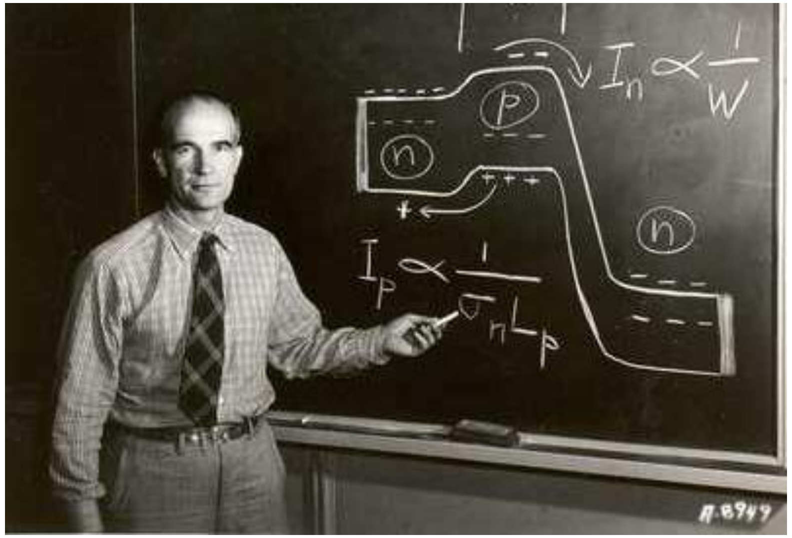
Early Monolithic CMOS Imagers

Chris Kenney

7/31/2026

William Shockley– before CMOS



- Shockley was a pioneer in studying photon-semiconductor physics
- His Nobel prize speech is all about photoconduction and the physics of light exciting the semiconductor
- He also goes on at length about highly energetic electrons
- And bulk crystal damage

If light shines on a germanium crystal, then the pairs of electrons and holes that are formed will impart a conductivity to the crystal.
This conductivity is known as photoconductivity.

if electrons having an energy of several million electron volts fall upon a germanium crystal, the lifetime is subsequently reduced2. From the investigation at Purdue University, it is known that such bombardment produces disorder of the germanium atoms3. A high-energy electron can eject a germanium atom bodily from its normal position in the crystal structure

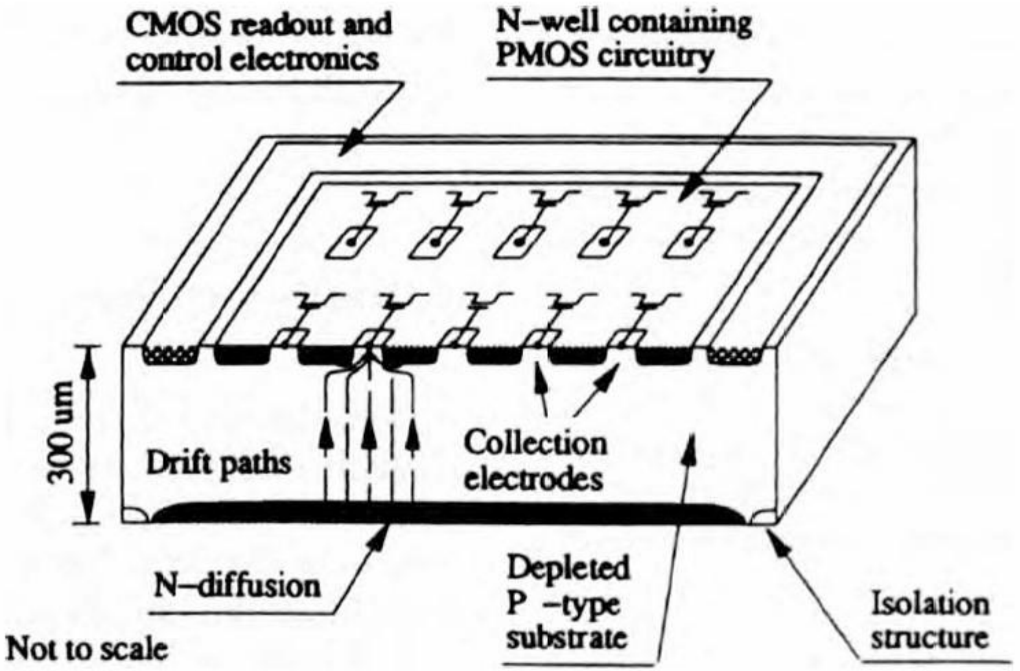
these disordering effects function as **deathnium**

