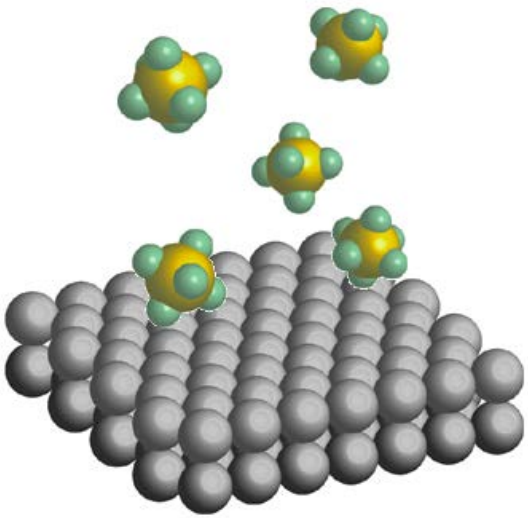
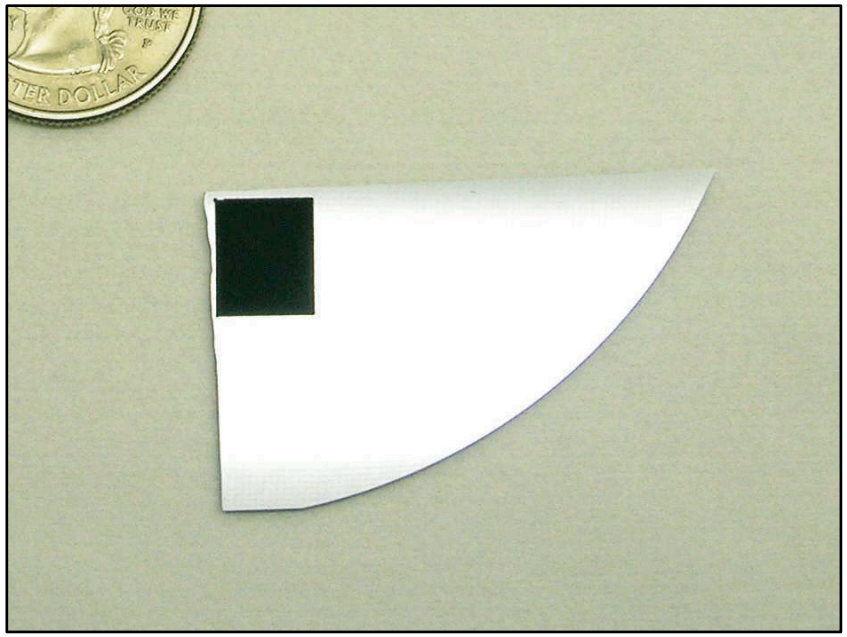
Nanosecond laser annealing of hyperdoped black silicon

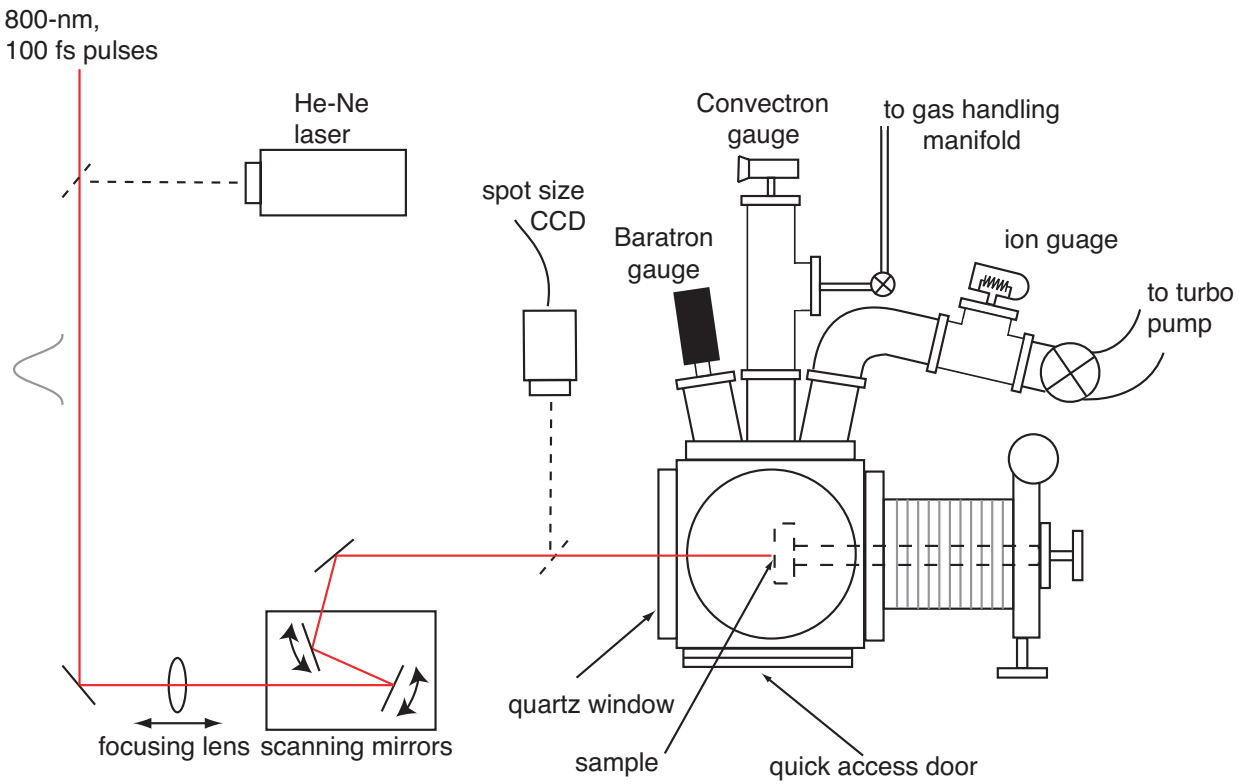
Benjamin Franta (Mazur Group, Harvard)

