National Aeronautics and
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The DUV stability of superlattice-doped CMOS detector arrays

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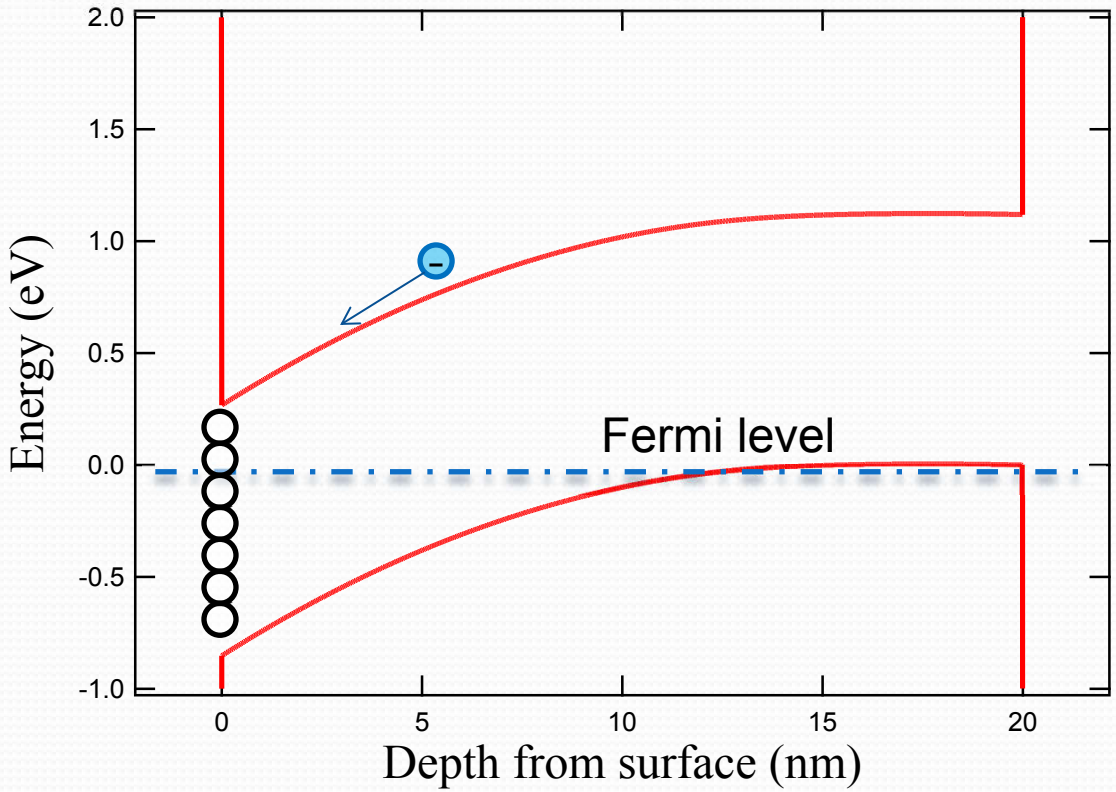
Interface traps and detector instability

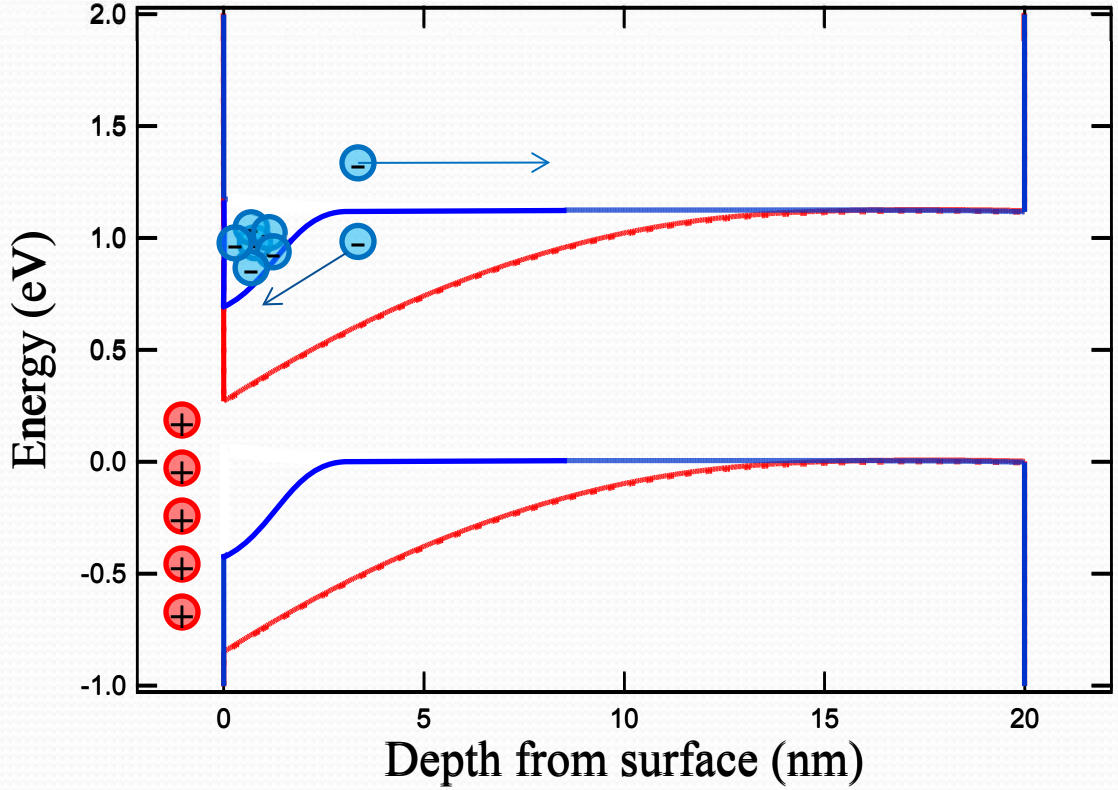


Low interface trap density → Surface potential is unstable
High interface trap density → Fermi level is pinned <u>midgap</u>

