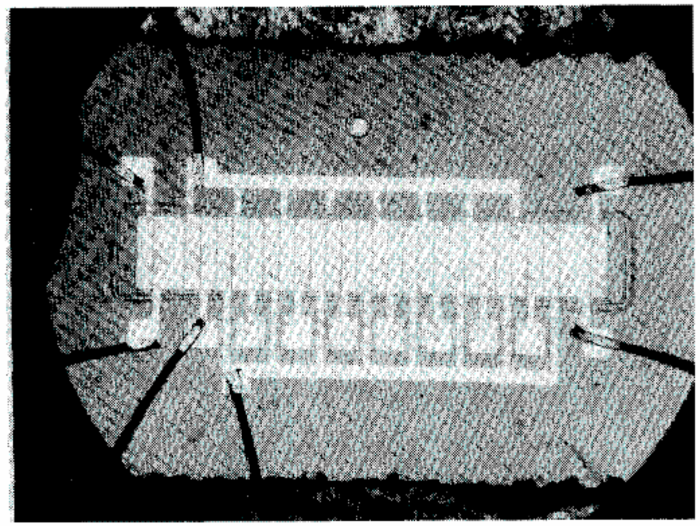
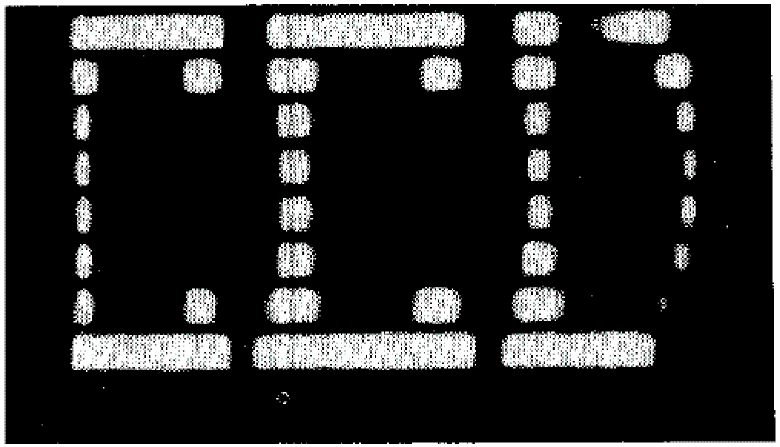
From Quarks to Quasars: Advanced Scientific Charge-Coupled Devices

Steve Holland

Lawrence Berkeley National Laboratory

June 15th, 2005





1st imaging CCD: Bell Labs 1970

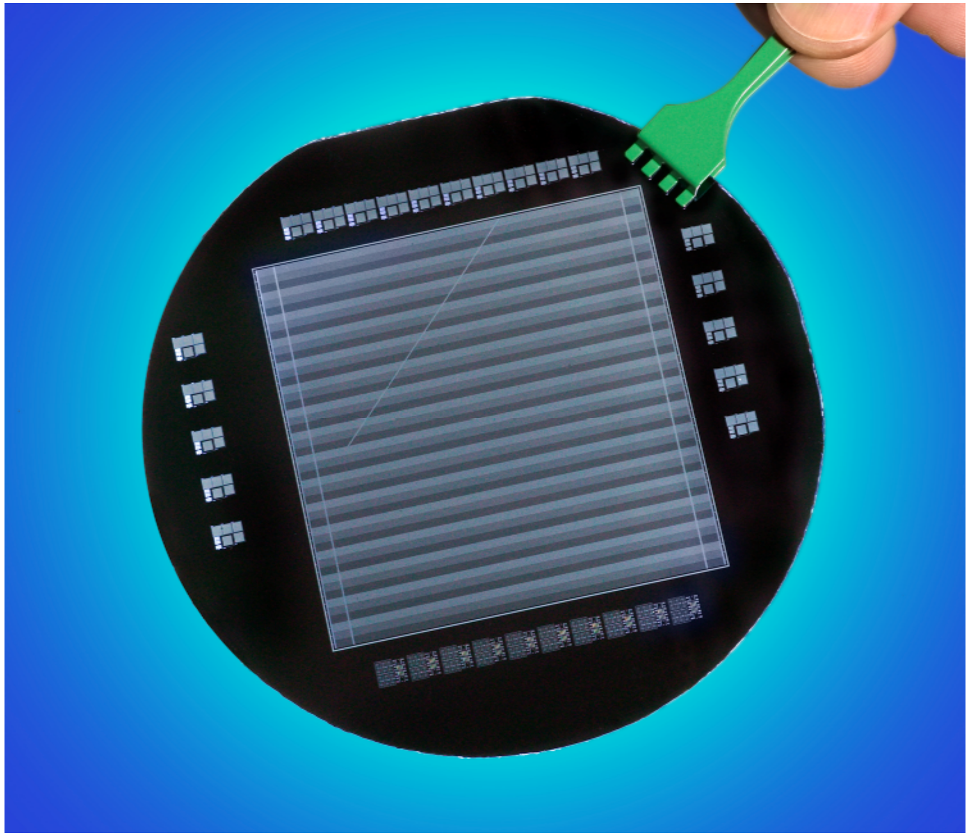
The “quarks” connection

Silicon strip detector fabricated on 100 mm, high-resistivity silicon wafers at the LBNL MicroSystems Laboratory

Technology is fully-depleted, p-i-n diode

Charged-particle detector for high-energy physics

Preceded LBNL work on fully depleted CCDs



Circa 1994

The Invention of the CCD

- **The Charge-Coupled Device was invented by Willard S. Boyle and George E. Smith of Bell Labs on September 8th, 1969**
- **Result of a directive from Jack Morton, Bell Labs Electronics Technology Vice-President, to develop a semiconductor equivalent of the magnetic bubble memory**
- **The basic concepts were conceived in a discussion session between Boyle and Smith "lasting not more than an hour" [1,2]**
- **The utility of the CCD as an image sensor was immediately recognized given Smith's prior work on the "silicon diode array camera tube" for the Bell Labs "PICTUREPHONE®"**

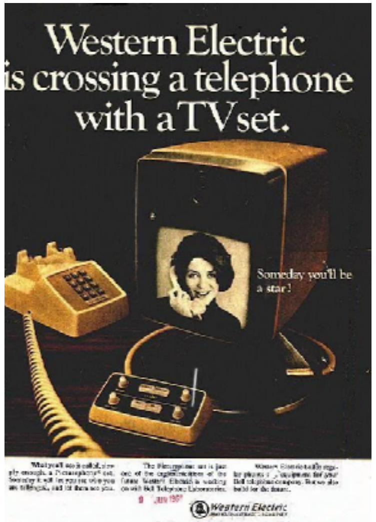
[1] W.S. Boyle and G.E. Smith, "The inception of charge-coupled devices," IEEE Trans.Elec. Dev., **23**, 661, 1976.

[2] G.E. Smith, "The invention of the CCD", Nucl. Instrum. Meth. A, **471**, 1, 2001.

Recollections of W. Boyle

Science.Canada Web Site (www.science.ca)

Bbbrrring, Bbbrrring. It's that damn videophone again. These things will never catch on, thinks Willard Boyle as he squirms in his chair before answering, trying to find a position that is comfortable but doesn't put his face in view of the camera. It's too early in the morning to be seen and Boyle knows who's calling--his boss Jack Morton, head of advanced research at Bell Labs in New Jersey, and the father of transistor electronics.



"Boyle?"
"Hello Jack."
"So what happened yesterday?" came the familiar refrain.

Boyle shifted a little more in his chair.

"I can't see you, Bill," said Morton.
"Right here, Jack."

"So what'd you guys do yesterday?"
"You know, more of the same. We're still working on those new transistors," said Boyle.

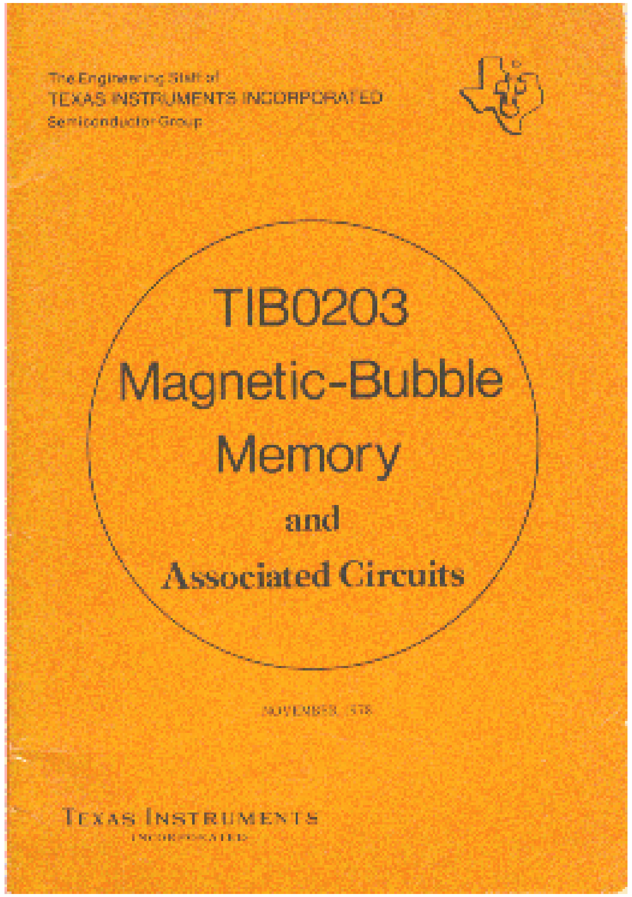
"Look Bill, the other guys are doing great stuff with magnetic bubbles. It's terrific. What are you semiconductor guys doing? The hell with transistors. Try and come up with something different. I'll call tomorrow." And he hung up.

Magnetic Bubble Memories [1,2]

- **Also invented at Bell Labs (A. Bobeck)**
- **Cylindrical magnetic domains (bubbles), i.e. stable localized magnetic states, could be formed in Orthoferrite materials ($RFeO_3$ where R is a rare earth element) when a magnetic field was applied normal to the surface of the Orthoferrite**
- **The magnetic bubbles were on the order of 10-25 μm in diameter and could be shifted within the Orthoferrite film with the application of a tranverse magnetic field**
- **A rotating tranverse field magnetized thin film "Permalloy" layers allowing for magnetic bubble shift registers**
- **Formed the basis for commercial non-volatile computer memory devices in the early 1970's**

[1] A. H. Bobeck et al, "Applications of Orthoferrites to domain-wall devices," IEEE Trans. on Magnetics, **5**, 544, 1969.
[2] A.J. Perneski, "Propagation of cylindrical magnetic domains in Orthoferrites," IEEE Trans. Magnetics, **5**, 554, 1969.

Magnetic Bubble Memories (cont')



intel PRELIMINARY

7110
1-MEGABIT BUBBLE MEMORY

Device	Case Op. Temp. °C	Non-Volatile Storage °C
7110-1	0–75°	−40 to +90°
7110-4	10–55°	−20 to +75°
7110-5	−20 to +85°	−40 to +100°

- **1,048,576 Bits of Usable Data Storage**
- **Non-Volatile, Solid-State Memory**
- **True Binary Organization: 512-Bit Page and 2048 Pages**
- **Major Track–Minor Loop Architecture**
- **Redundant Loops with On-Chip Loop Map and Index**
- **Block Replicate for Read; Block Swap for Write**
- **Single-Chip 20-Pin, Dual In-Line Leadless Package and Socket**
- **Small Physical Volume**
- **Low Power per Bit**
- **Maximum Data Rate 100 Kbit/sec**
- **Average Access Time 40 msec.**

The Intel Magnetics 7110 is a very high-density 1-megabit, non-volatile, solid-state memory utilizing magnetic bubble technology. The usable data storage capacity is 1,048,576 bits. The defect-tolerant design incorporates redundant storage loops. The gross capacity of Intel Magnetics bubble memory is 1,310,720 bits.

The 7110 has a true binary organization to simplify system design, interfacing, and system software. The device is organized as 256 data storage loops each having 4096 storage bits. When used with Intel Magnetics complete family of support electronics, the resultant minimum system is configured as 128K bytes of usable data storage. The support circuits also provide automatic error correction and transparent handling of redundant loops.

The 7110 has a major track–minor loop architecture. It has separate read and write tracks. Logically, the data is organized as a 512-bit page with a total of 2048 pages. The redundant loop information is stored on-chip in the bootstrap loop along with an index address code. When power is disconnected, the 7110 retains the data stored and the bubble memory system is restarted when power is restored via the support electronics under software control.

Magnetic Bubble Memories (cont')

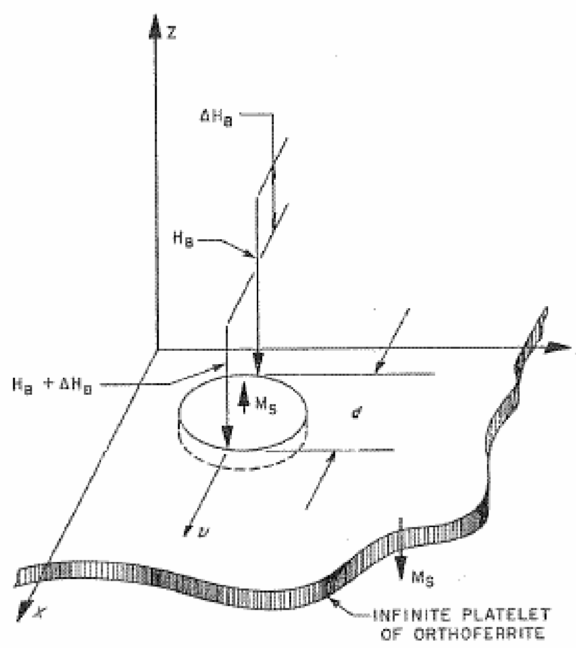


Fig. 1. An infinite platelet of orthoferrite containing a domain of diameter d lies in the x–y plane. In the vicinity of the domain the bias field H_B is directed downwards but decreases in magnitude along the $+x$ direction only. The bias field difference $|\Delta H_B| = (\partial H_B/\partial x)d$ across the domain causes the domain to move in the x direction.

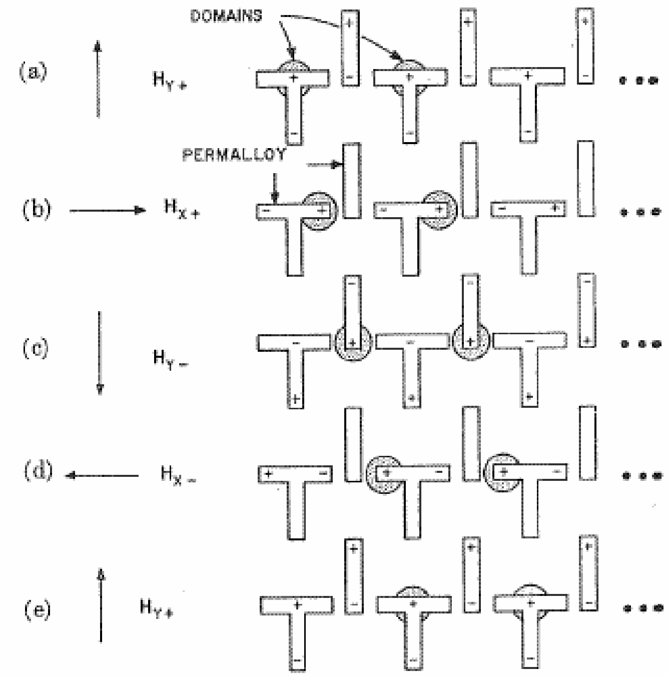


Fig. 3. T-BAR propagation. Cylindrical domains are attracted to + magnetic poles that appear when the in-plane field is directed along a long dimension of a T or bar. As the field sequences, or rotates clockwise, + poles always appear immediately to the right of the domains, causing them to propagate toward the right.

A.J. Perneski, "Propagation of cylindrical magnetic domains in Orthoferrites," IEEE Trans. Magnetics, **5**, 554, 1969.

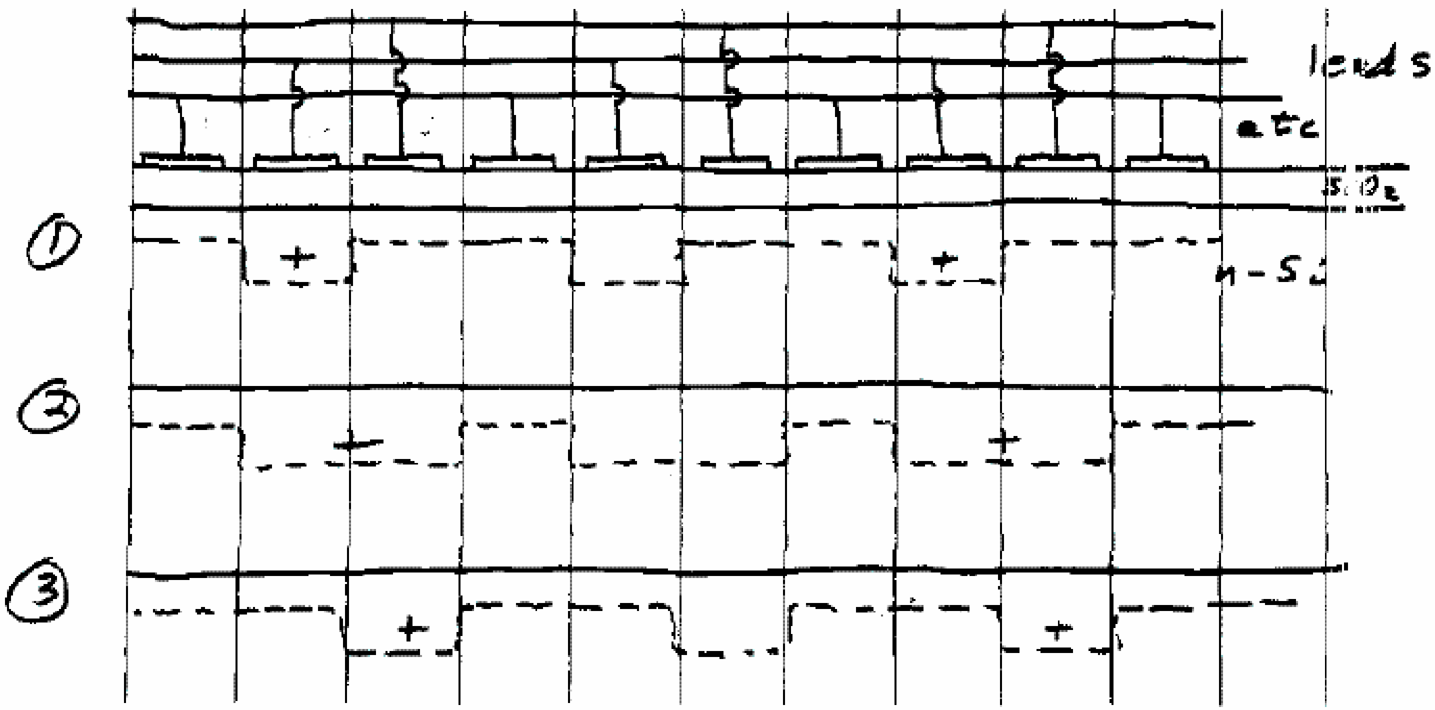
The Invention of the CCD (cont')

- **Boyle and Smith developed, on the blackboard, an analog of the magnetic bubble memory**
  - **An analog of the magnetic bubble is charge**
  - **Storage in localized area, i.e confinement, achieved via the depletion region of a Metal-Oxide-Semiconductor (MOS) capacitor**
    - **Semiconductor potential well**
      - **Normal electric field, bubbles confined with normal magnetic field**
  - **Shifting the signal charge accomplished with closely spaced electrodes**
- **Name comes about from "coupled potential wells" using "charge" as the information carrier (not voltage or current)**

[1] W.S. Boyle and G.E. Smith, "The inception of charge-coupled devices," IEEE Trans.Elec. Dev., **23**, 661, 1976.

[2] G.E. Smith, "The invention of the CCD", Nucl. Instrum. Meth. A, **471**, 1, 2001.

3-phase CCD diagram (lab notebook drawing Sept. 1969)



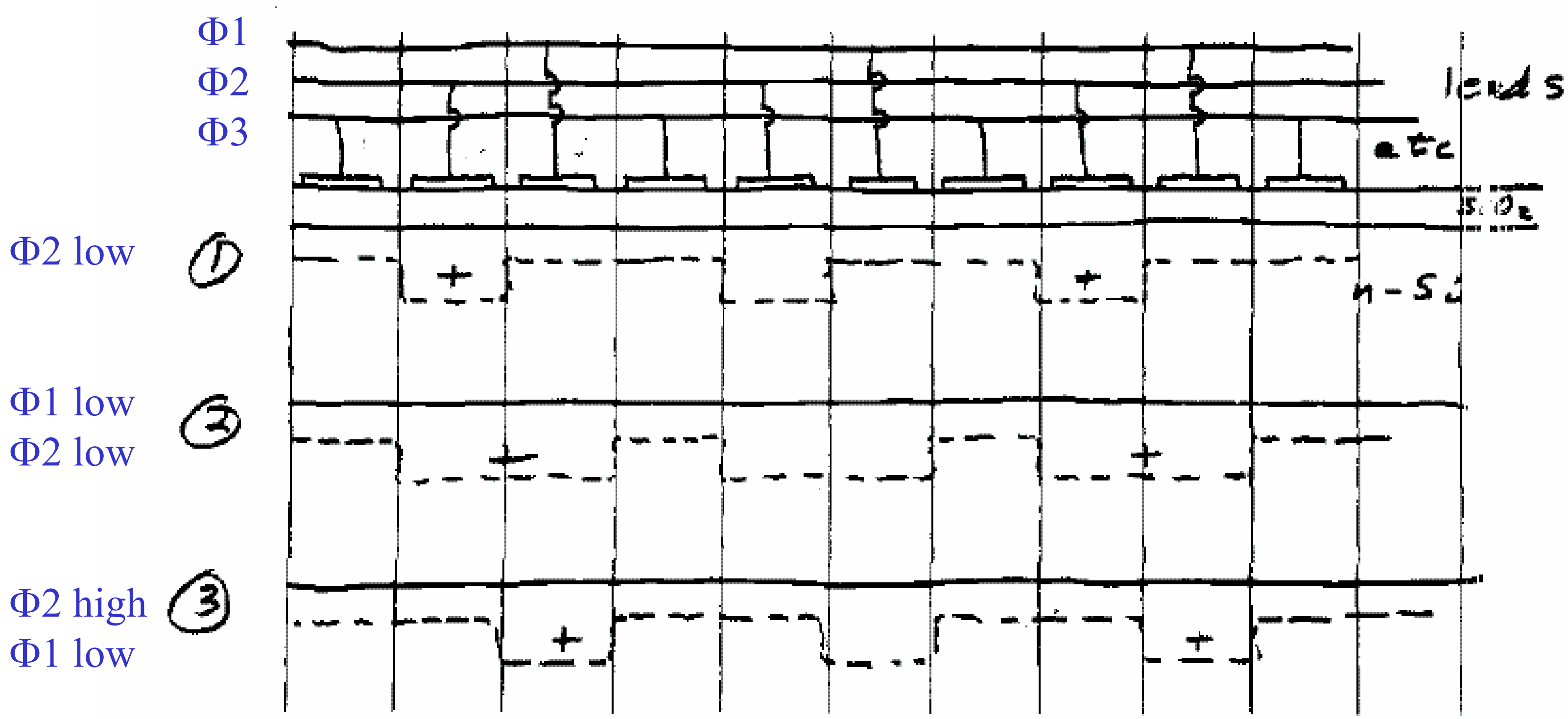
Dashed line denotes edge of depletion region

+ denotes storage of charge

Charge confined in potential wells formed by MOS capacitors

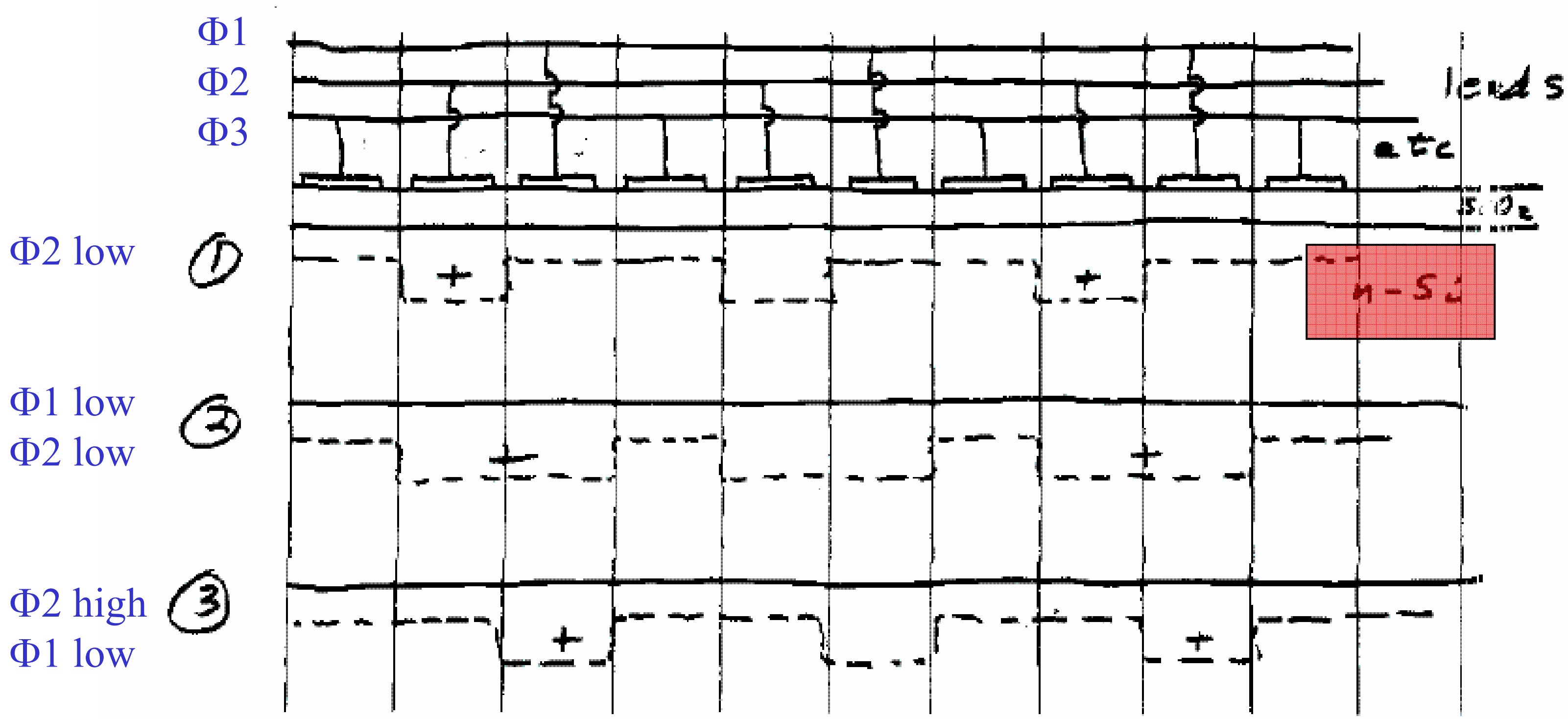
Charge transferred via clocking of closely spaced electrodes

3-phase CCD diagram (lab notebook drawing Sept. 1969)