Hyperdoped black silicon

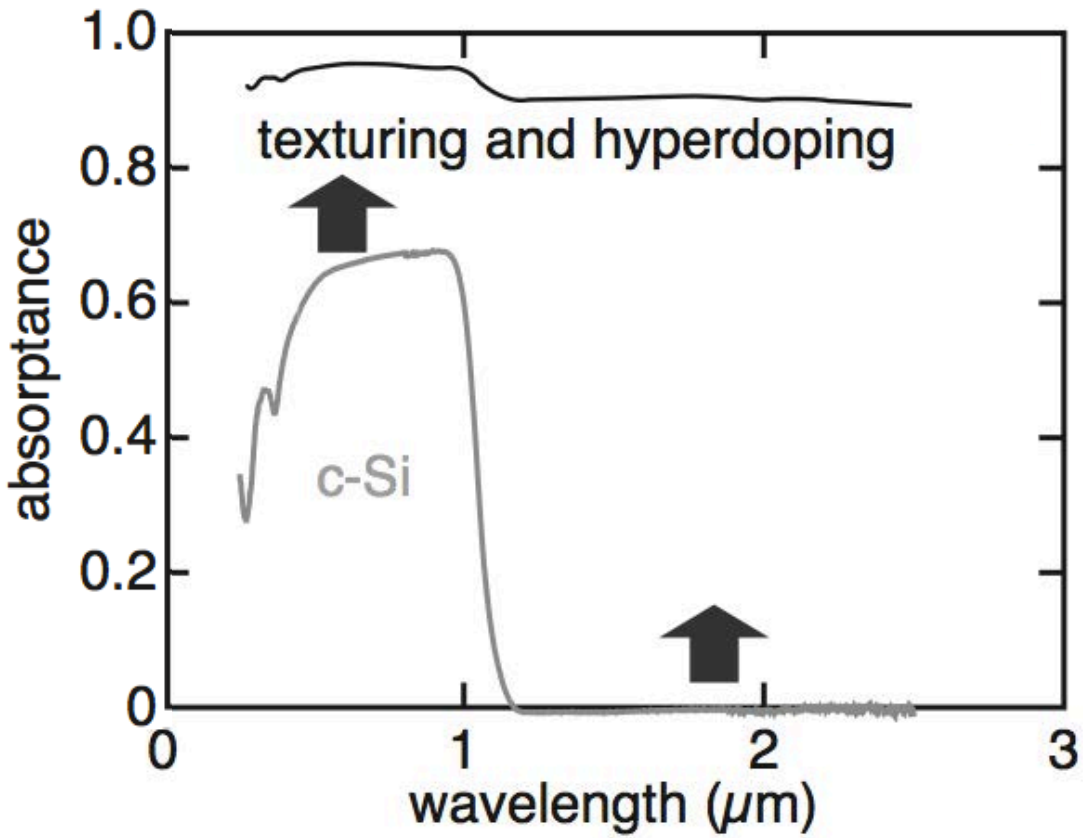




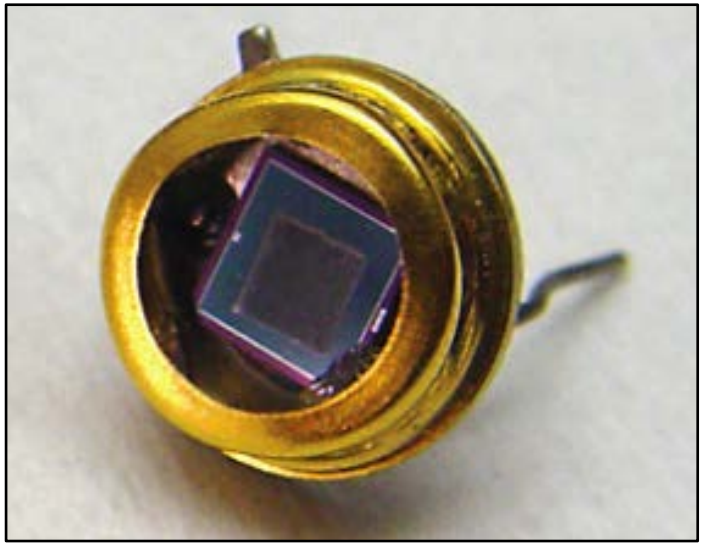
Fabrication

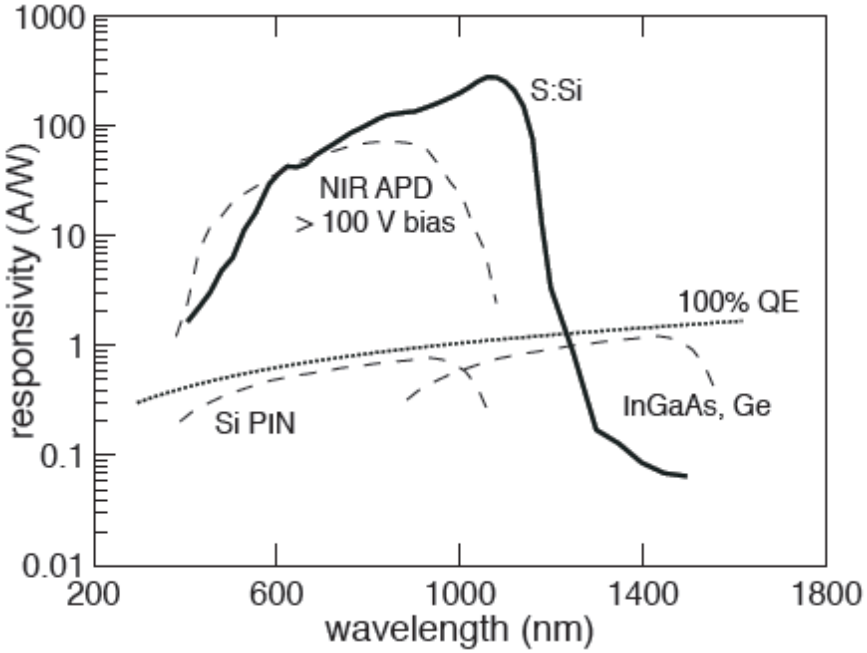


Strong optical absorptance

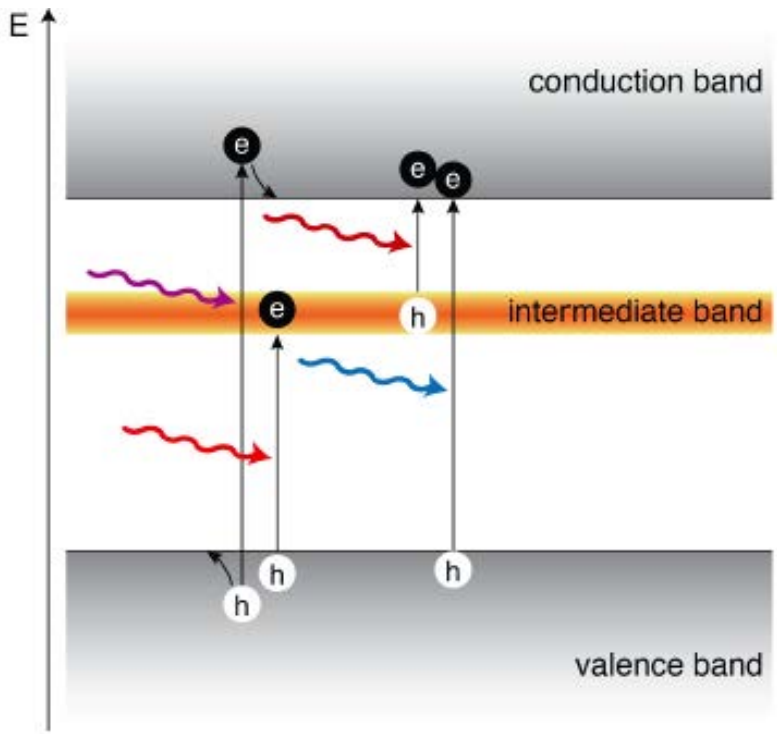


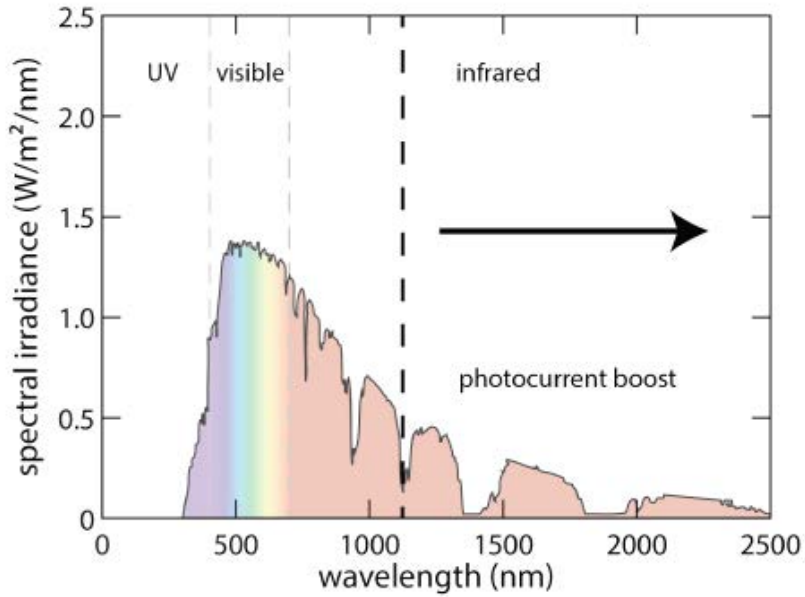
Photodetectors





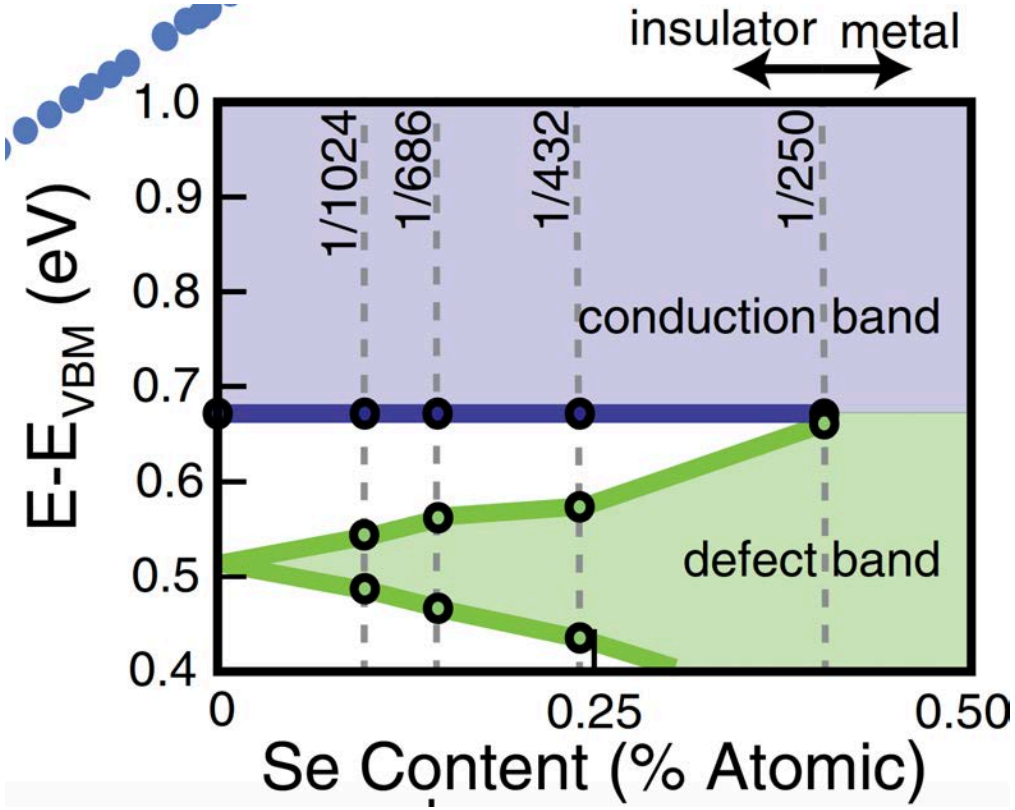
Photovoltaics





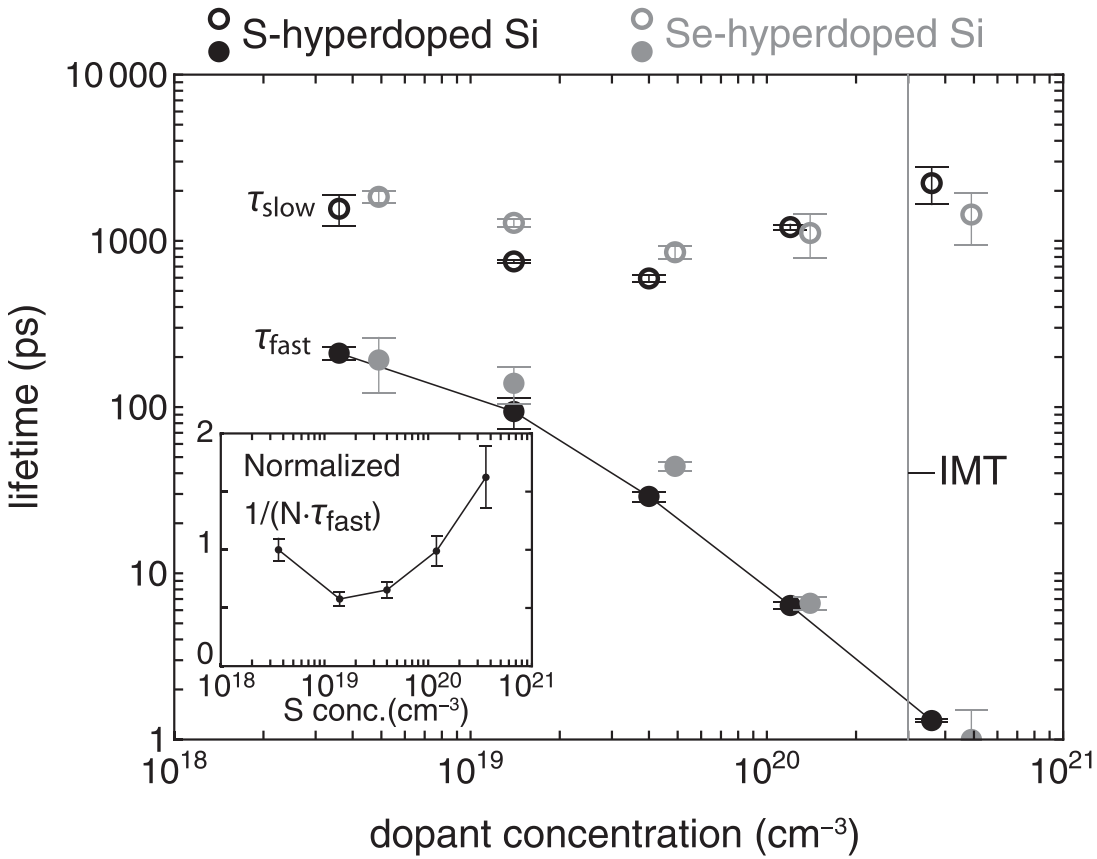
Recent advances

Observing the intermediate band