Surface damage and surface trapping cause instability and failure

Transient Instabilities

Quantum Efficiency Hysteresis and Persistence



Positive charge → Depletion

Illumination → Transient band flattening

Electron trapping leads to transient instabilities

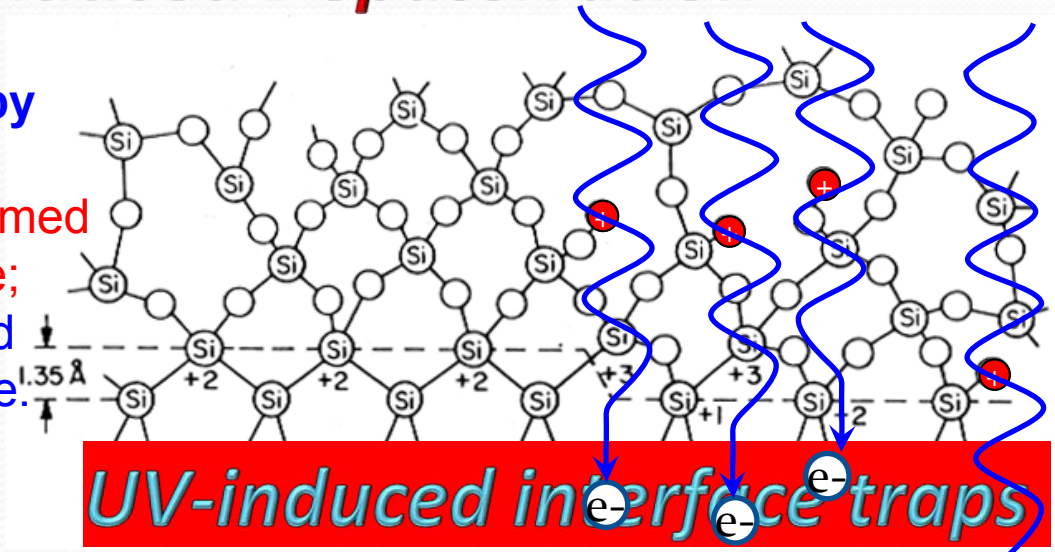
Permanent degradation

Damage-induced *Depassivation*

Far UV photons are not hydrogen…

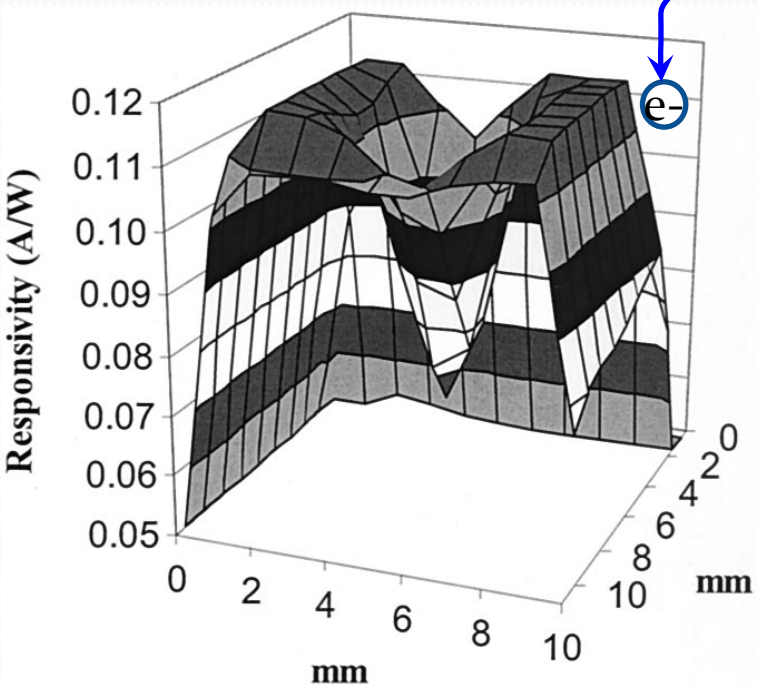
Silicon interface is populated by hydrogen near the Si surface…

- Hydrogen passivates traps formed by charging ions;
- Hydrogen is weakly bound and
- Traps are formed.



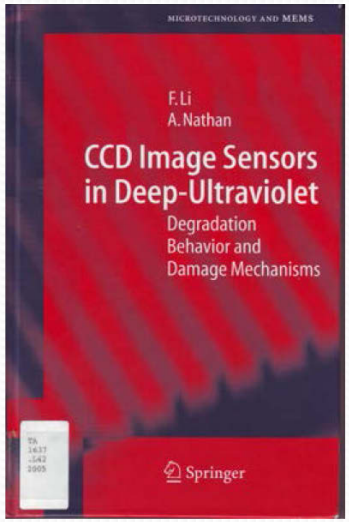
Far ultraviolet radiation depassivates detectors (Arp and Shaw 2005)

- Band structure in interface region is not fully developed
- Hot carrier damage is possible at low energies

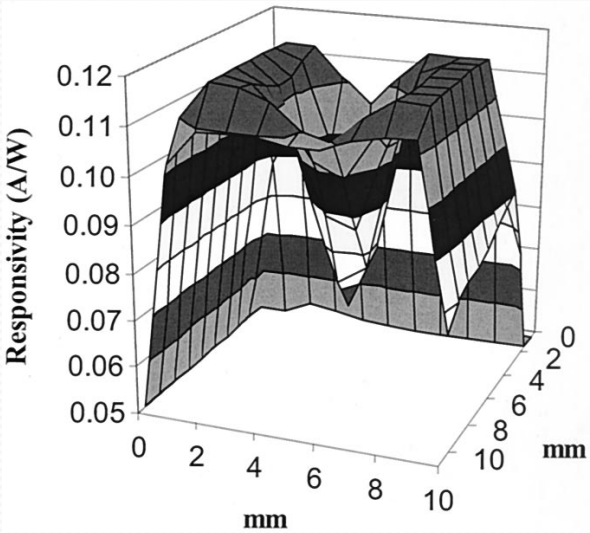


DUV damage causes instabilities and failure

- Li, FM & Nathan, A,
  CCD image sensors in deep-ultraviolet: degradation behavior and damage mechanisms,
  Springer, Berlin, 2005.



- Arp, U., Shaw, P.S., Gupta, R. and Lykke, K.R.,
  "Damage to solid-state photodiodes by vacuum ultraviolet radiation,"
  J. Electron Spectroscopy and Related Phenomena, **144-147**: 1039-1042, 2005.



Deep and far UV instabilities and mitigations:
- Thin oxides → reduce cross section
- Oxy-Nitrides → reduce damage

