National Aeronautics and
Space Administration

Delta doping Technology for UV Photon Counting Detector Arrays

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California Institute of Technology
Pasadena, California

The work described here was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

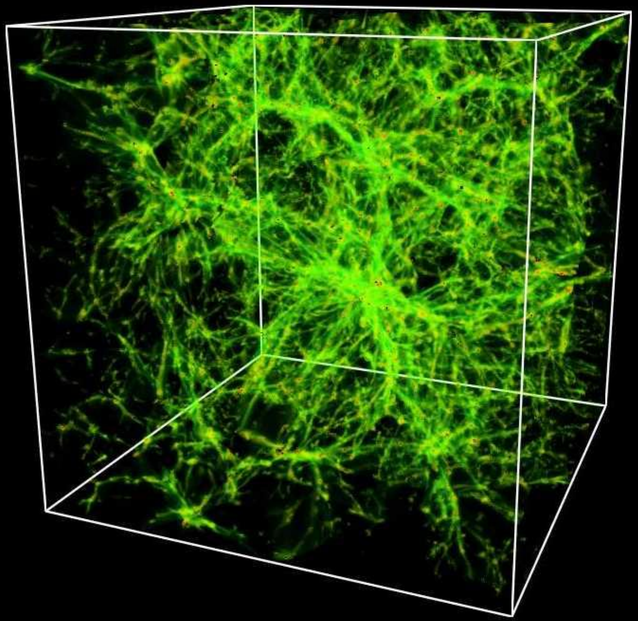
Outline

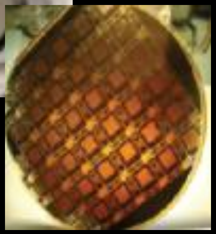
- Motivation – UV photon counting detectors
- Silicon surface physics and back surface passivation
- Delta-doping – nanostructured silicon by MBE
- Delta-doping with high throughput and high yield

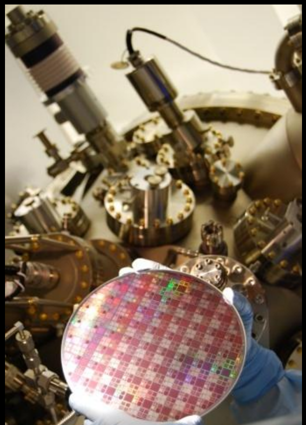
MIDEX-ISTOS Detector

MIDEX-ISTOS

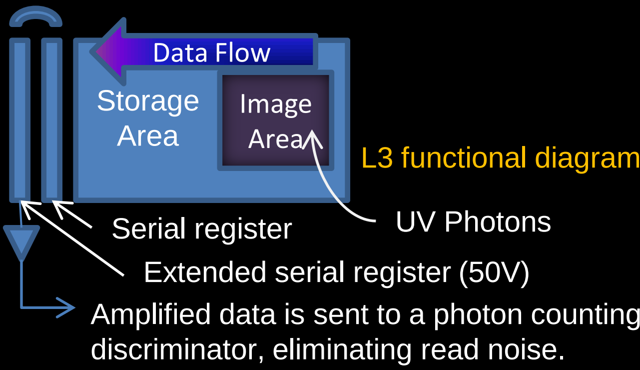
PI: Chris Martin, Caltech

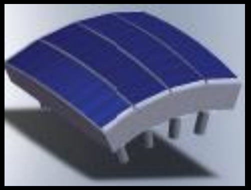


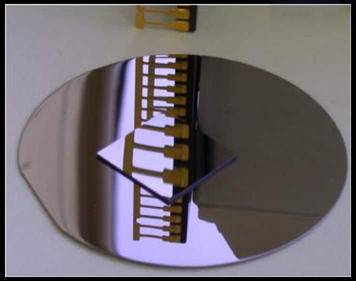


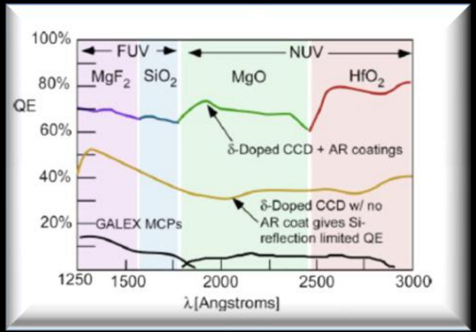


8” wafer, 30 CMOS imager









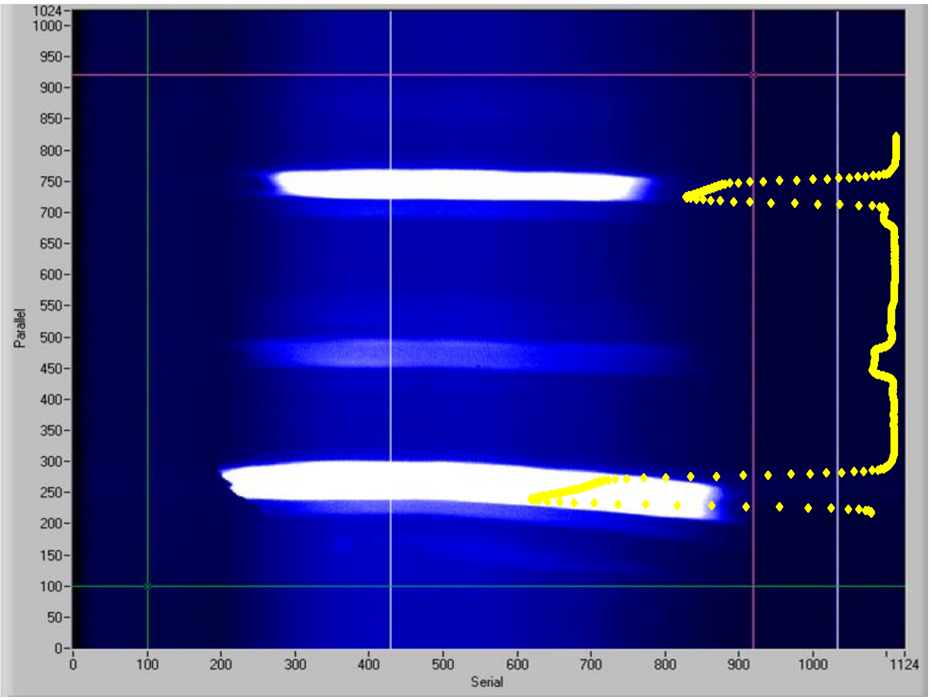
Detector Requirement:
Six cylindrically-curved ultraviolet photon counting detector array

Strategy:

Combine delta doping with avalanche gain CCDs and AR coatings, along with Curved FPA technology

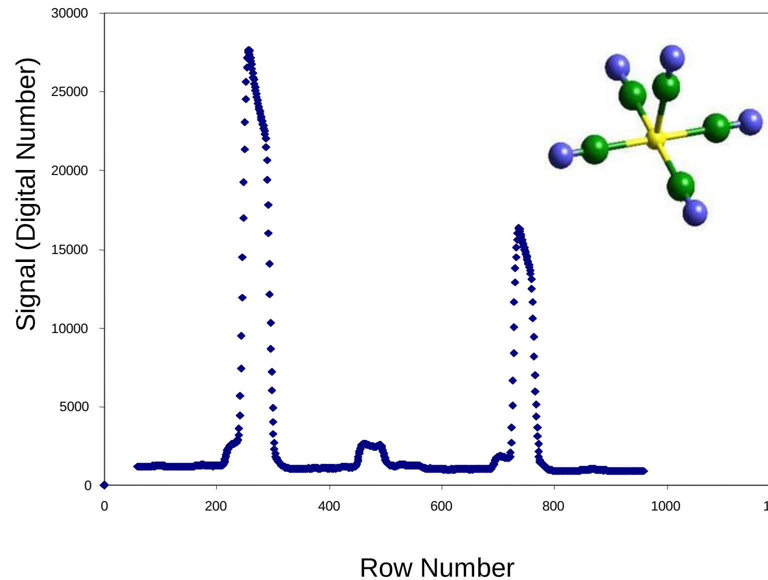
Low-energy Molecular Ion Detection

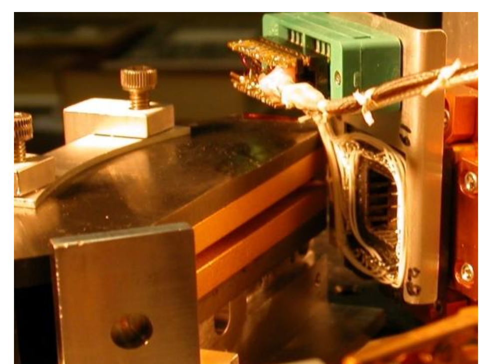
5000-10000dn shown – 60s exposure /80amu centered



Ion Image Data – Background Image Data = Spectrum Data

Iron Pentacarbonyl (196amu)

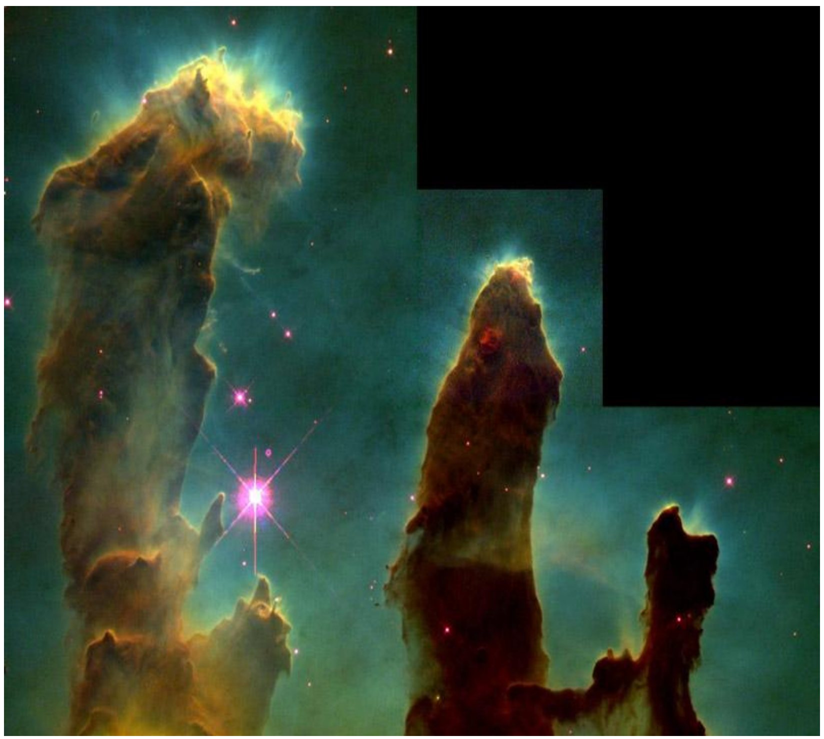




Silicon Imaging Arrays

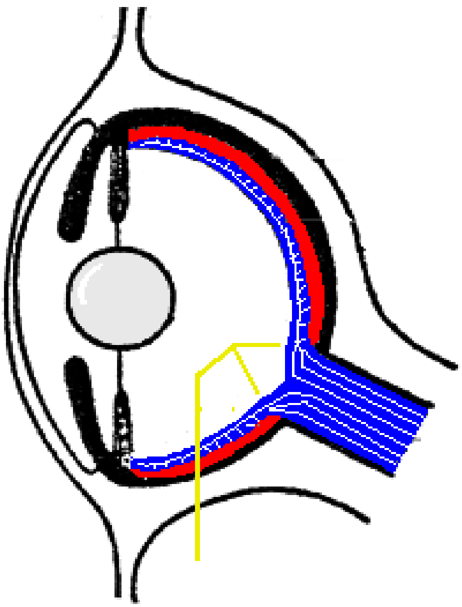
“CCDs were born in the Si-SiO_2 revolution and created their own revolution in widespread imaging device applications.”

-- George Smith, co-inventor of CCDs* and Nobel Laureate

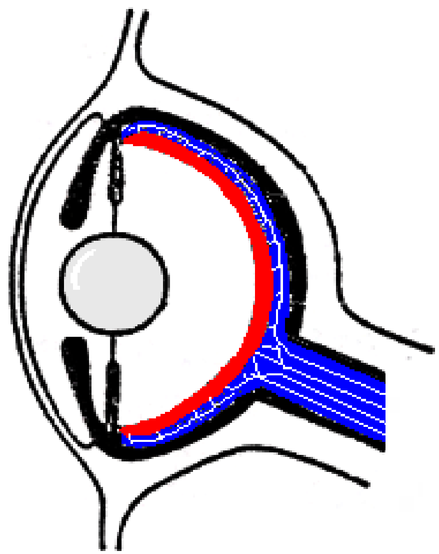


George E. Smith, “The invention and early history of the CCD,” Nuclear Instruments and Methods in Physics Research A, 607: 1-6, 2009.