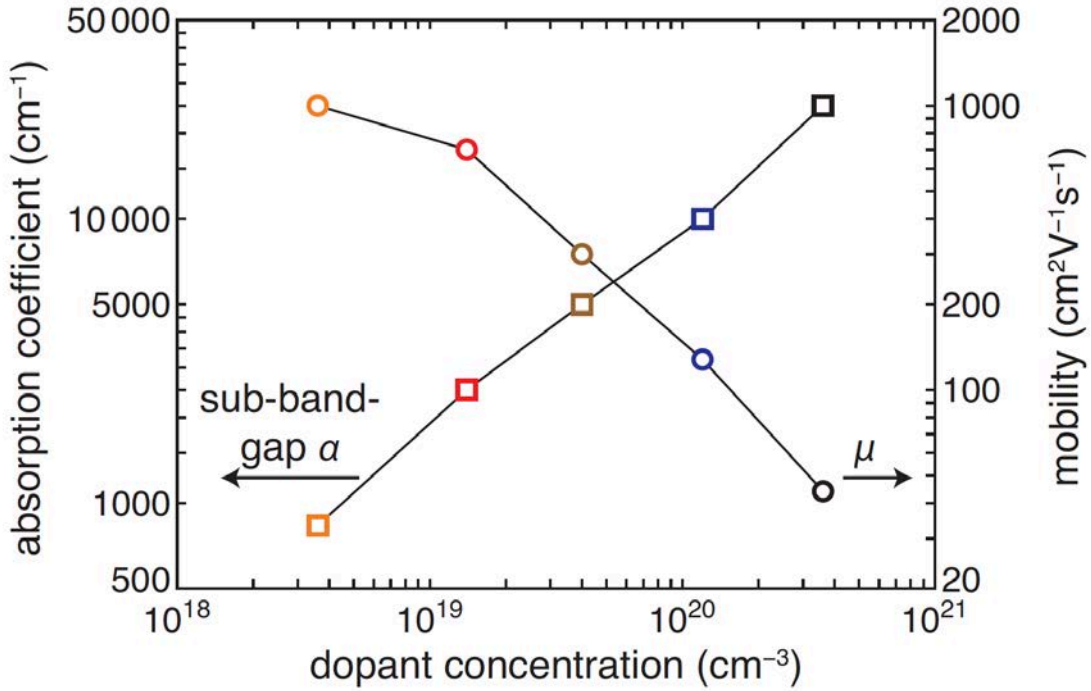
Ertekin, E., M. T. Winkler, D. Recht, A. J. Said, M. J. Aziz, T. Buonassisi and J. C. Grossman (2012). "Insulator-to-Metal Transition in Selenium-Hyperdoped Silicon: Observation and Origin." Phys. Rev. Lett. **108** .

Measuring the carrier lifetime



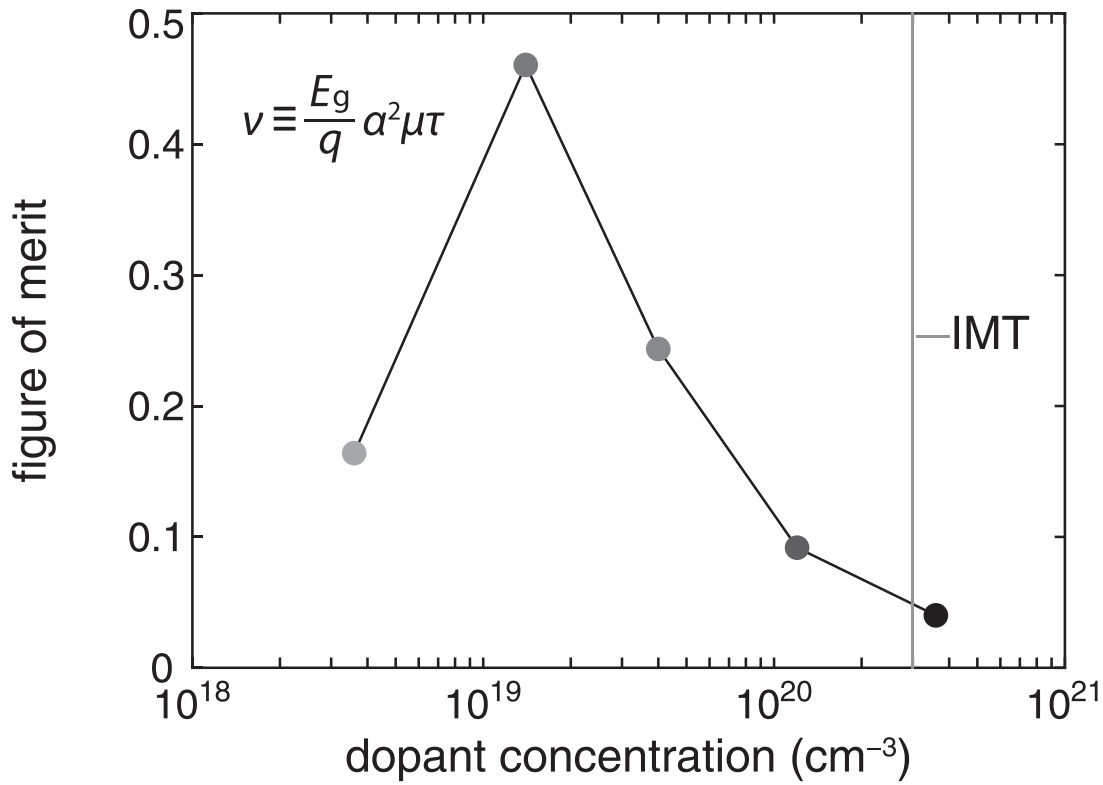
Sher, M.-J., et al., *Picosecond carrier recombination dynamics in chalcogen-hyperdoped silicon.* Appl. Phys. Lett, 2014. **105**: p. 053905.