Gene Weckler – the beginning

- Shockley Transistor Corp.
- One of the Fairchildren
- "Operation of p-n Junction Photodetectors in a Photon Flux Integrating Mode" (Journal of Solid-State Circuits, 2-3, Sept 1967) is cited as the original CMOS sensor paper.
- Founded Reticon
- Founded Rad-Icon – CMOS Imagers
  - X-ray imagers
  - Radiation imaging
  - Sold to DALSA / Teledyne

Stanford-Hawaii Monolithic CMOS Sensors

- Follow on to the one-dimensional imaging enabled by the Microplex ASIC
  - First ASIC designed for High Energy Physics
- Goal to provide non-ambiguous position of a track as it crosses a plane.
- Reduces material in the science volume
- Funded by the Superconducting Super Collider – both DOE and Texas
- **Full-depletion 300 microns**
- **First backside illuminated CMOS Imager**



Cross-sectional diagram depicting the central aspects of the pixel device architecture.

Stanford-Hawaii

- Walter Snoeys Ph. D. thesis
- Designed using PISCES (Stanford) and MAGIC (Berkely)
- Fabricated at Stanford's Center for Integrated Systems.
- 3 micron design rules

Stanford-Hawaii

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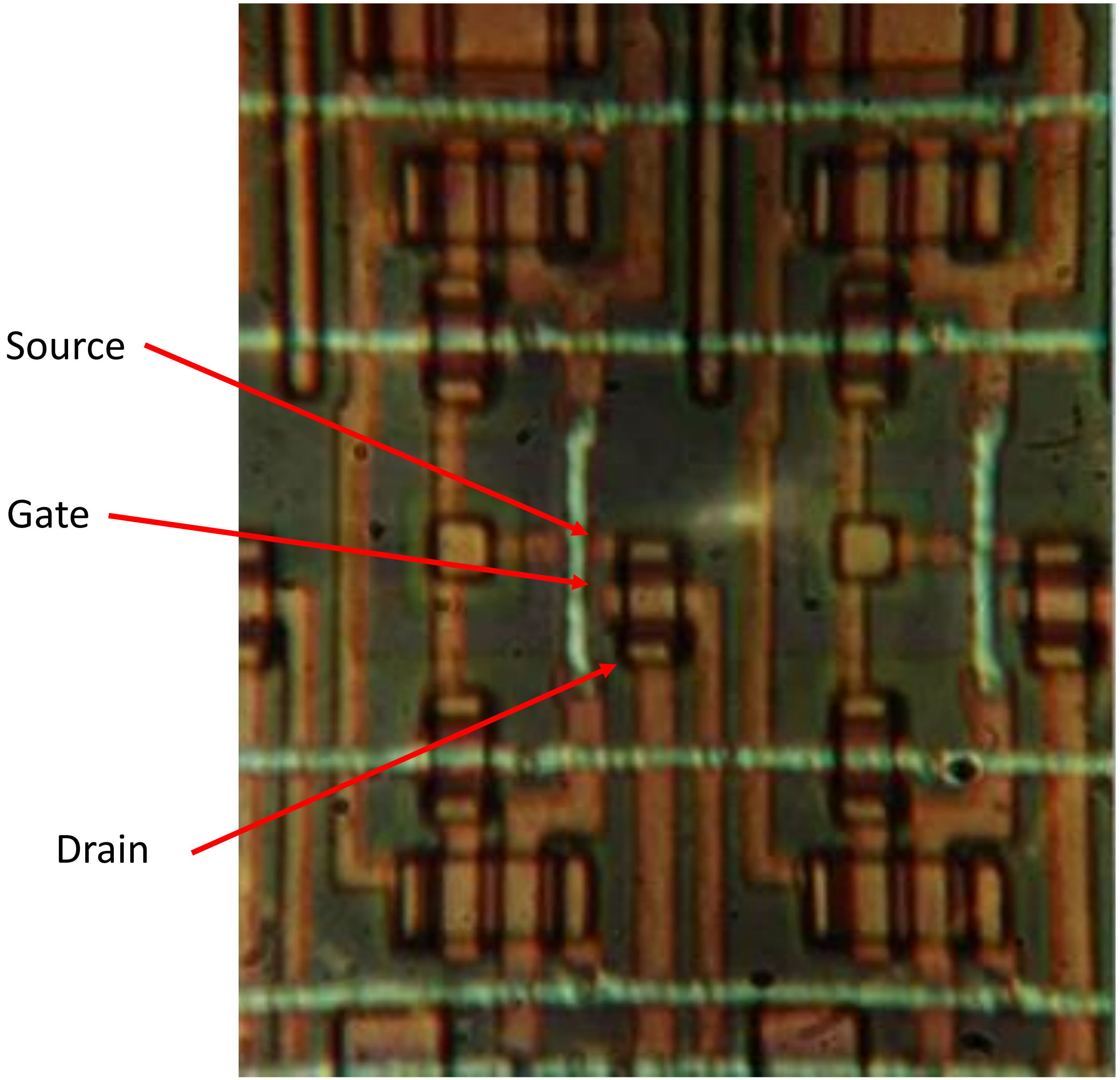
- Designed using PISCES (Stanford) and MAGIC (Berkely)
- Fabricated at Stanford's Center for Integrated Systems.
- 3 micron design rules
- Top dielectric left off for yield
  - Could probe all the nodes in the device
  - Super fun to see the response