A Brief History of Back Illumination



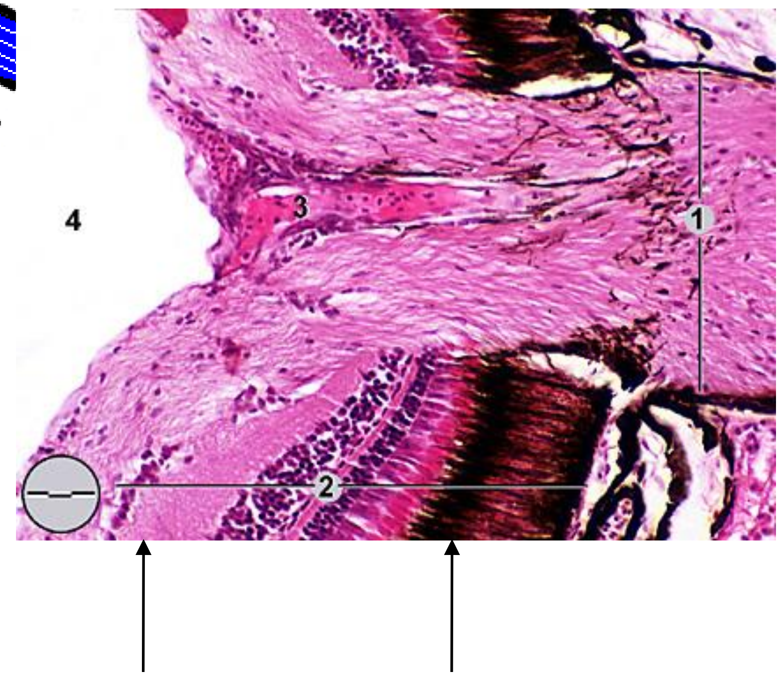
Vertebrate Eye



Cephalopod Eye

500 Million years of back-illumination

Cross section of human retina



Readout Detector

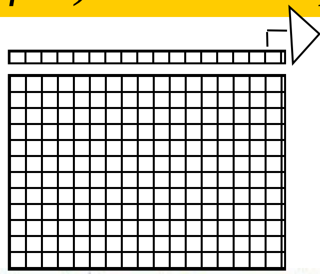
Vertebrates and mollusks developed the camera eye independently.

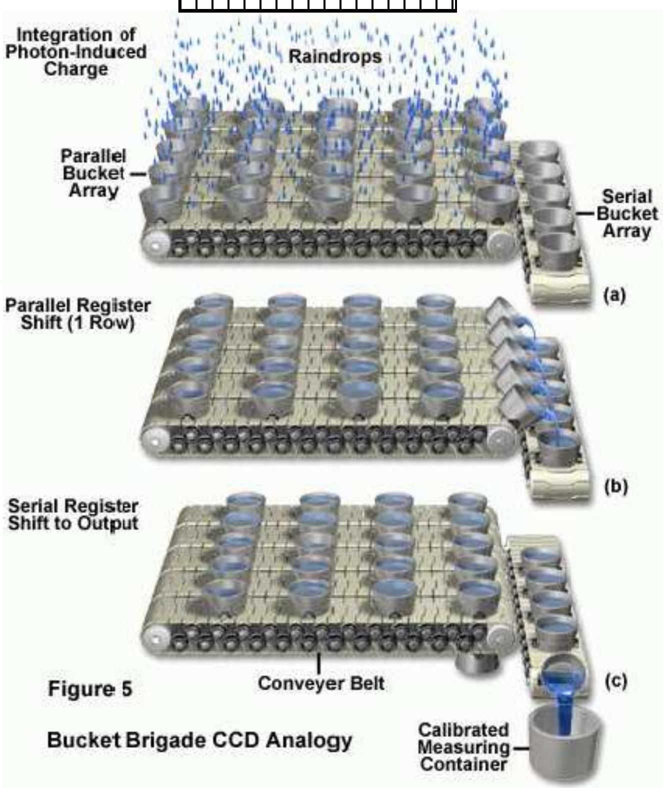
Vertebrate retina is less efficient than Mollusk retina.

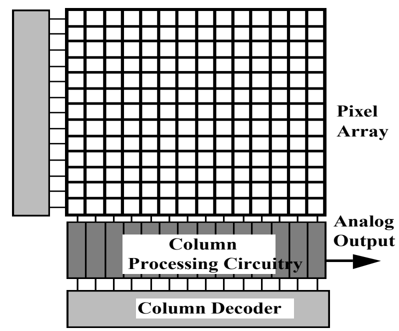
Silicon Imager Architectures: CCD vs. CMOS

Charge-coupled Device (CCD)
Serial readout device with charge transfer and one (or few) readout amplifiers.

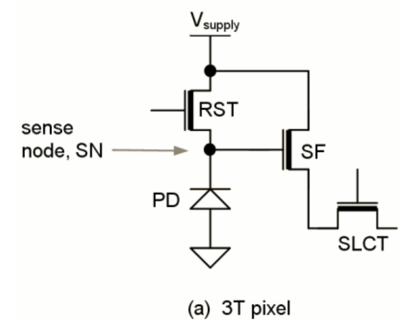
CMOS Imaging Array
Parallel readout with few charge transfers and one readout amplifier per pixel.

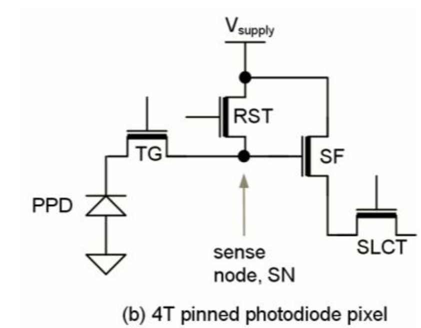






CMOS APS

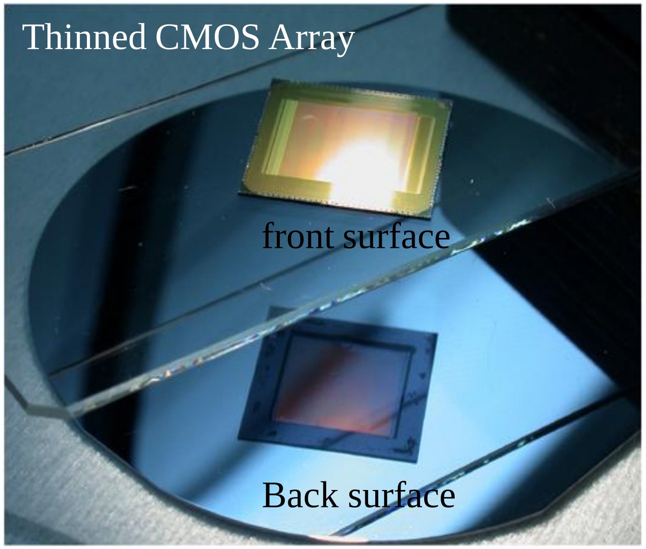


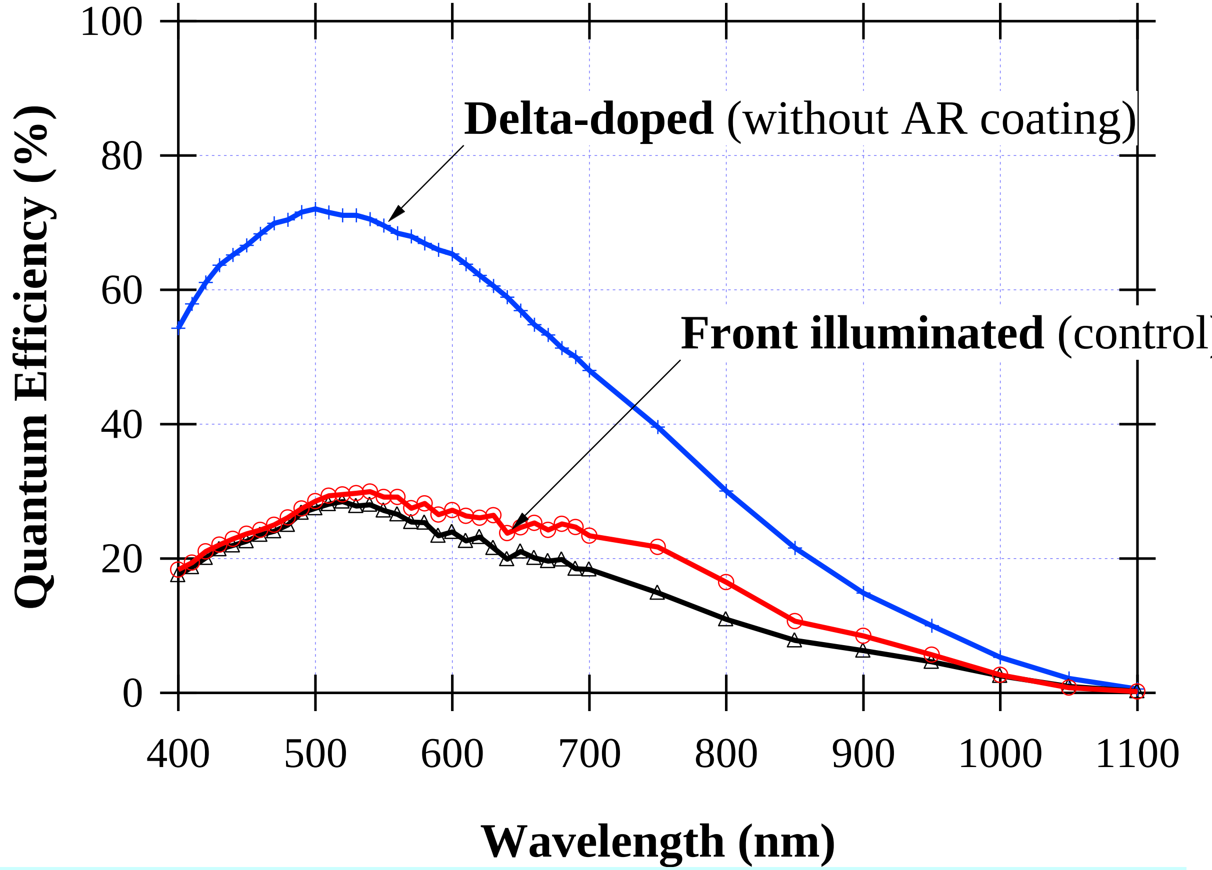


Scientific CMOS imagers are catching up with CCDs

– Jim Janesick, 2009

Back Illuminated CMOS Imager

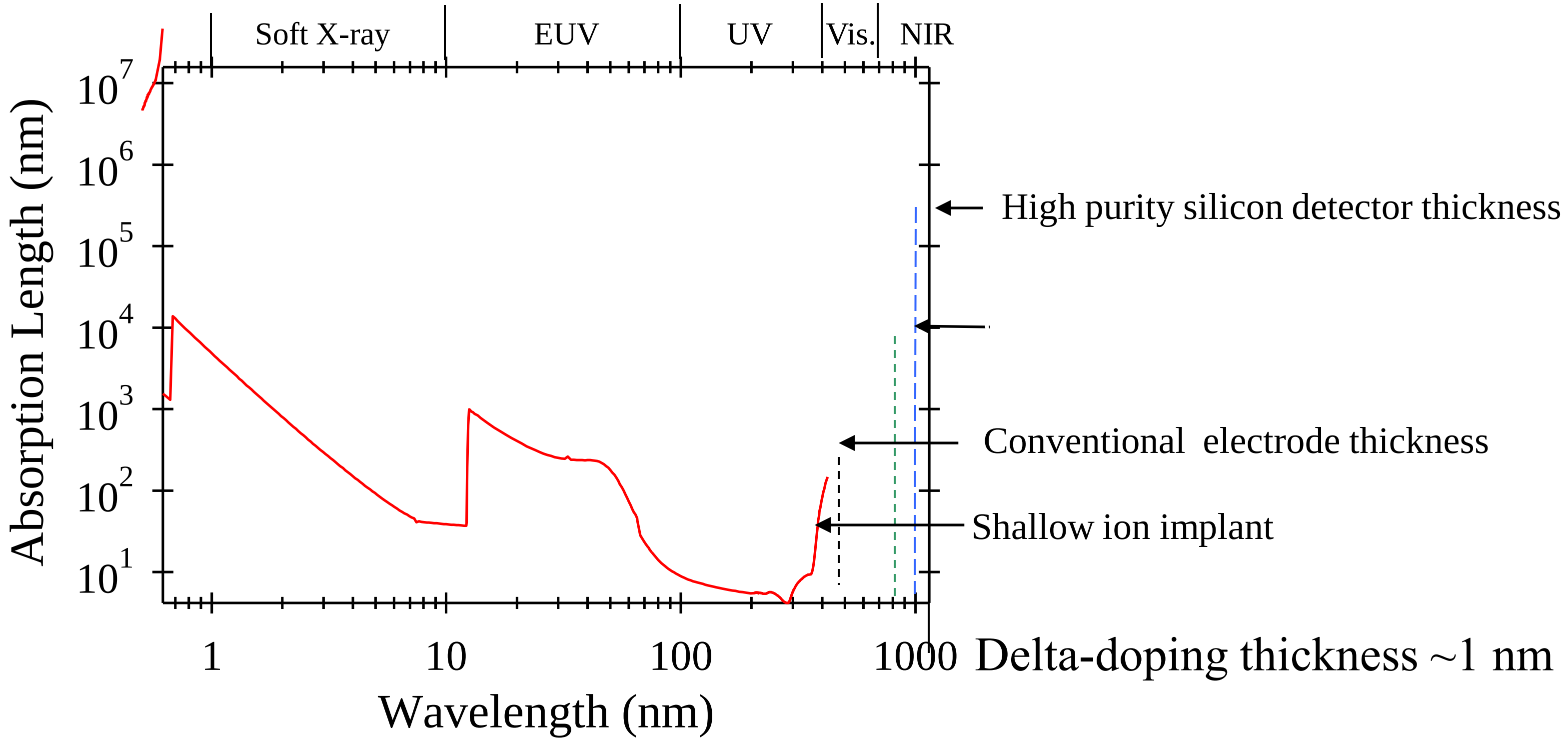




Thinning and back illumination can overcome limitations of silicon detectors:

- *Quantum efficiency*
- *Fill factor*
- *Spectral range (especially in the blue-UV range)*

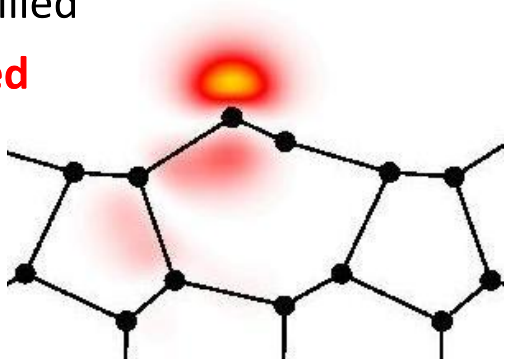
UV Photon Absorption in Silicon



Between Physics and Chemistry

Si-SiO_2 Surface States and Charging mechanisms

- Fast states / surface traps – ***QE hysteresis***
  - Acceptor-like – Neutral when empty, negative when filled
  - **Donor-like – Positive when empty, neutral when filled**
- Slow states
  - Surface charging
  - *e.g.*, oxygen ions generated in UV flood
- Fixed oxide charge
  - Radiation damage
  - e.g., positive charge from exposure to ionizing radiation (including UV light) flattens bands



