Hyperdoped black silicon

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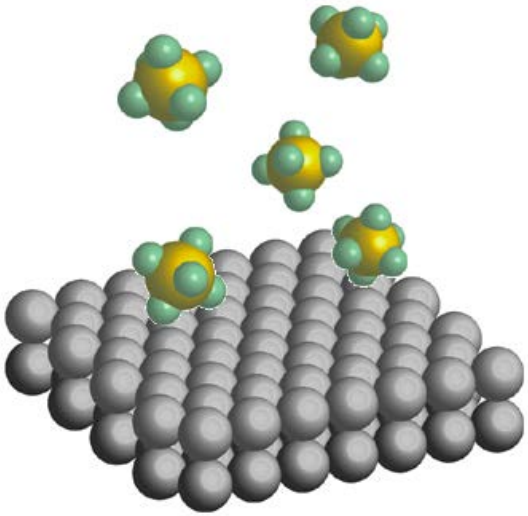
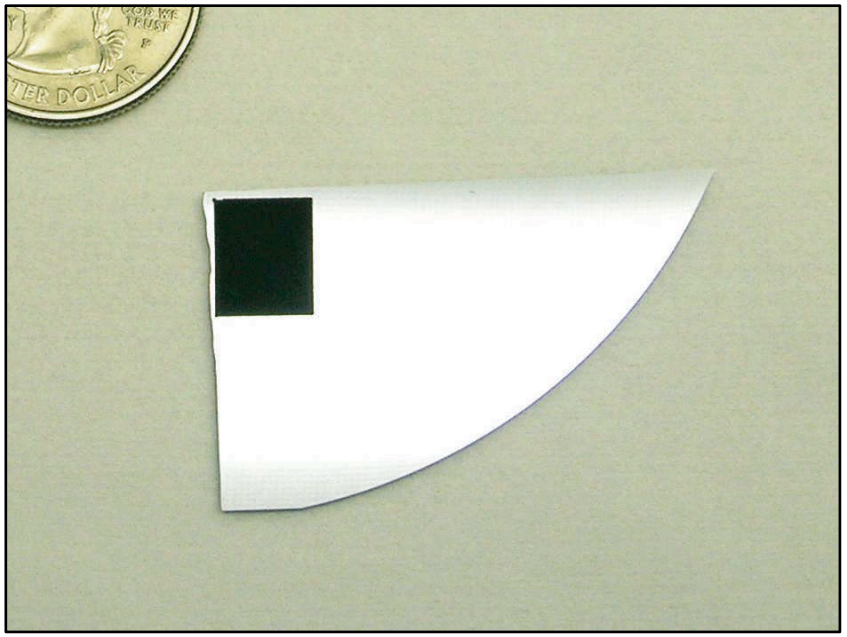
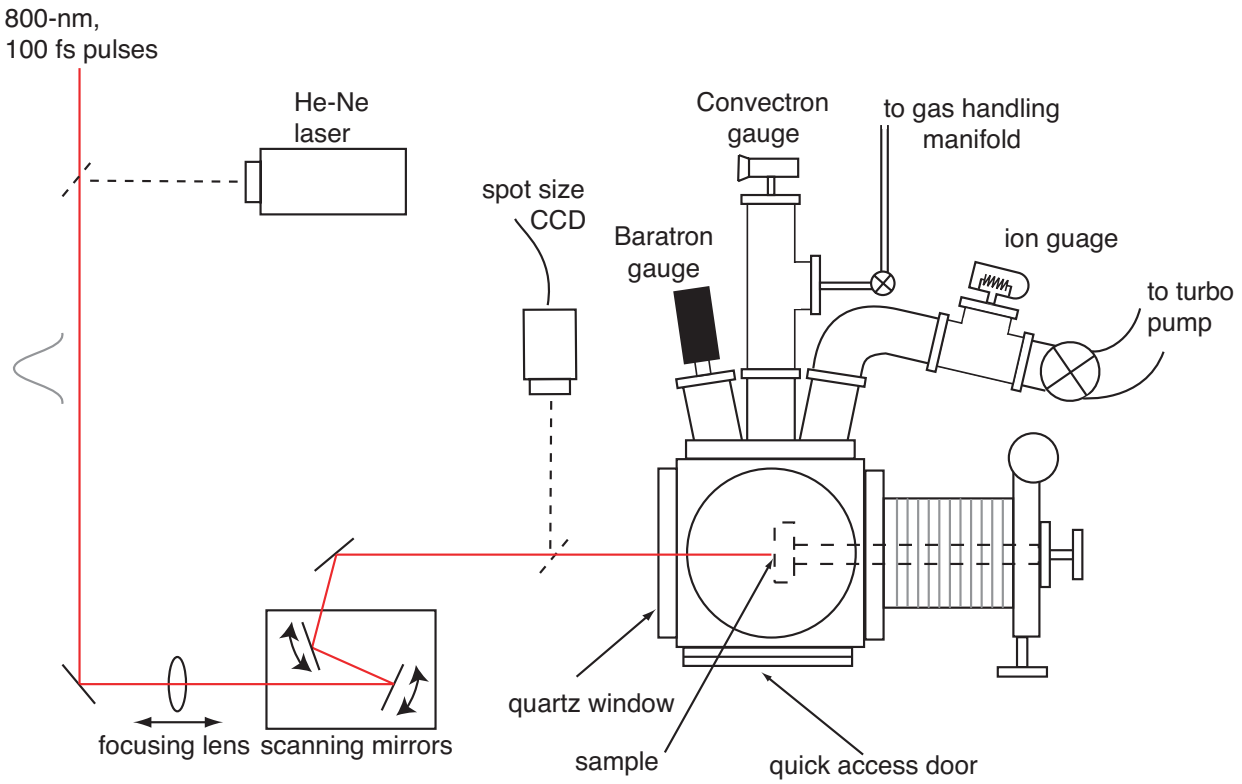
Hyperdoped black silicon