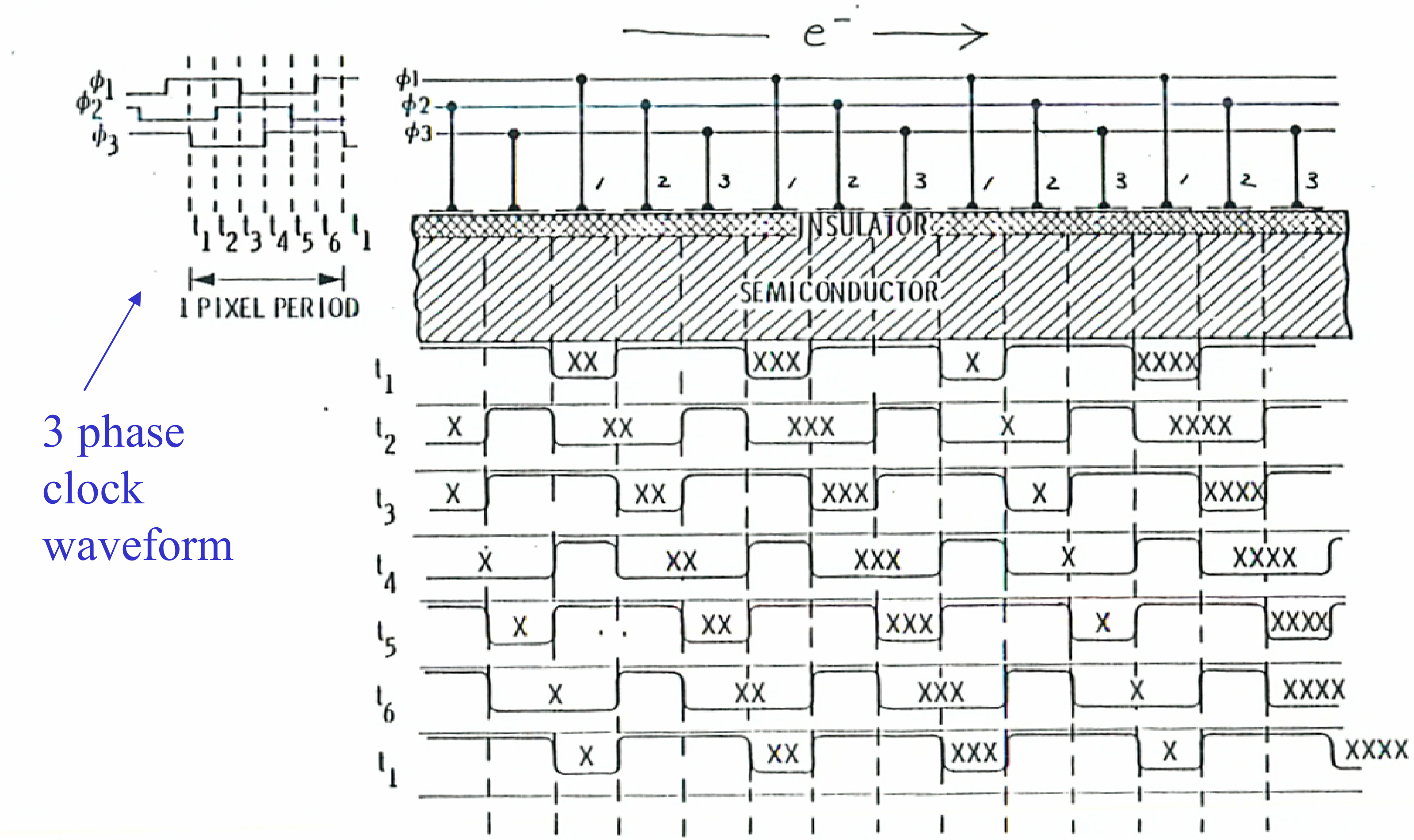
The 3-phase clocking arrangement shown above is still used in most modern scientific CCDs

3-phase CCD diagram (lab notebook drawing Sept. 1969)



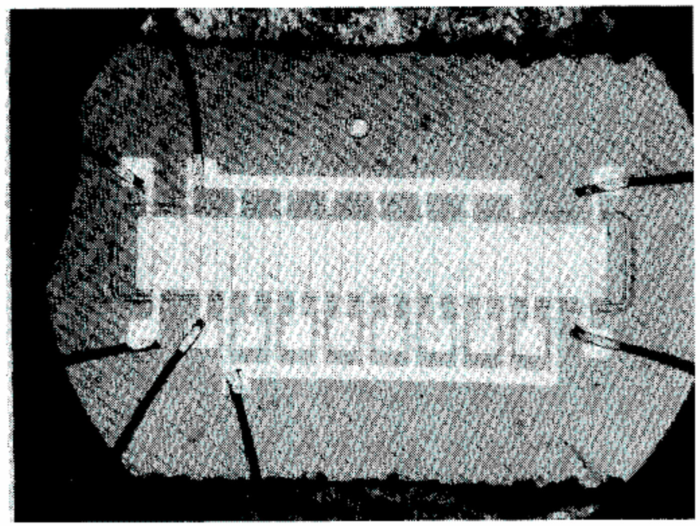
Note that the 1st CCD was p-channel
Information carried by holes, not electrons

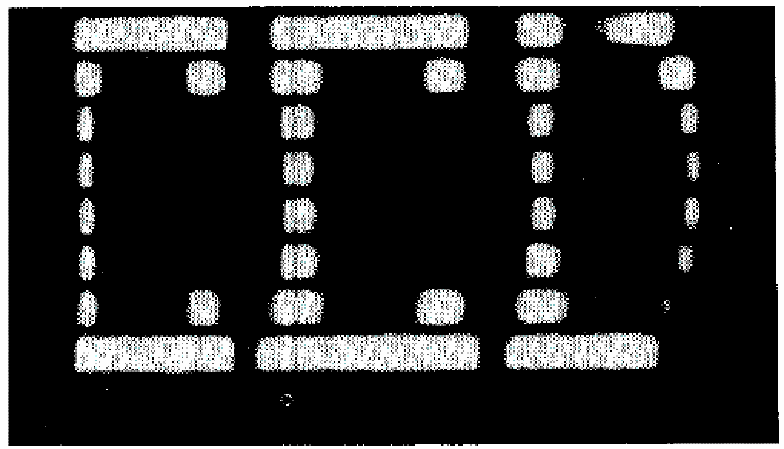
CCD Charge Transfer (3-Phase)



J. R. Janesick, *Scientific Charge-Coupled Devices*, SPIE Press, 2001

1^{st} light for the CCD

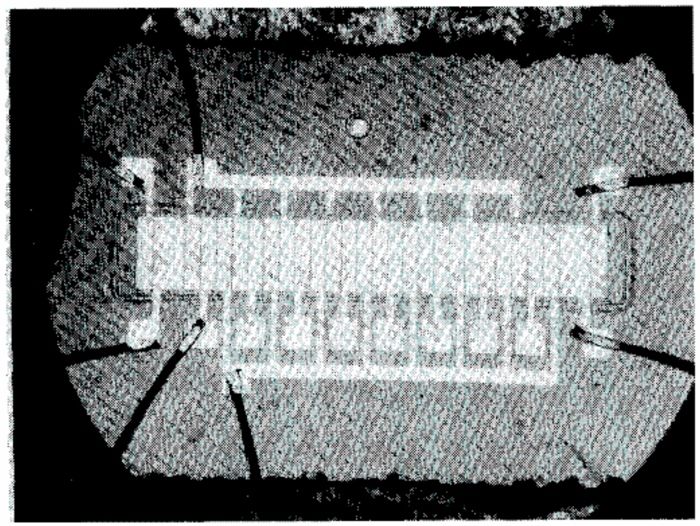


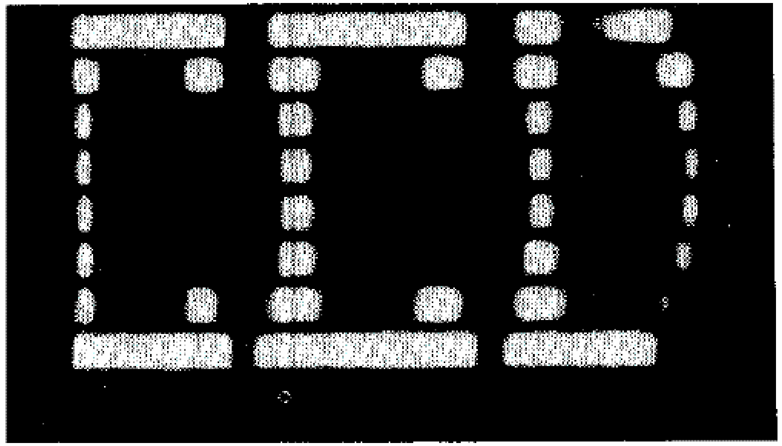


8 pixel, 3 phase metal gate CCD

M.F. Tompsett, G.F. Amelio, and G.E. Smith, "Charge-coupled 8 bit shift register," Appl. Phys. Lett., 17, 111, 1970

1st light for the CCD





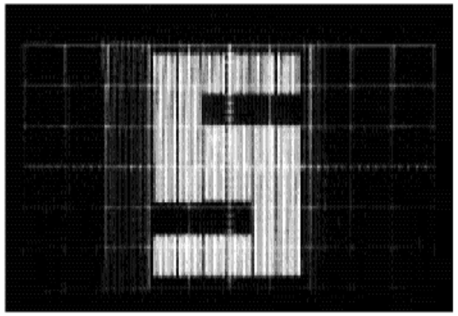
8 pixel, 3 phase metal gate CCD

M.F. Tompsett, G.F. Amelio, and G.E. Smith, “Charge-coupled 8 bit shift register,” Appl. Phys. Lett., 17, 111, 1970

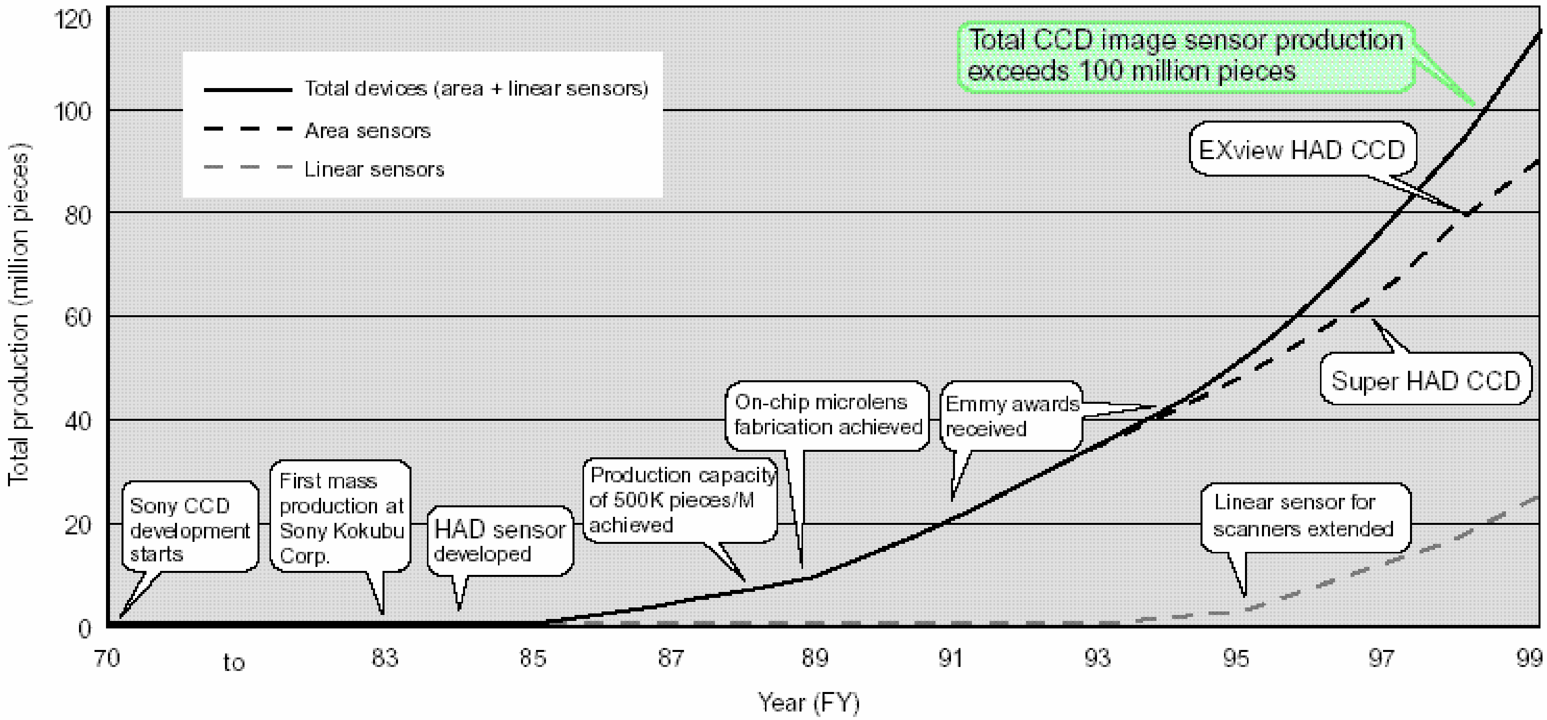
Amelio left Bell Labs in 1974 for Fairchild Semiconductor, which produced the first commercial CCD (100x100, 1973). Later became CEO of National Semiconductor and then Apple Computer.

Willard Boyle (left) and George Smith (right)

Sony CCD production up to 1999

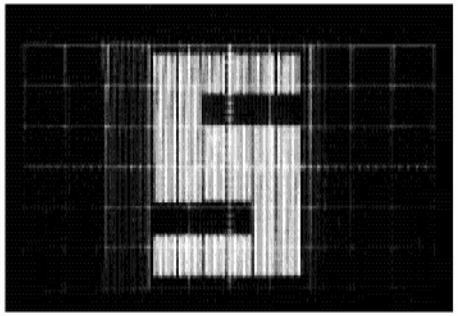


■ **Photograph 6 FT CCD Image with 8H × 8V (64 pixels) (1972)**

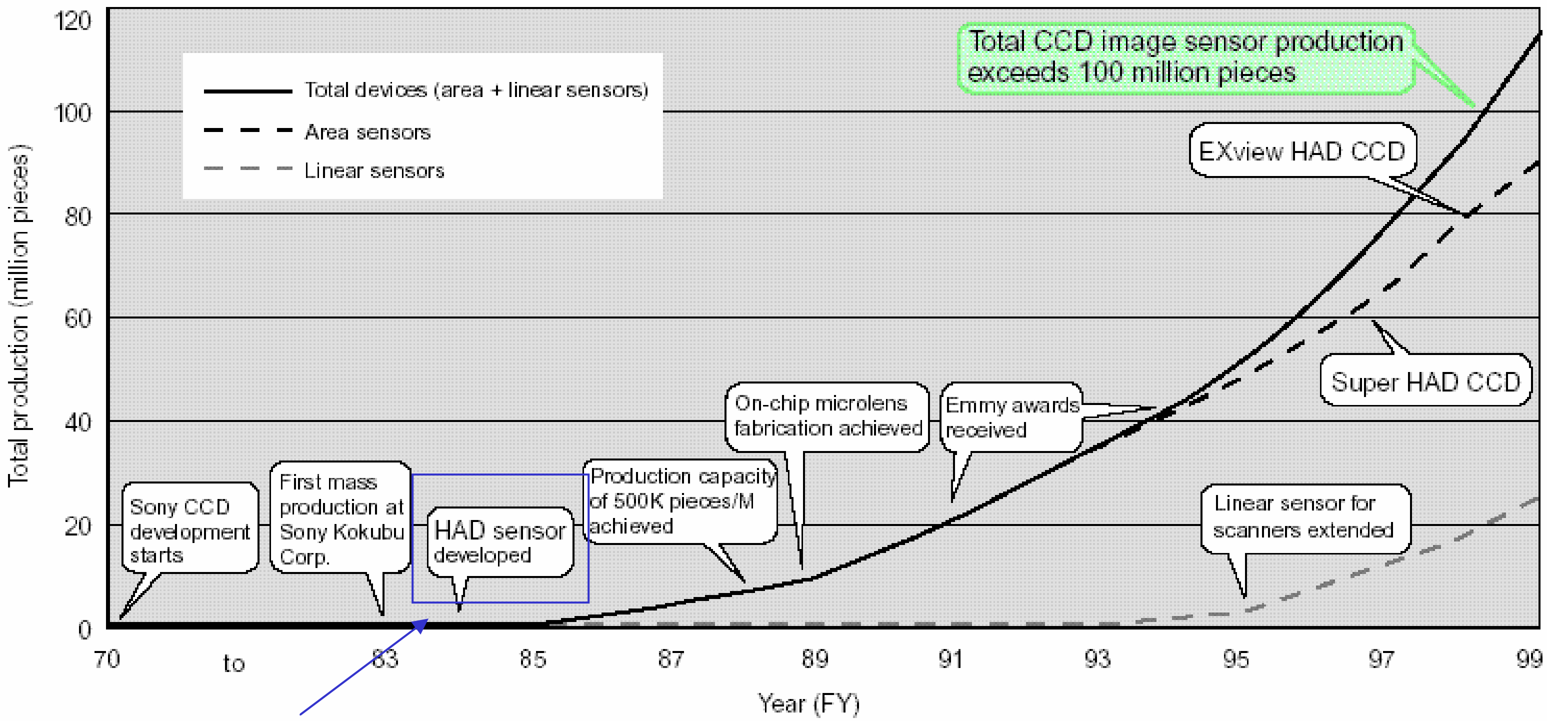


http://www.sony.net/Products/SC-HP/cx_news/vol19/pdf/tw.pdf

Sony CCD production up to 1999



■ **Photograph 6 FT CCD Image with 8H × 8V (64 pixels) (1972)**



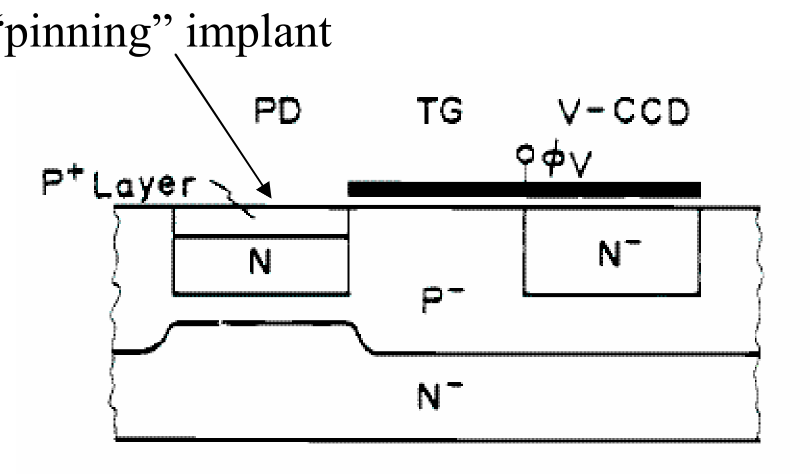
Considered significant milestone for Sony

Significant Milestones in CCD Development: Reduction of surface dark current

Dark current: Thermally-generated charge (aka “leakage current”)
Avoid depletion at silicon-SiO_2 interface, interface states and surface depletion lead to high dark current

Significant Milestones in CCD Development: Reduction of surface dark current

Dark current: Thermally-generated charge (aka "leakage current")
Avoid depletion at silicon-SiO_2 interface, interface states and surface depletion lead to high dark current



N. Teranishi *et al*, Int. Elec. Dev. Meeting, 1982.

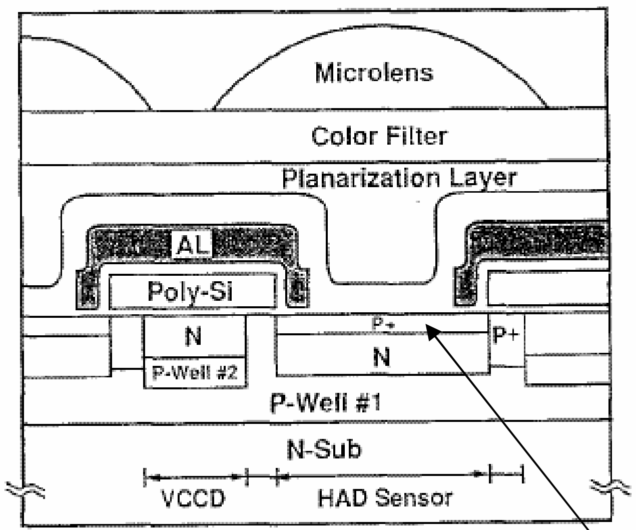


Fig.4 Cross-sectional view of the unit cell

HAD: Hole accumulation diode (p+ implant)

J. Furukawa et al, IEEE Trans. Consumer Elec., 38, 595, 1992.

Sony HAD with microlens

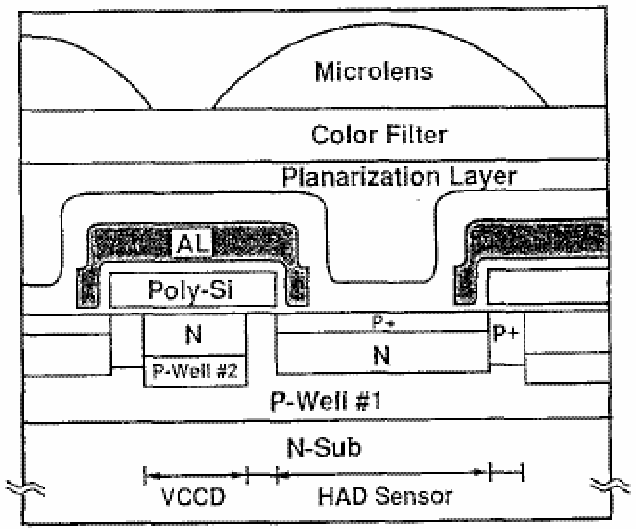


Fig.4 Cross-sectional view of the unit cell

HAD: Hole accumulation diode

Marketing with quantum mechanics

Interline transfer CCD shown above has limited fill factor due to Vertical CCD register with light shield – limits Quantum Efficiency

Development of Scientific CCDs

- **Introduced in 1972 by Bell Labs to NASA as potential detector for the proposed Large Space Telescope (later became Hubble Space Telescope)**
- **CCD development at NASA Jet Propulsion Laboratory**
  - **Commercial devices from RCA and Fairchild initially but both had drawbacks for scientific work**
  - **Fairchild CCD was interline transfer, limited fill factor**
  - **RCA CCD was back illuminated but surface channel (poor charge transfer)**
- **> 10 year NASA R&D effort between JPL and Texas Instruments to develop buried channel, back illuminated, frame transfer CCDs. Led to 800 x 800 CCDs for the Galileo mission and HST (Wide Field/Planetary Camera I).**
- **JPL "traveling camera" demonstrated at ground based observatories starting in 1976 (TI 400 x 400 CCD with 15 μm pixels)**

J. R. Janesick, *Scientific Charge-Coupled Devices*, SPIE Press, 2001

Texas Instruments thinned, back-illuminated CCD

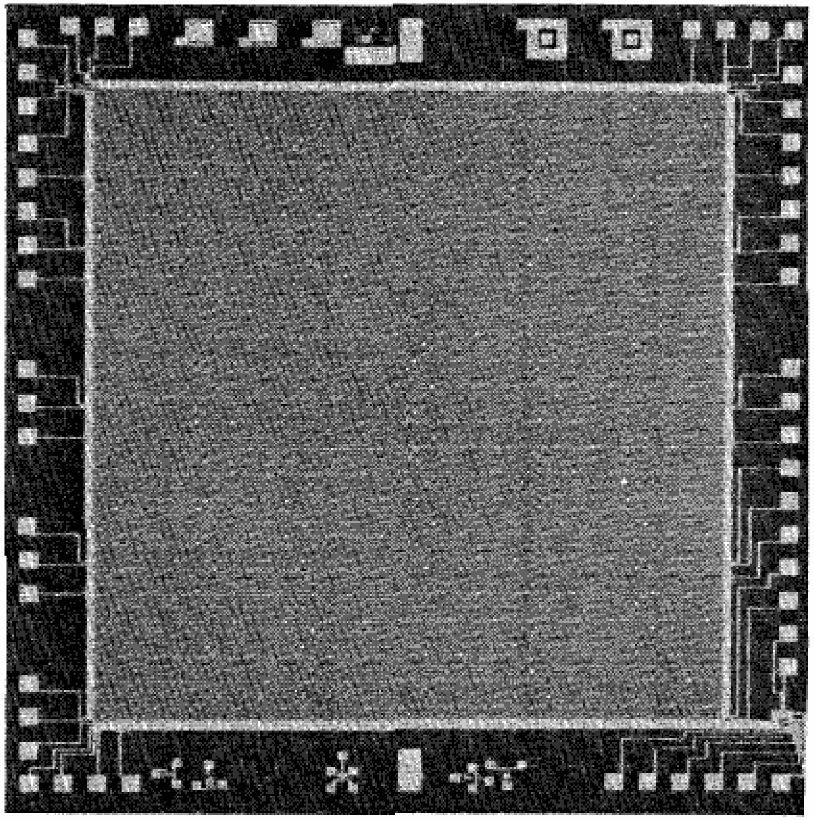


FIGURE 1–Photomicrograph of a 500 x 500 CCD chip.

FIGURE 5–Dark current pattern and imagery from a back-side illuminated 500 x 500 CCD.

M. Blouke et al "Three-phase, backside-illuminated 500 x 500 CCD," Int. Solid-State Circuits Conf., 1978

10 μm thick in imaging area. Preceded by the Bell Lab's Silicon diode array camera tube (believed to be the 1st thinned and back-illuminated semiconductor imaging device).

Significant Milestones in CCD Development: Invention of Correlated Double Sampling

IEEE JOURNAL OF SOLID-STATE CIRCUITS, VOL. SC-9, NO. 1, FEBRUARY 1974 1

Characterization of Surface Channel CCD Image Arrays at Low Light Levels

MARVIN H. WHITE, SENIOR MEMBER, IEEE, DONALD R. LAMPE, MEMBER, IEEE,

FRANKLYN C. BLAHA, MEMBER, IEEE, AND INGHAM A. MACK, MEMBER, IEEE

Abstract—The characterization of surface channel charge-coupled device (CCD) line imagers with front-surface imaging, interline transfer, and 2-phase stepped oxide, silicon-gate CCD registers is presented in this paper. The analysis, design, and evaluation of 1 × 64 CCD line arrays are described in terms of their performance at low light levels. The signal-to-noise(S/N) is formulated in terms of charge at the collection diode. A dynamic range of 80 dB and a noise equivalent signal (NES), where S/N = 1, of 135 electrons is achieved with a picture element time of 20 μs and an integration time of 1.32 ms in the absence of a fat zero. A unique CMOS readout circuit, which uses correlated double sampling within a picture element time window, removes the Nyquist noise of the reset switch, eliminates switching transients, and suppresses low-frequency noise to provide low-noise analog signal processing of the video signals. This paper describes the responsivity, resolution, spectral, and noise measurements on silicon-gate CCD sensors and CCD interline shift-registers. The influence of transfer inefficiency and electrical fat-zero insertion on resolution and noise is described at low light levels.

electrometer amplifier. Thus, with the CCD principle a photon-generated signal charge may be transported over long distances within the silicon and amplified at low input noise charge levels. Although the clock and video signal levels are noninteracting within the CCD imager, there is an interaction at the collection diode. We have developed a method of signal processing called *correlated double sampling* [5], [6] to remove the switching transients, eliminate the Nyquist noise associated with the reset switch/node capacitance combination, and suppress "$1/f$" surface-state noise contributions. With this technique we have realized the intrinsic noise equivalent signal (NES) of the CCD imager which is set by the thermal "shot" noise of the leakage current. In the CCD imager the video signal is processed within the array by an analog CCD shift register, whereas, in non-CCD arrays

M.H. White, D.H. McCann, I.A.G. Mack, F.C. Blaha, U.S. Patent 3,781,574, Dec. 1973

Invention of Correlated Double Sampling (cont')

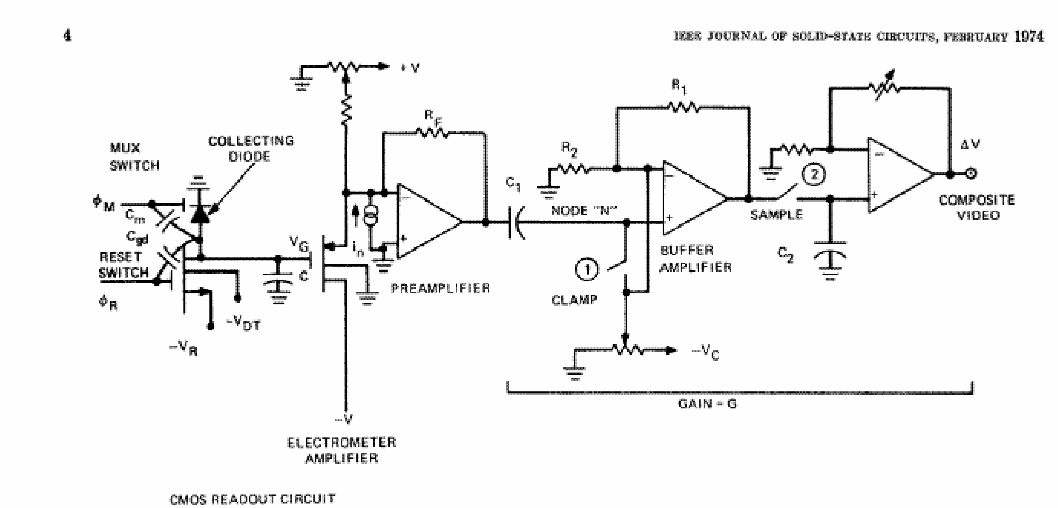


Fig. 5. Schematic diagram of a CDS processor with critical capacitances, noise sources, and signal nodes.

