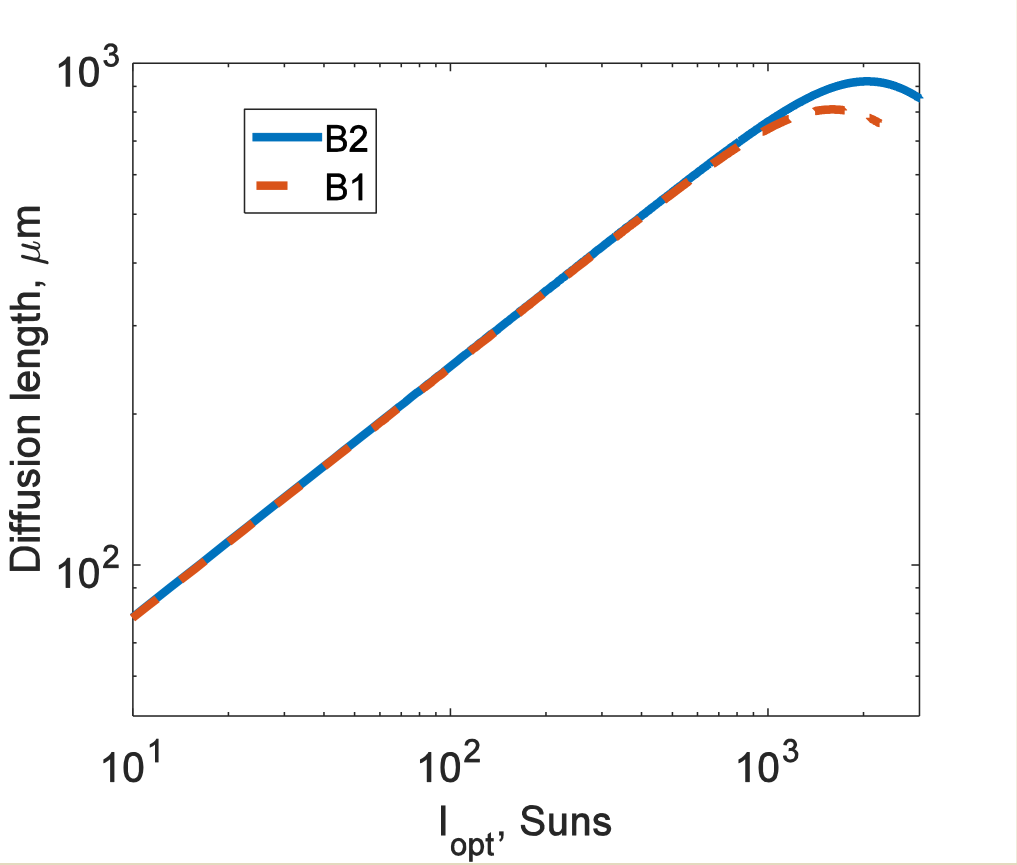
Extrapolated effective NR lifetime



$$\tau(n) \approx 1/(\frac{1}{\tau_{SRH}(n)} + \frac{1}{\tau_{Auger}(n)})$$

Extrapolated diffusion length for e

$$L_n = \sqrt{D_n \tau_{eff}} \text{ at T} = 300\text{K}$$



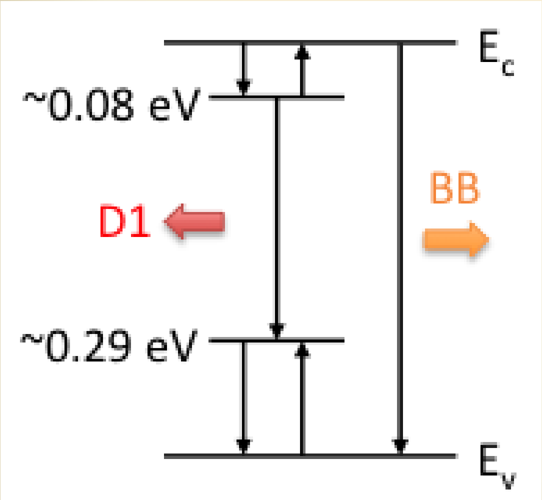
Conclusions

- SRH recombination process is identified to be dominant from PCD studies at incident intensities of up to 65 Suns;
- Macroscale (semi-classical) transport models are suitable for assessing effects of injection-dependent recombination;
- PL IR images help identify densities of extended defects that mediate recombination;
- Research in the project is highly suitable for both Engineering Science and Physics majors.

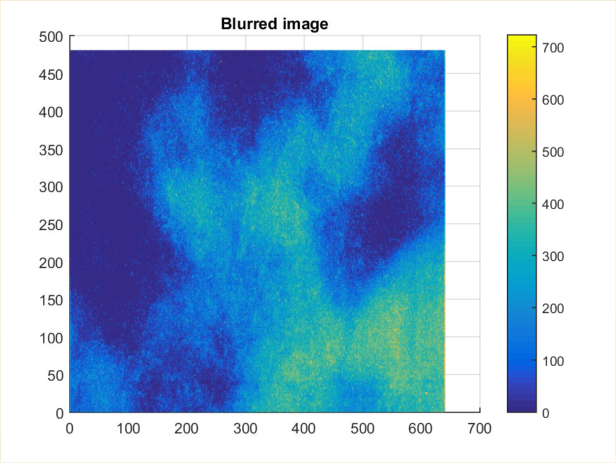
Future work: effects of microstructure

- Information about defects in poly-Si comes from IR PL images from Harley T. Johnson's group at UIUC;

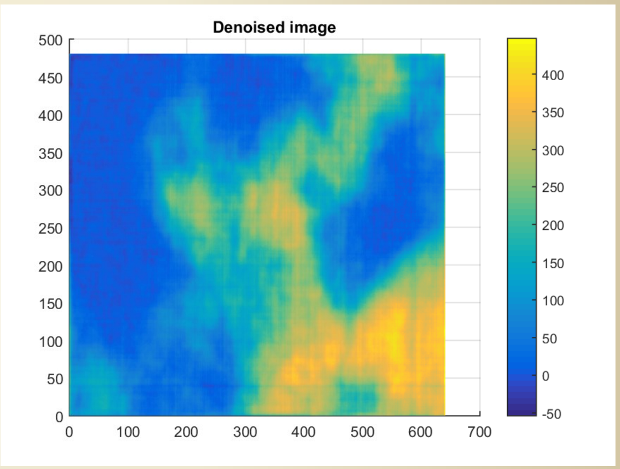
Spectral signature of a dislocation in poly-Si



Raw PL image



Processed PL image



PL images were taken at UIUC under the support of the NSF GOALI award 1300466.

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Thank you for your attention.