First Monolithic CMOS Sensor – Chemical Film Photo

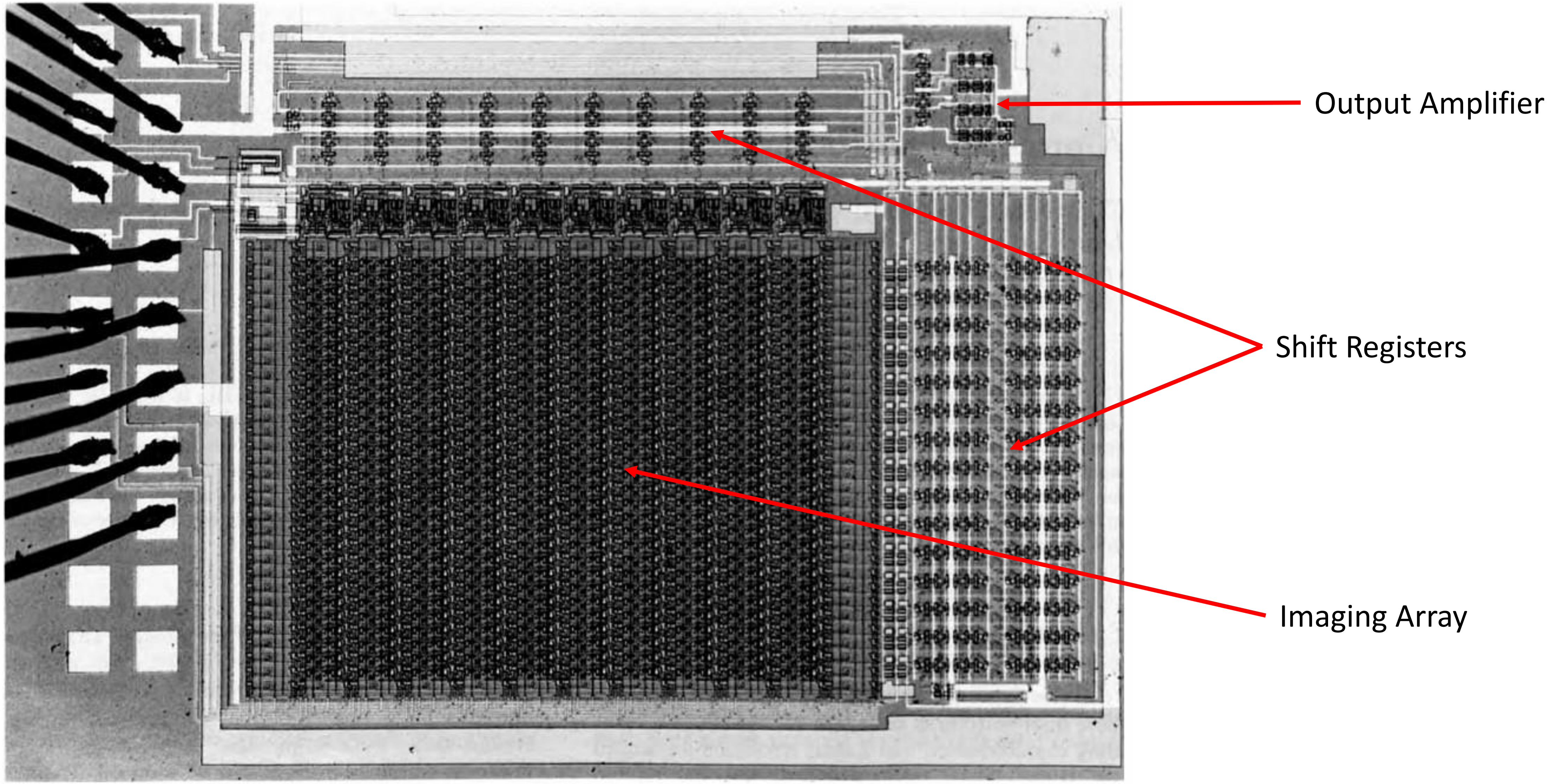
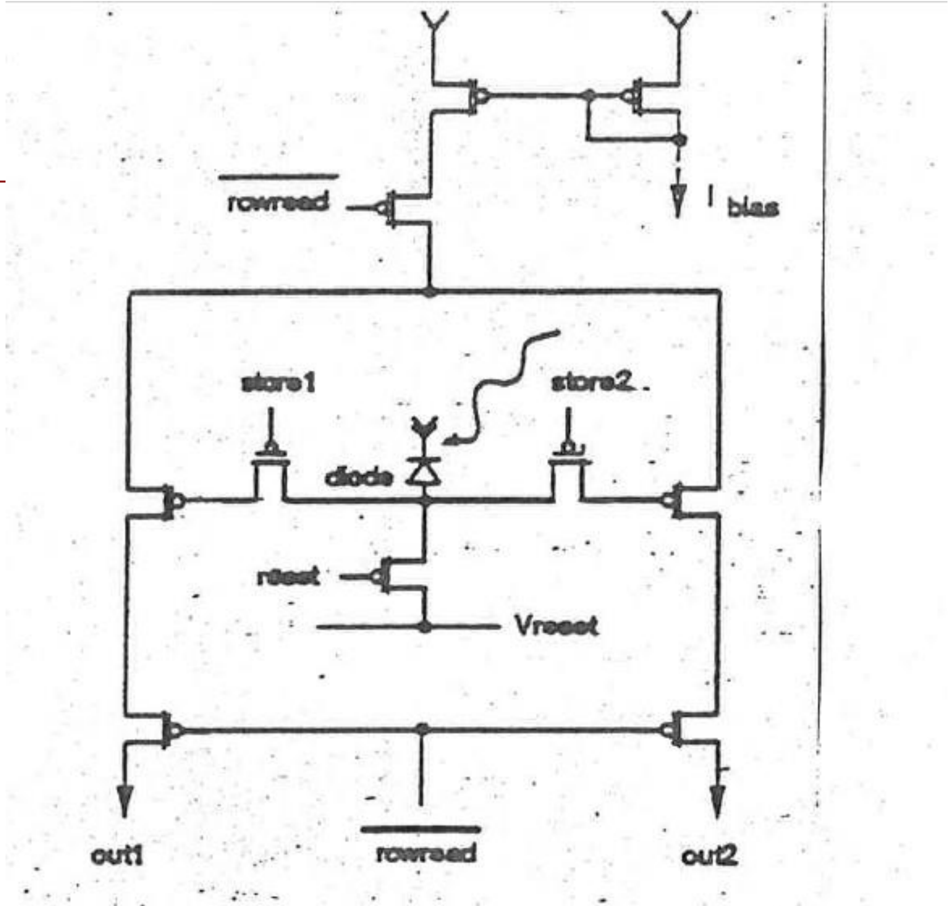