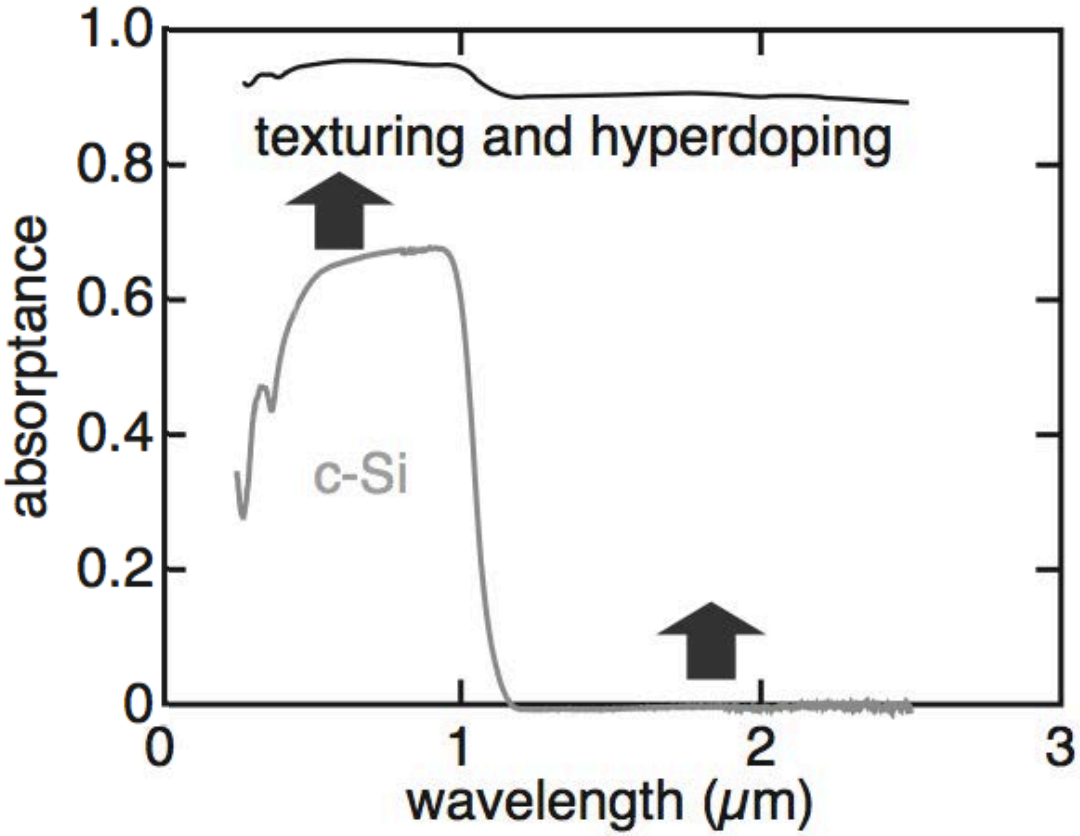




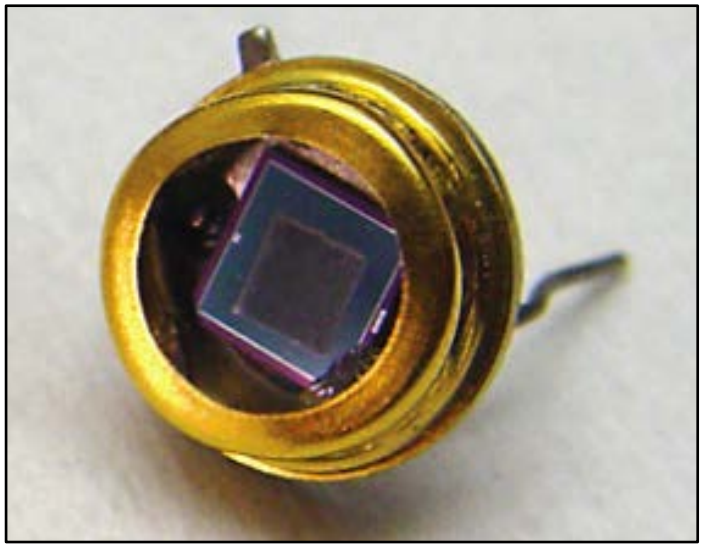
Fabrication

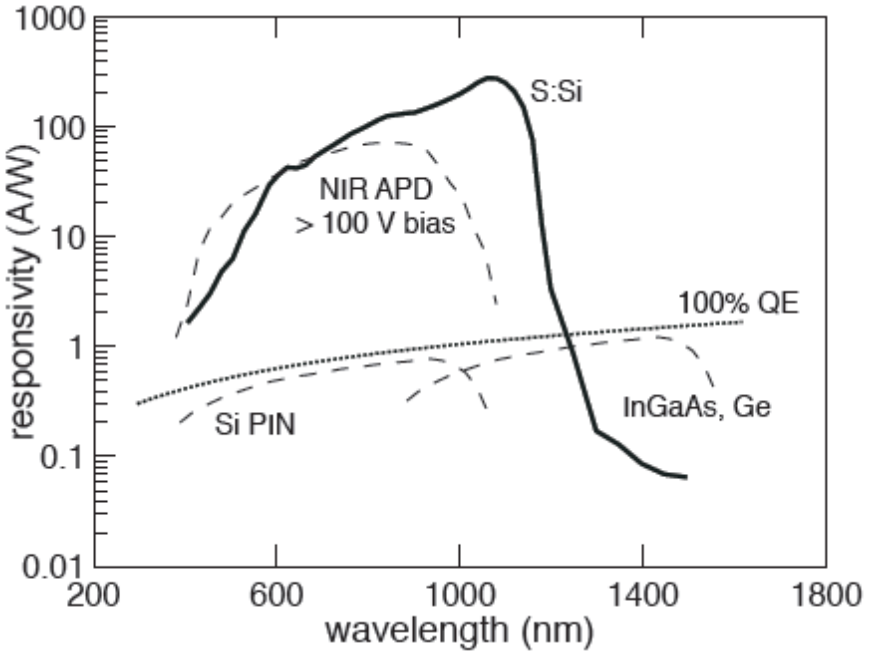


Strong optical absorptance

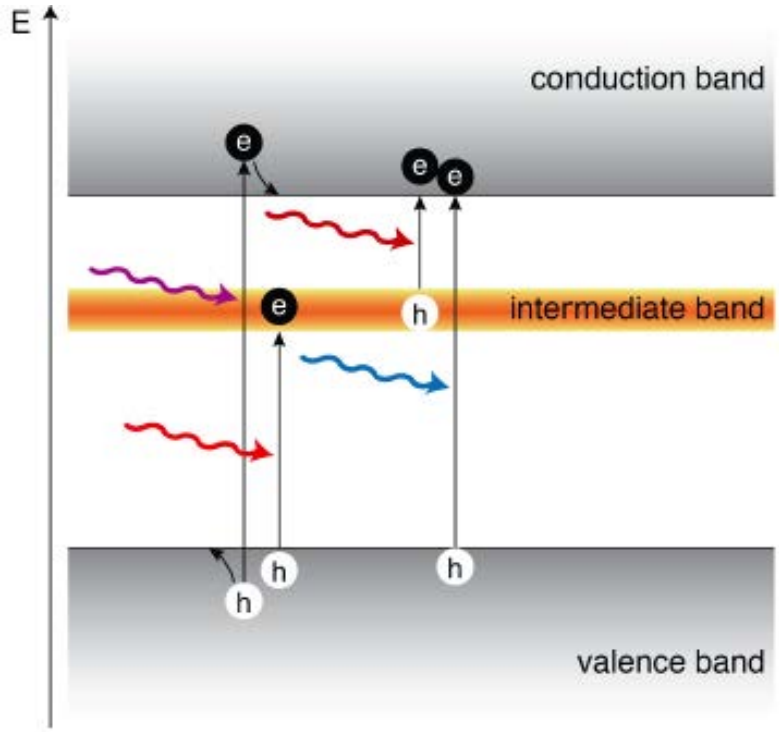


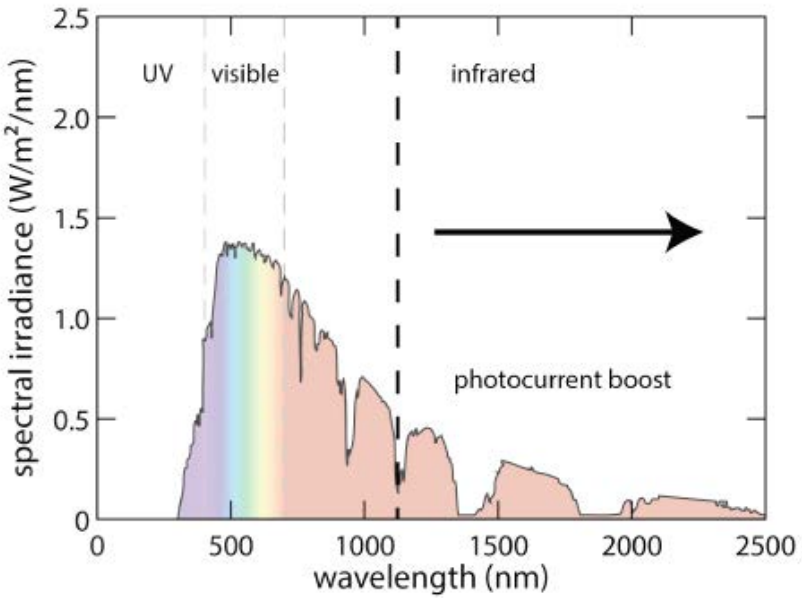
Photodetectors





Photovoltaics





Hyperdoped black silicon

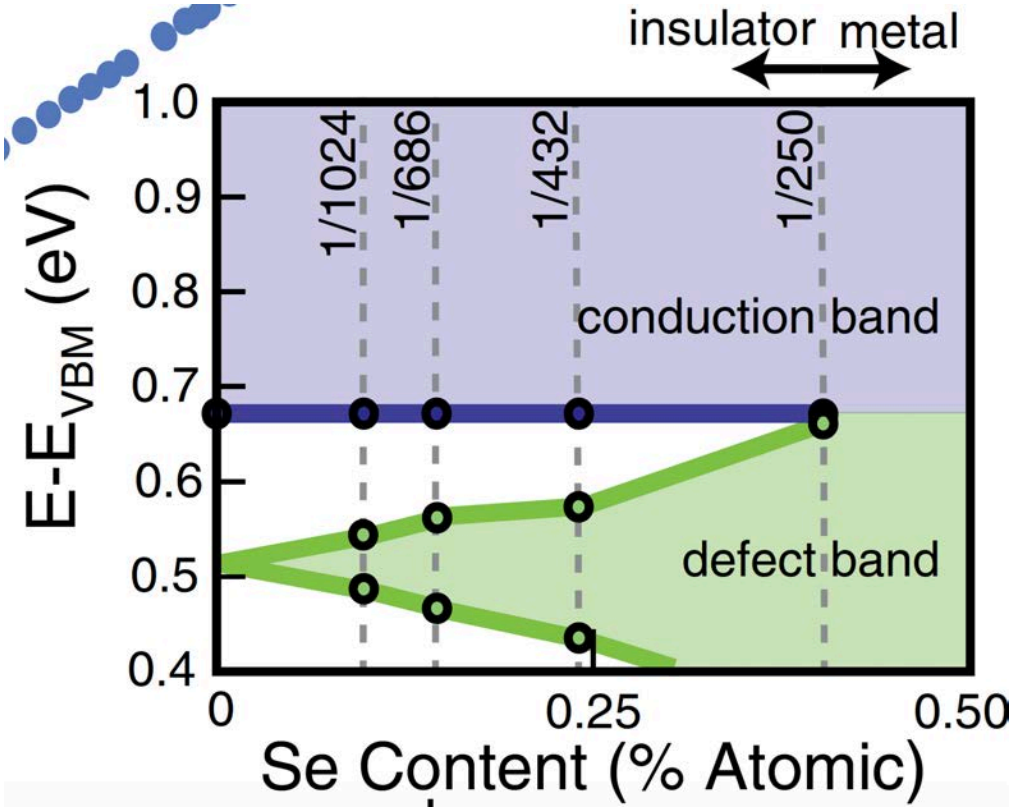
Recent advances

Pump-probe measurement of melt dynamics

Current and future work

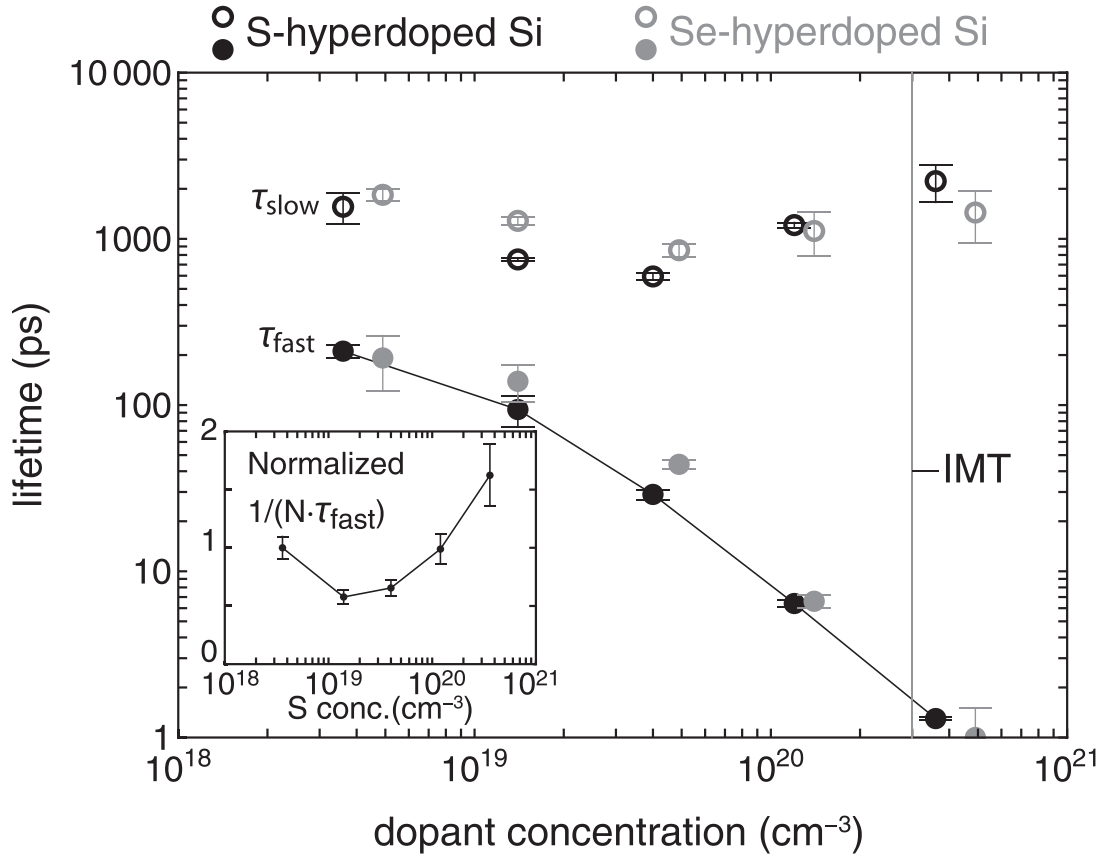
Recent advances

Observing the intermediate band



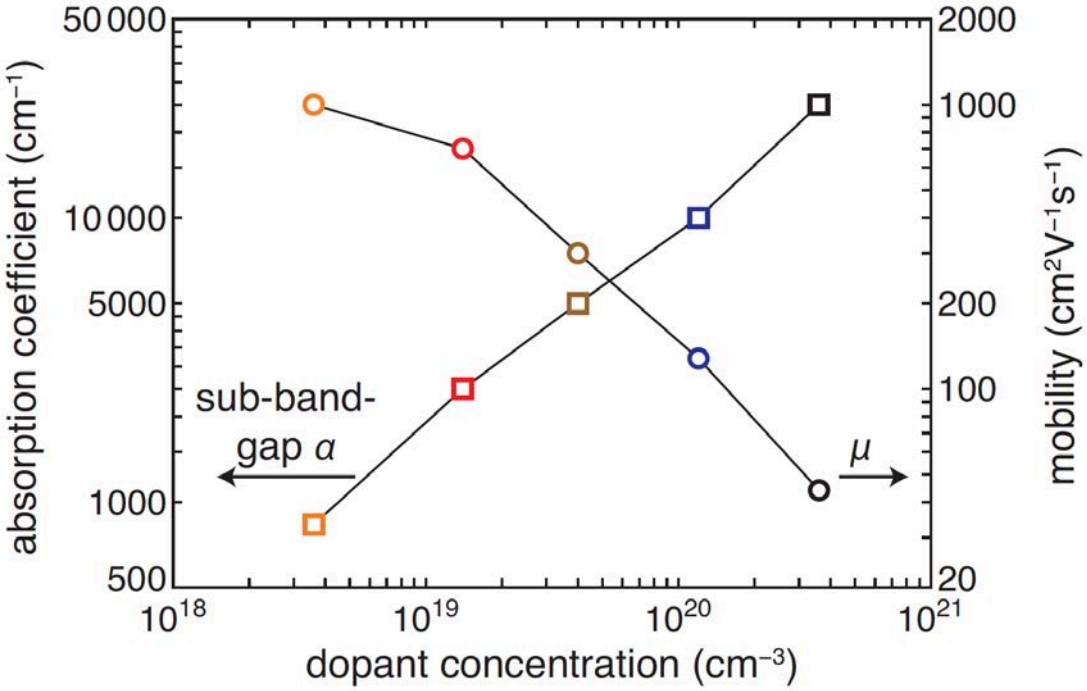
Ertekin, E., M. T. Winkler, D. Recht, A. J. Said, M. J. Aziz, T. Buonassisi and J. C. Grossman (2012). "Insulator-to-Metal Transition in Selenium-Hyperdoped Silicon: Observation and Origin." Phys. Rev. Lett. **108** .