Measuring alpha and mu



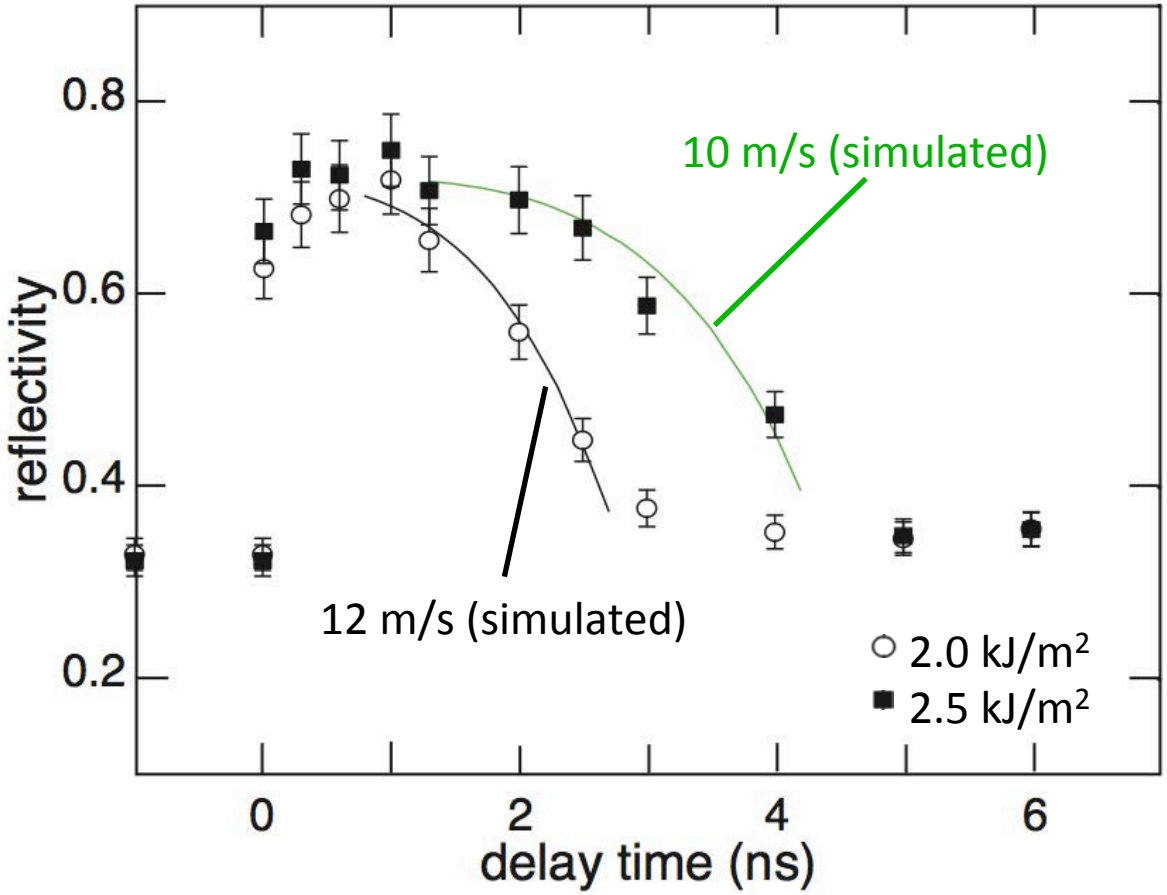
Sher, M.-J., et al., *Picosecond carrier recombination dynamics in chalcogen-hyperdoped silicon.* Appl. Phys. Lett, 2014. **105**: p. 053905. (Supplemental material and references therein.)

Calculating the figure of merit



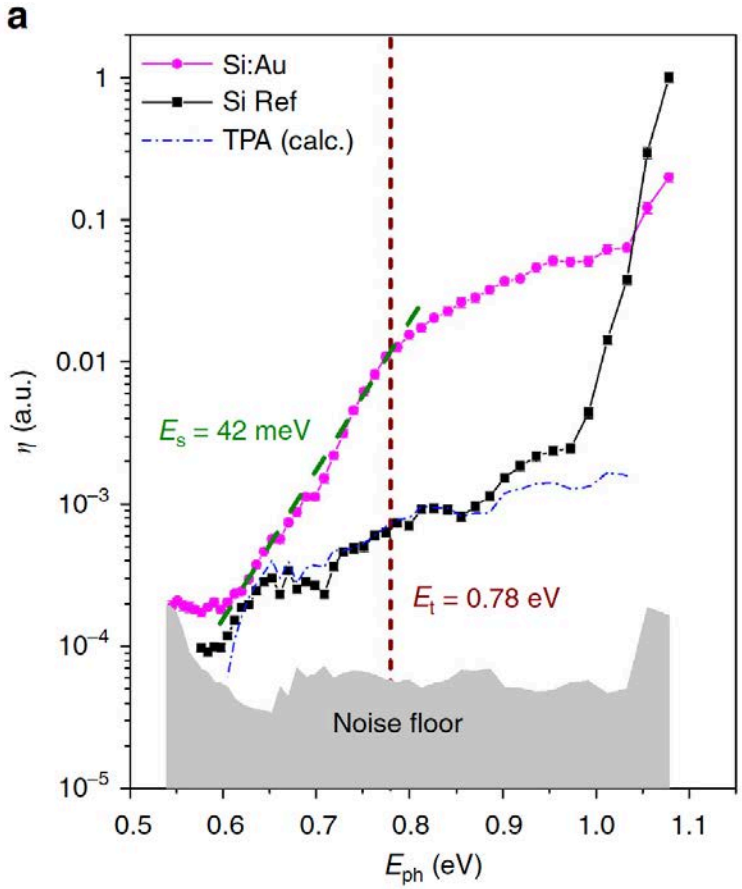
Sher, M.-J., et al., *Picosecond carrier recombination dynamics in chalcogen-hyperdoped silicon.* Appl. Phys. Lett, 2014. **105**: p. 053905.

Controlling resolidification velocity



Lin, Yu-Ting. 2014. Femtosecond-laser hyperdoping and texturing of silicon for photovoltaic applications. Doctoral dissertation, Harvard University.

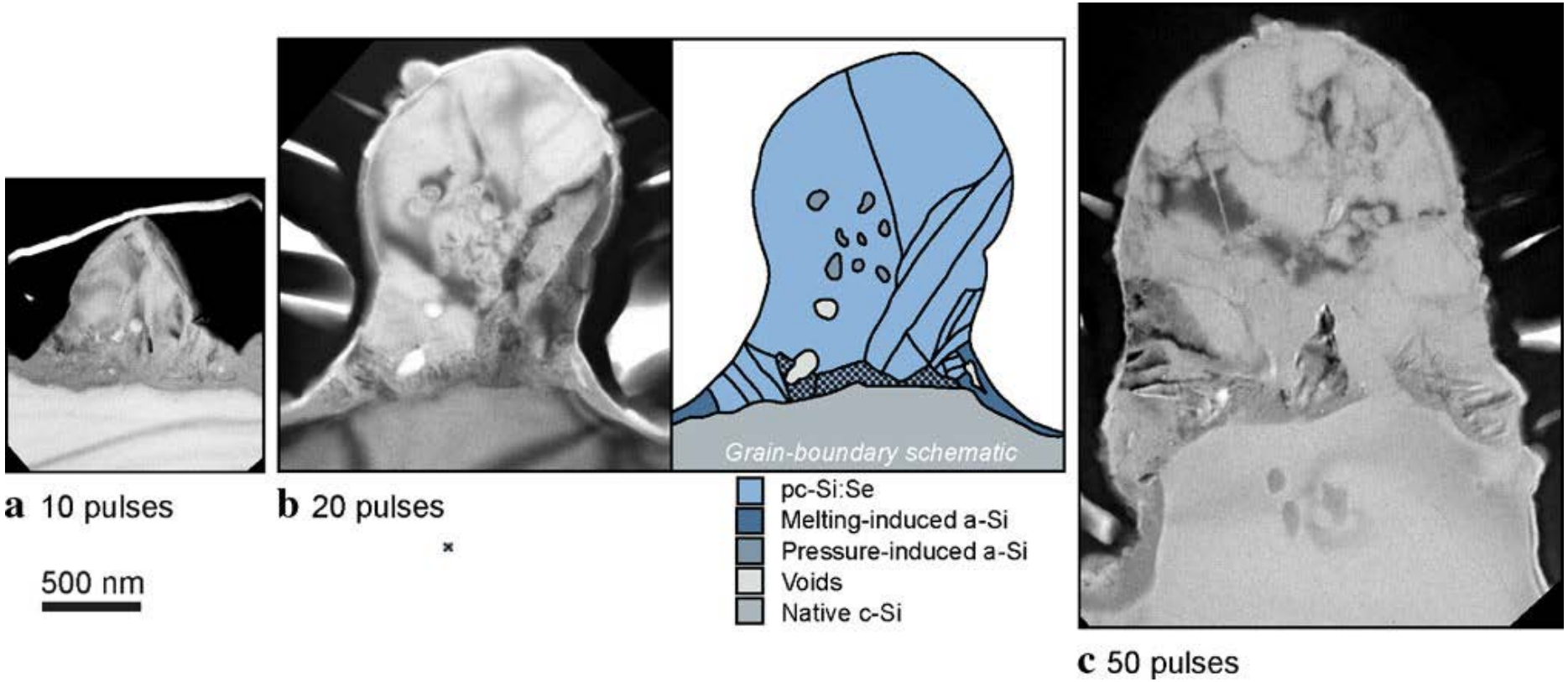
Observing sub-bandgap photoresponse



Mailoa, J. P., et al. (2014). "Room-temperature sub-band gap optoelectronic response of hyperdoped silicon." Nature Communications **5**: 3011.

