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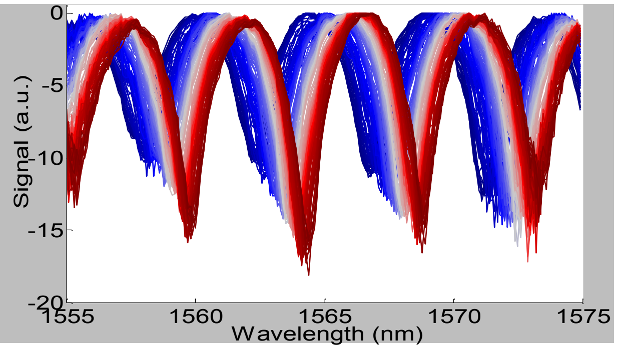

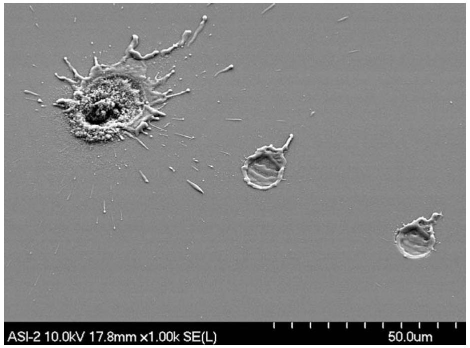

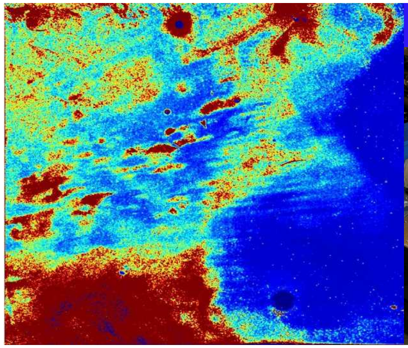

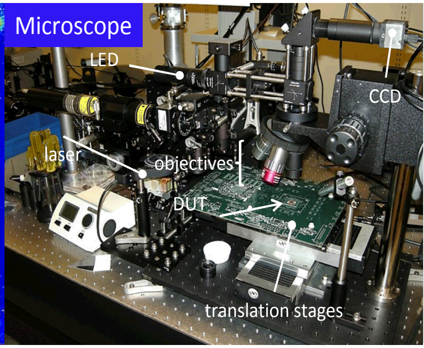

Precision laser annealing of Si devices for enhanced electro-optic performance

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U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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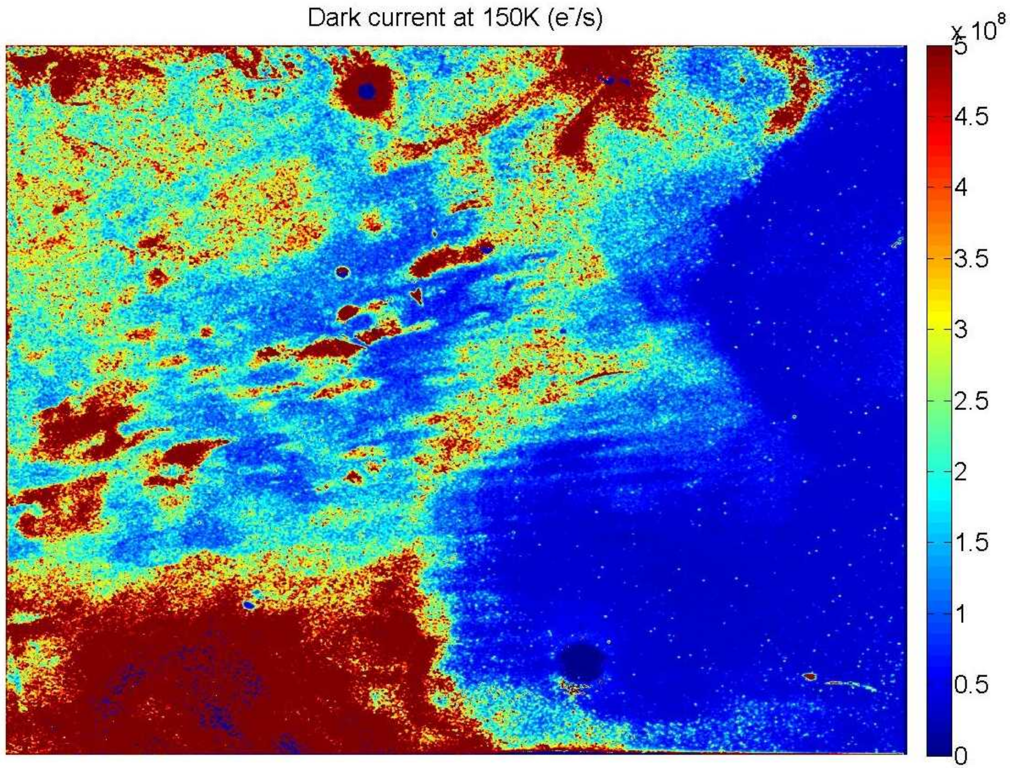
Highlights

1. Laser annealing can reduce dark current in damaged Si sensors by 10x
   - 100x in some cases with low reverse bias voltage

2. Laser annealing and phase tuning of Si waveguides
   - Longitudinal phase control of ≈15 mrad/pulse

Outline

- Targeted application
- Background and prior work
- How it works
- Results
  - Modeling
  - Experimental
- Future direction



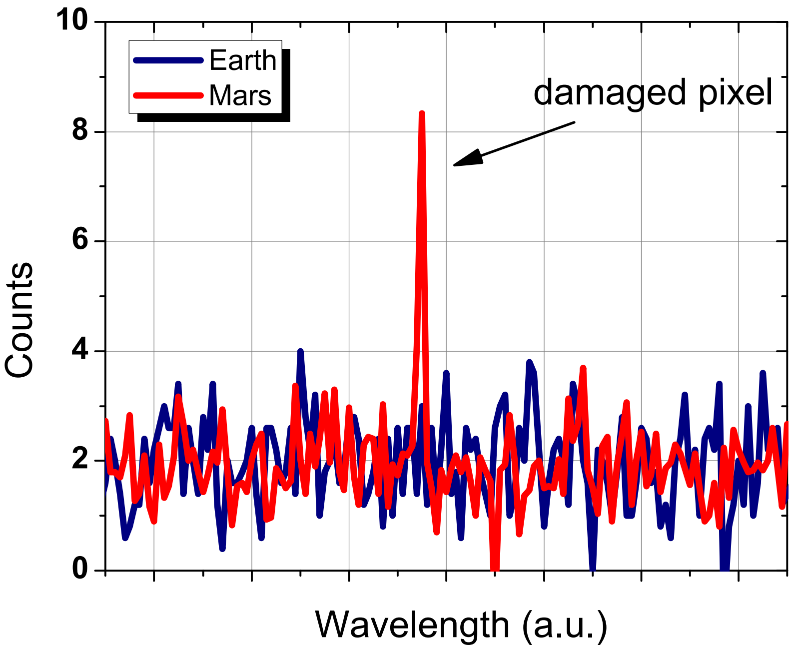
“Dark” counts for a MWIR MCT focal plane array

Motivation for Laser Annealing in Si

- Optical sensors sustain damage from
  - Manufacturing
  - Adversarial threats
  - Radiation
    - On orbit
    - Space travel
    - Nuclear power supplies

Mars rover Chem-Cam data taken on earth and on Mars after 254 days of space travel and 75 days on the Martian surface.

Chem-Cam UV spectrometer, dark collect*



Private communication with Chem-Cam team member

Spike is from sensor damage acquired during space travel, surface exposure or radiation from on board radioisotope thermoelectric generator (RTG).

