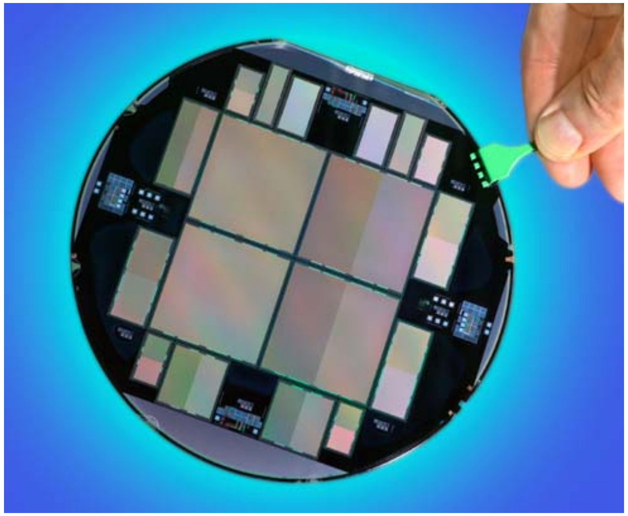
Fully Depleted Thick CCDs

Steve Holland
Lawrence Berkeley National Laboratory
April 3rd, 2006
International Symposium on the Development of Detectors for
Particle, Astro-Particle and Synchrotron Radiation Experiments



12.3 Mpixel (10.5 μm pixel), high voltage
compatible CCDs developed at LBNL

Outline

- Background
  - — How silicon detector R&D for high-energy physics led to the development of back illuminated, fully depleted CCDs
- Progress to date with fully depleted CCDs
  - — Quantum Efficiency
  - — Fringing
- Work in progress
  - — Development of CCDs for the SuperNova Acceleration Probe (SNAP)
    - Small pixel (10.5 µm)
    - Operation at high substrate bias voltages
      - — Improved spatial resolution
    - Radiation testing (not covered here)
  - — Direct x-ray detection with SNAP CCDs
  - — CCD fabrication technology development
- Summary

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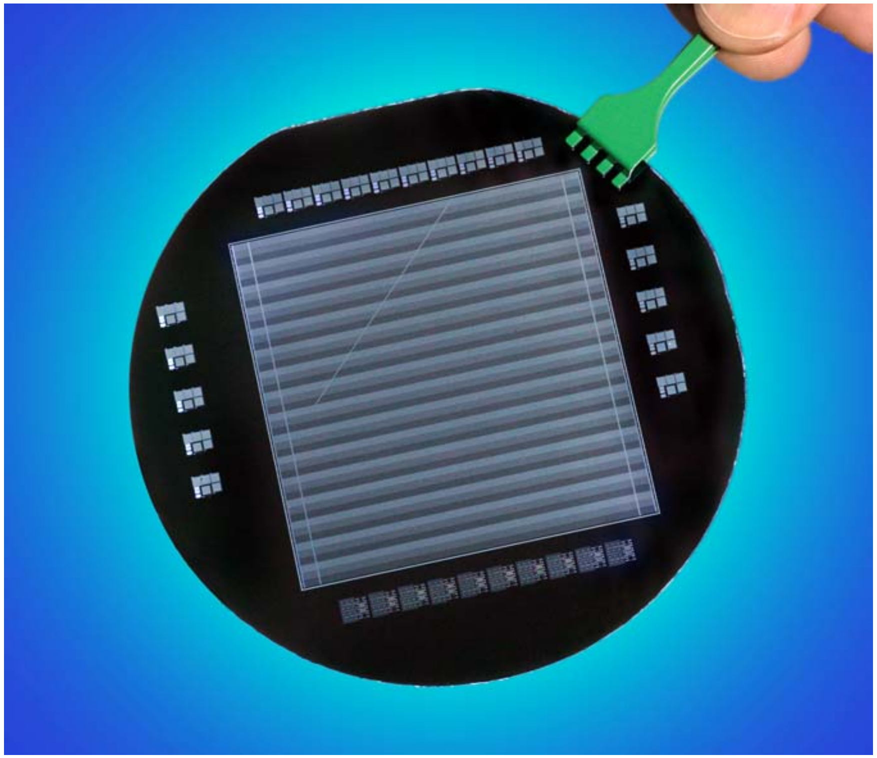
Background

- Silicon detector R&D at Lawrence Berkeley National Laboratory in the late 1980's and early 1990's led to the development of detector processing technologies for p-i-n diode strip and pixel detectors that yielded the following:
  - — Low dark current (reverse biased p-n junction leakage current)
  - — Compatible with high-temperature processing (900-1000C)
  - — Ability to integrate MOS transistor readout electronics on high-resistivity silicon

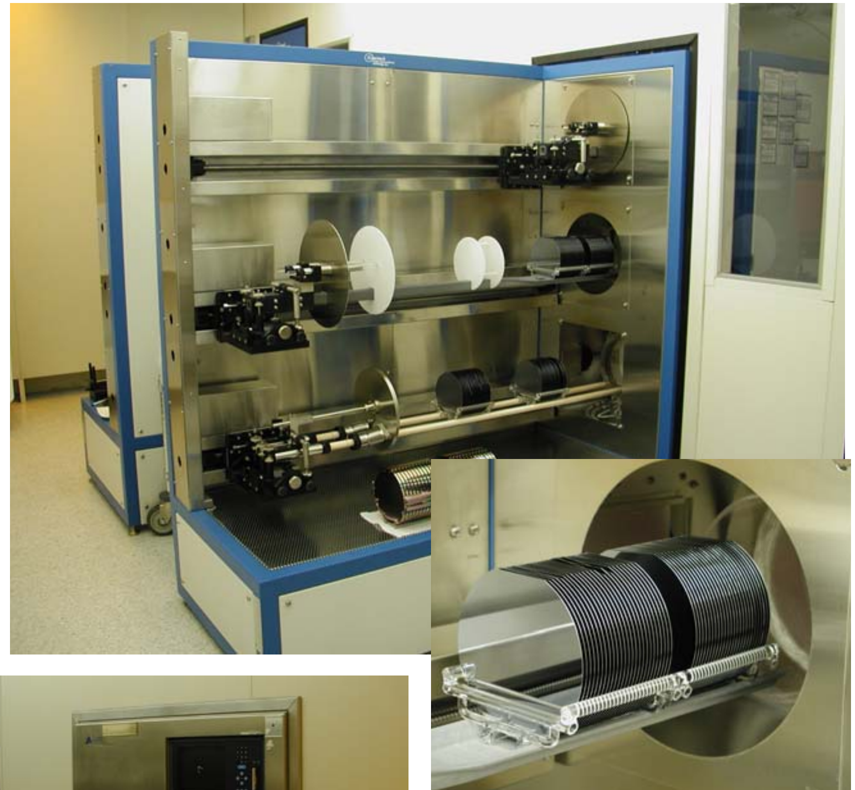


Prototype silicon strip detector for ATLAS fabricated on a 100 mm, high-resistivity silicon wafer

Background (cont')

- Technology development at LBNL MicroSystems Laboratory
  - — Class 10 semiconductor fabrication facility
  - — 150 mm upgrade nearly complete

Projection aligner lithography system

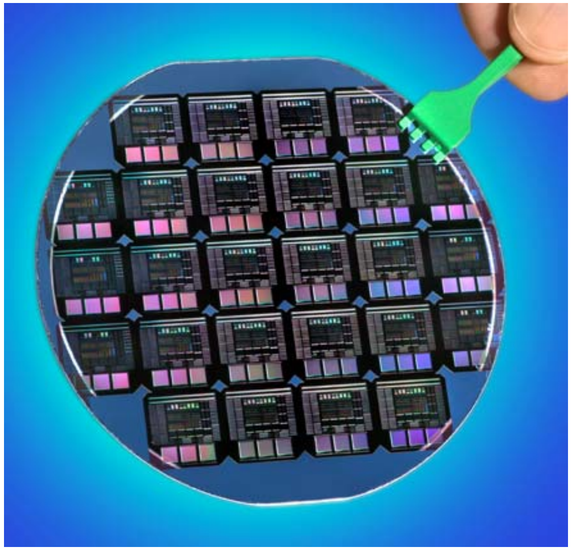


Dielectric plasma etcher

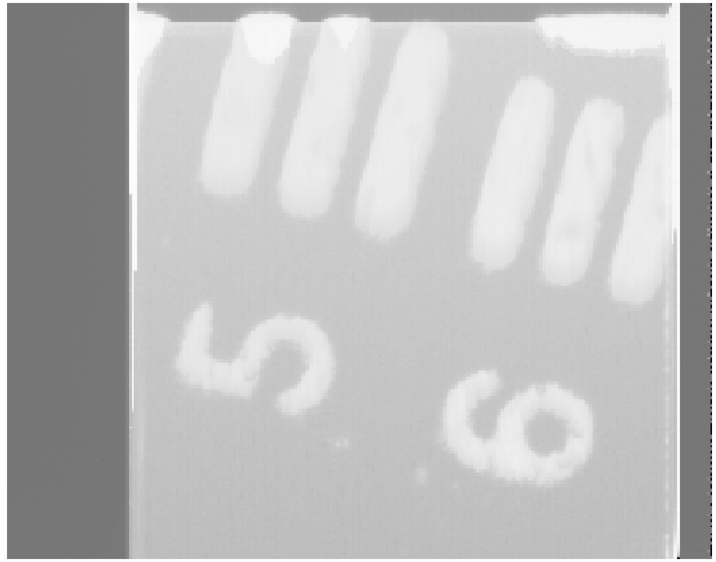
Atmospheric and low pressure chemical vapor deposition furnaces

Background (cont')

In 1996 we reported a novel, fully depleted, back-illuminated CCD fabricated on high-resistivity silicon[1]