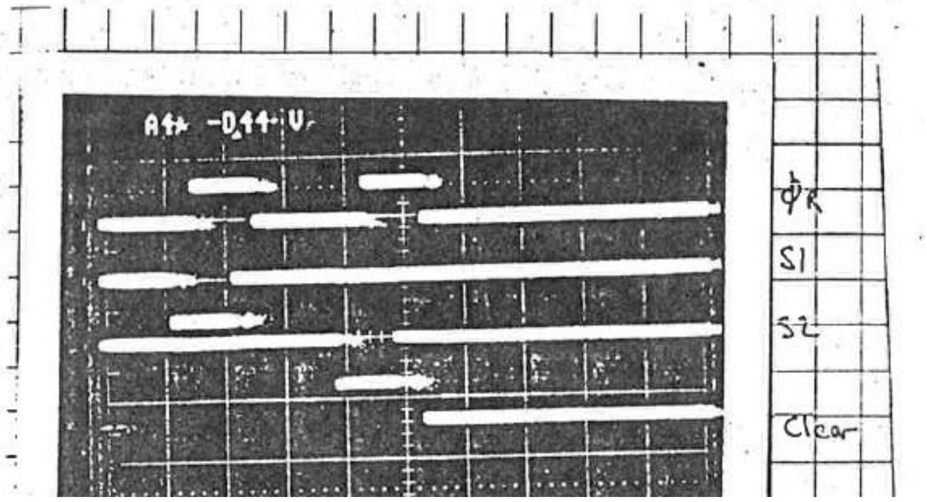
Fig. 1. A photograph of a pixel detector. A metal line near the right edge of the chip was omitted during circuit layout and was added afterwards using a focused ion-beam technique.

