Femtosecond laser doped silicon for photovoltaic applications

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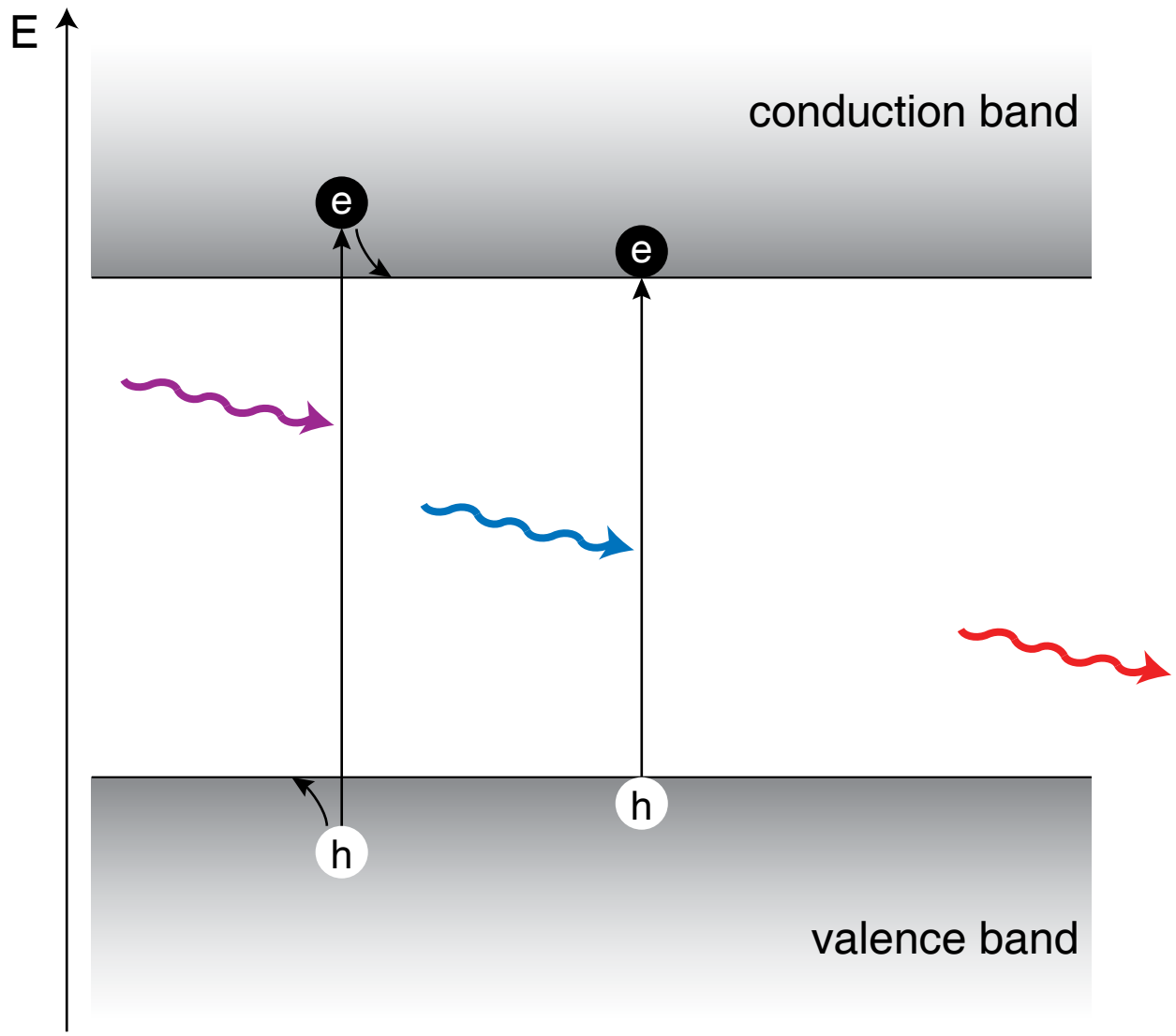
Harvard University
SPIE Optics & Photonics
2011/08/21

Intermediate-band photovoltaics



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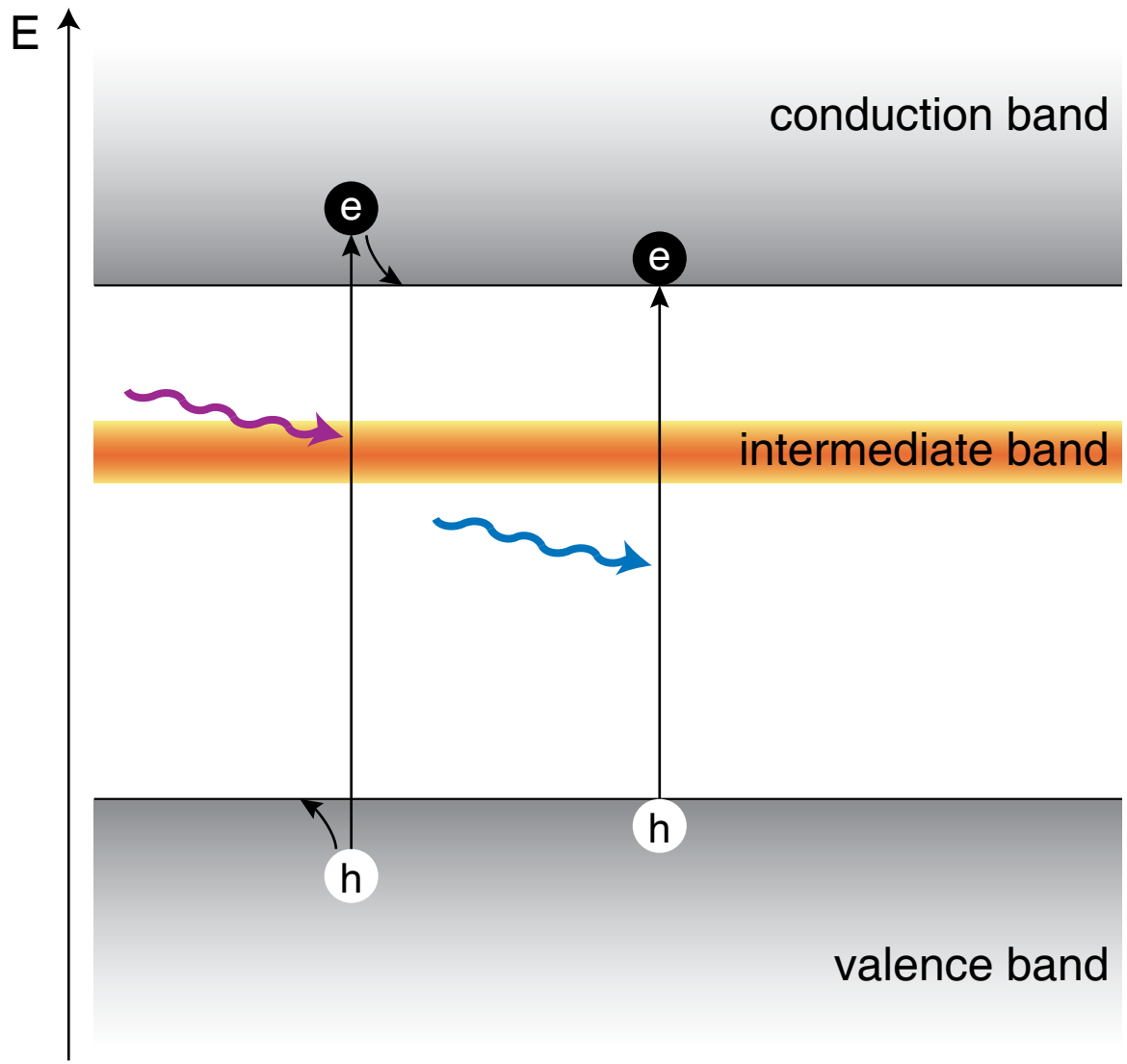

Luque and Marti, Phys. Rev. Lett. 78, 5014 (1997)

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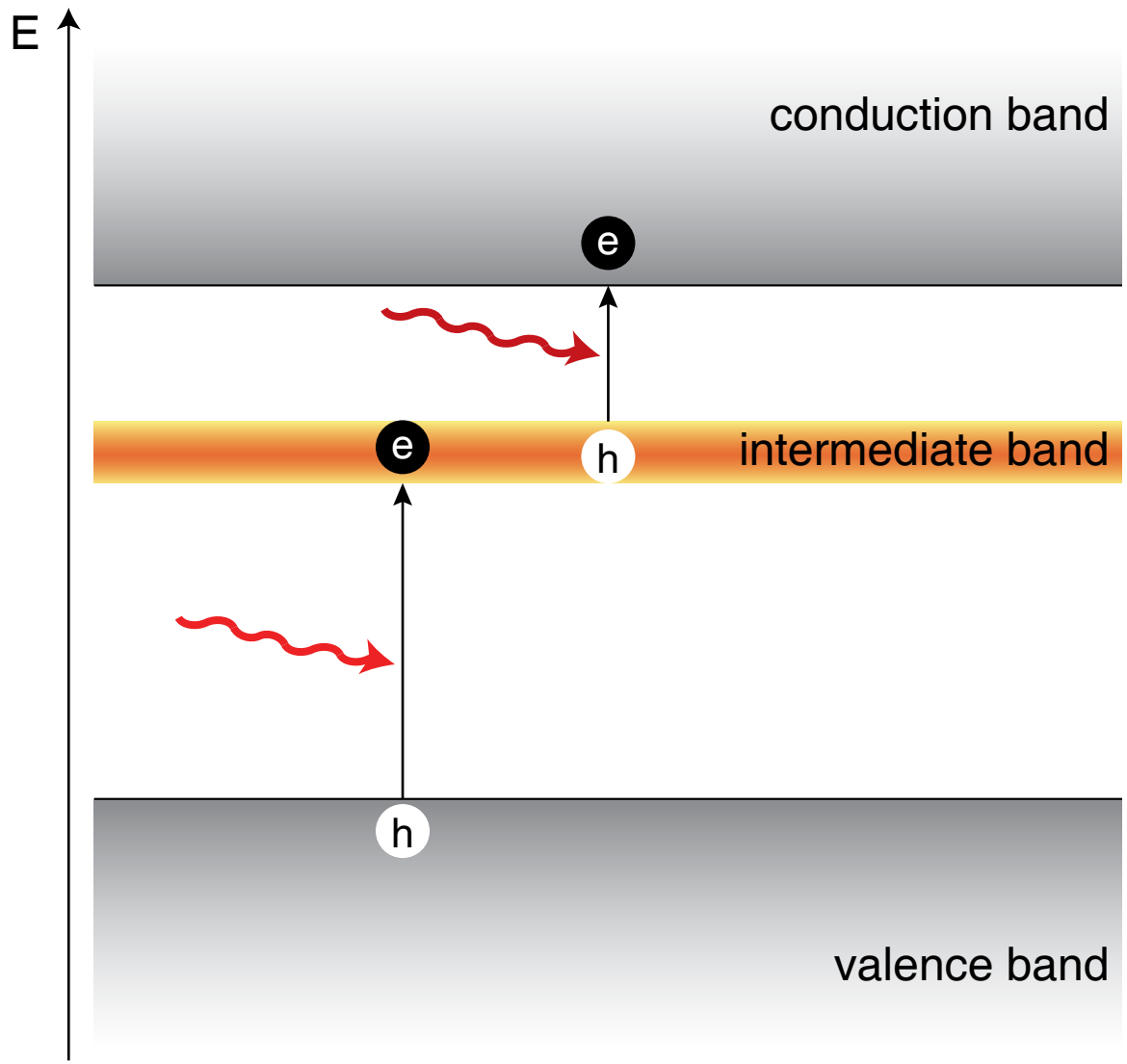

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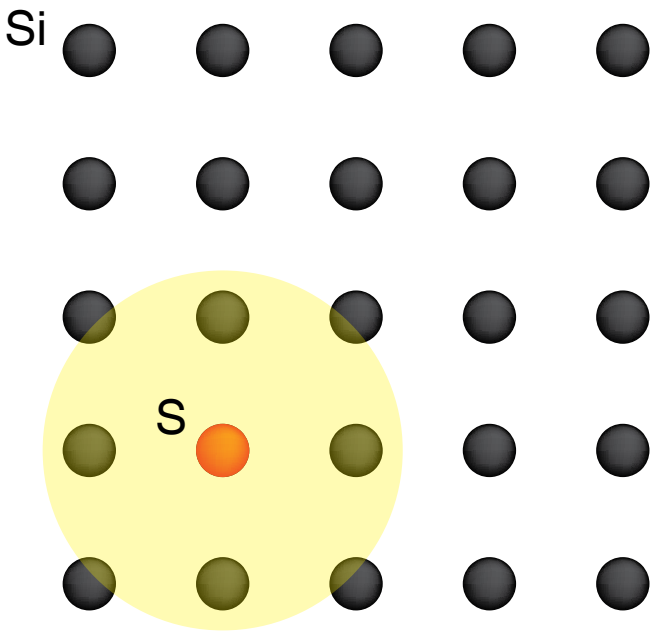

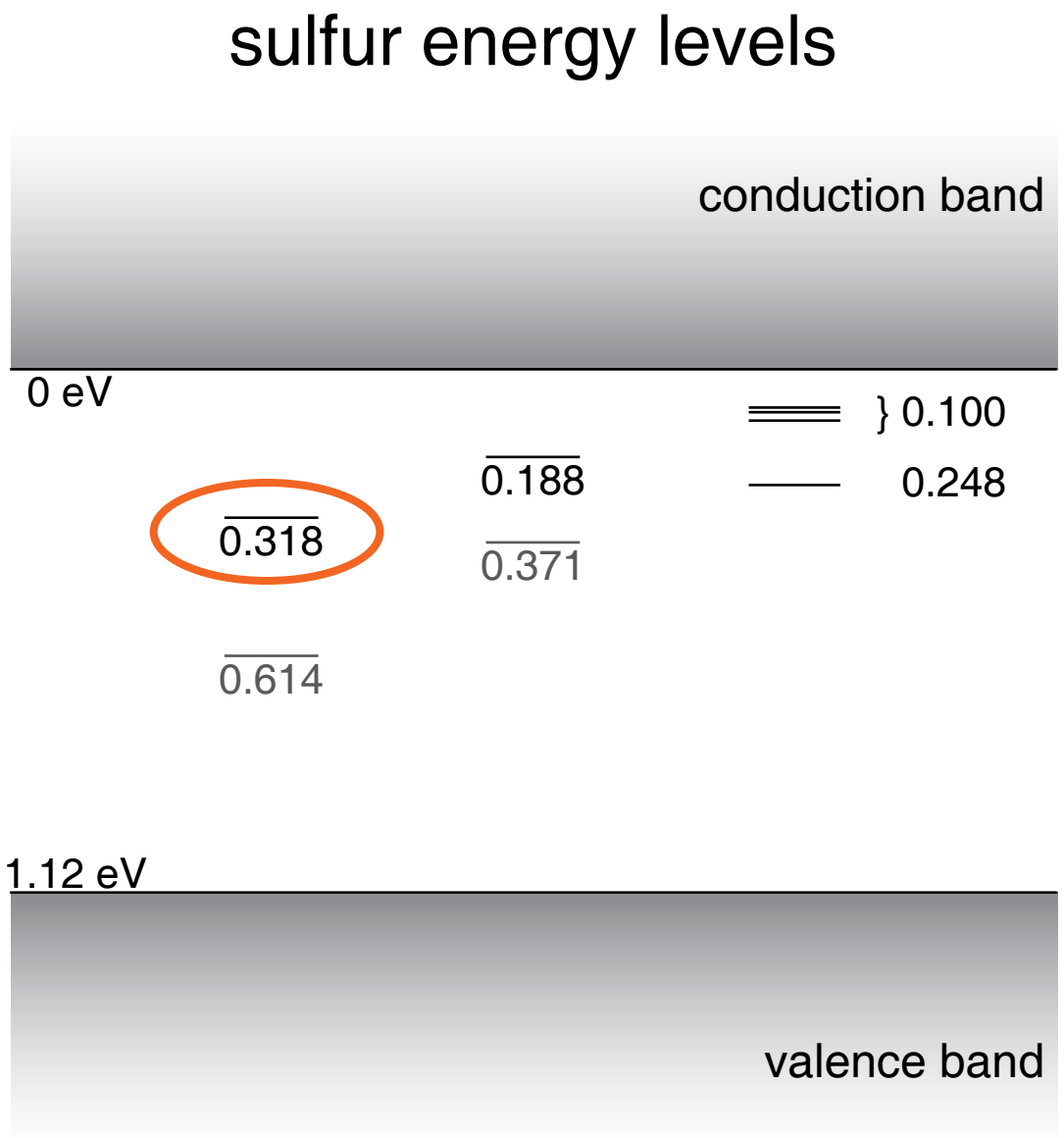

Janzén *et al,* Phys. Rev. B 29, 1907 (1984)