Measuring the carrier lifetime



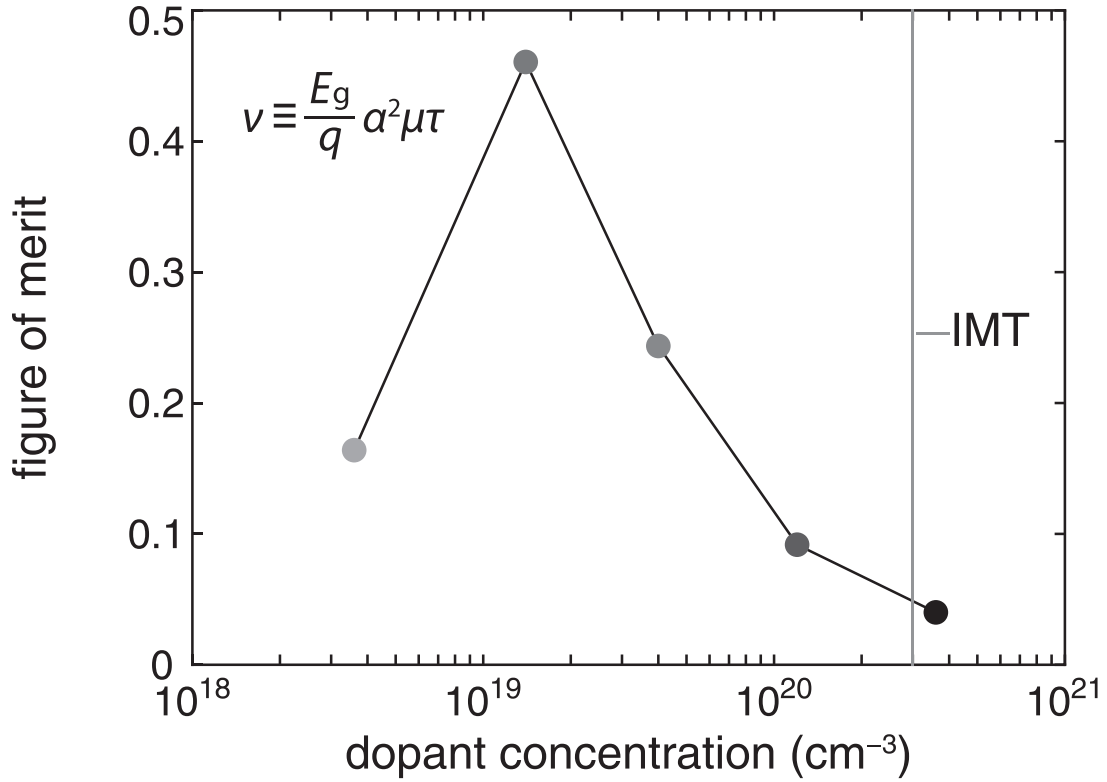
Sher, M.-J., et al., *Picosecond carrier recombination dynamics in chalcogen-hyperdoped silicon.* Appl. Phys. Lett, 2014. **105**: p. 053905.

Measuring alpha and mu



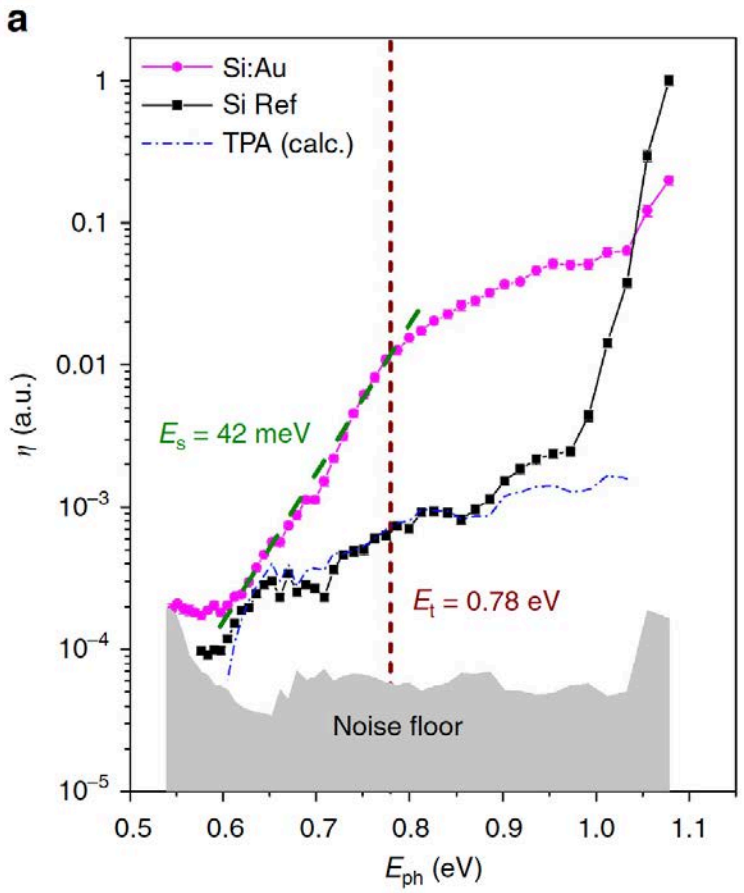
Sher, M.-J., et al., *Picosecond carrier recombination dynamics in chalcogen-hyperdoped silicon.* Appl. Phys. Lett, 2014. **105**: p. 053905. (Supplemental material and references therein.)

Calculating the figure of merit



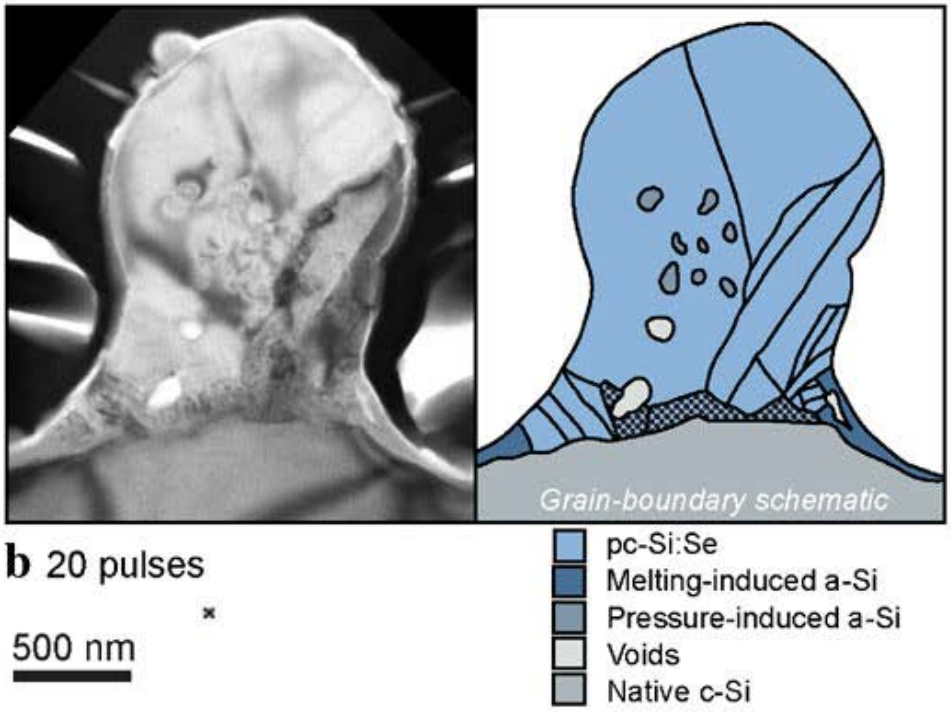
Sher, M.-J., et al., *Picosecond carrier recombination dynamics in chalcogen-hyperdoped silicon.* Appl. Phys. Lett, 2014. **105**: p. 053905.