Laser annealing offers an option to reduce effects from these sources of damage

Previous work in annealing

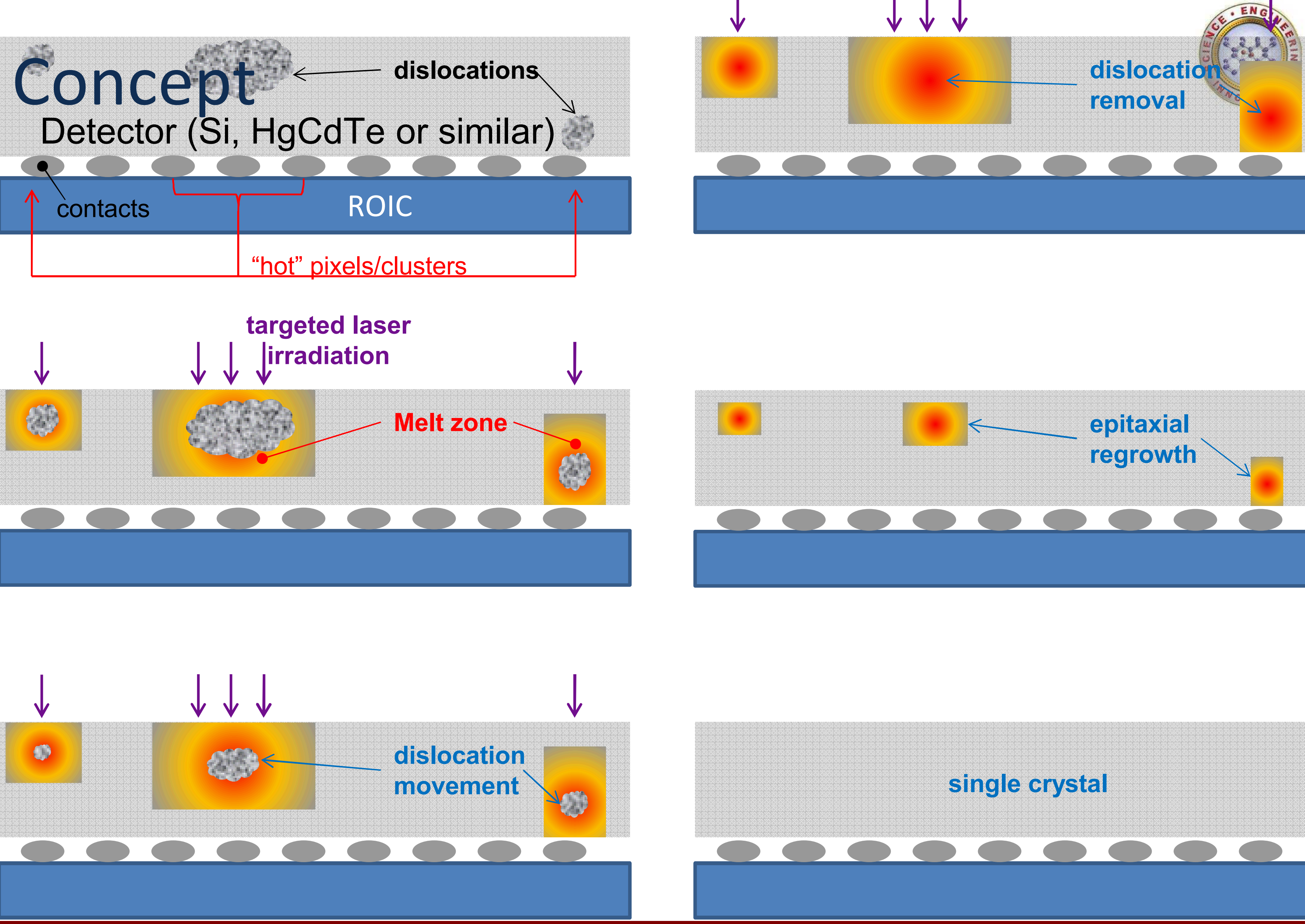
What others have done with laser annealing

- Lasers used to tune spectral response
- Dopant activation
- Lattice repair from machine damage

Thermal annealing work in semiconductors

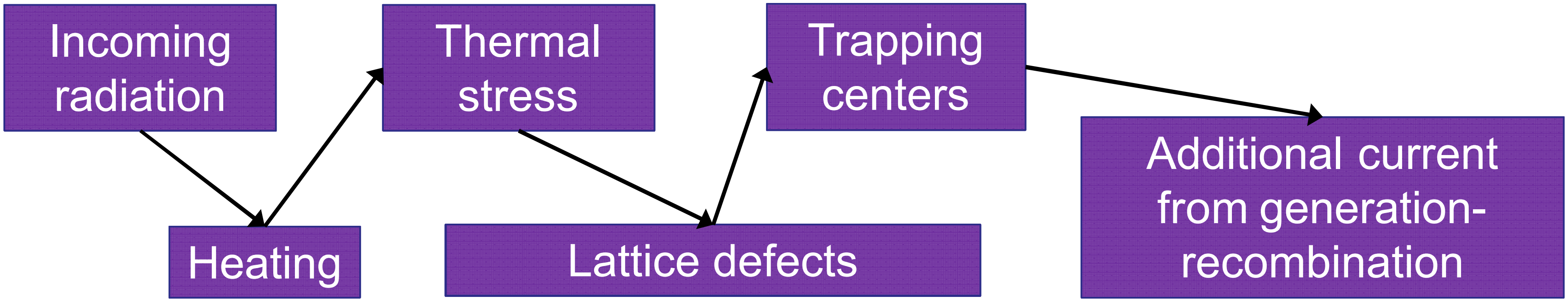
	Method	Pixel specific	Low thermal diffusion	ROIC insensitive
other work	Furnace			
other work	Flashlamp		✓	✓
other work	CW laser	✓		✓
this project	Pulsed laser	✓	✓	✓

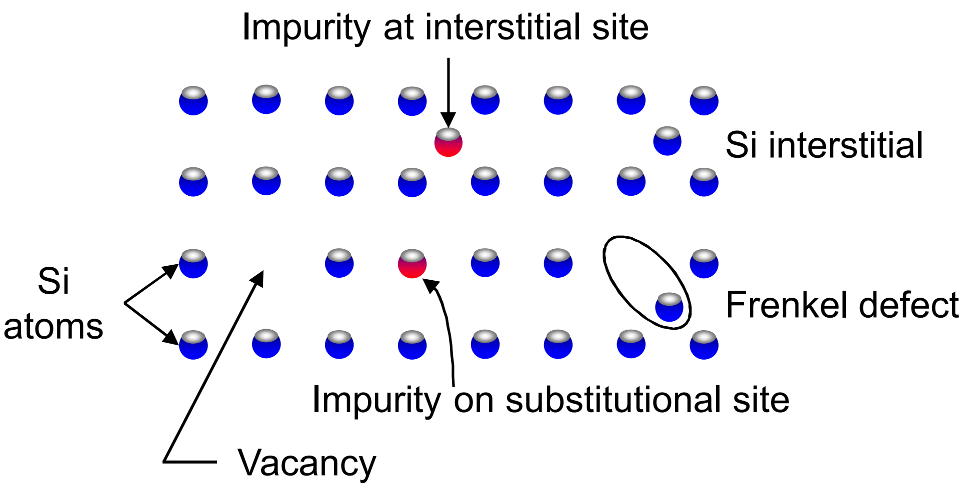
Concept


dislocations
Detector (Si, HgCdTe or similar)
contacts
ROIC
"hot" pixels/clusters
targeted laser irradiation
Melt zone
dislocation movement
dislocation removal
epitaxial regrowth
single crystal

The physical origin of defects

for lasers with ns – CW pulse durations *(different mechanism for fs pulses)*





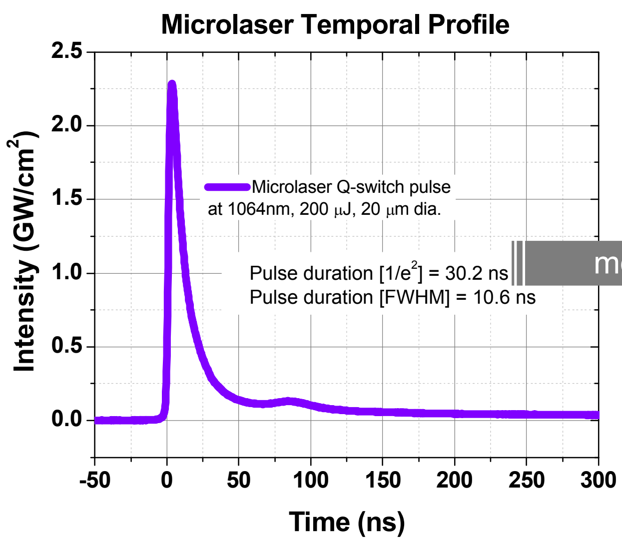
What is the thermal profile in Si after impulse excitation? -COMSOL Simulation Physics

- Thermal physics using classical Heat Equation: $$\frac{\partial T}{\partial t} = \frac{\kappa}{\rho c_p}\nabla^2 T + \frac{G}{\rho c_p}$$
- Optical absorption: $$\frac{\partial I}{\partial z} = -(\alpha + \sigma U)\, I$$
- Carrier dynamics: $$\frac{\partial u}{\partial t} = D_a \nabla^2 u - \frac{u}{\tau_a} + g$$
- Dopant diffusion: $$\boldsymbol{J}_k = n_k \boldsymbol{v}_k = -n_k\left(\tilde{D}_k \frac{\nabla n_k}{n_k} + D_k^{\mathrm{T}} \frac{\nabla T}{T}\right)$$
- Temperature dependent parameters:

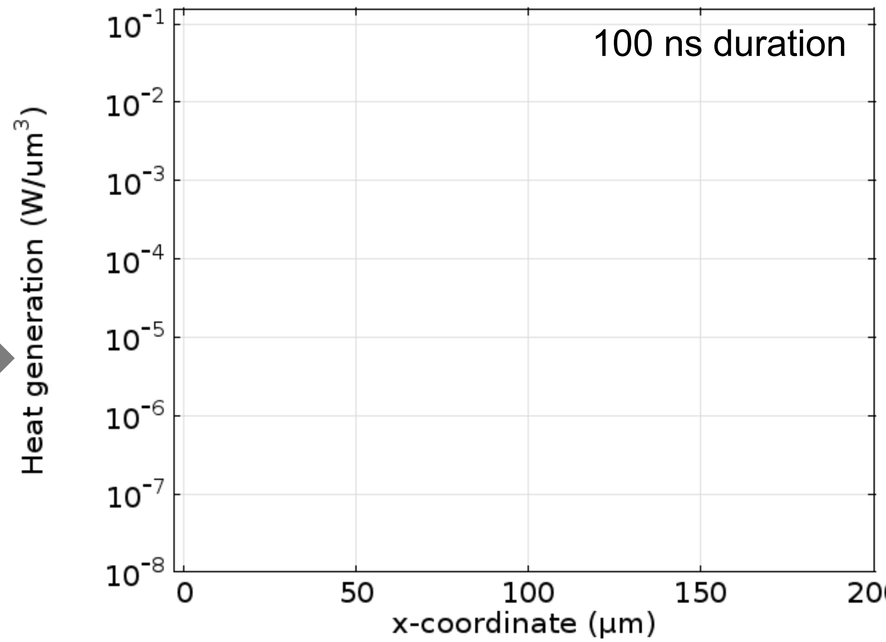
$$D_a\,(N_p + N_n, T),\ \tau_a\,(u, N_p, N_n, T),\ E_g\,(T),\ \kappa\,(T),\ \rho\,(T)\ \text{and}\ c_p\,(T)$$