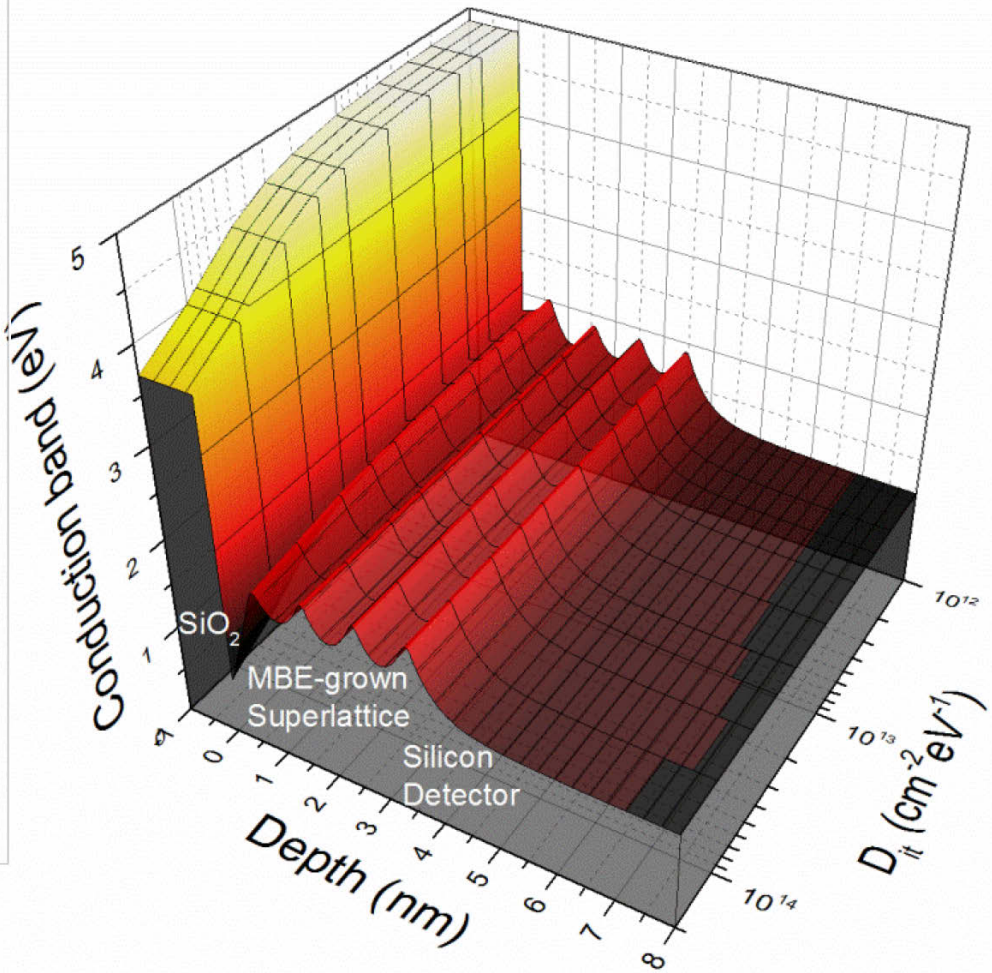
Superlattice doping

Multiple 2D-doped layers

- Tunnel barrier isolates surface traps
- Electron quantum confinement & transport suppresses surface trapping
- Hole confinement & transport increases effective bandgap and conductivity

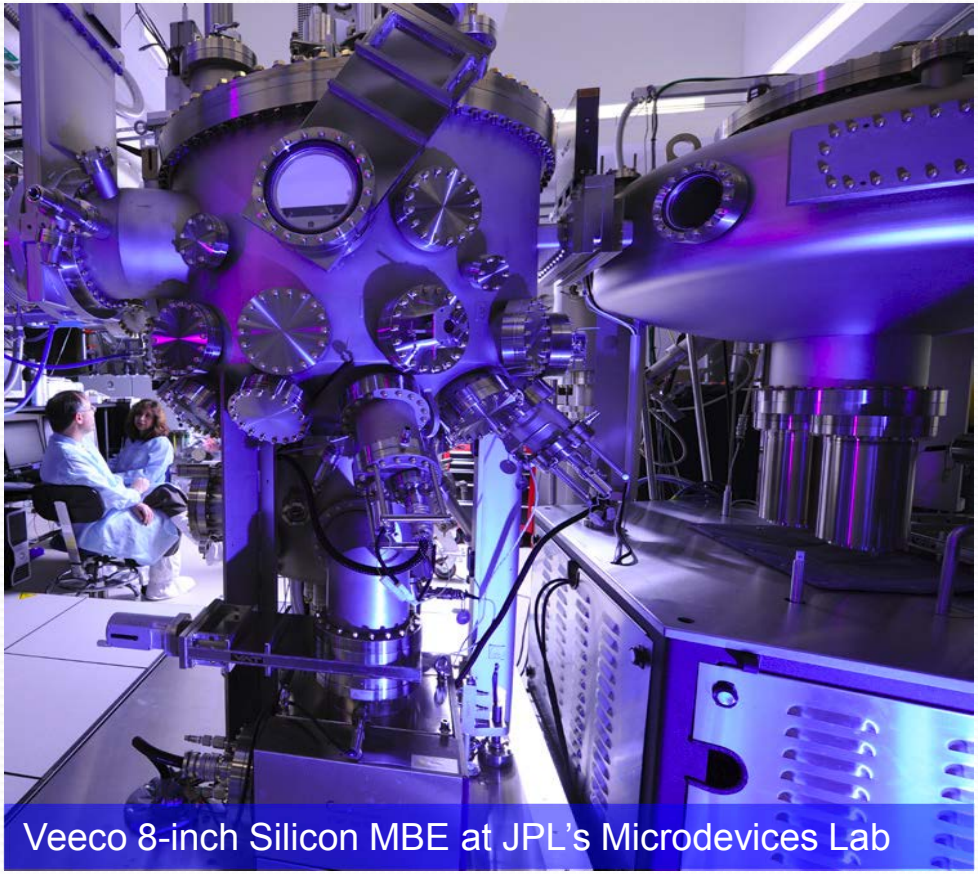
Insensitive to interface defects

- Excellent stability, robustness, conductivity, dark current.
- Nearly 100% internal QE.

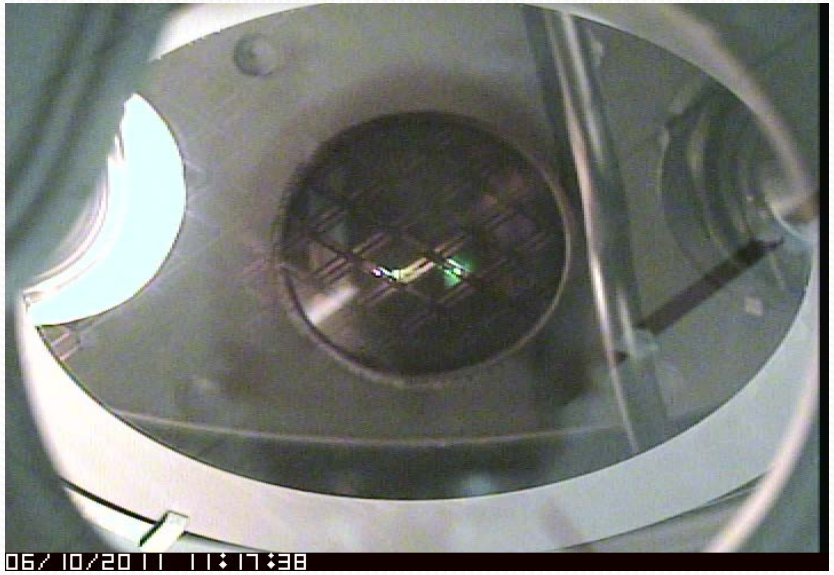


"Surface Passivation by Quantum Exclusion Using Multiple Layers,"
Michael E. Hoenk, U.S. Patent 8,395,243, issued March 12, 2013.