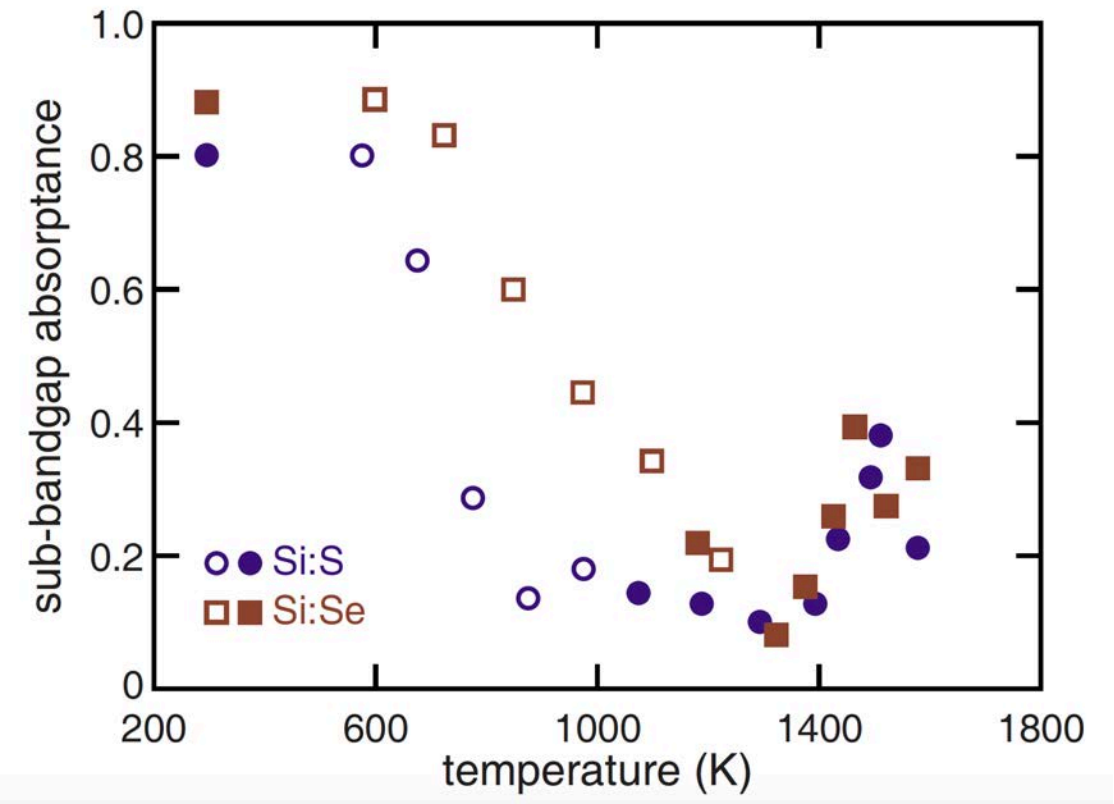
Outstanding challenges

The black silicon microstructure



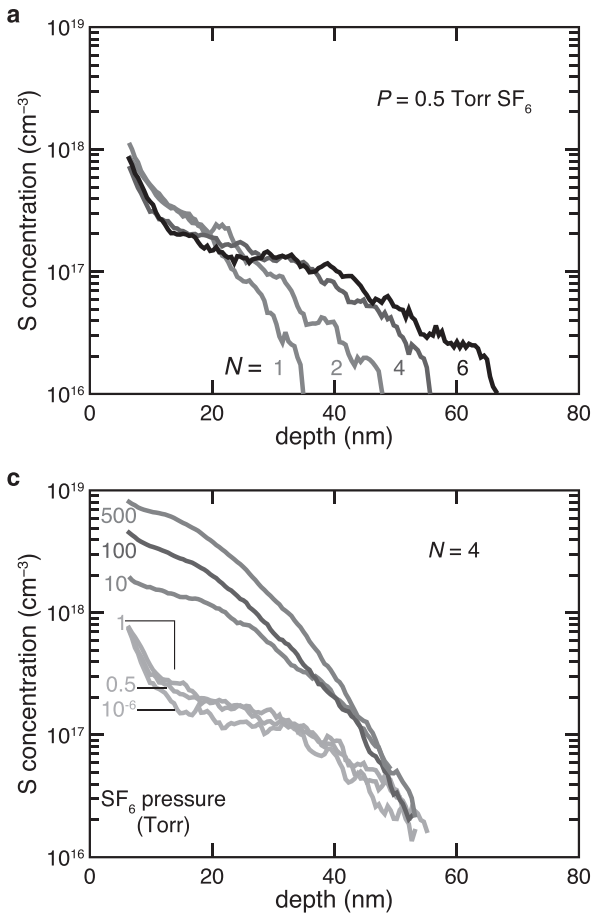
Smith, M. J., M.-J. Sher, B. Franta, Y.-T. Lin, E. Mazur and S. Gradecak (2014). "Improving Dopant Incorporation During Femtosecond- Laser Doping of Si with a Se Thin-Film Dopant Precursor." Applied Physics A **114**(4): 1009-1016.

Thermal annealing causes deactivation



Newman, B. K., M.-J. Sher, E. Mazur and T. Buonassisi (2011). "Reactivation of sub-bandgap absorption in chalcogen-hyperdoped silicon." Applied Physics Letters **98**(25): 251905

Hitting the right dopant conc.



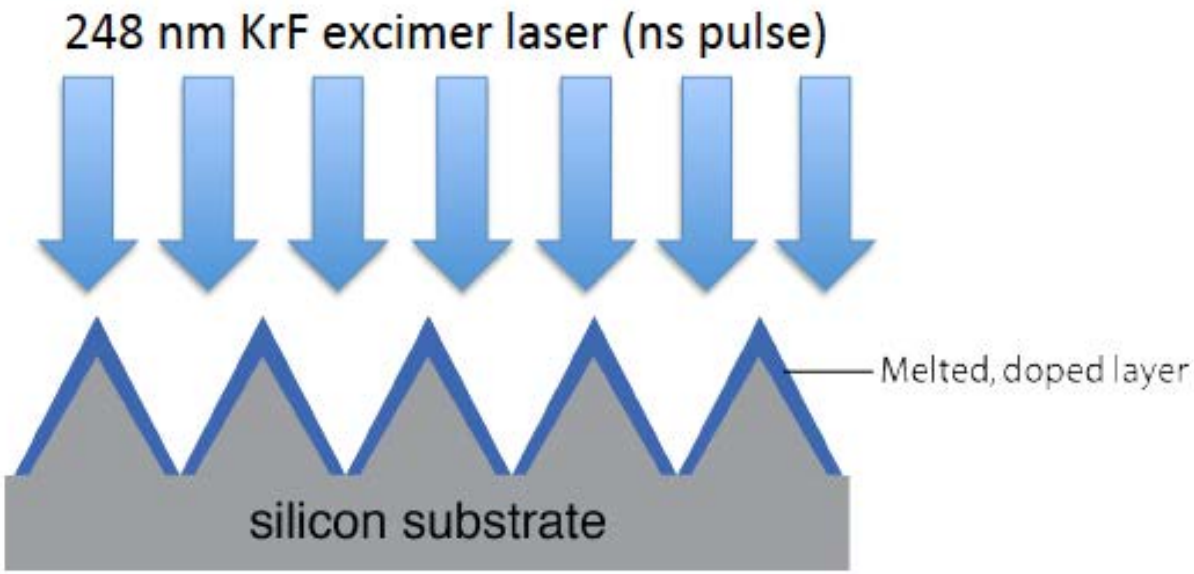
Sher, M.-J. et al. (2015). "Femtosecond-laser hyperdoping silicon in an SF6 atmosphere: Dopant incorporation mechanism." Journal of Applied Physics **117**(12): 125301.