CDS removes reset (kTC) noise (85 electrons in an LBNL CCD)

Charge domain is key: Reset collecting diode
Measure reset level (with kTC noise)
Shift charge to collecting diode
Subtract to remove kTC noise, μs correlation

Kodak CMOS Pixel

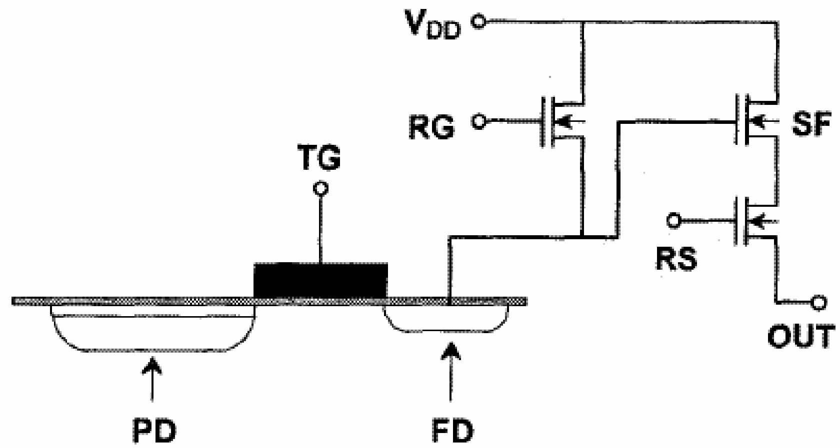


Fig. 1. Cross-section of pinned photodiode image sensor, showing the photodiode, transfer gate, and a schematic of the remaining transistors in the 4-transistor pixel cell.

R.M Guidash *et al*, IEDM, 1997

Modern day CMOS imagers used in high-end digital still cameras have a CCD-like pixel that allows for CDS processing

Canon, Nikon (Sony imager), Kodak

2004 Sony CMOS Pixel

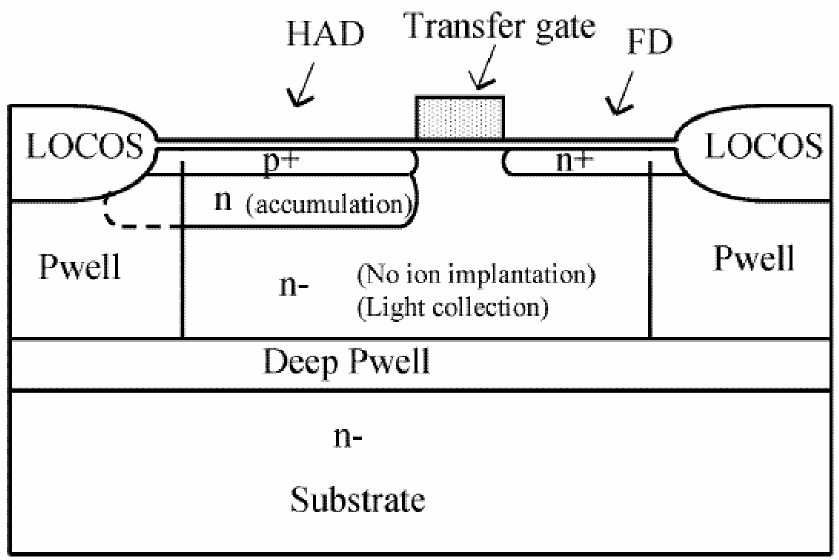


Figure 6.3.2: Cross section from HAD to FD.

K. Mabuchi *et al*, Int. Solid-State Circuits Conf., 2004

> 30 year old concepts (charge coupling, CDS) still valid and in use in modern day CMOS imagers

UC-Berkeley connections to CCD development

IEEE Trans. Elec. Dev., **21**, 712, 1974

Charge-Coupled Area Image Sensor Using Three Levels of Polysilicon

CARLO H. SÉQUIN, MEMBER, IEEE, FRANCIS J. MORRIS, SENIOR MEMBER, IEEE, THEODORE A. SHANKOFF, MICHAEL F. TOMPSETT, MEMBER, IEEE, AND EDWARD J. ZIMANY, JR.

Abstract—Charge-coupled area image sensors with 220 by 256 cells have been built using a three-phase overlapping electrode structure. Each of the three sets of electrodes is formed in a separate level of polysilicon which are isolated from each other by a thermally grown oxide. This approach relaxes the demands on mask making and photolithography that would otherwise be necessary and reduces the incidents of fatal shorts that render devices inoperable. The overlapping electrode structure results in stable performance and good transfer efficiency. The semitransparent polysilicon electrodes make the device usable with circuit side illumination although the spectral response is not very uniform. Average quantum efficiency in the visible part of the spectrum is 0.25. Measured resolution limits are 110 line pairs horizontally and 100 pairs vertically in accordance with present day PICTUREPHONE* specifications.

Manuscript received May 16, 1974.

C. H. Séquin, T. A. Shankoff, M. F. Tompsett, and E. J. Zimany are with Bell Laboratories, Murray Hill, N. J. 07974.
F. J. Morris is with Texas Instruments, Inc., Dallas, Tex. 75222.

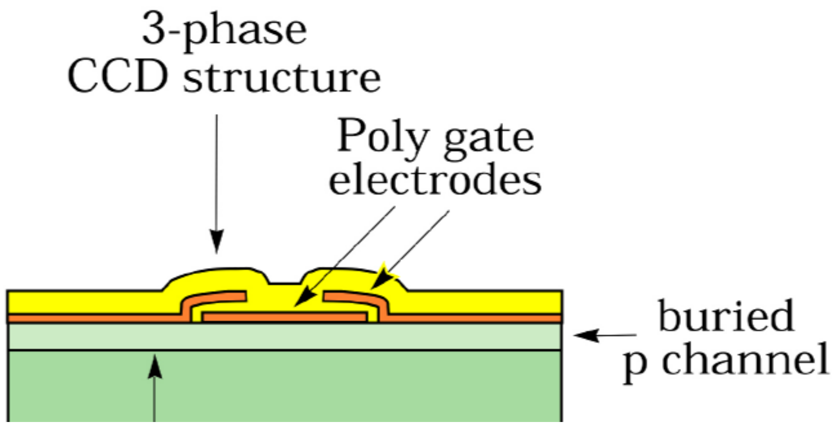
INTRODUCTION

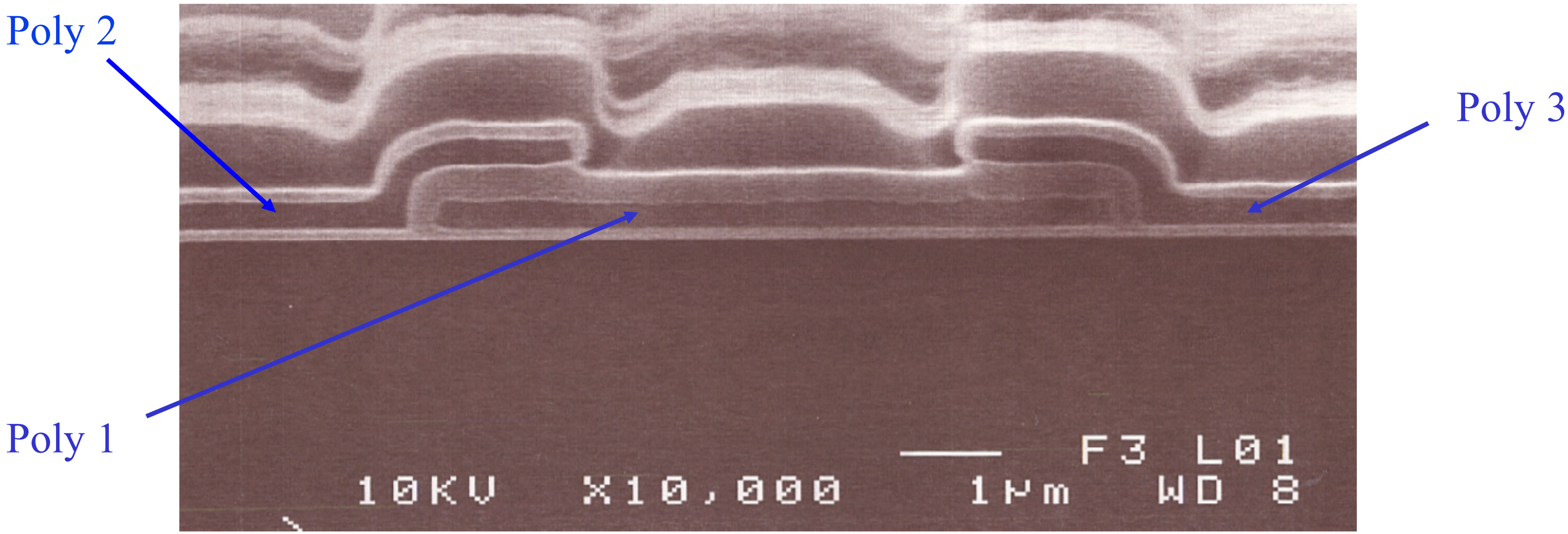
SOLID-STATE image sensors using the charge-coupled principle [1] were first constructed using a single level of metallization [2],[3]. In these devices a frame transfer organization [4] has been employed, in which the image is integrated in a separate imaging section and then, to prevent optical smearing, is quickly shifted in a parallel process along vertical columns into a storage area

* Registered service mark of American Telephone and Telegraph Company.

Carlo Sequin, UC-Berkeley Professor of Computer Science since 1977

3 - phase, overlapping triple polysilicon gate electrode pixel is the standard for scientific CCDs





UC-Berkeley connections to CCD development (cont’)

IEEE TRANSACTIONS ON ELECTRON DEVICES, VOL. ED-23, NO. 2, FEBRUARY 1976 215

Noise in Buried Channel Charge-Coupled Devices

ROBERT W. BRODERSEN AND STEPHEN P. EMMONS, MEMBER, IEEE

Abstract—In this paper we discuss the noise measured at the output of a buried channel charge-coupled device (BCCD) linear shift register. The measured noise arises from four sources; the electrical insertion of signal charge, the output amplifier, dark current, and bulk state trapping. In making these measurements the concept of correlated double sampling was used in an output circuit which had a noise level which was equivalent to less than 30 noise electrons. A critical component in this output was a low noise MOSFET which was achieved by use of the buried channel technology. A low noise input structure for electrical insertion of signal charge was used which introduced a signal which had a noise level which ranged from less than 10 e^- to as high as 60 e^- depending on the size of the signal charge. The dark current noise was found to be well characterized as a shot noise and levels on the order of 20 e^- were measured. The above low noise levels made possible direct measurement of the noise due to bulk state trapping, and depending on the signal size and clock rate noise levels were measured which ranged from less than 10 to over 100 noise electrons. One of the most important bulk traps was found to be due to gold impurities which had a density of $\sim 2 \times 10^{11}$ cm^{-3}.

input noise and bulk state trapping. In order to separate the contributions from these two sources it is necessary to make use of their characteristic spectral distributions. This is possible because the correlated nature of bulk state trapping noise [5] results in a suppression of bulk trapping noise at low spectral frequencies so that the noise measured at these frequencies is due only to the spectrally flat input noise.

II. Test Device Characteristics

A 150 stage linear BCCD was used in these noise measurements which uses overlapping four-phase electrodes (600 charge transfers) with an electrode size of 7.5 μm × 125 μm. The metallization masks were compatible with both Al-Al_2O_3-Al [6] and poly-silicon-aluminum double level metal systems [7]. Both of these metallization methods were used in fabrication without noticeable differences in device operation. The

Robert Brodersen, UC-Berkeley Professor of Electrical Engineering since 1976

UC-Berkeley connections to CCD development (cont’)

IEEE TRANSACTIONS ON ELECTRON DEVICES, VOL. ED-23, NO. 2, FEBRUARY 1976 215

Noise in Buried Channel Charge-Coupled Devices

ROBERT W. BRODERSEN AND STEPHEN P. EMMONS, MEMBER, IEEE

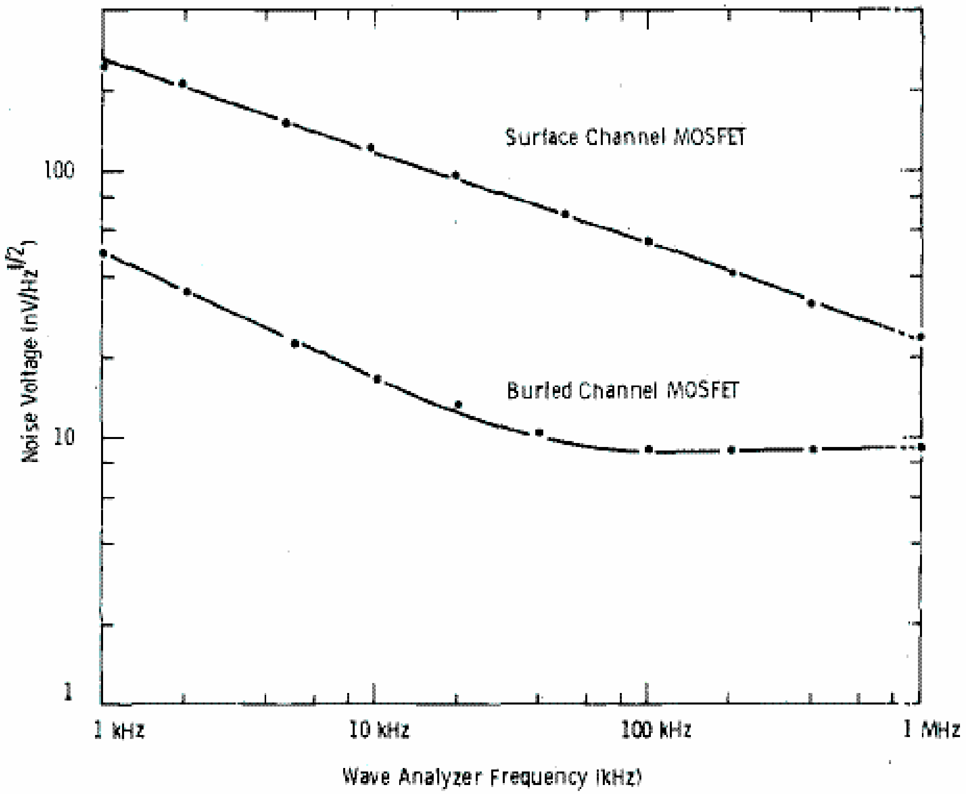
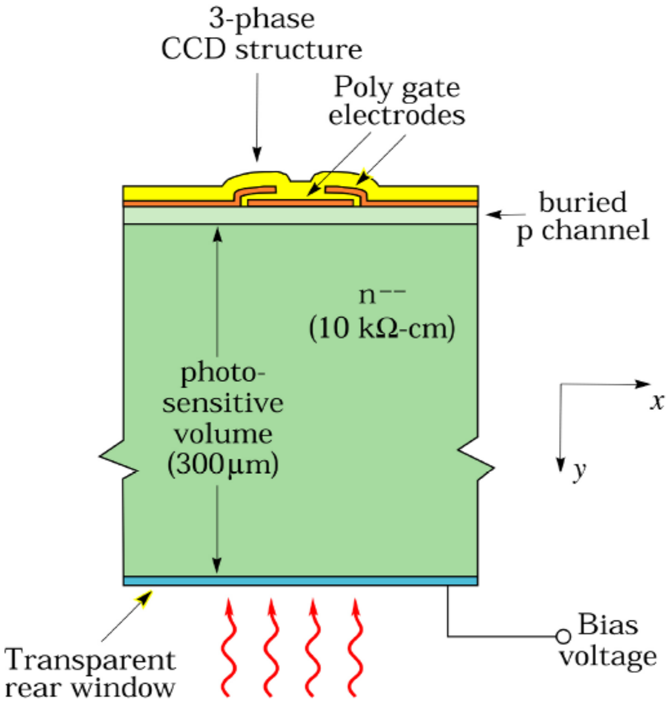


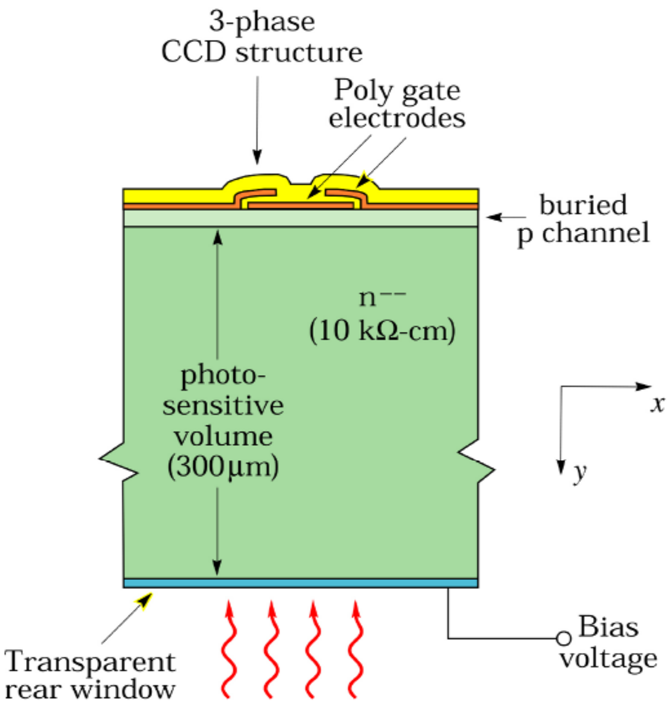
Fig. 4. Comparison of noise voltage for buried and surface channel MOSFET’s.

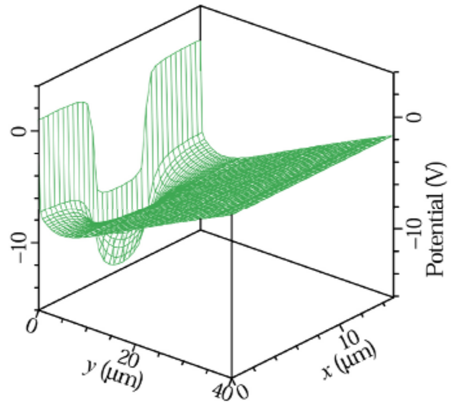
Fully depleted, back illuminated CCD



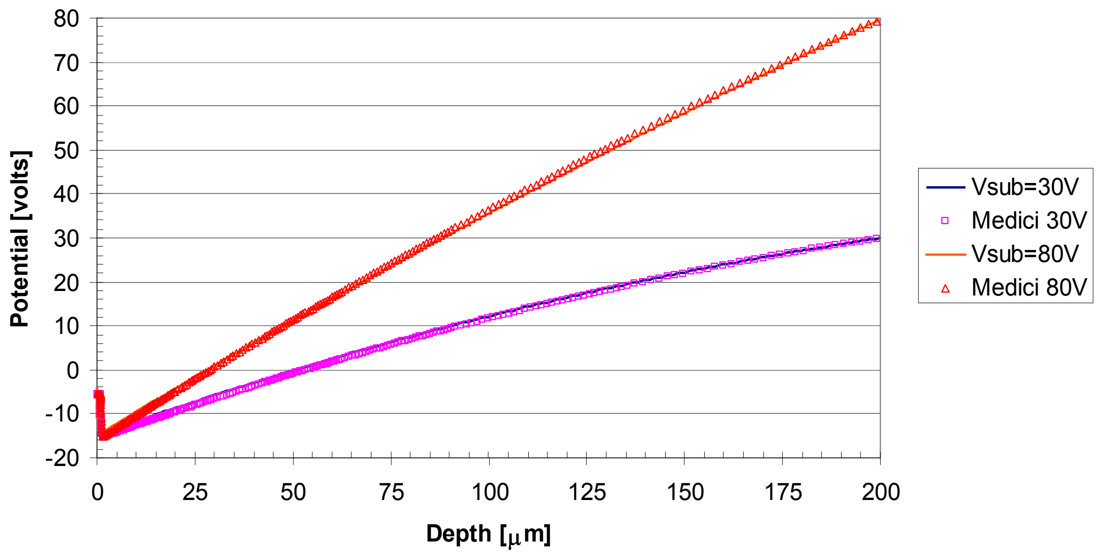
1) Conventional CCD fabricated on thick, high-resistivity silicon substrate
2) Substrate bias voltage used to fully deplete substrate
   Merging of p-i-n and CCD technology
3) High near-infrared QE and elimination of fringing
4) Control of PSF via thickness and substrate bias voltage
5) P-channel CCD – improved radiation hardness

Fully depleted, back illuminated CCD





MEDICI 2-D simulation



Potential versus depth along center of pixel
1-D potential calculations and Medici simulation

S. E. Holland, D.E. Groom, N.P. Palaio, R.J. Stover, M. Wei,
IEEE Trans. Elec. Dev., vol. 50, no. 1, p. 225, January 2003

Basic functions of a CCD

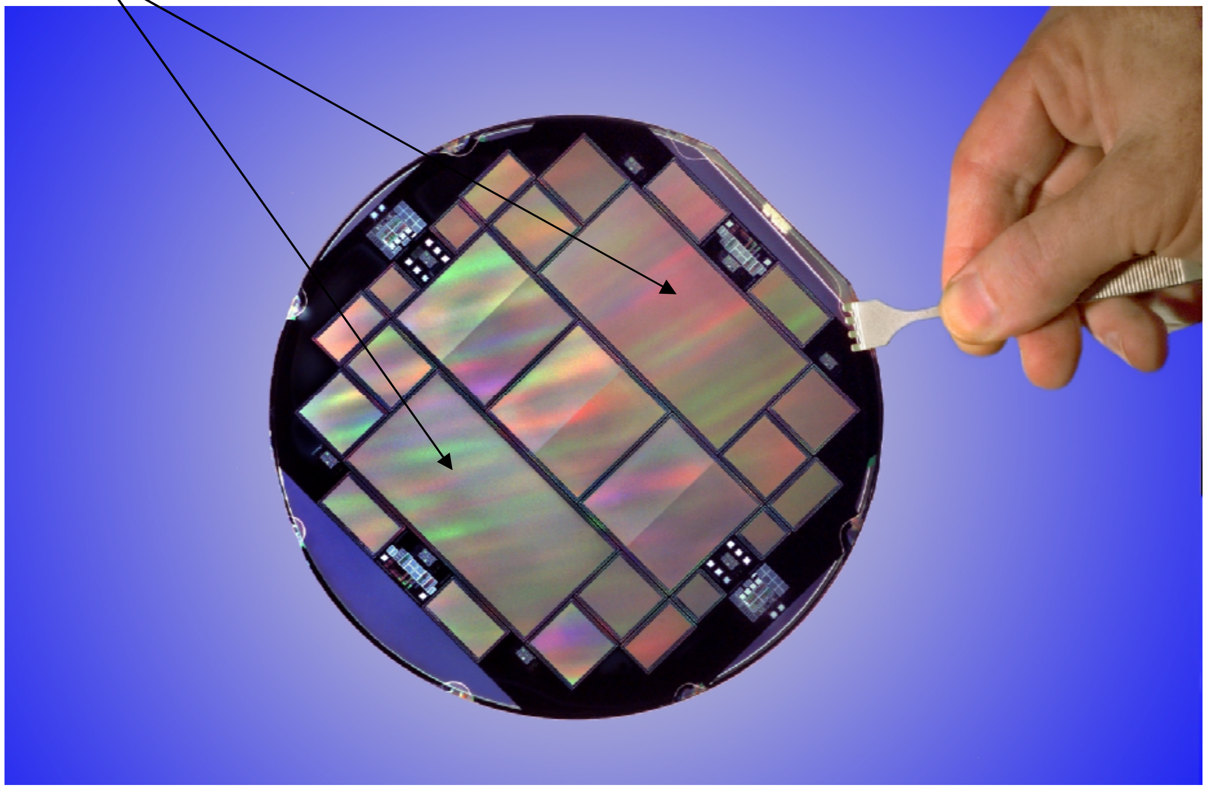
- Charge generation
  - Conversion of light to electron-hole pairs
  - Figure of merit: **Quantum Efficiency (QE)**
- Charge collection
  - Transport of charge to CCD potential wells
  - Figure of merit: **Point Spread Function (PSF)**
  - Spatial resolution issue
- Charge transport
  - Charge shifting to output amplifier
  - Figure of merit: **Charge Transfer Efficiency (CTE)**
- Charge measurement
  - Figure of merit: **Noise**

Unique features of fully depleted, back-illuminated CCDs fabricated on high-ρ silicon

- Charge generation
  - High near-infrared QE
  - Lack of fringing
- Charge collection
  - Tunable and generally good spatial resolution due to an electric field throughout the volume of the CCD
- Charge transport
  - High-purity silicon generally free of traps, high CTE
  - P-channel CCD more resistant to the damaging effects of space protons
- Charge measurement

Characteristics of Scientific CCDs used in Astronomy

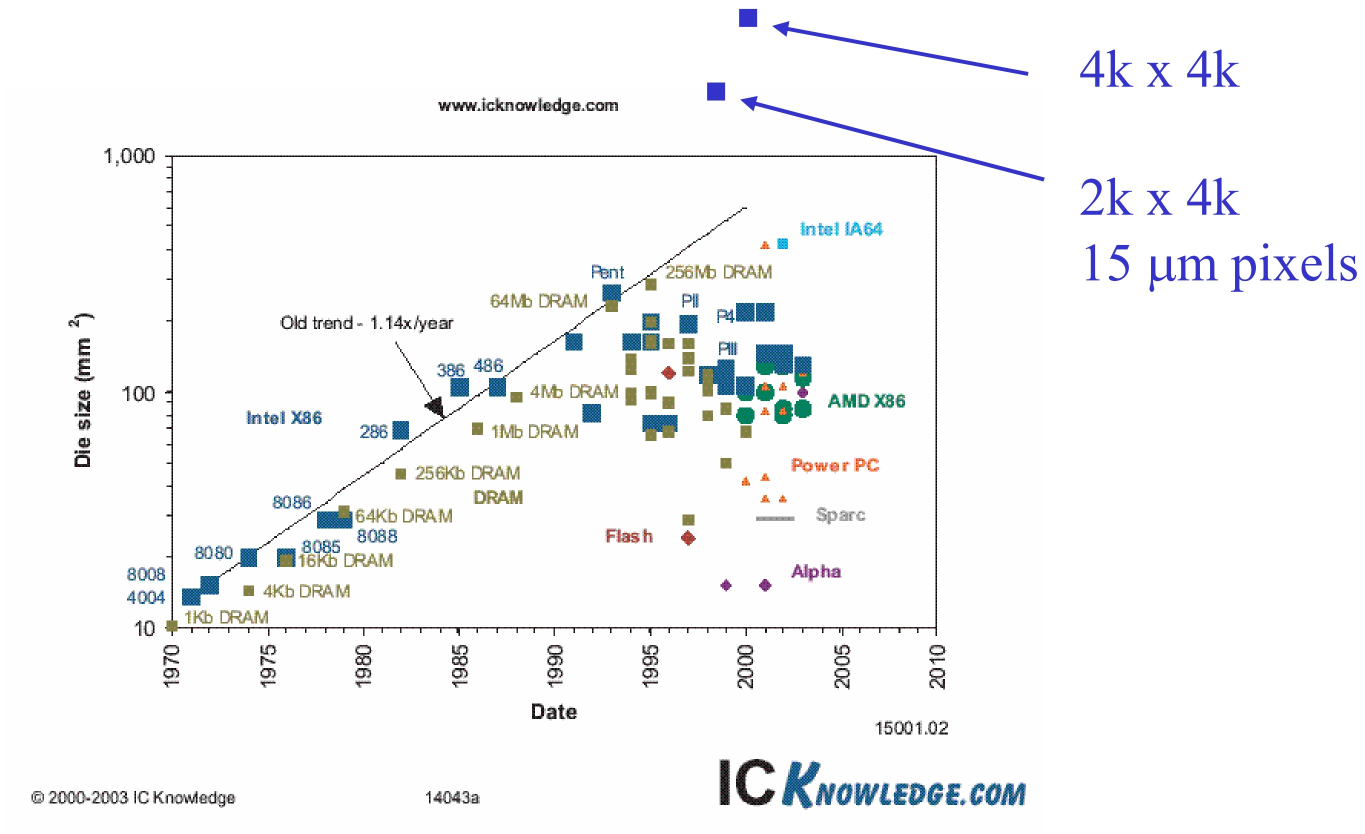
- **Large format and area**
  - **2048 x 4096, 4096 x 4096 (15 μm pixel)**