Wafer-scale Superlattice Doping



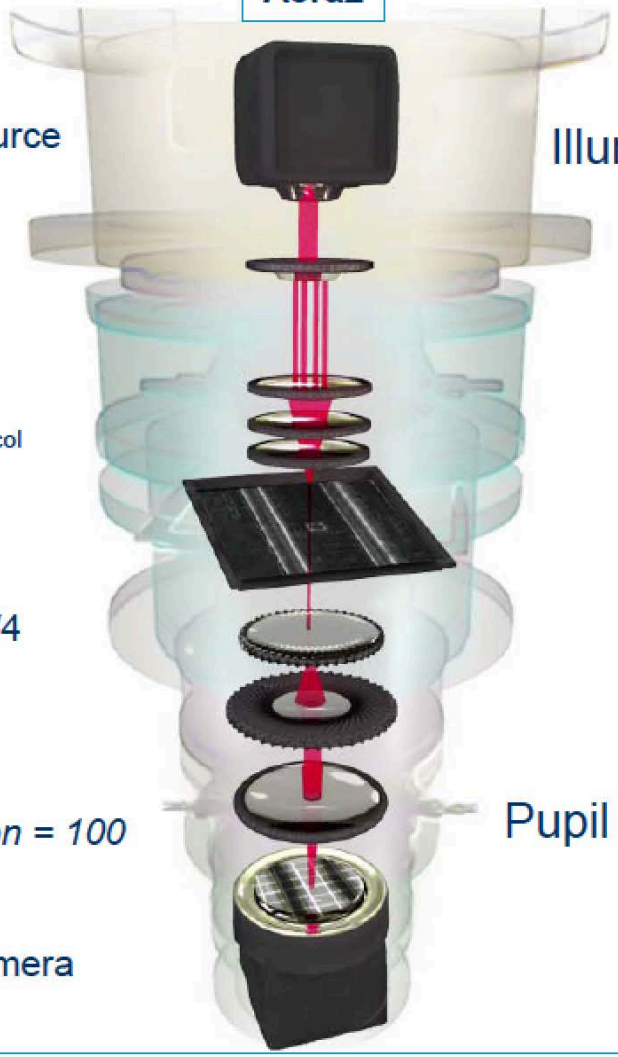
Veeco 8-inch Silicon MBE at JPL's Microdevices Lab