In addition we take into account…

1. Laser pulse parameters



model input

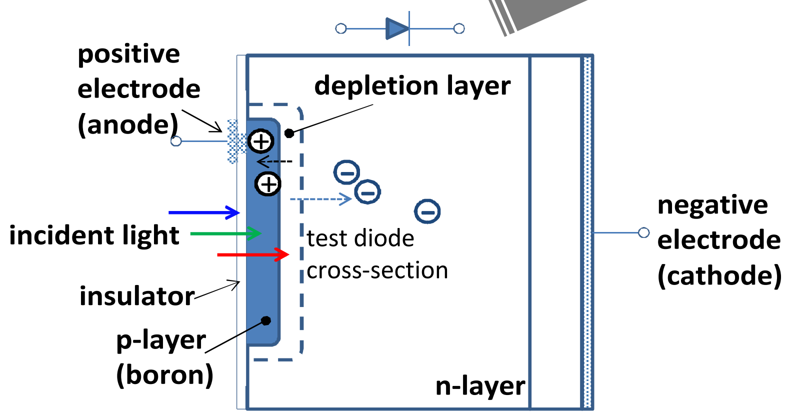


Model of heat generation with

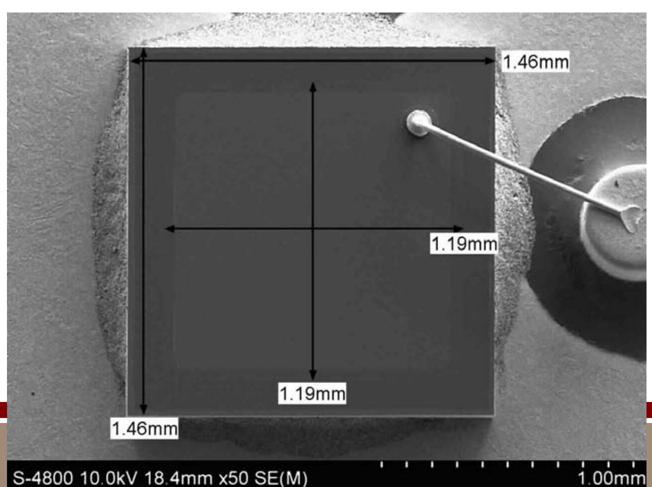
1. **Free-carrier absorption**
2. **e-h recombination**
3. **Carrier relaxation**

2. Device structure

model input

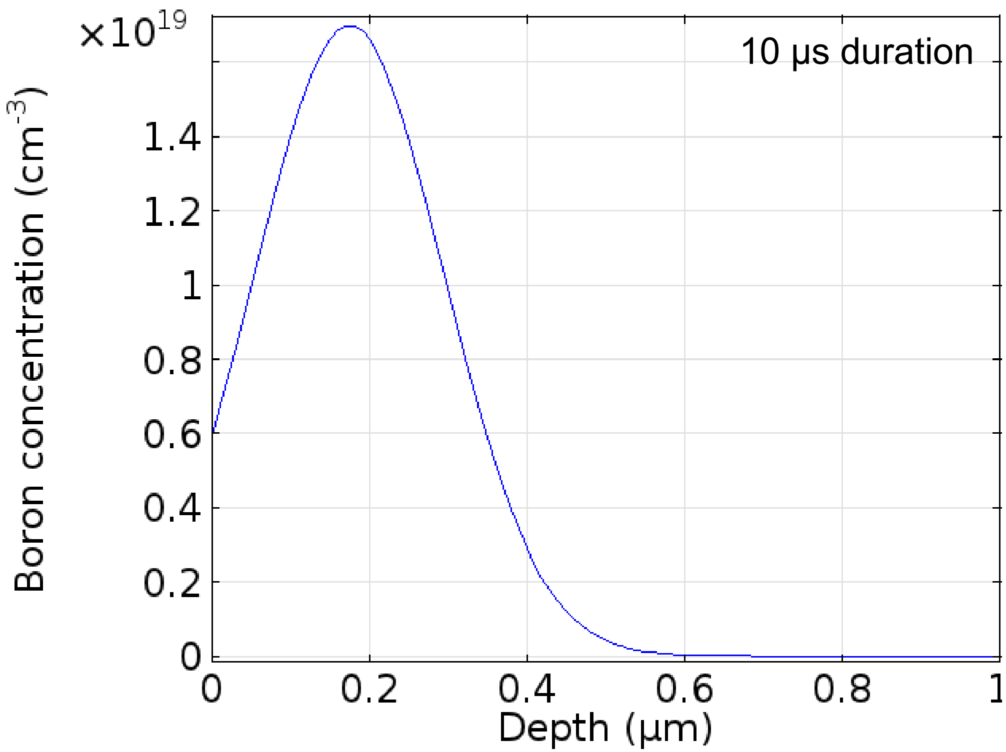


Device cross-section



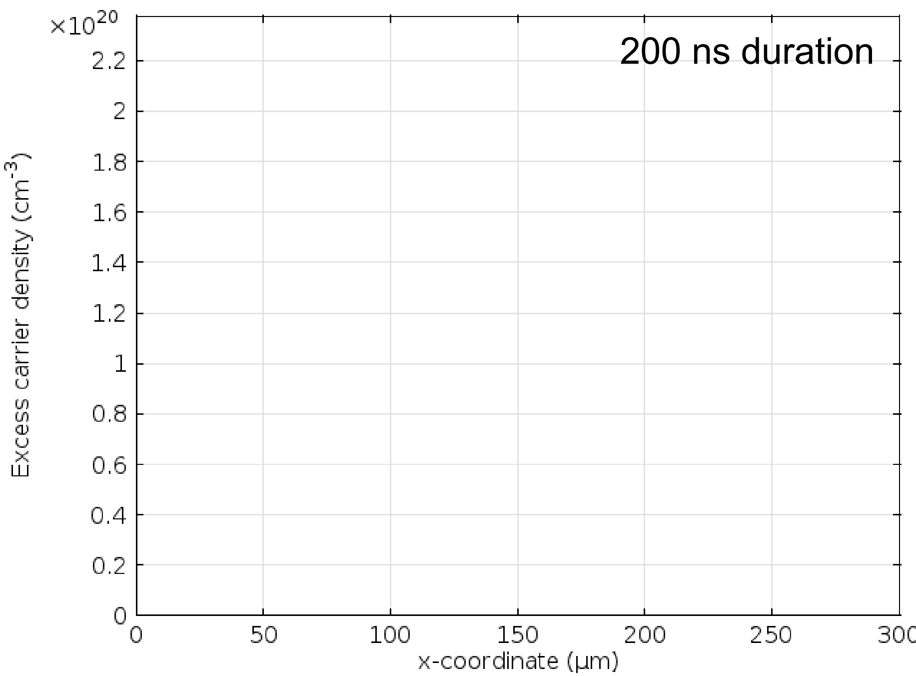
Device top view

Additional modeling results



Model of boron diffusion in Si shows no unwanted diffusion of B away from the junction.

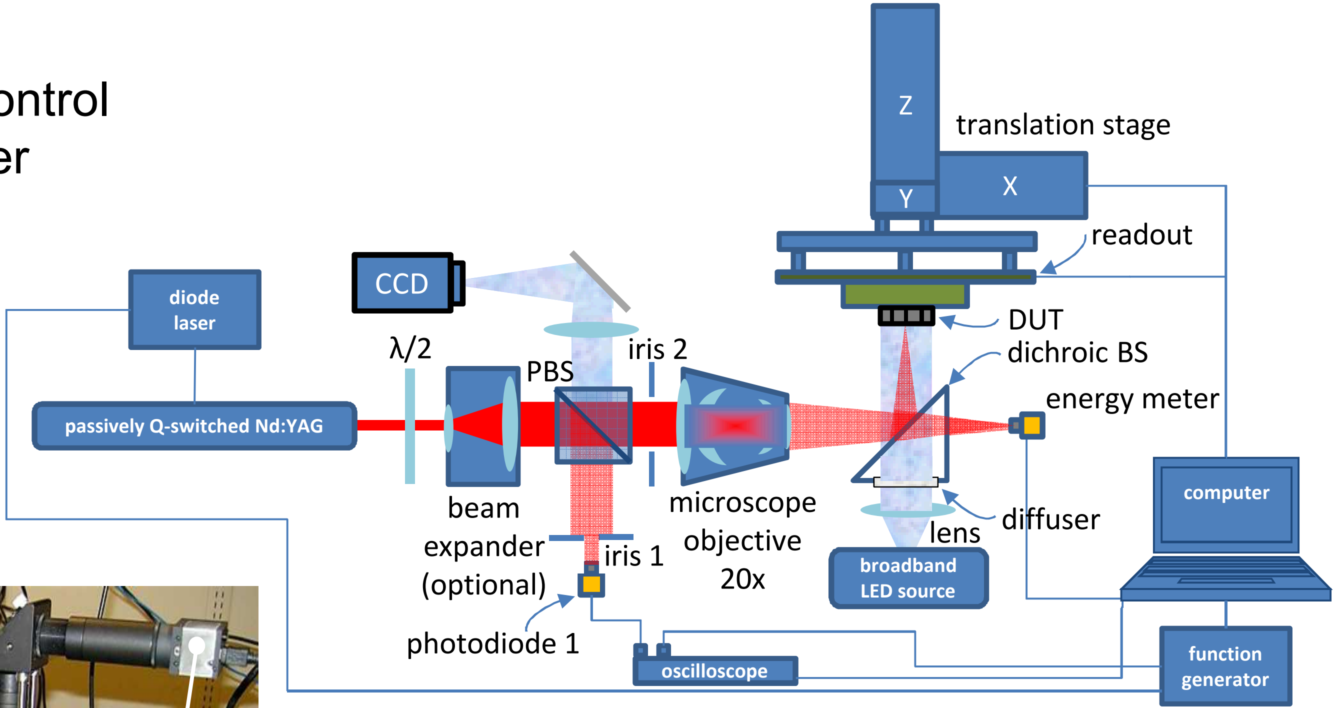
Photo-carriers are created throughout sample depth due to weak absorption in Si @ 1064 nm.