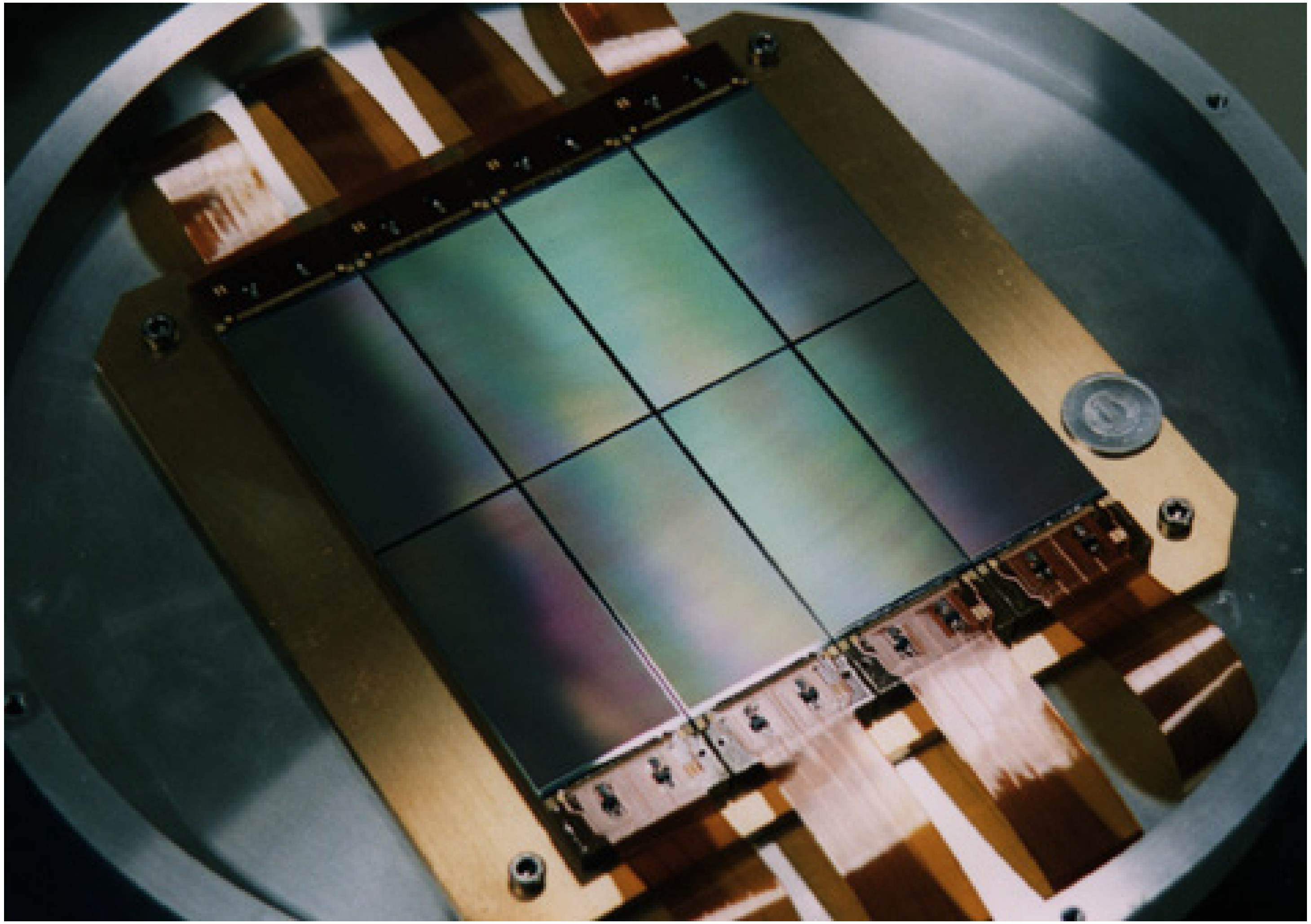
150 mm diameter wafer fabricated for LBNL by DALSA Semiconductor

Characteristics of Scientific CCDs used in Astronomy

- **Large format and area**
  - **2048 x 2048, 2048 x 4096, 4096 x 4096 (15 μm pixel)**



Astronomy Cameras: Subaru Suprime-CAM



8 x 2048 x 4096 CCDs from MIT/Lincoln Laboratory

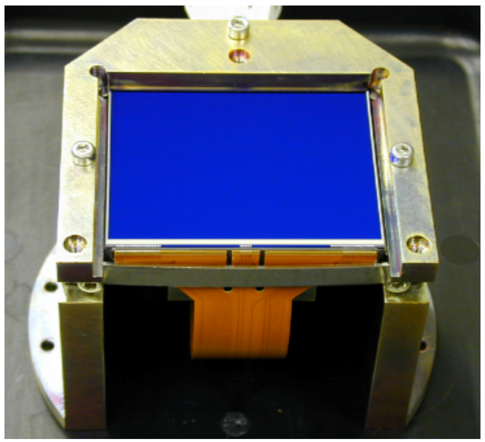
Astronomy Cameras: CHFT Megacam

40 2048 x 4612 CCDs
13.5 μm pixels
340 Mpixels total
Operated at –120C
CCDs from e2V

Characteristics of Scientific CCDs used in Astronomy

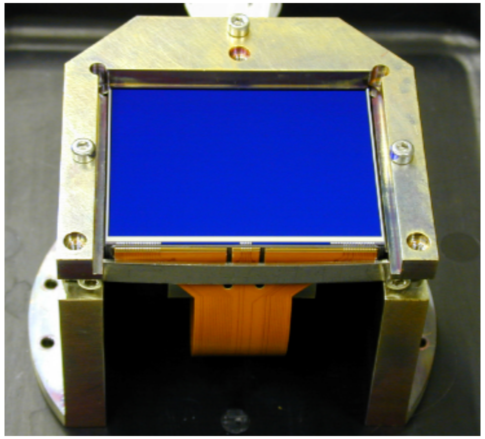
- **Cost**
  - **Presently available from 2-4 commercial CCD vendors**
  - **> $50-80k per 2048 x 4096 astronomical grade device**

Back-illuminated CCD



What else can you buy for $50-80k?

Back-illuminated CCD



Single CCD
prices

Volume prices

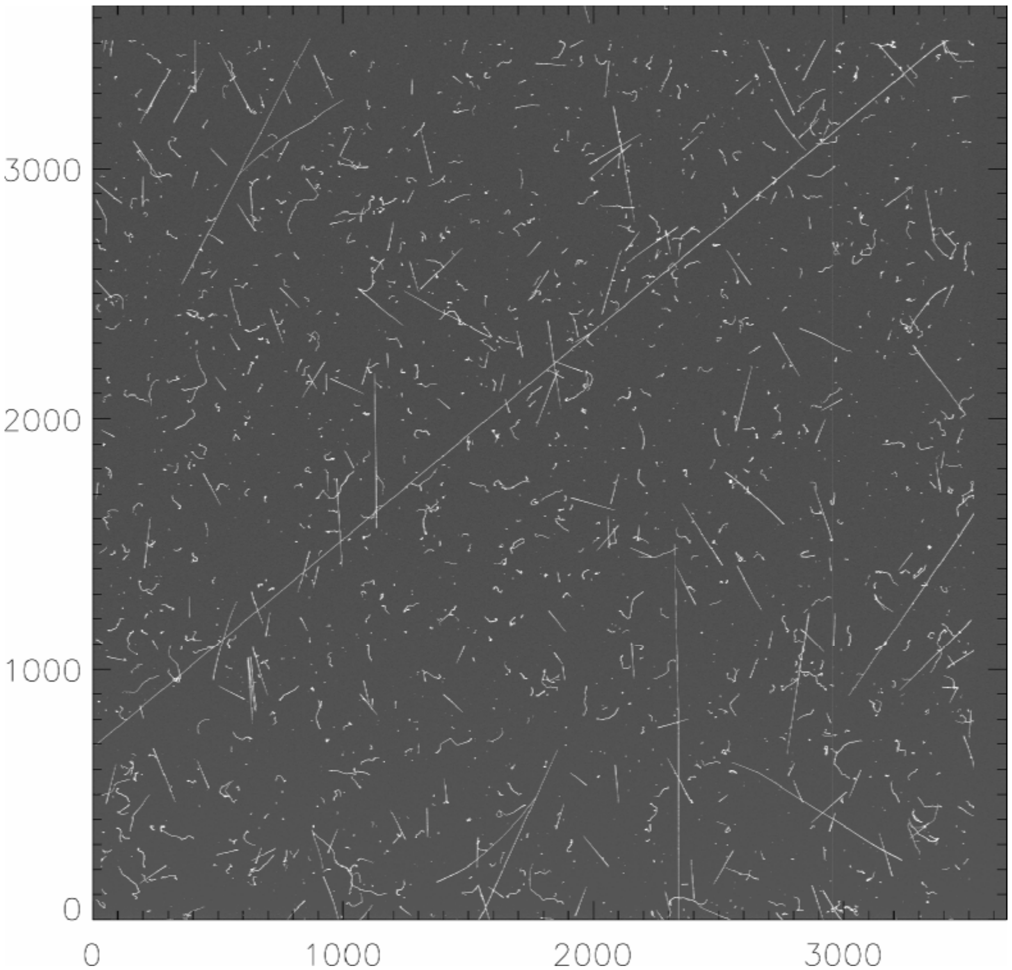
"Oh Lord, Won't you buy me a Mercedes Benz?
My friends all drive Porsches, I must make amends."

Janis Joplin, 1971

Characteristics of Scientific CCDs used in Astronomy

- **Cooled**
  - **-90C to -140ºC**
  - **Minimize dark current and associated shot noise**
  - **Typical dark current : few electrons/pixel-hour**
  - **Allows for long exposures (minutes to hours)**

<u>30 minute</u> dark exposure at –140C: Front-illuminated, fully depleted, 650 μm thick, 12.3 Mpixel LBNL CCD



CCD 107409.16.11 at V_{SUB}=206V (10.5 μm pixels)

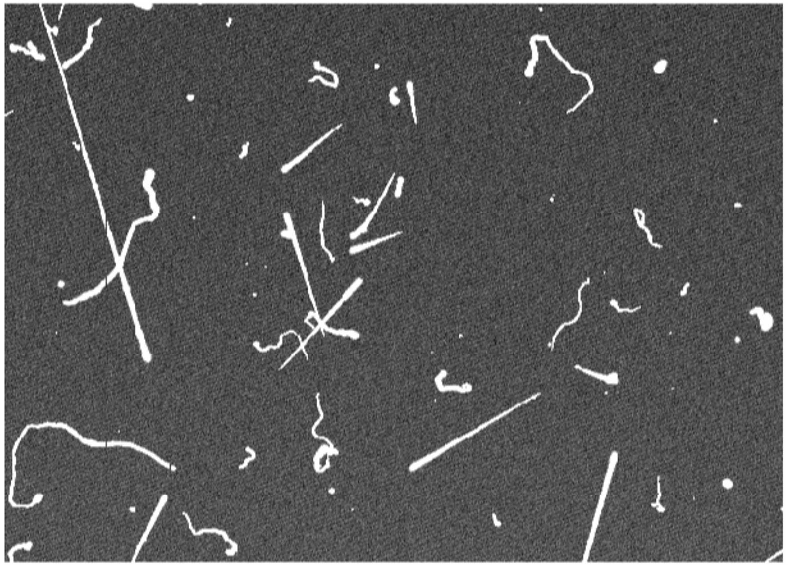
0.6 e-/pixel-hour dark current

Background from cosmic rays and Compton electrons

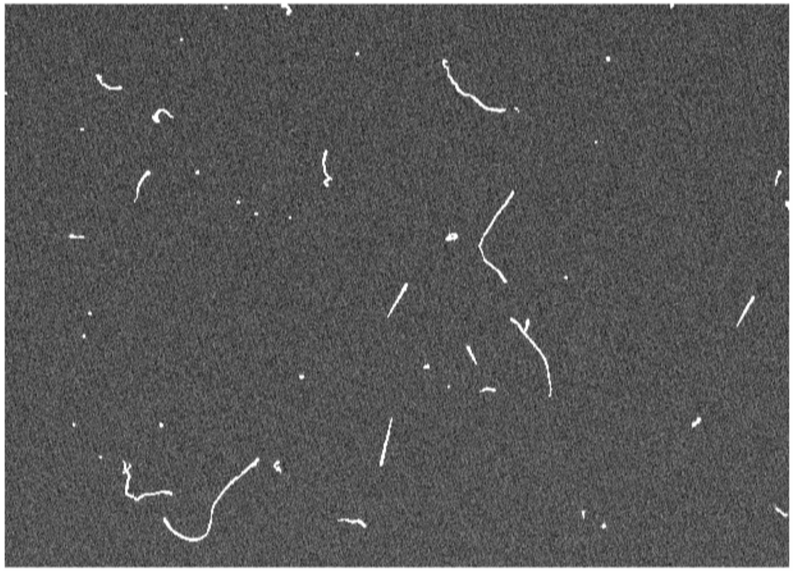
Long tracks due to thick depletion regions

Unique "feature" of thick, fully-depleted CCDs derived from HEP charged-particle detectors

Cosmic ray/Compton Electron Gallery



107409.14.7 650 μm thick



105868.15.11 200 μm thick

Background essentially disappears if the LBNL CCD is operated deep underground (180 meters rock) in a special lead vault

LBNL Low Background Facilities

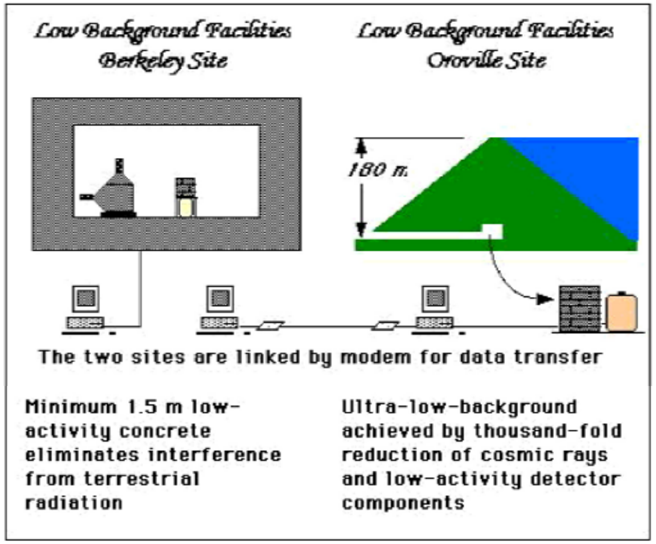
The Low Background Facilities are laboratories especially designed to shield out cosmic and terrestrial radiation to allow the ultra-sensitive analysis of radioactivity in samples normally considered non-radioactive. Examples of this are building materials and electronic components for neutrino and dark matter detectors, environmental samples, and cosmic ray activated samples.

- *LBF Overview*
- *LBF User Info*
- *LBF Staff*
- *LBF Publications*
- *Neutron Activation*
- *Field Measurements*
- *Annual Reports*
- *NSD Home Page*
- *LBNL Home Page*
- *Disclaimer*

Site Webmaster:

Dick McDonald: rjmcdonald@lbl.gov

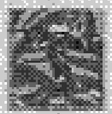
Version 2/17/99



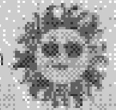
LBNL Low Background Facility key to determining the terrestrial source (U/Th/K etc) of the Compton background (Richard McDonald and Al Smith)

ENTERTAINMENT
Shanghai Noon
Mission Impossible 2 - 8A

SPORTS
Prep Track NSCIF
1C



WEATHER
Sunny and Mostly clear with warm daytime temperatures 88-57



OROVILLE
MERCURY-REGISTER

AN EDITION OF THE ENTERPRISE-RECORD, Oroville, Ca. www.orovillemr.com SATURDAY, May 27, 2000 VOLUME 127, NO. 127 47¢ plus tax

Astronomers go deep in dam to see more out there

BY RICK LONGLEY
Education Writer

It may seem strange that scientists who study the stars would go 600 feet underground to do research, but that's exactly what is happening at the Edward Hyatt Powerhouse in Oroville.

Astronomers from the University of California at Santa Cruz visited the power facility Monday and Tuesday to conduct experiments on CCD or Charged Coupled Device parts to be used in their telescope at the Lick Observatory.

They were invited by Lawrence-Berkeley Laboratory scientists Belle Hurley and Al Smith to use "Merlin," a lead-shielded computer, to test for radiation in the telescope materials.

For the past decade, Hurley and Smith have been researching radiation levels in everything from space shuttle parts to computer silicon chips under Oroville Dam.

They have a small upstairs corner in the powerhouse where "Merlin" and their other equipment is located. It is called Lawrence Berkeley National Laboratory's Low-Background Facility. This is all done in cooperation with the California Department of Water Resources which runs the powerhouse.

The scientists are there because working under the dam blocks out the sun's rays and other forms of natural radiation that would interfere with their radioactivity research. Merlin detects minute traces of radiation, so it's important not to have outside radiation sources interfering with its readings.

UC. Santa Cruz research astronomers Richard Stover and Mingzhi Wei were joined by senior development engineer Bill Brown and LBL staff scientist Steve Holland at the powerhouse to do some initial research and take their findings back to Santa Cruz.

A CCD is a device that turns light into electrical signals which the computer can measure. It is used in digital cameras and also in telescopes on a much larger scale than in cameras, Stover said.

Stover and other group members are developing a readout system for the telescope that takes the place of "traditional" photographic emulsion. The system uses the CCD sensor which registers the optical information information directly into computer-compatible format. CCDs are made from semiconductor-grade silicon wafers, using the same technologies employed to make semiconductor chips, Smith said.

However, the astronomers and engineers said they have some performance things they are examining. Experience with the operating CCD readout system has shown the presence of numerous "background" radiation (BKG) tracks when the sensor is not exposed to any external illumination or light from the stars. The scientists believe some of these BKG tracks belong to cosmic rays, and they suspect many other BKG events may be caused by radioactivity in materials close to the CCDs.

To test that idea, Stover and his colleagues brought a computer disc to Oroville that had recorded light and radiation spots at Santa Cruz.

They compared these spots, or rays and electrons, with images collected on another disc sitting in the research station in Oroville. It still had some extra images. Then, the scientists put the CCD inside Merlin and found very few spots on the computer screen due to its lead screen.

According to Stover, the object of the research is to find ways to stop atmospheric radiation from blocking out distant stars on the telescope. This background contamination from local radiation recordings annoys astronomers, he said.

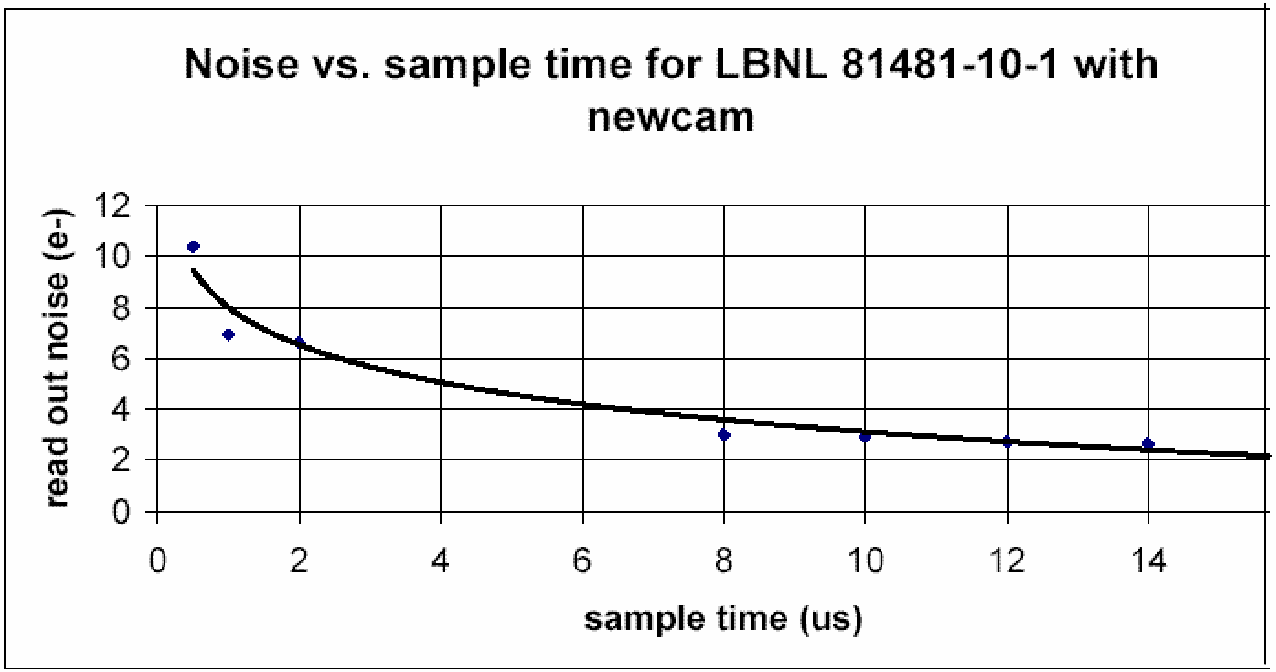
So that is why they came to Oroville to use "Merlin," and Smith assisted with some of the research as well.

He told Stover and the others, plastic parts in the CCDs were not good for eliminating particle interference, so Stover concluded they'd probably get rid of them.

Characteristics of Scientific CCDs used in Astronomy

- **Slow readout**
  - **Frame readout time can be minutes (50 - 100 Kpixels/sec)**
  - **Noise proportional to (Pixel Rate)$^{1/2}$**
  - **Typical noise : < 5 electrons rms**

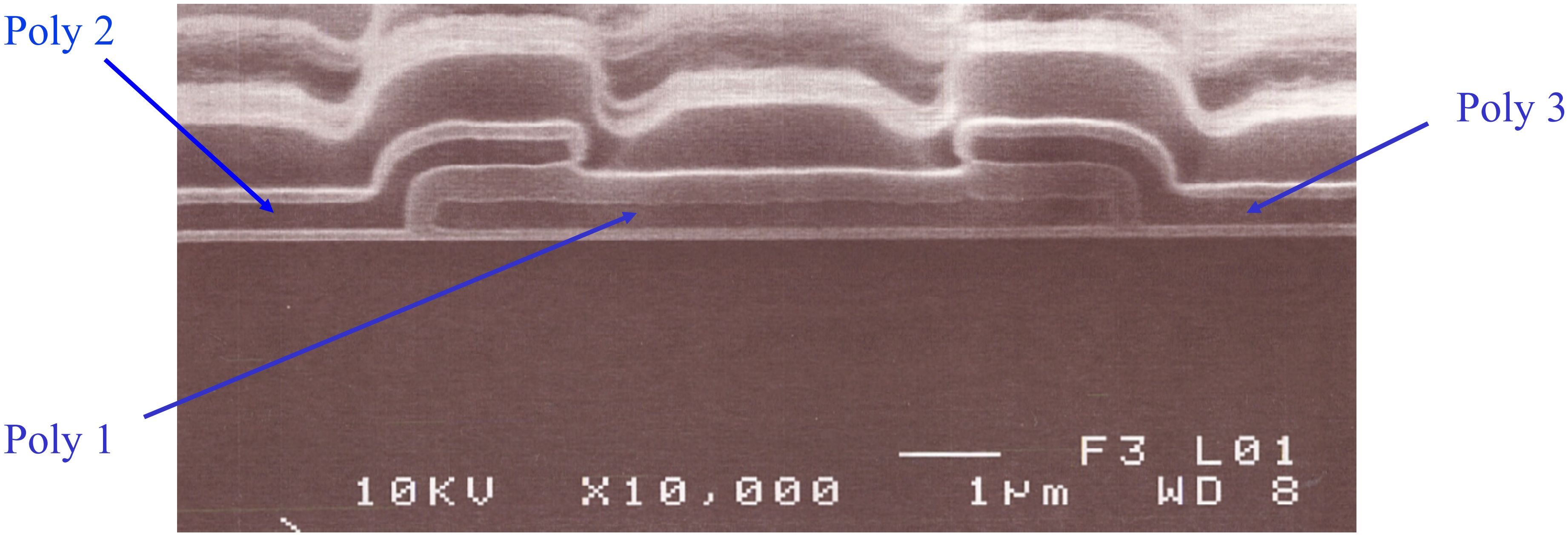
Noise measurement: LBNL 2k x 4k



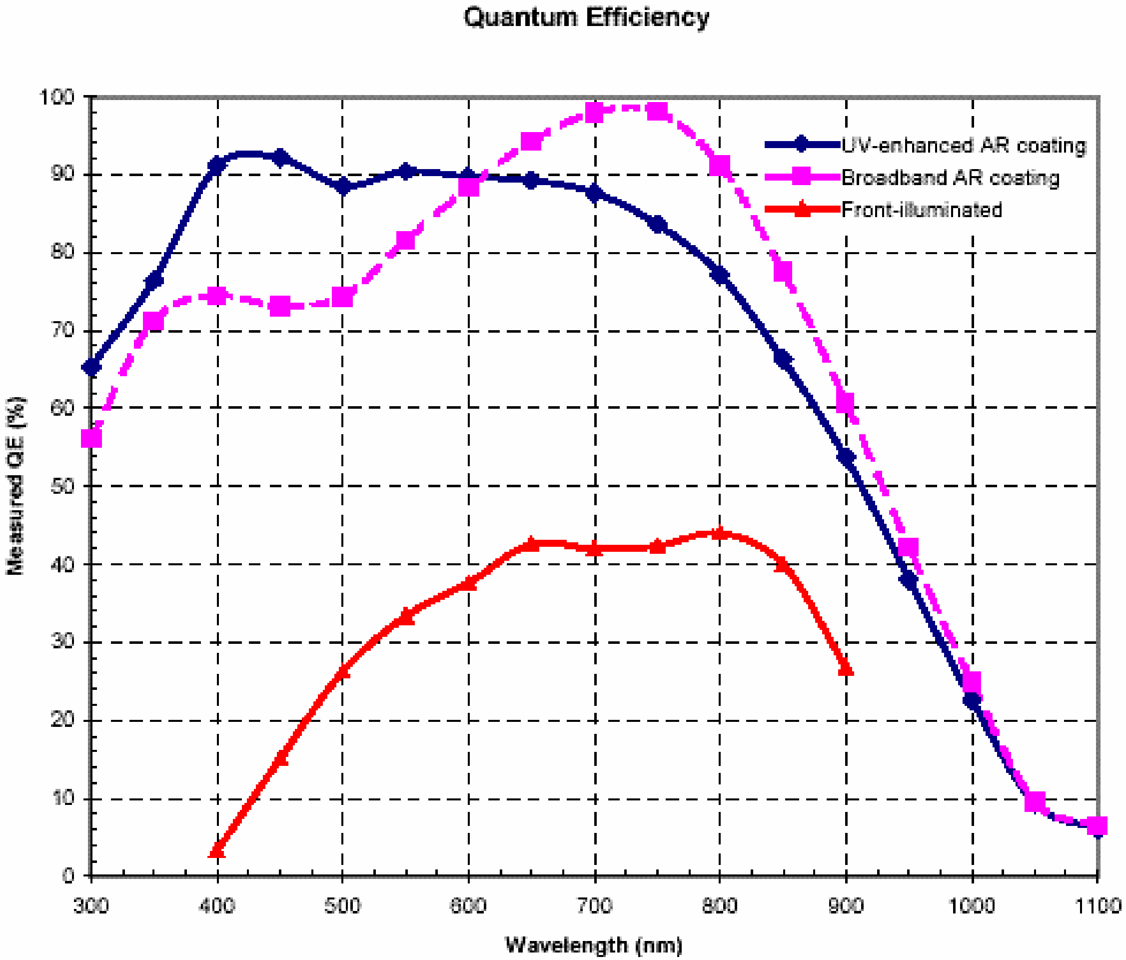
Measurement from Lick Observatory
Sample time refers to correlated double sampling time

Characteristics of Scientific CCDs used in Astronomy

- **Back illuminated**
  - **Necessary because front-illuminated operation results in significant light absorption in the polysilicon gate electrodes, especially in the blue**
  - **High quantum efficiency (peak > 90%, film 1%)**



Quantum Efficiency: Front vs Back illumination



Fairchild Imaging CCD datasheet

Unique features of fully depleted, back-illuminated CCDs fabricated on high-ρ silicon

- Charge generation
  - **High near-infrared QE**
  - **Lack of fringing**
- Charge collection
  - Tunable and generally good spatial resolution due to an electric field throughout the volume of the CCD
- Charge transport
  - High-purity silicon generally free of traps, high CTE
  - P-channel CCD more resistant to the damaging effects of space protons
- Charge measurement

Unique characteristics of back-illuminated CCDs fabricated on high-resistivity substrates

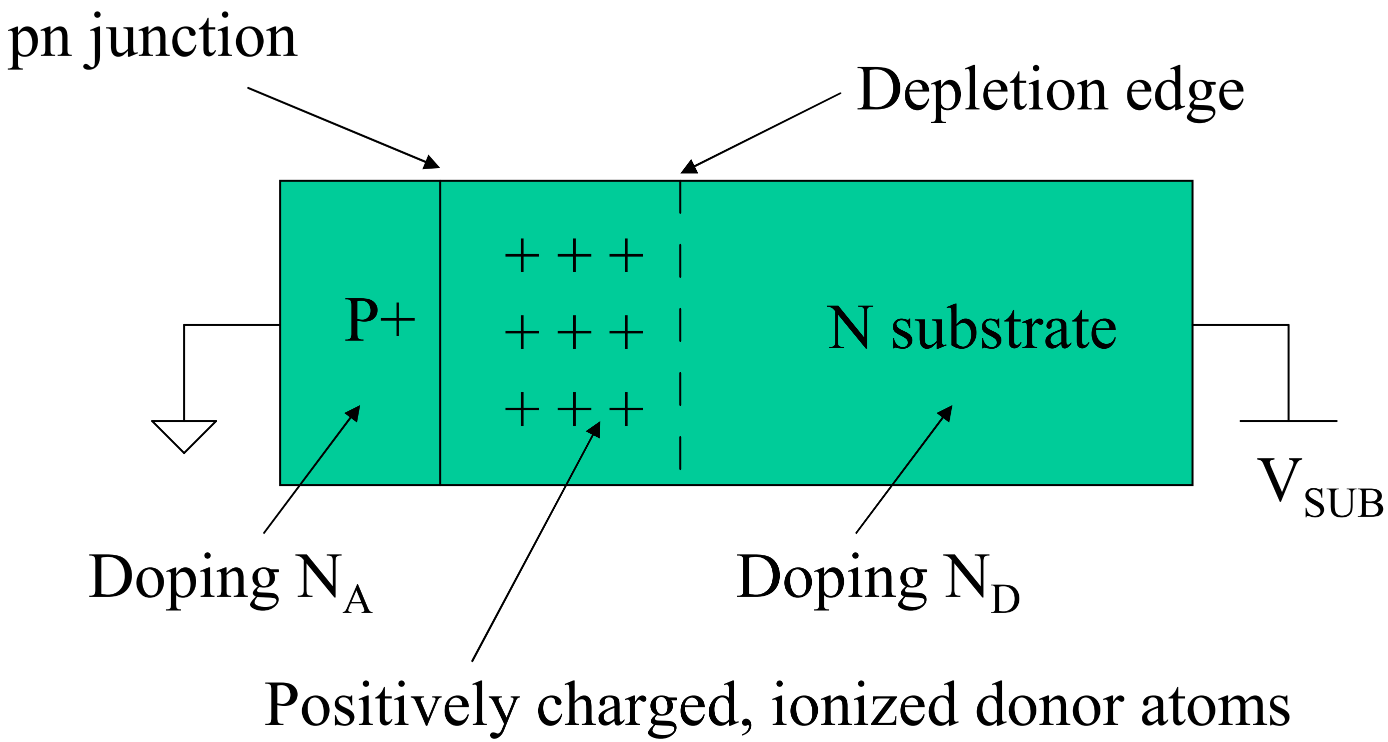
- Depletion thickness varies as the inverse square root of substrate doping density