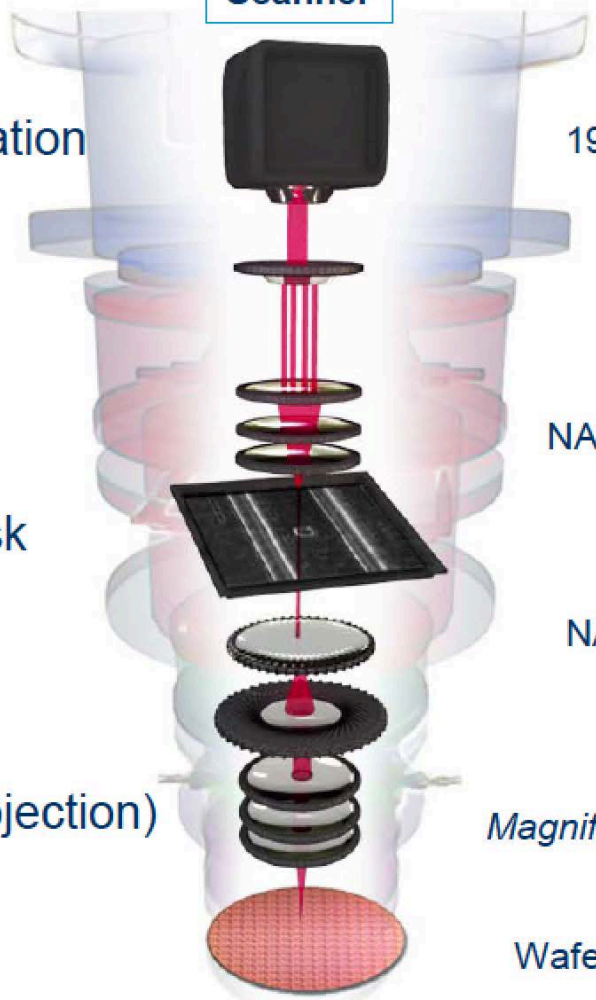


8-inch CMOS wafer during MBE growth at JPL's Microdevices Lab

See Shouleh Nikzad's talk

Applied Aera2 Aerial Imaging Technology





Illumination

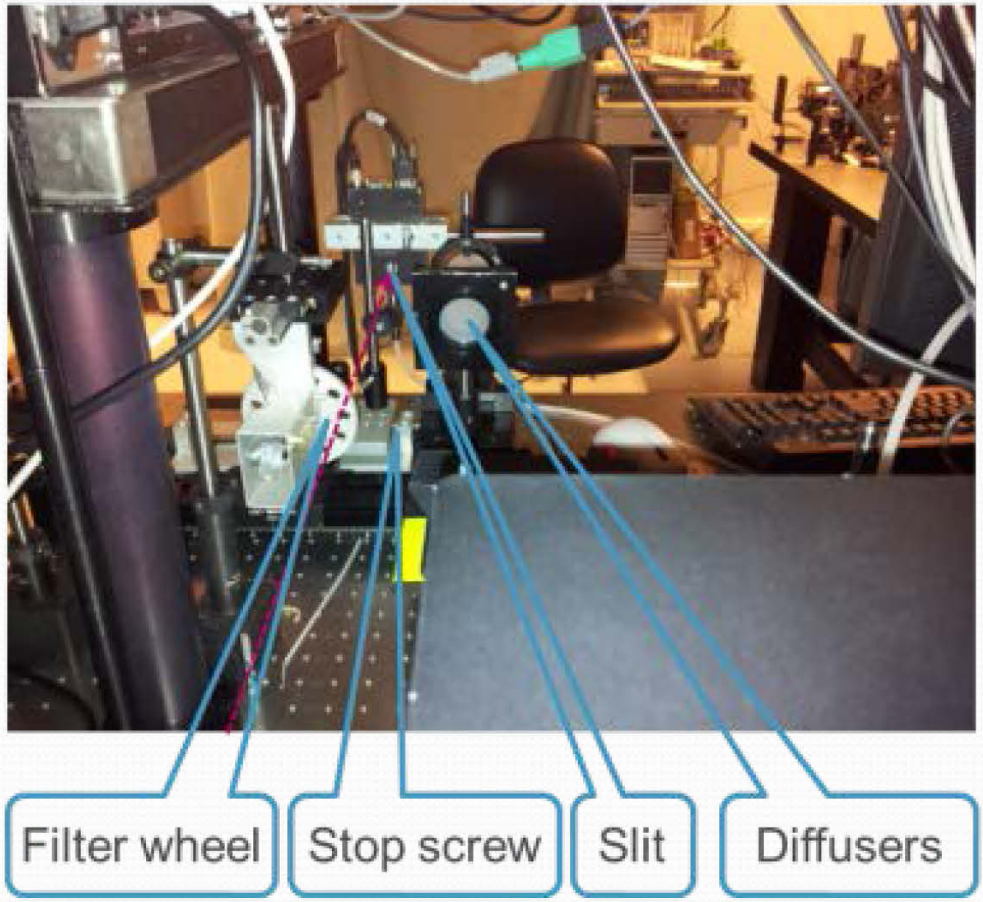
Mask

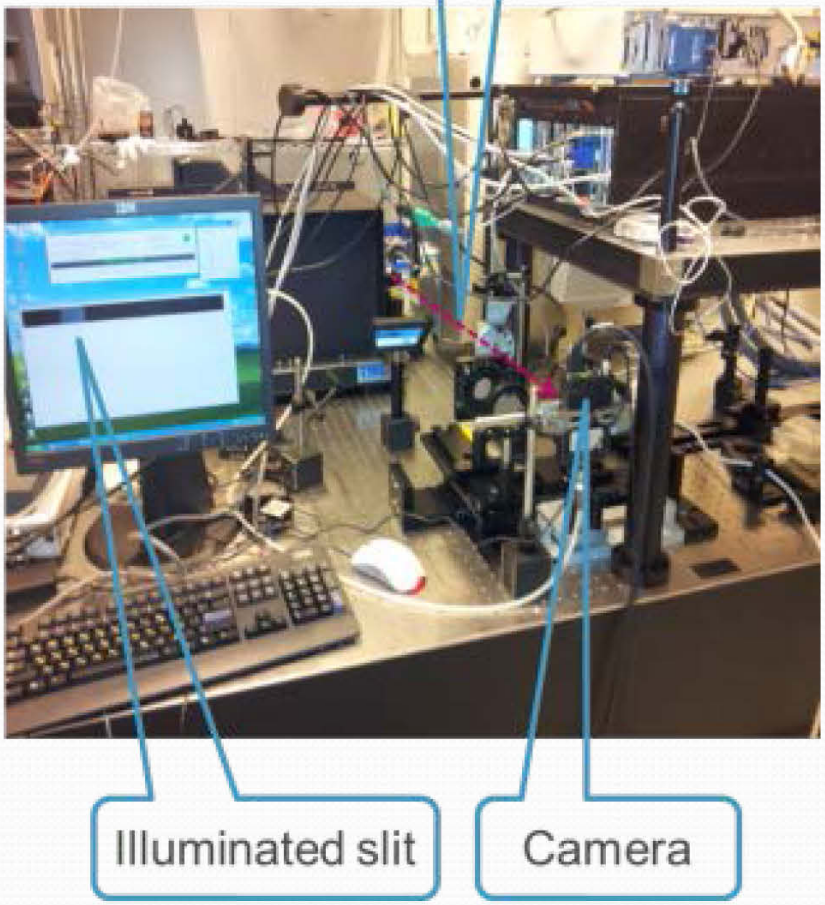
Pupil (projection)