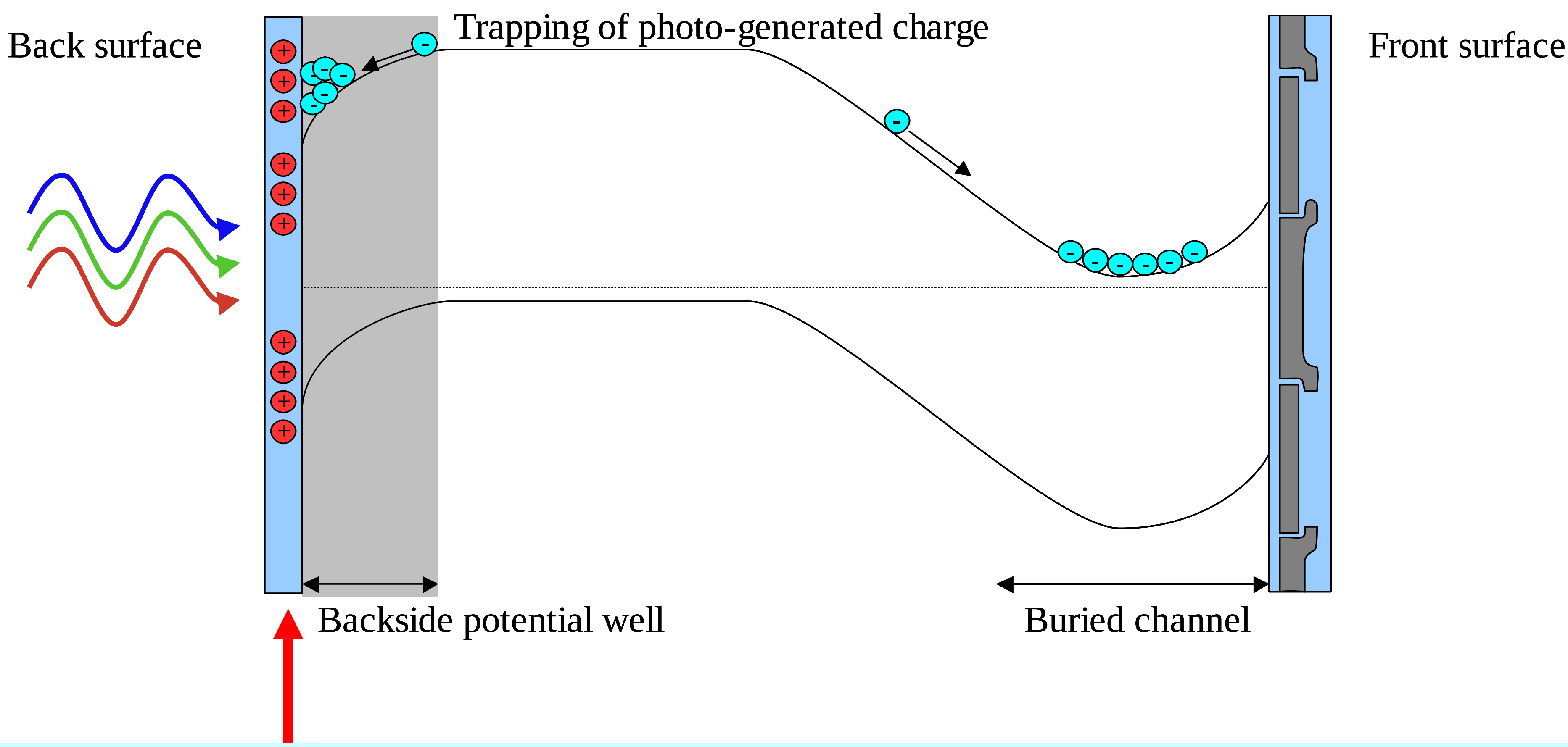
http://rohlfing.physik.uni-osnabrueck.de/

Surface Passivation

- Reduce surface state density
- Control surface potential

Back Illumination and QEH

In 1984, ***quantum efficiency hysteresis*** was discovered during thermal vacuum testing of Wide Field Camera (WFPC-1).



<u>Quantum efficiency hysteresis</u> – CCD response depends on prior illumination history

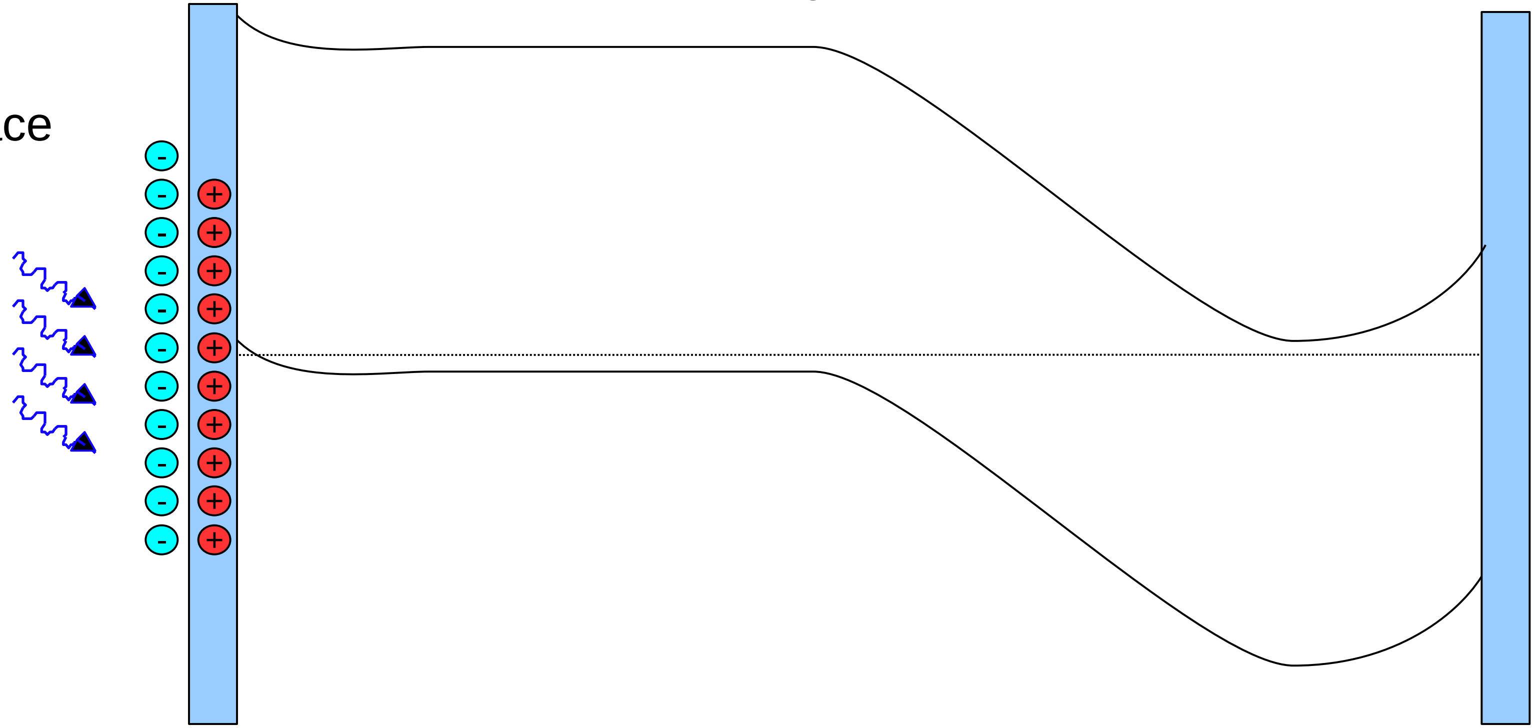
- Unacceptable – Hubble needs stability to 1% over 30 days…
- Passivation of surface defects is necessary to solve the problem.

UV Flood

JPL developed the “UV flood” to stabilize the response (Jim Janesick and Tom Elliott).

The Hubble Space Telescope optics were redesigned to allow a “UV flood” in space.

Back surface



During the mid- to late- 19800’s, WFPC-1 was plagued with stability problems

To help solve this problem, JPL formed a tiger team, which included MDL scientists.

Hubble launched in 1990 with WFPC-1 on board.

NASA installed WFPC-2 in 1993, with front-illuminated, lumogen-coated CCDs.

In 1992, JPL’s Microdevices Laboratory demonstrated the first delta-doped CCD.

Quantum Efficiency Hysteresis in WF/PC 1 & 2

WF/PC1 (1983-1992) Massive UV flood at 250 nm through light pipe

WF/PC2 (1983-1992) Flash gate, biased flash gate

WF/PC2 (1992-2009) Front illuminated Loral CCDs with lumogen

John T. Trauger, "Sensors for the Hubble Space Telescope Wide Field and Planetary Cameras (1 and 2)," in *CCDs in astronomy: Proceedings of the Conference, Tucson, AZ, Sept. 6-8, 1989 (A91-45976 19-33)*, San Francisco, CA, Astronomical Society of the Pacific, 1990, p. 217-230

The Evolution of CCD Surface Passivation on Hubble

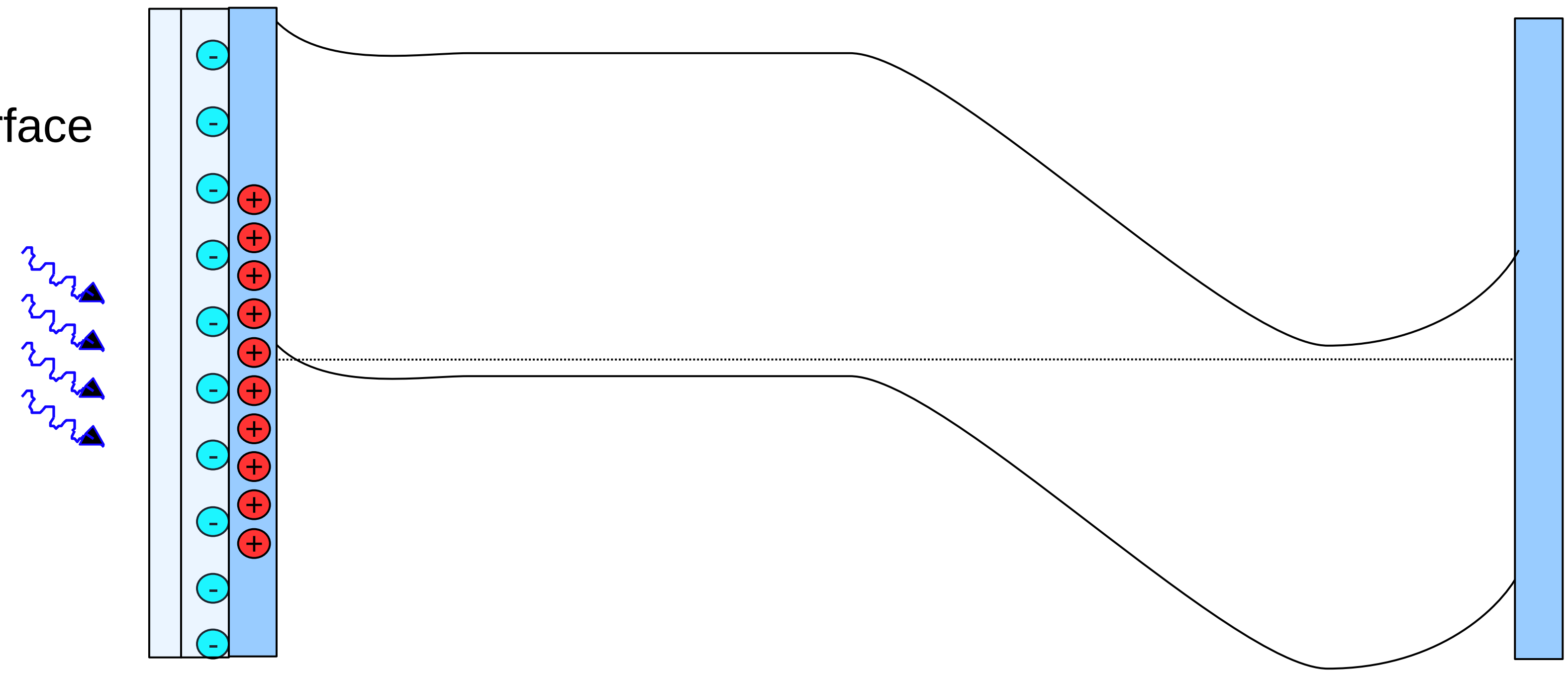
- *Unpassivated*
  - Doping by controlled thinning (*early WF/PC 1*)
- *Surface charging*
  - UV flood (*late WF/PC 1*)
  - Platinum flash gate (*WF/PC 2 – never flown*)
  - Chemisorption charging (*ACS HRC*)
- *Unthinned CCD*
  - Front-illuminated with phosphor (*WF/PC 2*)
- *Surface doping*
  - Ion implantation (*WFC3*)

Platinum Flash Gate

High work function metal induces surface charge

- *Vulnerable to environmental contaminants (notably hydrogen)*
- *Encapsulation required for stability*
- *Passivation layer doubles as antireflection coating*