Nanosecond laser annealing

Obtain high crystallinity and optical absorptance

ns laser annealing

ns laser annealing



ns laser annealing

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Benjamin Franta

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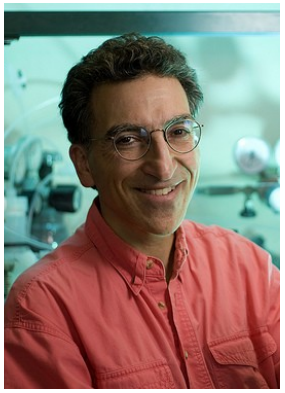
Hemi Gandhi

Paul Rekemeyer

Silvija Gradečak

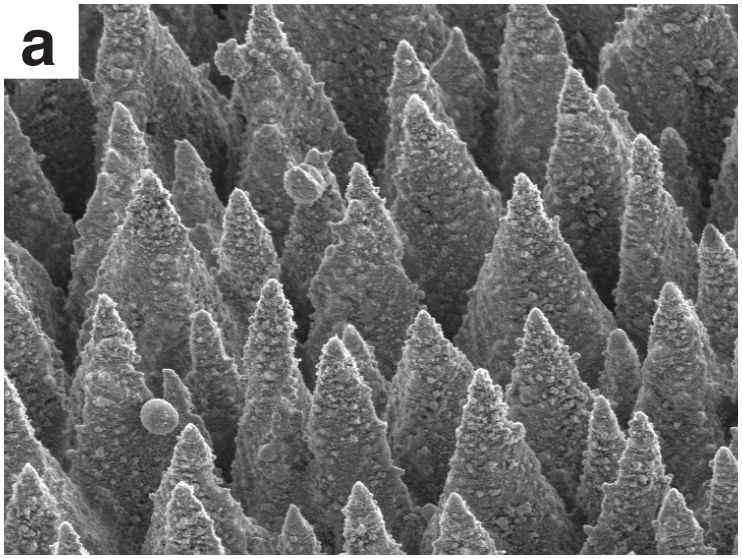


Mike Aziz

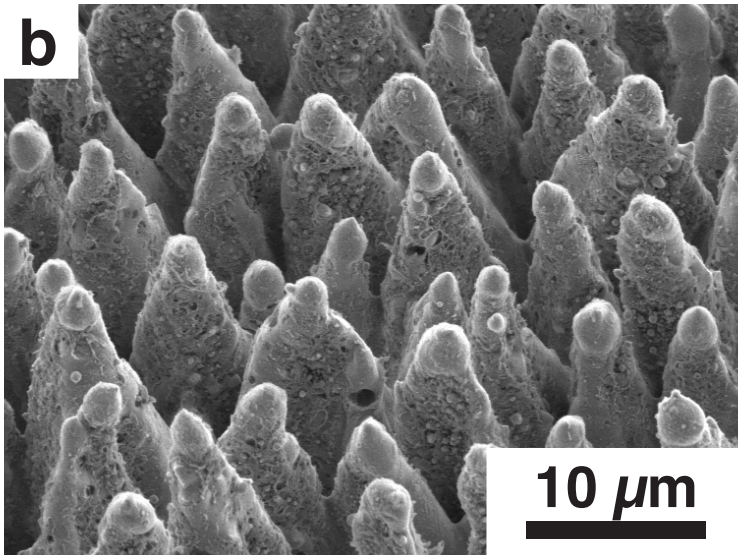
Eric Mazur

Structural effects

Structural effects

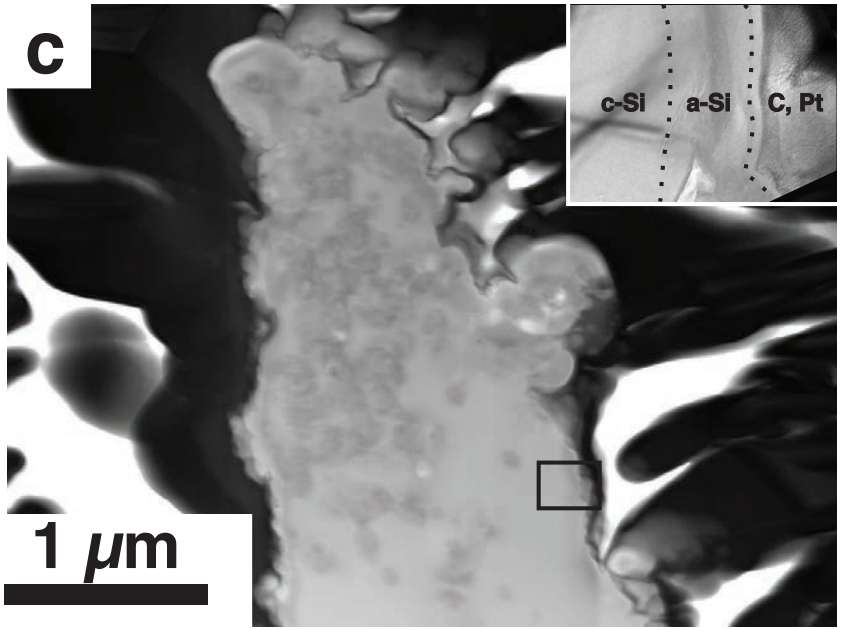


Before ns laser anneal



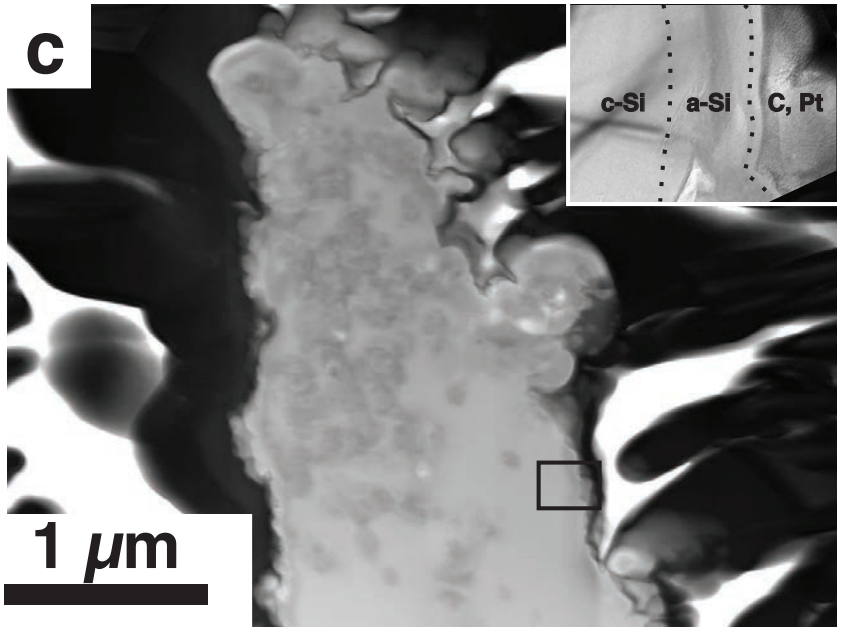
After ns laser anneal (2.2 J/cm^2)

Structural effects



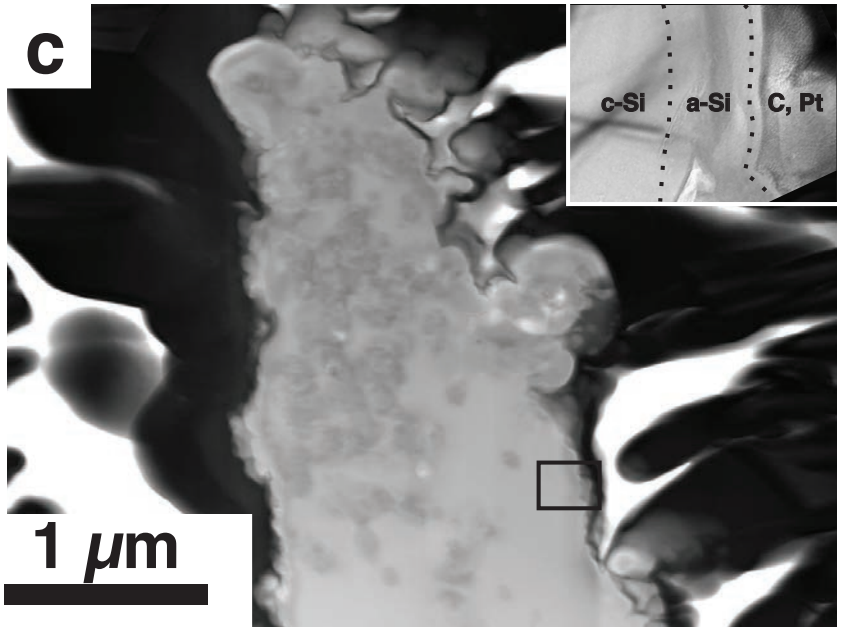
Before ns laser anneal

Structural effects

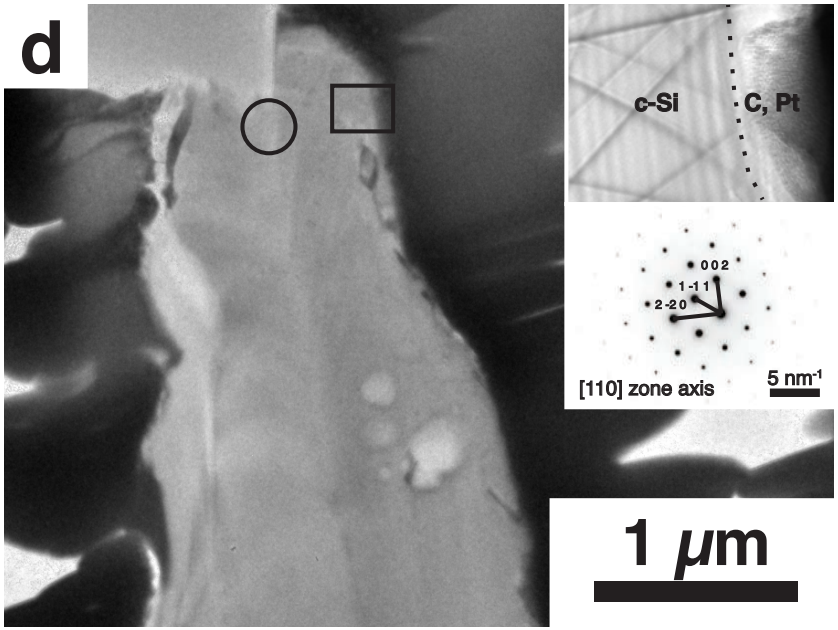


Before ns laser anneal

Structural effects



Before ns laser anneal



After ns laser anneal (2.2 J/cm^2)