1st Generation Pixel Circuit

- Signal charge remains on readout node
- Discrete reset
- Correlated double sampling
- Differential readout

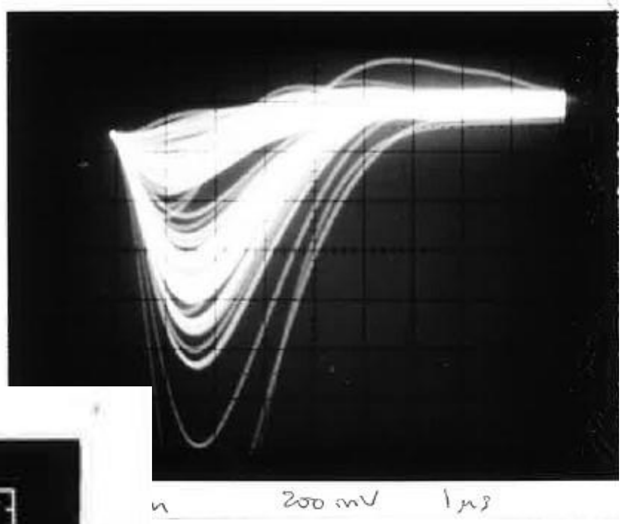
Our first digital DAQ used an Apple McIntosh