- Conventional CCD's have doping levels in the 10^{14} – 10^{15} cm^{-3} range
  - Implies depletion depths on the order of 10—20 μm and thinning to a comparable thickness to minimize electric-field free regions that degrade spatial resolution

- Float-zone refined silicon can have doping levels in the mid-10^{11} to low 10^{12} cm^{-3} range
  - Depletion depths of 100's of μm possible at reasonable bias voltages
  - Silicon atomic density is 5×10^{22} atoms/cm^3 so purity levels in high resistivity silicon are approximately 1 part in 10^{11}

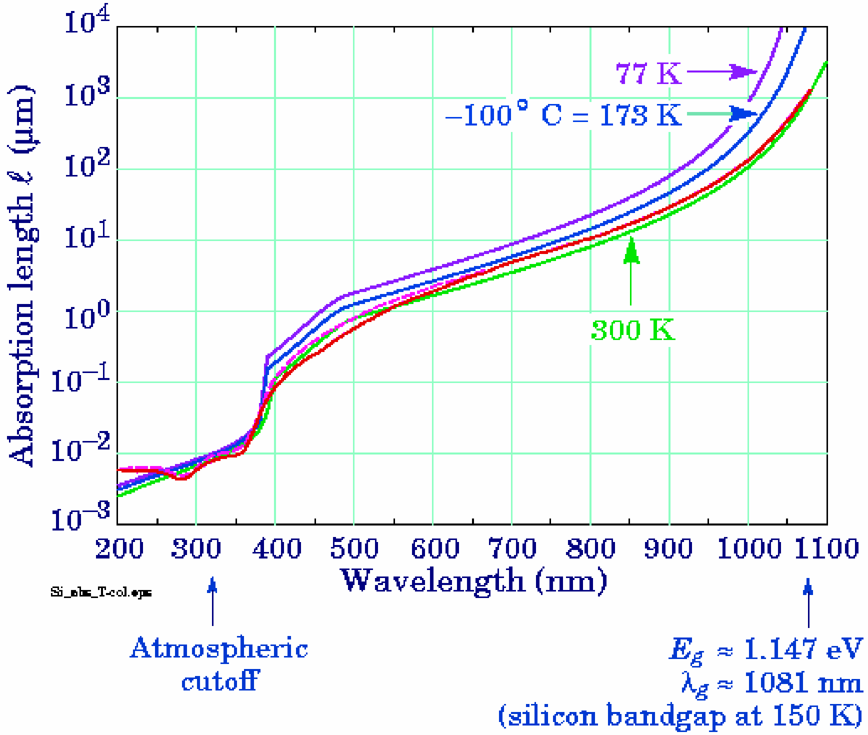
- **Thick CCD's have greatly improved near-infrared quantum efficiency**

pn-junction basics



Depletion depth $x_D = \sqrt{\dfrac{2\varepsilon_{Si}(V_{SUB} + \phi_{BI})}{qN_D}}$ for $N_A >> N_D$

Quantum Efficiency and Fringing



D. Groom et al, "Quantum efficiency of a back-illuminated CCD imager: an optical approach," Proc. SPIE, 3649, 80, 1999.

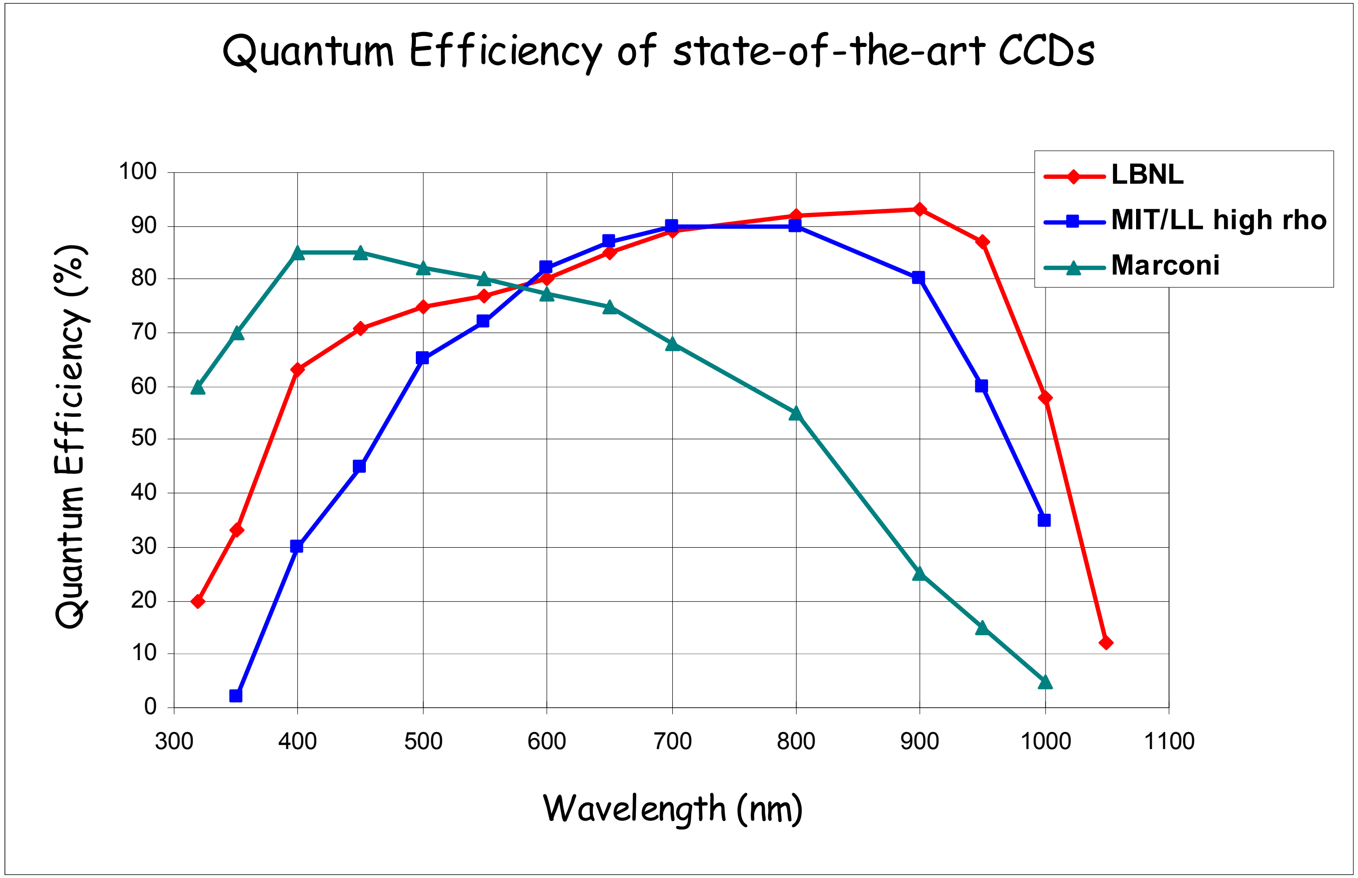
Light intensity $I = I_o \exp(-\alpha x)$

α = Absorption Coefficient = $1/\ell$

Silicon is an indirect bandgap material requiring phonons (lattice vibrations) to conserve momentum during light absorption for hν < ~ 2.5 eV (λ > ~ 500 nm)

Absorption length ~ 100 μm at a wavelength of 950 nm and temperature of –100C

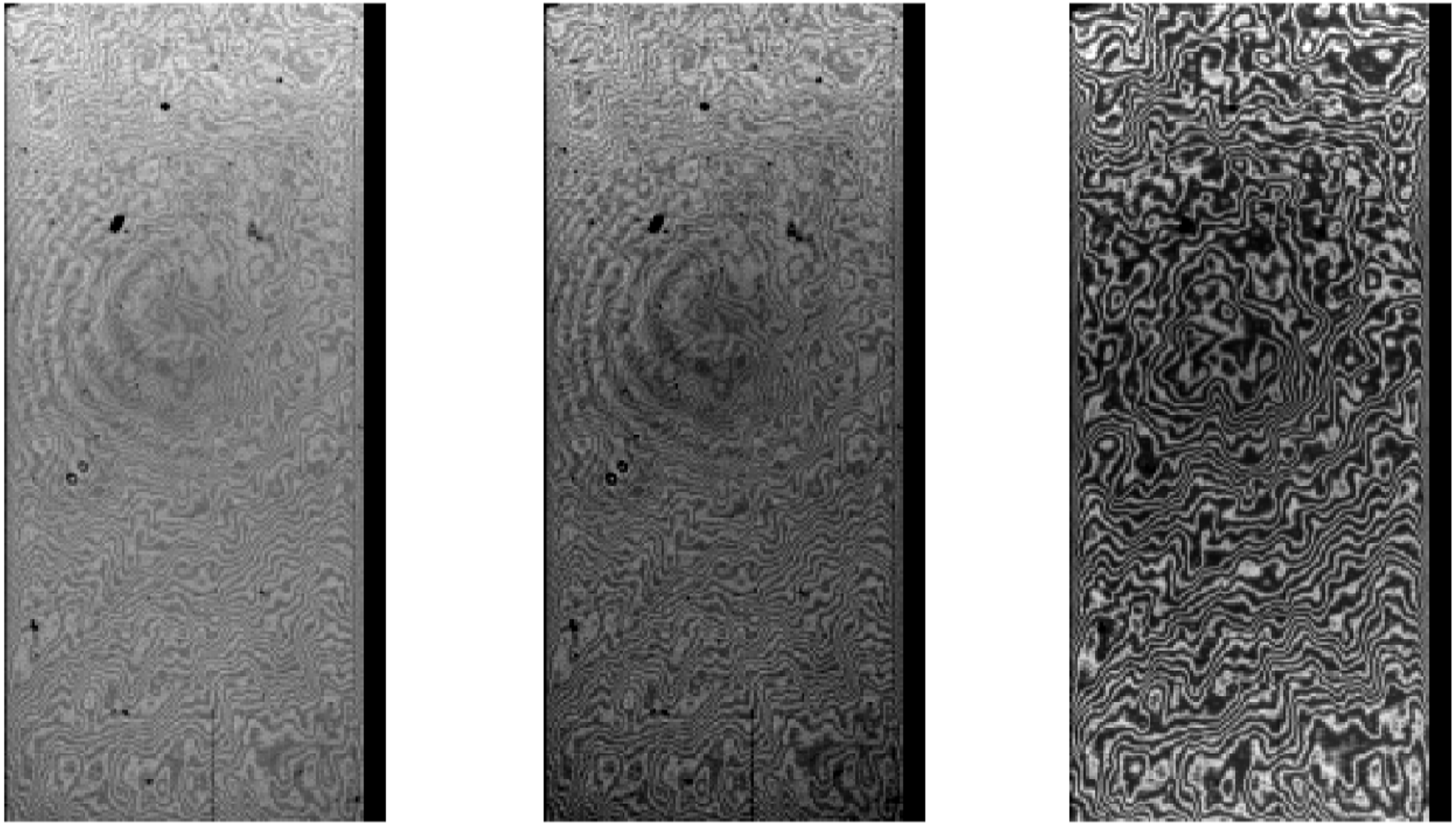
LBNL 2k x 2k Quantum Efficiency



From "An assessment of the optical detector systems of the W.M. Keck Observatory," J. Beletic, R. Stover, K Taylor, 19 January 2001.

2 layer anti-reflection coating: ~ 600A ITO, ~1000A SiO_2

Fringing in thinned CCDs



$\lambda = 800$ nm | 900 nm | 1 μm

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

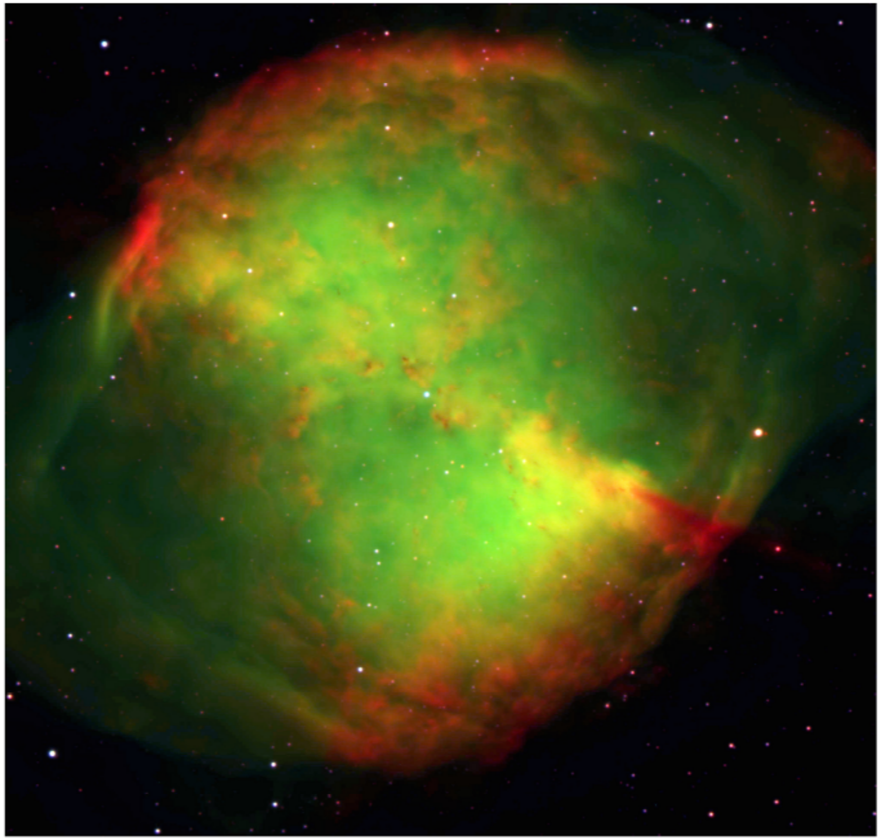
Dumb-bell nebula

LBNL CCD

Blue: H-α at 656 nm

Green: SIII at 955 nm

Red: 1.02 μm

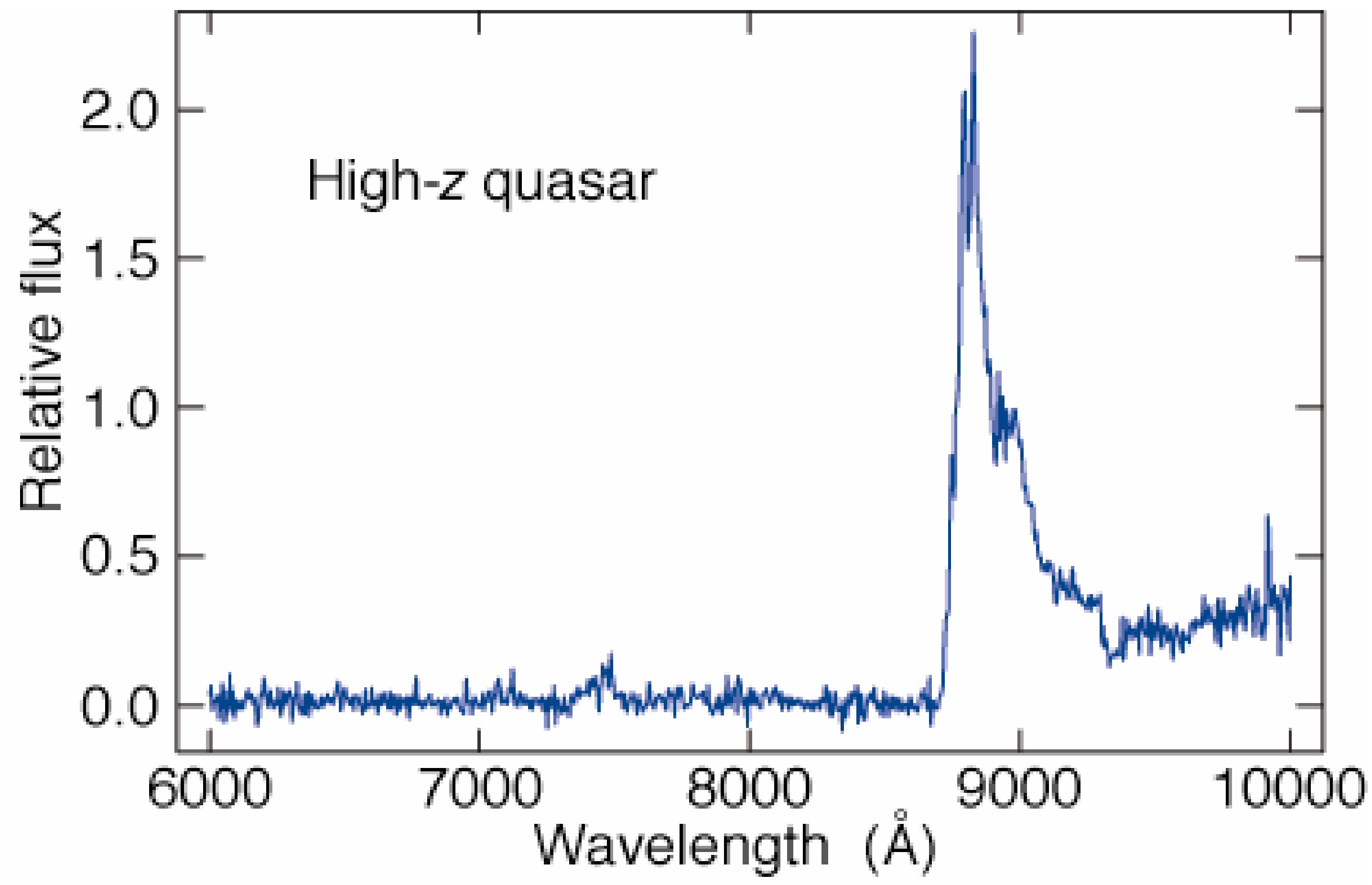


Planetary Nebula NGC 6853 (M 27) - VLT UT1+FORS1

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

ESO

Science result from NOAO MARS



Data courtesy of Xiaohui Fan, University of Arizona
Astronomy Department and the Sloan Digital Sky Survey

Spectroscopy of $z \sim 6$ Quasars with MARS

Xiaohui Fan (University of Arizona), Joseph F. Hennawi, Michael A. Strauss, Gordon T. Richards (Princeton University) & Donald P. Schneider (Penn State University) for the SDSS Collaboration

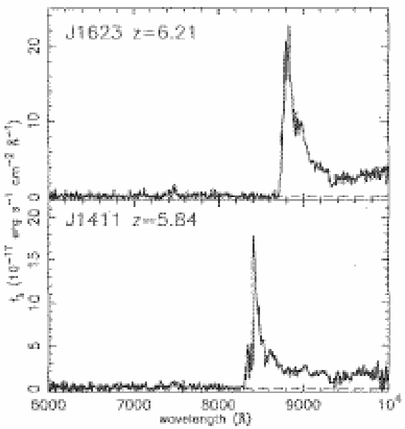
The past few years have seen a dramatic increase in both the number of known high-redshift quasars and the highest known quasar redshift. Powerful multicolor surveys, such as the Sloan Digital Sky Survey (SDSS), have led to the discovery of more than 600 quasars at $z > 4$, including more than 30 at $z > 5$. The quasar with the highest measured redshift is now at $z = 6.4$. These quasars provide insight into the formation of early generations of galaxies and quasars. Powered by accretion onto black holes of several billion solar masses, their evolution traces the history of black hole growth in the early universe. Many quasars show signs of active star formation and rapid chemical enrichment in their environments, indicating a close relationship between black hole formation and galaxy evolution. In addition, Lyα absorption in the quasar spectra is found to evolve strongly at $z > 5$, as the ionizing background declines quickly with increasing redshift. Gunn-Peterson troughs in the spectra of the highest redshift objects at $z > 6.2$ suggest that the intergalactic medium was reionized at $z \sim 6.2$.

The SDSS is being carried out at Apache Point Observatory, NM, using a dedicated 2.5-m telescope equipped with a large-format CCD camera. Images in five broadband filters (u, g, r, i, and z) are being obtained over 10,000 deg^2 of high-Galactic-latitude sky. With the inclusion of the z-band filter centered at ~9000 Å, quasars can be detected up to redshifts of $z \sim 6.6$. Over the past four years, we have used the SDSS imaging data to identify quasars at $z \sim 6$. Quasar candidates are selected based on their extremely red i–z colors (i–$z > 2.2$) that result from strong Lyα absorption in the i-band at this redshift. They are extremely rare objects on the sky and are difficult to identify from the SDSS data alone because they are often close to the detection limit. They may also be confused with cosmic ray hits and brown dwarfs with similar colors. To improve our selection efficiency, we first obtain additional optical and near-IR photometry of candidates on other telescopes, then carry out detailed spectroscopic observations of these faint, red sources using larger telescopes.

Some of our recent spectroscopy has been carried out with the new Multi-Aperture Red Spectrometer (MARS) on the Kitt Peak 4-m telescope. MARS is equipped with a thick LBNL CCD that has a high quantum efficiency in the red, as well as new optics and a grism with high red throughput. Fully optimized for the red region ($\lambda > 8000$ Å), MARS is well suited for follow-up spectroscopy of these very red, faint quasar candidates.

With MARS, we have an opportunity to identify and obtain high-quality spectra of $z \sim 6$ quasars, a task that was previously possible only with larger telescopes. The figure shows the spectra of two $z \sim 6$ quasars that were observed with MARS during our run in Spring 2003 (Fan et al., submitted). J1623 (top, $z = 6.21$) is the third highest redshift quasar known. It has an extremely strong Lyα emission line and shows a clear Gunn-Peterson trough blueward of Lyα, which is consistent with those observed in other $z > 6.1$ quasars. The spectra also demonstrate the red sensitivity of MARS: the signal-to-noise does not decline even at $\lambda > 9000$ Å, and compares favorably with those taken with larger telescopes under similar conditions. As an added bonus, the data show little fringing in the red and near-IR, a problem that afflicts most thinned CCDs.

These results bring to 11 the number of $z > 5.7$ quasars found thus far. Our survey is ongoing and we expect to establish a sample of more than 20 quasars at $z > 5.7$ in the next three years. With this sample of quasars, we will be able to address basic questions about the early evolution of quasars, the relationship between early supermassive black holes and galaxy formation, and the evolution of the intergalactic medium at the reionization epoch.



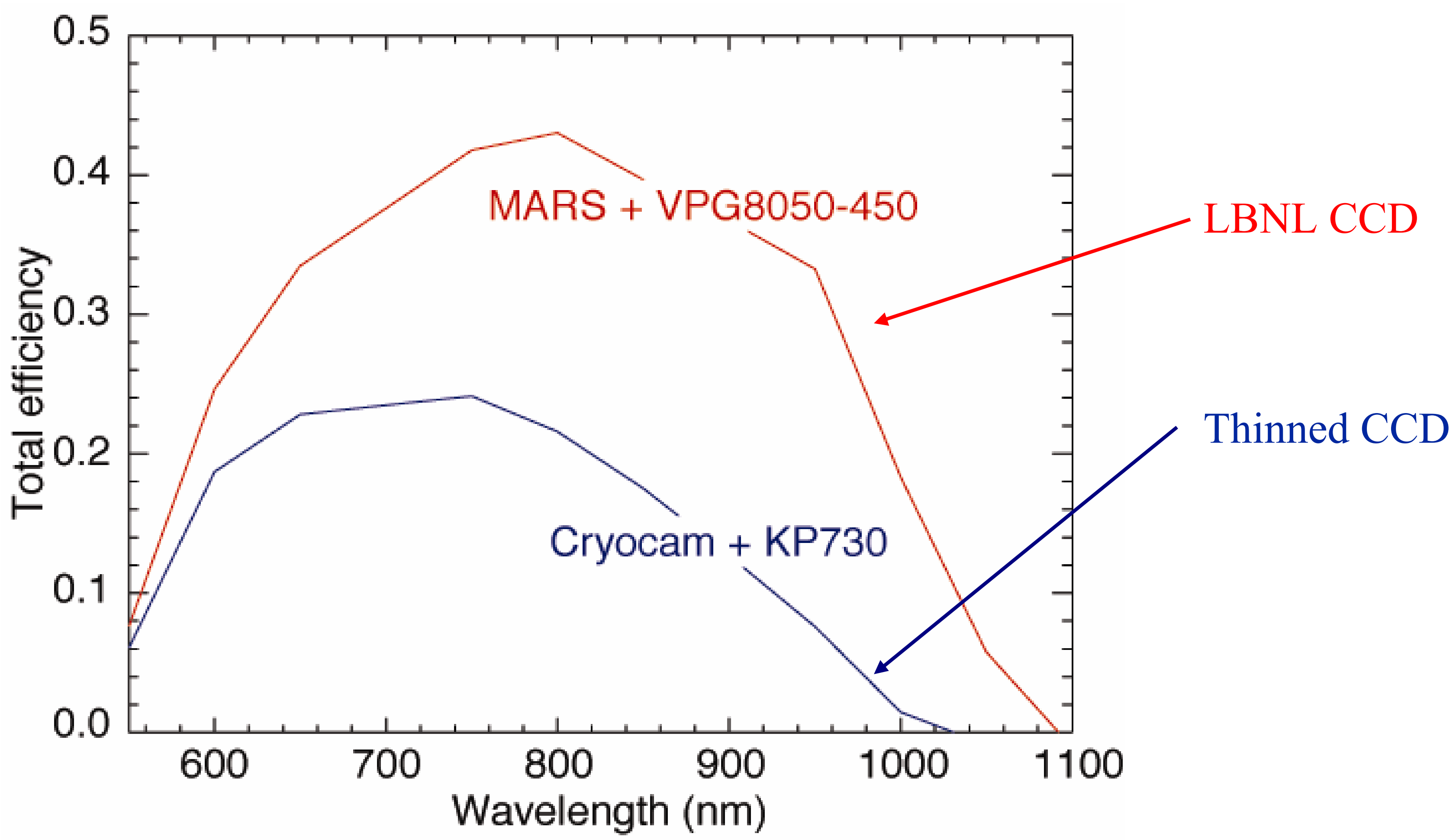
Spectra of two high-redshift quasars observed with MARS in June 2003. J1623 (top), at z = 6.21, is the third highest-redshift quasar known. It has an extremely strong Lyα emission line, and a clear Gunn-Peterson trough. The high throughput of MARS at λ > 8000 Å is well suited to the spectroscopy of quasars at z ~ 6.