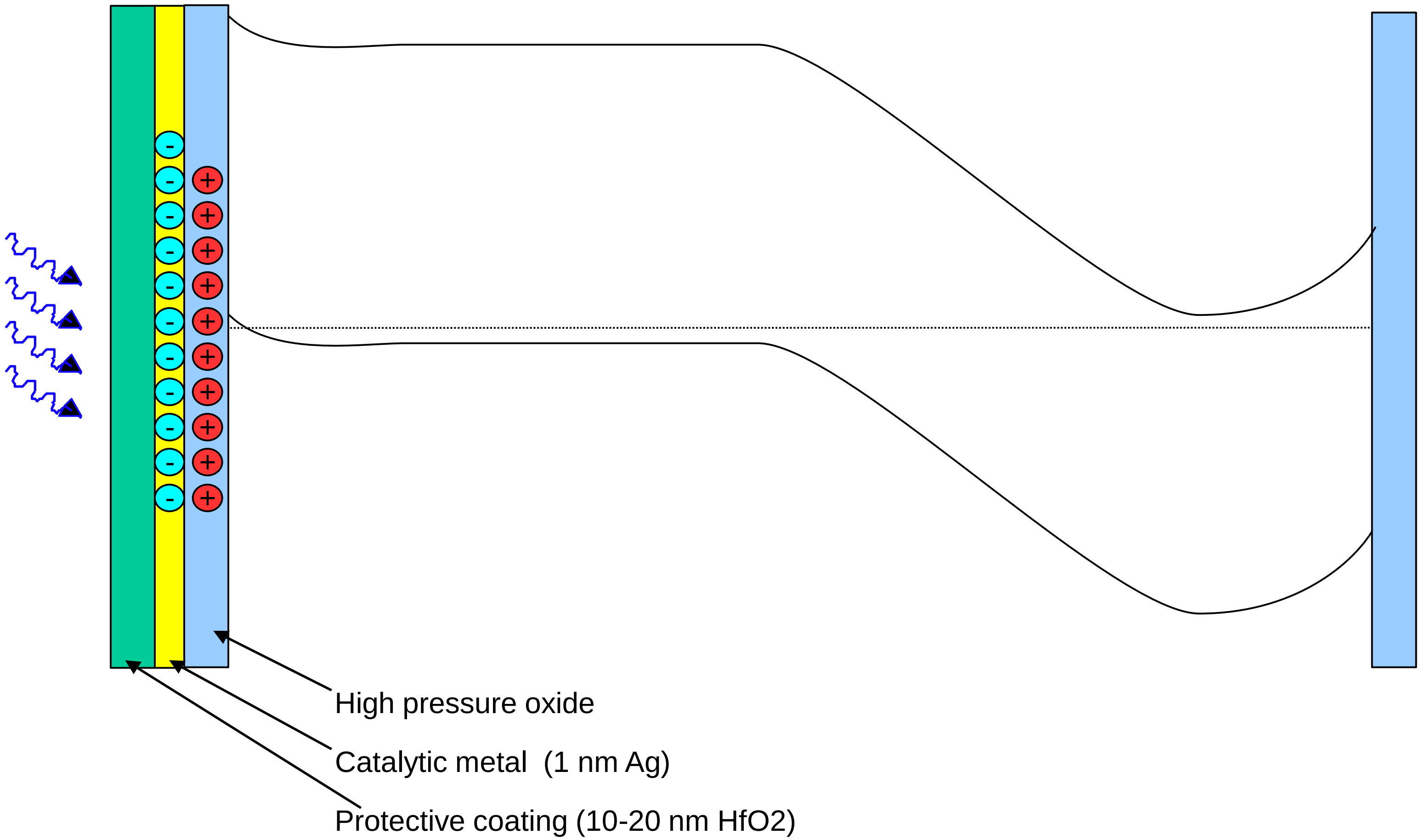
Back surface



Unlike MBE, surface charging methods provide poor control to environmental changes. Not suitable for high speed readout

Chemisorption Charging

Metal catalyst binds O_2^- ions on the surface. Encapsulation / AR coating stabilizes the charge.



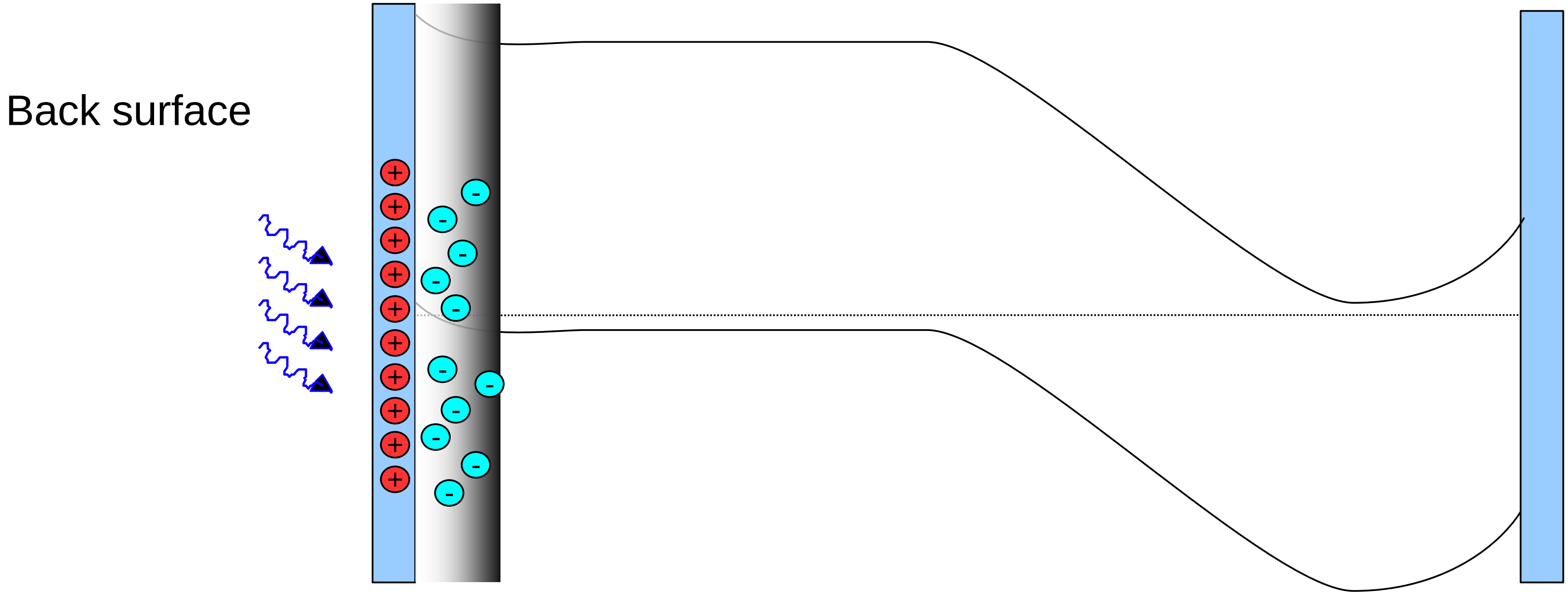
"Chemisorption charging can be a permanent charging process if there are no other processes which either chemically react to remove the oxygen or contribute significant positive charge to produce a net positive charge on the surface."

—*Michael Lesser*, "CCD backside coatings optimized for 200-300 nm observations," *SPIE Proc.* ***4139****: 8-15, 2000.*

Ion Implantation and Laser Anneal

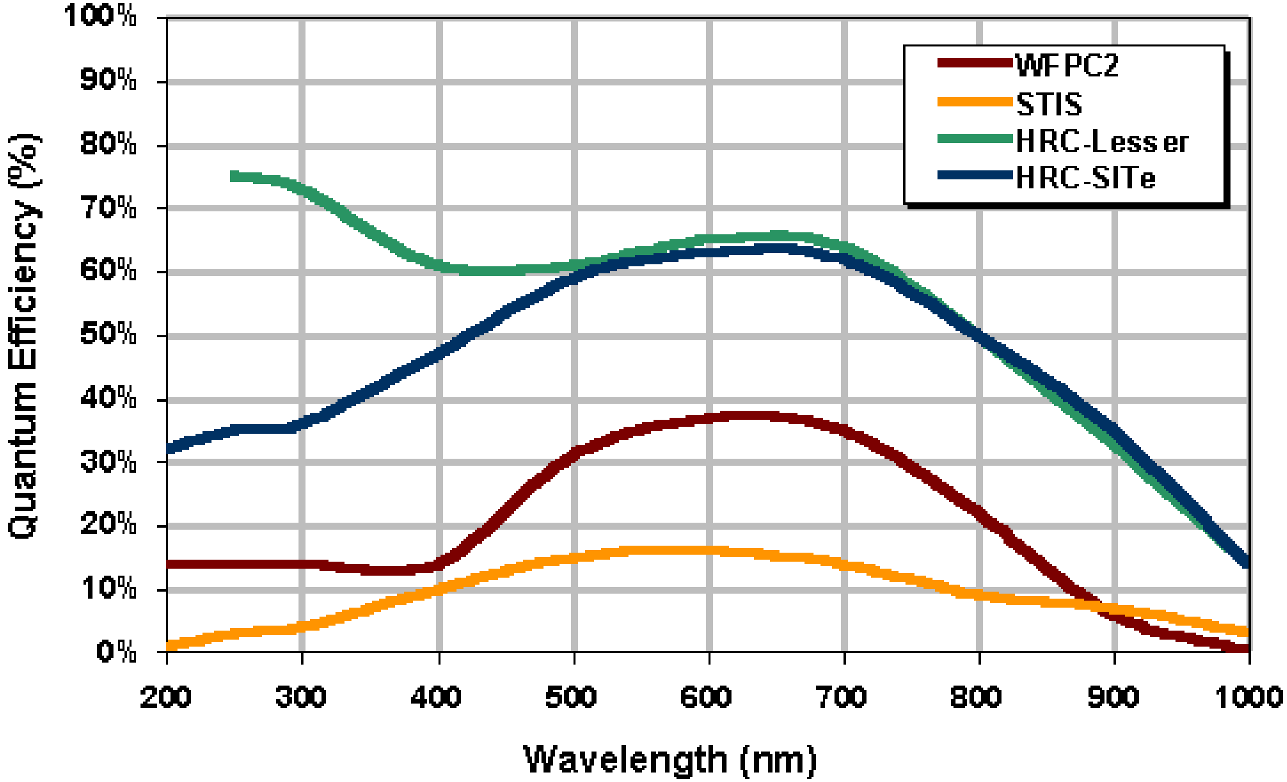
Doping the surface introduces fixed charge into the silicon lattice

- *Dopant profiles are generally broad – thinner is better, but problems with traps*
- *Damaged lattice creates traps & dark current*
- *"Brick wall" pattern in flat field images from laser anneal process*



Hubble's Wide Field Camera 3 uses ion-implanted CCDs.
Quantum efficiency hysteresis is still a problem.

The Evolution of Detector Efficiency on Hubble

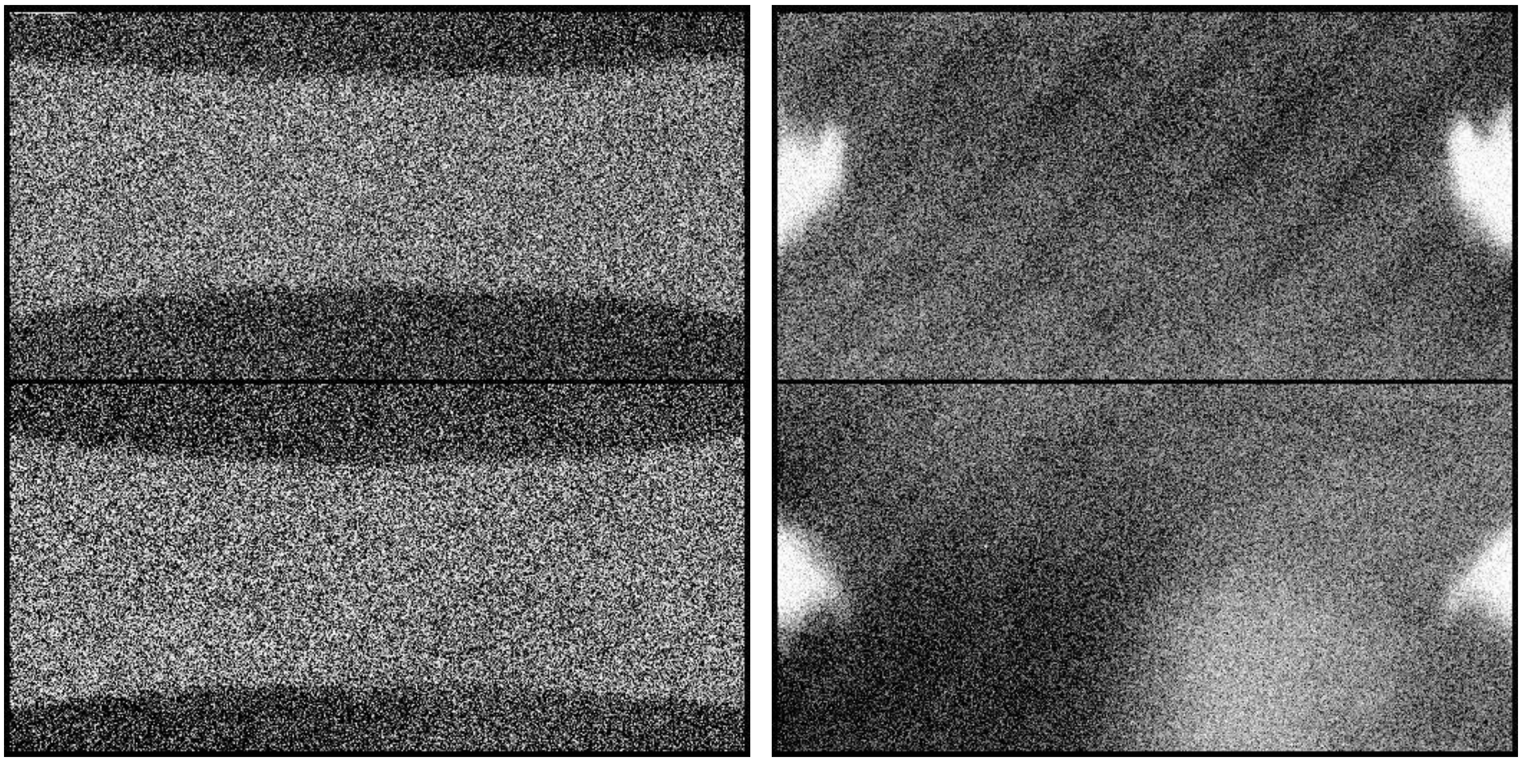


Mark Clampin, “UV-Optical CCDs”, *Proceedings of the Space Astrophysics Detectors and Detector Technologies Conference*, STScI, Baltimore, June 26-29, 2000.