Observing sub-bandgap photoresponse



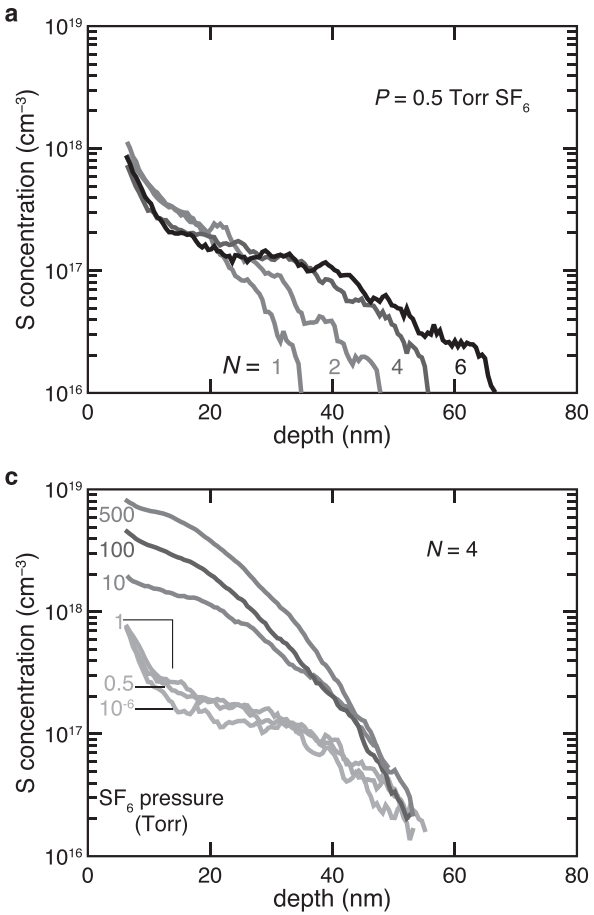
Mailoa, J. P., et al. (2014). "Room-temperature sub-band gap optoelectronic response of hyperdoped silicon." Nature Communications **5**: 3011.

Studying the black silicon microstructure



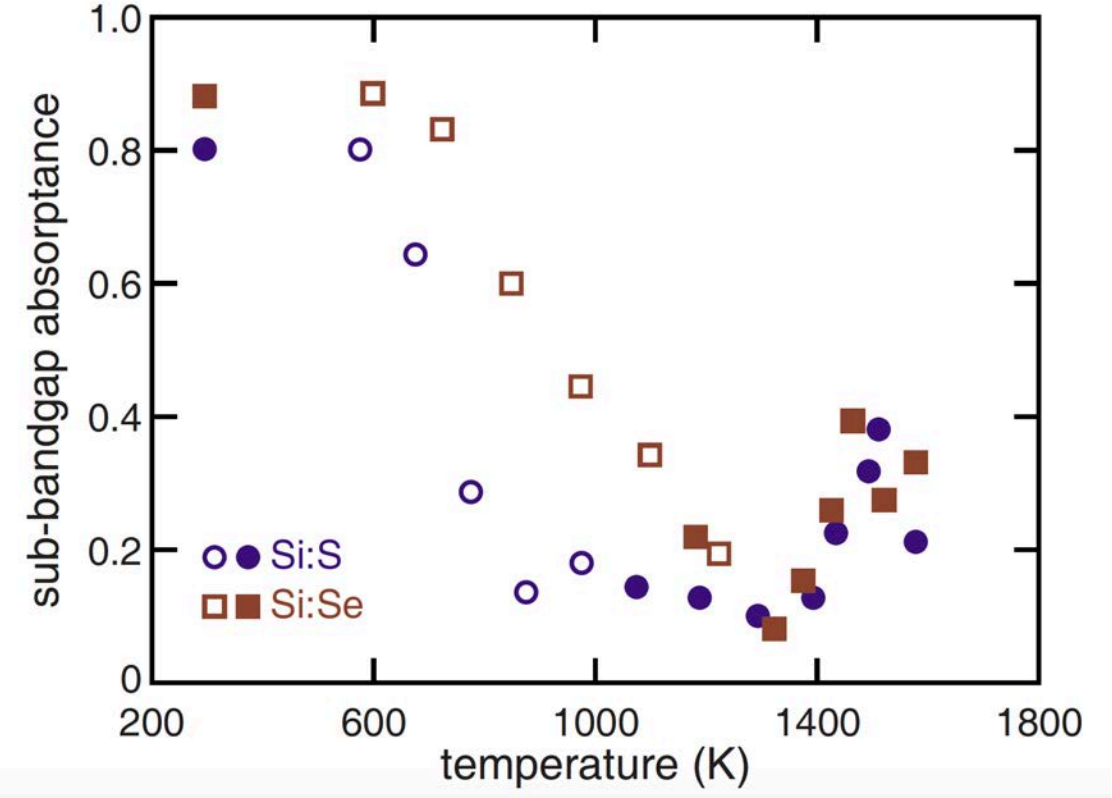
Smith, M. J., M.-J. Sher, B. Franta, Y.-T. Lin, E. Mazur and S. Gradecak (2014). Improving Dopant Incorporation During Femtosecond- Laser Doping of Si with a Se Thin-Film Dopant Precursor.

Measuring the dopant profile



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

Deactivating and reactivating absorptance



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

Melt dynamics

Pump-probe reflectometry

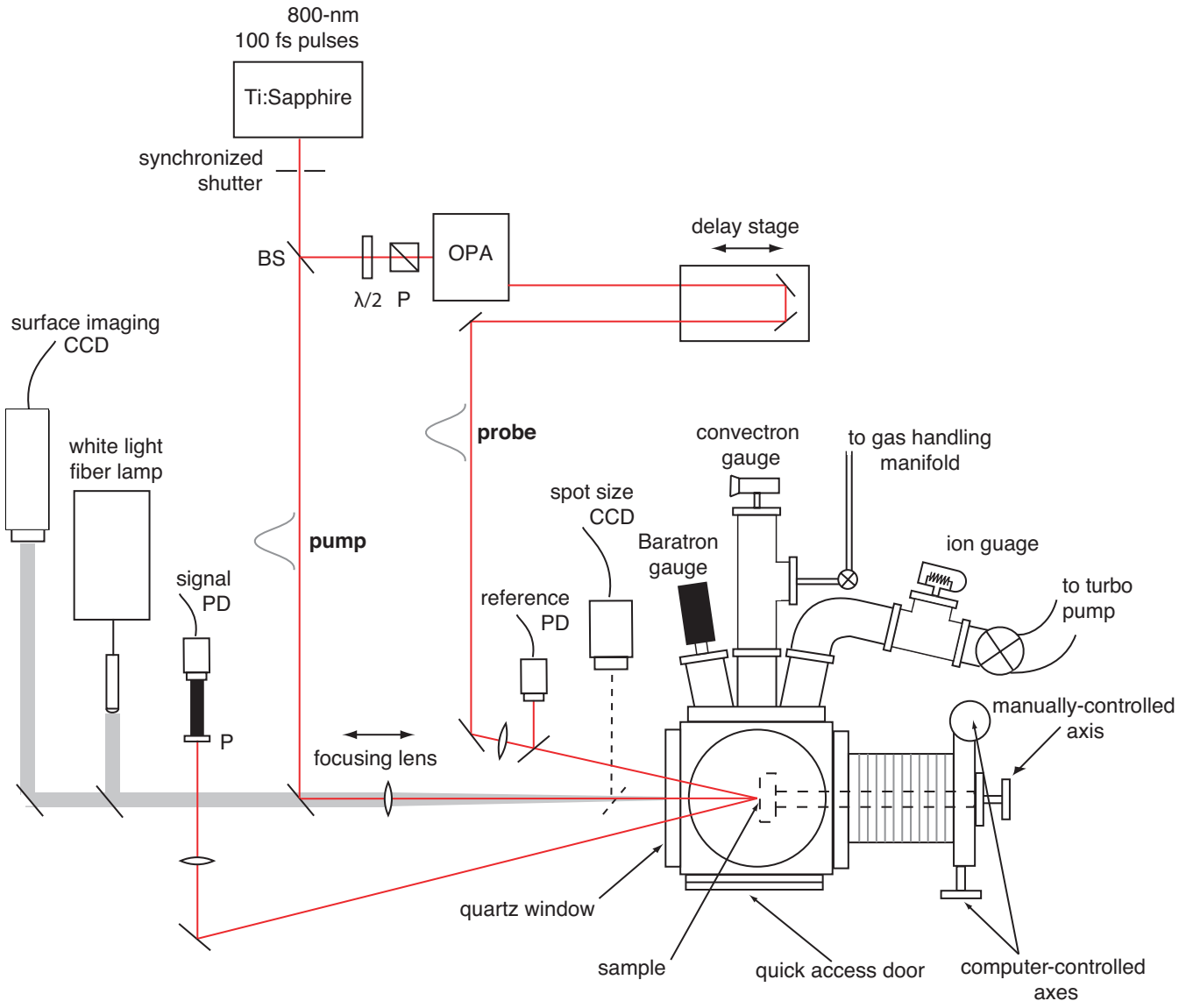
Questions

1. What is the melt duration and velocity?

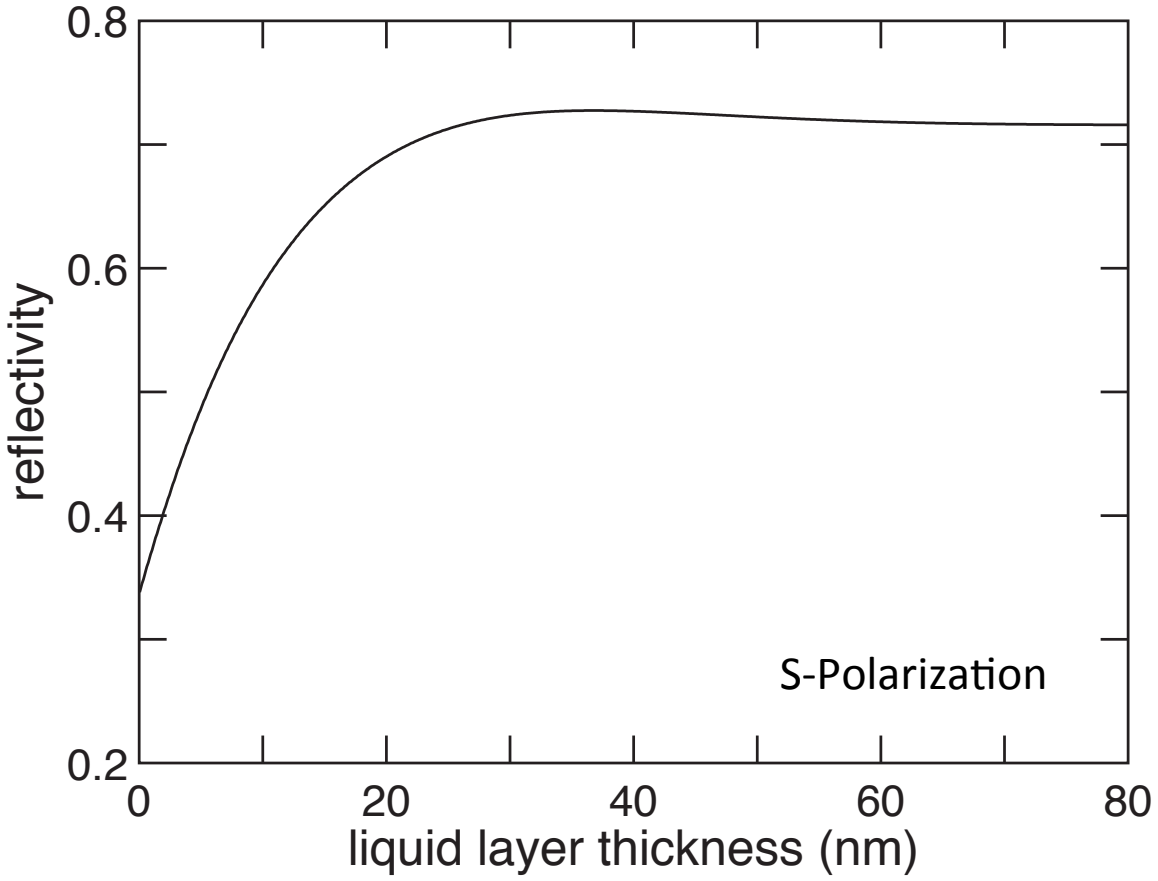
2. Can we control the resolidification velocity?