LBNL 1980 x 800 (15 μm pixel) CCD

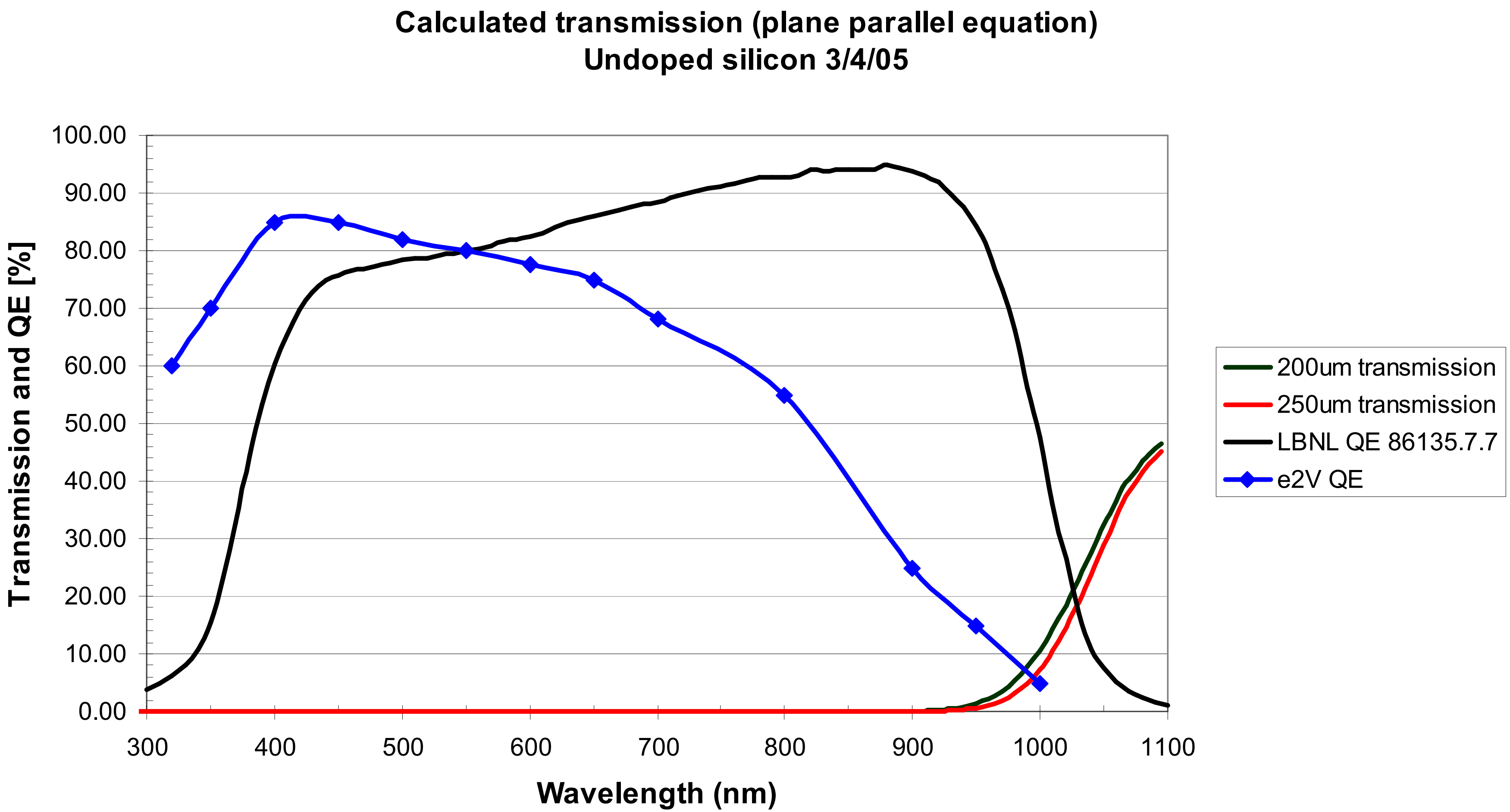
See Feb. 2005 issue of "Sky and Telescope" magazine for article on high-red shift quasars

National Optical Astronomy Observatory Dec. 2003 newsletter

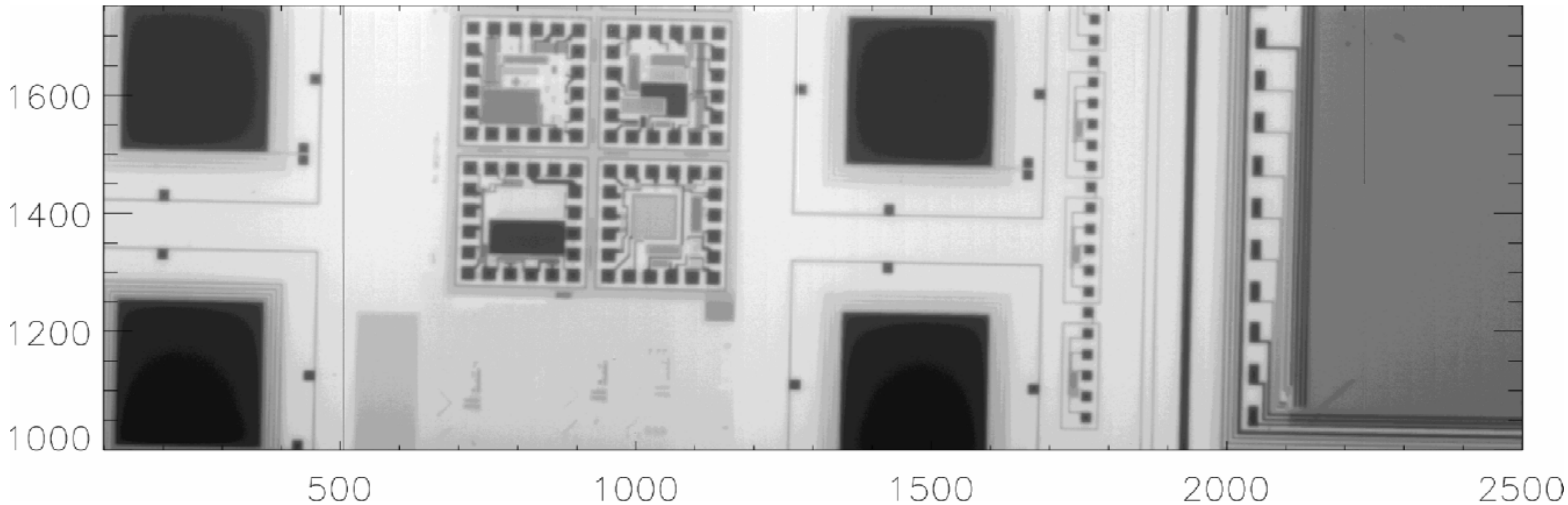
NOAO Multi-Aperture Red Spectrometer



Transmission and QE plot

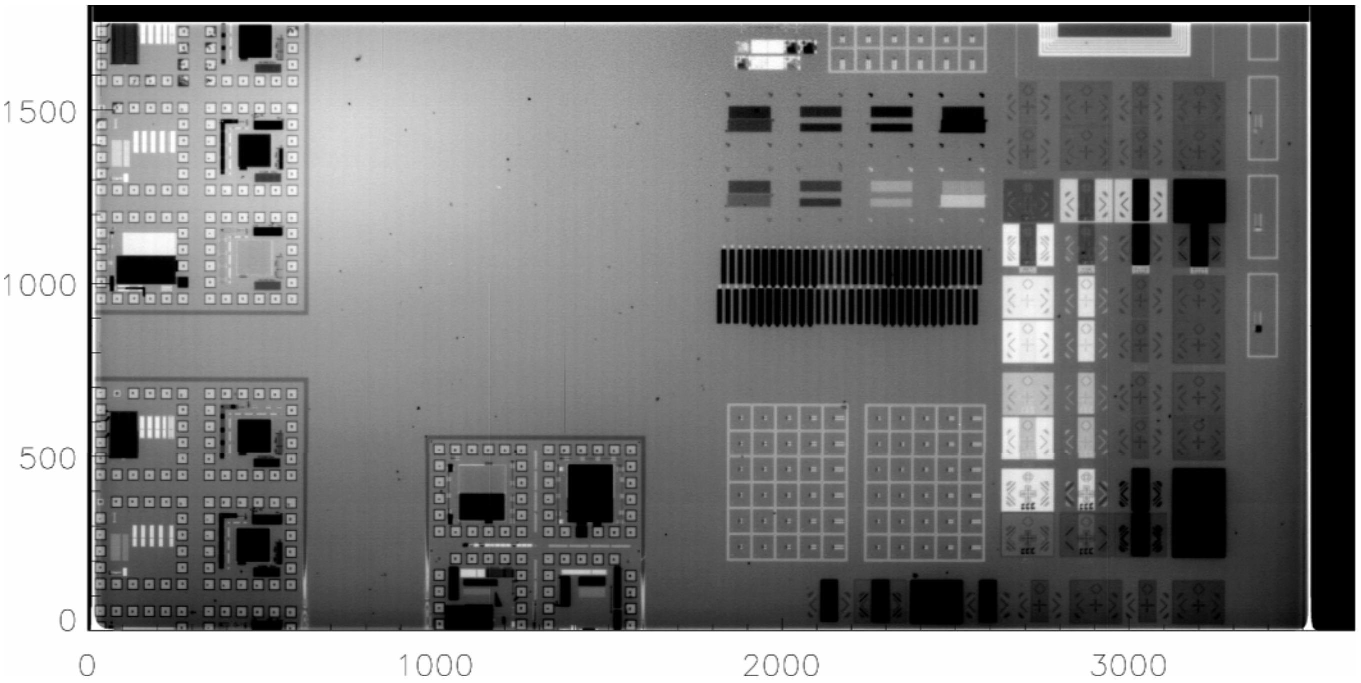


Seeing through silicon with a thick, fully-depleted, back-illuminated CCD



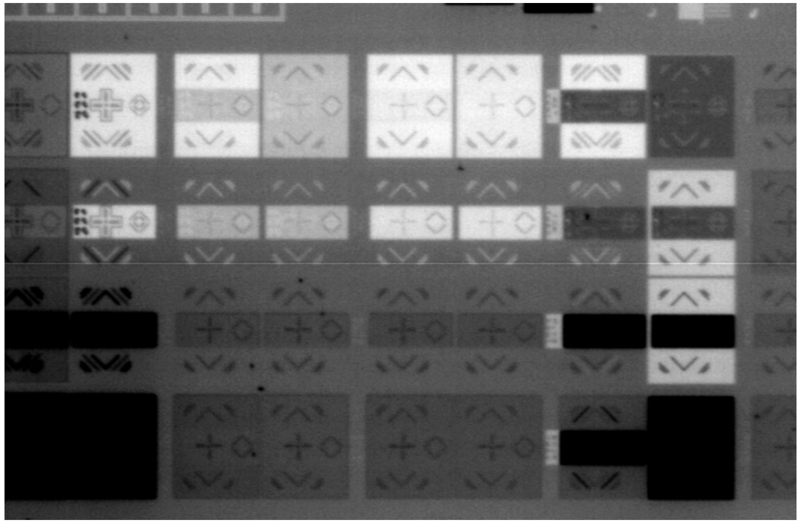
Labsphere projector system was used to project a slide constructed from CCD wafer test structures. Exposure was 4 seconds at f/22 using Nikon macro lens. 250 μm thick die with aluminum metal.

Seeing through silicon with a thick, fully-depleted, back-illuminated CCD

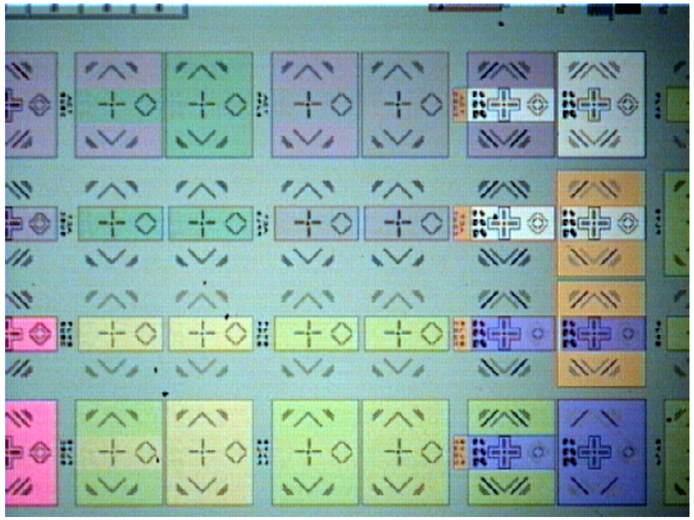


200 μm thick die, no aluminum metal

Seeing through silicon with a thick, fully-depleted, back-illuminated CCD



Transmission imaging



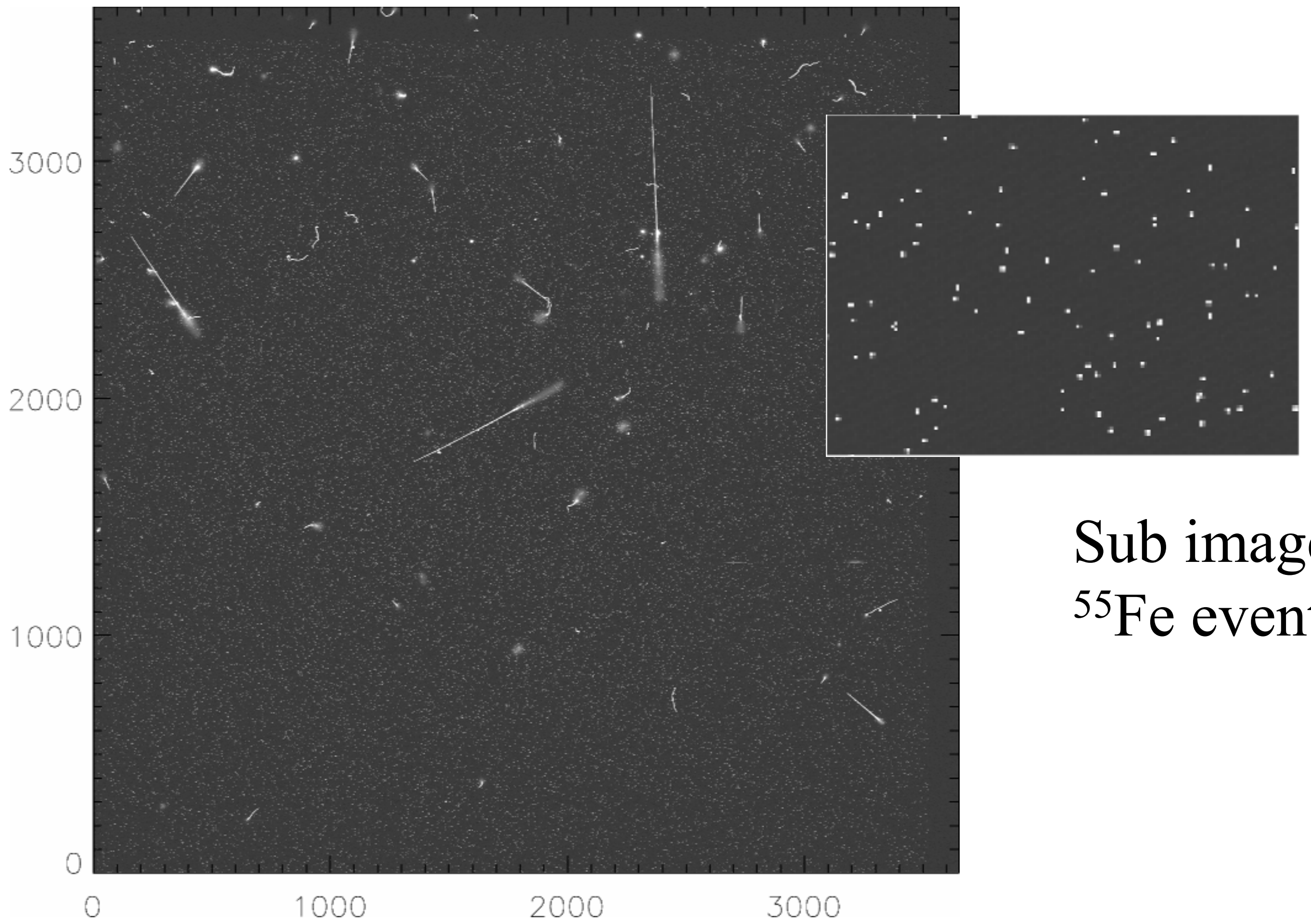
Optical micrograph

200 μm thick die, no aluminum metal

Unique features of fully depleted, back-illuminated CCDs fabricated on high-ρ silicon

- Charge generation
  - High near-infrared QE
  - Lack of fringing
- Charge collection
  - Tunable and generally good spatial resolution due to an electric field throughout the volume of the CCD
- Charge transport
  - **High-purity silicon generally free of traps, high CTE**
  - **P-channel CCD more resistant to the damaging effects of space protons**
- Charge measurement

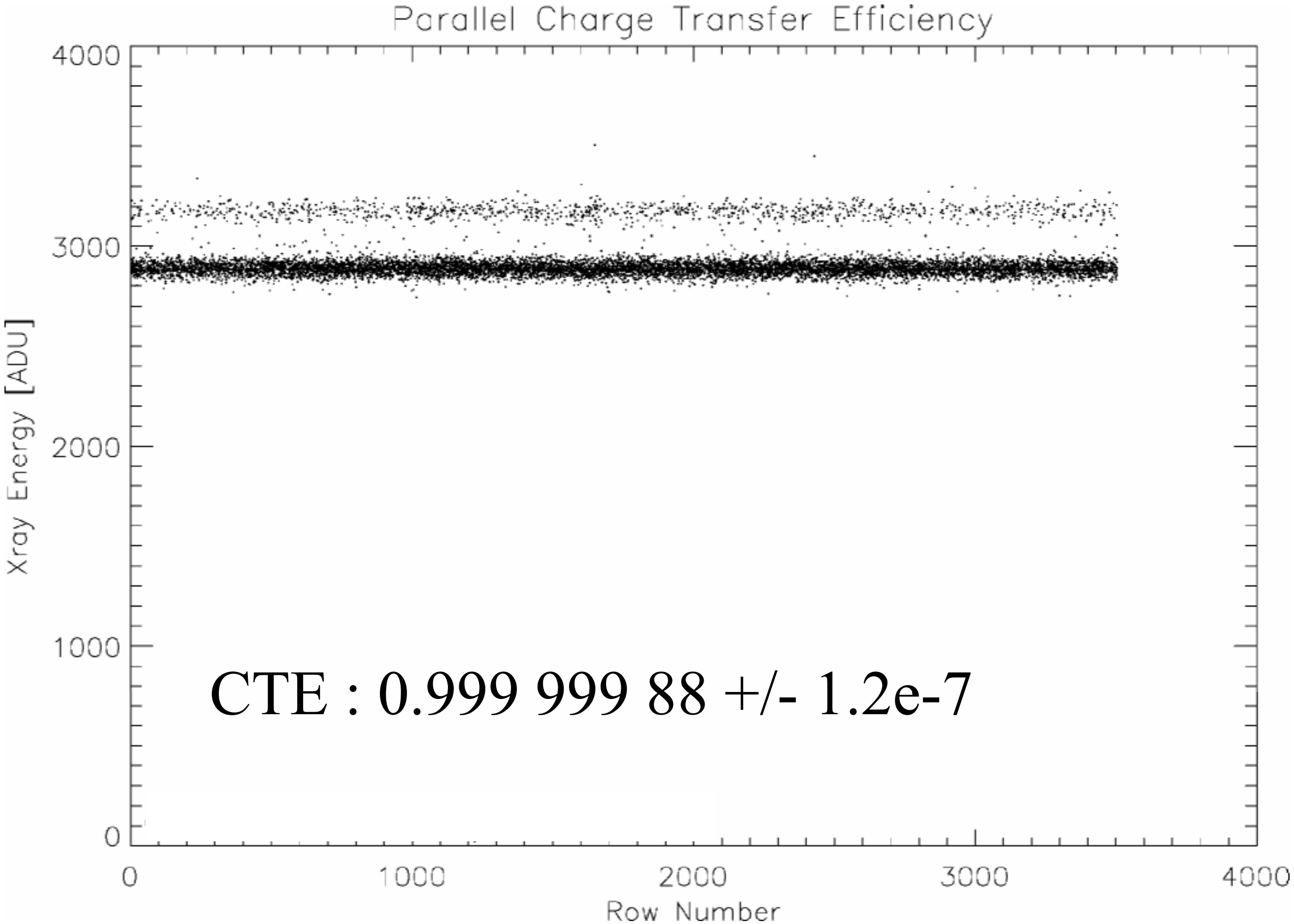
^{55}Fe image



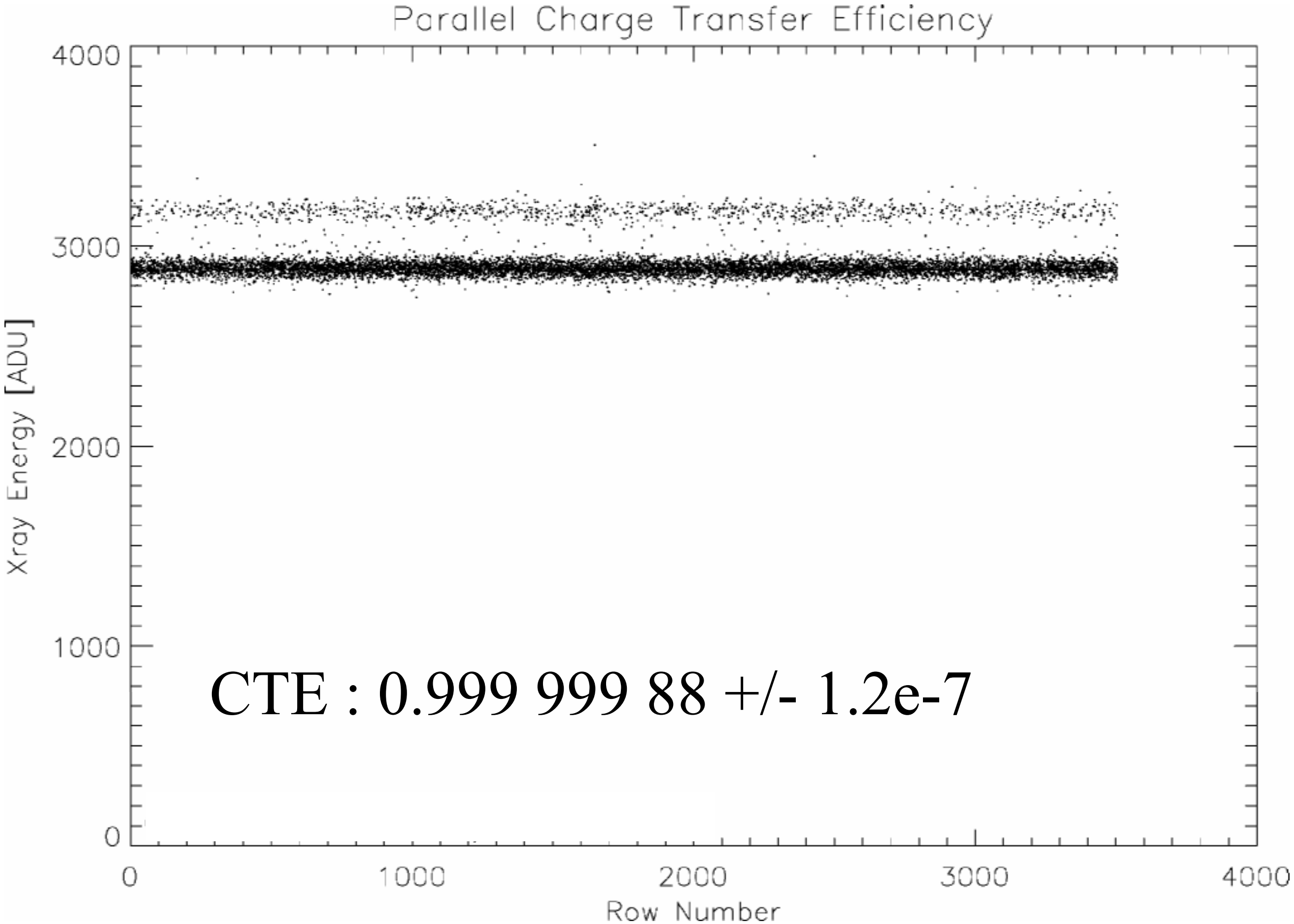
Sub image
^{55}Fe events

Mn K_{α} x-ray photons from ^{55}Fe produce 5.9keV/3.65=1620 e/h pairs
Known signal level used to calibrate CCD gain and measure CTE

Charge transfer efficiency measurement with ^{55}Fe x-rays



Charge transfer efficiency measurement with ^{55}Fe x-rays



1620 hole charge packet transferred as far as 3512 x 10.5 μm = 3.7 cm

1997 email from Jim Janesick (then at JPL)

From MYPIXEL@aol.com Mon Mar 10 18:19 PST 1997
From: MYPIXEL@aol.com
X-Authentication-Warning: mh1.lbl.gov: Host emout01.mx.aol.com
[198.81.11.92] claimed to be emout01.mail.aol.com
Date: Mon, 10 Mar 1997 21:18:31 -0500 (EST)
To: holland@ux5.lbl.gov, richard@ucolick.org

Subject: Radiation Damage VS DDCCD

Steve, Richard,

As a side benefit to your p-channel technology it should perform well in a radiation environment. As far as we know we don't see any natural traps to degrade CTE as we do for n-channel CCDs which characteristically have P-V centers (0.43 eV . . . bad news critters). We will also test for this very important characteristic.

Jim

Dominant hole trap is the di-vacancy. Formation 2^{nd} order compared to phosphorus-vacancy (P-V center) in n-channel CCDs. P-channel CCD should be more resistant to the effects of displacement damage in the space environment.

Marshall *et al*, SPIE 5499 (June 2004)

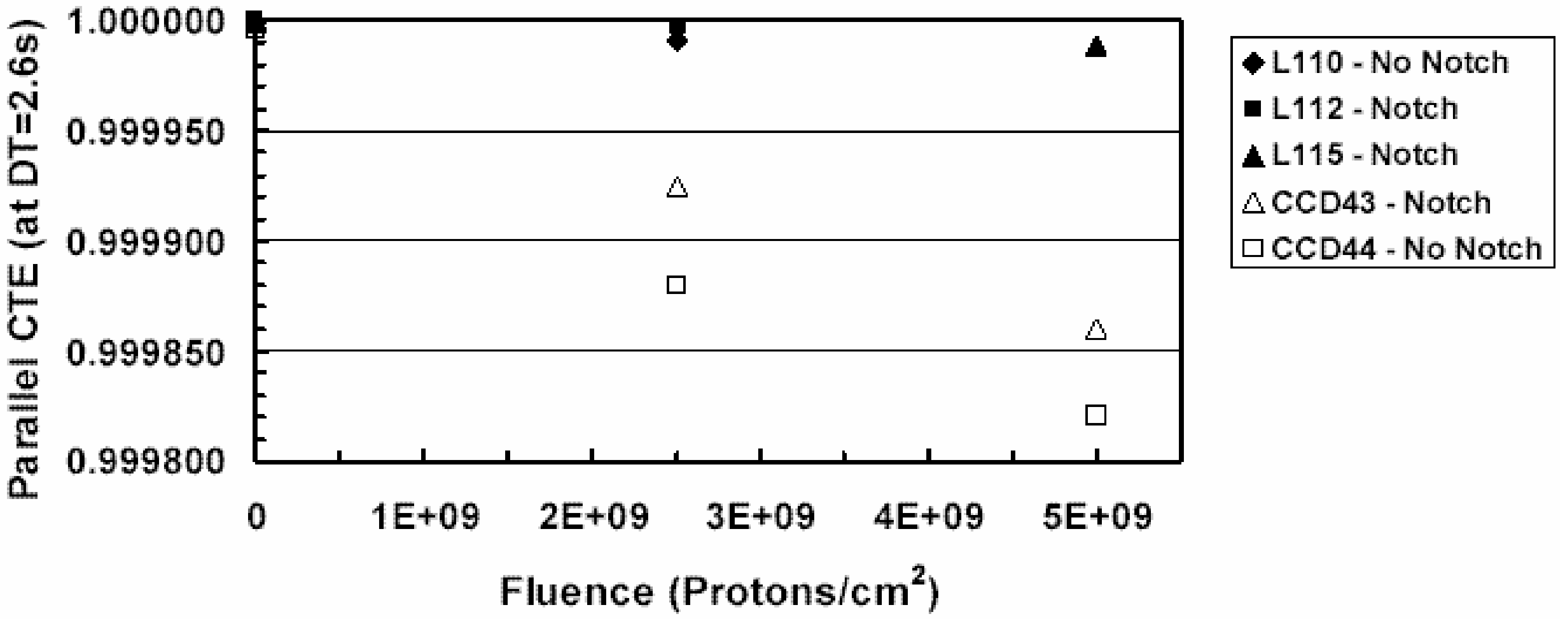


Figure 8: The CTI at -84°C is shown for the current p-channel CCD and compared to the WFC3 n-channel CCD results of Waczynski et al. [6] as a function of 63 MeV proton fluence. The x-ray densities are comparable (1in 60 pixels for the WFC3 n-channel CCD and our p-channel CCD results). The WFC3 timing was used for all measurements.