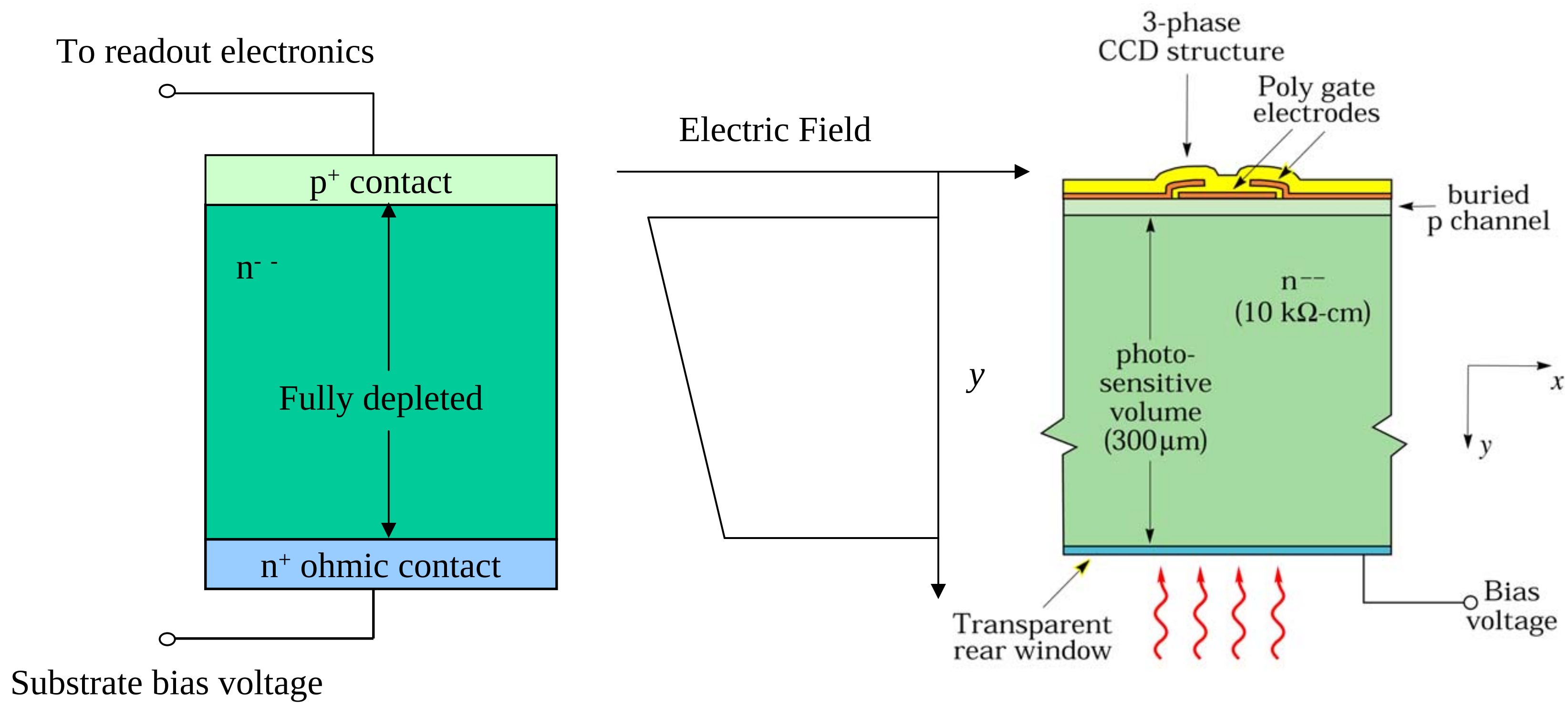
1st CCD wafer fabricated at LBNL (100mm wafer)



1st light: 40 kpixel CCD

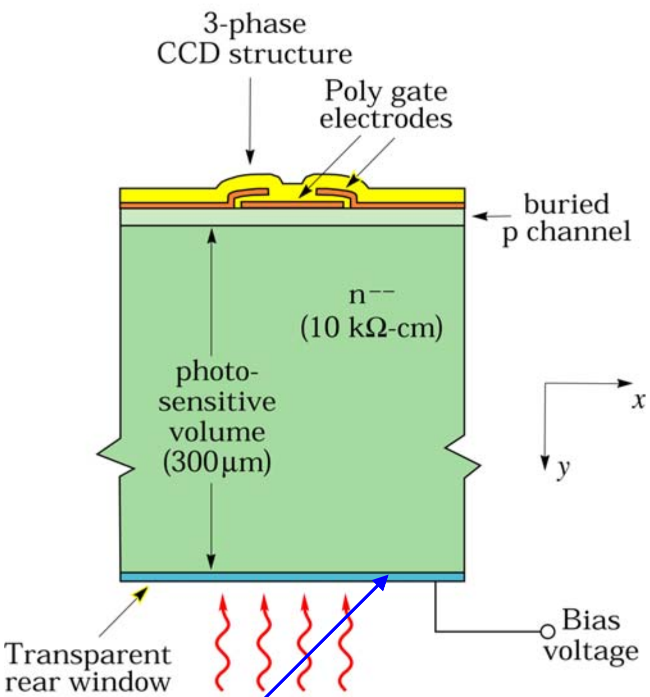
[1]S.E. Holland *et al*, "A 200 x 200 CCD Image Sensor Fabricated on High-Resistivity Silicon", International Electron Devices Meeting, pp. 911–914, December 1996.

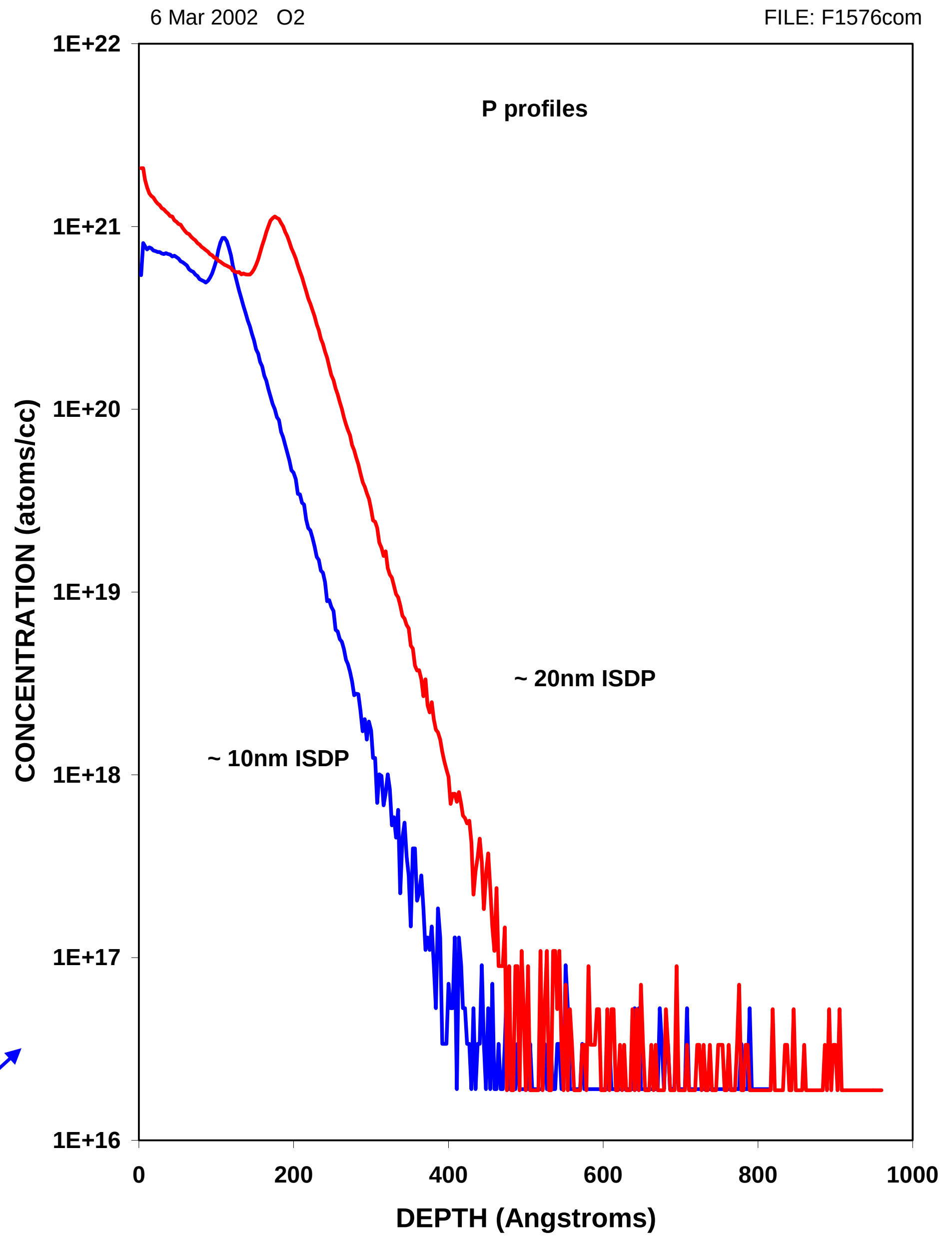
p-i-n diodes and fully depleted CCDs



Fully depleted p-i-n diode	vs	Fully depleted CCD
1) Linearly varying E field in depleted substrate		Same, except near the buried channel junction
2) 3–5 photomasks, polysilicon bias resistors		11+ masks, overlapping, triple polysilicon technology
3) ~ 1 µm thick n^+ ohmic contact		10–20 nm for blue response