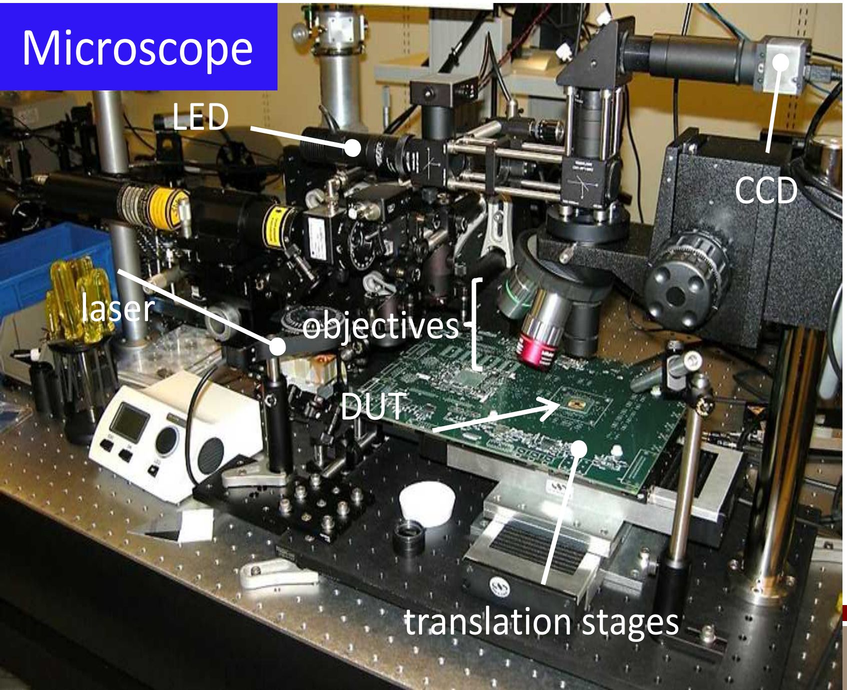


Experimental setup

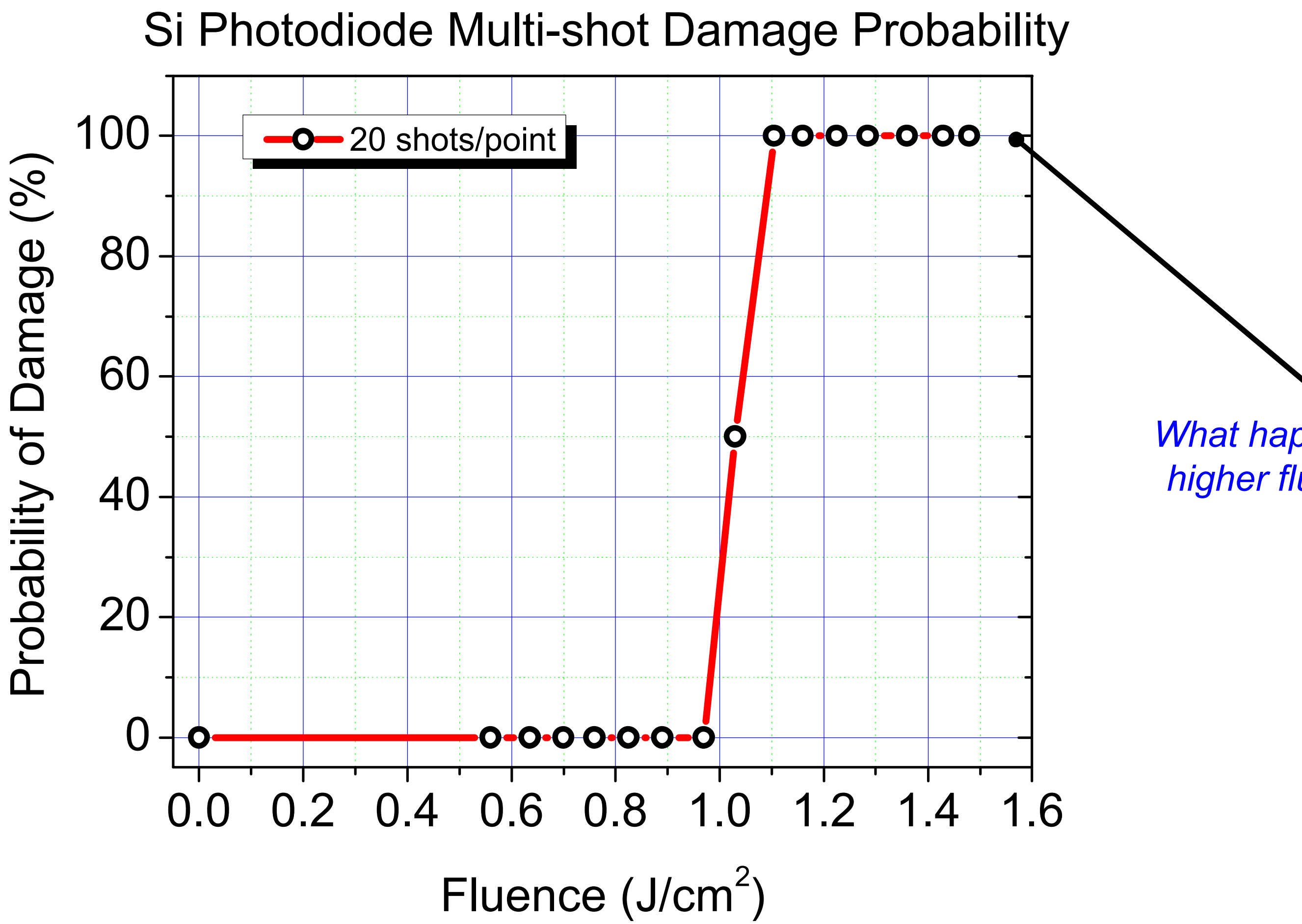
Laser is used to both create and anneal damage