Closed symbols: LBNL p-channel CCD Open symbols: n-channel
Sometimes it pays to be lucky

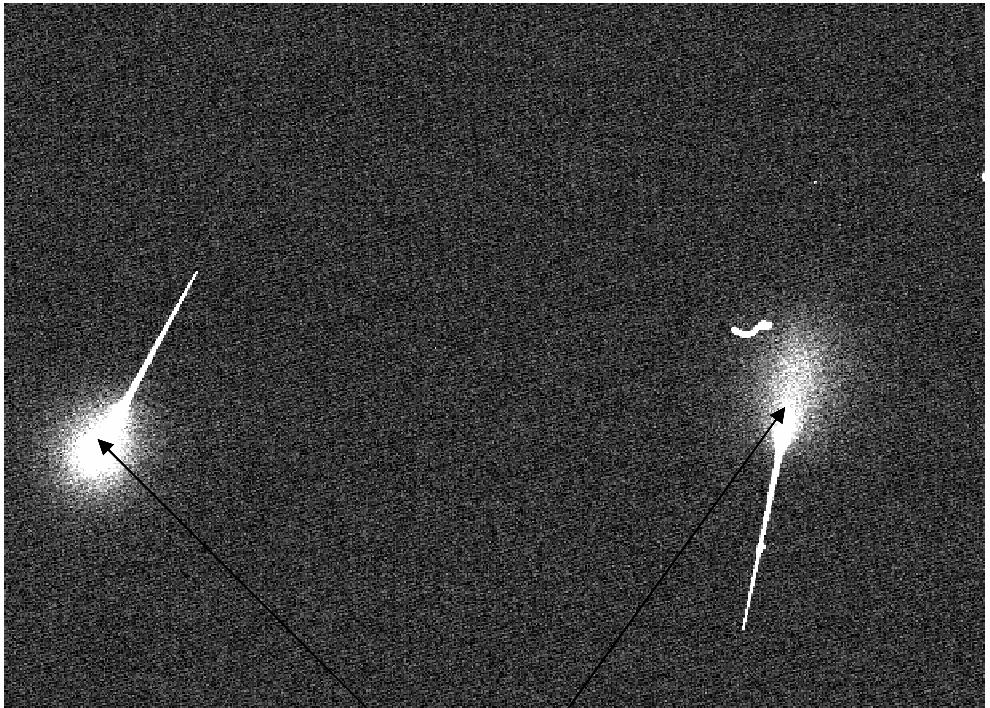
Unique features of fully depleted, back-illuminated CCDs fabricated on high-ρ silicon

- Charge generation
  - High near-infrared QE
  - Lack of fringing
- Charge collection
  - **Tunable and generally good spatial resolution due to an electric field throughout the volume of the CCD**
- Charge transport
  - High-purity silicon generally free of traps, high CTE
  - P-channel CCD more resistant to the damaging effects of space protons
- Charge measurement

Spatial Resolution (PSF)

- The existence of an electric field in the depletion region “steers” the photogenerated charge to the potential wells
- Conventional thinned, back-illuminated CCD’s have electric-field free regions that can dominate the spatial resolution
- A fully depleted CCD has a spatial resolution proportional to thickness and inversely proportional to the square root of substrate bias voltage
- **PSF is the key requirement that has led to the development of the “high-voltage compatible CCD” for the SuperNova Acceleration Probe (SNAP)**

Thick, partially depleted CCD

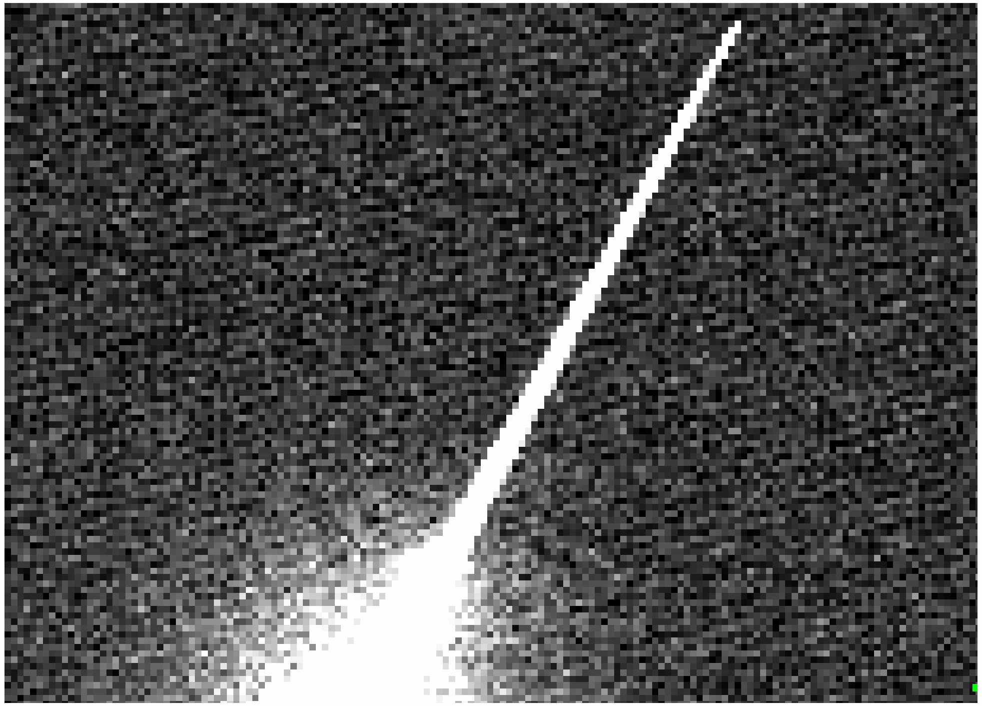


Cosmic rays traversing undepleted (electric-field free) silicon

107409.14.7

Thick, partially depleted CCD

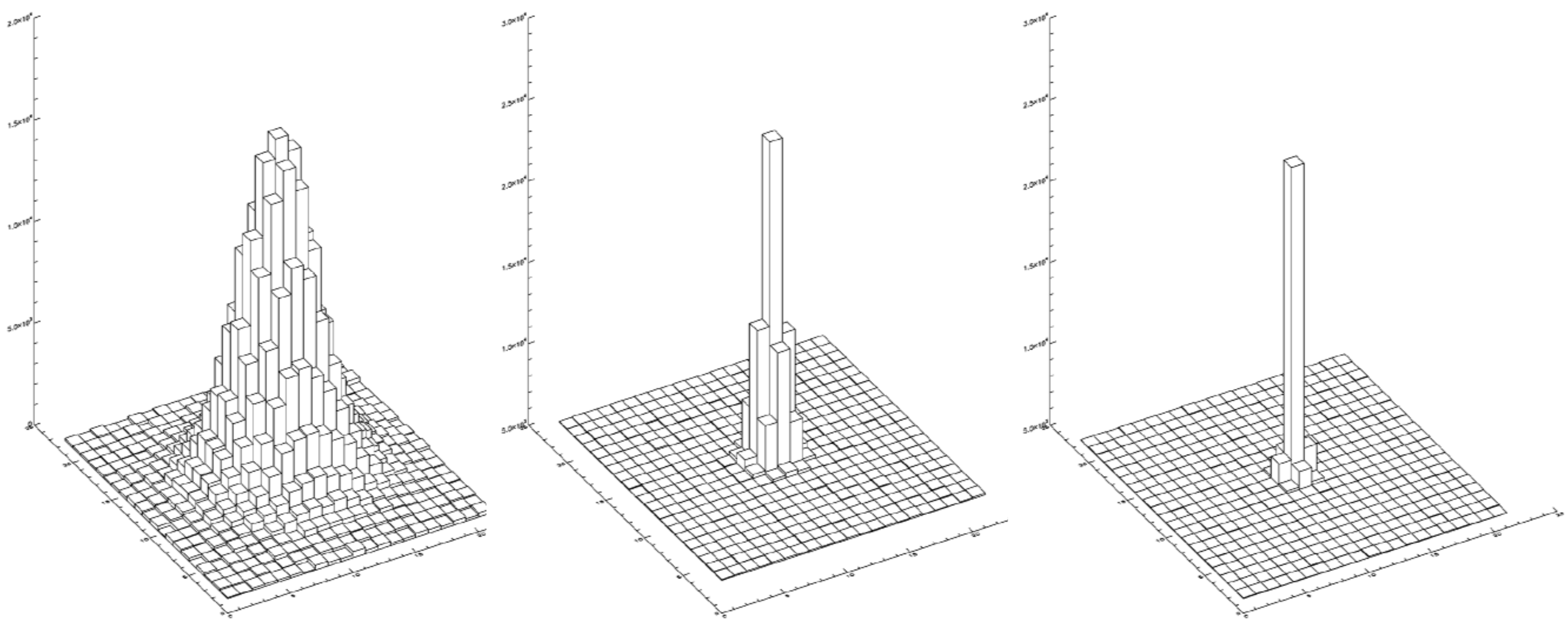
107409.14.7



Broadening of track due to increasing depth of charge generation as the cosmic ray traverses the silicon. Deeper depth implies more lateral charge diffusion and degraded spatial resolution.

PSF measurements on 200 μm thick CCD

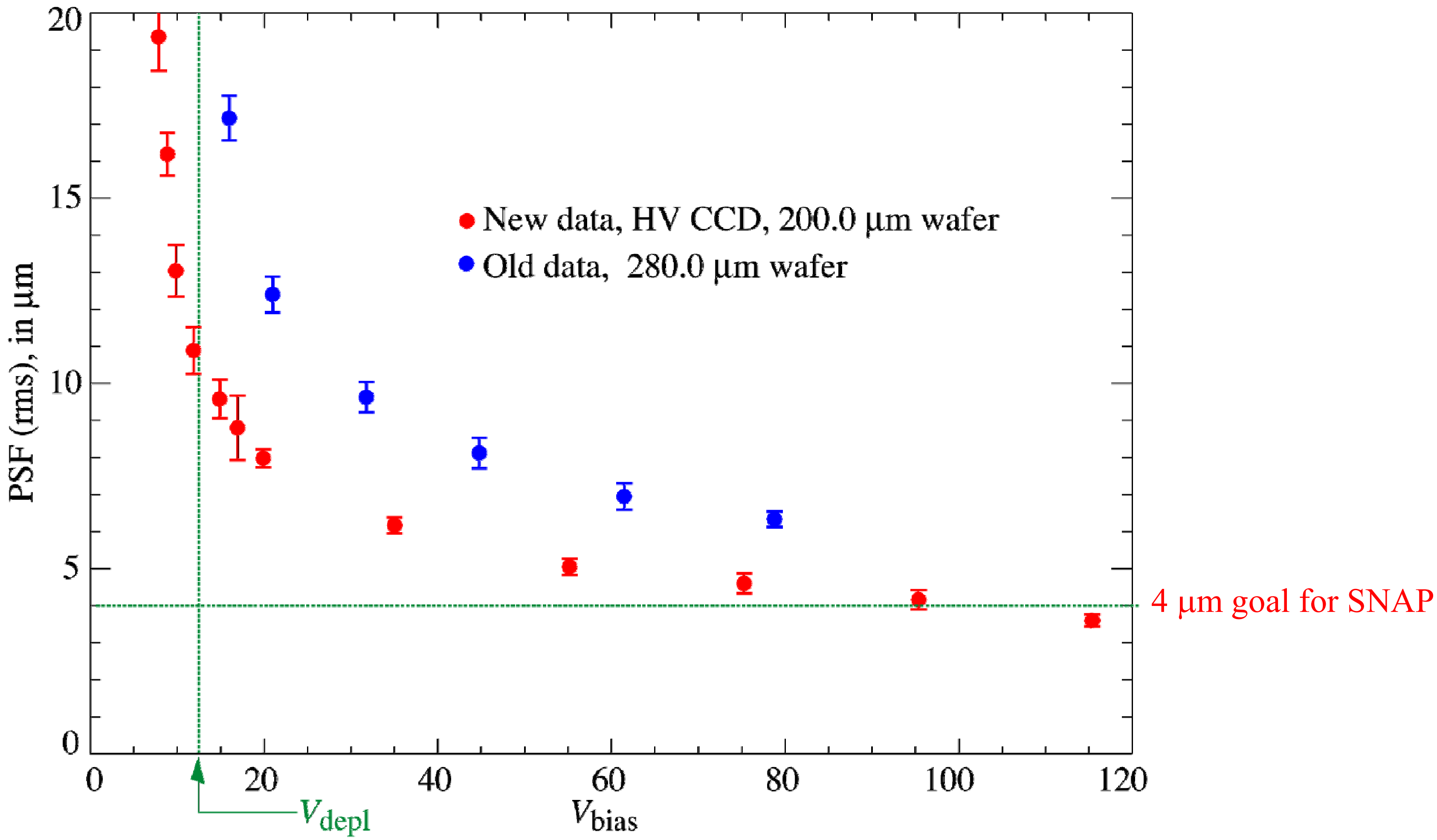
$V_{SUB} = 5V$ 20V 115V



1.3 μm rms pinhole illumination on backside of CCD

$$\sigma_{rms} = y_{SUB}\sqrt{2\frac{kT}{q(V_{SUB} - V_J)}}$$

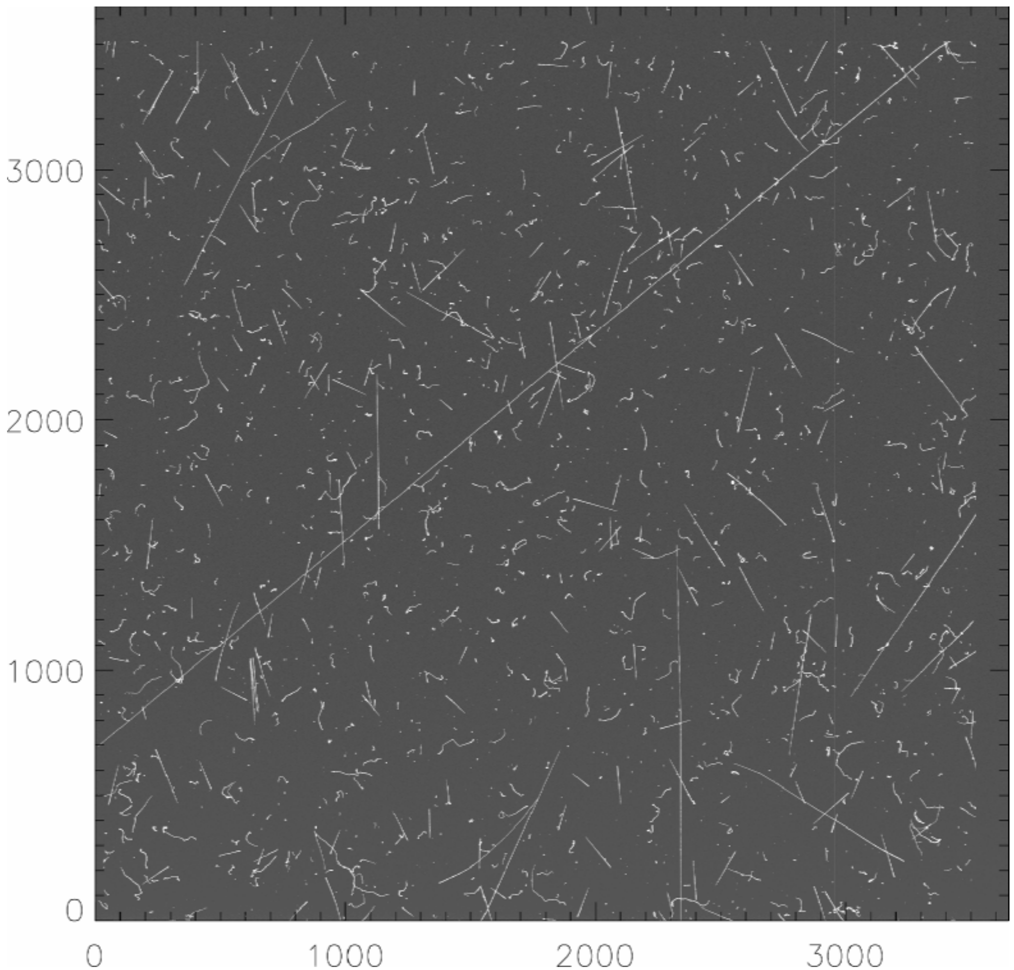
PSF measurements on 200 μm thick CCD



Spin off of HV-compatible CCD development

- Operation at high V_{SUB}
  - Improves spatial resolution for given thickness
    - Thinned, 200 μm thick CCD's for SNAP where spatial resolution is the key parameter
  - Increases depletion depth for given V_{SUB}
    - Possibility to deplete thick CCD's with potential applications in direct detection of hard x-rays

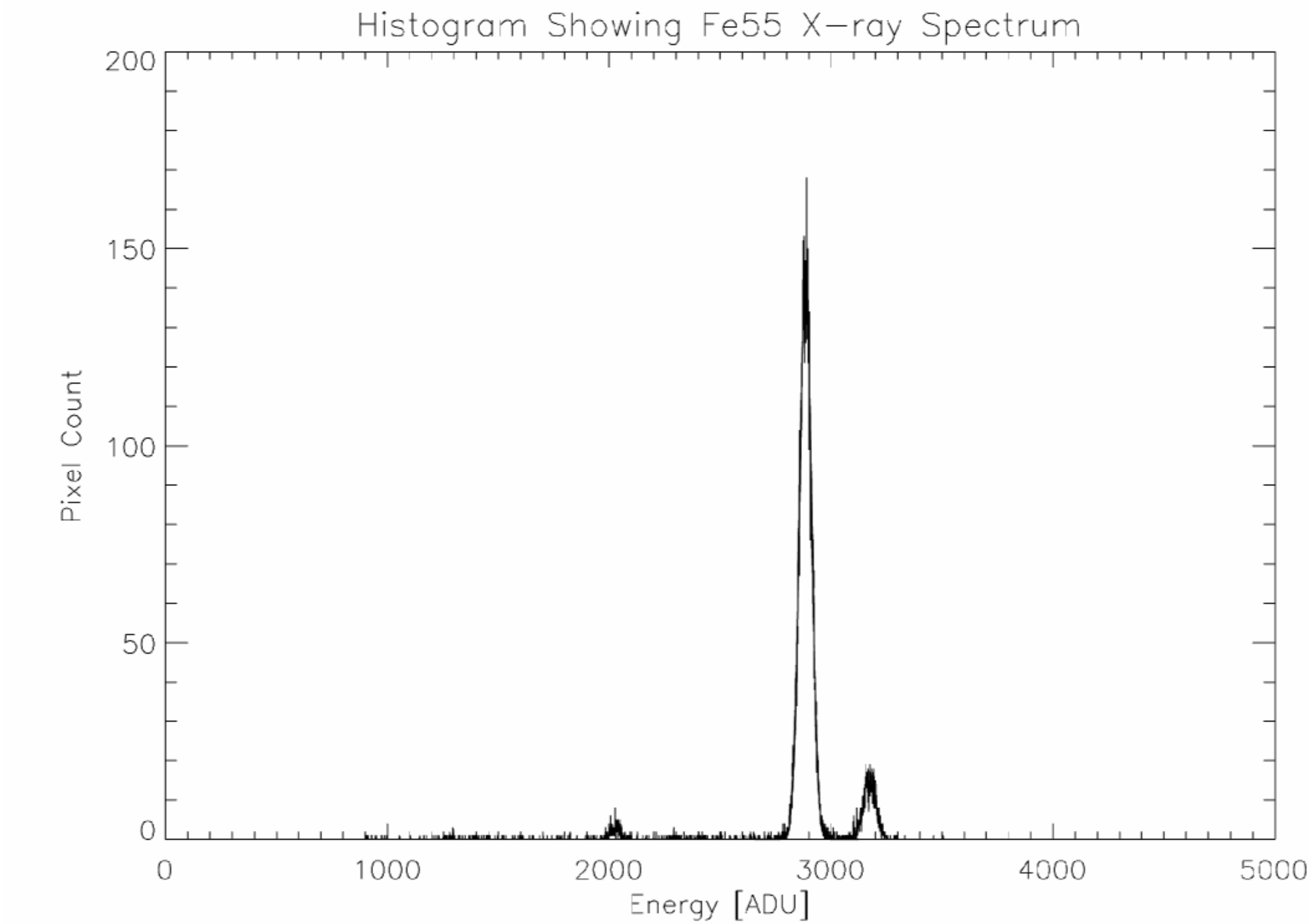
Fully depleted, 650 μm thick SNAP V2 CCD



1800s dark at Vsub = 207V yields 0.63 e-/pixel-hour

Front-illuminated control device 107409.16.11, fully depleted at 207V

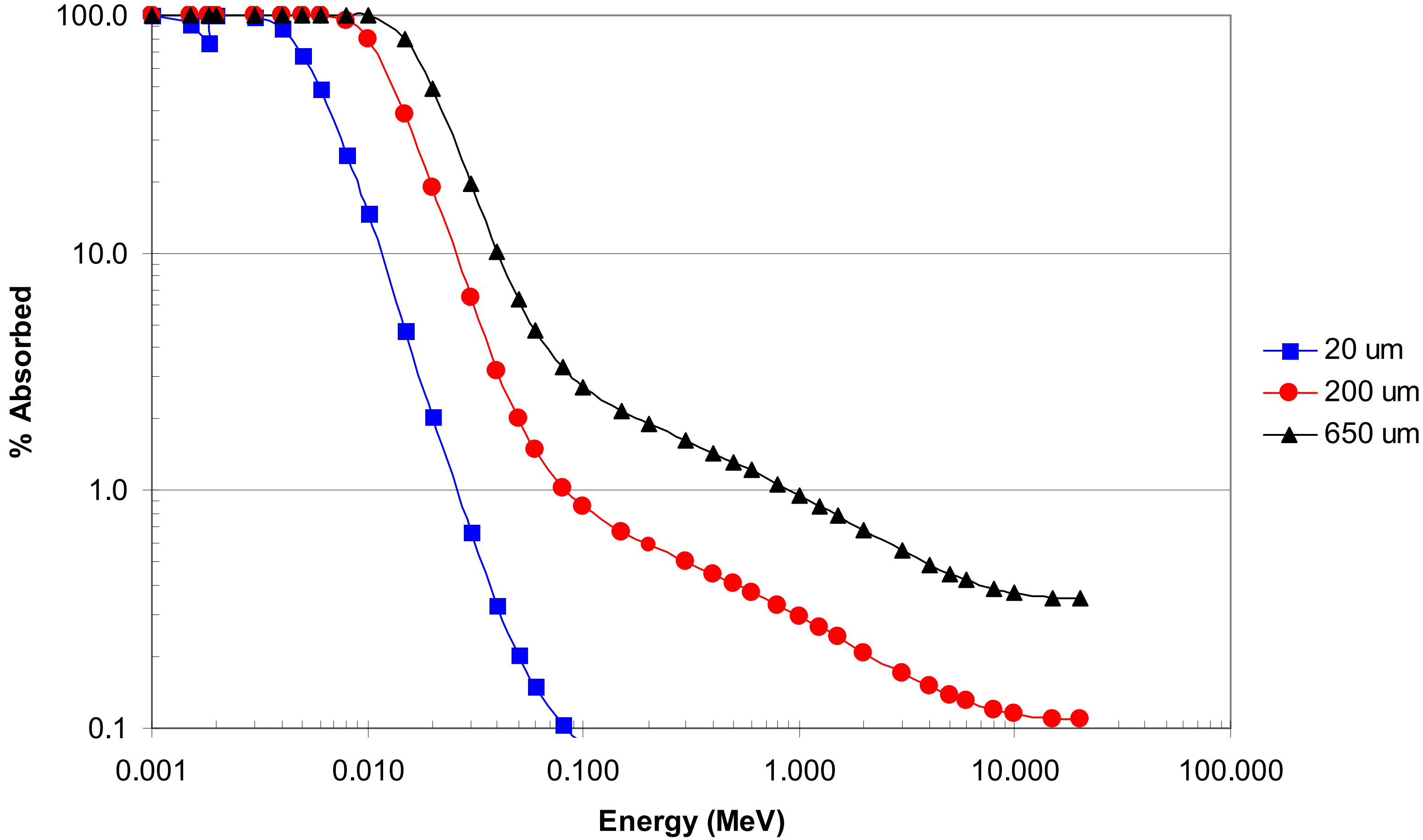
CCD 107409.14.7



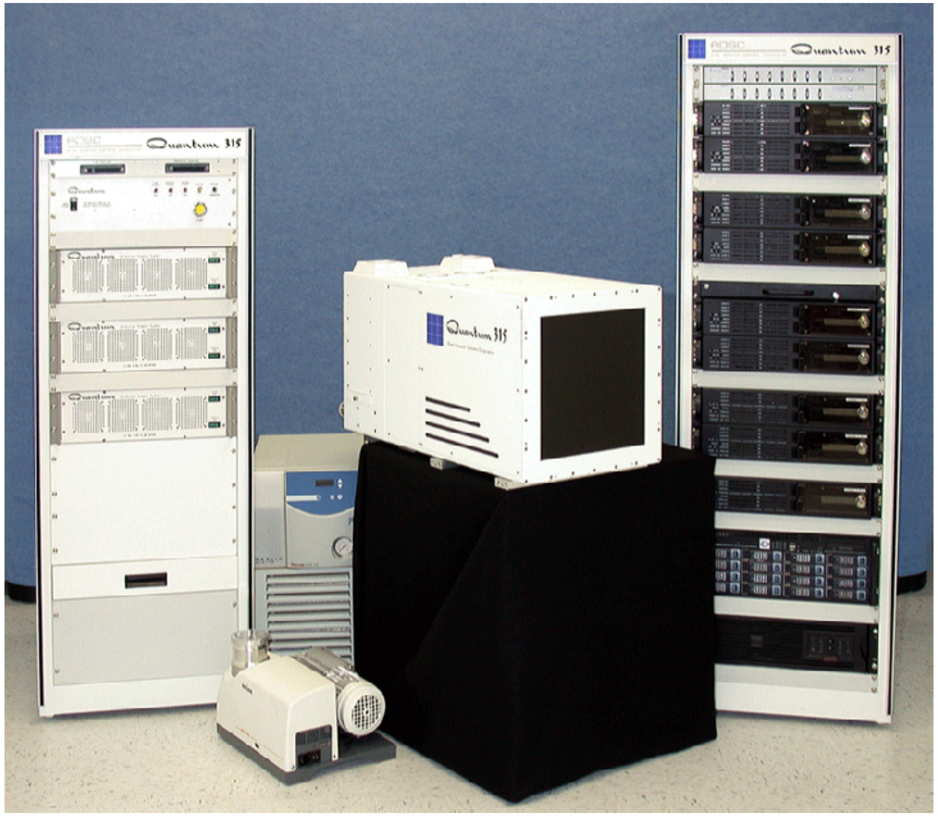
Mn K_α
FWHM
129 eV

^{55}Fe x-ray histogram for this device. Read noise was 3.6 e- rms at 70 kpixels/sec.