Optical emulation of immersion lithography – pupil shape, NA, and σ

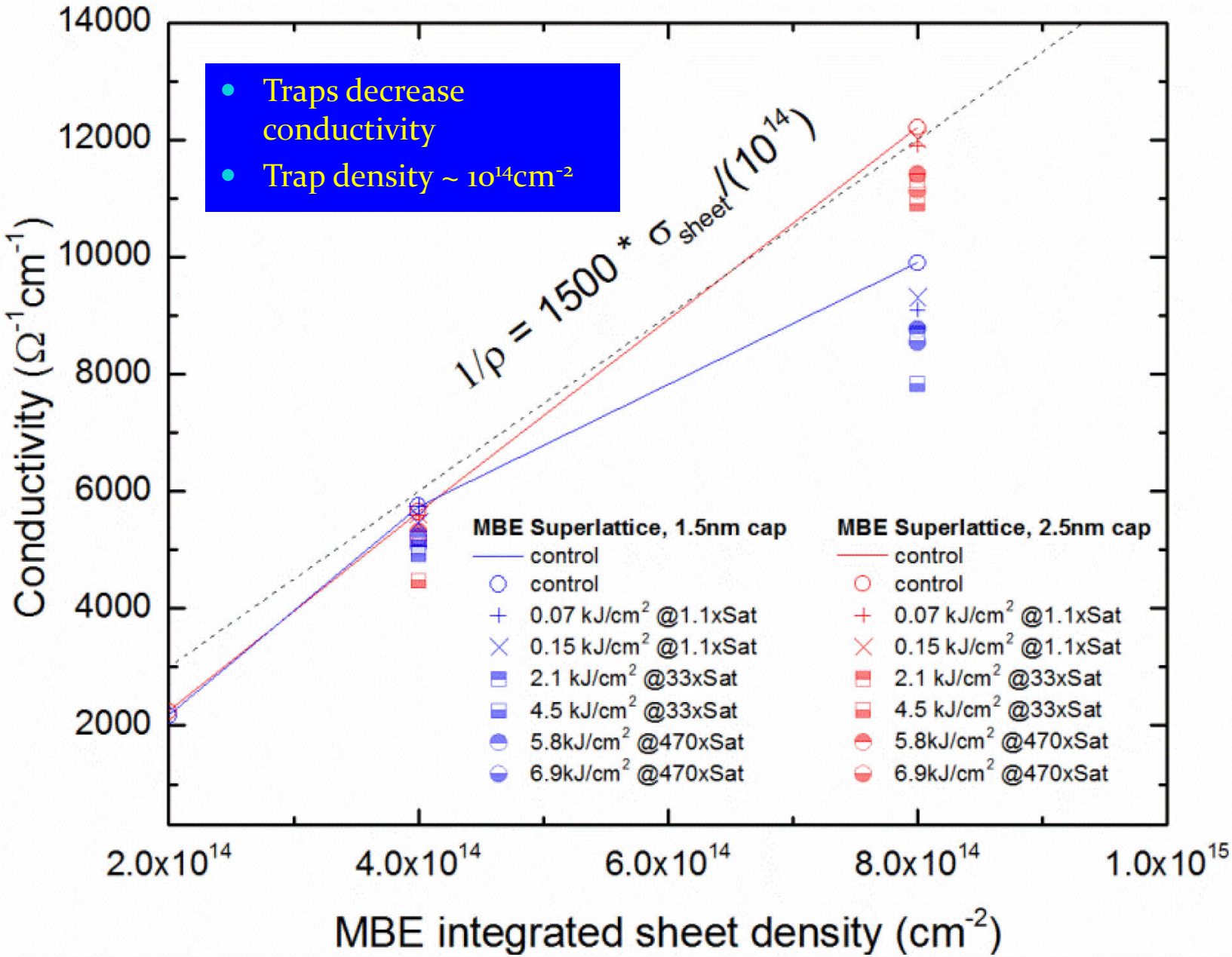
Lifetime Testing with Pulsed DUV Lasers

193 nm test setup





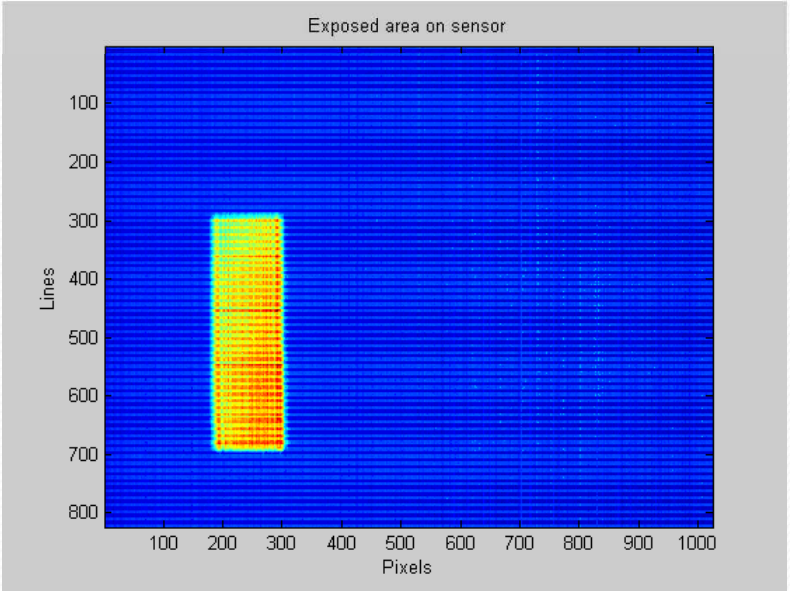
Calibrating DUV laser damage with test wafers



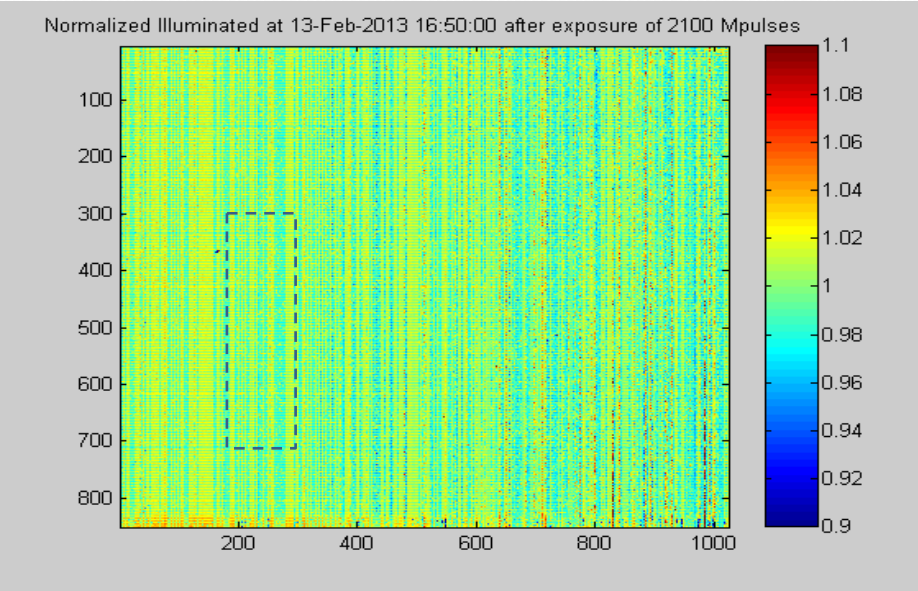
Superlattice-doped detector stability

193nm Results

- >2 Billion laser pulses at full saturation
- No measureable change (within +1%)
- Estimated Lifetime > 10B laser pulses.
- Internal QE ~100% (excluding Quantum Yield)
- No blooming and no image memory at 1000 fps.



Exposure slit position on sensor

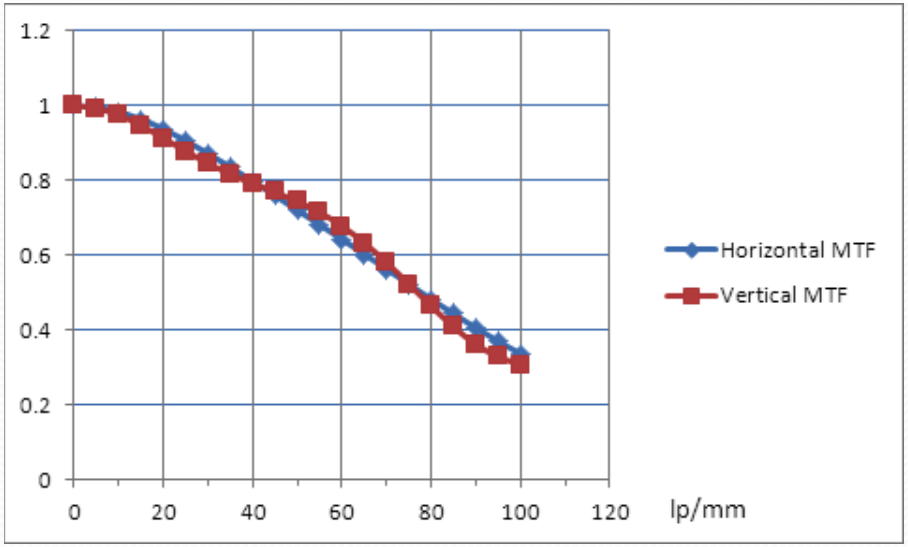


Normalized Spatial Response following 2.1 B pulses

Superlattice-doped detector stability

263nm Results

- Pulsed 263 nm laser up to x257 camera saturations
- **QE = 64%** with AR-coated sensor – 28nm Al_2O_3
- QE and dark current stable to maximum tested dose (3.1 kJ/cm²)
- No blooming and no image memory were present even at the high saturation levels.
- High modulation transfer function (MTF)



Physics of 3D doping

Surface traps and dead layer

Poisson's equation…

$$\nabla^2\varphi = \frac{-\sigma_{surface}\delta(0) + \rho(x)}{\kappa\varepsilon_0}$$

$$\nabla\varphi = \frac{-\sigma_{surface}u(0) + \int_0^x \rho(\alpha)d\alpha}{\kappa\varepsilon_0}$$

Charge neutrality

$$Depletion\ \ depth \approx \frac{\sigma_{surface}}{\rho_{3D}}$$

Depletion depth depends on trap density

DUV damaged surface, $\sigma_{surface} \sim 10^{14}\ cm^{-2}$

- $\rho_{3D} = 10^{19}\ cm^{-3}$ → Depletion depth ~100 nm
- $\rho_{3D} = 10^{21}\ cm^{-3}$ → Depletion depth ~1 nm
- **3D doping limit <2.5x10^{20}cm^{-3}**

2D doping is necessary for DUV robustness

Physics of 2D doping

Stable self-ordered surface phase, up to 0.5 monolayer ($3x10^{14}cm^{-2}$)

Poisson's equation…

$$\nabla^2\varphi = \frac{-\sigma_{surface}\delta(0) + \sigma_{2D}\delta(x_{2D}) - \rho_{holes}(x)}{\kappa\varepsilon_0}$$