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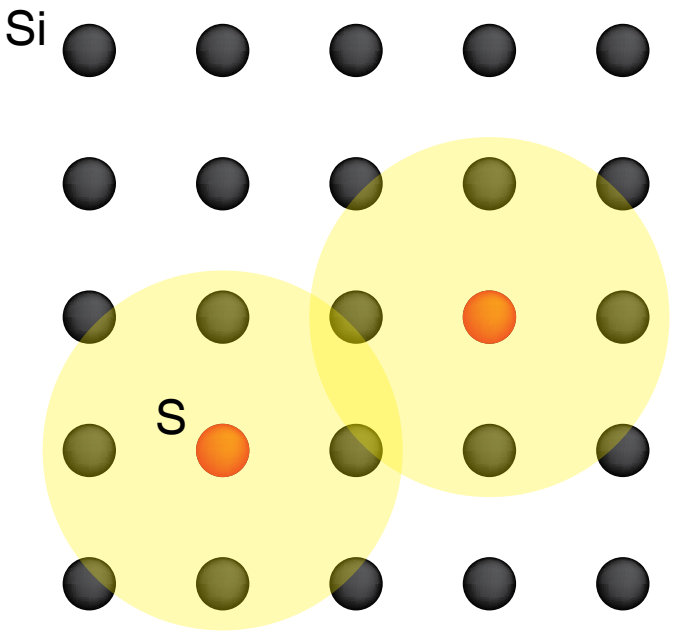
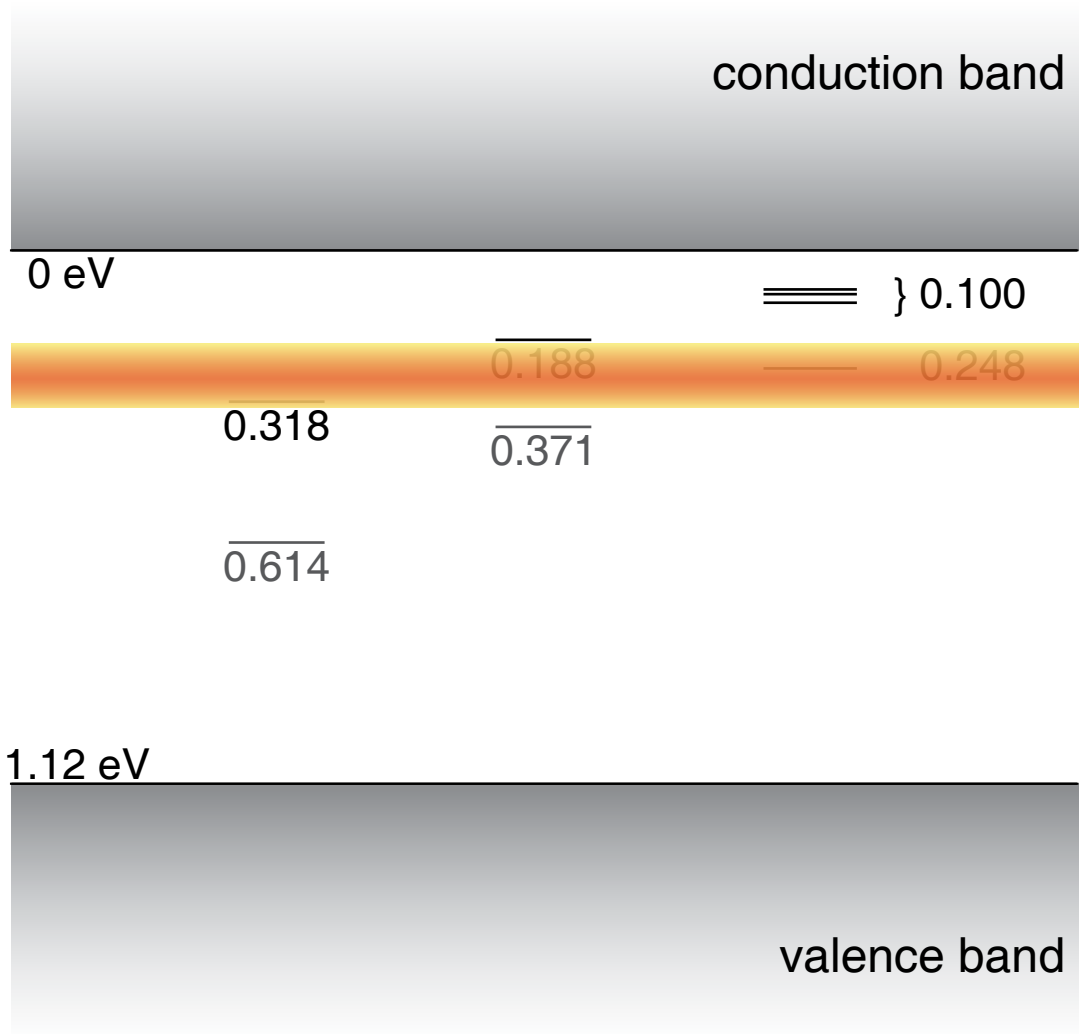


metal-insulator transition



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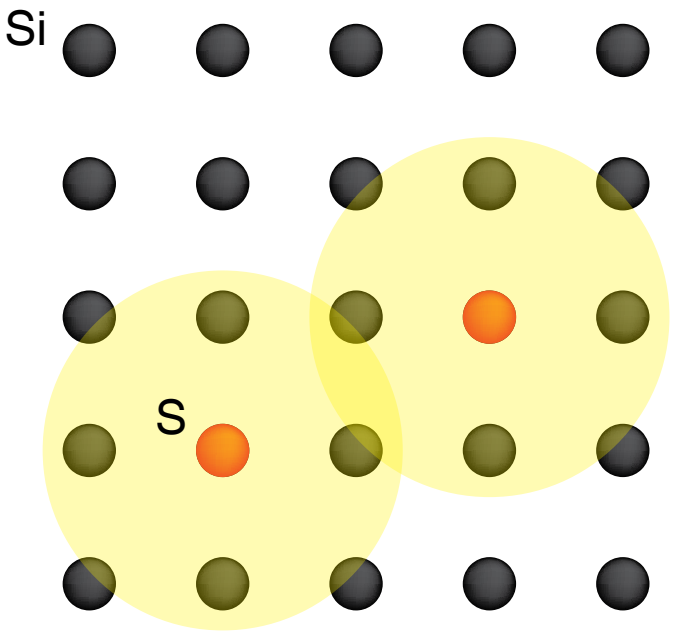

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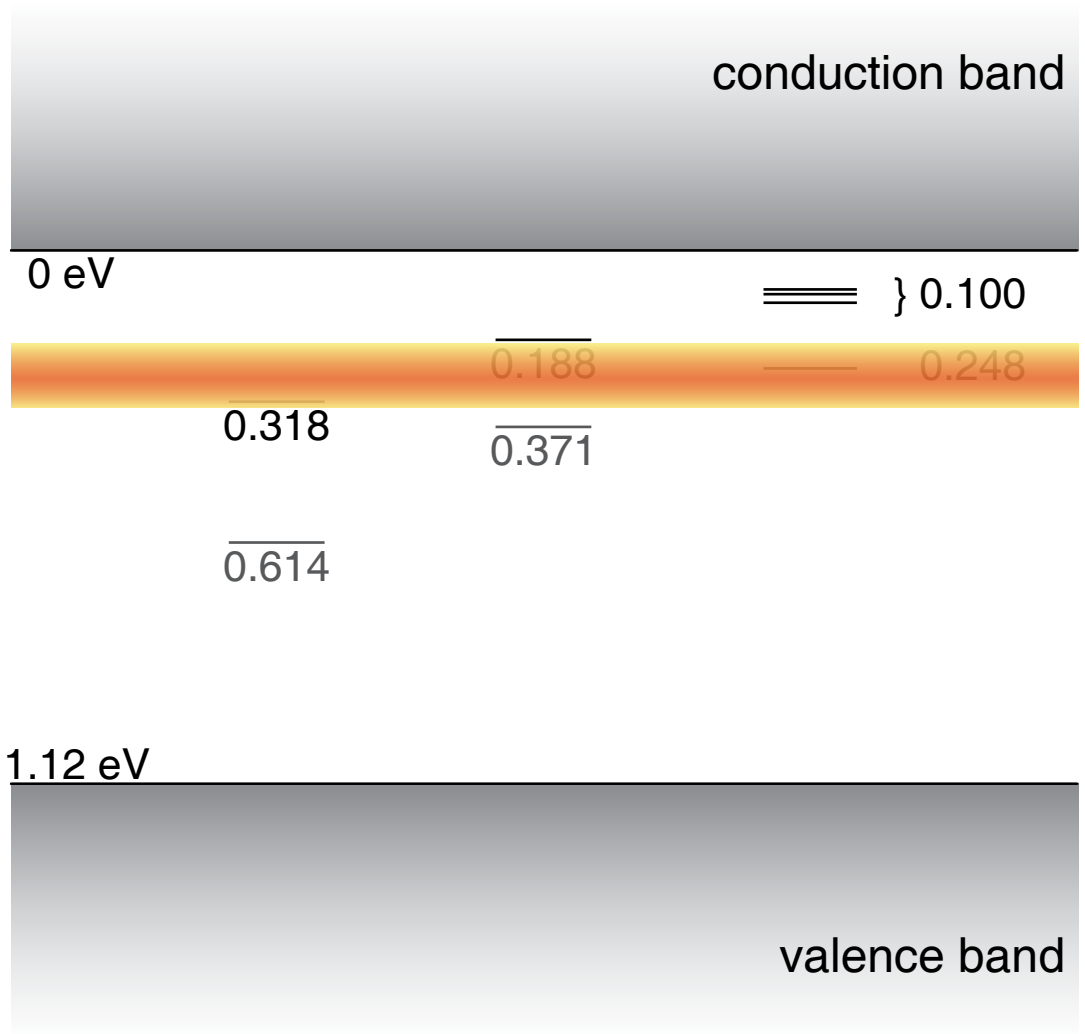
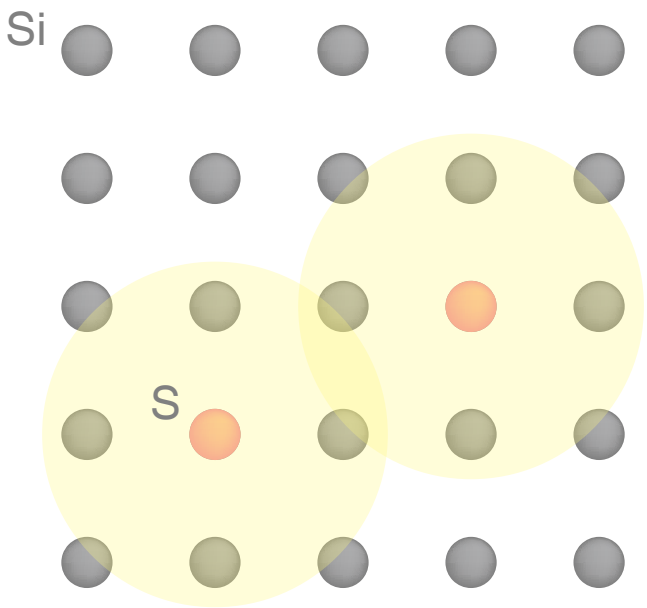


deep level
high concentration

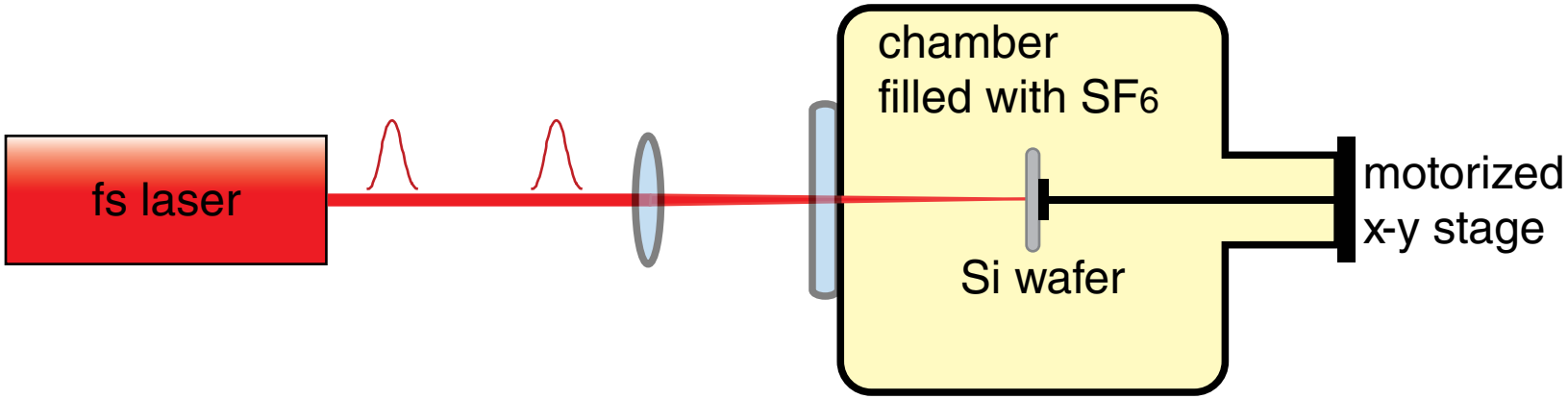
Janzén *et al,* Phys. Rev. B 29, 1907 (1984)

Outline

- black silicon
- optical and electronic properties
- improve fs-laser doping
- annealing & dopant diffusion



Introduction



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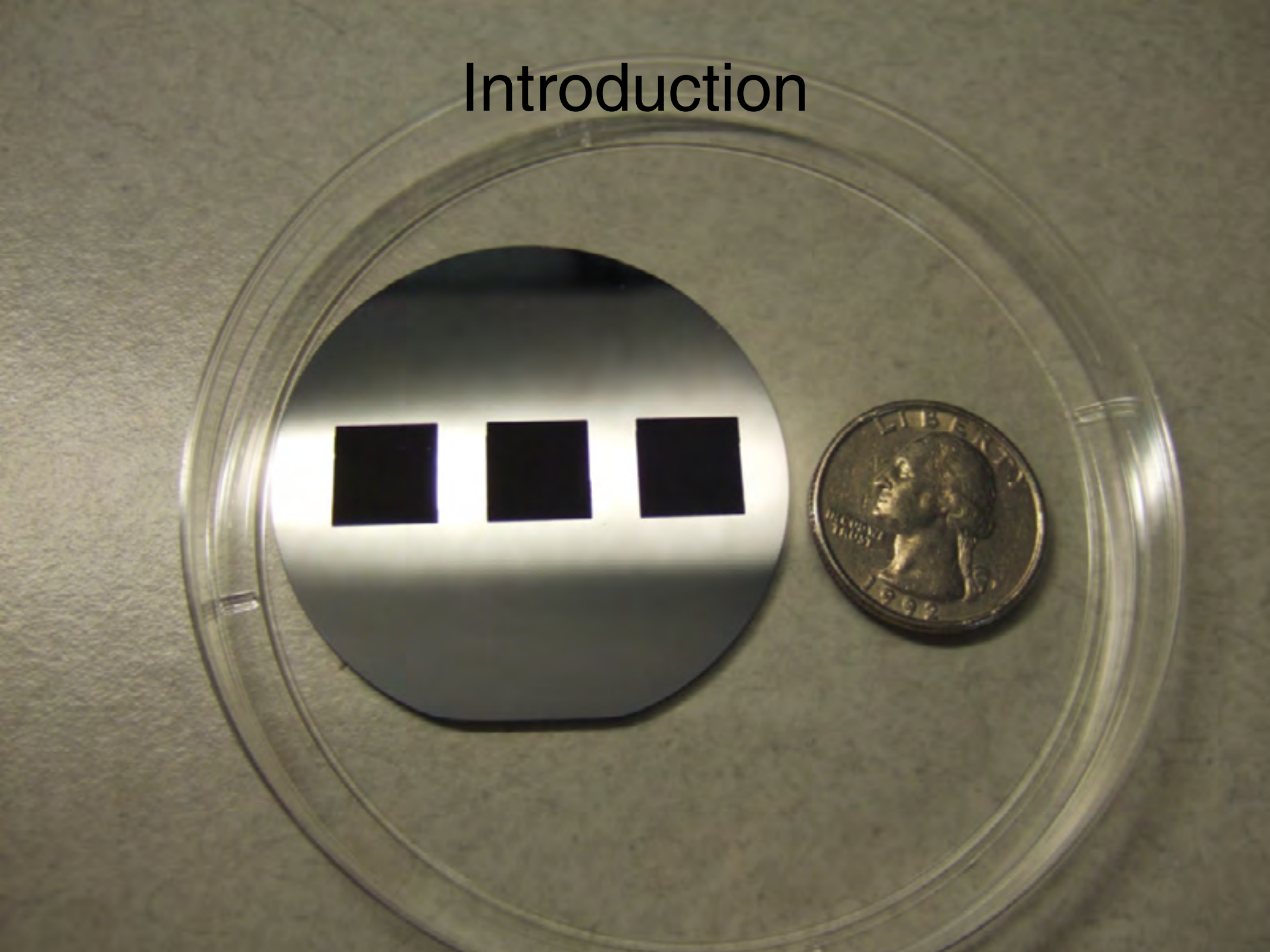
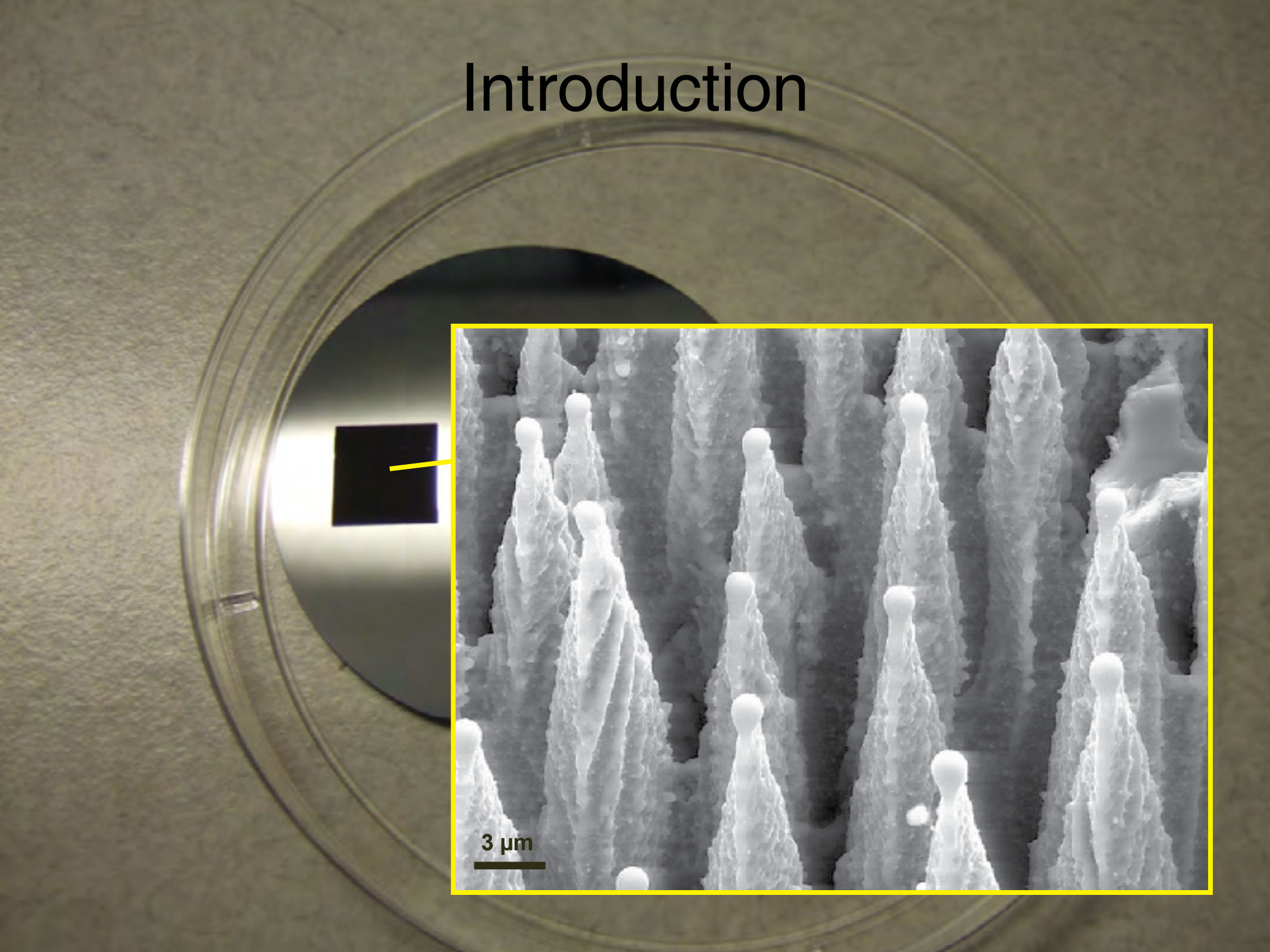