“The WFPC2 CCDs are ***thick, front-side illuminated devices*** made by Loral Aerospace. They support multi-pinned phase (MPP) operation which eliminates ***quantum efficiency hysteresis***. They have a Lumogen phosphor coating to give UV sensitivity.”

http://www.stsci.edu/instruments/wfpc2/Wfpc2_hand4/ch1_introduction2.html

Quantum Efficiency Hysteresis in WFC3



Wide Field Camera 3

- Instabilities on the order of a few percent
- Mitigated by on-orbit flooding with visible light to fill surface traps

Collins *et al.* SPIE proceedings 7439A-10, San Diego, CA, August 2009.

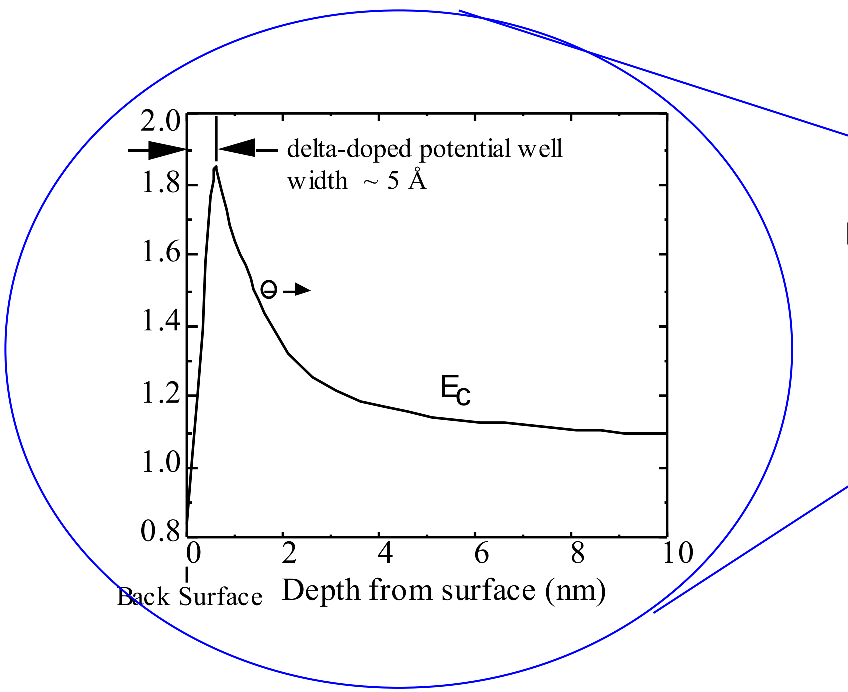
Delta doping

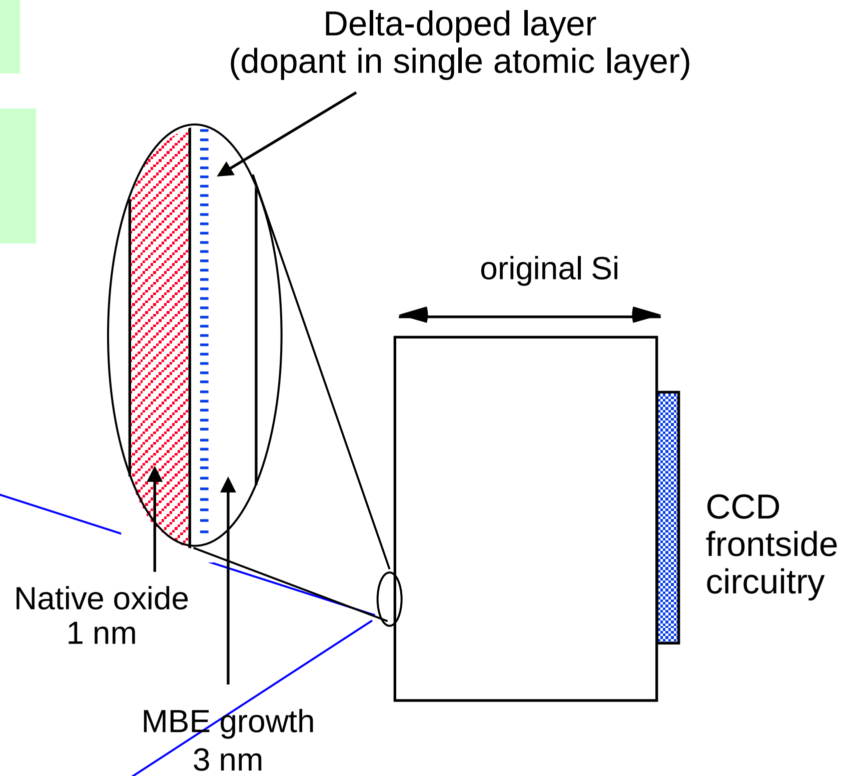
Bandstructure engineering for optimum performance

Atomic layer control over device structure

Low temperature process, compatible with VLSI, fully fabricated devices (CCDs, CMOS, PIN arrays)

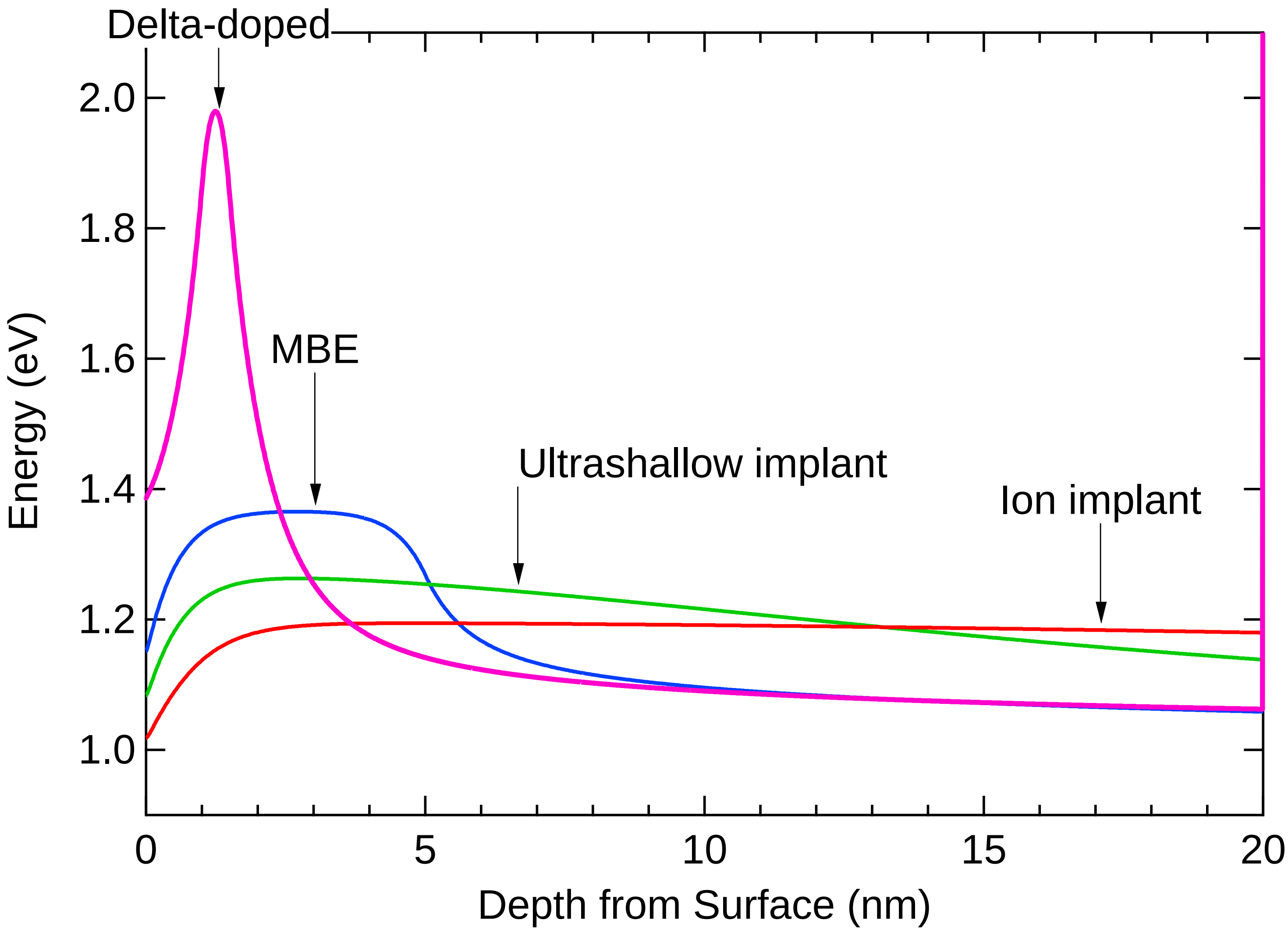
Hoenk et al., *Applied Physics Letters*, 61: 1084 (1992)





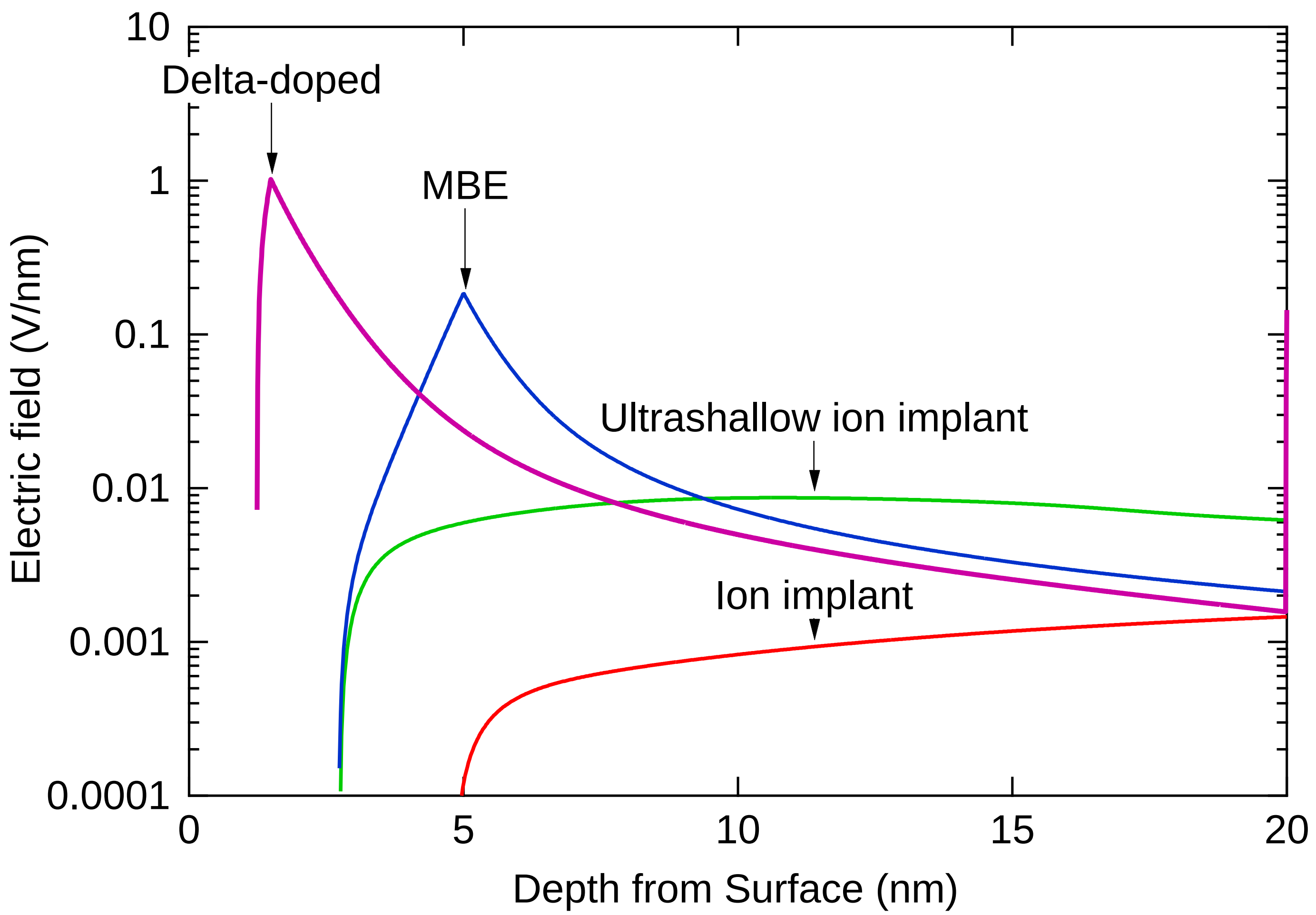
Fully-processed devices are modified using Molecular Beam Epitaxy (MBE)