3. Can melt dynamics be used to control doping?

Pump-probe reflectometry

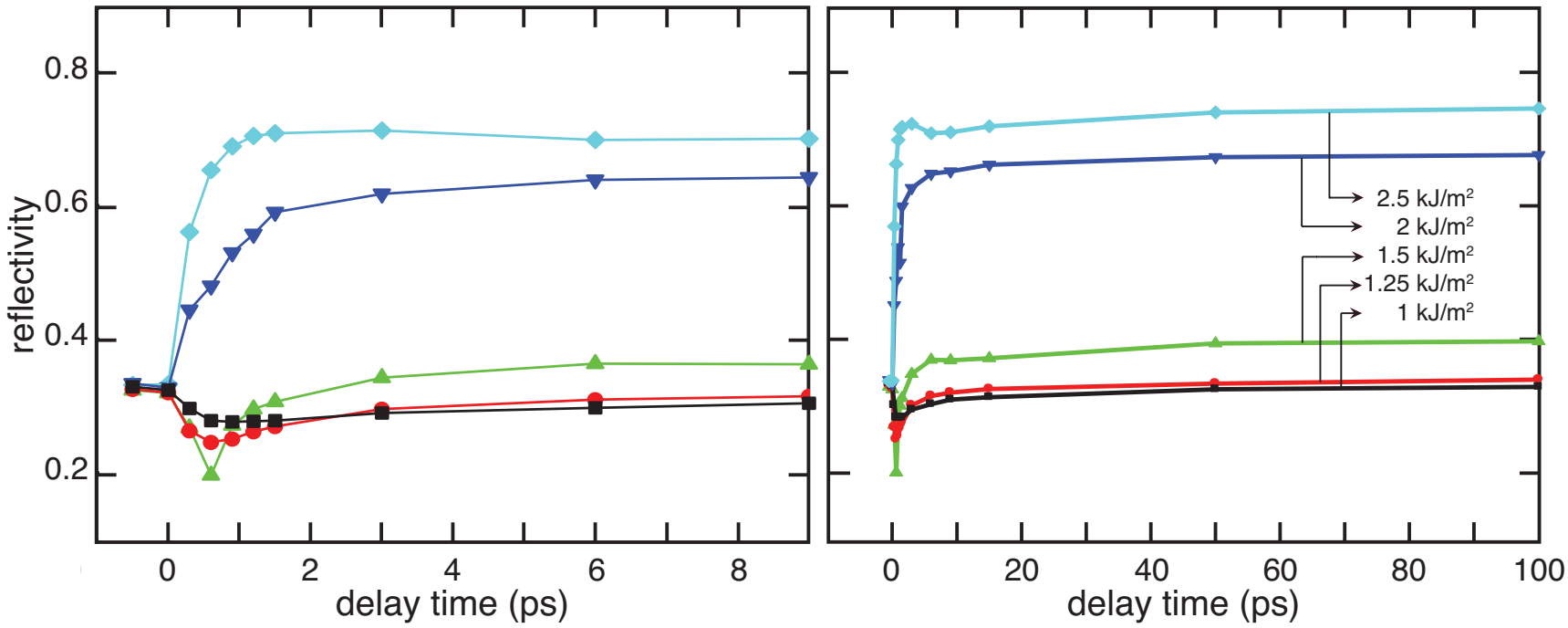


Multi-layer model of reflectivity



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

Melting velocity



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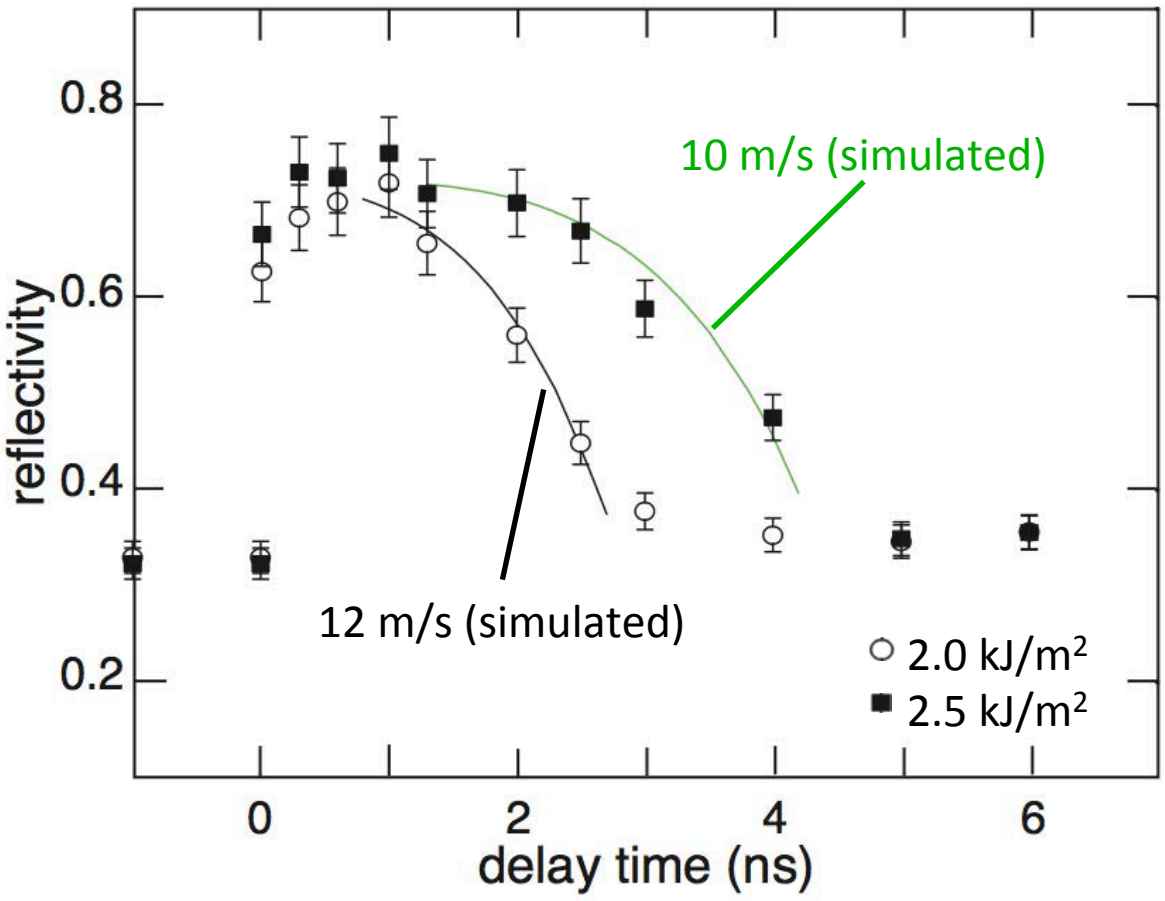
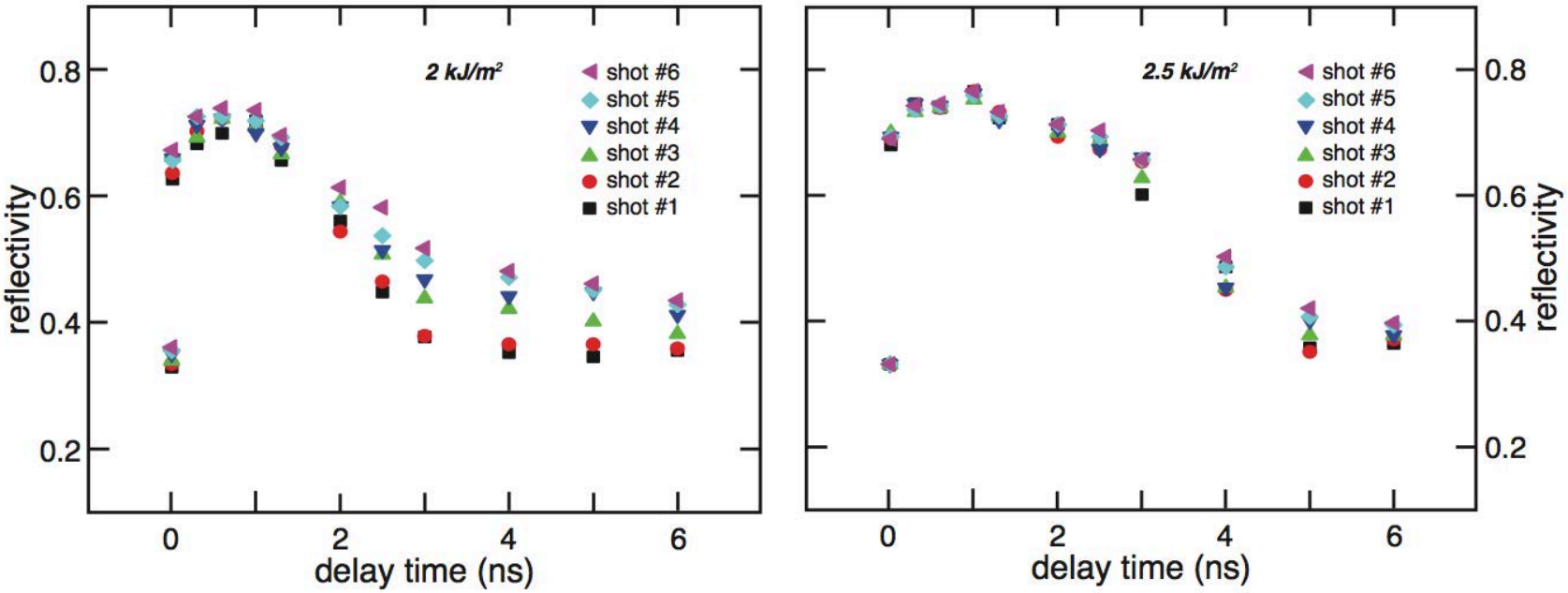
Resolidification velocity