Quantifying crystallinity

- Raman spectroscopy:
  - amorphous Si: broad transverse optical mode centered at 480 cm^{-1}.
  - crystalline Si: sharp optical mode at 520 cm^{-1}.
  - lattice stress and grain size: width of c-Si peak.

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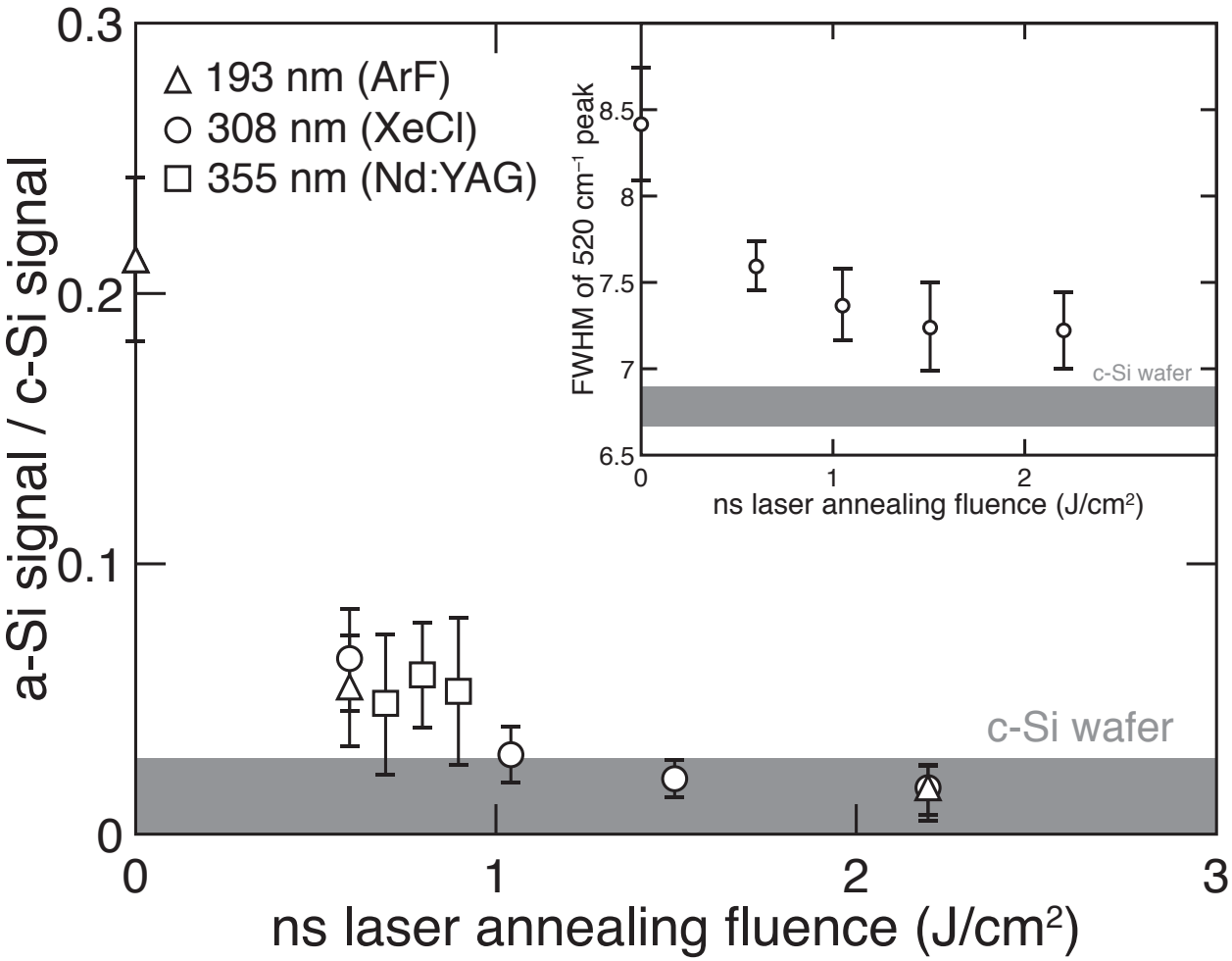
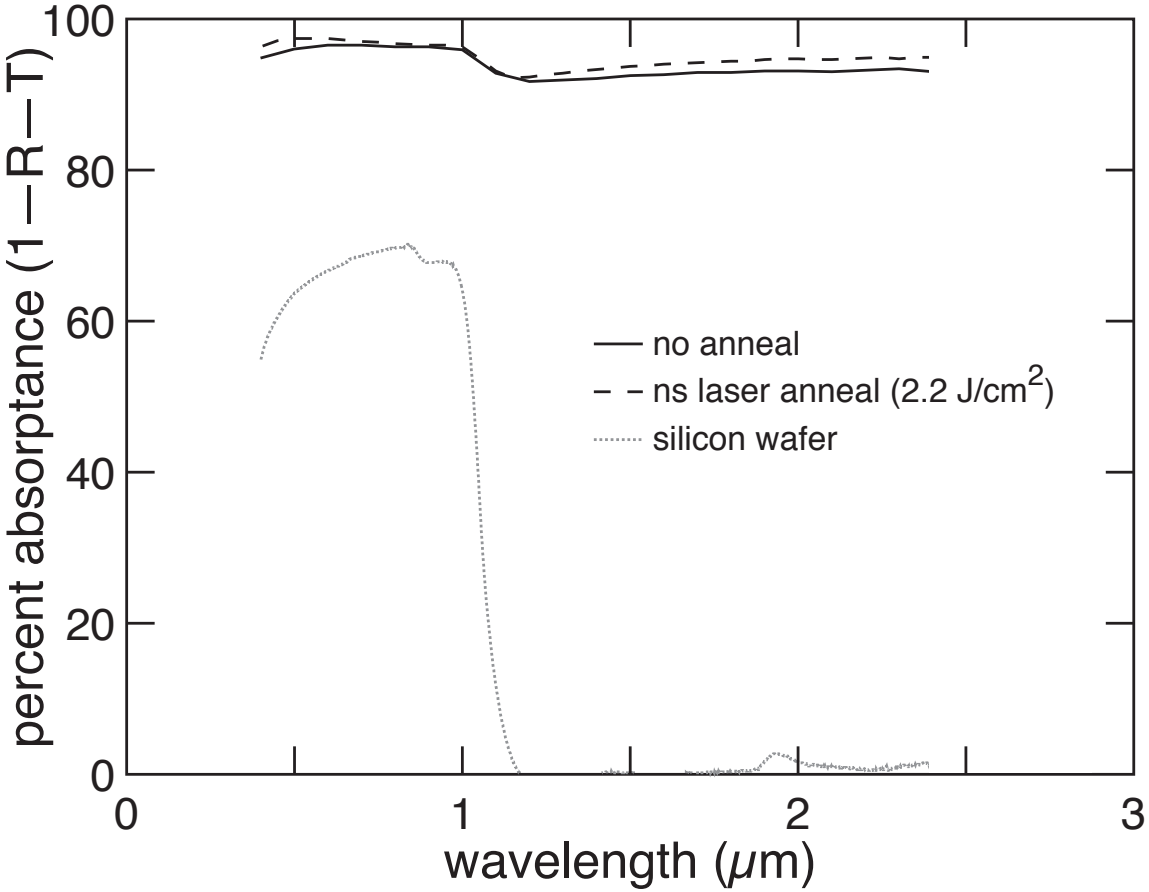
- Raman spectroscopy:
  - amorphous Si: broad transverse optical mode centered at 480 cm^{-1}.
  - crystalline Si: sharp optical mode at 520 cm^{-1}.
  - lattice stress and grain size: width of c-Si peak.
- Quantification:
  - normalized a-Si signal: a-Si peak / c-Si peak.
  - FWHM of c-Si peak.
  - monocrystalline wafer used as baseline.