Introduction

Doped Region
~1% Sulfur

Introduction



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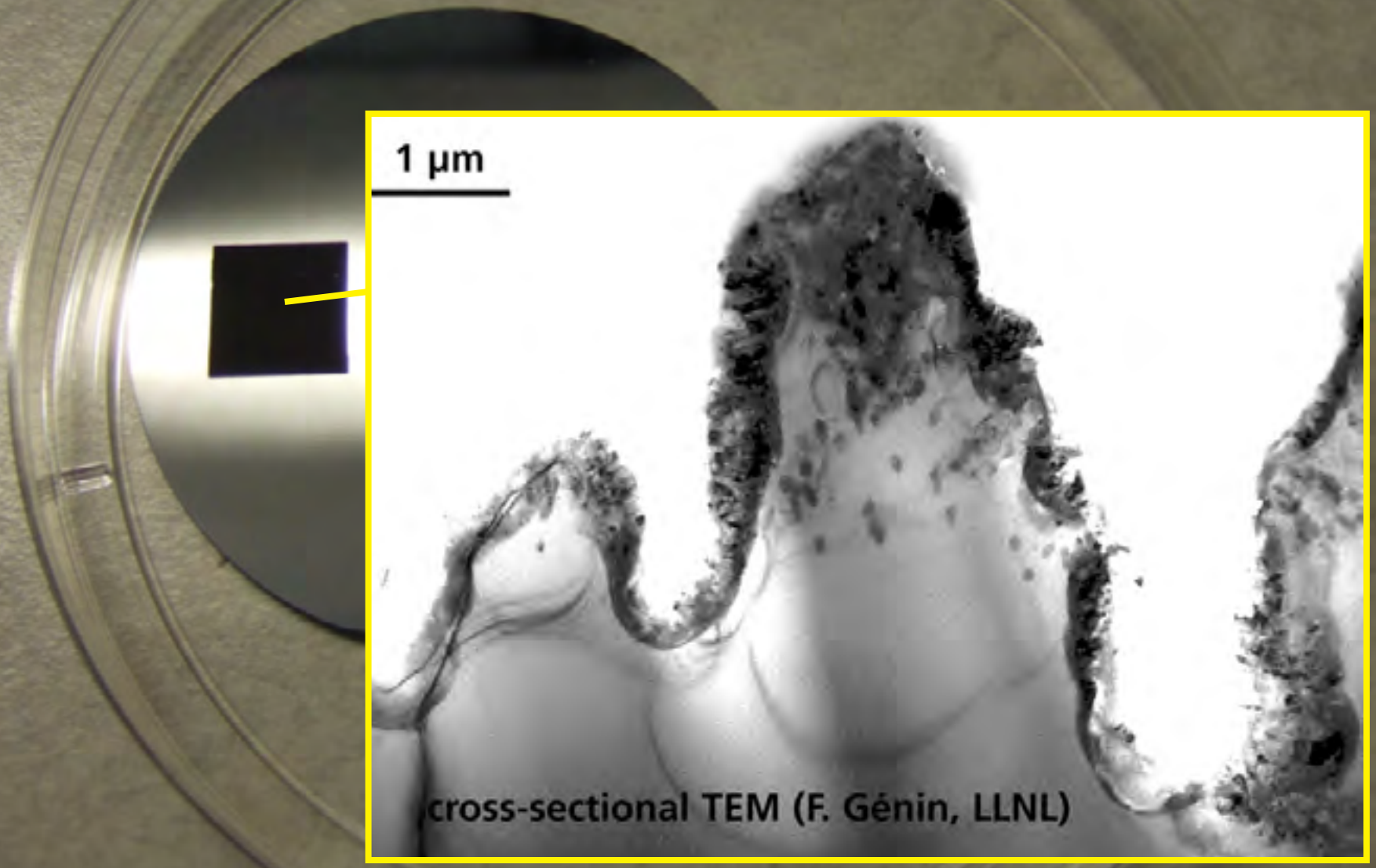
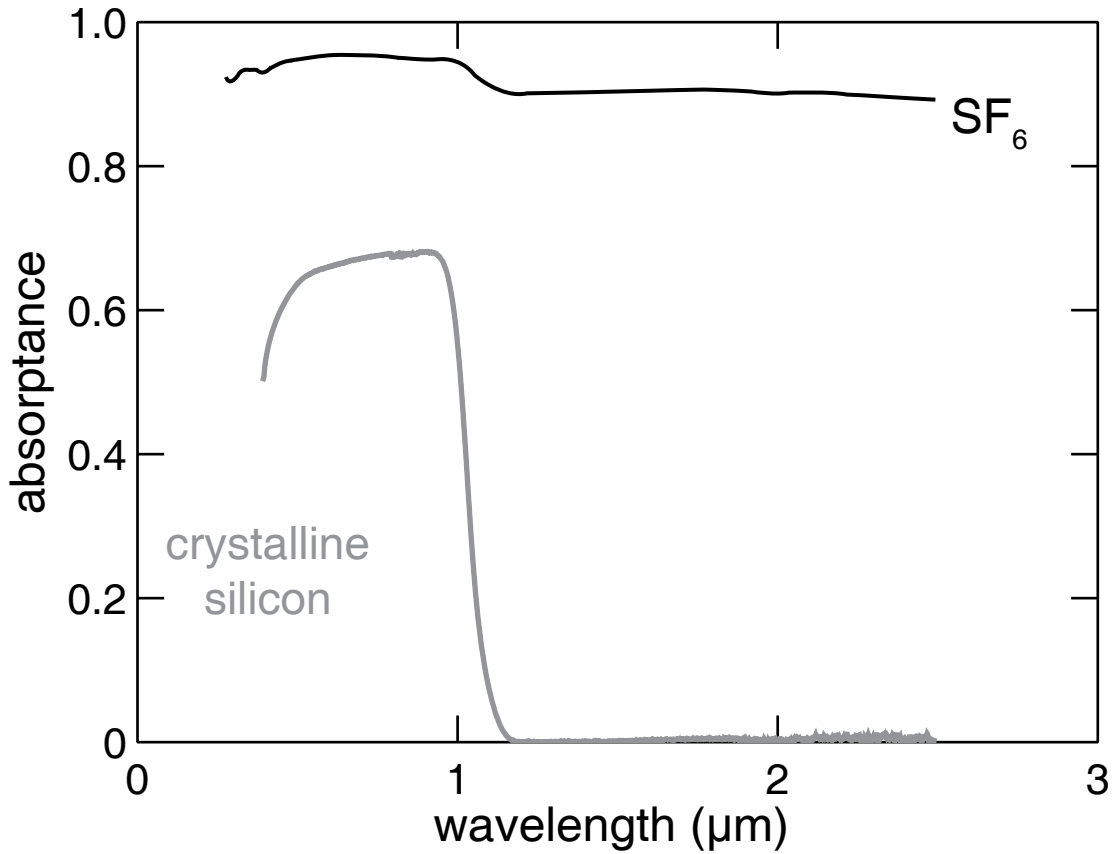


Introduction

$$A = 1 - T_{int} - R_{int}$$



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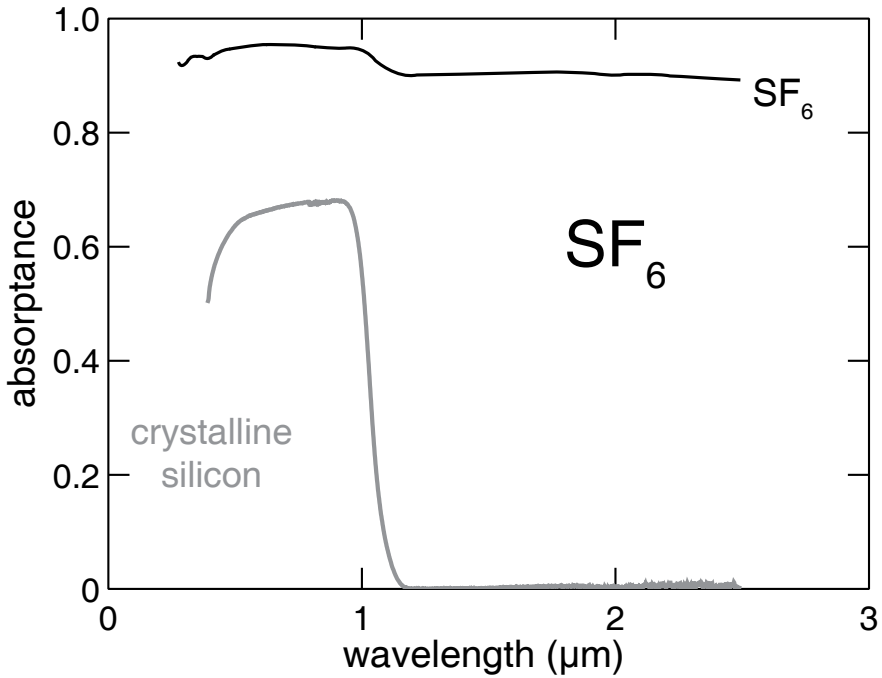
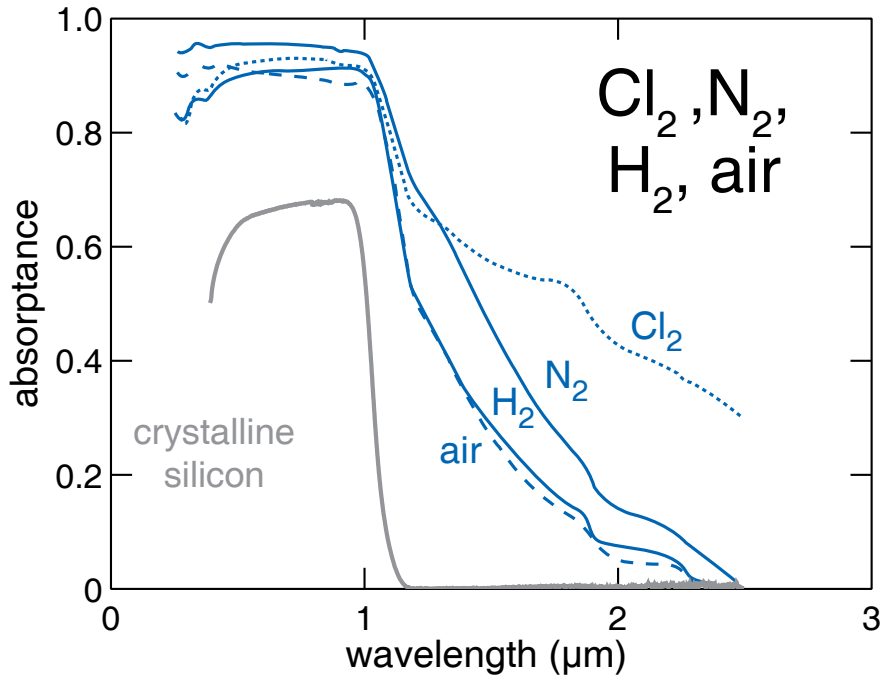
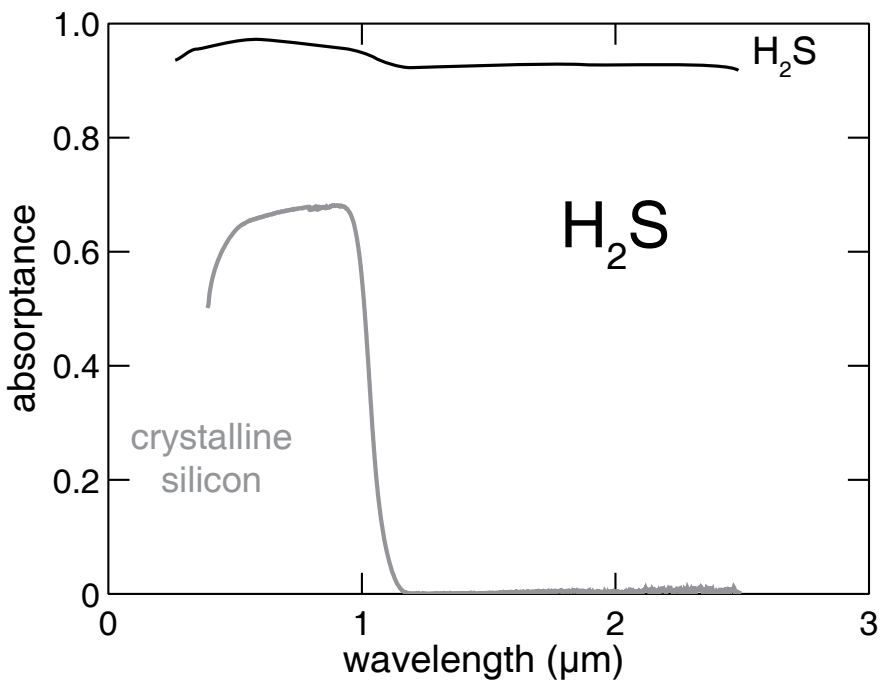
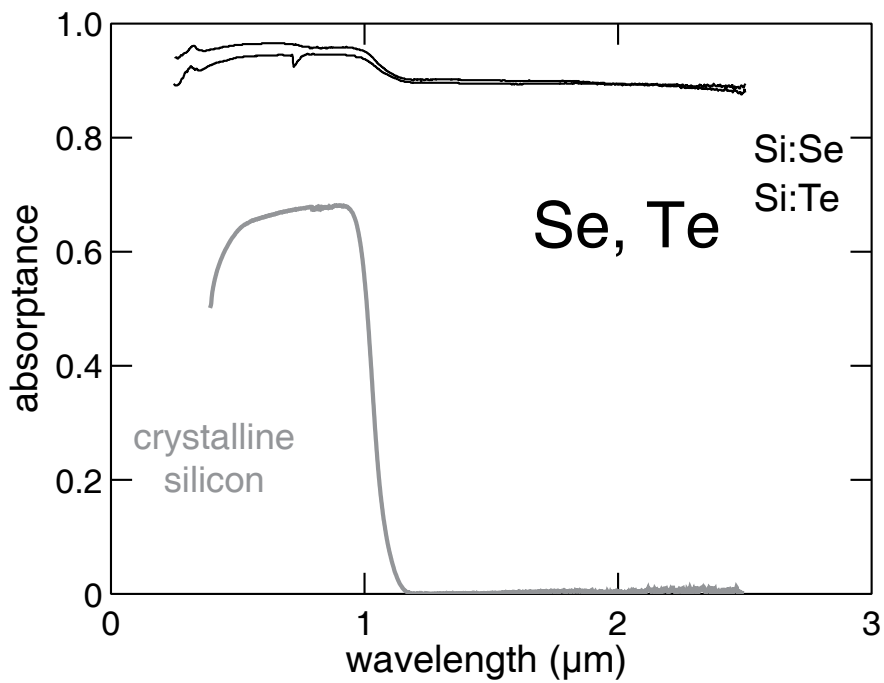




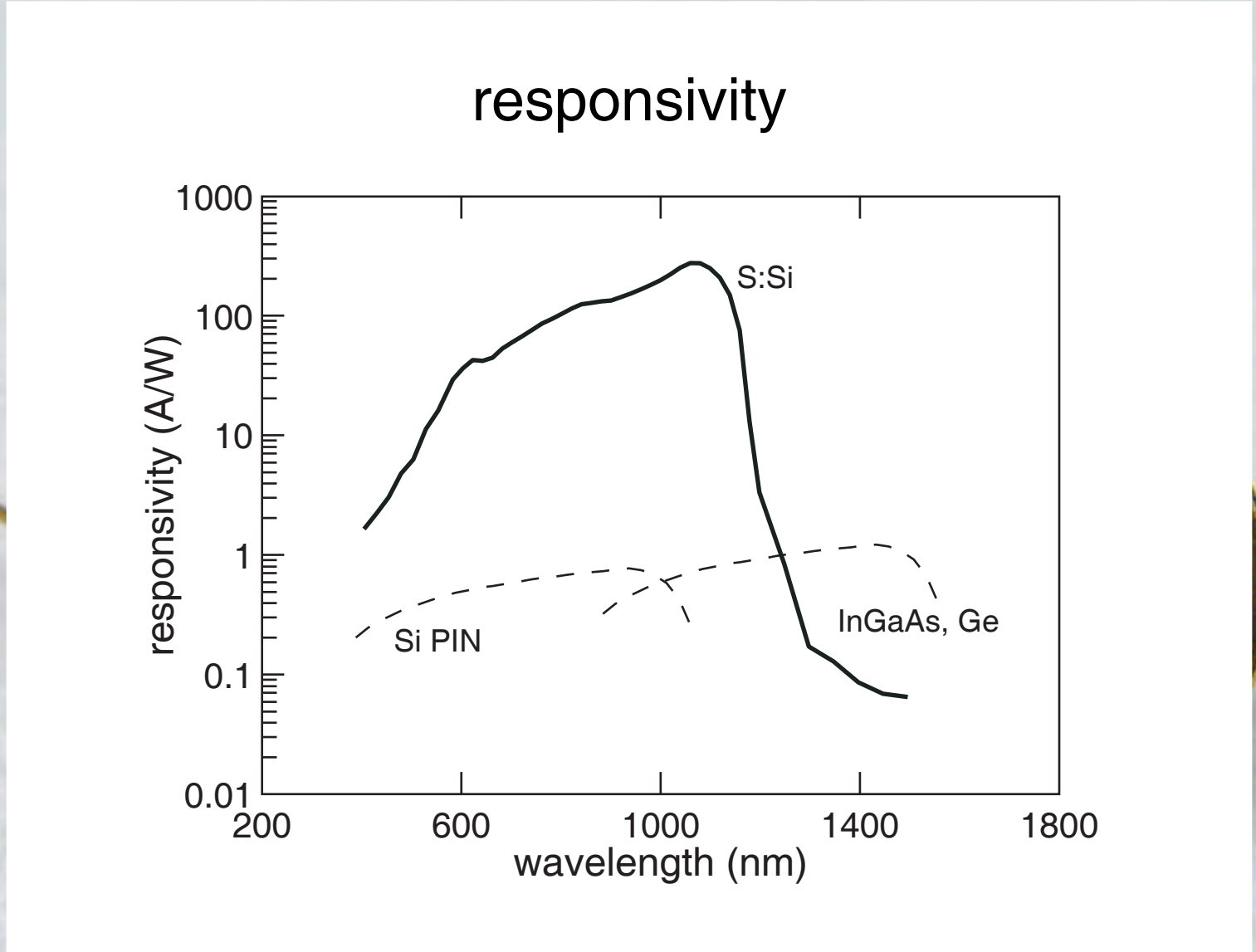




Introduction

www.sionyx.com

Introduction



Carey *et al.* Opt. Lett., 30, 1773-1775 (2005)