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

Formation of amorphous Si at low fluence



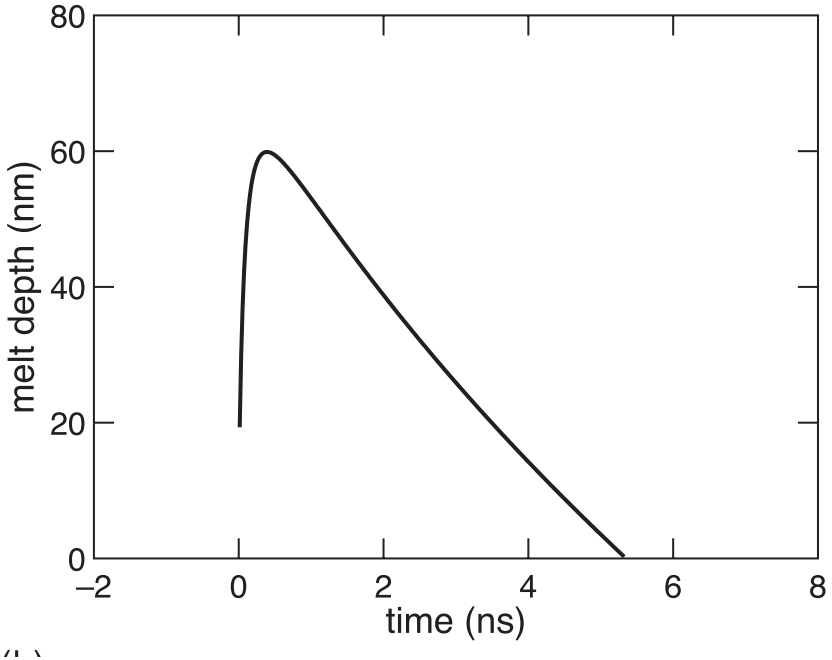
Lin, Yu-Ting. 2014. “Femtosecond-laser hyperdoping and texturing of silicon for photovoltaic applications”. Doctoral dissertation, Harvard University.

Pump-probe conclusions

Melt Duration	Melt Velocity	Resolidification Velocity
1–10 ns	30 km/s (athermal)	10–16 m/s

- Resolidification velocity in range of phase transition (a-Si above 15 m/s)
- Can model dopant profile using classical description of solute transport and trapping

Simulating the melting process



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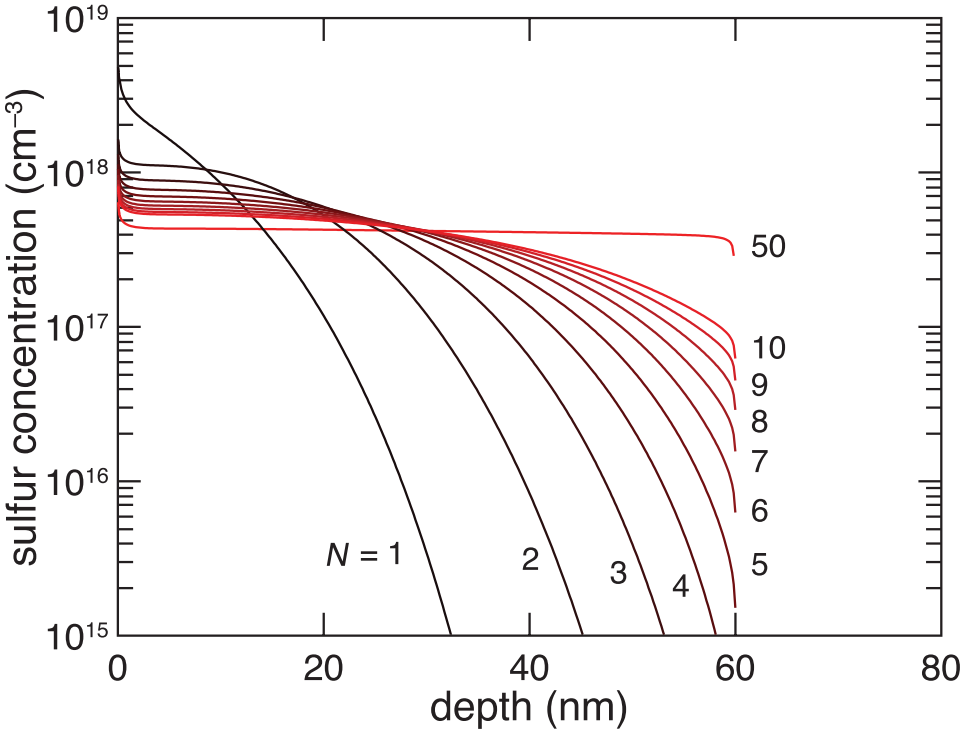
Simulating the dopant profile



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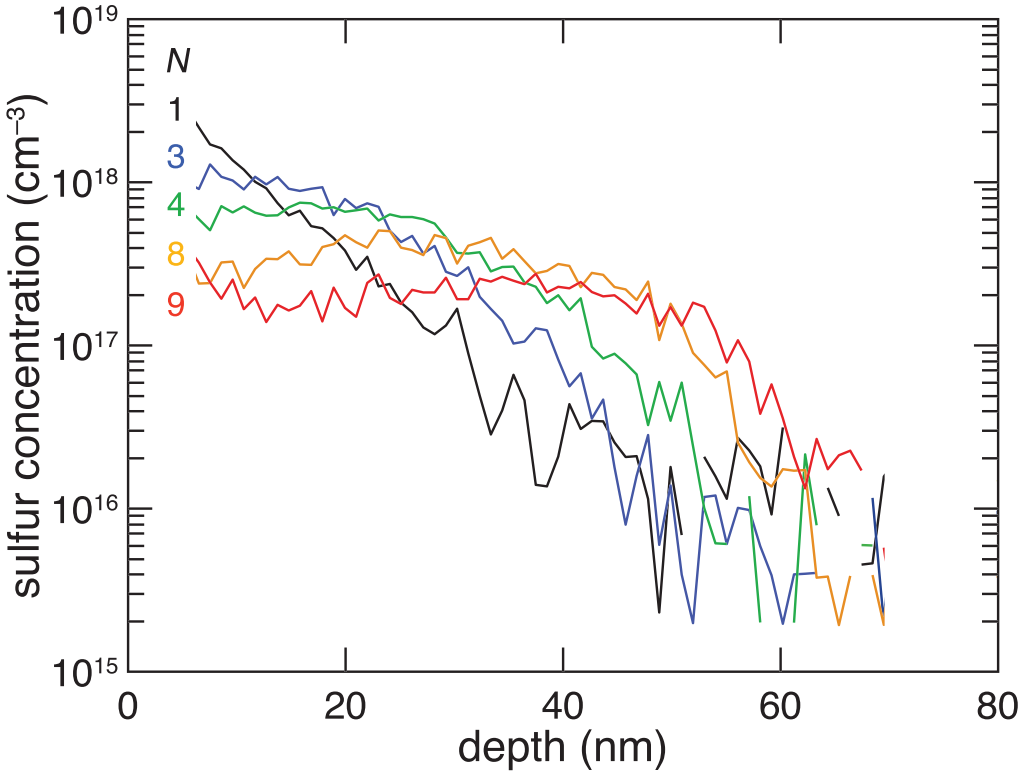
Manipulating the dopant profile



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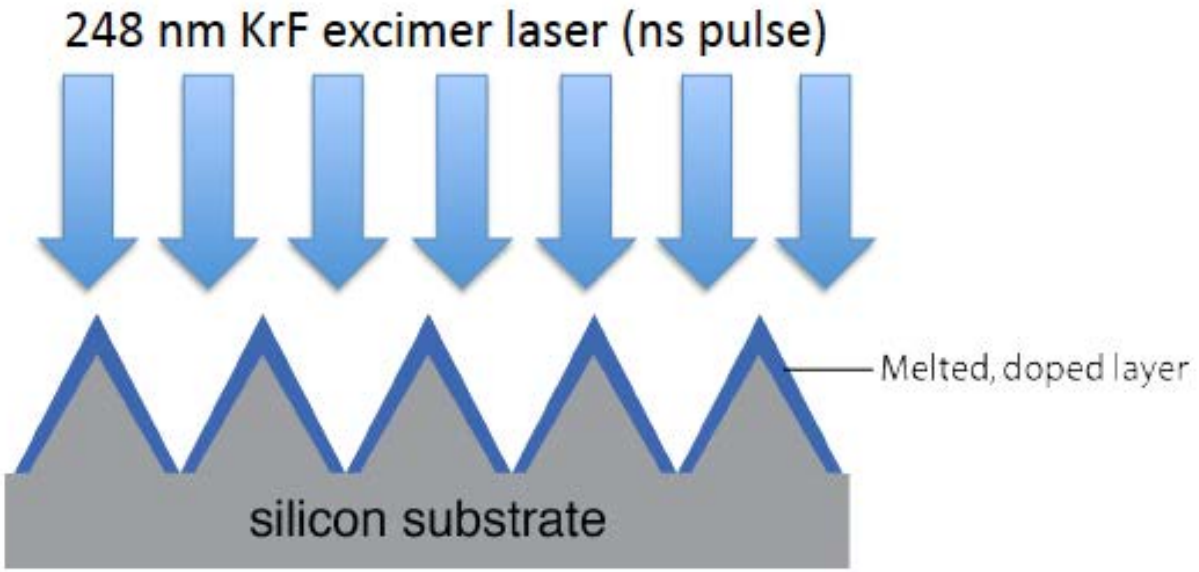
Current and future work