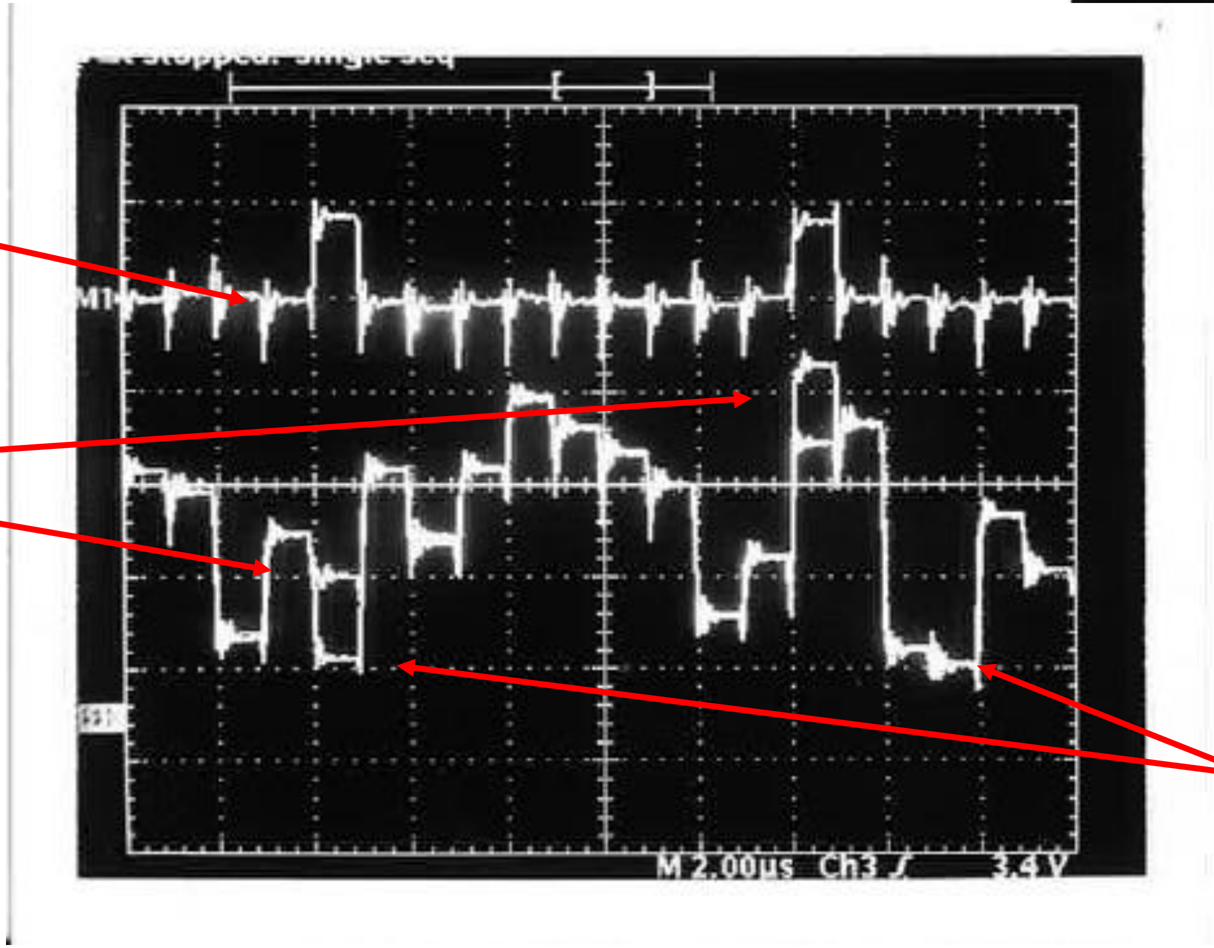
First light on first device

- Use a 1 Curie Am-241 source
- First pedestal subtracted CMOS Imager image?