Outline

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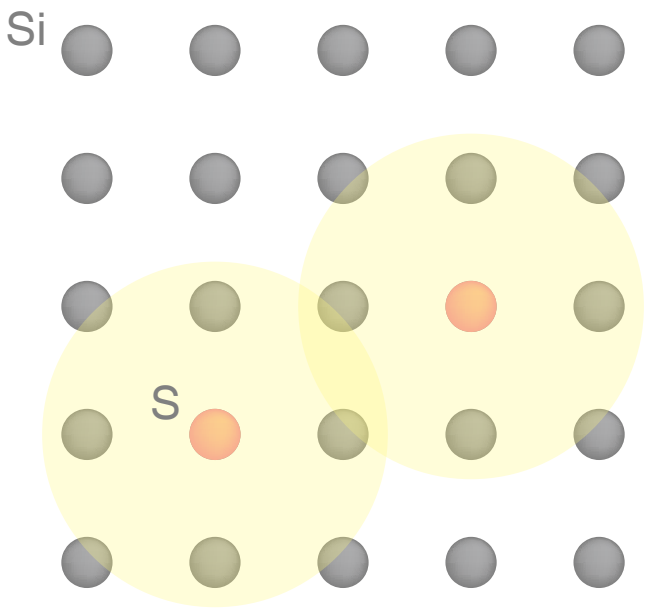
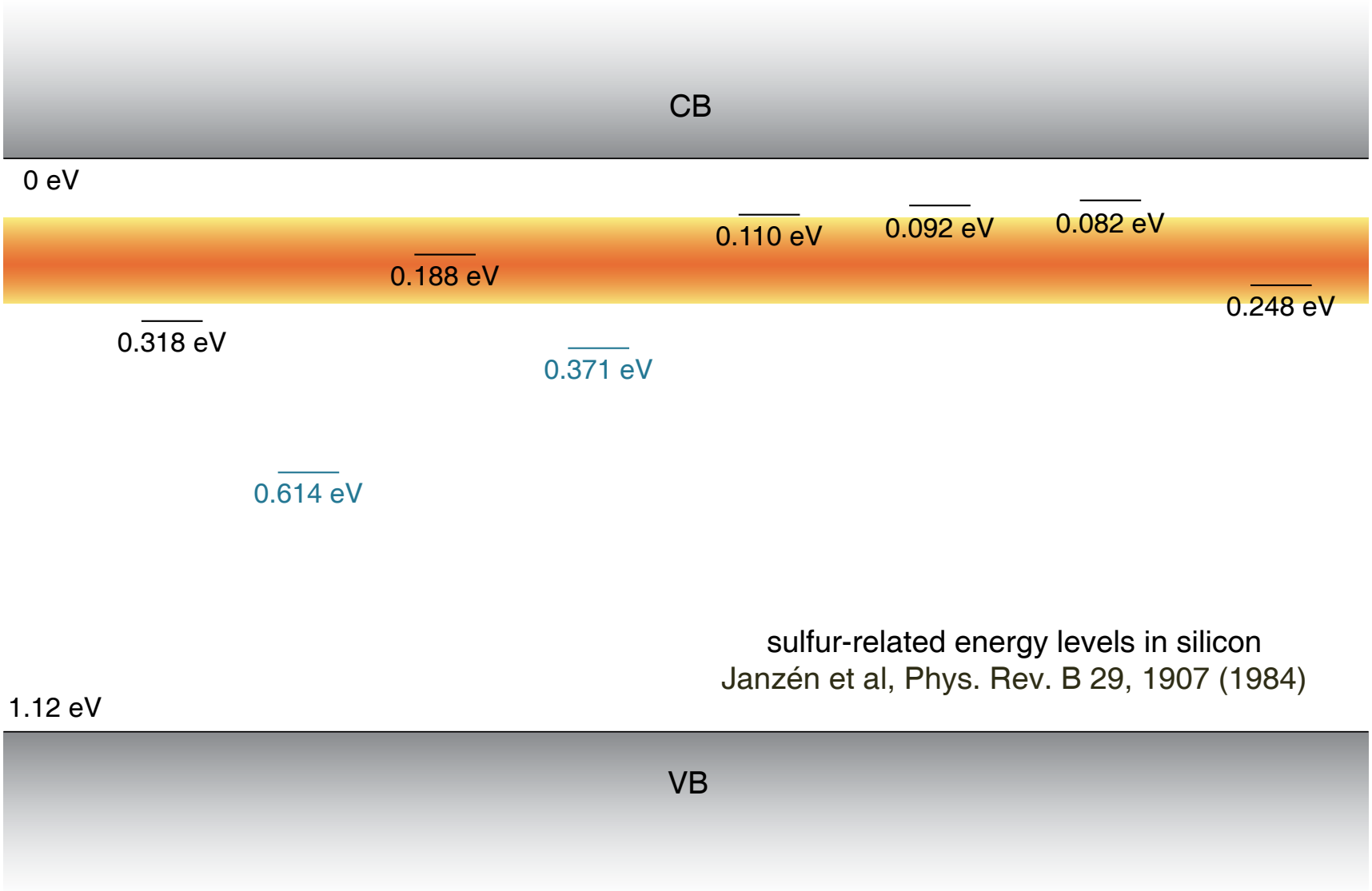
- optical and electronic properties
- improve fs-laser doping
- annealing & dopant diffusion



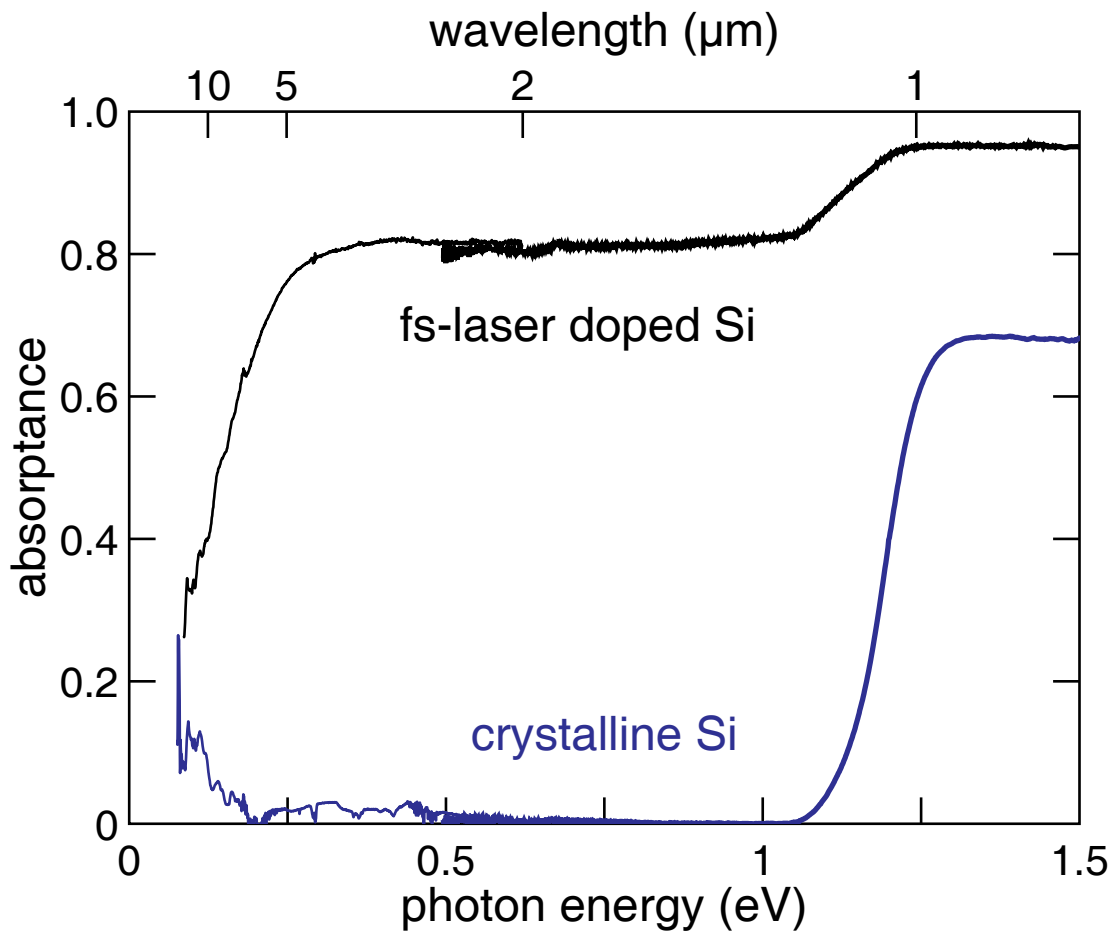
Optical and electronic properties



sulfur-related energy levels in silicon
Janzén et al, Phys. Rev. B 29, 1907 (1984)

Optical and electronic properties

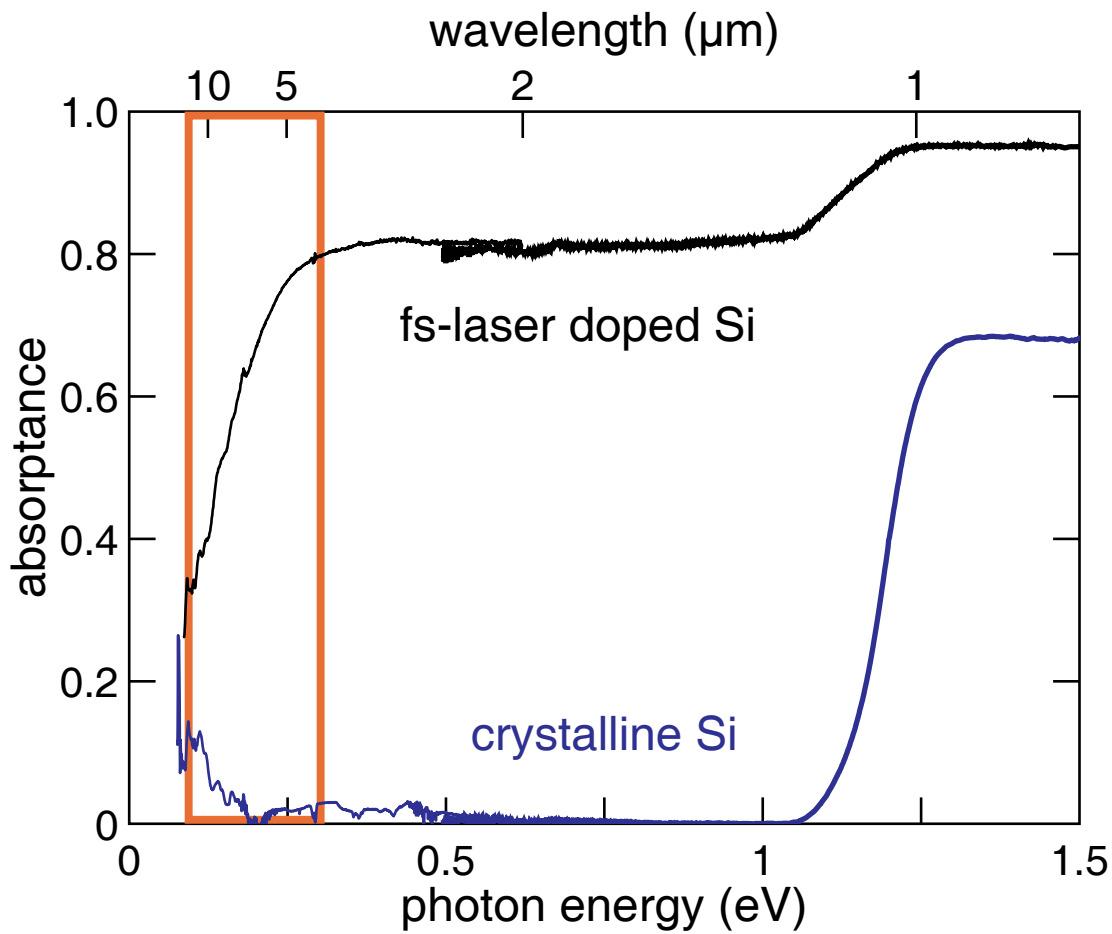
Mid-IR absorption



C. Pruner and A. Asenbaum, University of Salzburg, *unpublished*

Optical and electronic properties

dopant energy level ~ 0.2 eV



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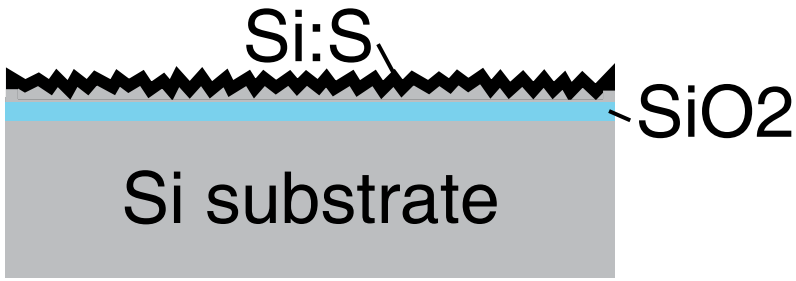
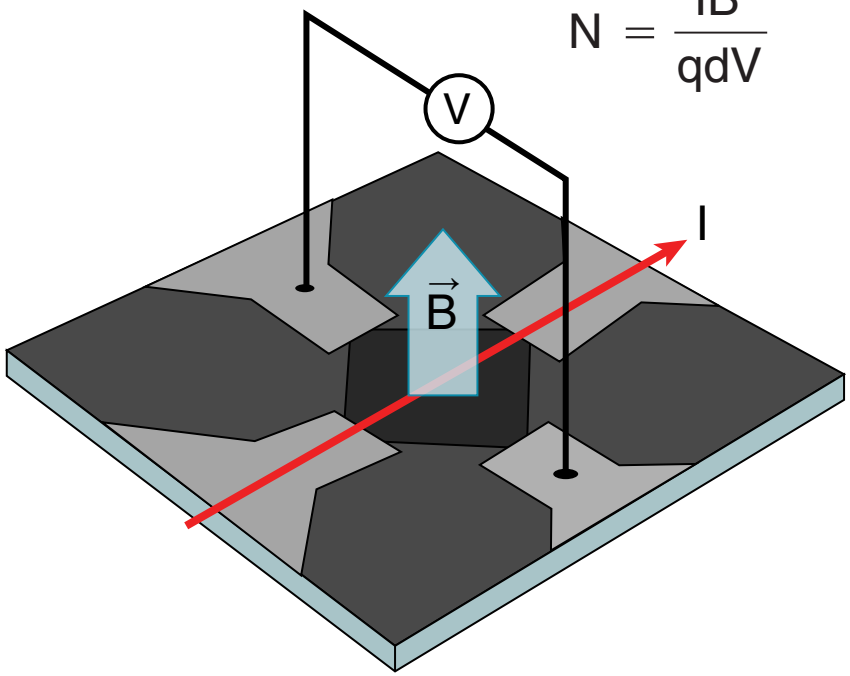
Optical and electronic properties



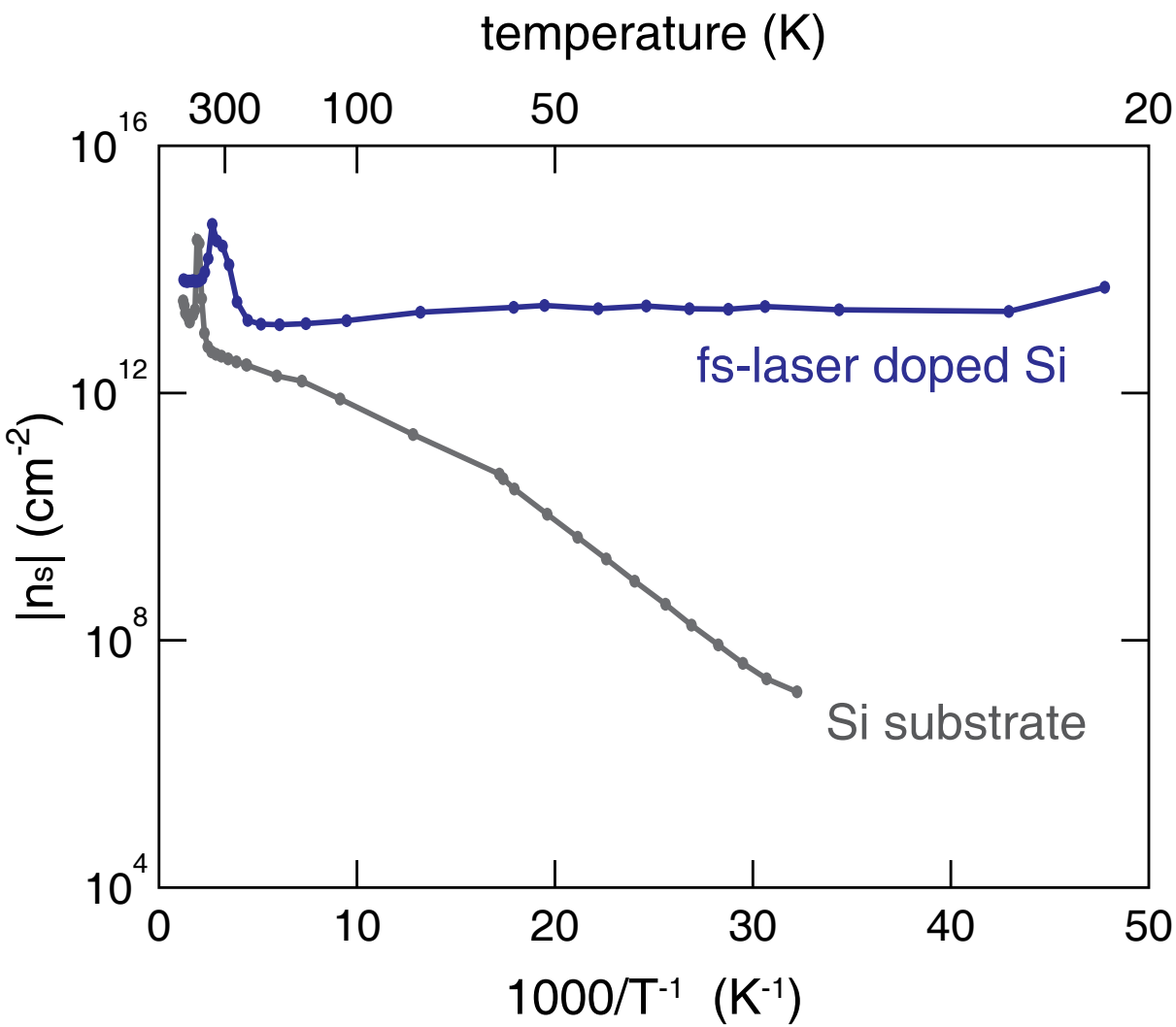
$$N = \frac{IB}{qdV}$$



Hall measurements

Optical and electronic properties

insulator-metal transition



Optical and electronic properties

insulator-metal transition

similar system:

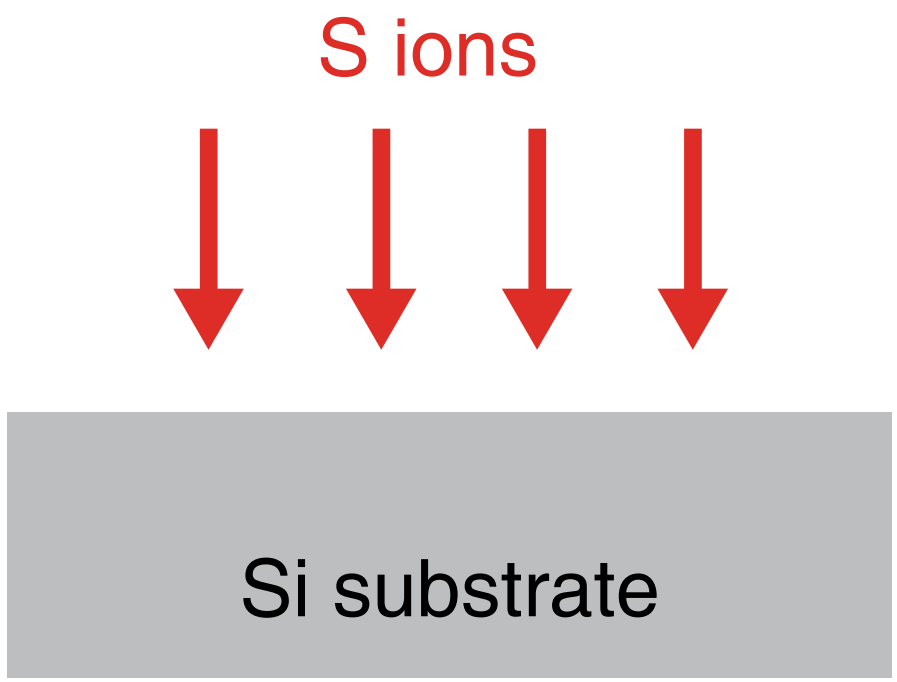
ion-implantation + pulse laser melting

Optical and electronic properties

Si substrate

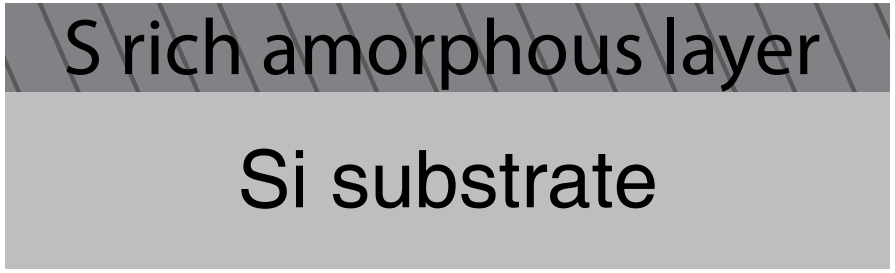
ion-implantation + pulse laser melting

Optical and electronic properties



ion-implantation + pulse laser melting

Optical and electronic properties



ion-implantation + pulse laser melting

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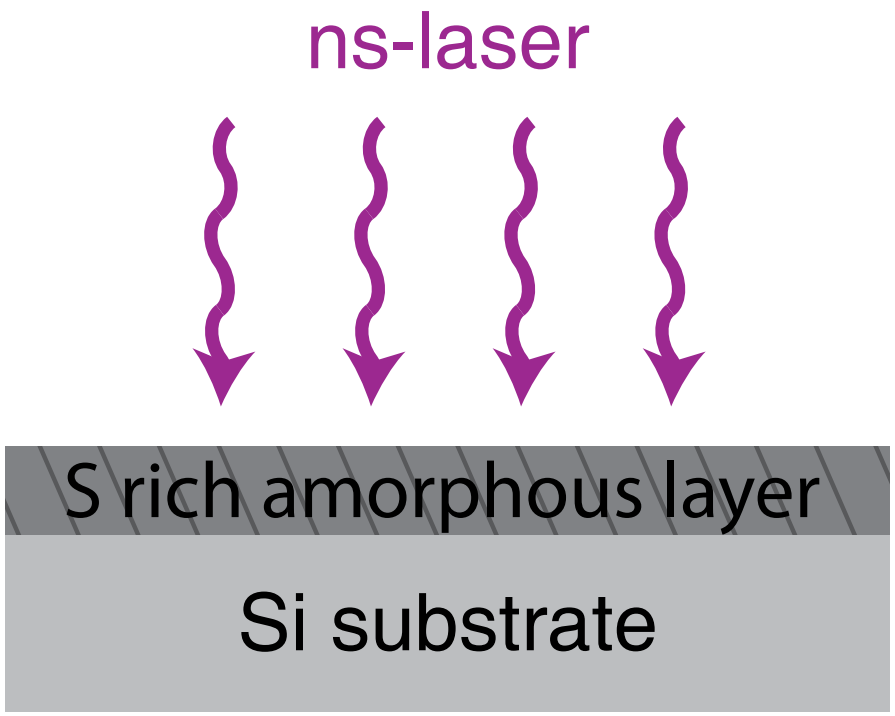

ion-implantation + pulse laser melting

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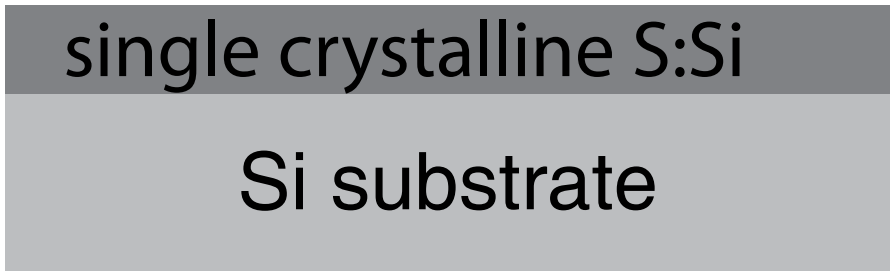
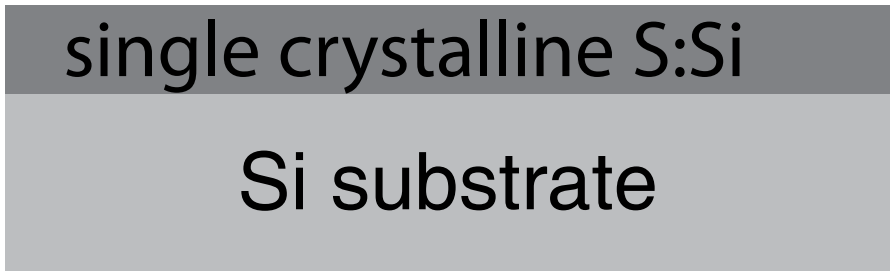


ion-implantation + pulse laser melting

Optical and electronic properties

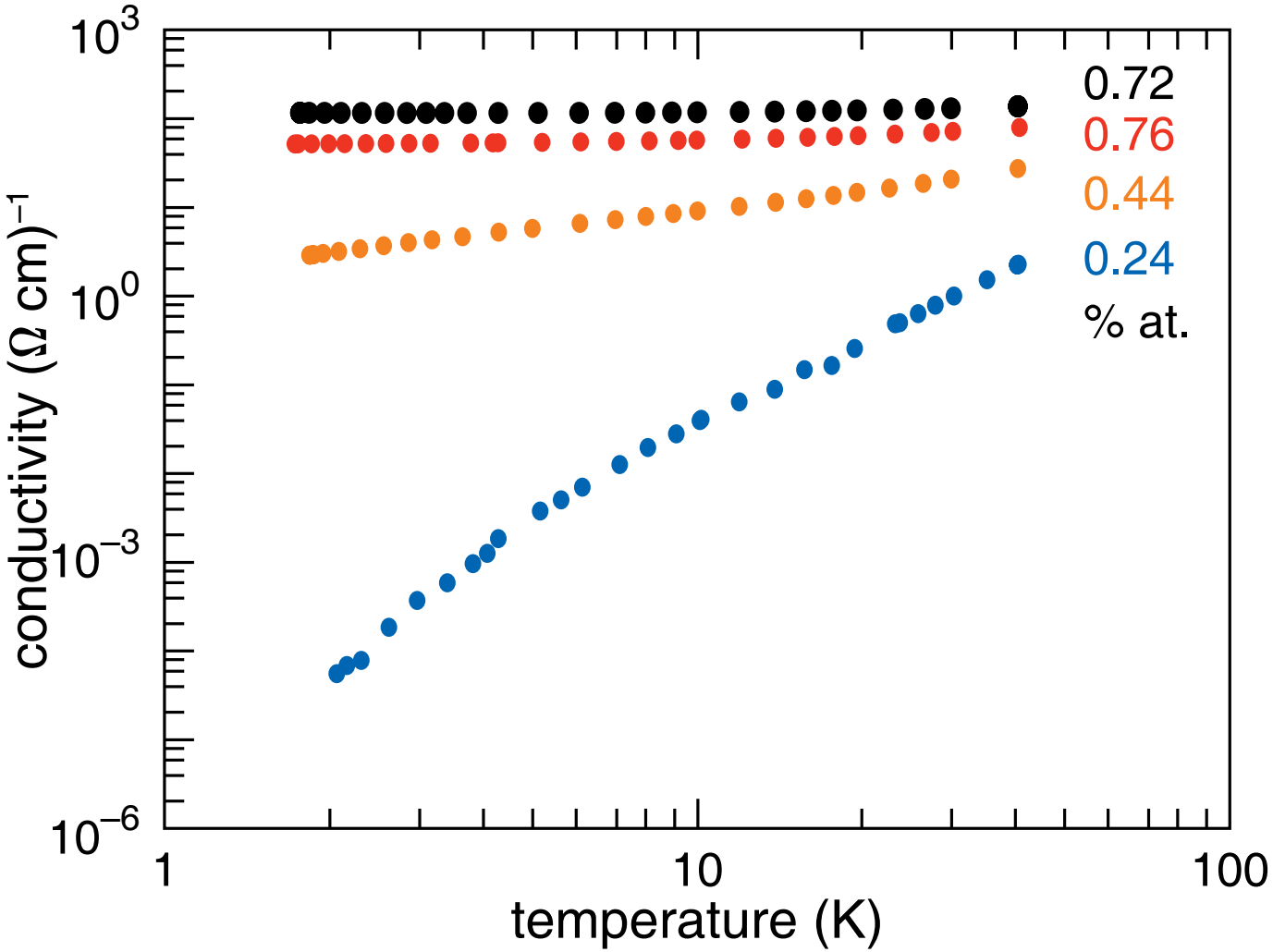
Samples:

dose (cm^{-2})	concentration (% at.)
9×10^{15}	0.72
10×10^{15}	0.76
4×10^{15}	0.44
3×10^{15}	0.24



Optical and electronic properties

Hall measurements



Winkler *et al.*, Phys. Rev. Lett., 106, 178701 (2011)

Optical and electronic properties

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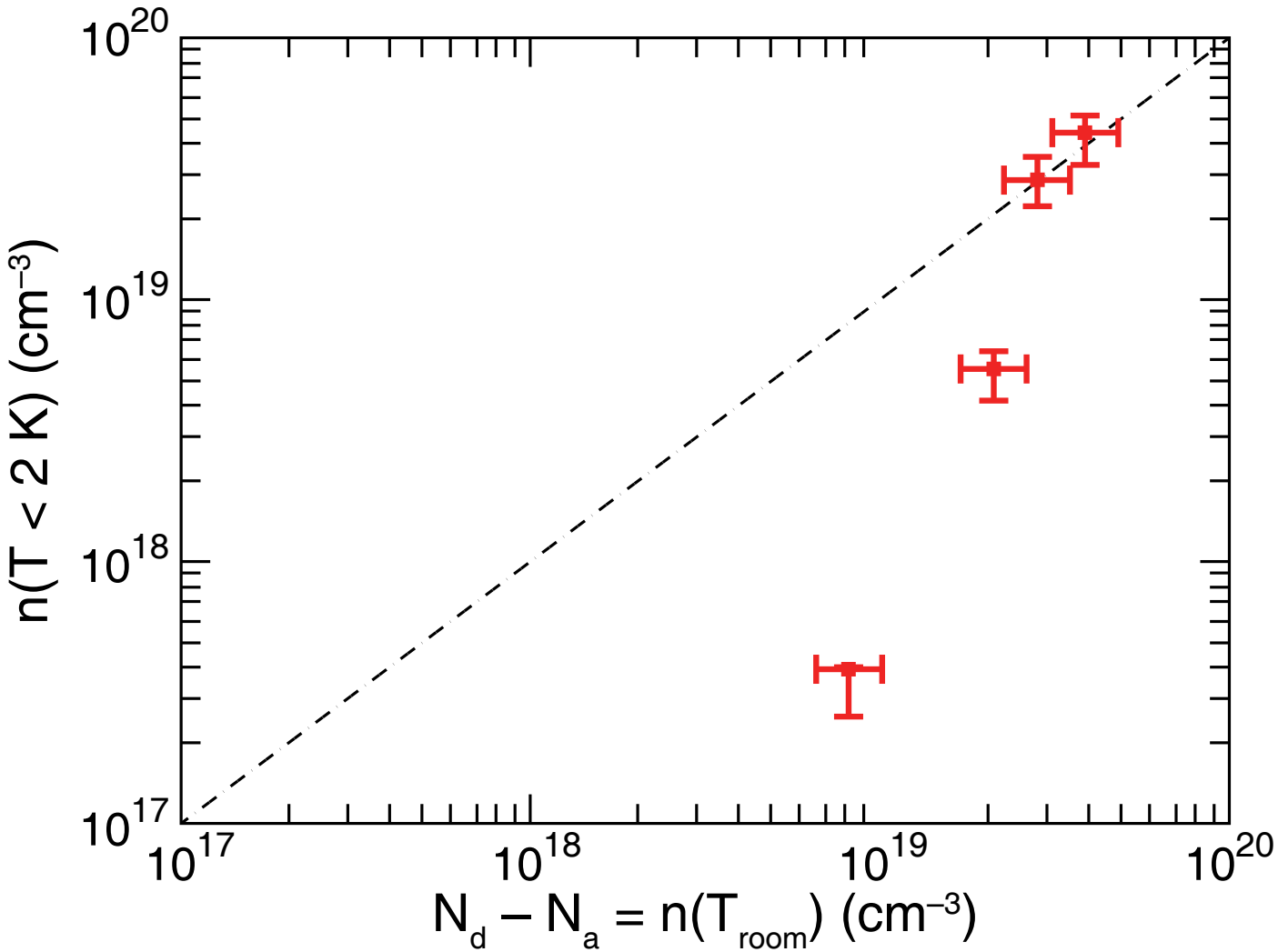
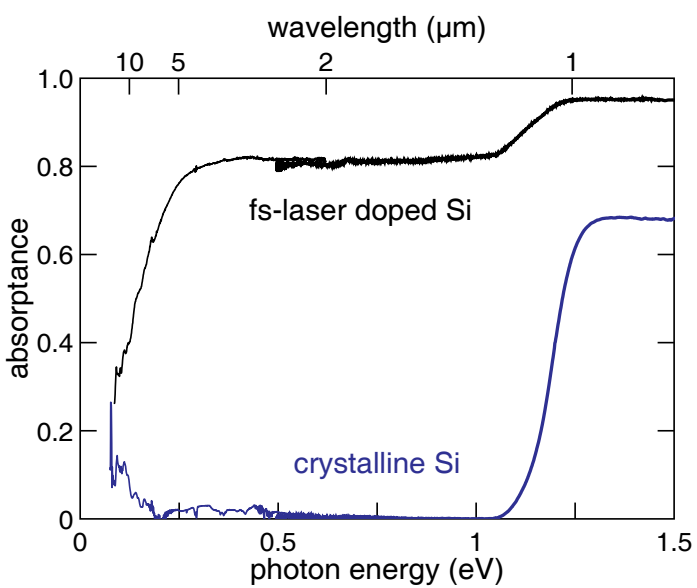


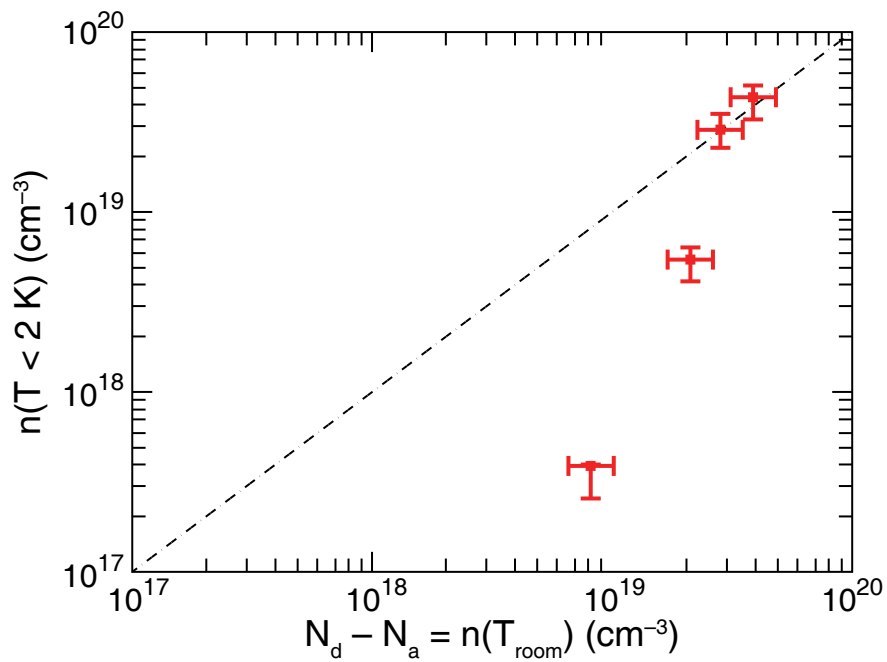
Winkler *et al.*, Phys. Rev. Lett., 106, 178701 (2011)

Optical and electronic properties

- IR absorption and T-Hall measurements
  - absorption to $\lambda \approx 8$ μm
  - $n_s(T=300K) \approx n_s(T=21K)$
  - evidence of intermediate band formation

- insulator-metal transition in a similar material system





Outline

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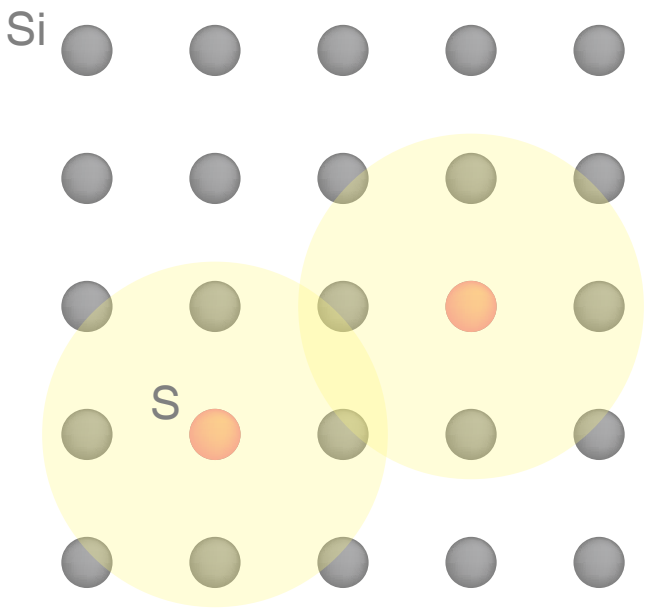
- improve fs-laser doping
- annealing & dopant diffusion