Delta-doped Imaging Detectors

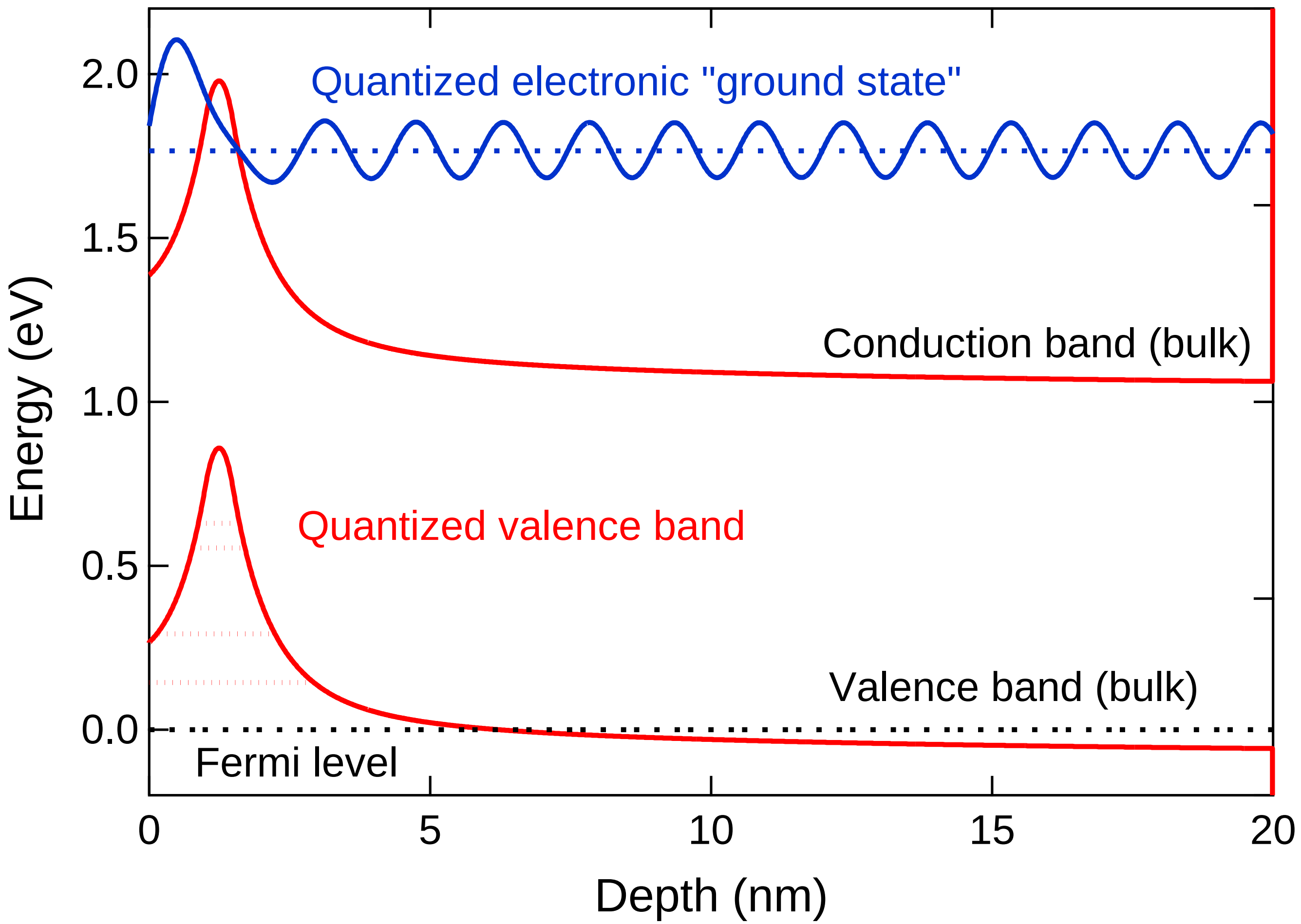


Delta doping produces ideal surface passivation in back-illuminated CCDs

Electric Field



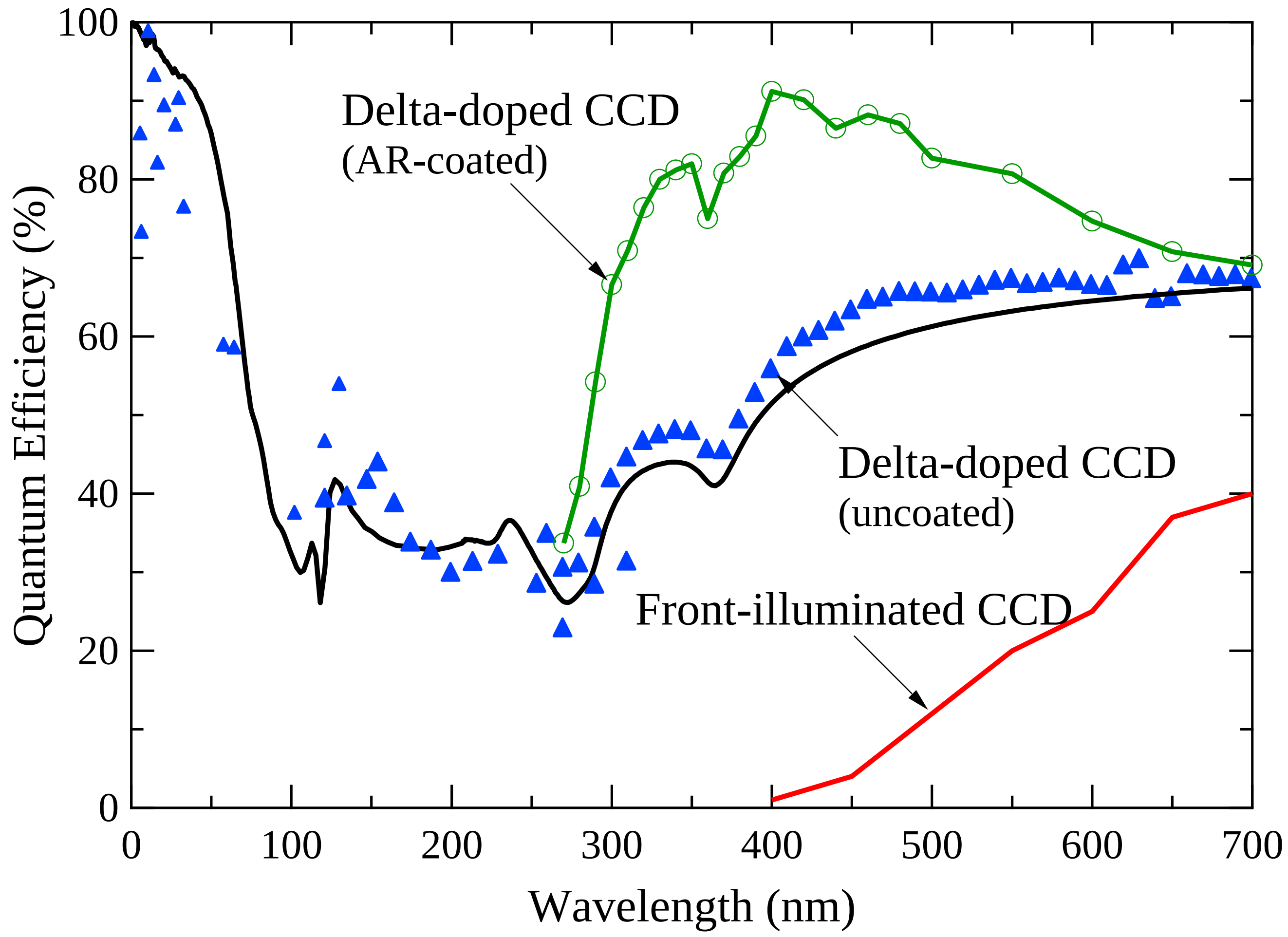
Quantized States in Delta-doped Detectors



Quantum Confinement in Delta-doped Surface

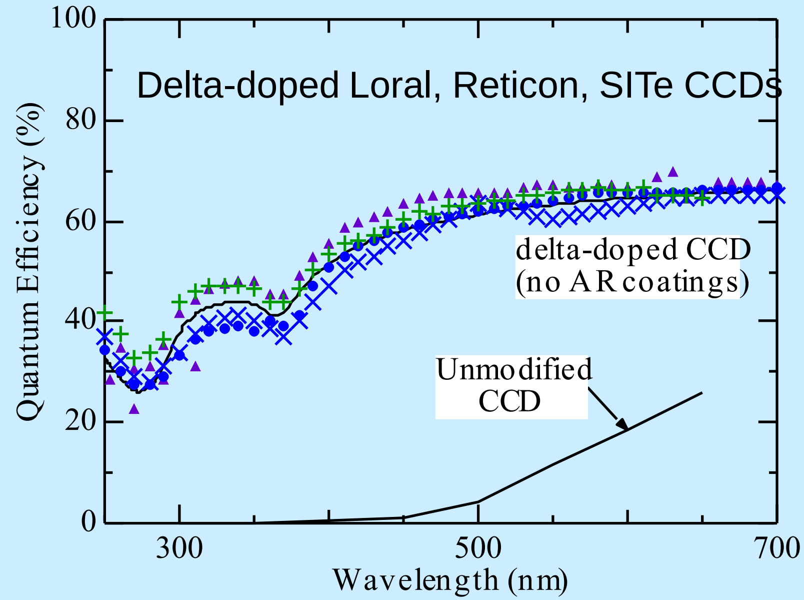
- Quantized states in delta-doped surface
  - Holes form 2DEG with quantized subbands
    - High conductivity surface
    - Quantum-confinement enhanced potential and fields
      - Strongly peaked potential at delta-layer
  - Electrons
    - Width of potential well ~1.5nm
    - Electrons isolated from surface by high fields
    - Quantized subbands with few quasi-bound states
- Passivation by Delta-doping
  - MBE creates abrupt interfaces, electric field ~10^7 V/cm
  - Buried electronic "surface" confines electrons to bulk
  - Surface dark current suppressed by quantum confinement

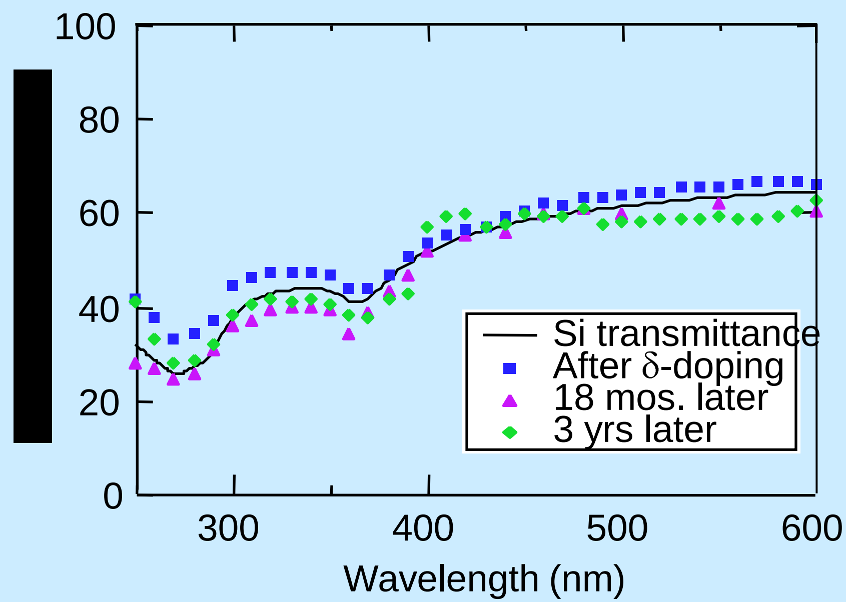
Quantum Efficiency of Delta-doped CCDs



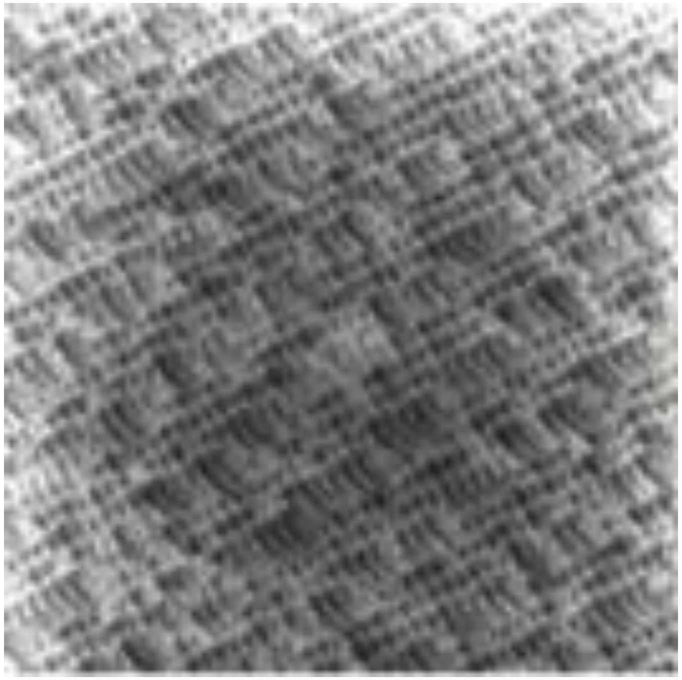
Delta-doped CCD Stability and Reproducibility

- Near 100% internal QE is measured years after the MBE modification of the CCDs
- Reproducible and compatible with different formats and CCD manufacturing processes
- No hysteresis is observed in delta-doped CCDs
- Stable response over several years
- Precision photometric stability measured by the Kepler group