- Complete computer control
- 0.5 μm resolving power
- 5 μm laser spot size



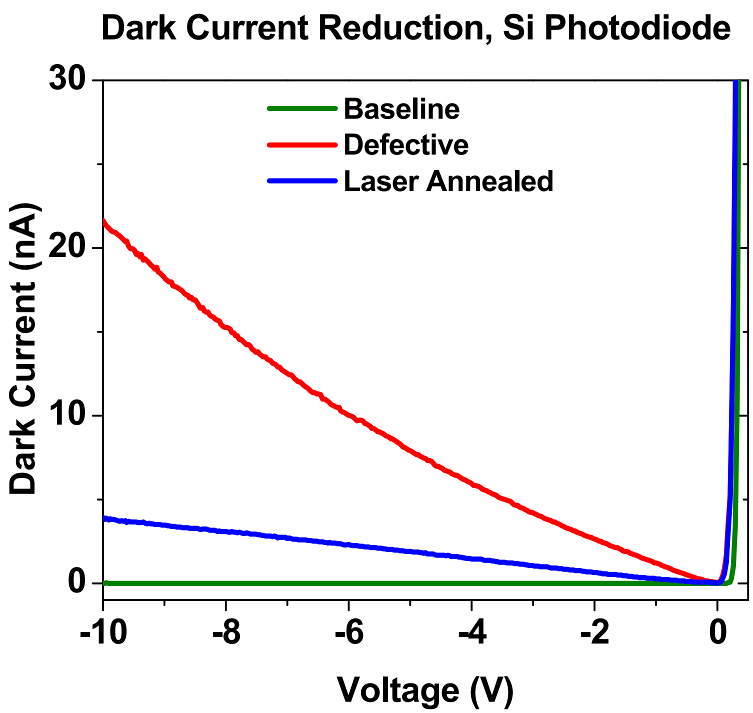


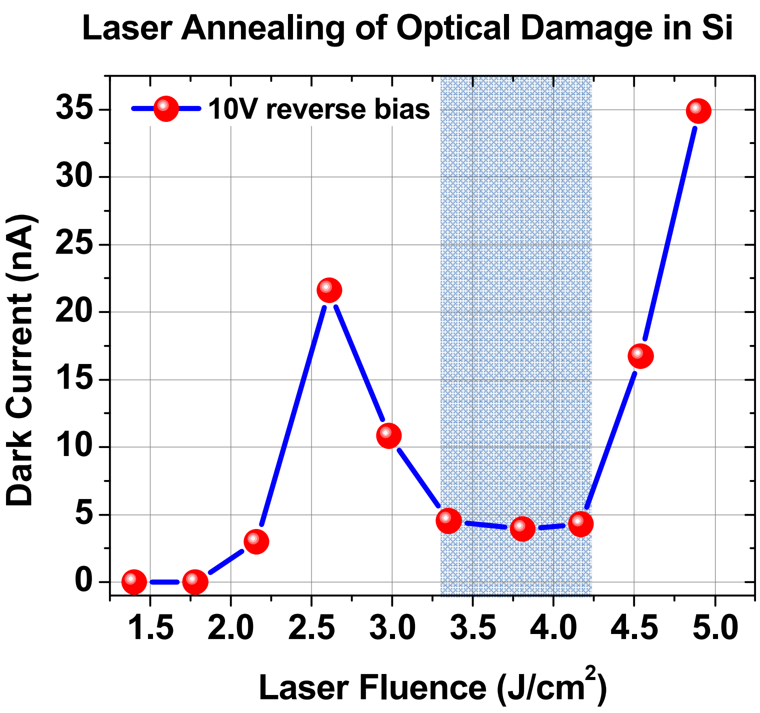
Observed typical laser damage threshold in Si



What happens at higher fluence?

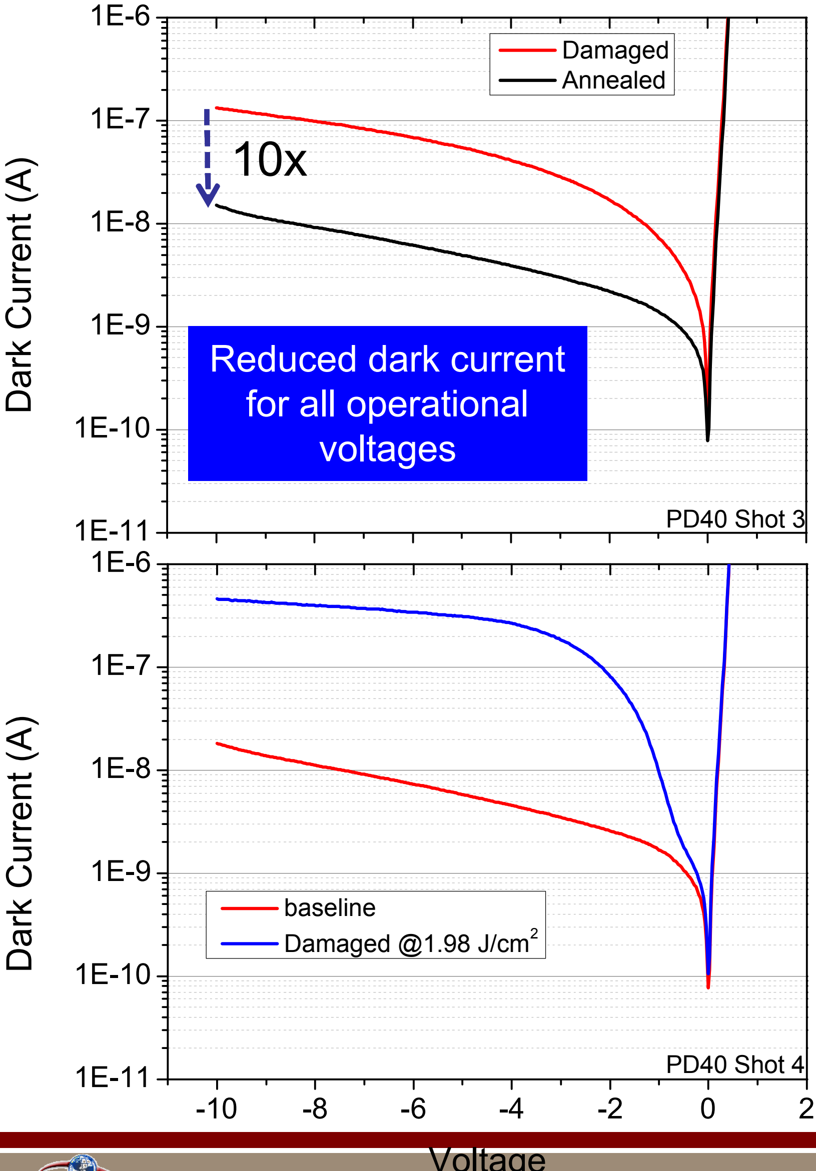
At higher fluence electrical damage can be partially reversed