Pedestal Subtracted Signal

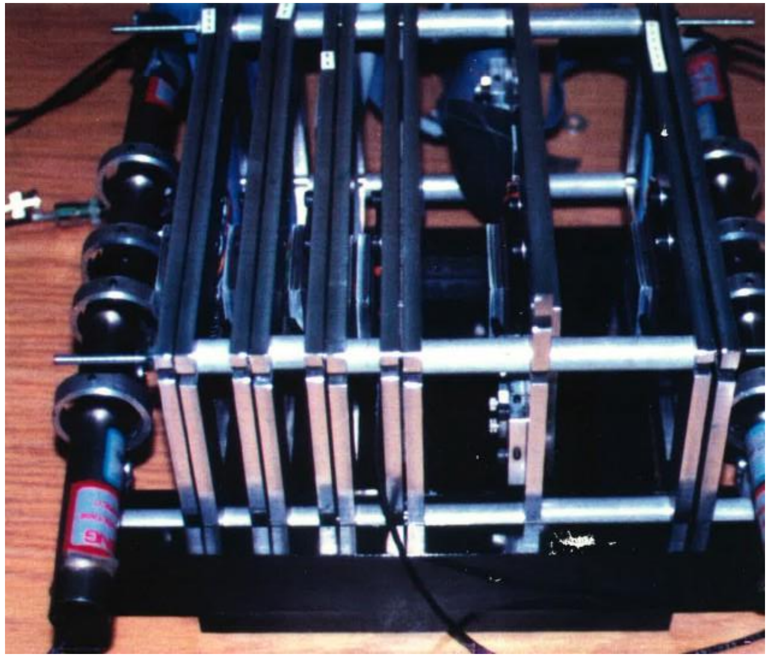
Readout with X-Ray Hits



Dark averaged PEDESTAL

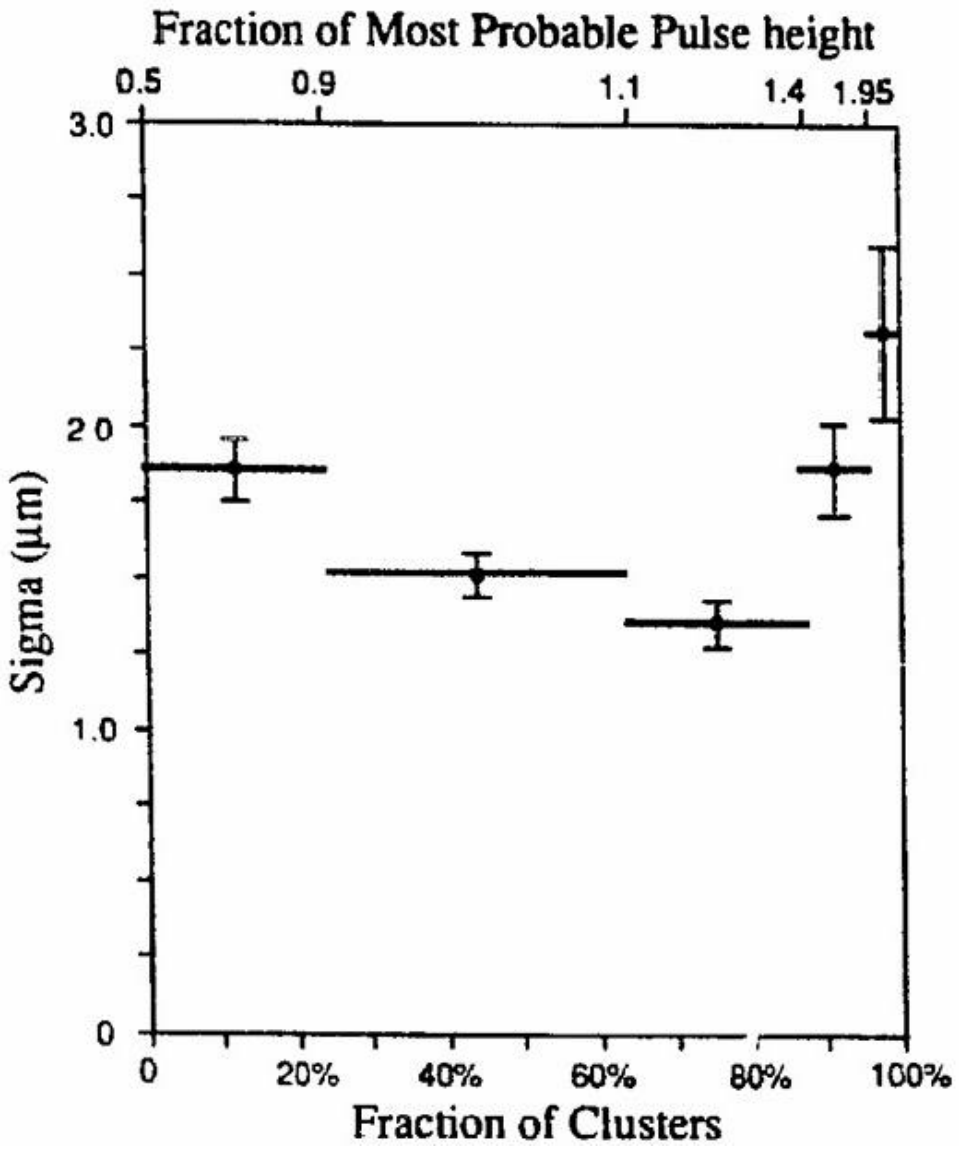
Beam Test

- FNAL
- 250 GeV muon beam (beautiful)
- **First MAPS beam telescope**
  - 3 Fixed planes
  - 1 Rotatable plane
  - 4 scintillator triggers
- **Spatial resolution below 2 microns**