Integrate…

$$\nabla\varphi = \frac{\sigma_{2D}u(x_{2D}) - \sigma_{surface}u(0) - \int_0^x \rho_{holes}(\alpha)d\alpha}{\kappa\varepsilon_0}$$

Near surface potential is dominated by doping-induced dipole…

$$Dipole\ \ width = x_{2D}$$

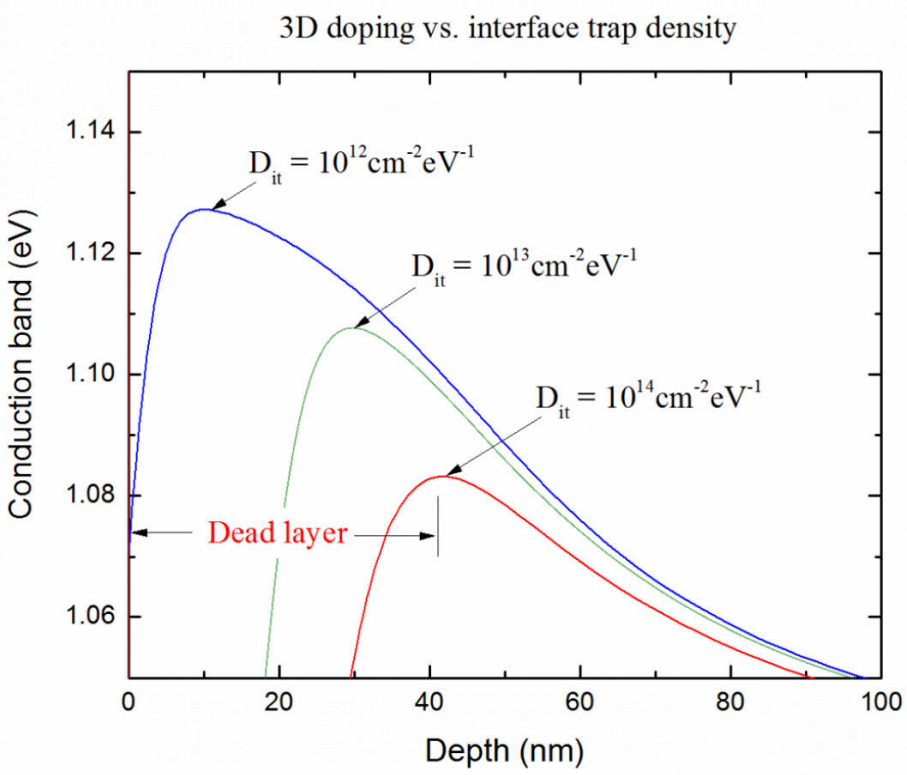
2D doping induced dipole width is independent of trap density

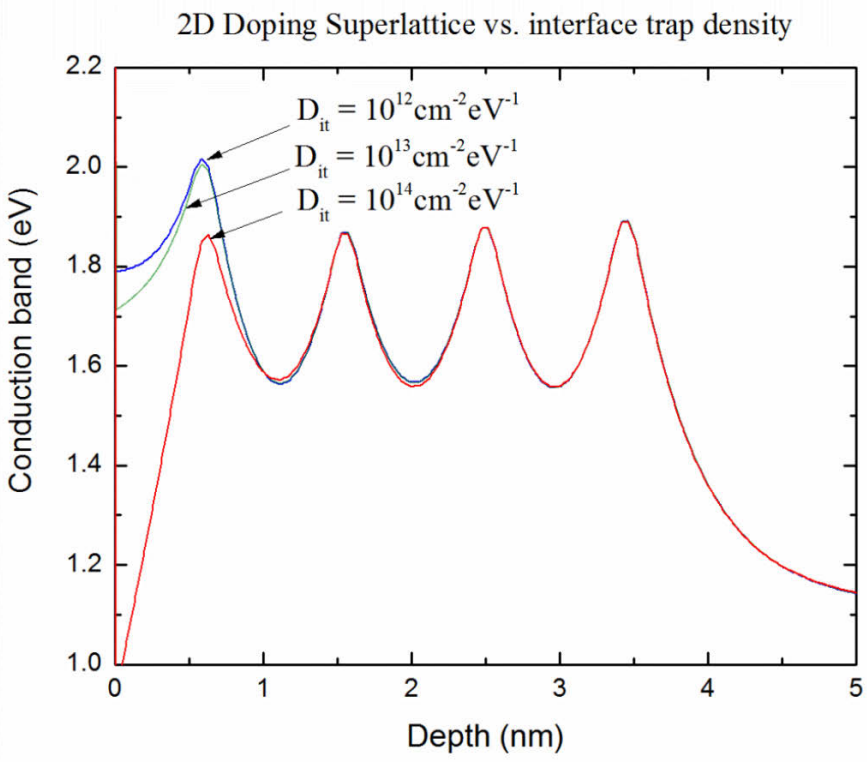
If x_{2D} < 1nm… **surface state density decreases significantly**