Thin backside n$^+$ ohmic contact development

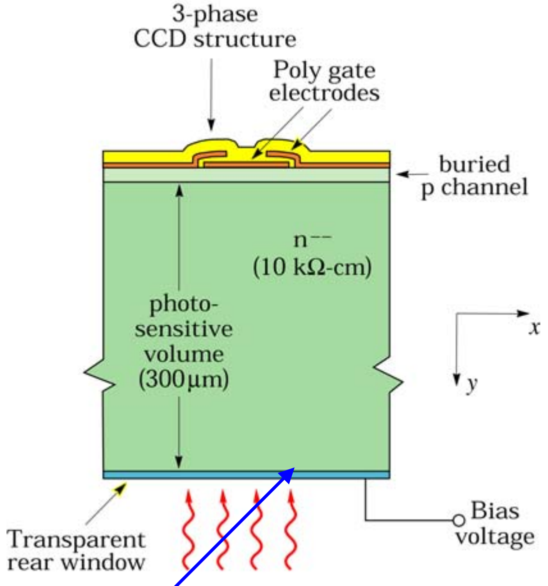


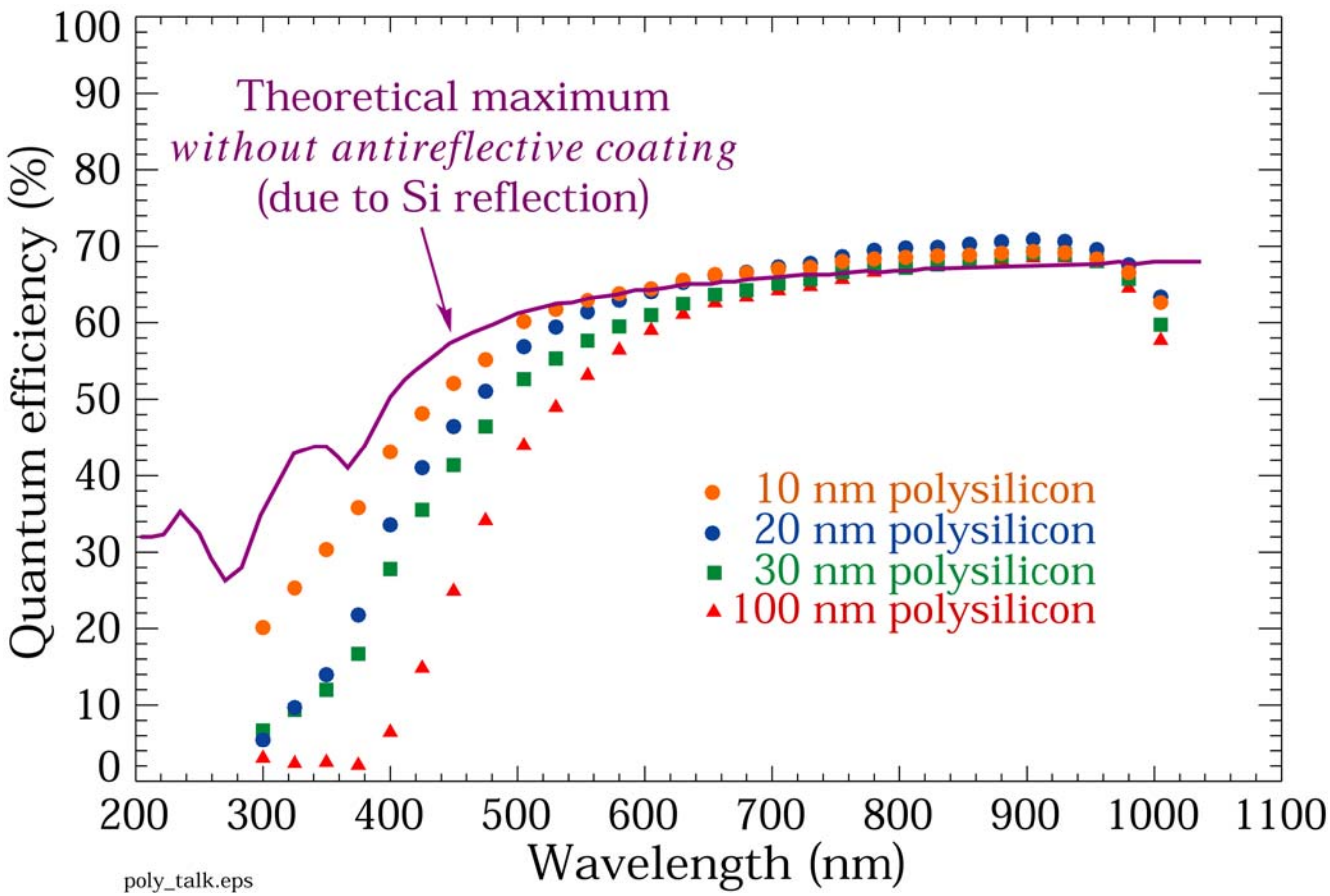


Thin backside n$^+$ contact for good blue response formed by in-situ doped polysilicon (ISDP) deposition

SIMS phosphorus depth profile

Thin backside n$^+$ ohmic contact development





Thin backside n$^+$ contact for good blue response formed by in-situ doped polysilicon (ISDP) deposition

Measured quantum efficiency (room temperature photodiodes)

Key issues from p-i-n diode to fully depleted CCD:

1) More complex fabrication process (numerous high T steps)
2) Development of thin backside ohmic contact

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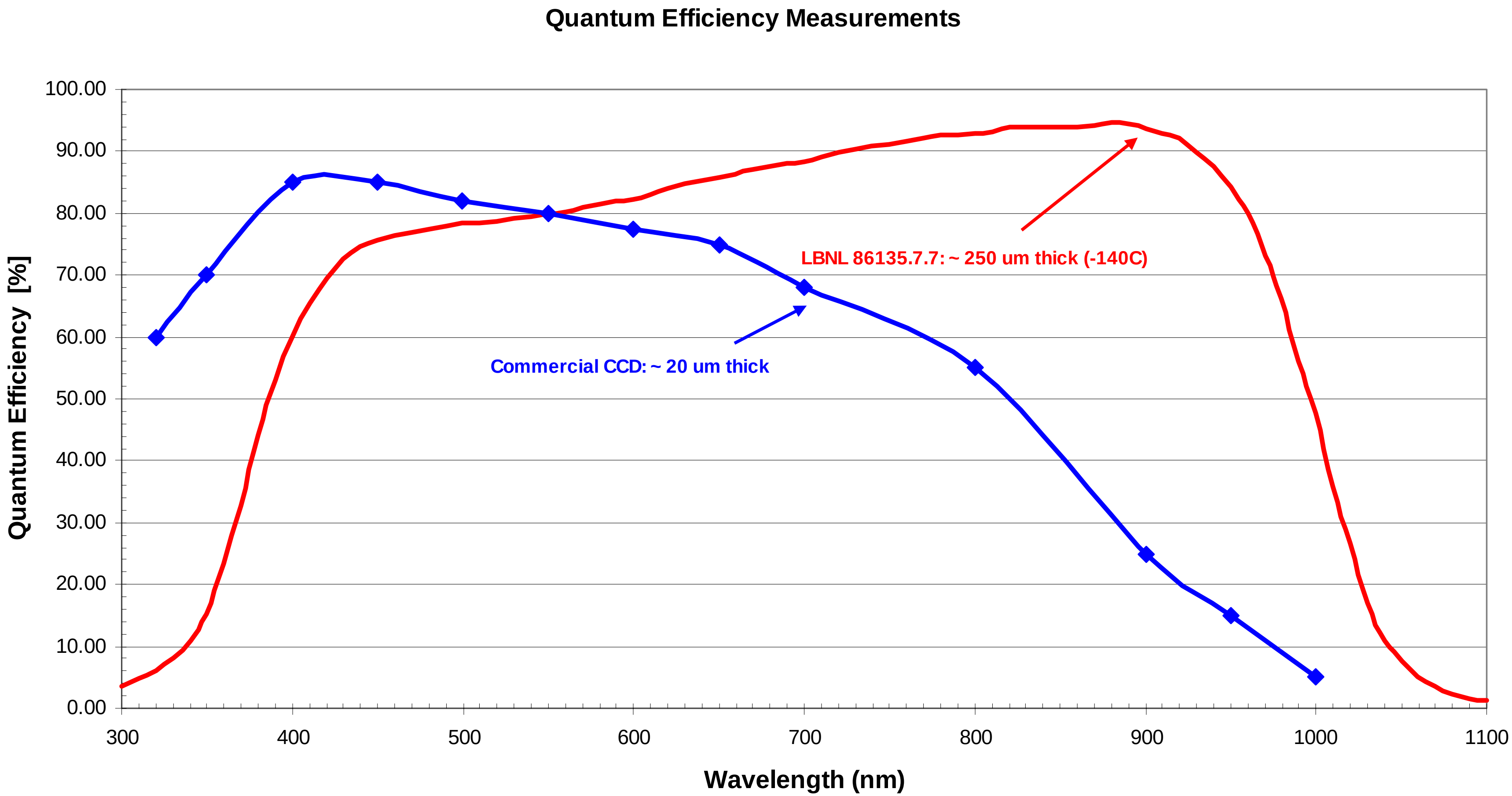
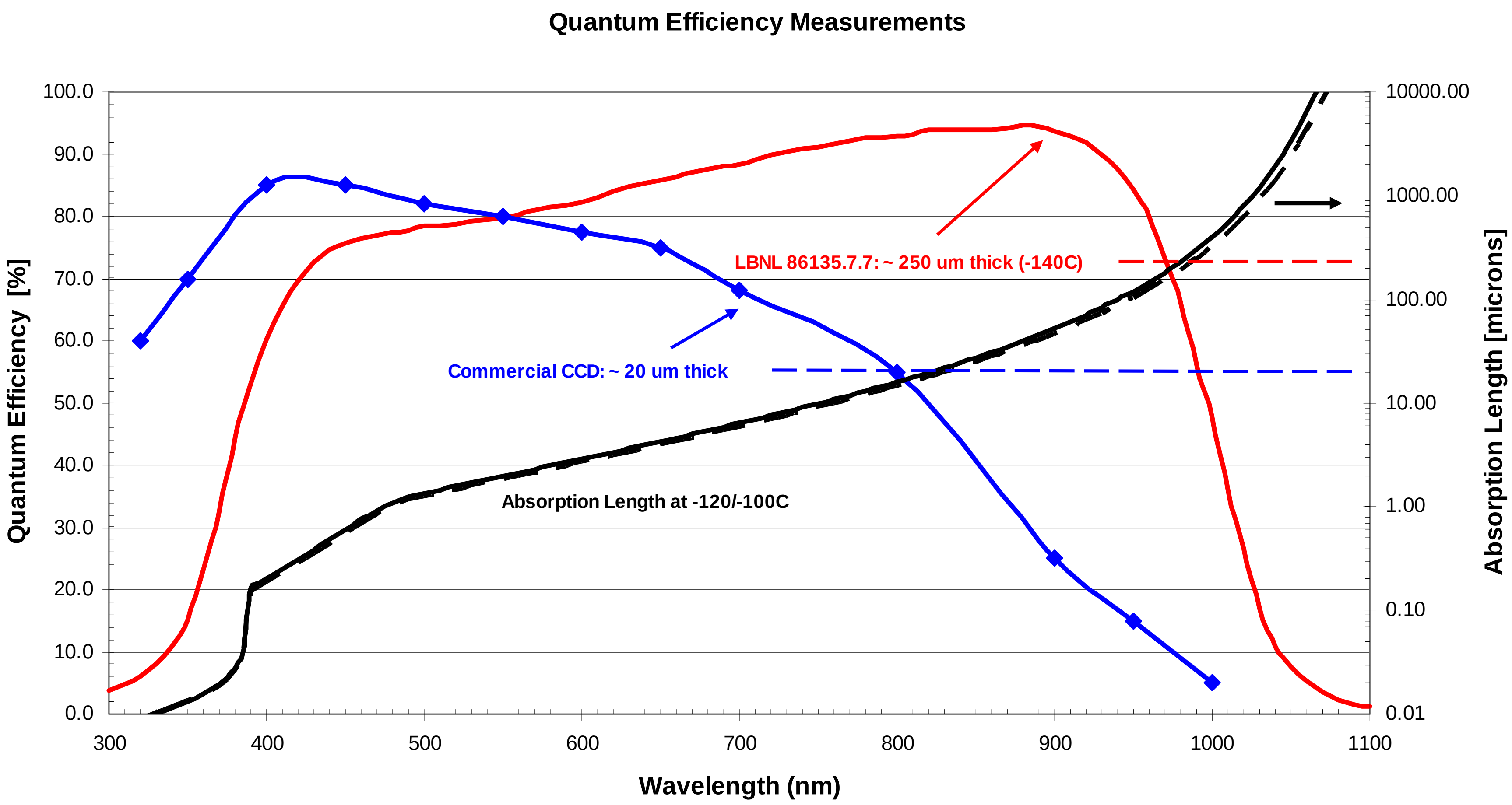
Near infrared imaging and spectroscopy

A key advantage of thick CCDs (~200–300 µm thick) compared to thinned scientific devices (~10–20 µm thick) is improved near infrared response and lack of fringing