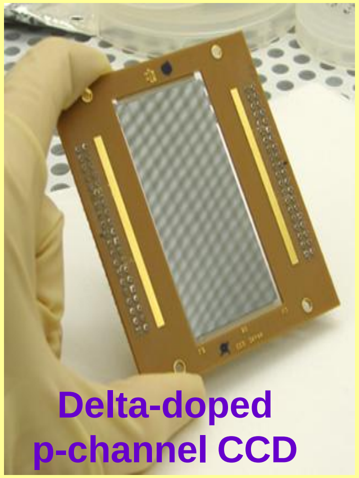
Uniformity



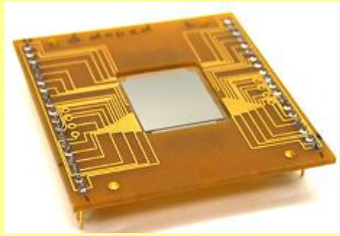
E2v CCD ion implant/laser anneal

Delta doped CCD

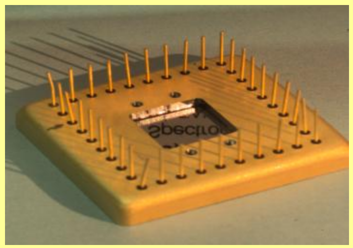
Delta doped CCDs and CMOS Arrays



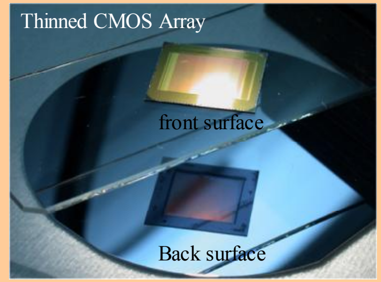
Delta-doped p-channel CCD LBNL 2k x 4k

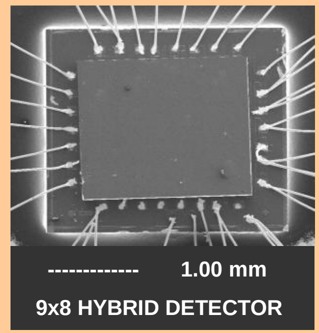


Delta-doped p-channel CCD, LBNL 1k x 1k

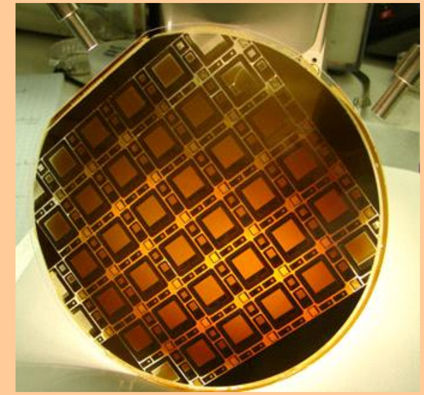


Delta-doped n-channel CCD with structurally supported membrane

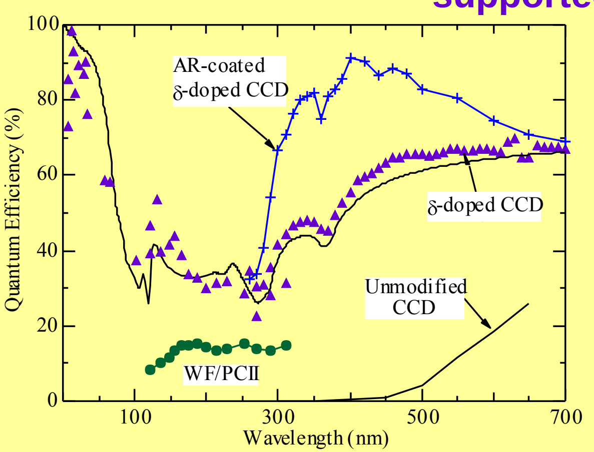




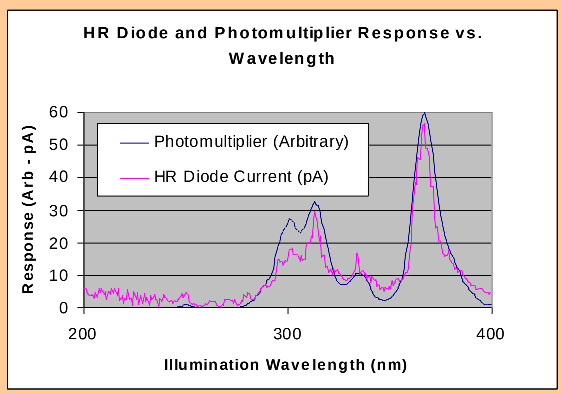
9x8 δ-doped diode array bump-bonded to APS readout

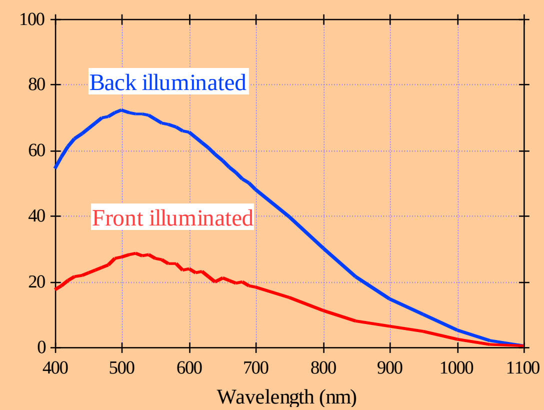


A thinned (6-µm thick) 6" wafer containing 30 CMOS devices supported by a quartz wafer.



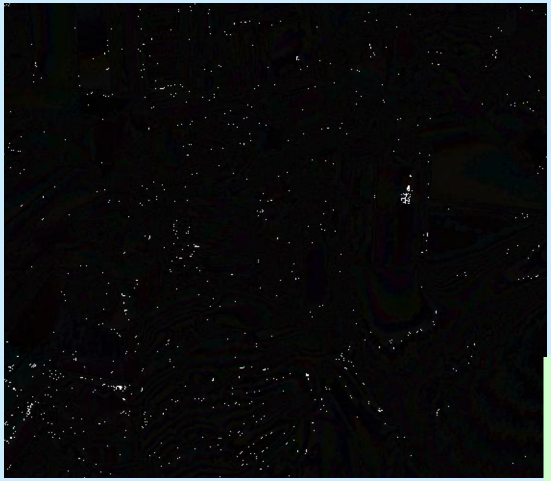
QE of delta doped CCDs showing 100% internal QE





QE of a 1kx1k delta doped CMOS-APS array

JPL Facilities for End-to-end Post-Fabrication Process



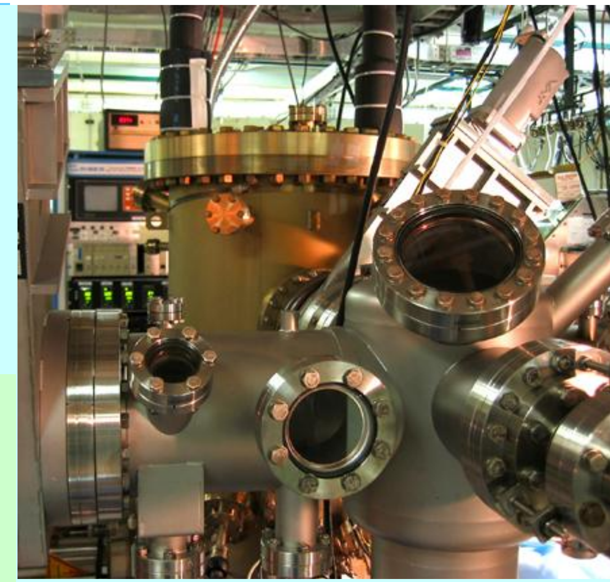
Fully-processed arrays fabricated at outside foundries are obtained.

Bonding: Thermocompression bonding or post MBE bonding is used for achieving flat, robust membranes

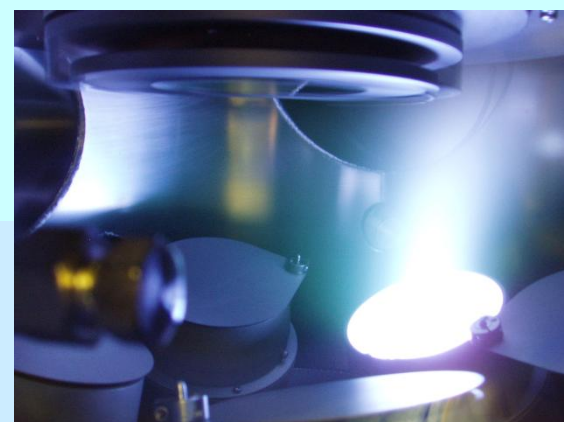
Thinning: Excellent quality thinned CMOS and CCDs have been demonstrated.

AR Coatings and Filters Modeling capability and PECVD and sputtering system for deposition of filters and AR coatings

Chemical Mechanical Polishing (CMP)

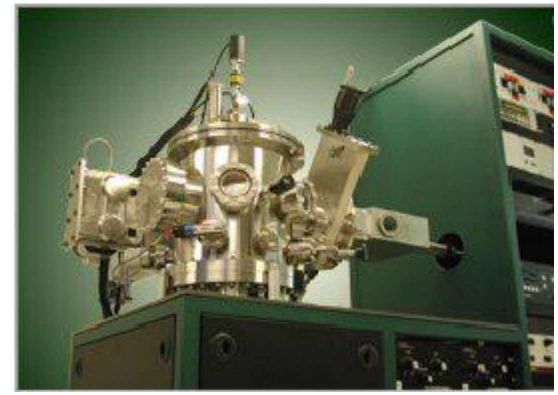


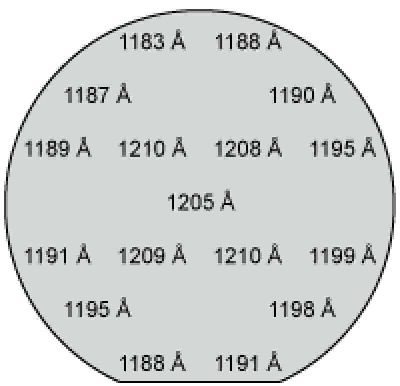
Delta doping MBE is used to grow a delta-doped layer of Si on the backside of fully processed silicon arrays .Response of CCD Si imager is enhanced to the theoretical limit.

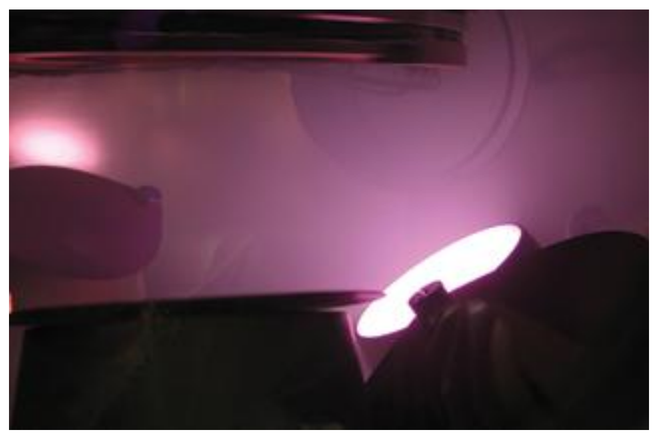


Versatile approach makes it possible to work with various imaging arrays and technologies