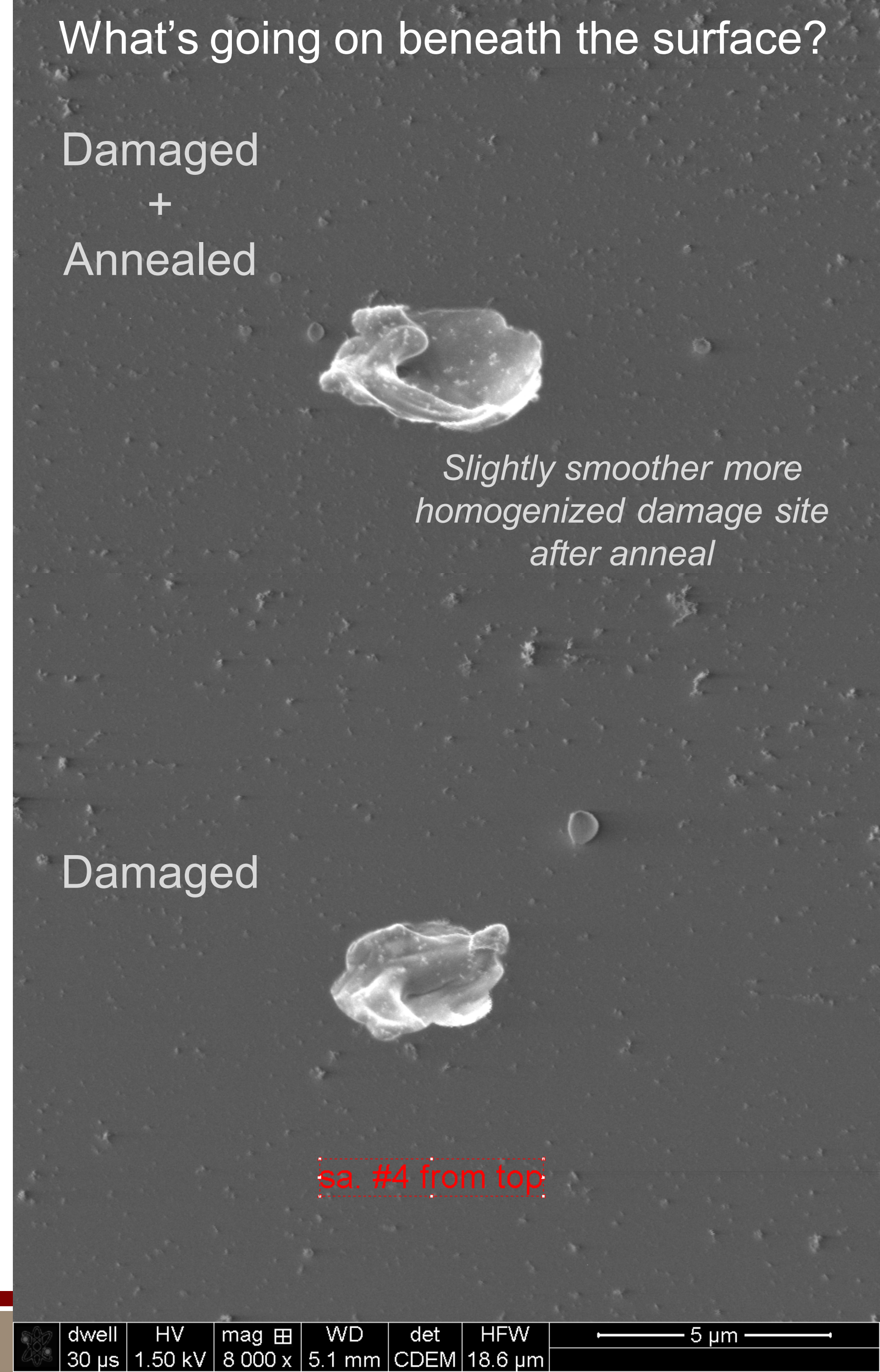




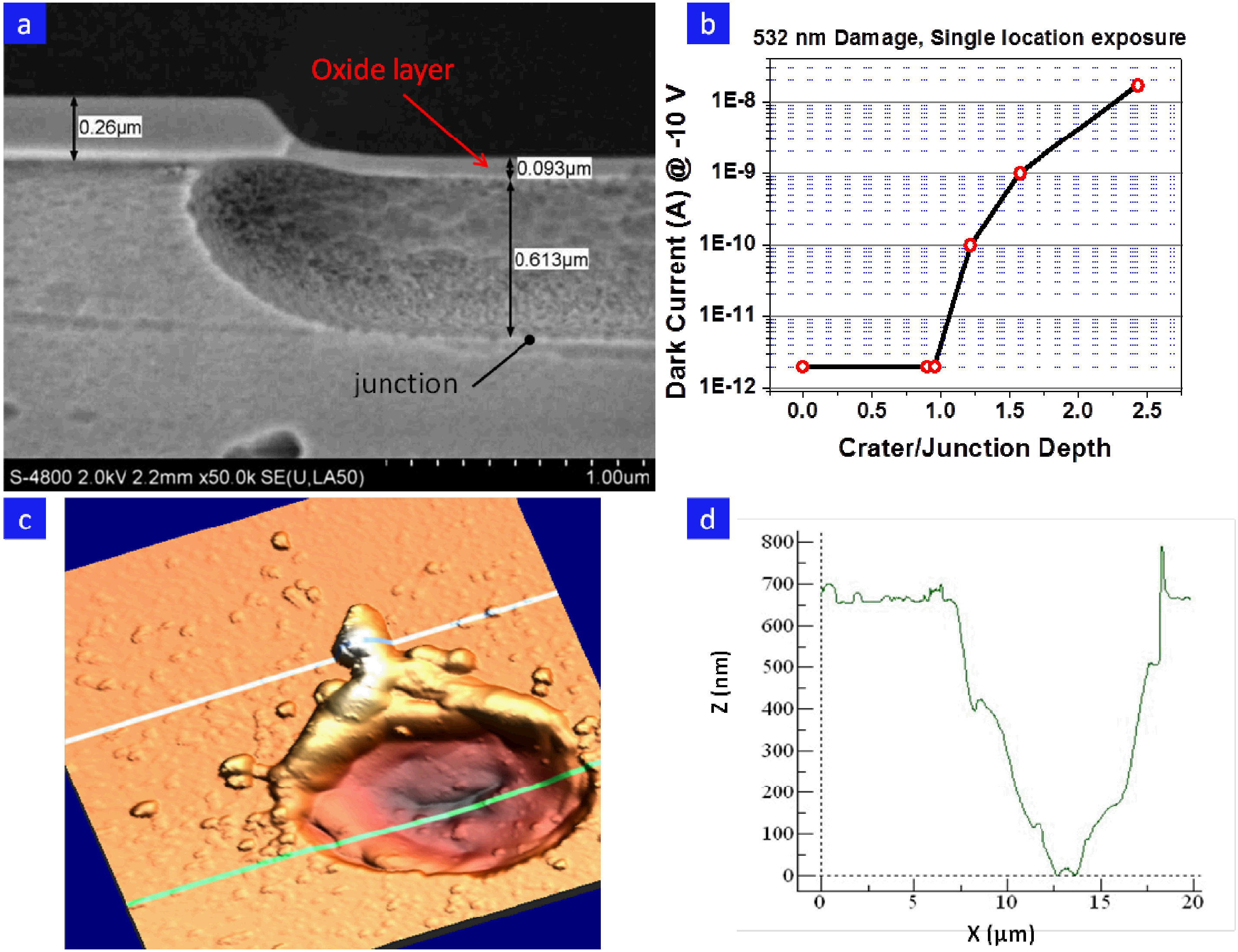
Each laser shot is in the same location, increasing fluence with each successive shot

Laser annealing reduces damage by 10X





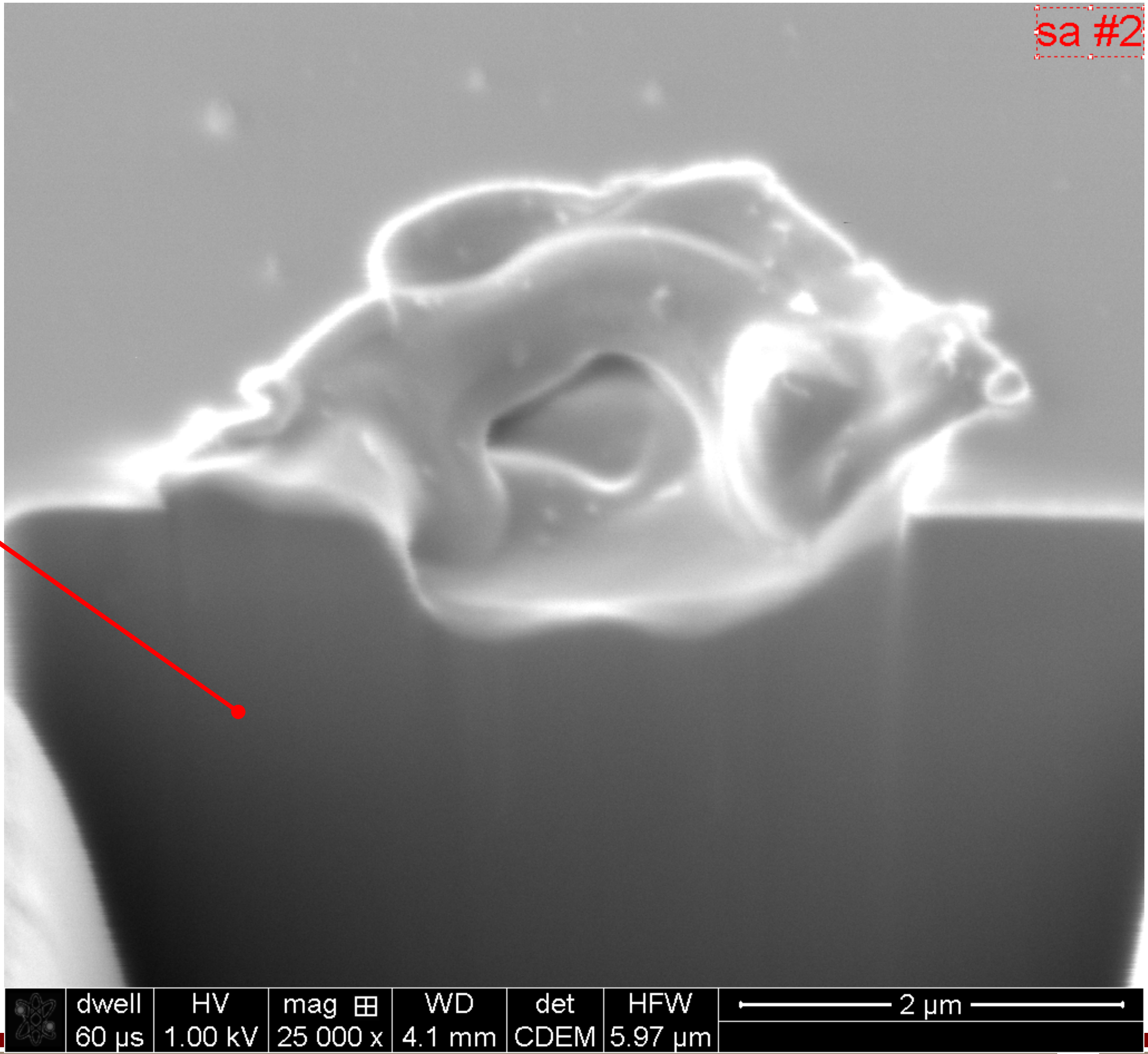
Failure analysis reveals junction at damage



a) Junction cross-section
b) Dark current from damage
c) Morphology of damage
d) Damage crater depth profile