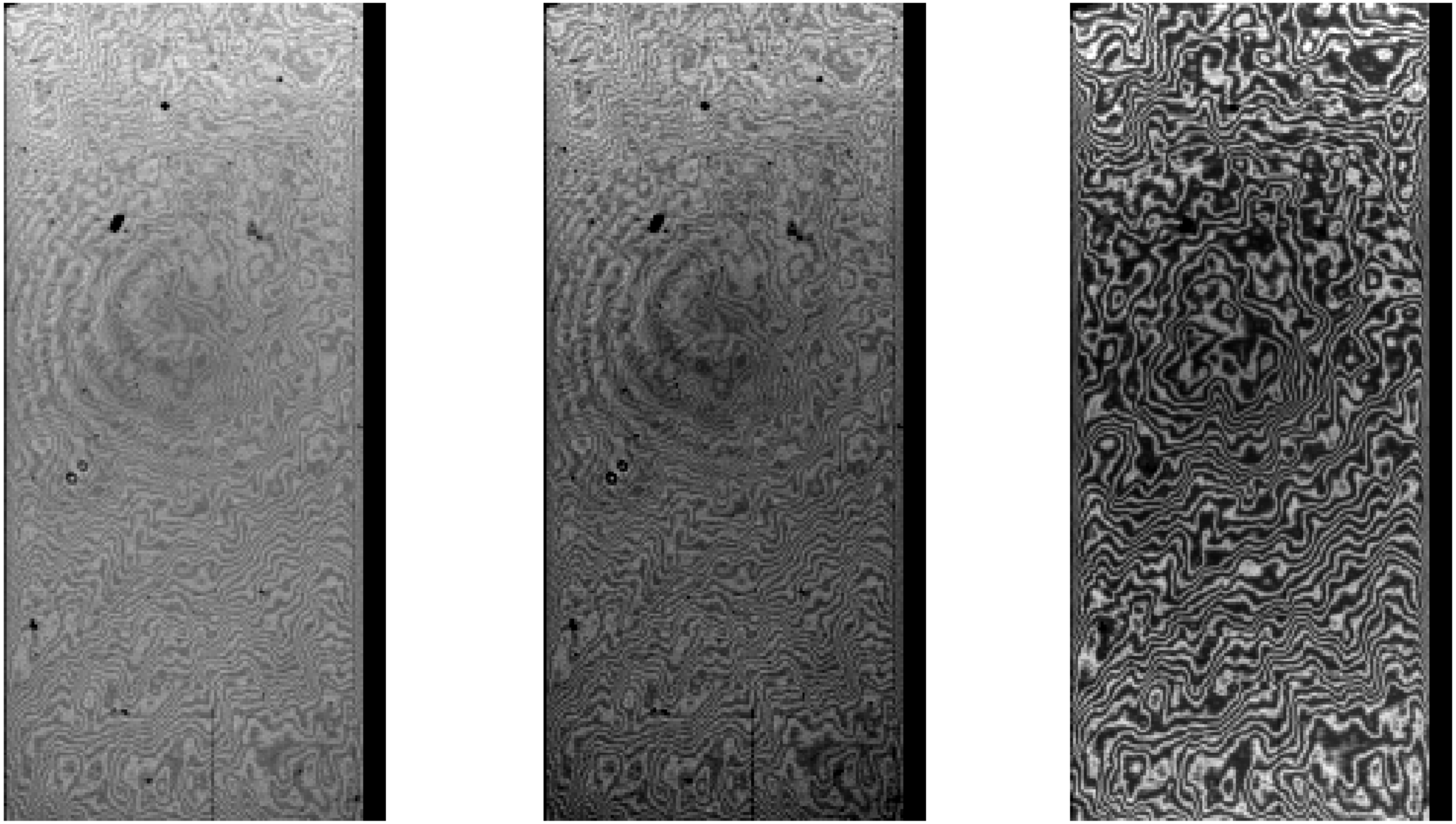
Near infrared imaging and spectroscopy (cont')

- The absorption length in silicon becomes large at near infrared wavelengths due to the indirect bandgap of silicon (phonons required for momentum conservation)
- When the absorption length is greater than the silicon thickness fringing can occur



Fringing in thinned CCDs

Fringing due to multiply-reflected light (uniform illumination, 10–20 μm thick CCD)



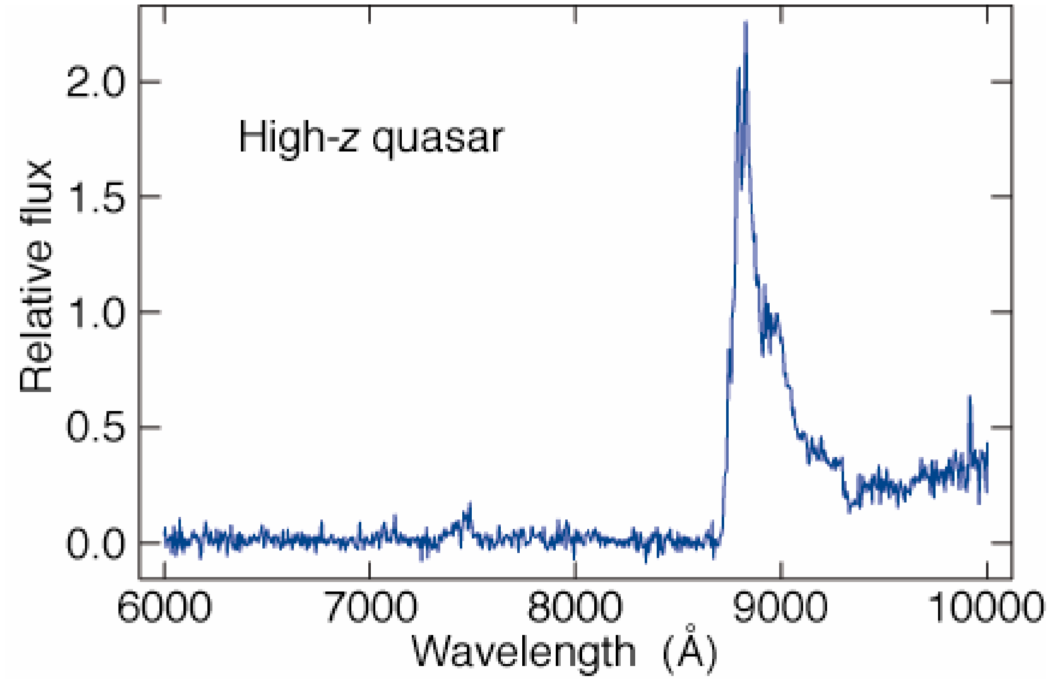
λ = 800 nm 900 nm 1 μm

Measurements courtesy of R. Stover, M. Wei of Lick Observatory

Near infrared imaging and spectroscopy

LBNL 2k x 4k CCD: Blue: H-α at 656 nm
Green: SIII at 955 nm Red: 1.02 μm

LNBL 1980 x 800 CCD: z > 6 Quasar spectrum
NOAO Multi-aperture Red Spectograph



Data courtesy of Xiaohui Fan, University of Arizona Astronomy Department and the Sloan Digital Sky Survey, and Arjun Dey of the National Optical Astronomy Observatory

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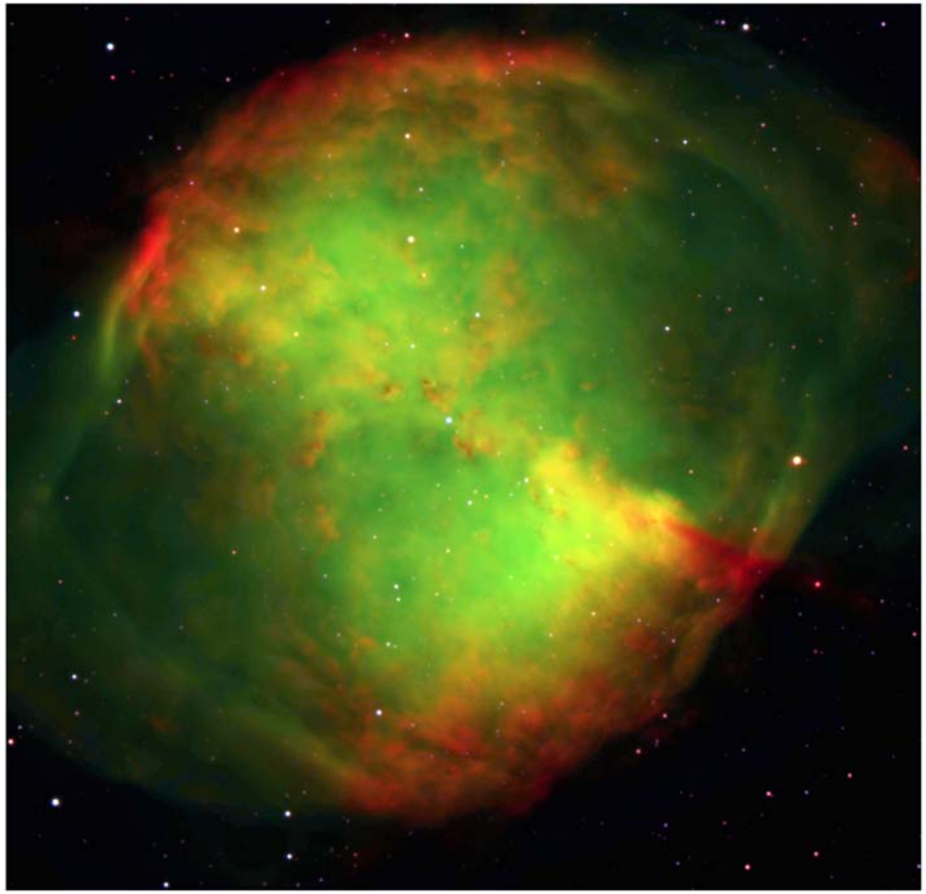
Near IR vs Visible image (Dumbbell nebula)

LBNL 2k x 4k CCD: Blue: H-α at 656 nm
Green: SIII at 955 nm Red: 1.02 μm

ESO image at visible wavelengths: 429/501/656 nm



Planetary Nebula NGC 6853 (M 27) - VLT UT1+FORS1

ESO PR Photo 38a/98 (7 October 1998)