Nanosecond laser annealing

Obtaining non-metallic hyperdoped black Si

ns laser annealing

ns laser annealing



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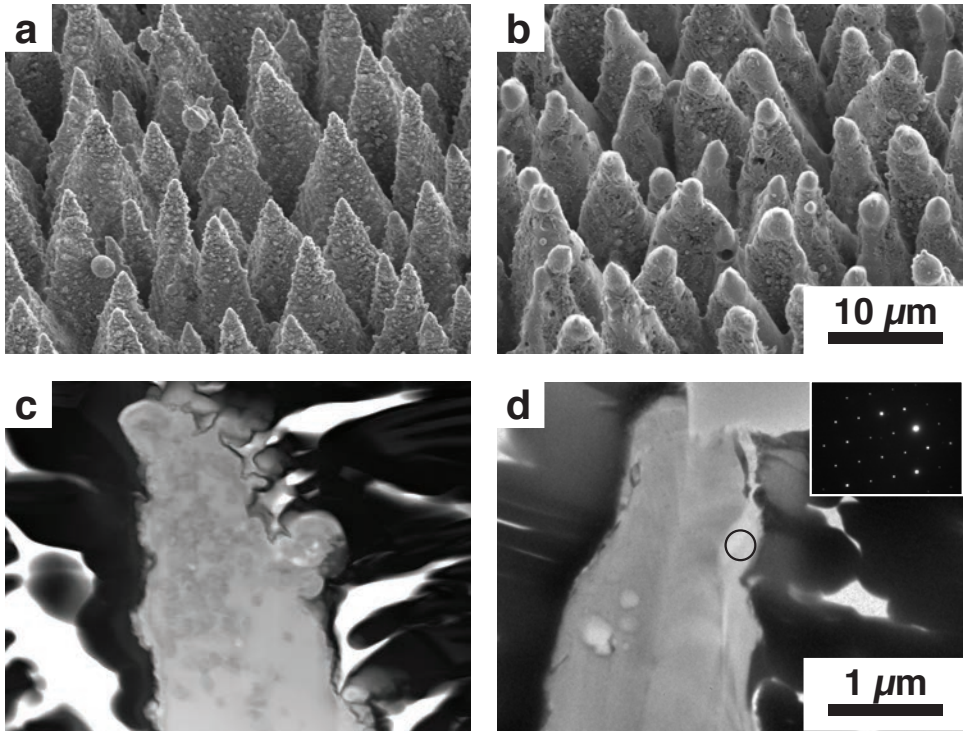
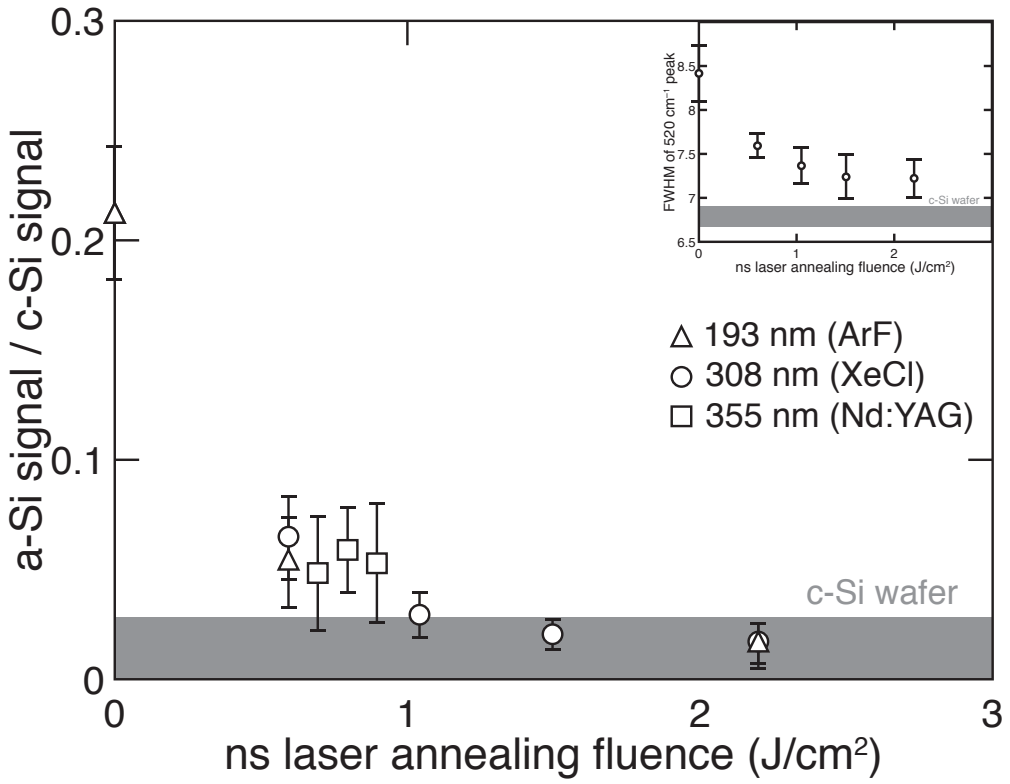


Before ns laser anneal After ns laser anneal (2.2 J/cm^2)

Franta, B., D. Pastor, H. Gandhi., P. Rekemeyer., S. Gradečak, M. Aziz, E. Mazur . "Increasing the crystallinity and optical absorptance of hyperdoped black silicon using nanosecond laser annealing." In preparation.

ns laser annealing



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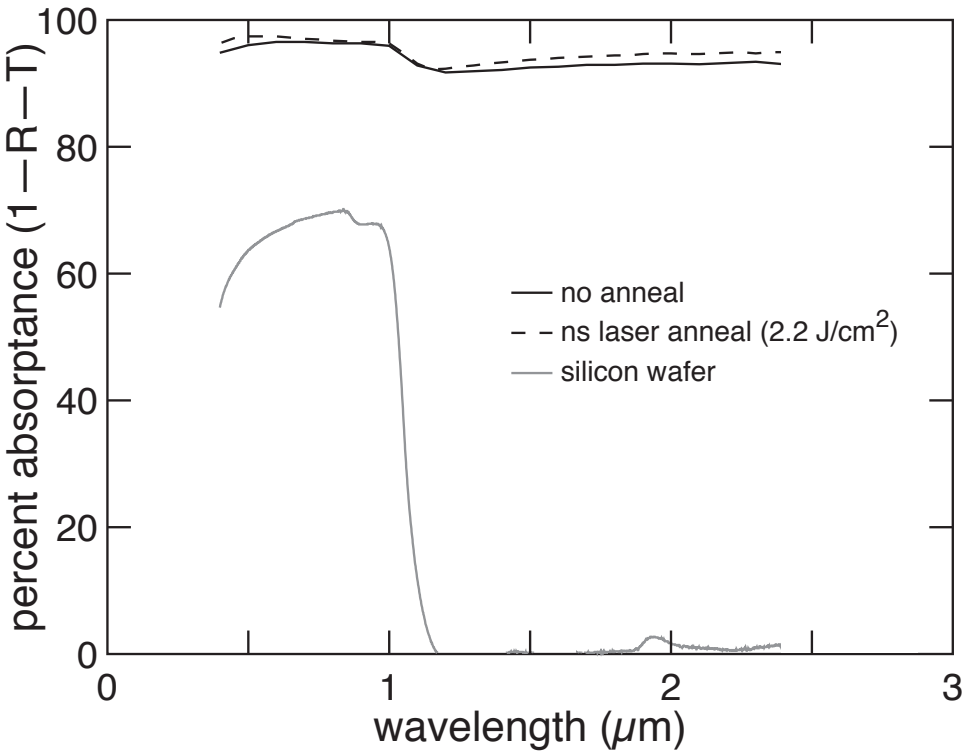

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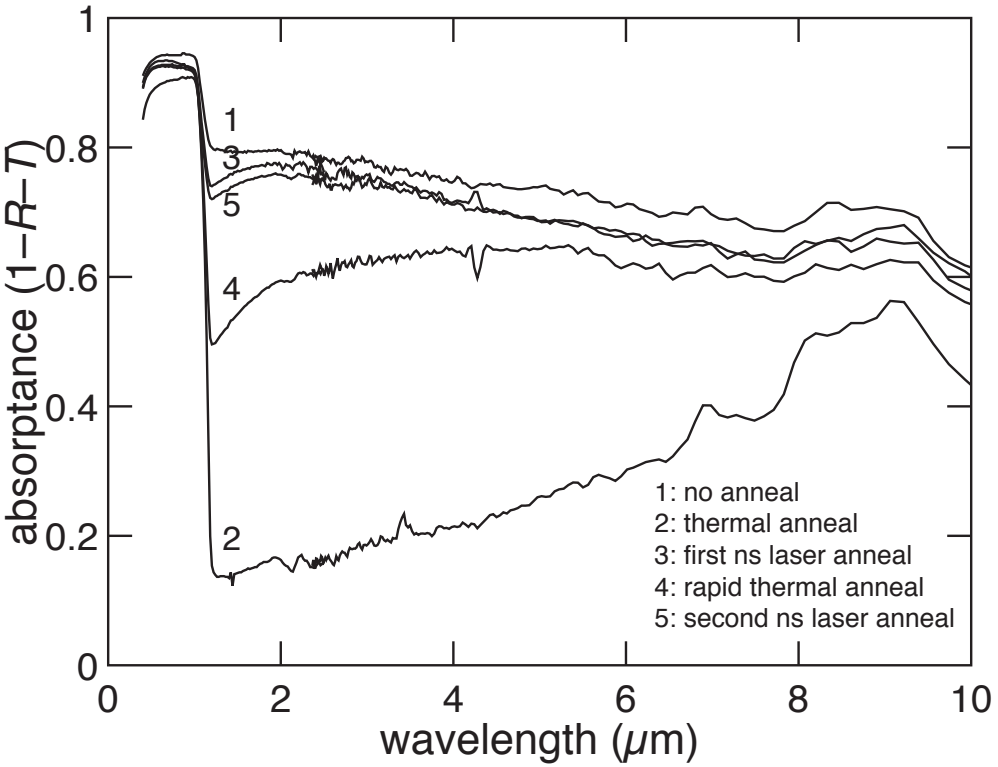

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Next: Obtaining non-metallic hyperdoped black silicon

- Need to obtain <0.4 at. % doping concentration *and* strong optical absorptance at same time
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- Potential methods:
  - Nanosecond laser pulses to remove dopants from hyperdoped black silicon
  - Ablate hyperdoped skin off hyperdoped black silicon, then laser dope
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Conclusions