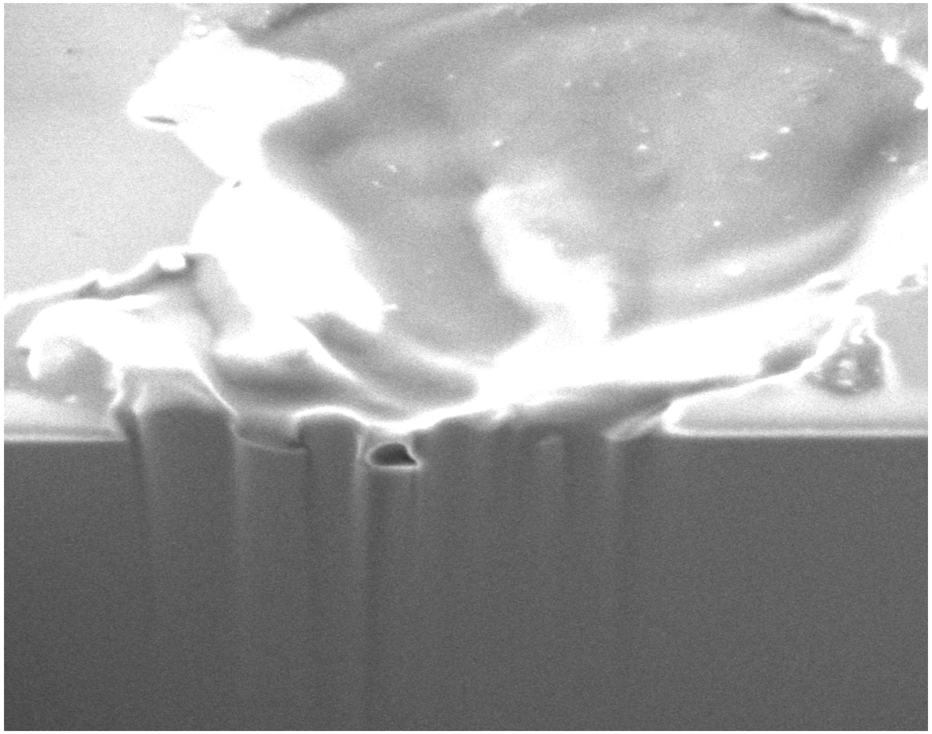
Si reflow from laser anneal

FIB cut and SEM cross-section



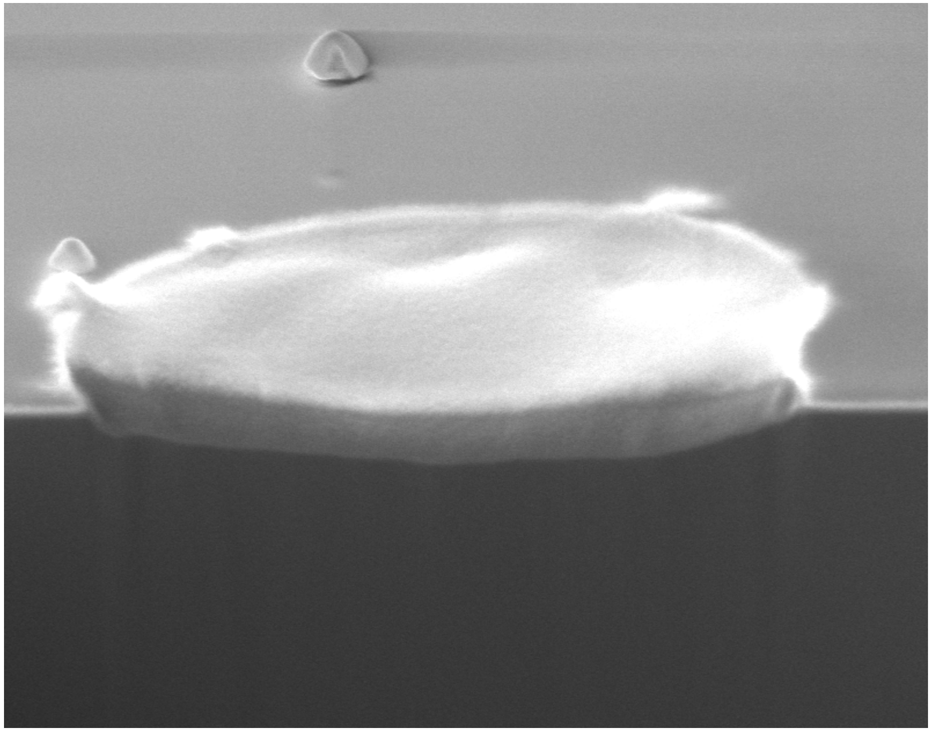
Cross-sectional SEM analysis of annealing