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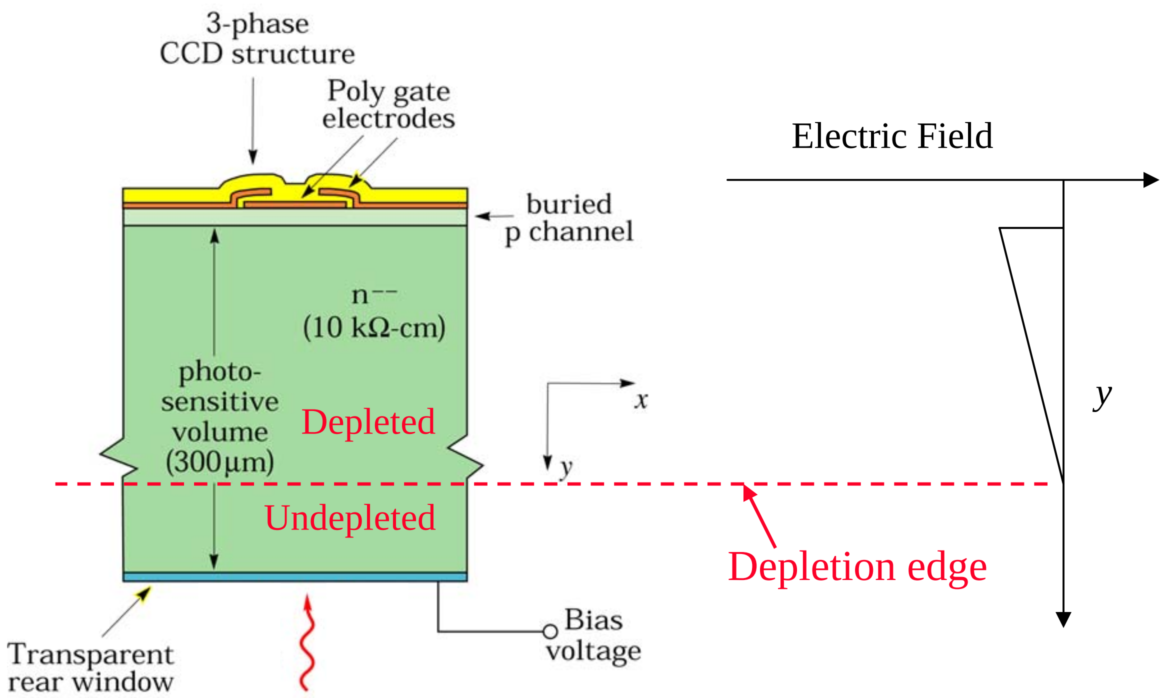
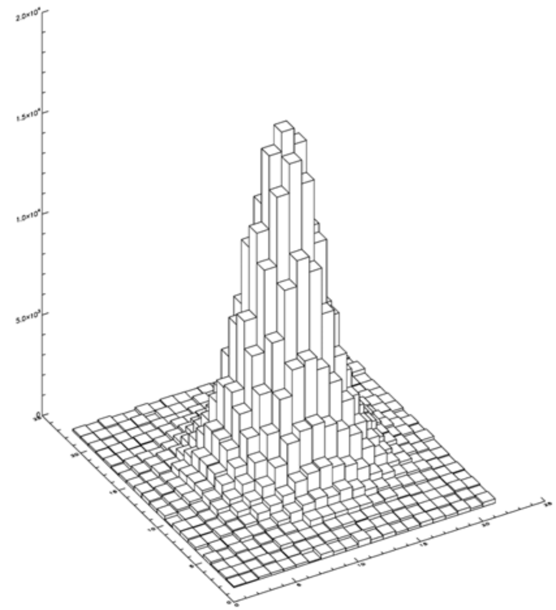
Work in progress

- Since the initial CCD development we have directed our efforts towards
  - — Improved theoretical understanding of fully depleted CCDs
    - Internal potentials and electric fields
      - — S.E. Holland et al, IEEE Trans. Elec. Dev., 50, 225, 2003.
    - Quantum efficiency and fringing
      - — D.E. Groom et al, Proc. SPIE, 3649, 80, 1999.
    - Spatial resolution (Point Spread Function)
      - — C.J. Bebek et al, to be published, IEEE Trans. Nucl. Sci.
  - — Development of space qualified CCDs for the SuperNova Acceleration Probe
    - Desire for improved spatial resolution has led to the development of high-voltage compatible CCDs that can be operated at substrate bias voltages of at least 200V
    - Possible spin off: Direct x-ray detection with fully depleted CCDs
      - — 200 μm thick SNAP CCD is ~ 100% efficient for 8 keV x-rays

Spatial resolution as affected by the substrate bias voltage



Point source illumination

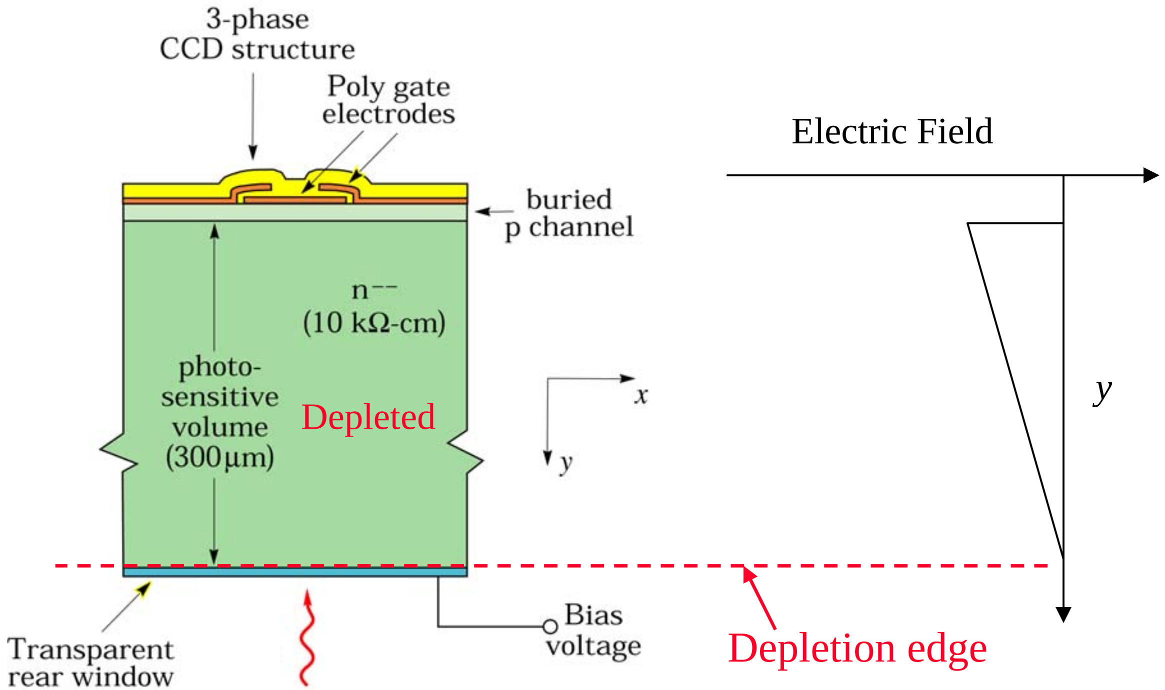


Measured charge distribution
Each square represents 1 pixel

At low substrate bias voltages the CCD is not fully depleted

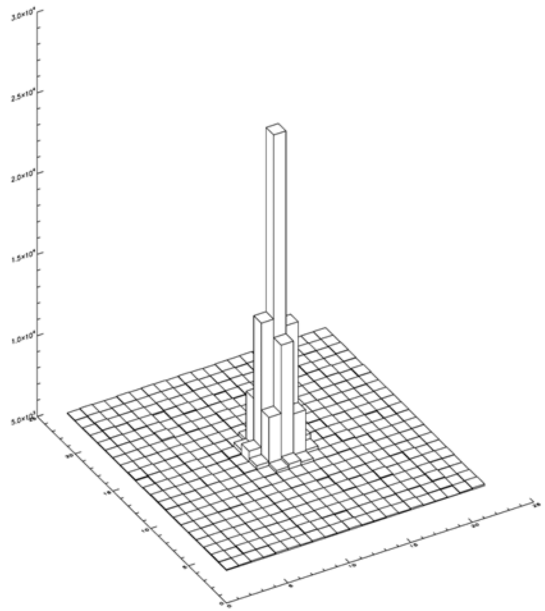
The PSF is dominated by diffusion in the undepleted silicon

Spatial resolution as affected by the substrate bias voltage



Point source illumination

V_{SUB} = 20V



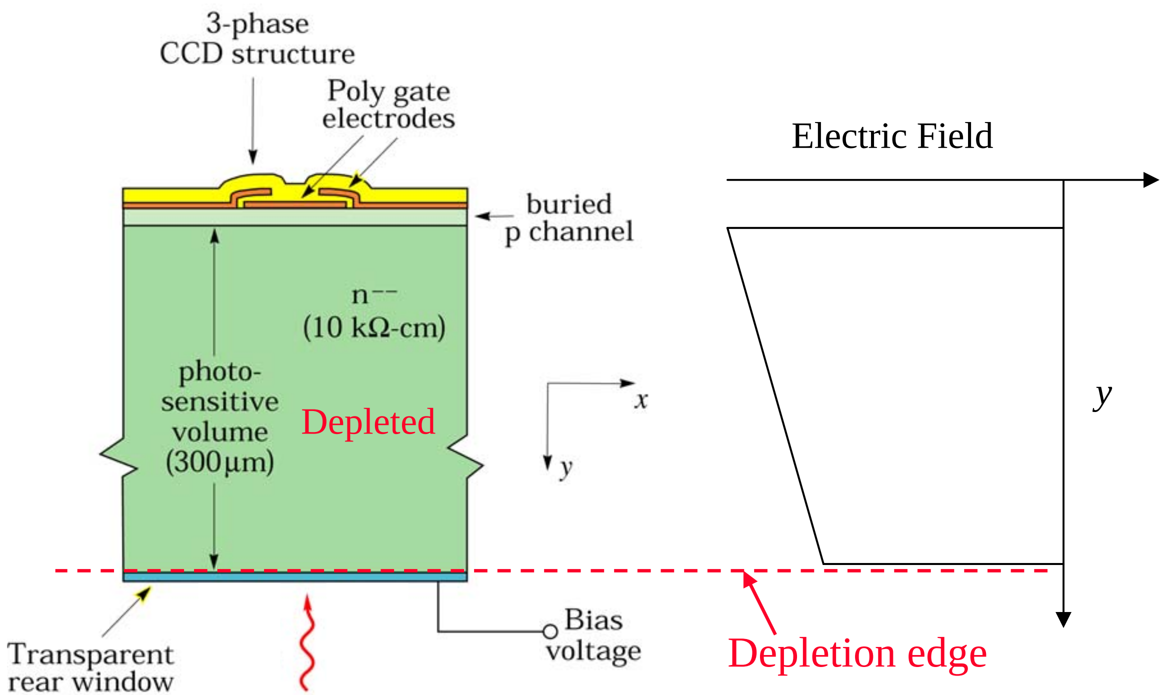
Measured charge distribution
Each square represents 1 pixel