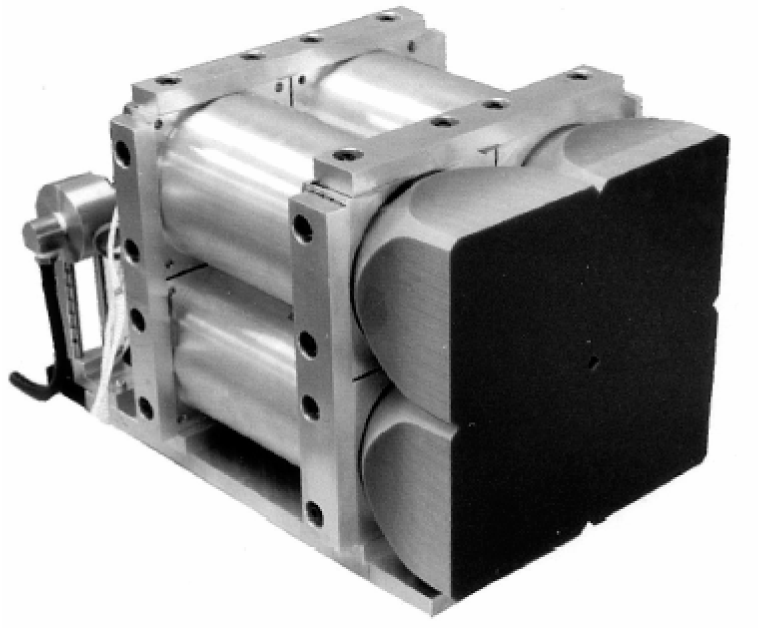
x and γ-ray absorption in Silicon



The standard synchrotron x-ray detector: phosphor - reducing fiber - CCD



ADSC Q315 3x3 CCD

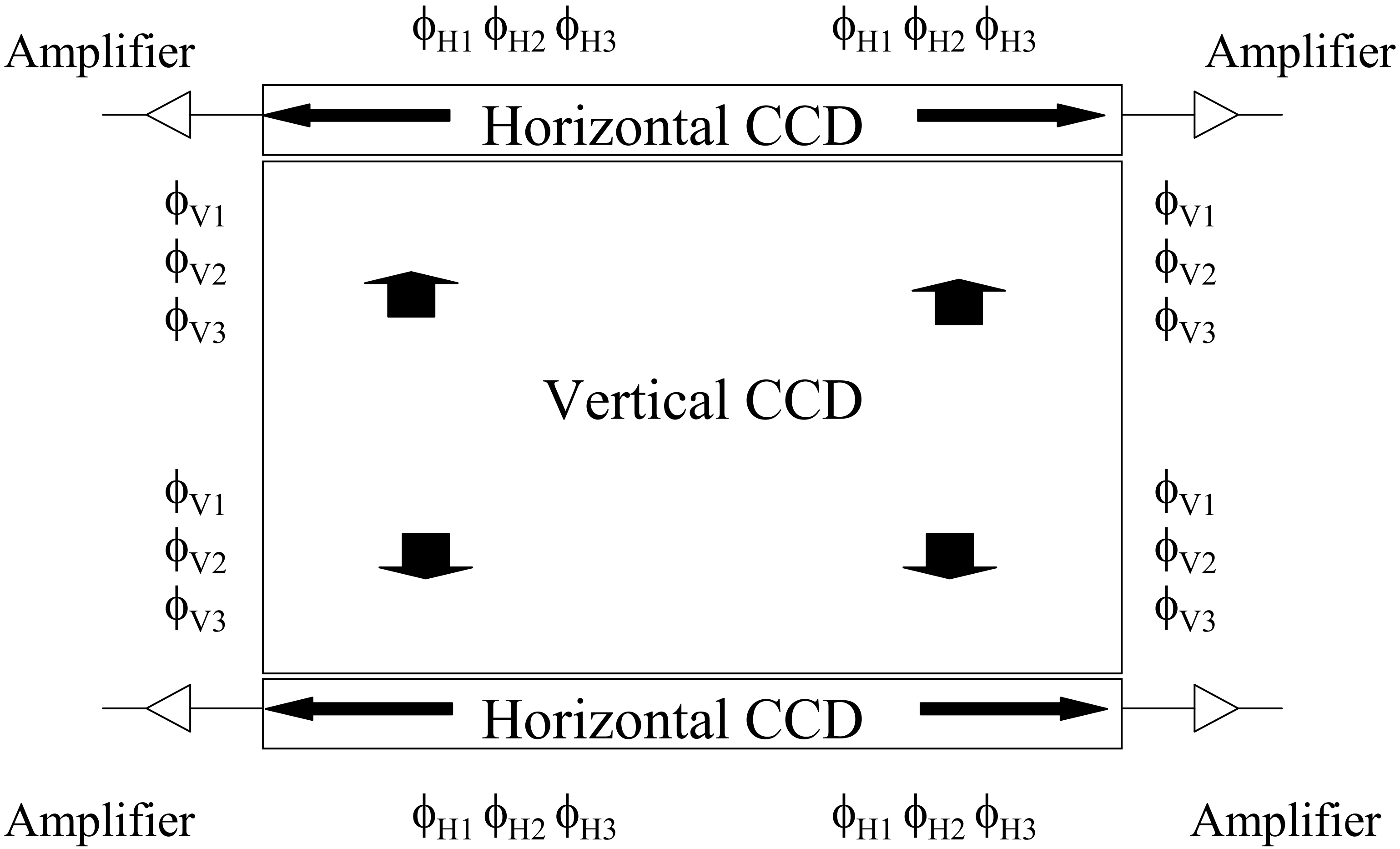


Brandeis 2x2 CCD

- good high signal DQE: poor low signal DQE

- slow readout

Typical Scientific CCD functional diagram



Increase CCD Readout Speed by up to 1000X

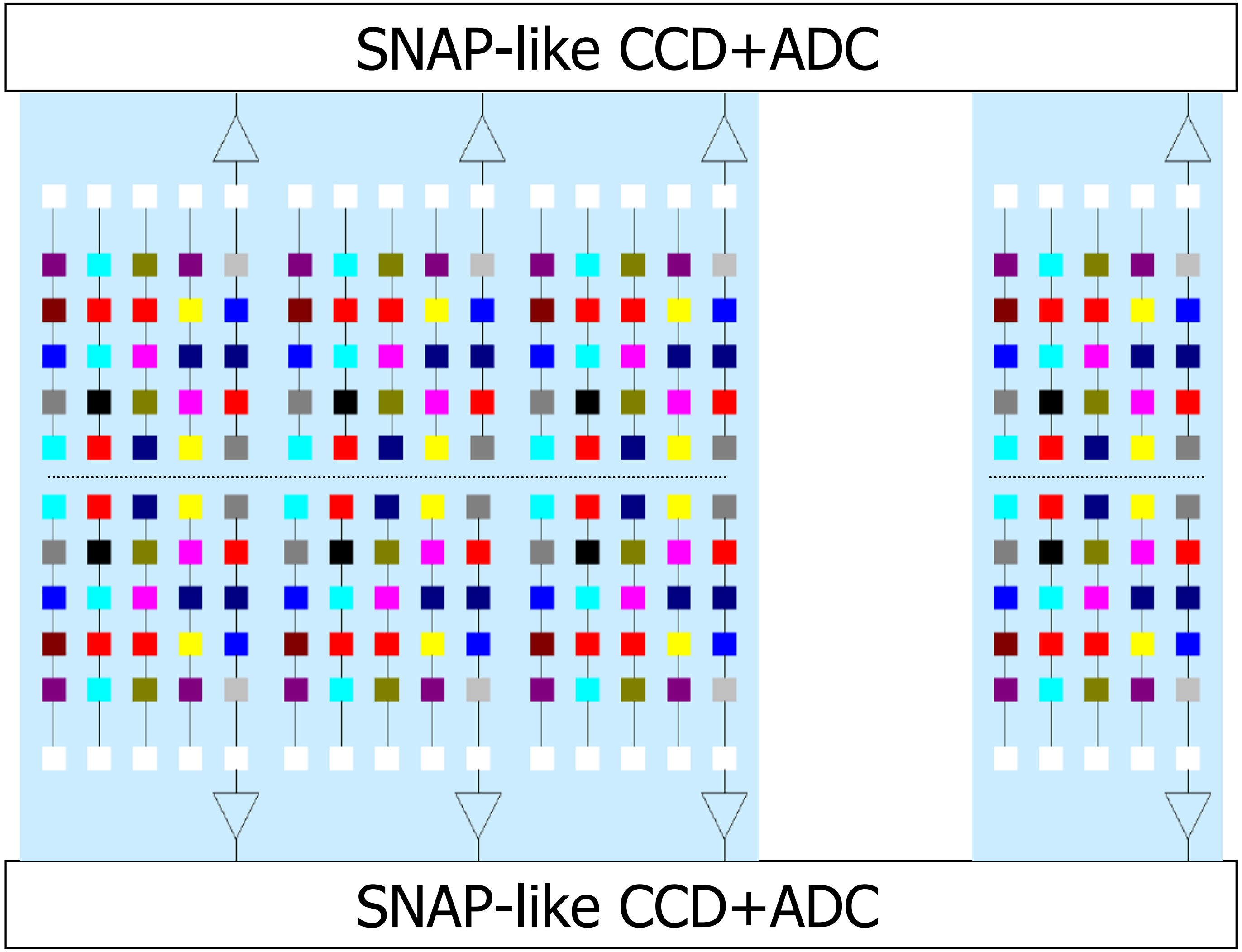
What areas could benefit from this today at ALS ?

- **Tomography**: (Earth Science, Materials Science, Health)
  - acquisition time / frame 5 msec, readout time 1 sec:
    - **- improvement in performance of 200**
- **Time-resolved small angle scattering**: (Biology, Materials Science)
  - acquisition time / frame 100 msec with 95% of detector used as memory
    (10 msec / frame and 100 % of detector used for x-rays required)
    - **- improvement in performance of 200**
- **Laue micro x-ray diffraction:** (Materials Science)
  - acquisition time / frame 20 msec, readout time 5 seconds
    - **- improvement in performance of 25**
- **Soft x-ray speckle:** (Condensed Matter Physics, Materials Science)
  - acquisition over 1 pixel (fast) or 1 frame (slow)
    - **- improvement in performance of 200**

- . . . . + + +

Slide courtesy of H. Padmore

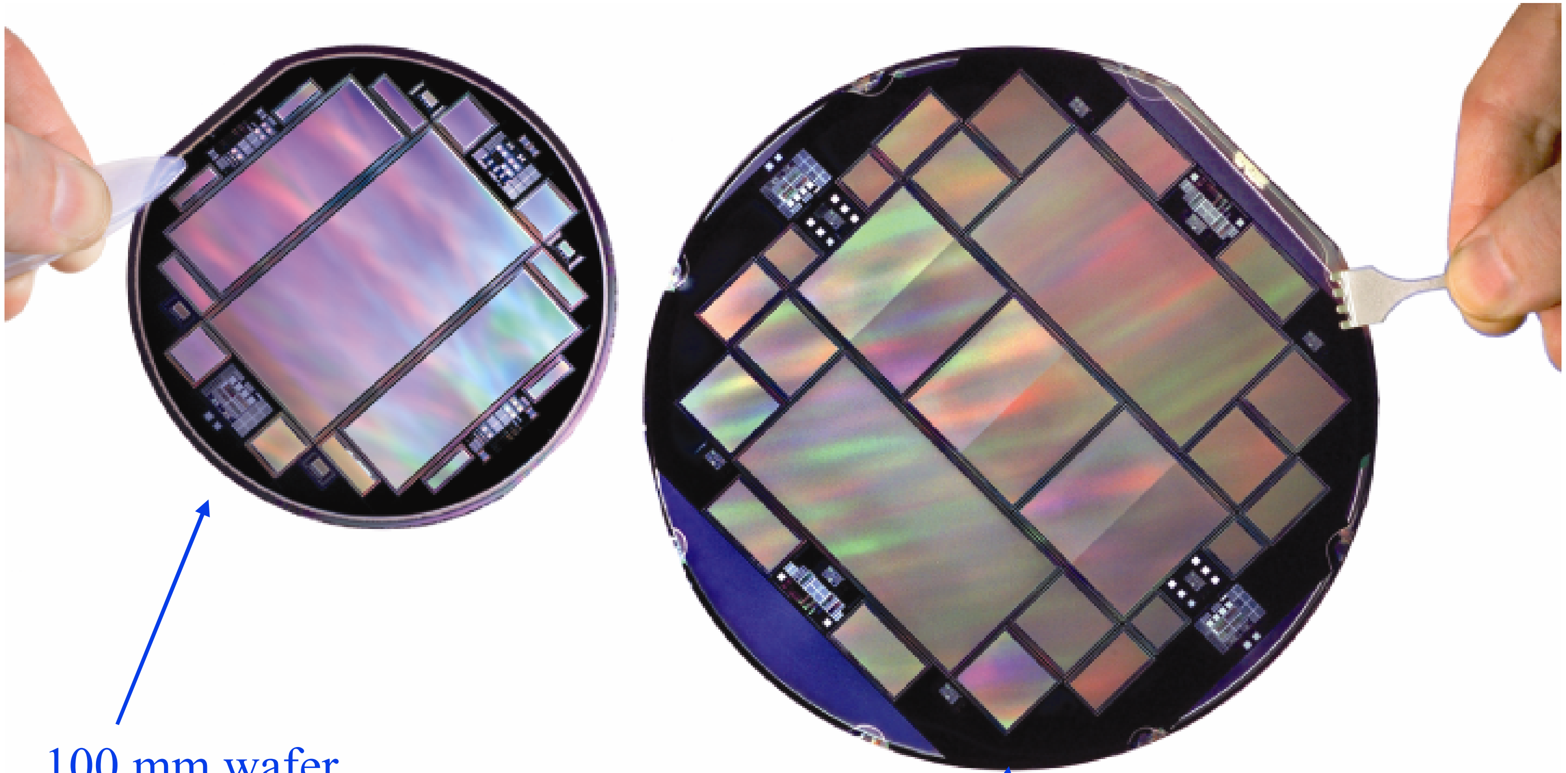
Solution – Column Parallel CCD



P. Denes and H. Padmore

- Readout based on SNAP multi-slope CDS and pipelined ADC
- LBNL or Fairchild CCD
- **Massive integration**

CCD Fabrication



100 mm wafer
fabricated at LBNL

(All LBNL CCD's on
ground-based telescopes
fabricated at LBNL)

150 mm wafer fabricated at
DALSA Semiconductor

CCD fabrication technology advancements are critical

LBNL MicroSystems Laboratory

Class 10 clean room
Full 100 mm CCD fabrication capabilities except for ion implantation
150 mm upgrade in progress

Thermco furnaces at LBNL Microsystems Laboratory

Brief history of CCD development and fabrication at LBNL

You can't always get what you want
Repeat
Repeat
But if you try sometime, you just might find,
You just might find,
You get what you need

K. Richards and M. Jagger, 1969

Brief history of CCD development and fabrication at LBNL

FY1995 LDRD[1]: "Development of High-resistivity Charge-Coupled Devices for Imaging"

Investigators: S. Perlmutter, G. Goldhaber, C. Pennypacker, H. Spieler, S. Holland, R. Stover (UCSC), industrial partner

Also inspiration from D. Nygren

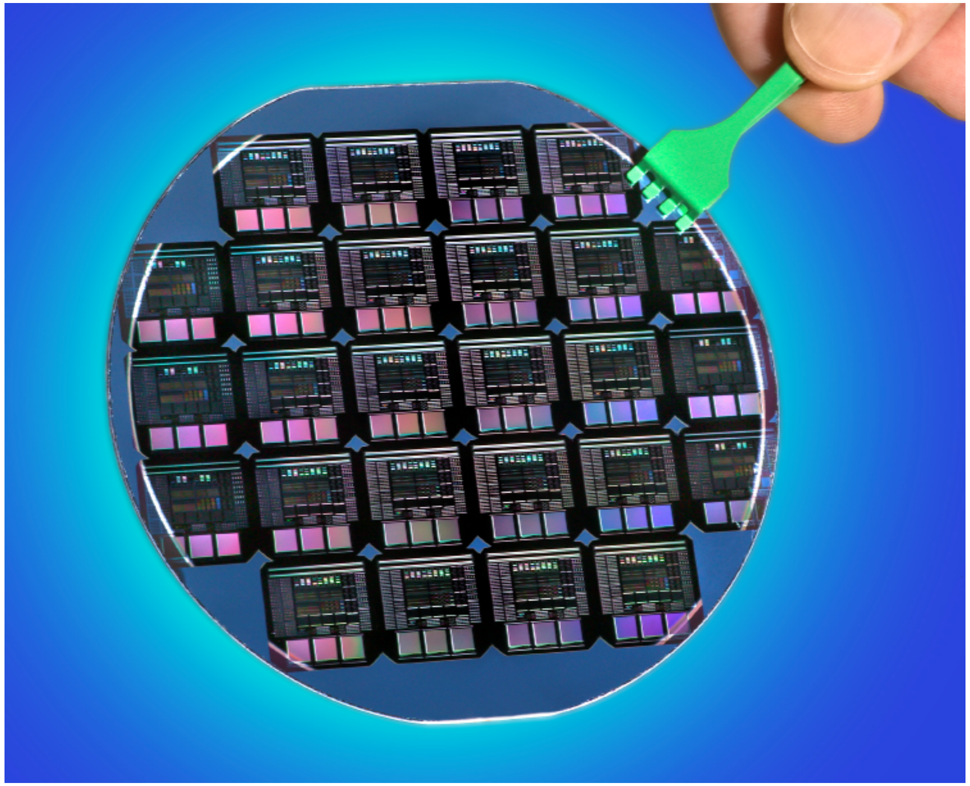
[1]Laboratory Directed Research and Development
LBNL internal funding

Brief history of CCD development and fabrication at LBNL

FY1995 LDRD: LBNL to develop back-illumination technology
Commercial integrated-circuits foundry to fabricate CCDs
Foundry doesn't come through, LBNL to fabricate CCDs[1]

1st high-ρ CCDs fabricated at LBNL on 100 mm wafers

Stepper lithography
3 CCDs per die
Format 200 x 200
(15 μm pixels)



[1]J. Janesick very helpful with LBNL CCD startup

Brief history of CCD development and fabrication at LBNL (cont')

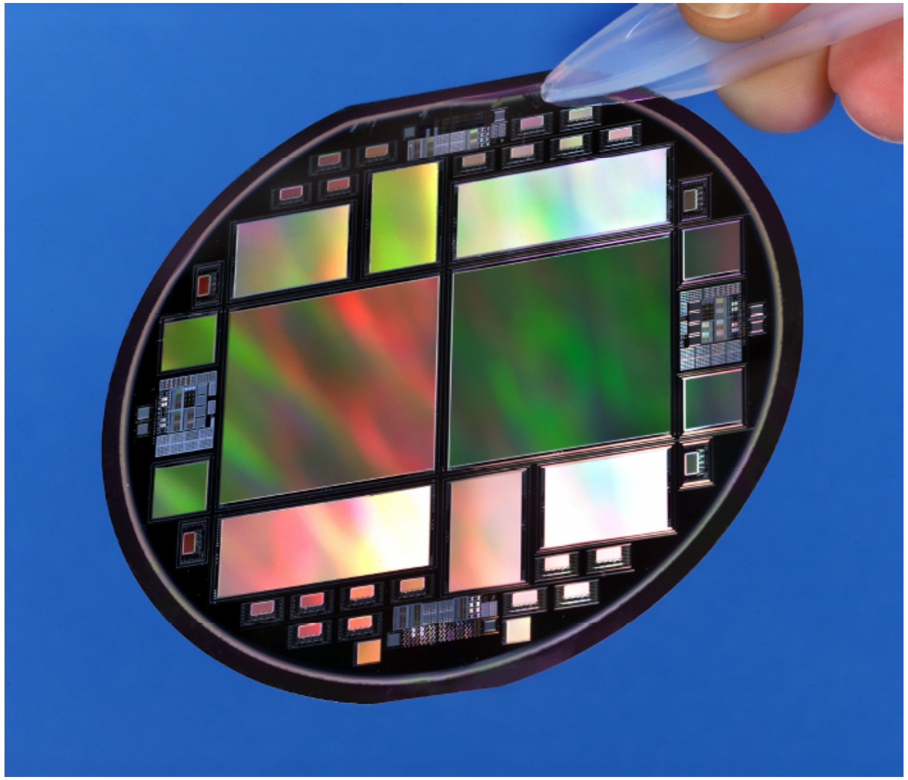
Scale up to large format requires 1 to 1 projection lithography

Lithography equipment donated to UC-Berkeley by Intel Corp.

Installed at LBNL Microsystems Laboratory

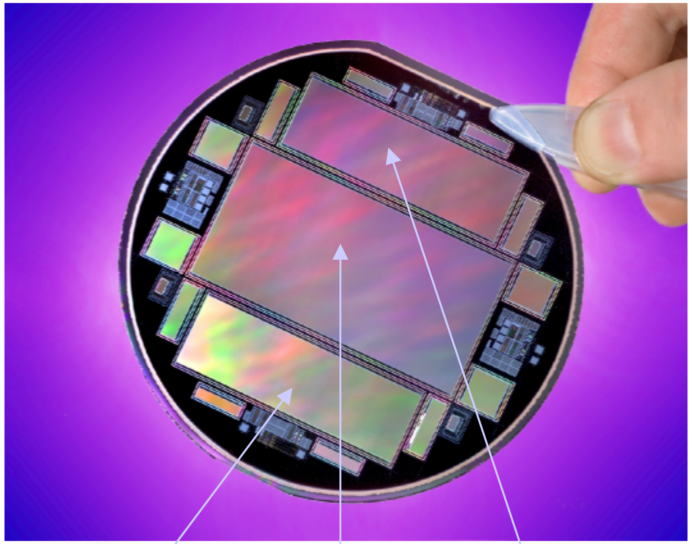
Brief history of CCD development and fabrication at LBNL (cont')

1st large format CCD developed at LBNL (2k x 2k, 15 μm pixels)



Brief history of CCD development and fabrication at LBNL (cont')

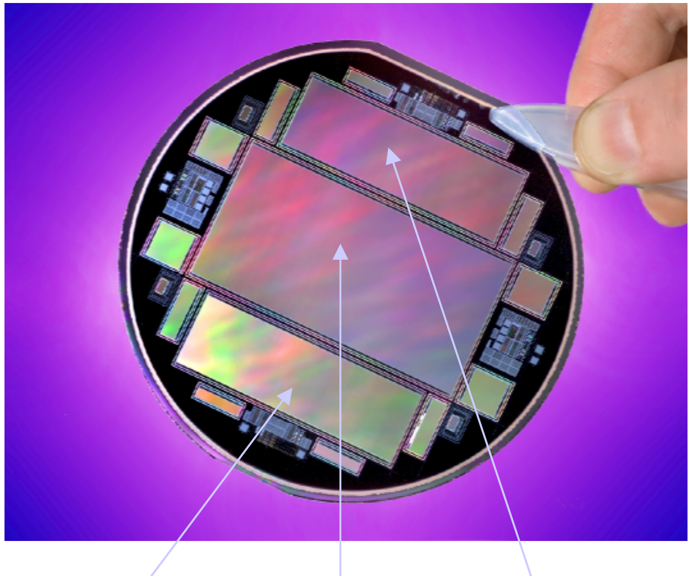
Addition of polysilicon/silicon nitride plasma etch capability
Partially funded by Keck Telescope for 2k x 4k development



1478 x 4784	2k x 4k	1294 x 4186
10.5 µm	15 µm	12 µm

Brief history of CCD development and fabrication at LBNL (cont')

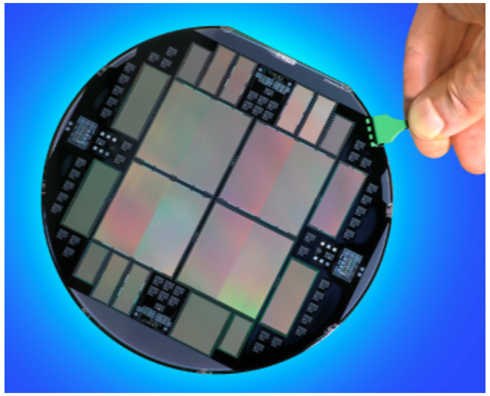
Addition of polysilicon/silicon nitride plasma etch capability
Partially funded by Keck Telescope for 2k x 4k development
~ start of the "Michael Levi" era: key to "get what you need"

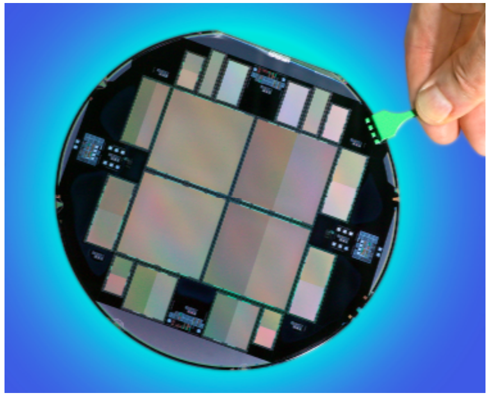


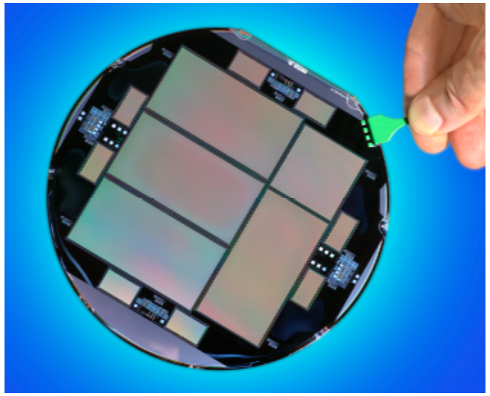
1478 x 4784	2k x 4k	1294 x 4186
10.5 µm	15 µm	12 µm

Brief history of CCD development and fabrication at LBNL (cont')

Development work with DALSA Semiconductor on 150 mm wafers







DALSA ships partially processed wafers that are completed at LBNL
Back-illumination technology development at LBNL

DALSA
SEMICONDUCTOR

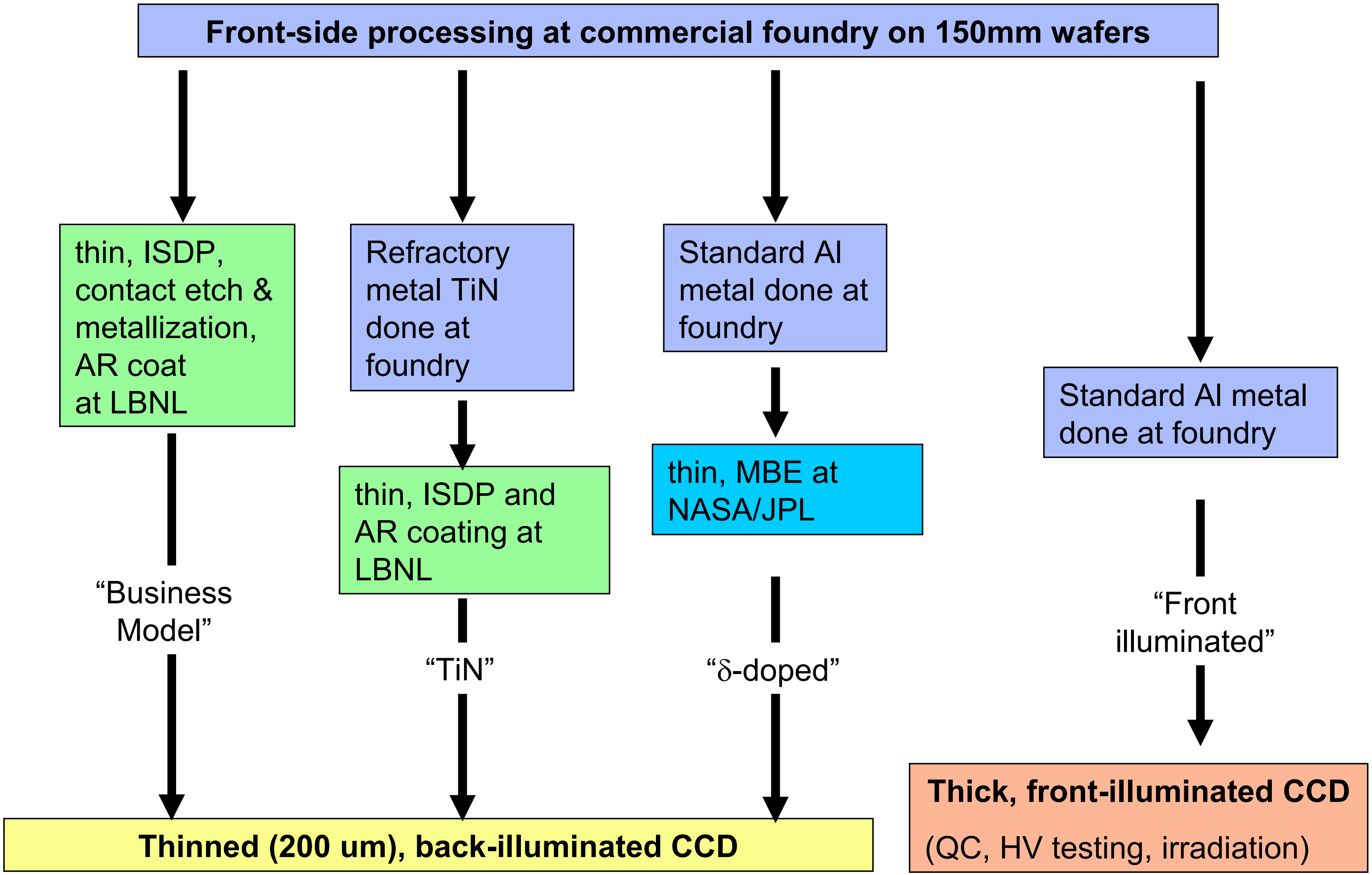
Brief history of CCD development and fabrication at LBNL (cont')

150 mm equipment at LBNL MicroSystems Laboratory

150 mm lithography tool

Oxide plasma etcher
Texas Instruments auction

LBNL CCD Process Flow



LBNL CCD Process Flow

Front-side processing at commercial foundry on 150mm wafers

↓

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

↓

"Business
Model"

↓

Thinned (200 um), back-illuminated CCD

Back-illuminated processing done at wafer level (not die)

Amenable to volume manufacturing

To date 20, 200 μm thick business model wafers have been completed at LBNL

7 wafers have been cold probed at Lick Observatory (Richard Stover) with 23 of 28 SNAP CCD's "imaging and free of major defects"

The latter does not imply "Science grade" but is nonetheless encouraging

Funding Acknowledgements

Office of Science
U.S. DEPARTMENT OF ENERGY

National Science Foundation
WHERE DISCOVERIES BEGIN

NATIONAL RECONNAISSANCE OFFICE
UNITED STATES OF AMERICA

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Jet Propulsion Laboratory
California Institute of Technology

Acknowledgements

Present day CCD group: C. Bebek, N. Roe, D. Groom[1], W. Kolbe, A. Karcher, J. Emes, N. Palaio[1], G. Wang, S. Bailey[2], K. Dawson[2], J. Fairfield, M. Fabricius, J. Saha, W. Lorenzon

Past and present Physics Division/Engineering Division/Lab directors: G. Trilling, P. Oddone, R. Cahn, J. Siegrist, J. Triplett, K. Robinson, C. Shank, S. Chu

Lick Observatory Collaborators: R. Stover[1], M. Wei[1], W. Brown[1]
NOAO Collaborators: A. Dey, R. Reed

Alumni: W. Moses, N. Wang, V. Prasad[2], M. Wagner, J. Steckert, H. Oluseyi[2], R. Kadel, J. Bercovitz, B. Turko, H. Bertsch, K. Gilmore, S. Kurz, J. Lundy, M. Uslenghi

[1]Greater than 10 years service to LBNL CCDs
[2]Shared with SuperNova Cosmology Project