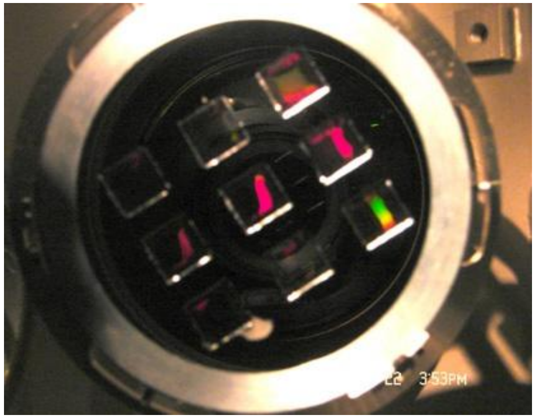
AR Coating Systems



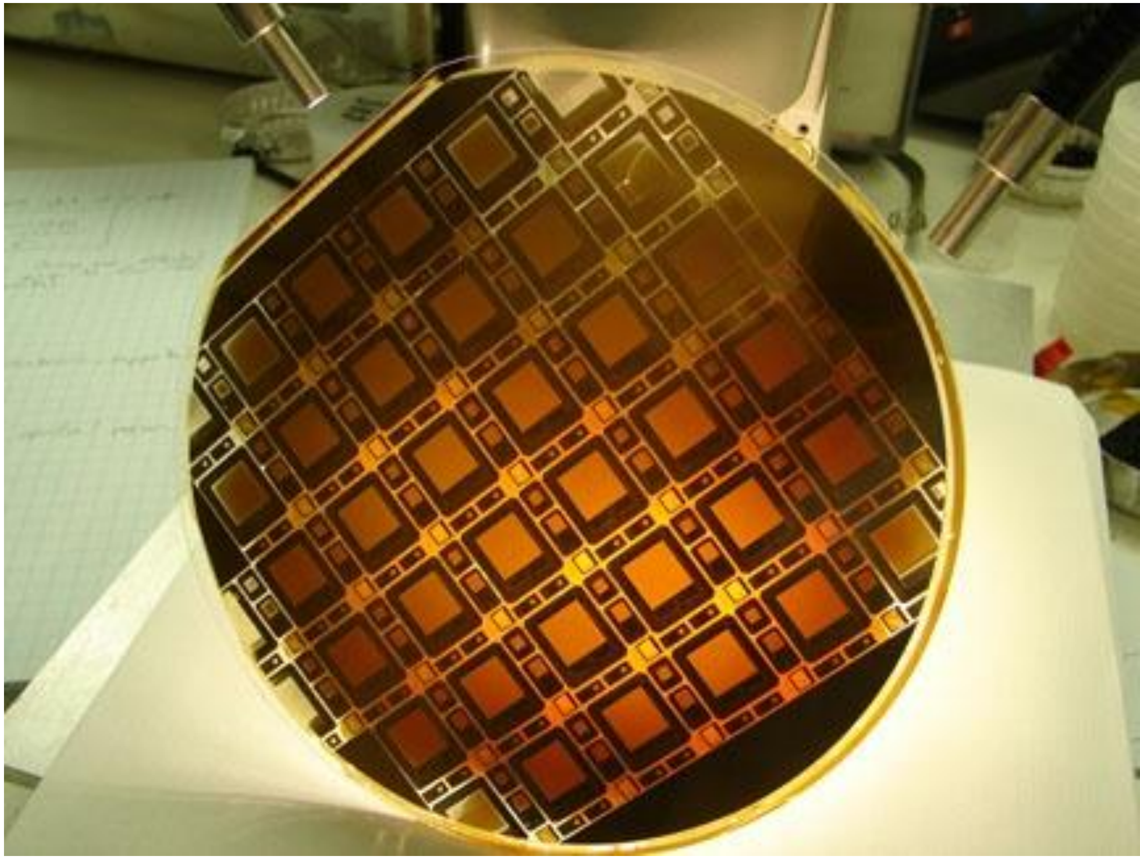




Full Wafer Processing with 8” MBE

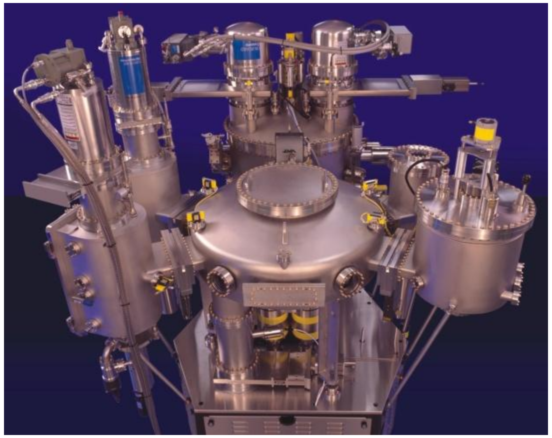


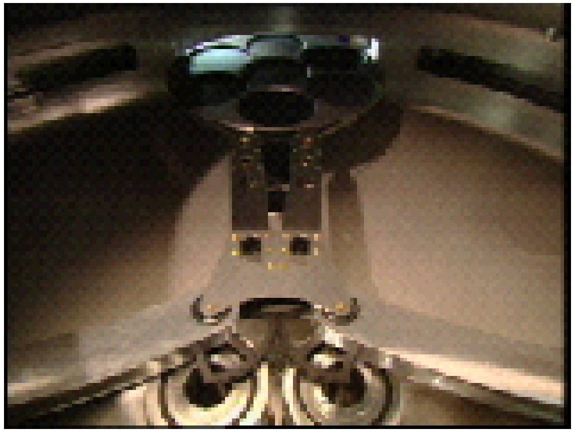
Raft of 9 thinned CMOS Imagers Mounted in 3” MBE

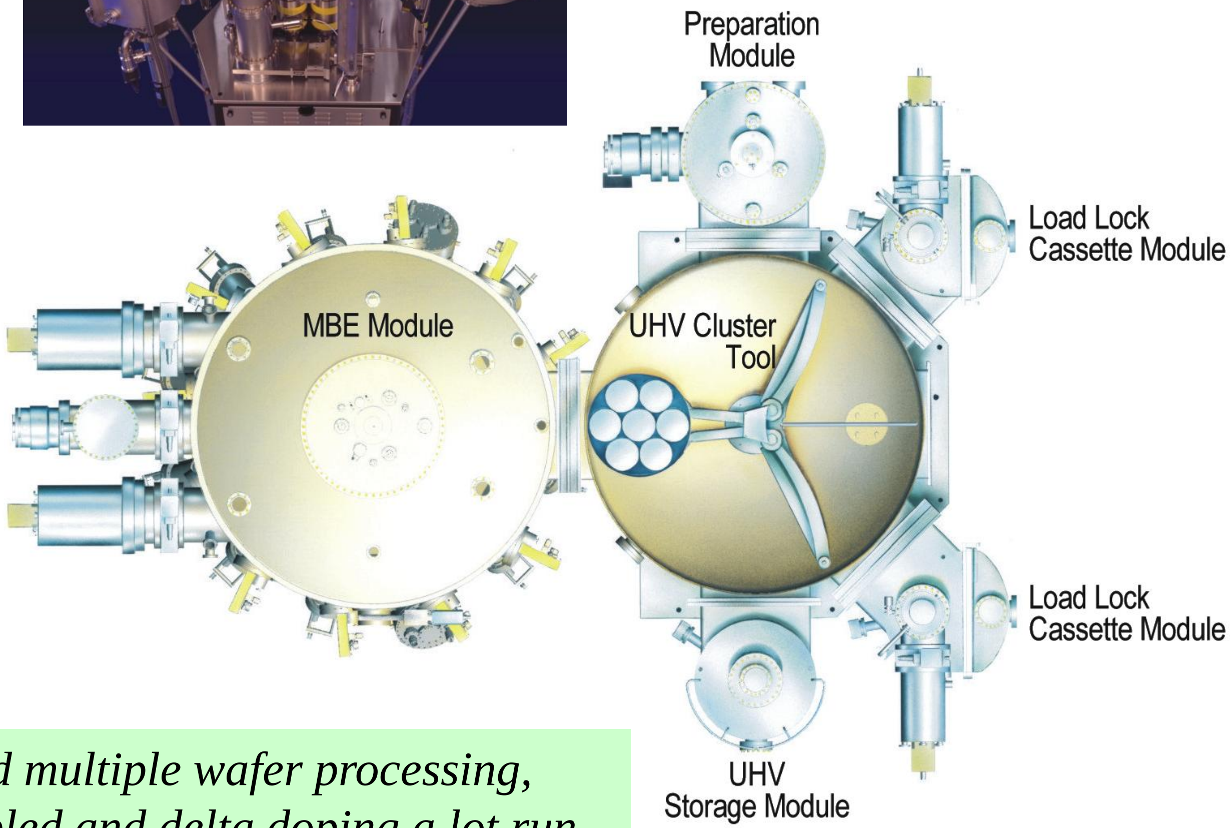


Thinned 6” wafer with 32 CMOS Imagers

8-inch Wafer Silicon MBE

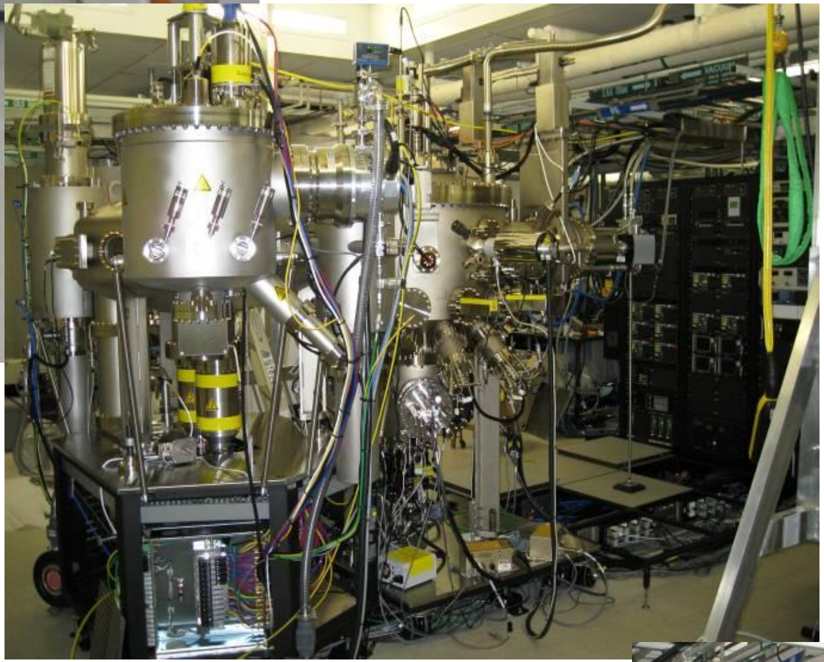






With large size wafer capacity and multiple wafer processing, high throughput processes is enabled and delta doping a lot run can be achieved in short period of time

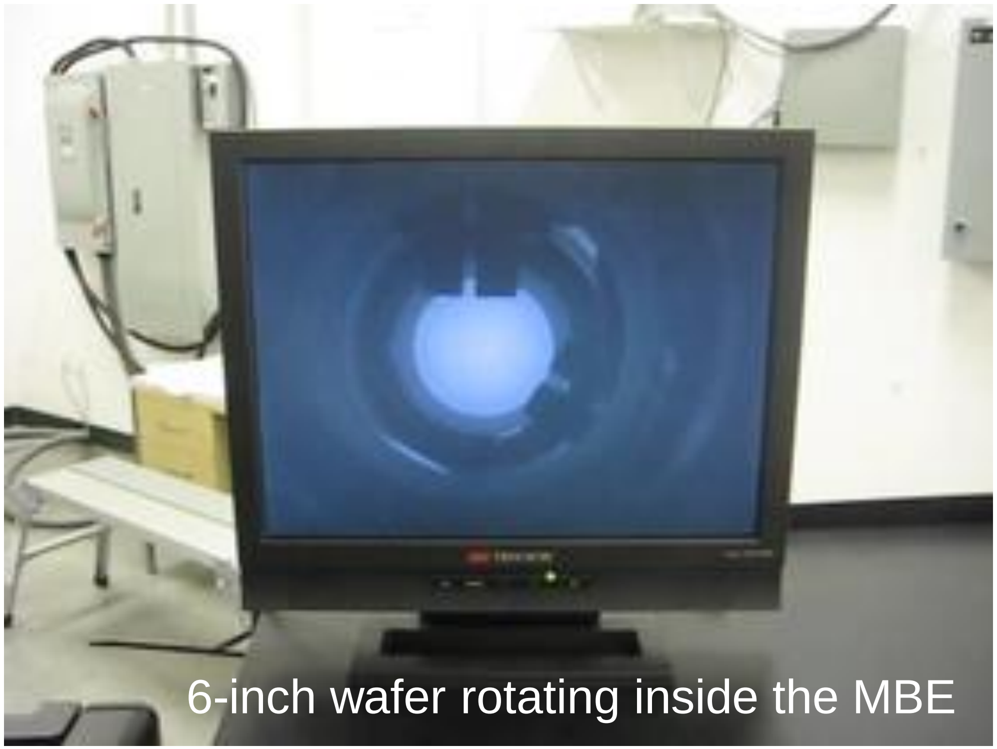
MBE Installation in JPL's Microdevices Laboratory

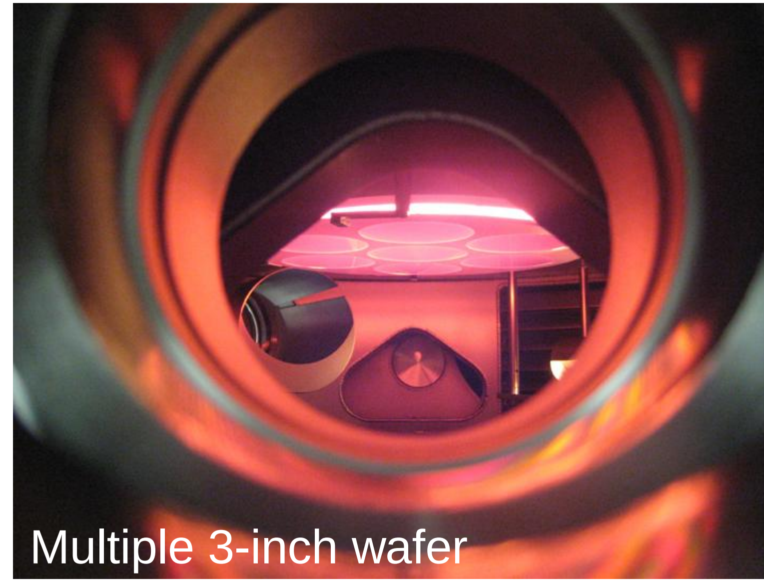


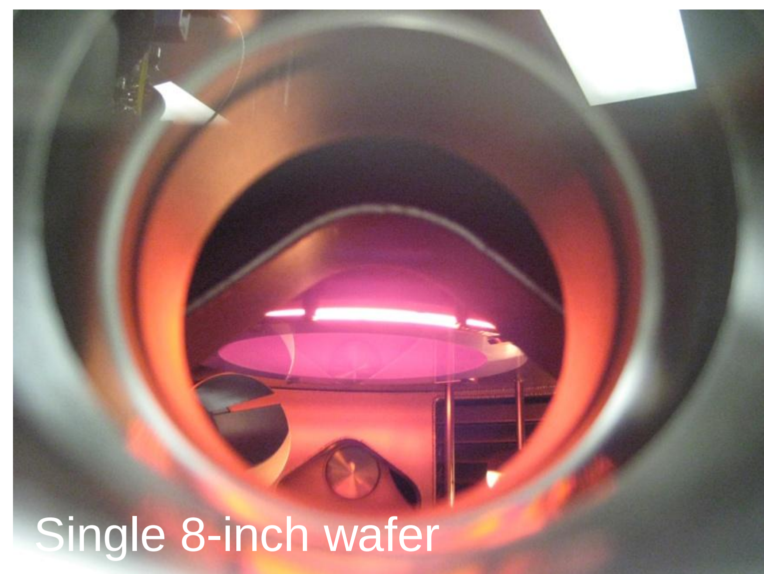
MBE after Initial Hook-up at JPL

MBE under bake

Photographs of wafers heating inside MBE


6-inch wafer rotating inside the MBE


Multiple 3-inch wafer


Single 8-inch wafer

Conclusions

- **Delta-doped single photon detectors for UV astronomy**

  ***ISTOS Mission**: Chris Martin, David Shimonovich, Patrick Morrissey, Shouleh Nikzad*

- **Silicon surface physics and passivation**

  Requires atomic scale control of dopant profile

- **Delta-doping**

  Nanostructured surface by MBE

  Strong electric field (107 V/cm) and quantum exclusion

  Proven performance

- **Future**

  Delta-doped L3CCDs for UV photon counting

  Delta-doping at wafer level for high yield and throughput