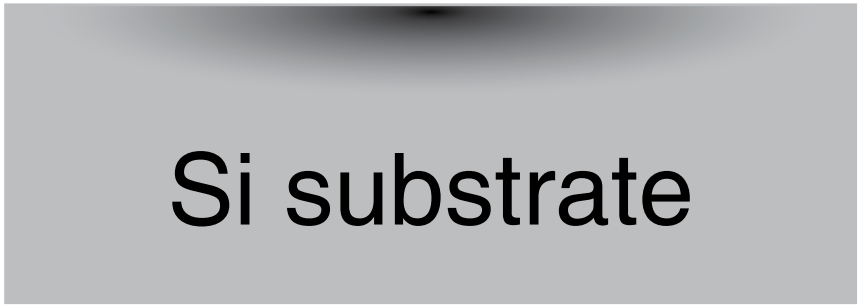
Fs-laser doping

Si substrate

– control dopant concentration

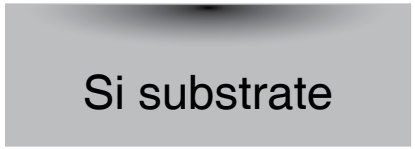
– decouple doping and surface texturing

Fs-laser doping

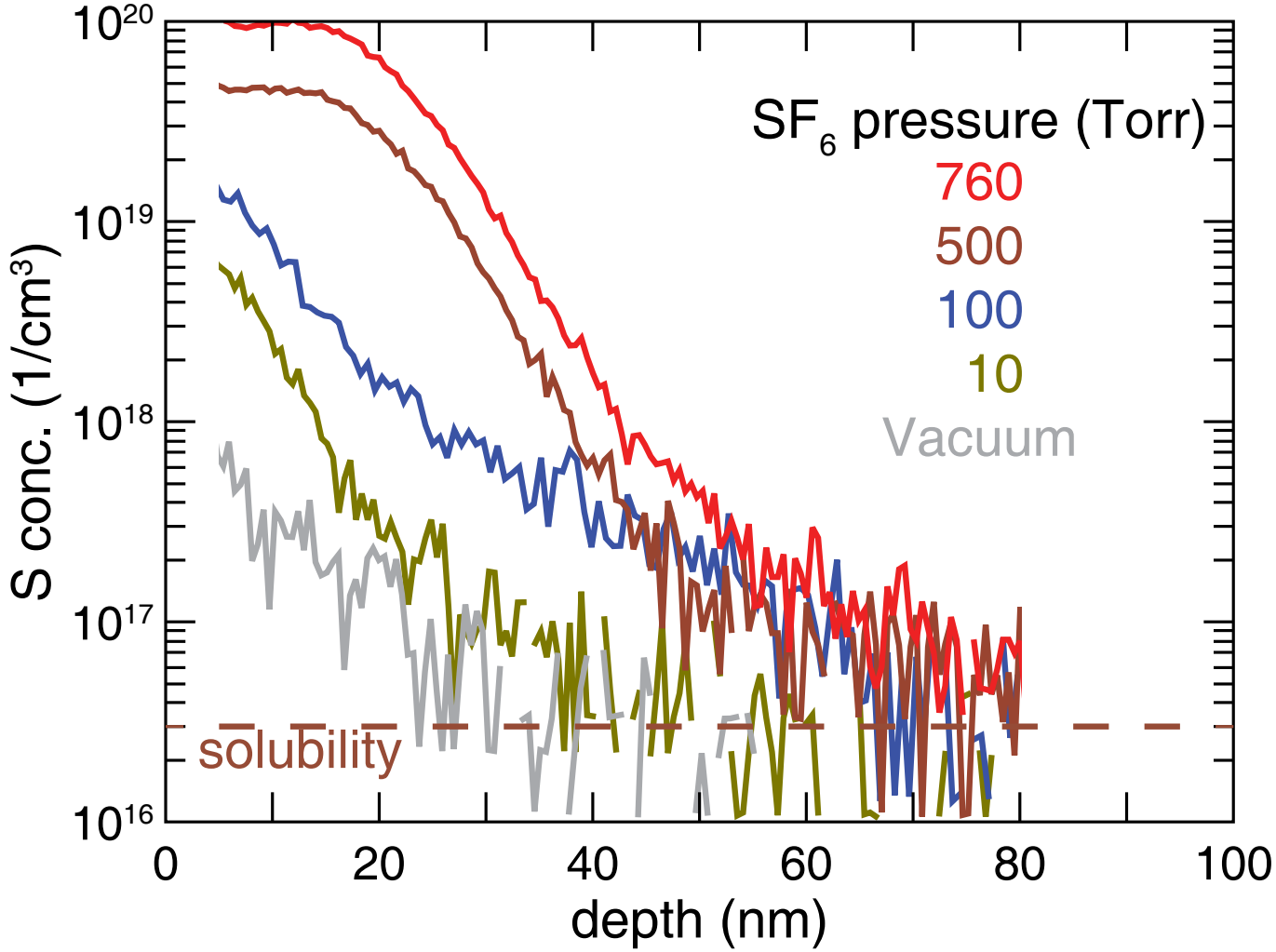


1 fs-laser pulse (800 nm, 80 fs, 6 kJ/m^2)
varying SF_6 pressure

Fs-laser doping

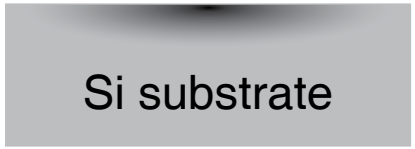


SIMS



Carlson *et al.*, J. Physics and Chemistry of Solids 8, 81 (1959)

Fs-laser doping



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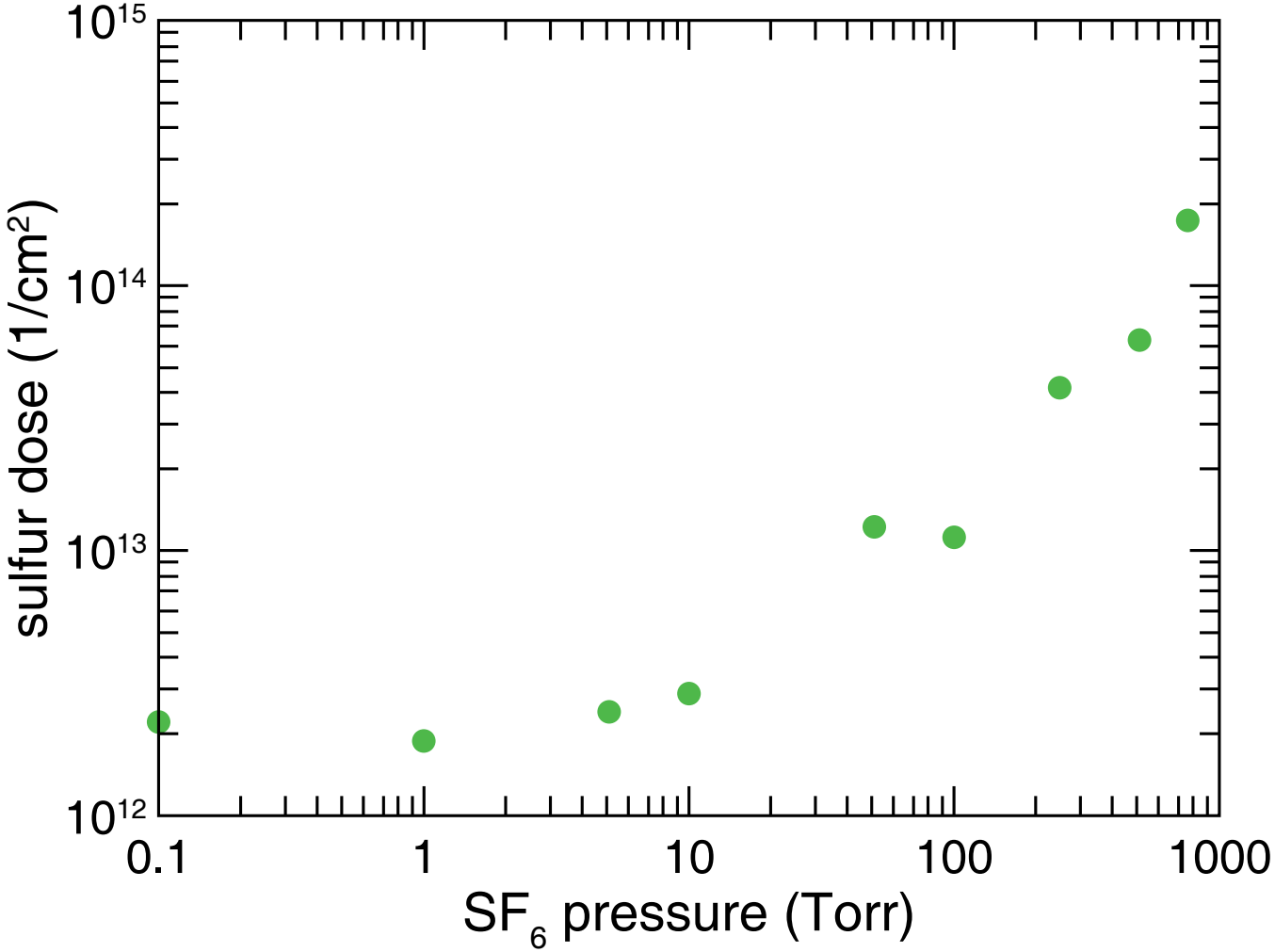
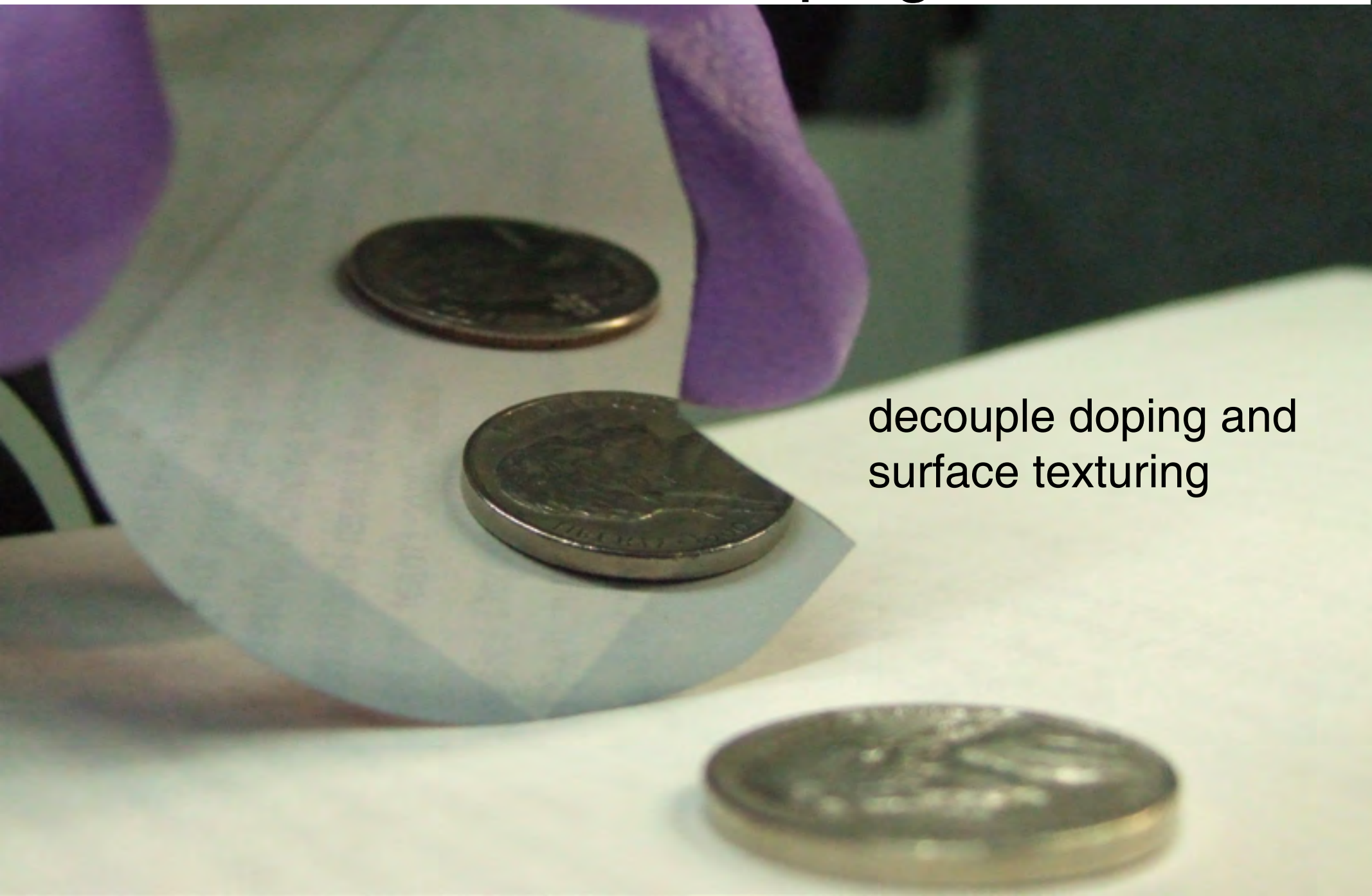


Fs-laser doping

SF_6 pressure – control dopant concentration

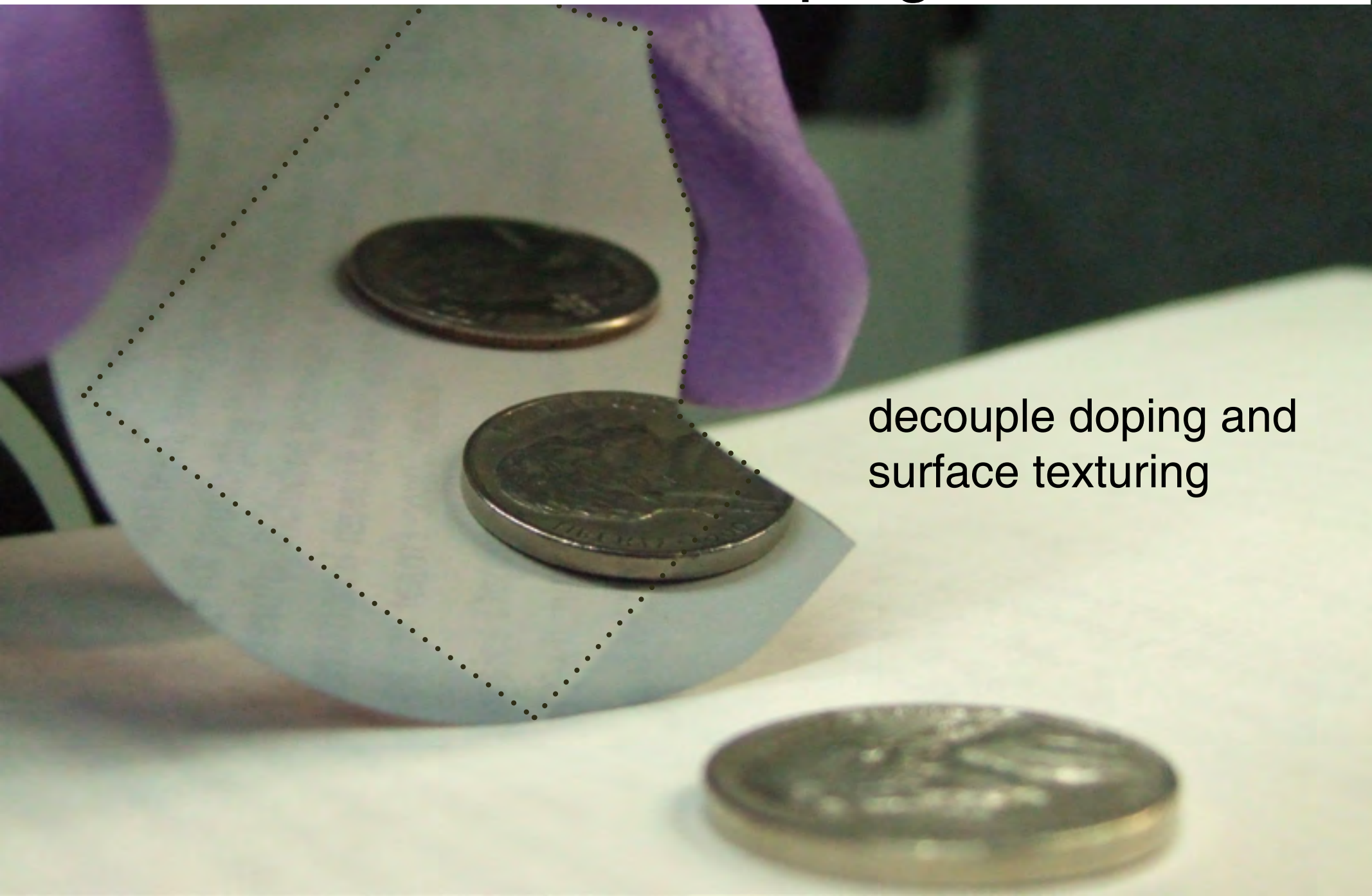
laser parameter – decouple doping and surface texturing