At 20V the CCD corresponding to the data is just fully depleted

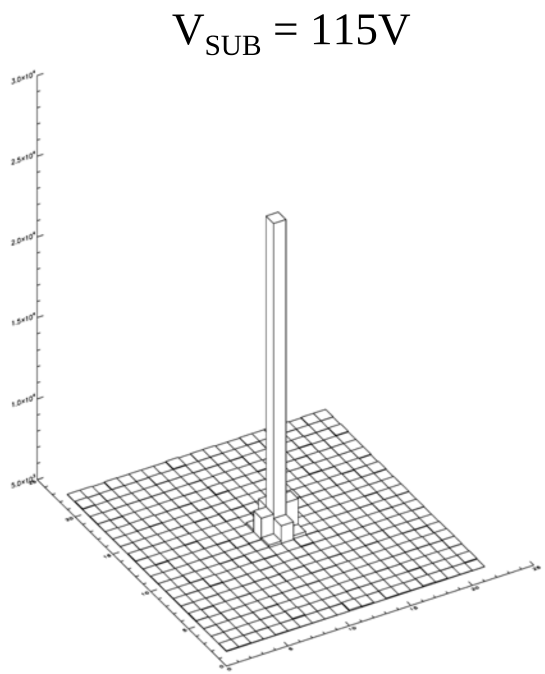
The PSF is limited by the transit time of the photogenerated holes

$$\sigma = \sqrt{2Dt_{tr}}$$

Spatial resolution as affected by the substrate bias voltage



Point source illumination

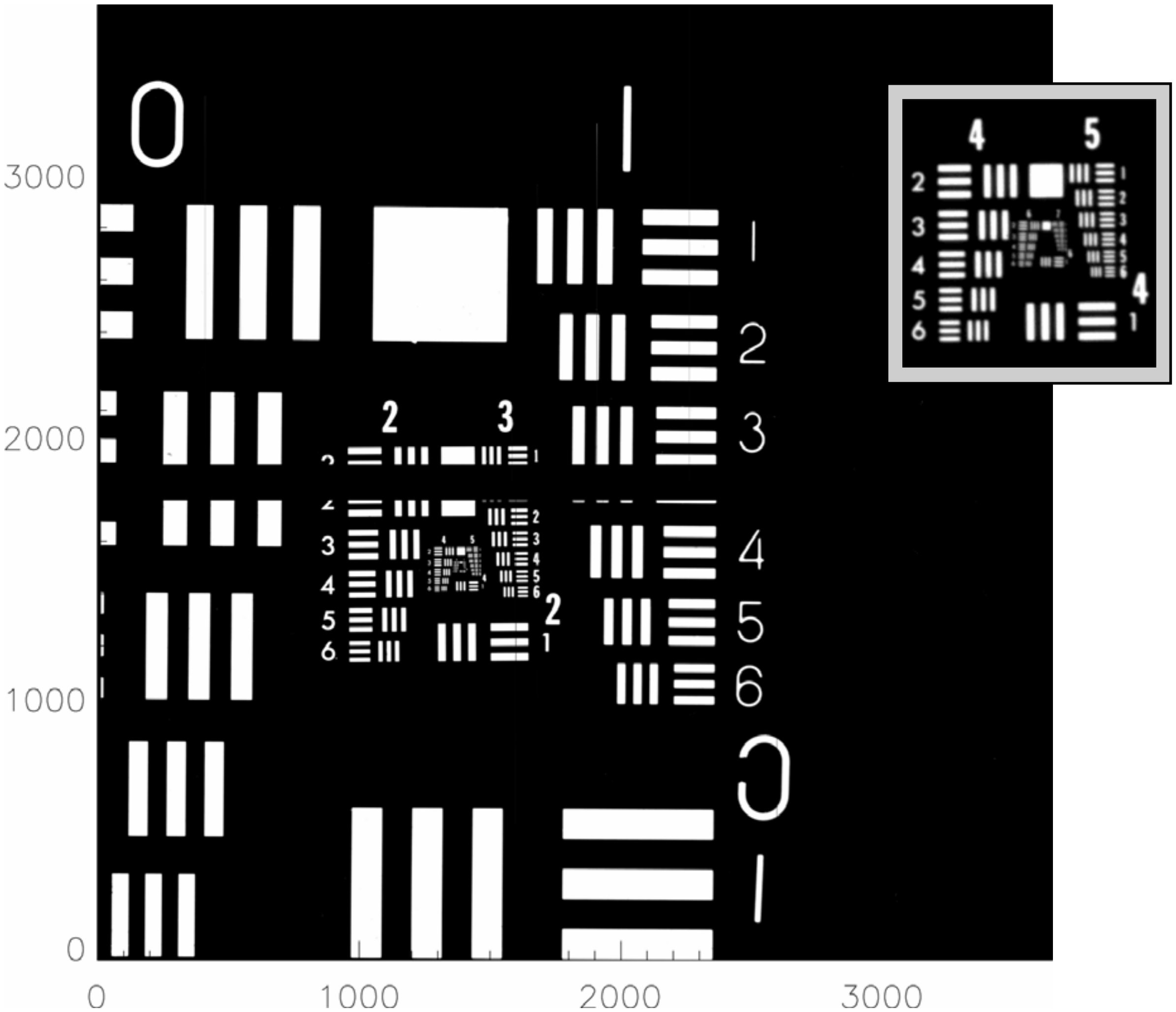


Measured charge distribution
Each square represents 1 pixel

The PSF continues to improve as V_{SUB} in increased
At V_{SUB}=115V the rms diffusion is 3.7 ± 0.2 µm

Over-depleted operation places significant demands on the thin backside n^+ ohmic contact

200 µm thick, BI SNAP V2 CCD at 206V

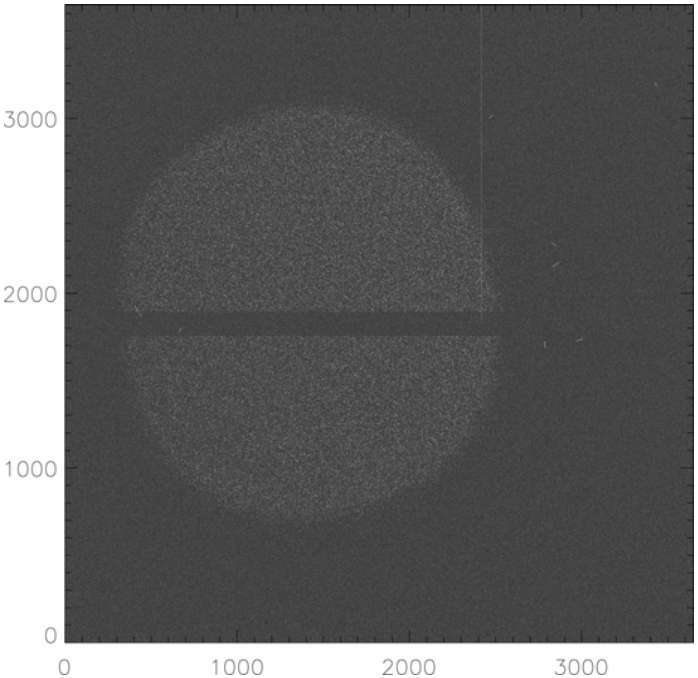


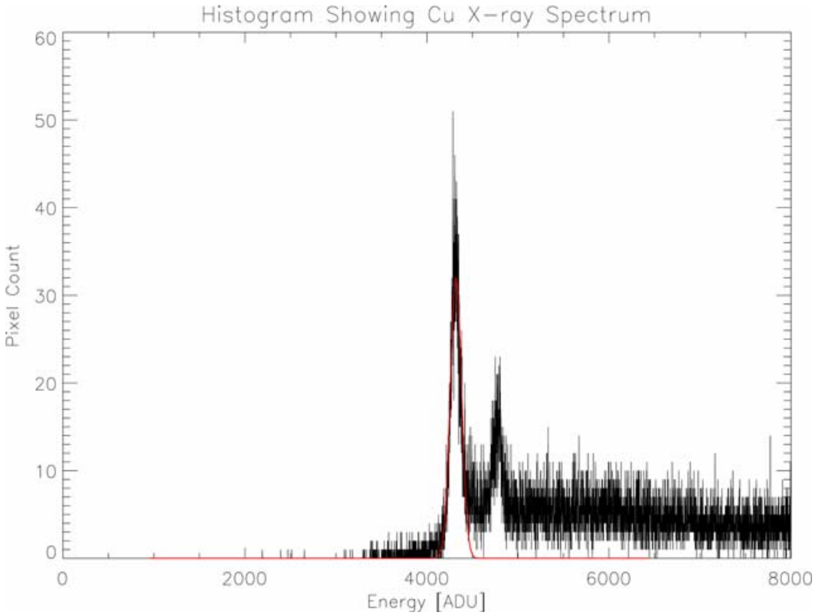
CCD 105868.13.6

12.3 Mpixel SNAP CCD

Test pattern image taken at 206V substrate bias (-140C)

SNAP CCD as an x-ray detector





Cu K_{α} (8.048 keV) and K_{β} (8.901 keV) x-ray image and histogram

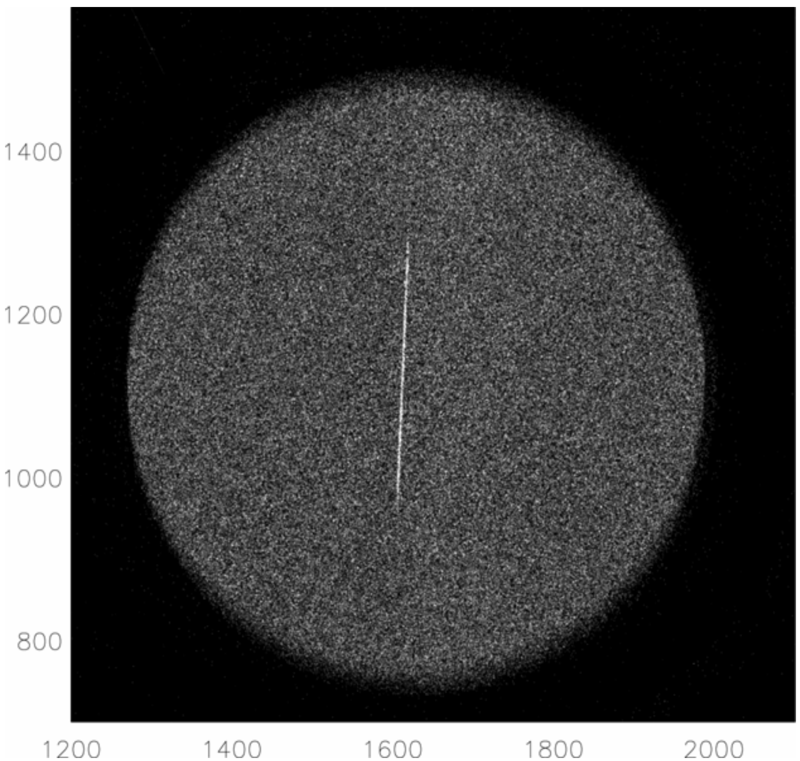
5 ms exposure

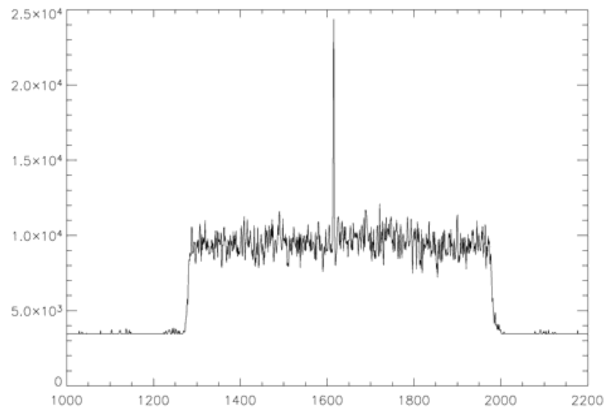
3 x 3 summation of x-ray spot intensities