Quantum confinement enhances QE and suppresses dark current

2D vs. 3D doping

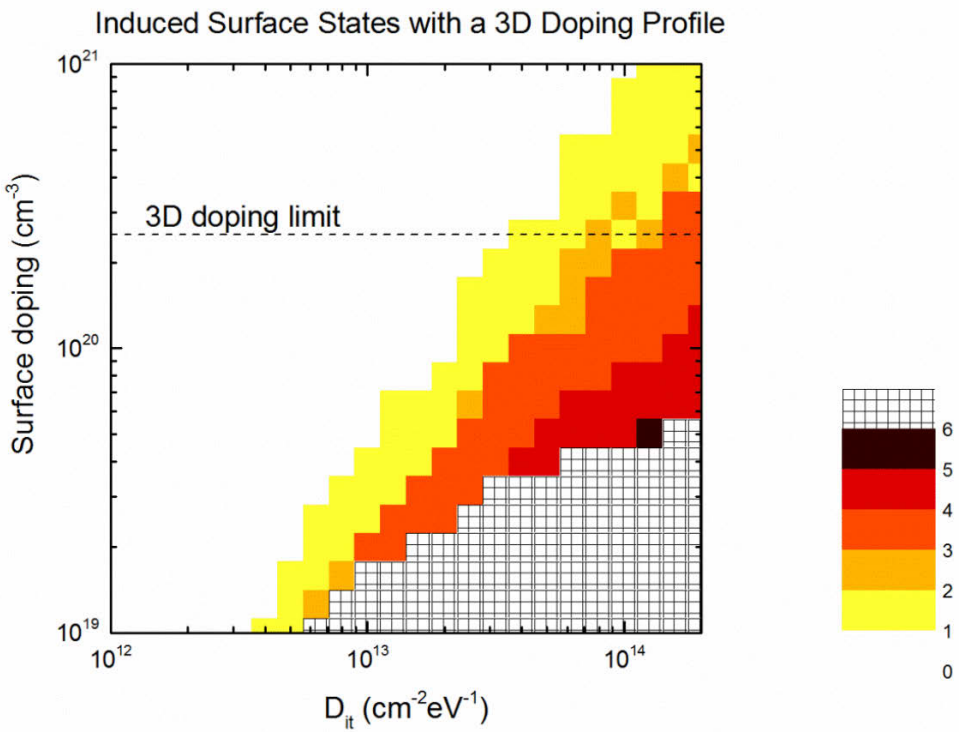
Stability vs. Traps

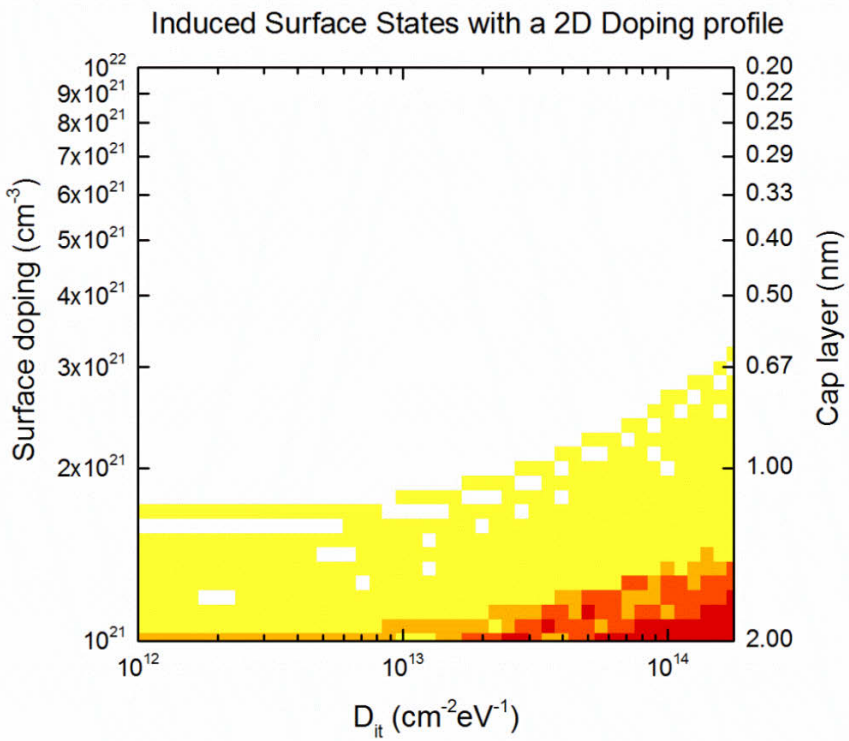




2D vs. 3D doping

Electron trapping



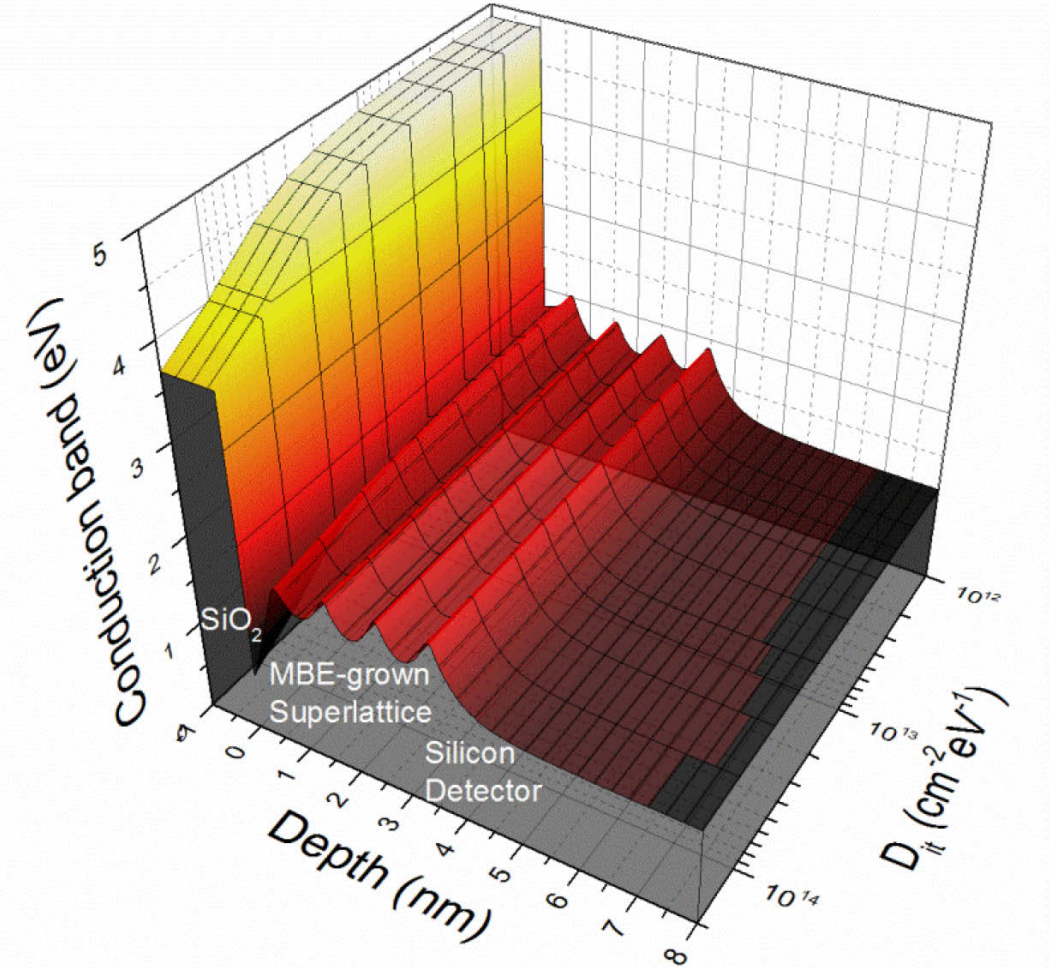


Superlattice-doped BSI DUV Detectors

Summary of DUV stability results

- 193nm
  - >2 Billion laser pulses at full saturation
  - QE and dark current stable (within +1%)
  - Estimated Lifetime > 10B laser pulses.
  - Internal QE ~100% (excluding Quantum Yield)
  - No blooming and no image memory at 1000 fps.
- 263nm
  - >2 Billion laser pulses at 257x saturation
  - QE and dark current stable (within +1%)
  - QE = 64% with AR-coating (28 nm Al_2O_3)
  - No blooming and no image memory
  - High modulation transfer function (MTF)

Superlattice-doped BSI DUV Camera



Alacron Inc. BSI DUV camera with superlattice-doped, AR-coated CMOS imaging array.

"Surface Passivation by Quantum Exclusion Using Multiple Layers,"
Michael E. Hoenk, U.S. Patent 8,395,243, issued March 12, 2013.