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- Hyperdoped black silicon
  - A lot of recent advances
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  - Determined melting velocity, resolidification velocity, melt duration
  - Can control crystallinity with fluence
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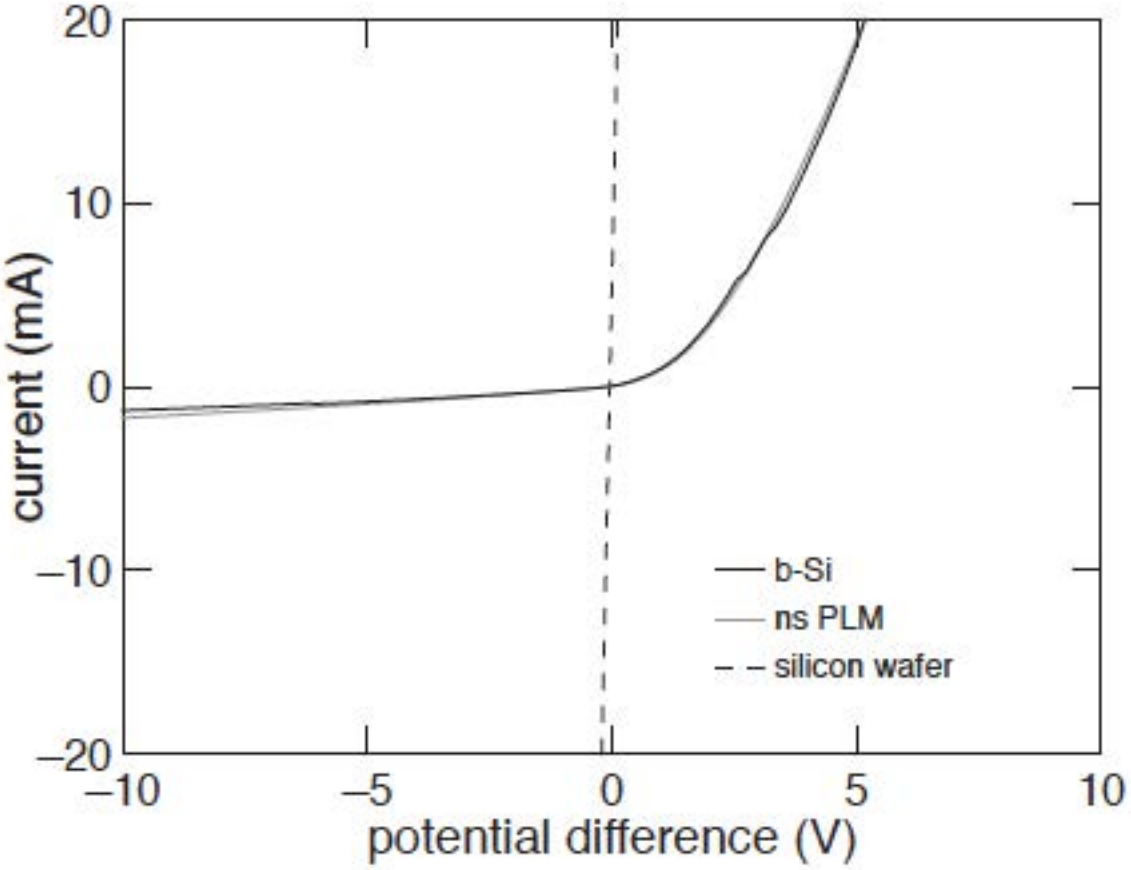
- Current and future work
  - Nanosecond laser annealing
  - Obtaining non-metallic hyperdoped black silicon

Thank you

Discussion

Extra slides

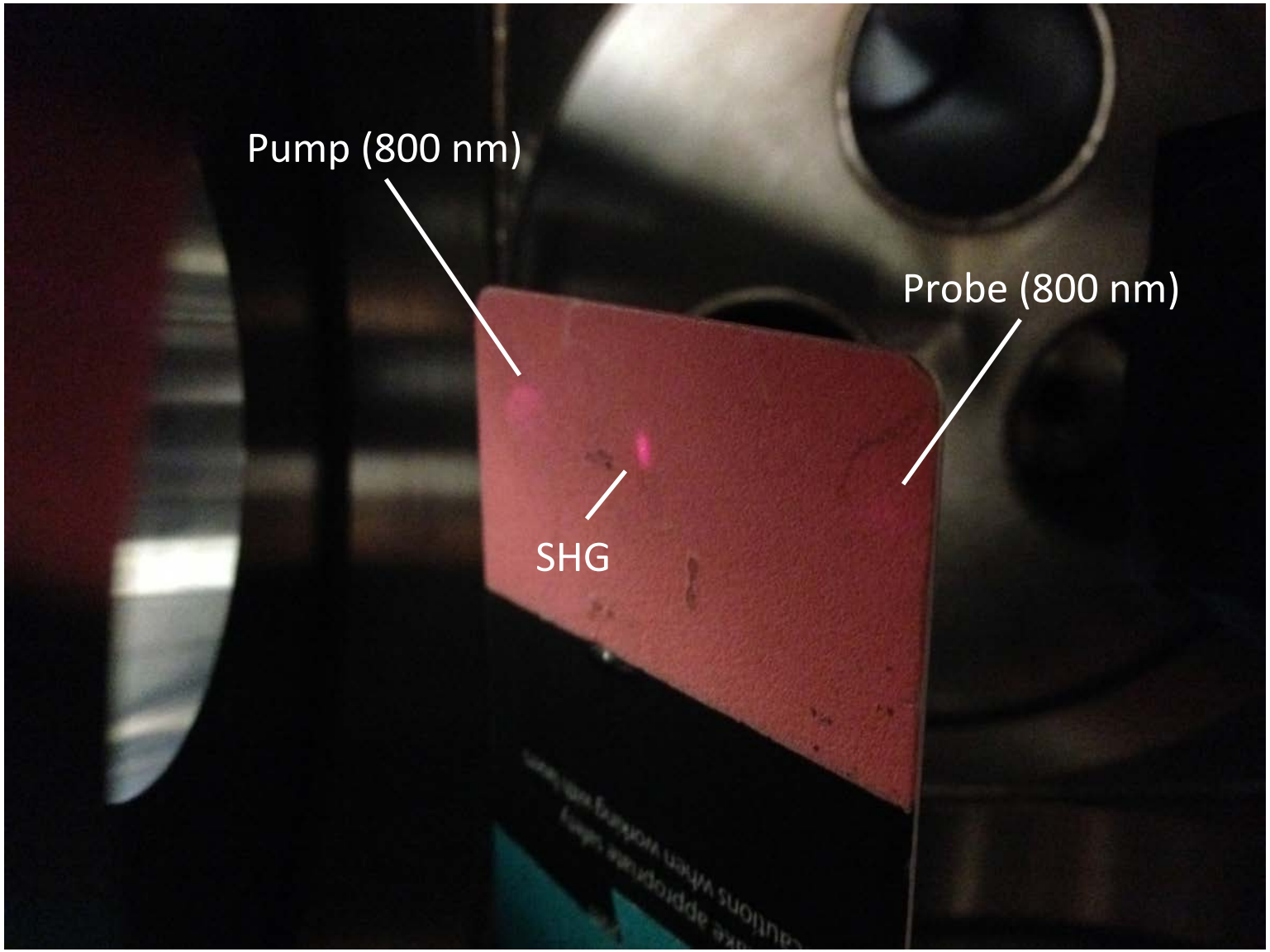
ns laser annealing



November Update with R. Parra

- Add additional, manual stage to measure ns delays
- Modeling of melting and diffusion
- Replace pump laser for amplifier (pump for seed already replaced)
- Improve setup to directly measure carrier dynamics

Pump / Probe Reflectometry



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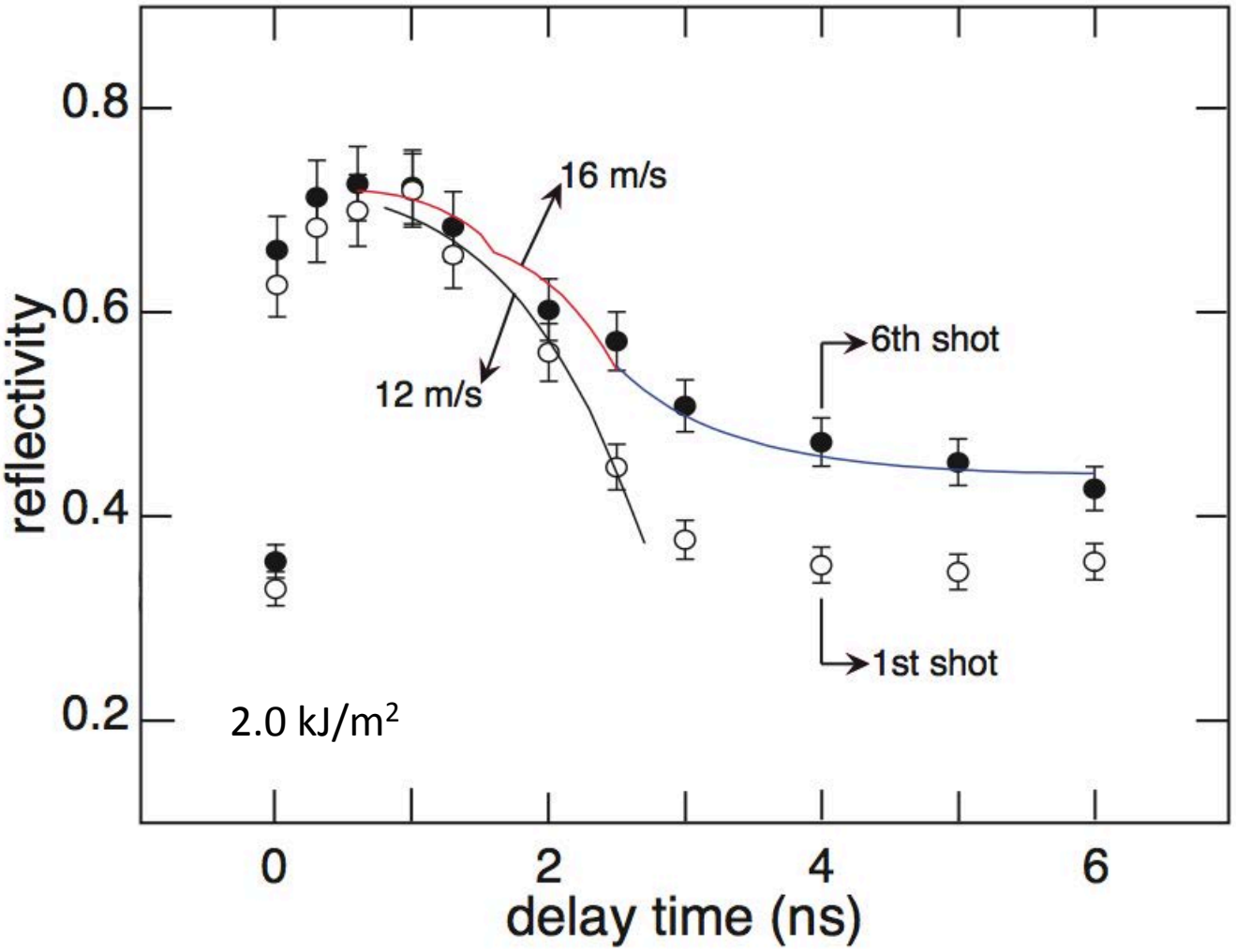

Timeline

Deliverables	Section	Year 1	Year 2	Year 3
Optimize pump-probe setup	*4.1*			
Determine the IRF for silicon far from equilibrium	*4.1*			
Study dopant incorporation with pump-probe	*4.2*			
Simulate hyperdoping process and compare to SIMS data	*4.2*			
Simulate irradiation of textured surfaces	*4.3*			
Test simulation of irradiation of textured surfaces using TEM analysis	*4.3*			