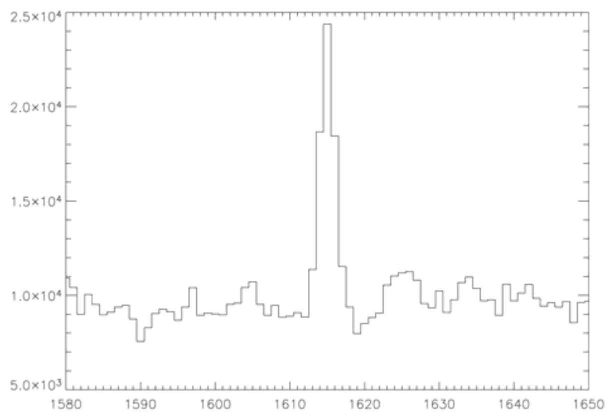
200 μm thick, 12.3 Mpixel (10.5 μm pixel), back-illuminated CCD at -140C

Be dewar window

x-ray imaging of 5 µm wide slit with SNAP CCD





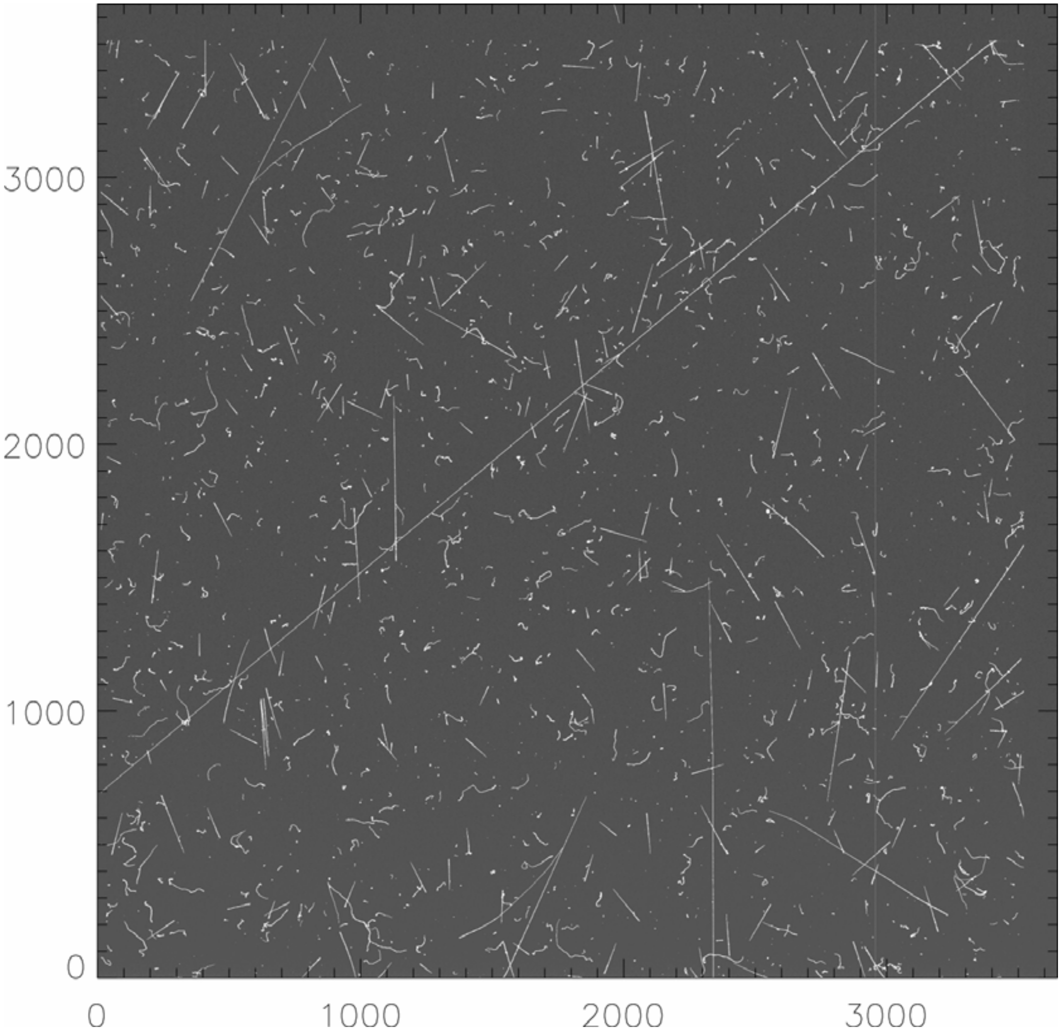


Stainless steel target (partially transparent to x-rays) containing a 5 µm wide slit.

X-rays generated by a Cu anode tube operating at 15 kV.

Plots along row 1200 of the image shown in graphs.

Fully depleted, 650 µm thick SNAP V2 CCD



The ability to operate at high substrate bias voltages allows for full depletion of thicker CCDs (650–675 µm in this case)

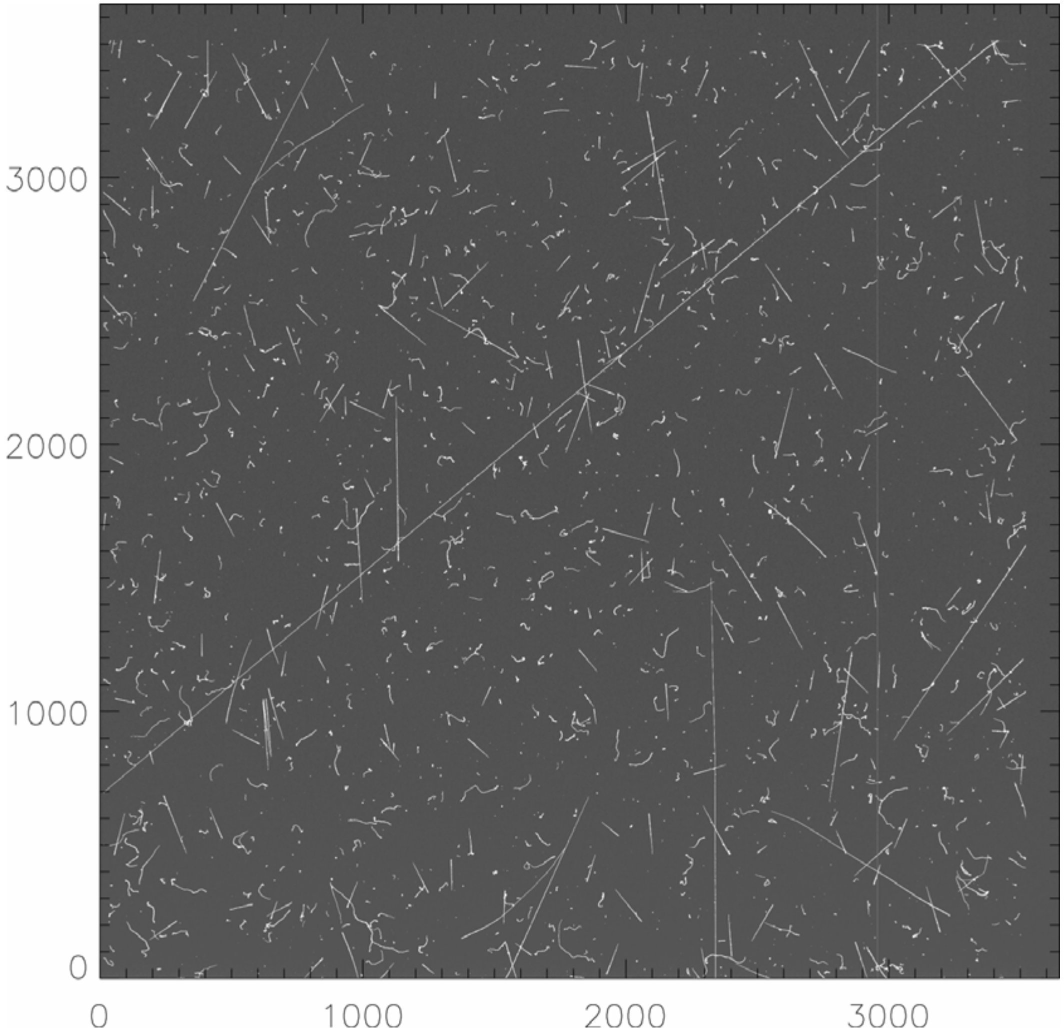
Background in the image is from cosmic rays and Compton electrons from terrestrial radiation in this 30 minute dark exposure

Dark current at -140C is 0.63 e-/pixel-hour

Note: Depletion depth goes as $(\text{thickness})^2$

CCD 107409.16.11 fully depleted at 207V

Fully depleted, 650 µm thick SNAP V2 CCD



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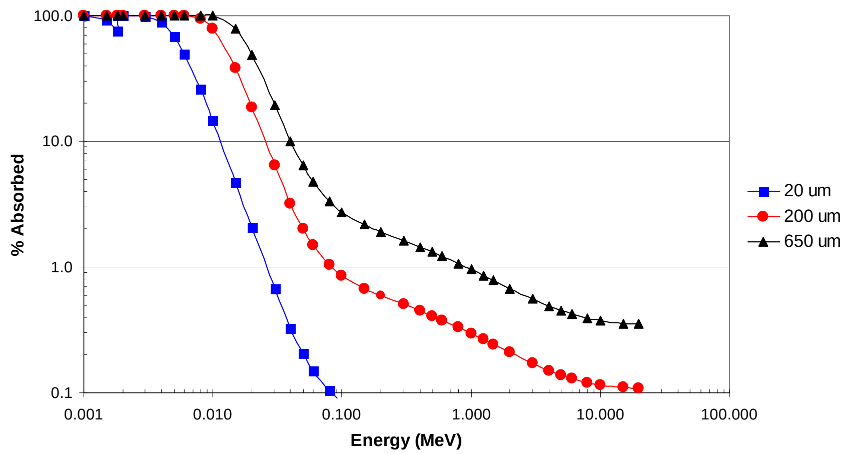
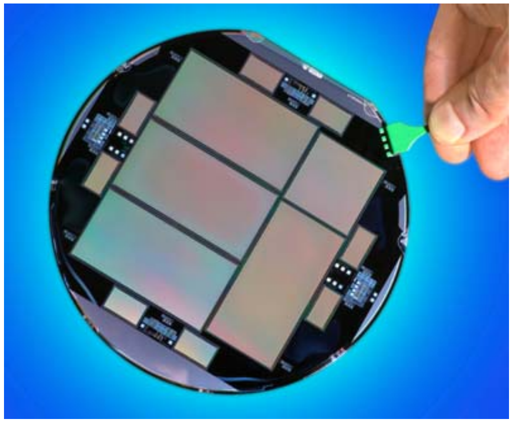