Damaged



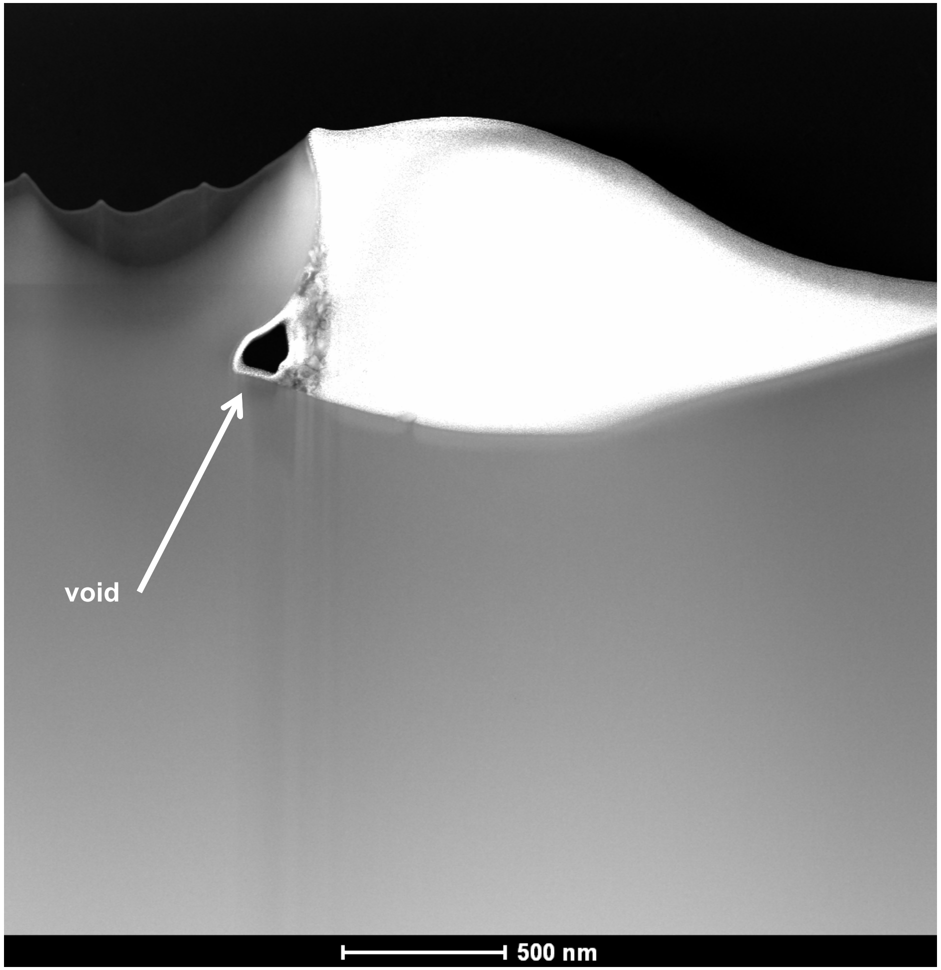
Observation of subsurface void defect

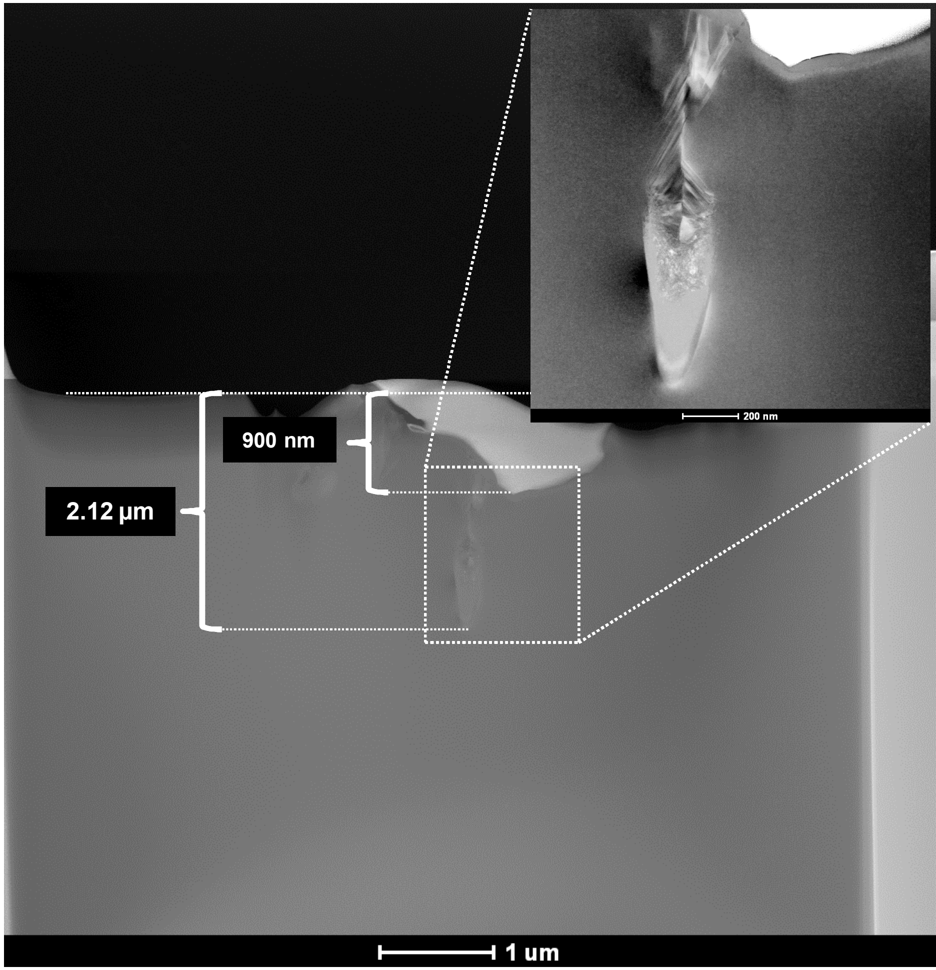
Damaged + Annealed



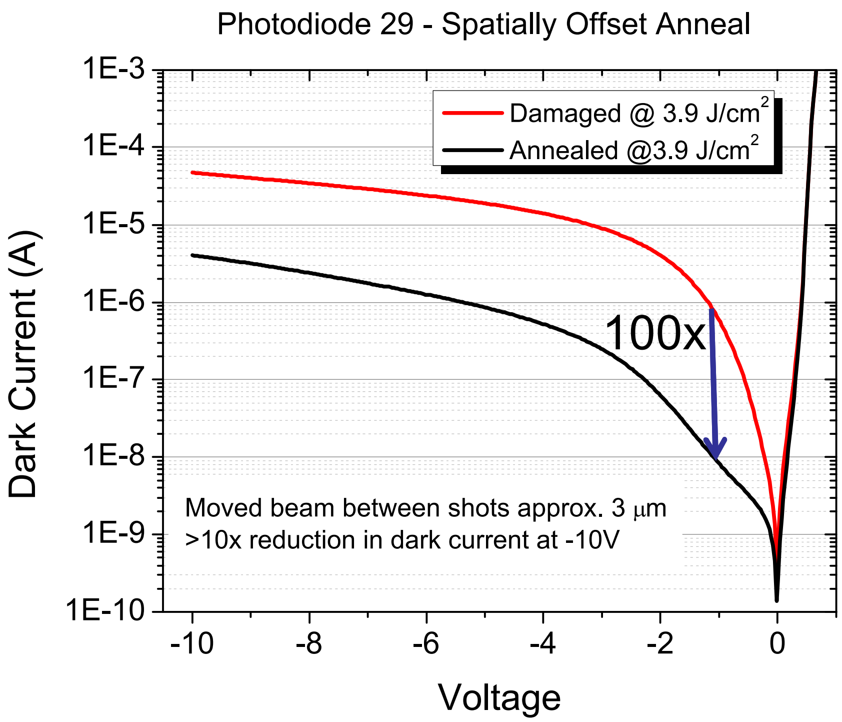
Uniform cross-section

TEM images show subsurface defects

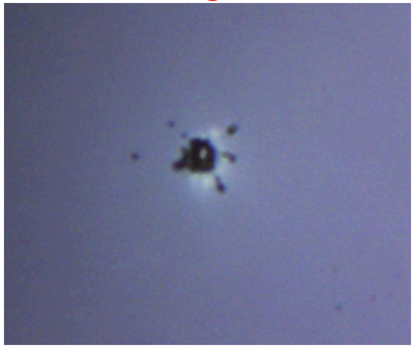




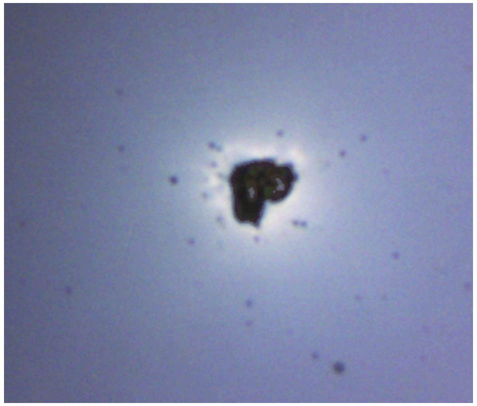
Spatially offset annealing can give greater reduction in dark current



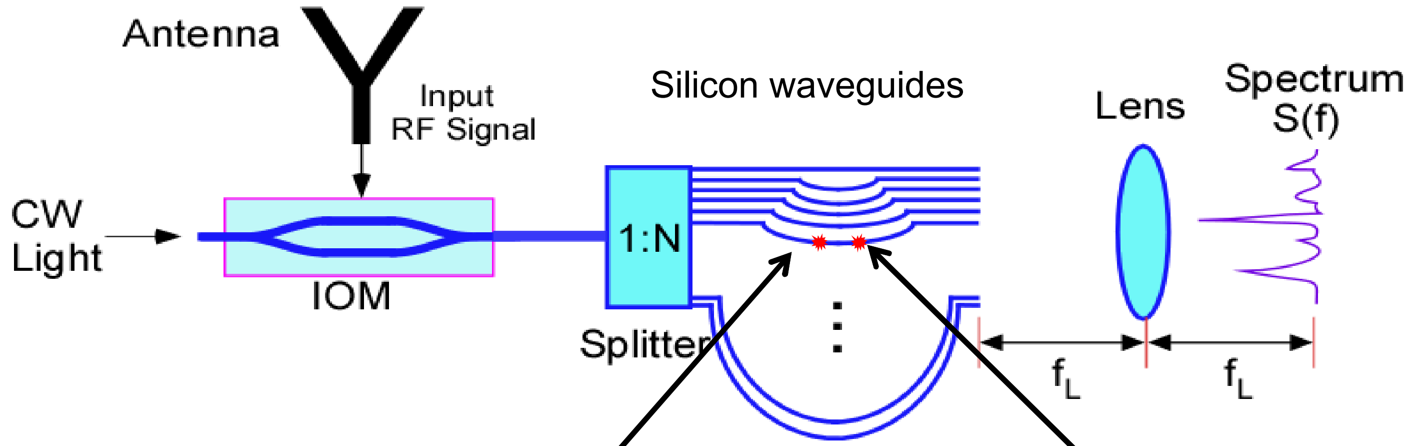
Damage site



Offset anneal site



Longitudinal phase tuning of optical waveguides in Si



Waveguides have random phase error due to inhomogeneity of Si

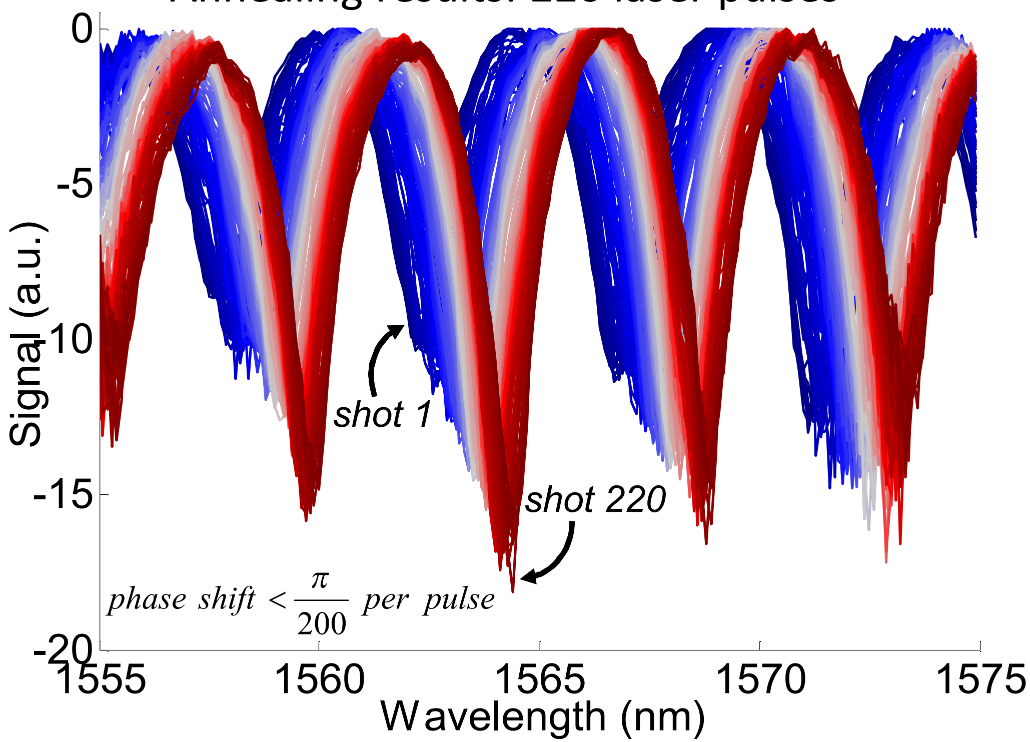
Waveguides must be tuned to have the same phase

Local laser anneal tunes waveguide propagation phase by melting and re-growing Si

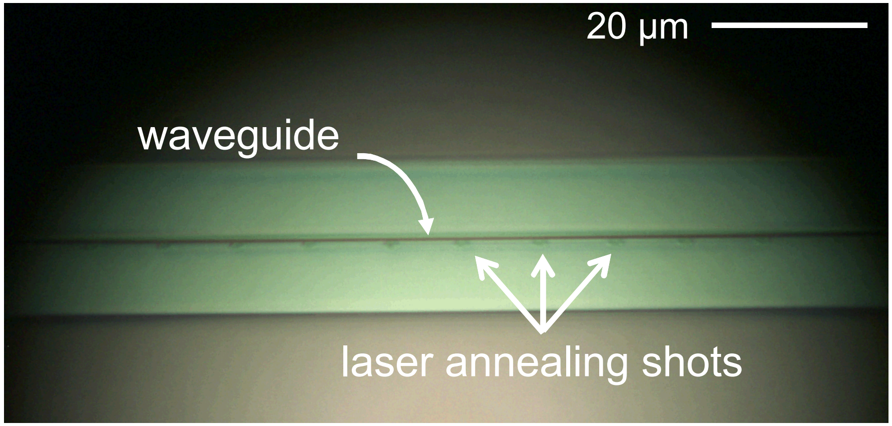
$$E_1(\bar{r}_1,t)e^{i(\bar{k}_1\cdot\bar{r}_1+\omega t)} = E_2(\bar{r}_2,t)e^{i(\bar{k}_2\cdot\bar{r}_2+\omega t)} \ldots = E_N(\bar{r}_N,t)e^{i(\bar{k}_N\cdot\bar{r}_N+\omega t)}$$

Longitudinal phase tuning of optical waveguides in Si

Annealing results: 220 laser pulses



optical image of Si waveguide



Fringe pattern shifting indicates change in propagation phase

Summary & future work

- Laser annealing in Si
  - Reduced dark current in damaged Si photodiodes by 10-100x
  - Tune longitudinal phase propagation in Si waveguides
- Future work: transition to HgCdTe (MCT)
  - Build tunable system suitable for MCT bandgap
  - Adapt thermal electro optic model to MCT
  - Initial testing with photodiodes
  - Anneal IR focal plane arrays.