Fs-laser doping



decouple doping and
surface texturing

Fs-laser doping



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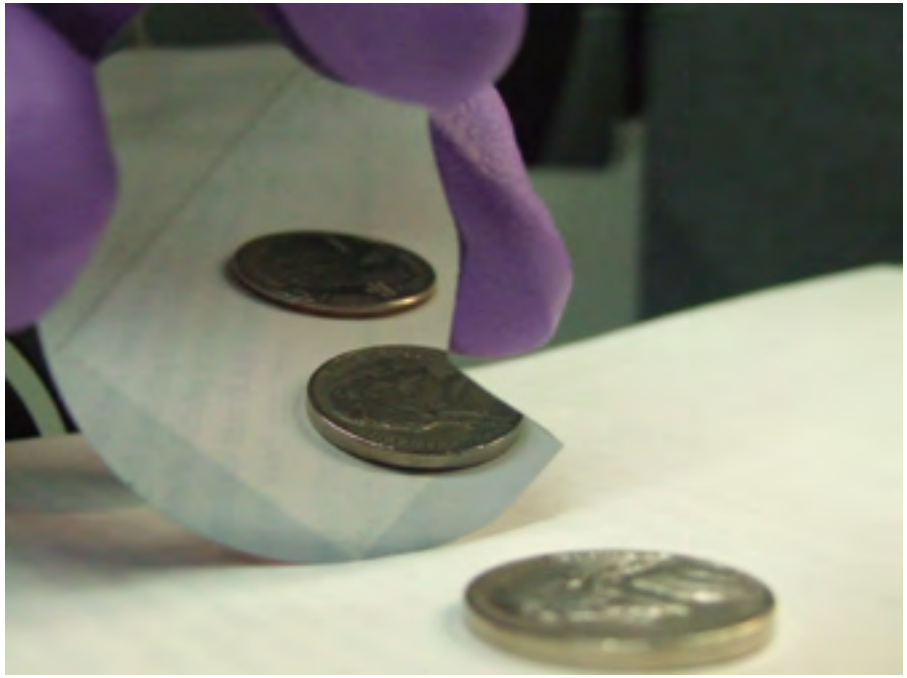
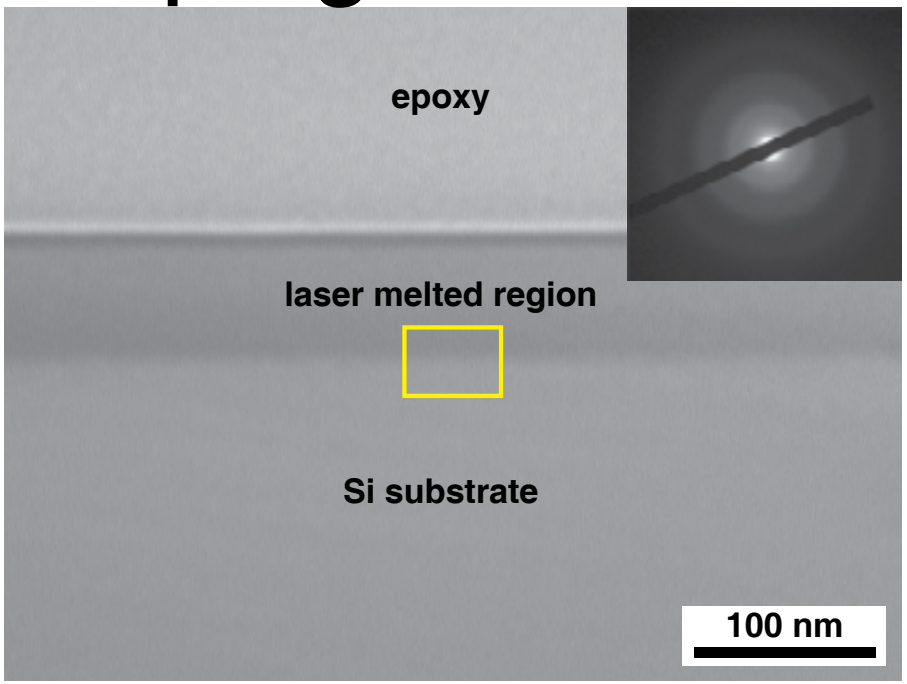
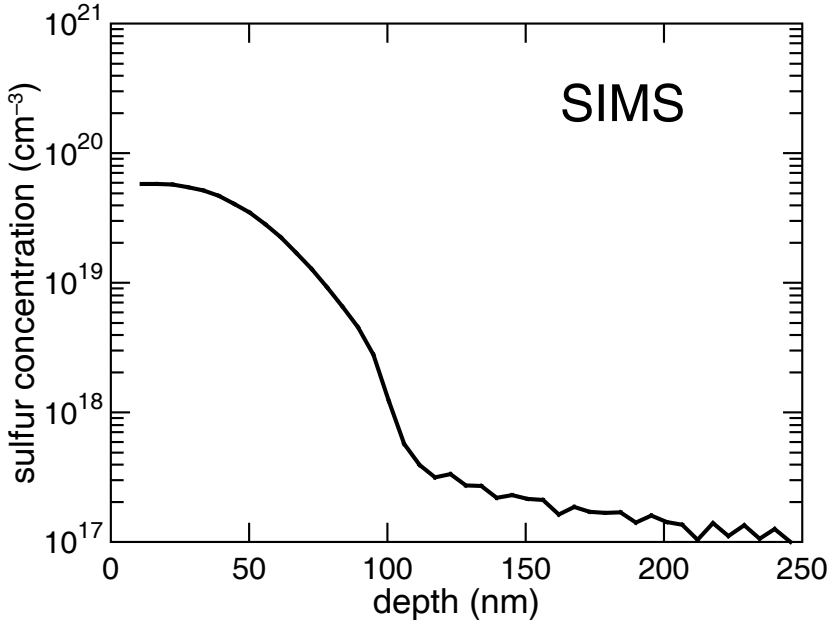
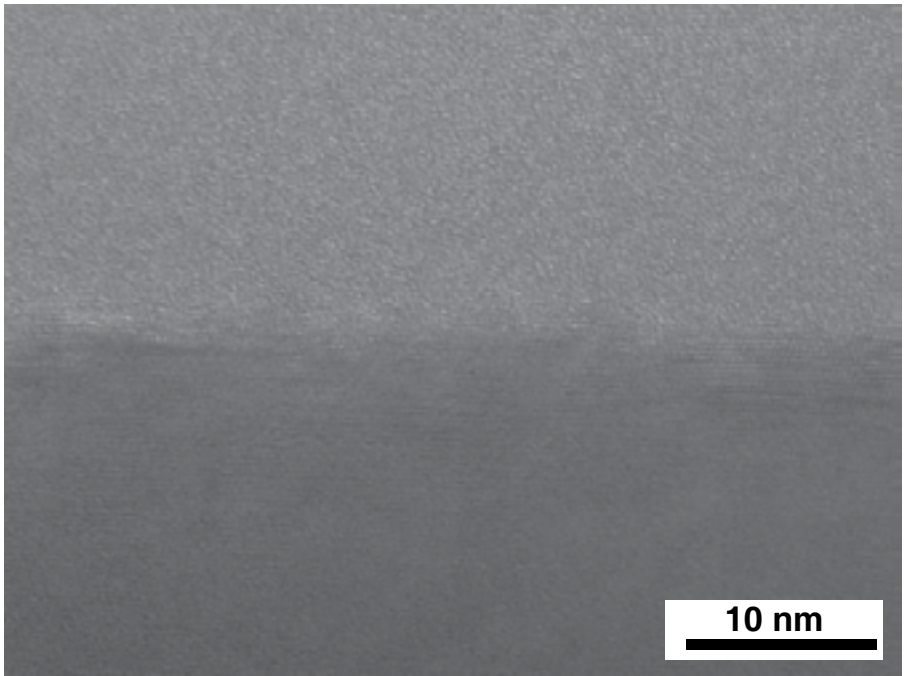
Fs-laser doping



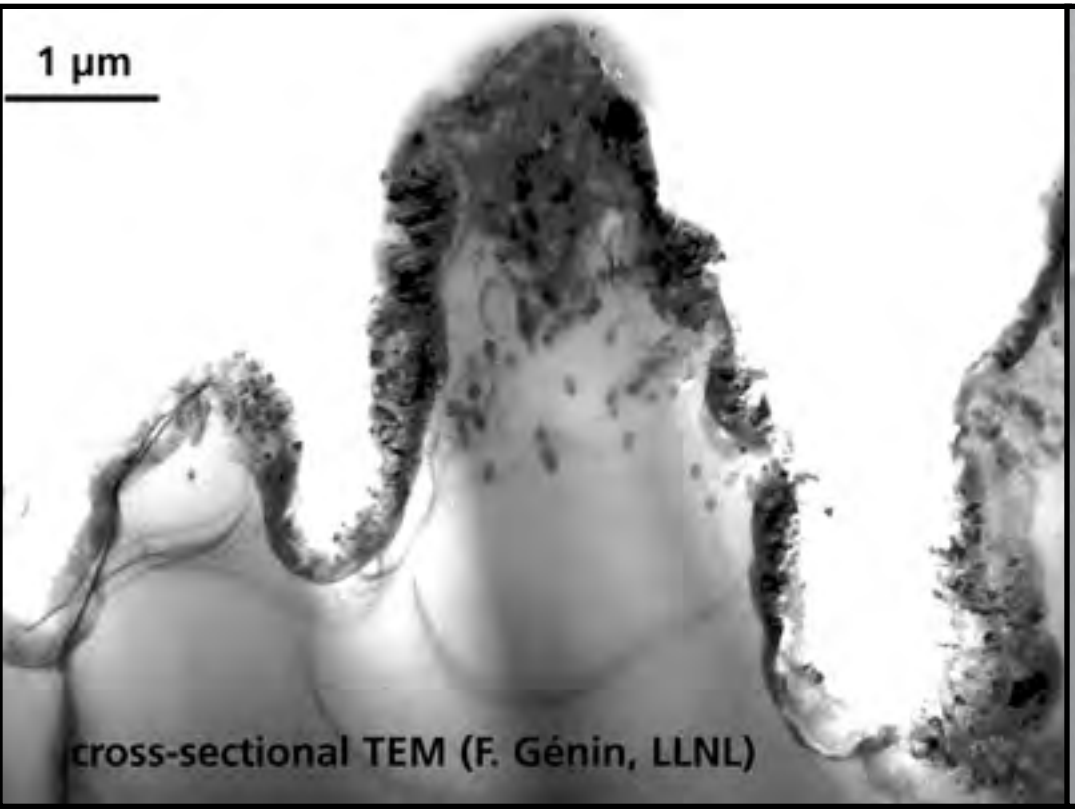


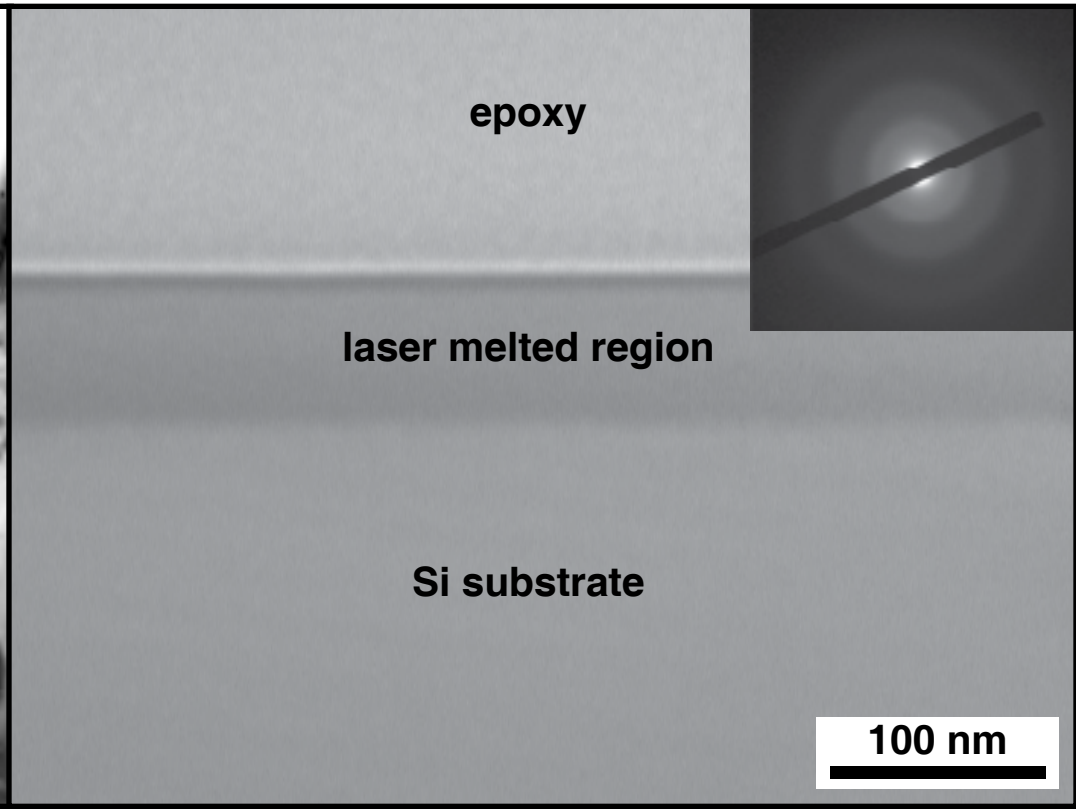




Fs-laser doping

- non-equilibrium concentrations of chalcogen in Si
- decouple doping and surface texturing





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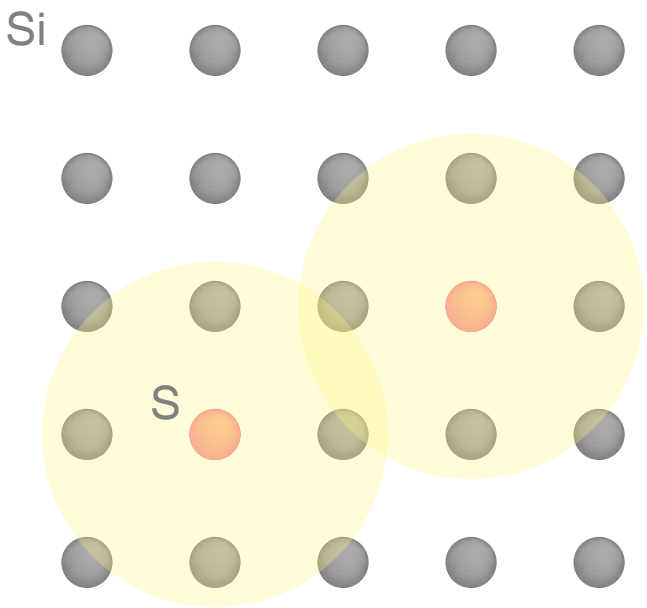
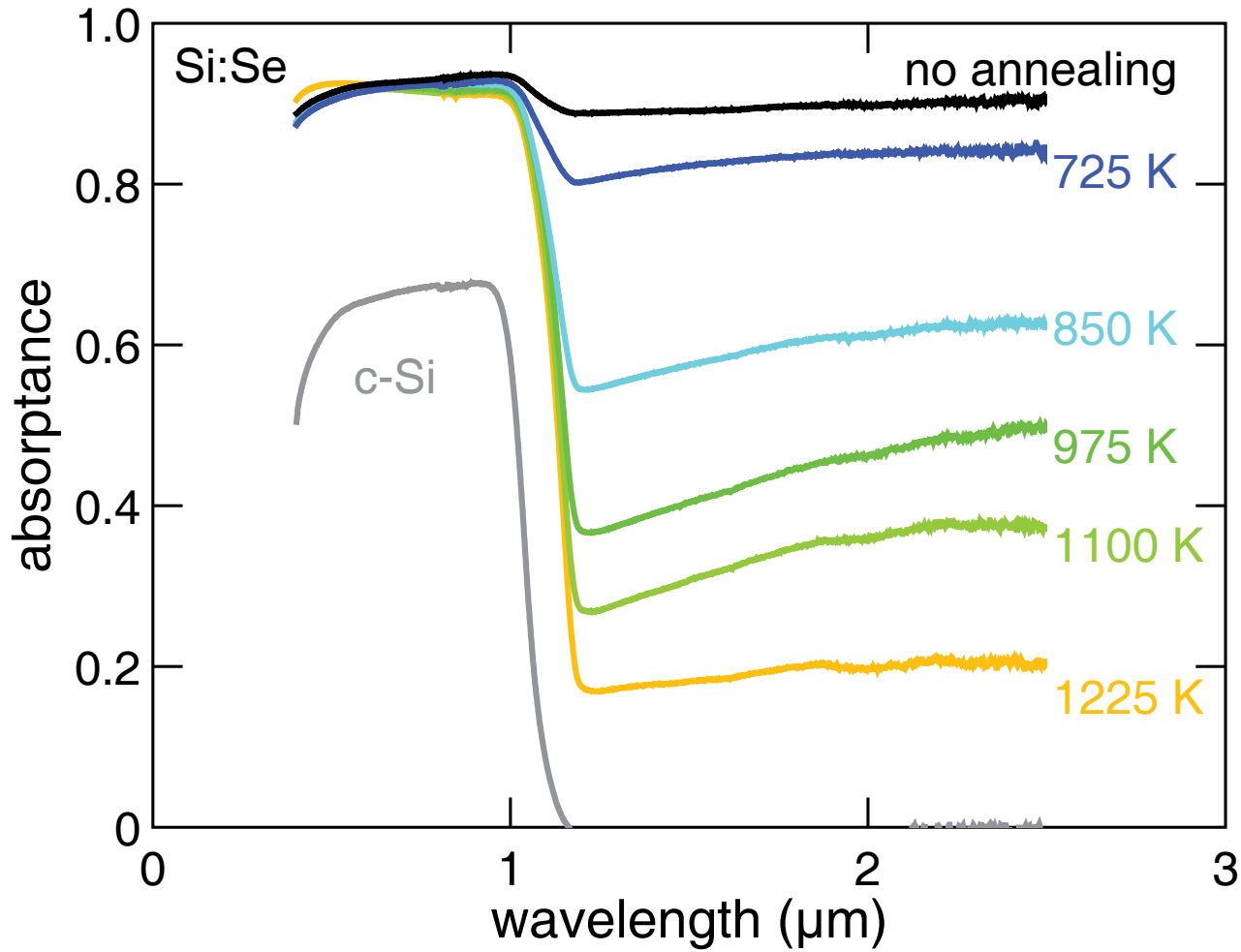


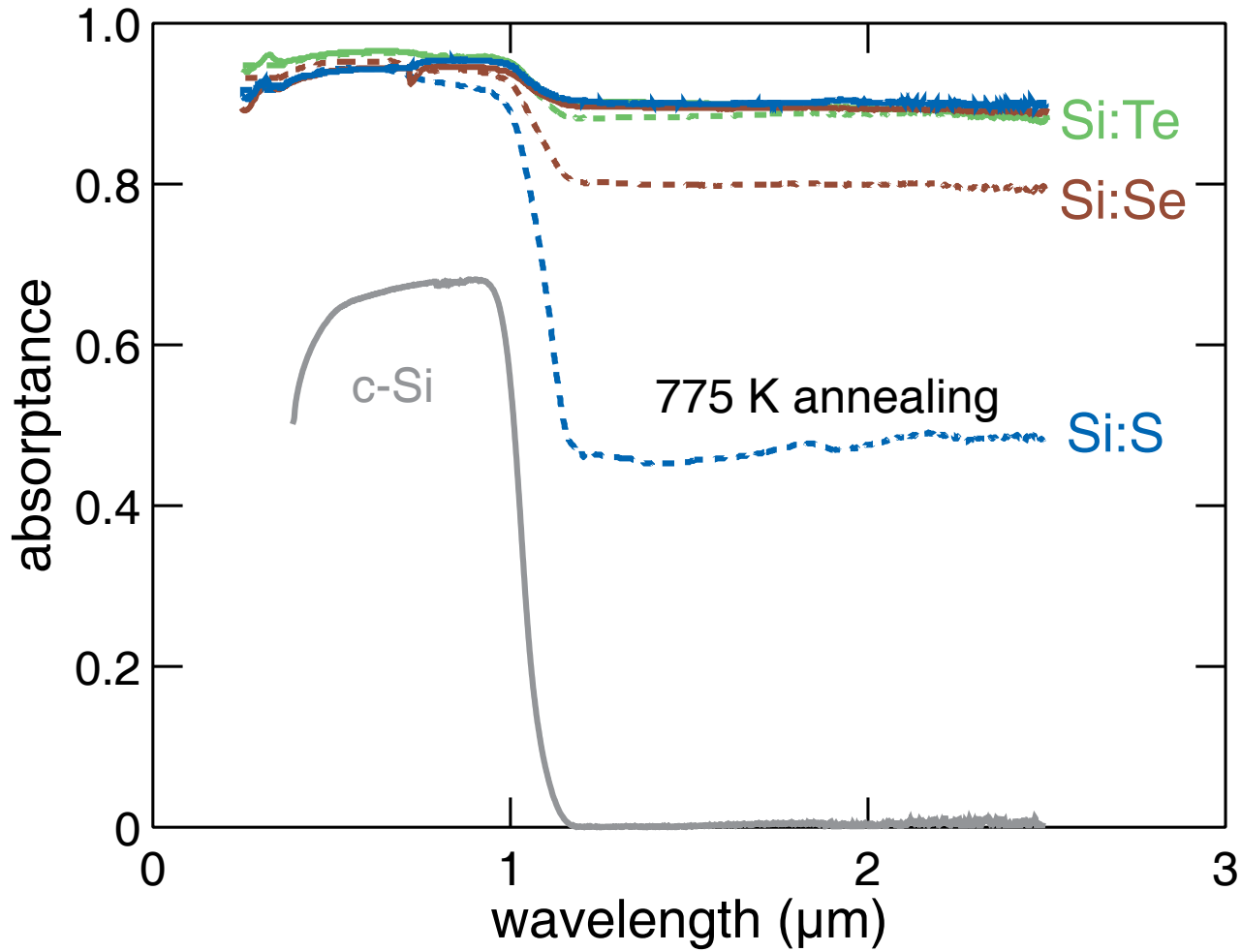
Annealing and dopant diffusion



annealing reduces infrared absorption

Newman *et al.*, 24th EU PVSEC, 2009

Annealing and dopant diffusion



reduction of absorption correlates with dopant diffusion

Tull *et al.*, Appl. Phys. A, 96, 327-334 (2009)