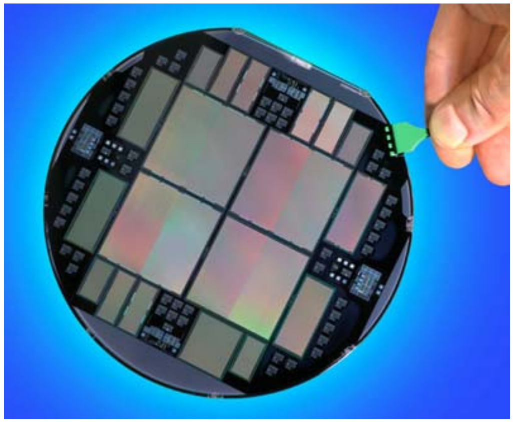
x and γ-ray absorption in Silicon

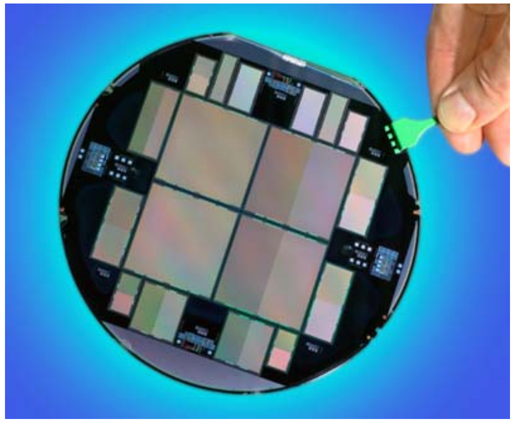
Work in progress (cont')

- A major part of the current effort is in CCD fabrication technology development
  - — Development of robust, reproducible technology for back illuminated CCDs
    - Batch mode processing on 150 mm wafers
    - Important for proposed large focal planes for ground and space-based telescopes (SNAP, GAIA, LSST, FNAL Dark Energy Survey, etc)



8 Mpixel CCDs for
ground-based astronomy
(FNAL Dark Energy Survey camera)





12 Mpixel, high voltage compatible CCDs for
space-based imaging (LNBL SuperNova Acceleration
Probe) with potential applications in direct x-ray detection

150 mm diameter wafers fabricated at DALSA Semiconductor and LBNL

LBNL CCD Process Flow

Front-side processing at commercial foundry on 150 mm wafers

thin, ISDP, contact etch & metallization, AR coat at LBNL

650–675 µm thick wafers from DALSA Semiconductor sent to LBNL just before Mask 9 (contact mask)

Thinned commercially to 200–250 µm

Remainder of processing at LBNL including ISDP deposition, lithography, etch, thin film deposition, etc

Batch mode process: Steps necessary for back illumination done at wafer level

"Business Model"

Thinned (200–250 µm), back-illuminated CCD

LBNL CCD Process Flow

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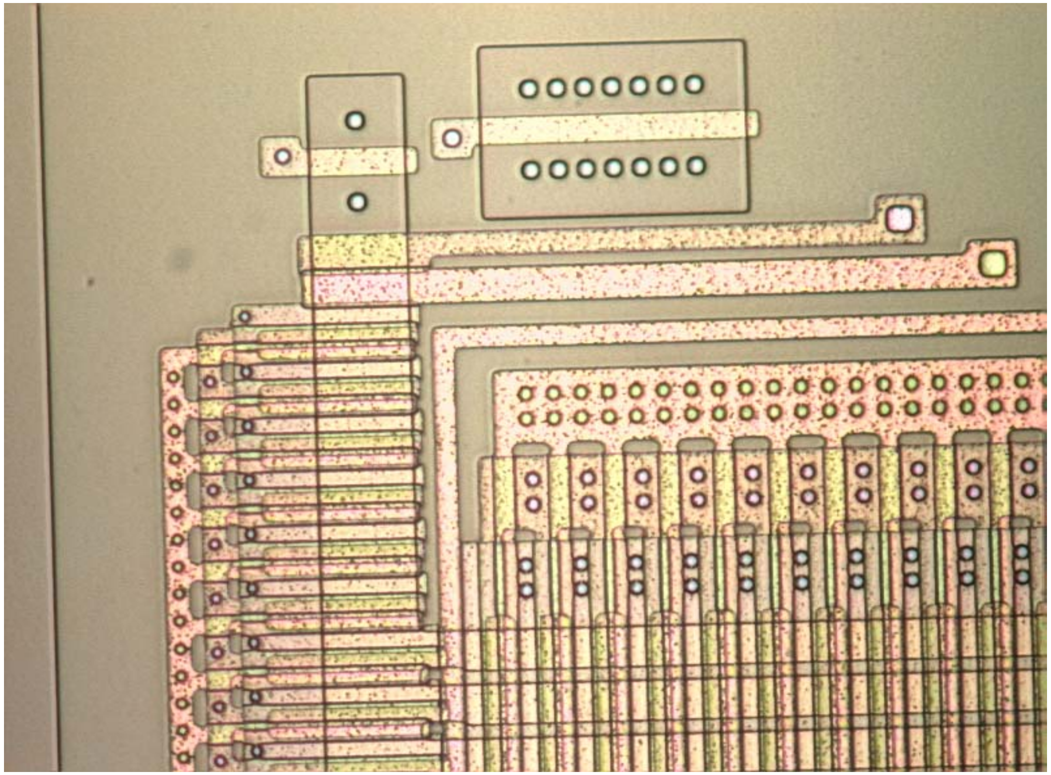
thin, ISDP, contact etch & metallization, AR coat at LBNL

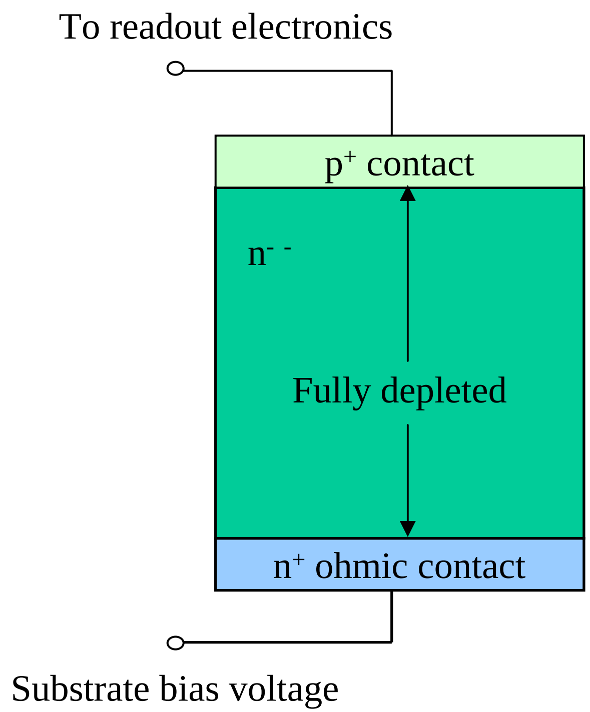
"Business Model"

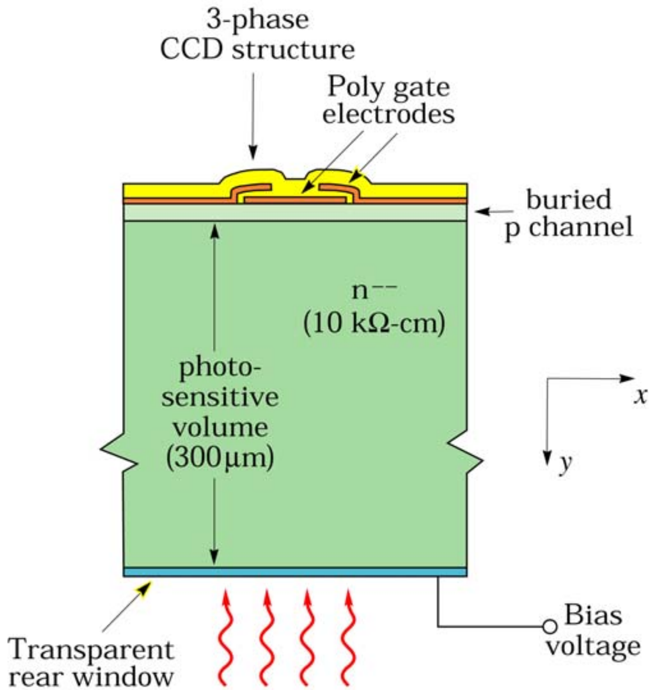


Photomicrograph of CCD with contact openings done at LBNL with preceding processing done at DALSA Semiconductor (triple polysilicon processing, implants, etc)

Thinned (200–250 μm), back-illuminated CCD

Area for improvement: Readout speed





<u>Fully depleted p-i-n diode</u> vs <u>Fully depleted CCD</u>

1) Charge-sensitive preamplifier readout

Noise-less charge transfer
Q to V conversion with on-chip source follower
True double-correlated sampling
Noise as low as ~ 2 e^- slow scan (~ 50–100 kpixels/s)

2) Highly integrated readout electronics for HEP

2–4 readout channels/CCD typical
More required for future applications (e.g. Synchrotrons)

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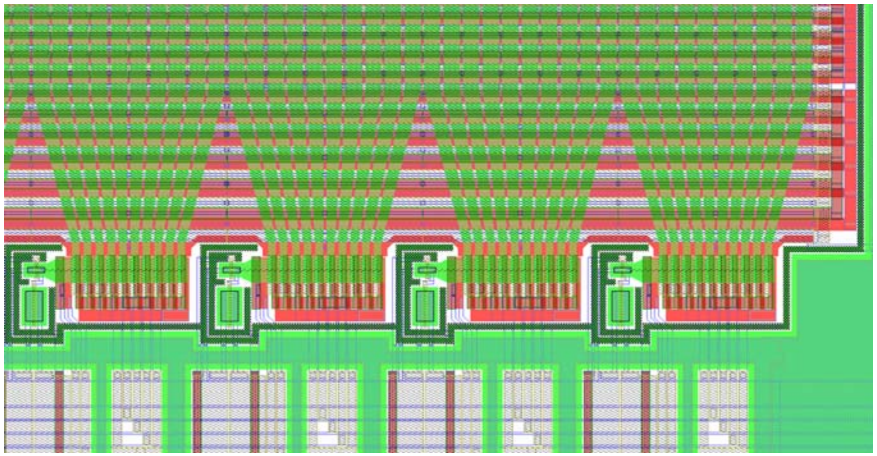
Summary and future work

- HEP detector R&D led to fully depleted CCDs for astronomy
- Requirements for space-based operation led to high-voltage compatible CCDs
- Faster readout of CCDs is of interest at LBNL for synchrotron applications



High frame rate CCD with amplifiers every
10 columns, 300 µm pitch, 1Mpixel/sec-amp (P. Denes)

Custom IC readout with 16 channel LBNL CRIC chip
(preamplifiers, double-correlated sampling, ADC's)

Fabrication starts soon

- Continued efforts in CCDs for SNAP and FNAL Dark Energy Survey Camera

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Fermilab

NASA Jet Propulsion Laboratory
California Institute of Technology

Yale

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- DALSA Semiconductor: Robert Groulx
- FNAL: T. Diehl, J. Estrada, B. Flaugher
- Lick Observatory: R. Stover, M. Wei, W. Brown
- NOAO: A. Dey, R. Reed
- JPL: J. Blacksberg, M. Hoenk, S. Nikzad
- Yale: C. Baltay, W. Emmet, D. Rabinowitz, A. Szymkowiak

[1]Poster presentation at this meeting