Quantifying crystallinity

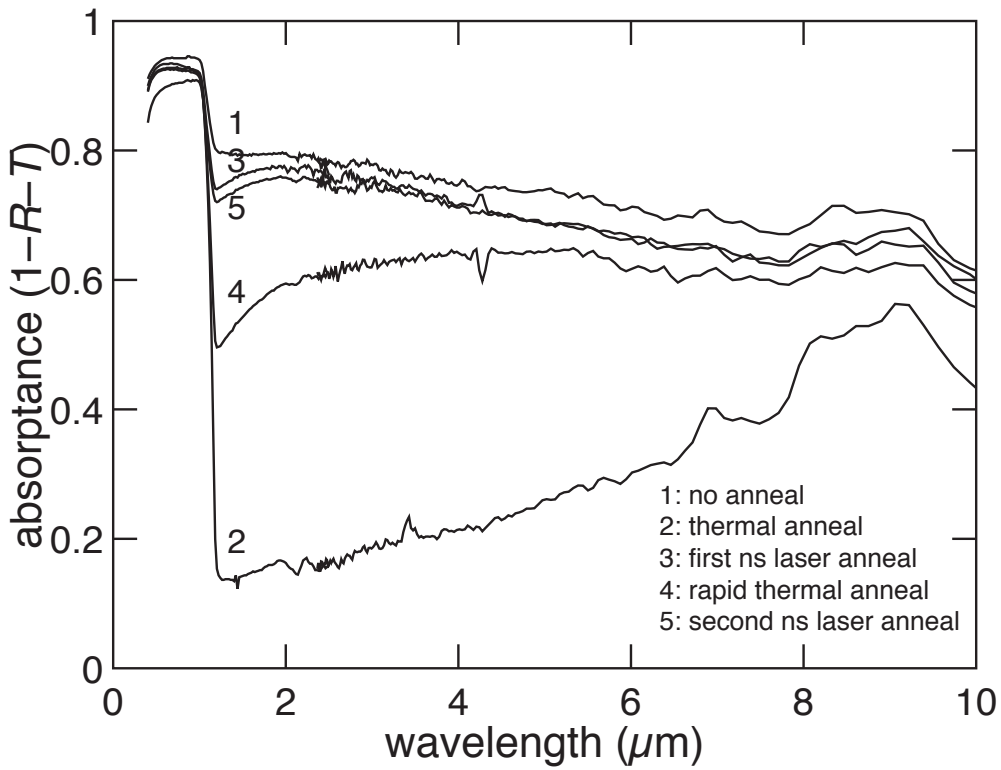


Optical absorptance

Optical absorptance

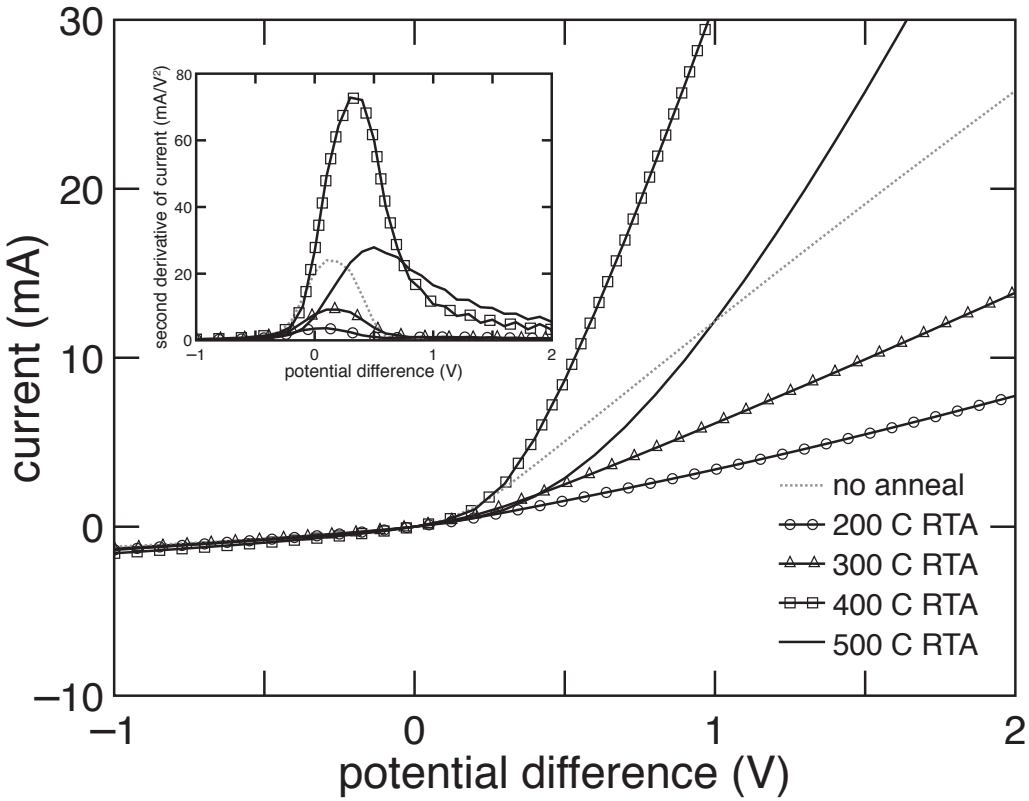


Optical absorptance reactivation

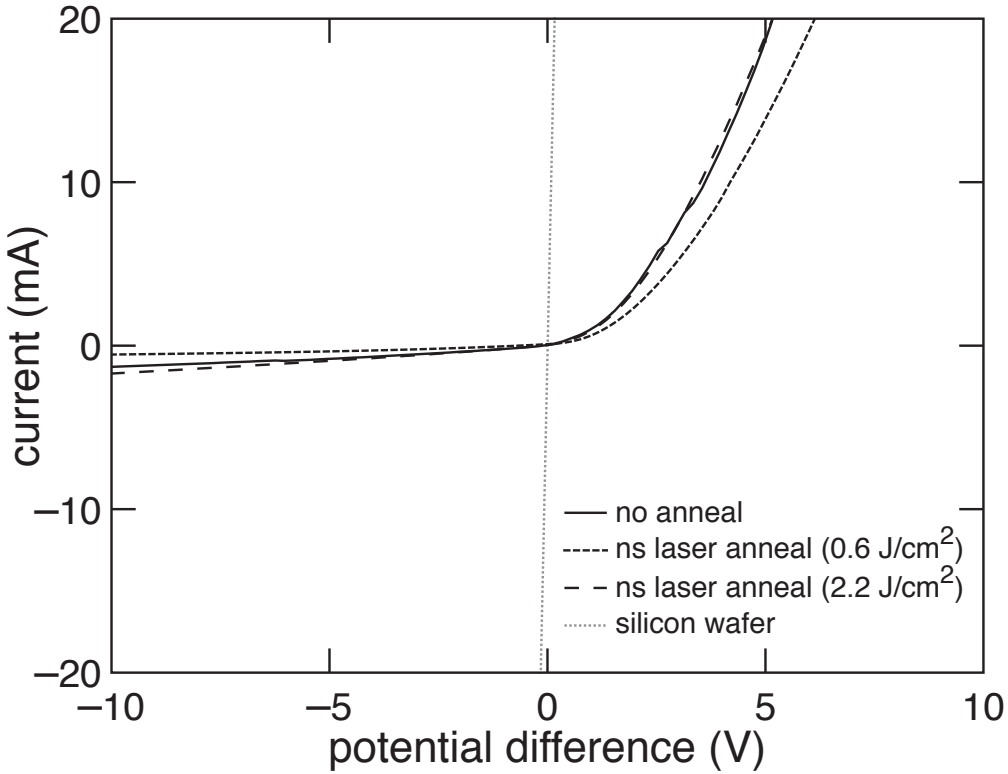


Electrical

Need RTA for electrodes



After laser annealing, still a diode



Conclusions

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- A lot of recent advances

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  - Observing intermediate band, measuring carrier lifetime, alpha, mu, calculating figure of merit, controlling resolidification velocity (with fs laser), observing sub-bandgap photoresponse.

Conclusions

- Outstanding challenges

Conclusions

- Outstanding challenges
  - Need the quality of hyperdoped flat Si with the absorptance of hyperdoped black Si.
  - Control crystallinity, optical absorptance, and dopant concentration at the same time.

Conclusions

- Nanosecond laser annealing
  - High crystallinity, high optical absorptance, diode behavior at the same time.

Conclusions

- Nanosecond laser annealing
  - High crystallinity, high optical absorptance, diode behavior at the same time.

- Next: need to control doping concentration in hyperdoped black silicon.

Thank you

Discussion

Extra slides

Next: Obtaining non-metallic hyperdoped black silicon

- Need to obtain <0.4 at. % doping concentration *and* strong optical absorptance at same time
  - Requirement for high-efficiency sub-bandgap devices, but has not yet been done

- Potential methods:
  - Nanosecond laser pulses to remove dopants from hyperdoped black silicon
  - Ablate hyperdoped skin off hyperdoped black silicon, then laser dope
  - Ablate hyperdoped skin off hyperdoped black silicon, then ion implant