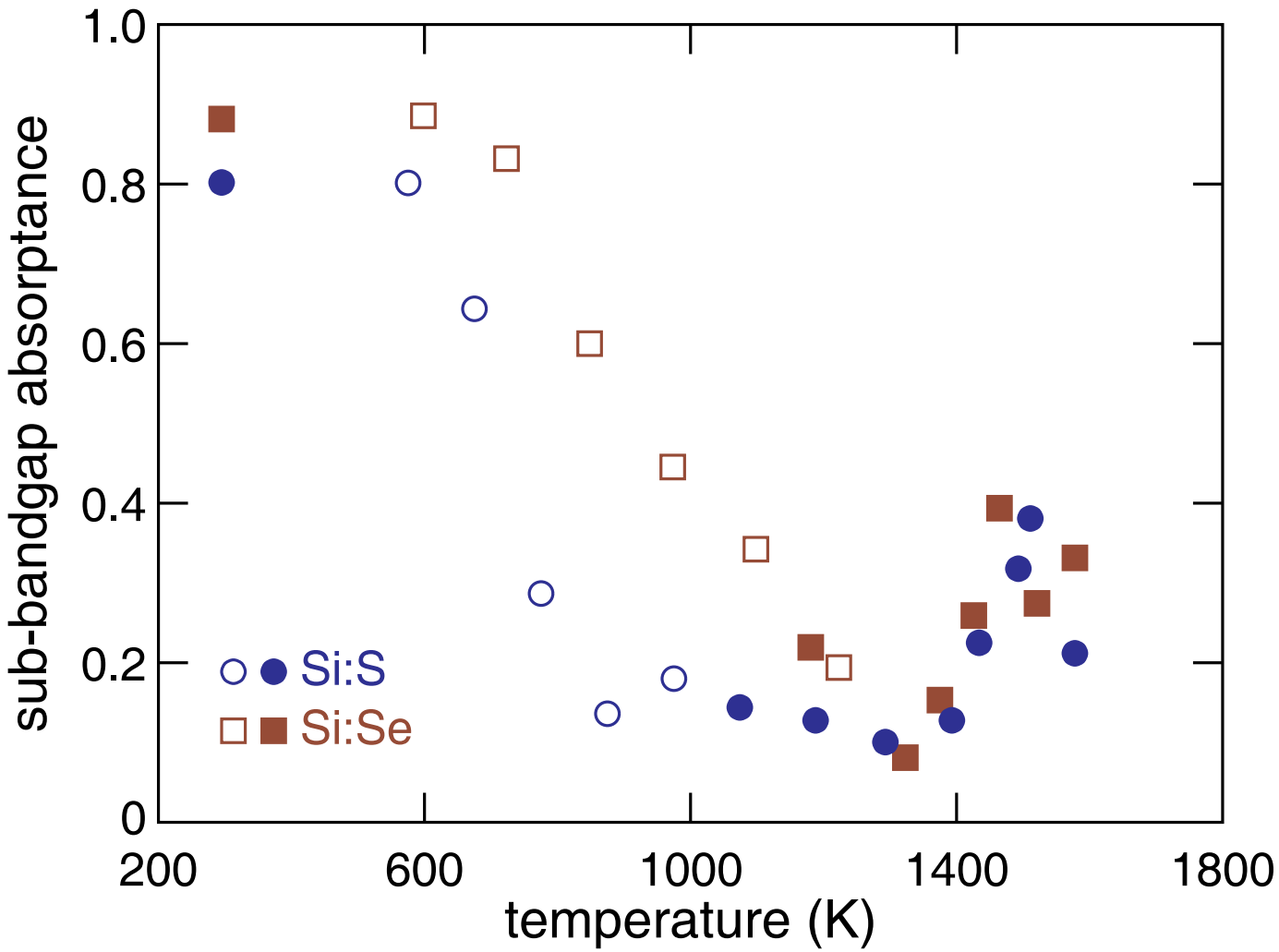
Annealing and dopant diffusion

to retain IR absorption:

high temperature annealing (> 1350 K)
+ rapid quench (> 50 K/s)

Newman *et al.*, Appl. Phys. Lett., 98, 251905 (2011)

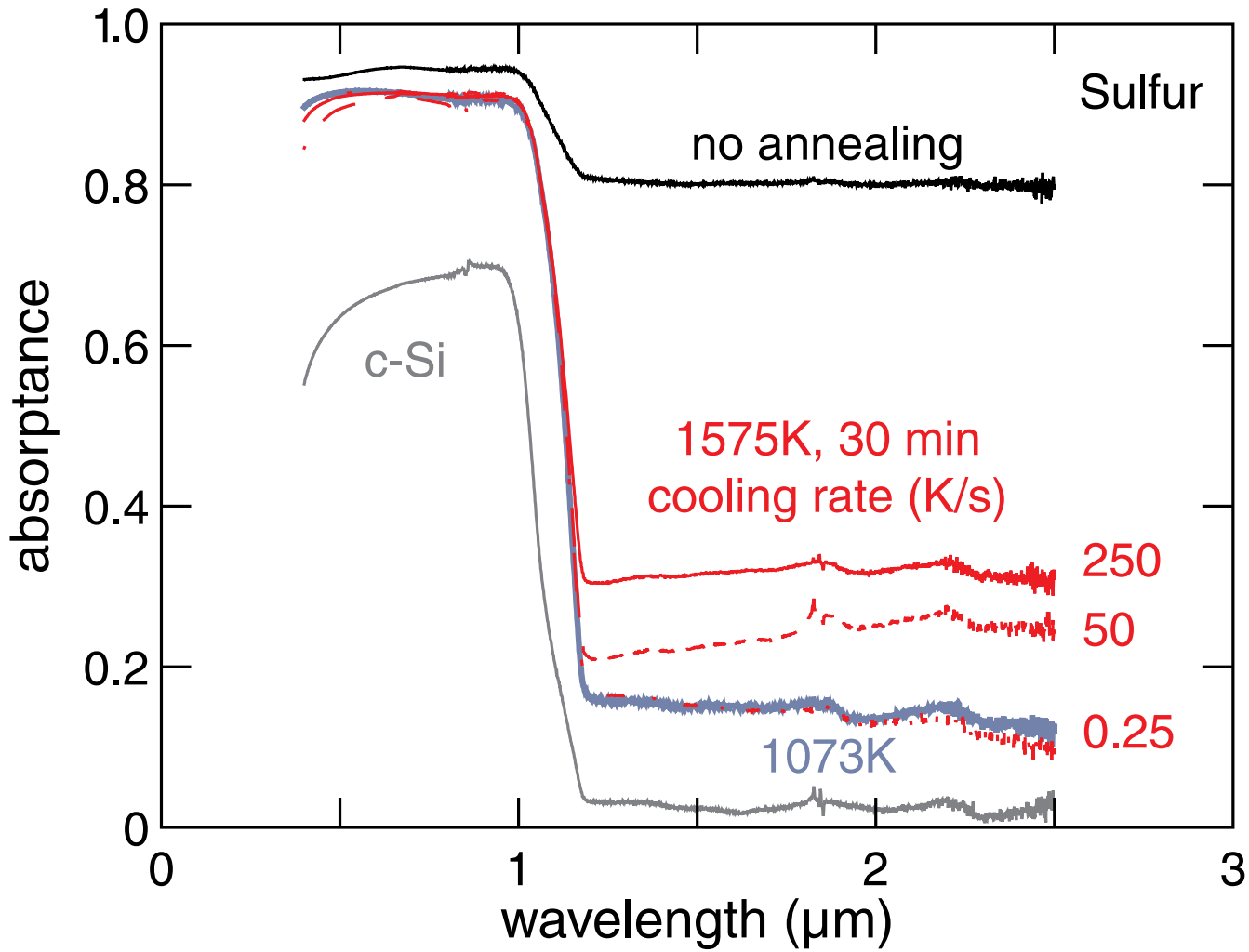
Annealing and dopant diffusion



reactivation occurs for T > 1350 K

Newman *et al.*, Appl. Phys. Lett., 98, 251905 (2011)

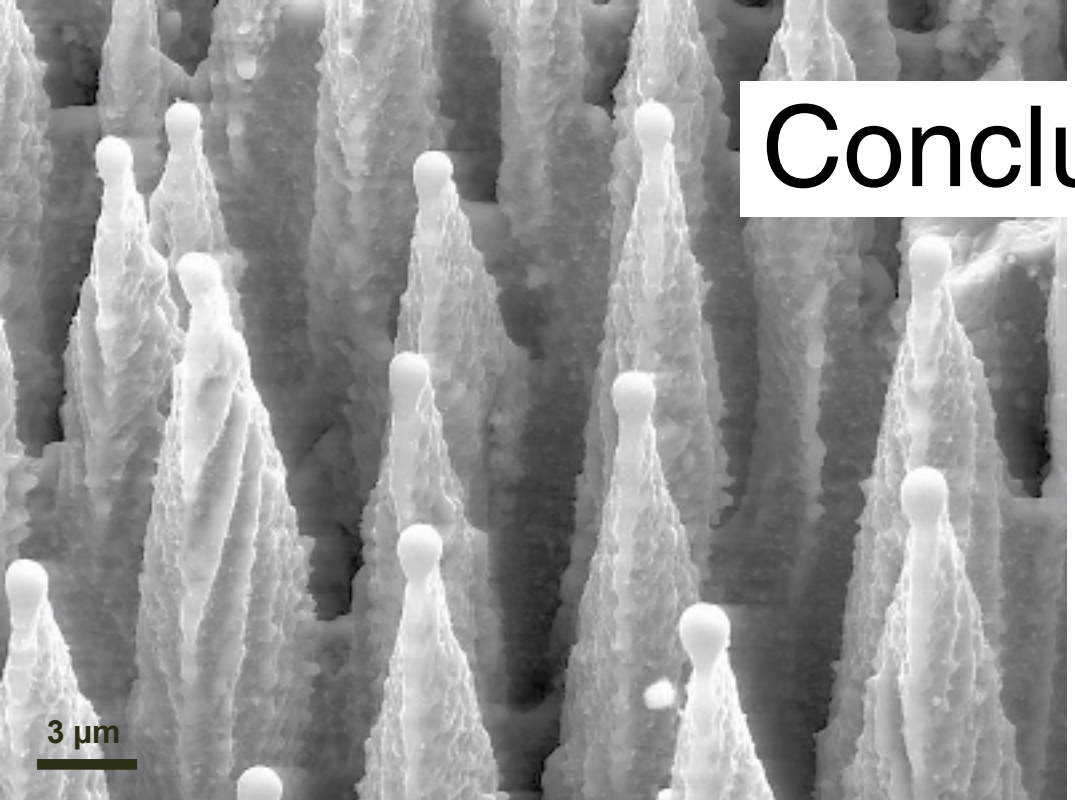
Annealing and dopant diffusion

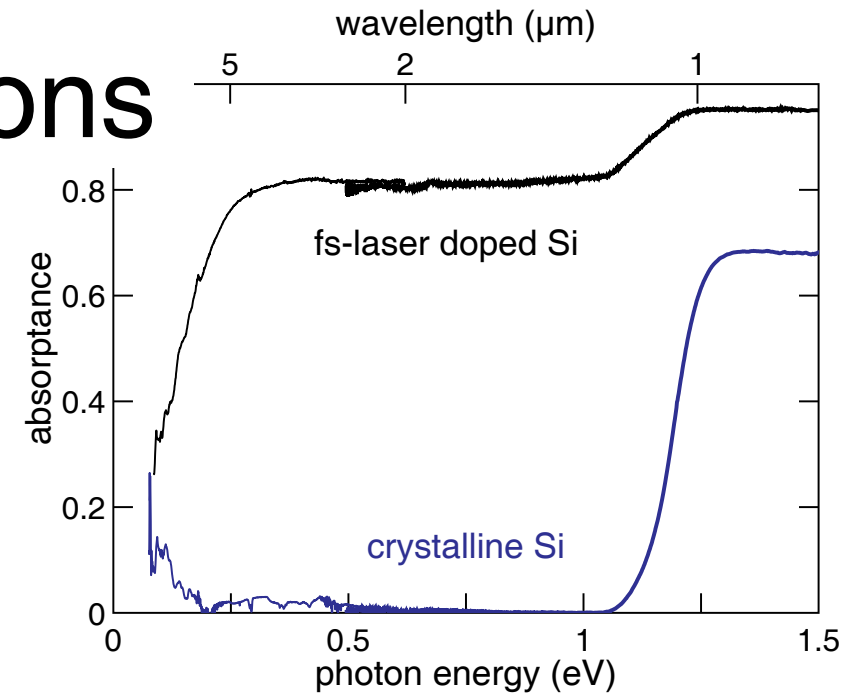


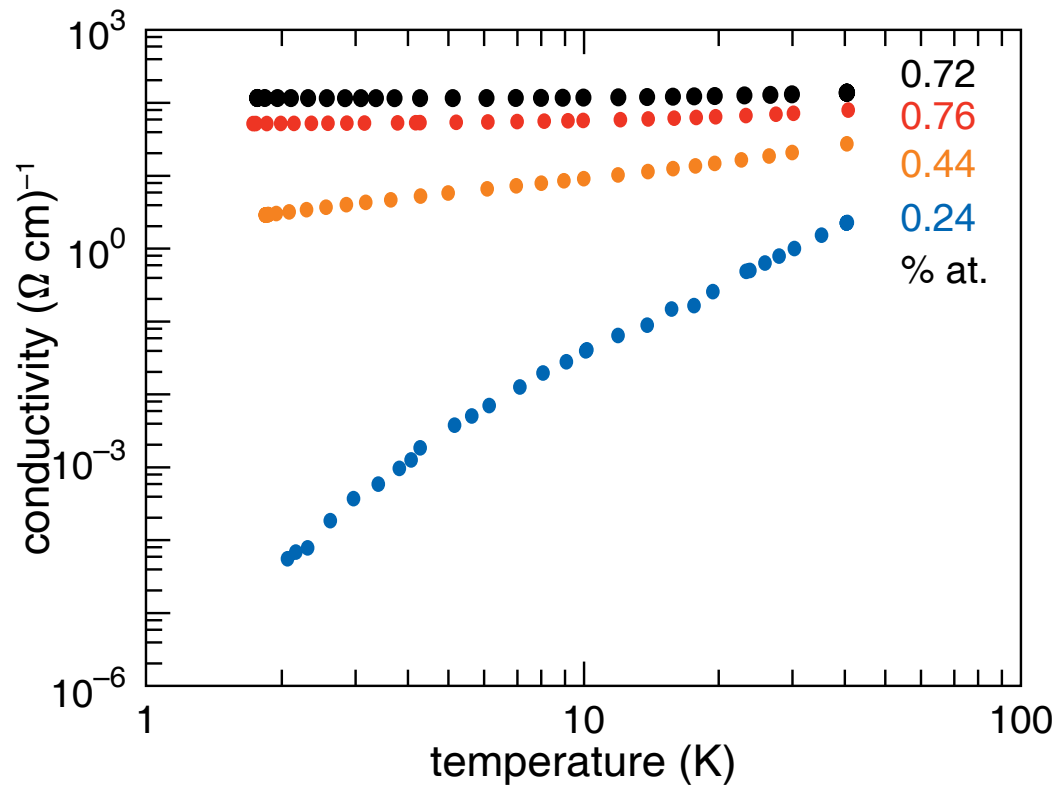
reactivation occurs for cooling rate > 50 K/s

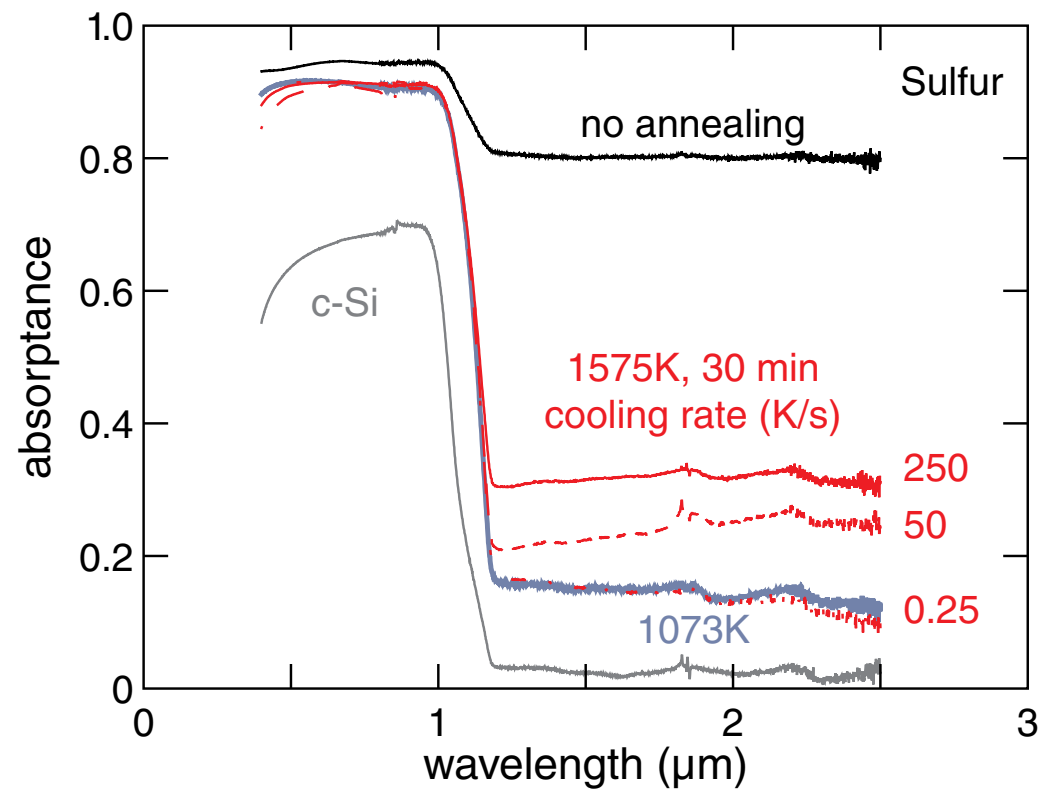
Newman *et al.*, Appl. Phys. Lett., 98, 251905 (2011)

Conclusions









Thanks!

Questions?

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Conclusions

- IR absorption and T-Hall measurements
  - absorption to $\lambda \approx 8\ \mu m$
  - $n_s(T=300K) \approx n_s(T=21K)$
  - evidence of intermediate band formation

- insulator-metal transition in similar material systems

- fs-laser doping
  - non-equilibrium concentrations of chalcogen in Si
  - decouple doping and surface texturing

- reactivation of IR absorption via high-temperature annealing & quenching