

# Femtosecond laser doping of silicon for photovoltaic devices

Department of Physics and School of Engineering and Applied Sciences  
Harvard University, Cambridge, MA 02138



Mark Winkler



Brian Tull



Eric Mazur

## Irradiation and doping

We irradiate a crystalline silicon wafer with femtosecond laser pulses in the presence of a chalcogen-containing gas or film to produce a black surface that is roughened on the microscale.

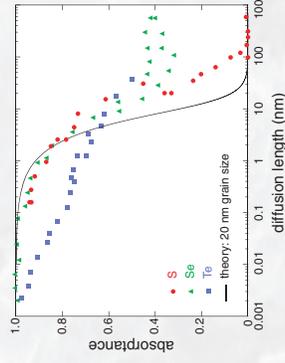
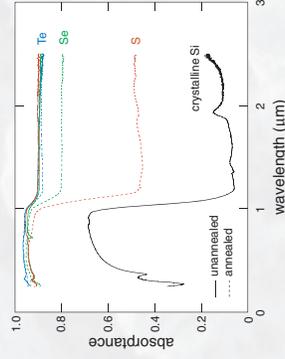
The outer 300 nm of the roughened surface is highly disordered silicon doped with up to 1% of chalcogen.

This surface layer has unique optical and electronic properties — such as strong sub-bandgap, infrared absorption — that make it appealing for use in photodetectors and solar cells.



## The effect of annealing on optical properties

The chalcogen-doped surface absorbs more visible and infrared light than an undoped silicon wafer, exhibiting strong infrared absorption. Initial data shows that upon annealing, sub-bandgap absorption decreases less for heavier chalcogens (i.e., selenium and tellurium), suggesting that diffusion to grain boundaries in the nanocrystalline surface layer causes reduced absorption.



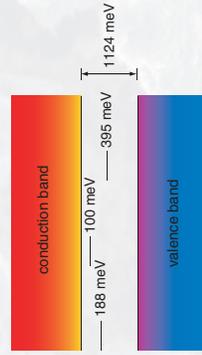
$$l = \sqrt{Dt}$$

Additionally, we measure the drop in infrared absorbance as a function of annealing time and temperature to produce various diffusion lengths. The data agrees well with theory, showing that diffusion of the dopant accounts for the drop in absorbance.

The model does not include grain growth, which accounts for discrepancies at both long-diffusion-length and at low diffusivity  $D$ .

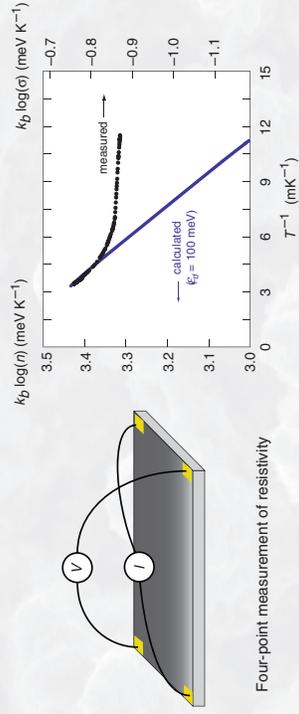
## Energy states of the dopants

Sub-bandgap absorption often arises from optically active impurity states within the gap. Many such states have been observed for sulfur in silicon. We would like to know which, if any, of these states are formed by femtosecond laser doping.



Which donor levels are created?

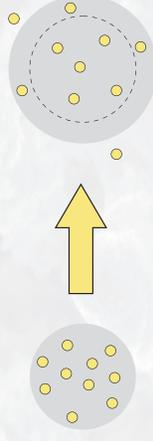
To identify impurity states, we study the temperature dependence of the conductivity in a sulfur-doped sample. The slope of the temperature dependence on an Arrhenius plot identifies the impurity level.



Preliminary measurements indicate an impurity level 100 meV below the conduction band edge.

## Future work

We are currently expanding our diffusion model to include grain growth.



Annealing causes diffusion and grain-growth

The roughened surface of the samples presents challenges for many measurements. We are exploring the feasibility of etching away the silicon substrate, thus exposing a smoother surface.