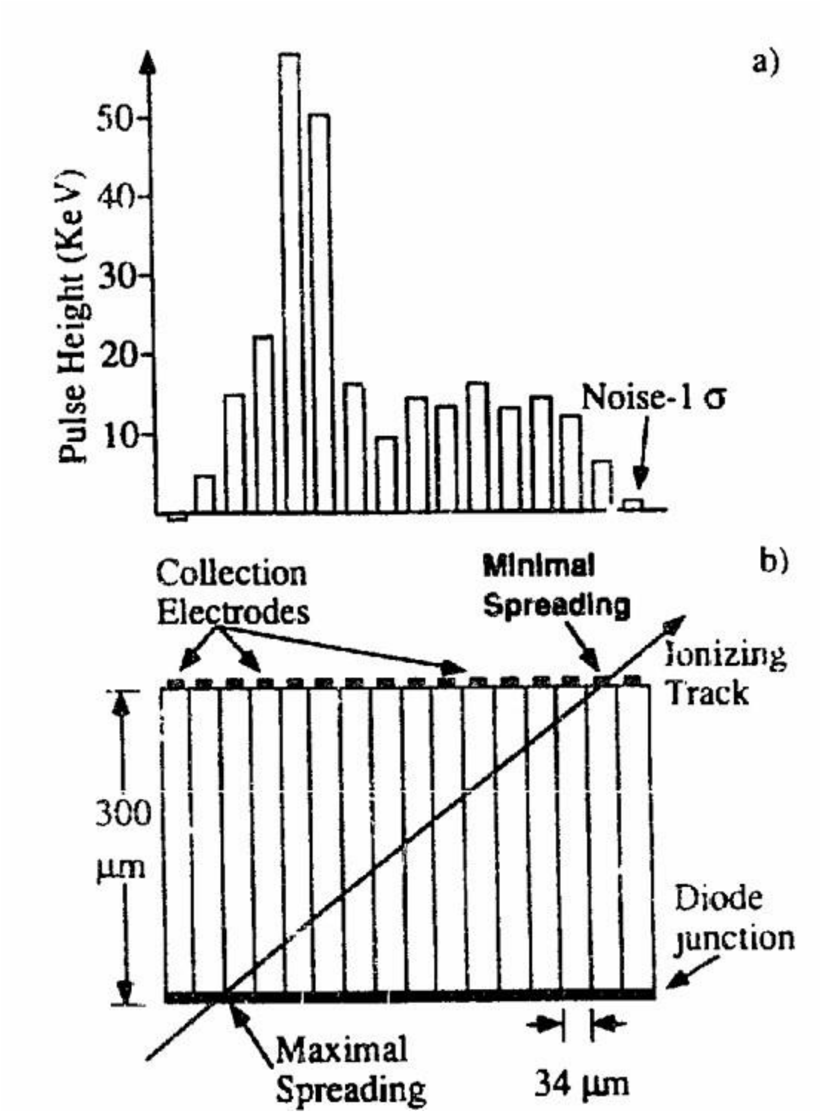


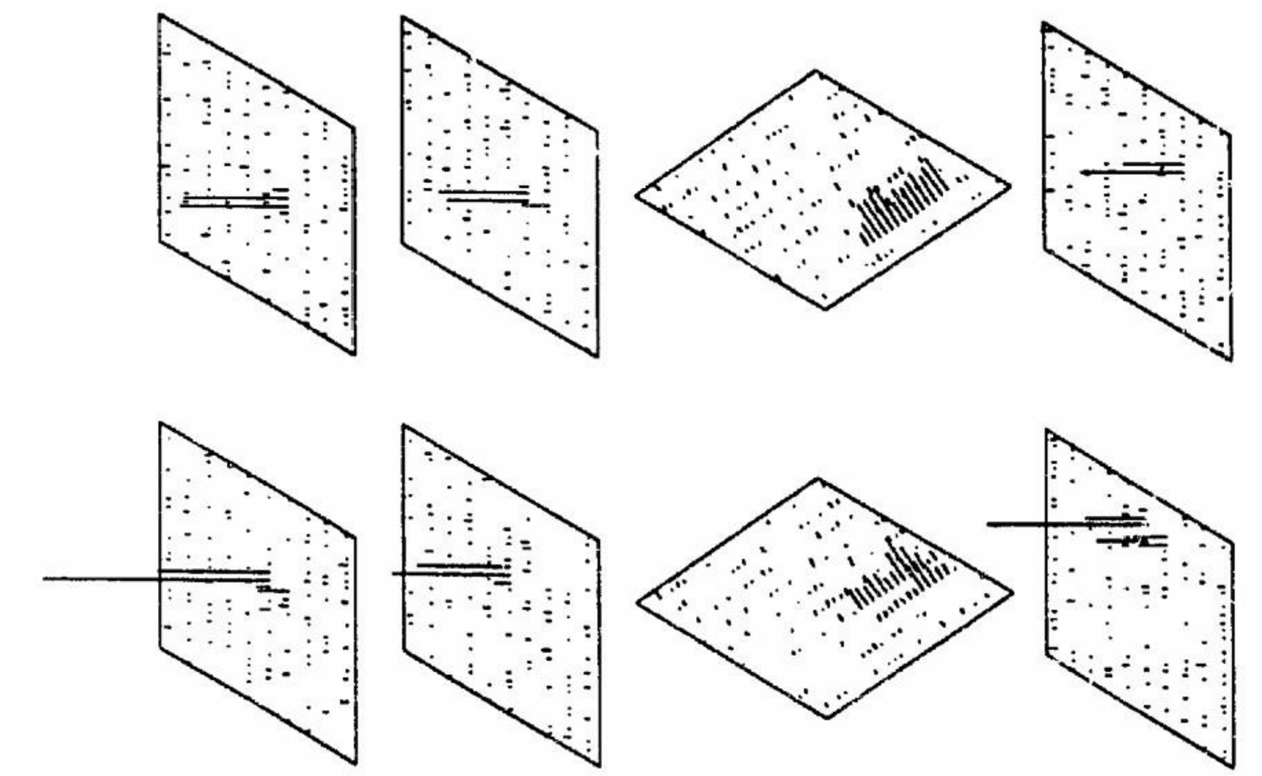
Beam Test – Spatial resolution

- FNAL
- 250 GeV muon beam (beautiful)
- **Spatial resolution below 2 microns**



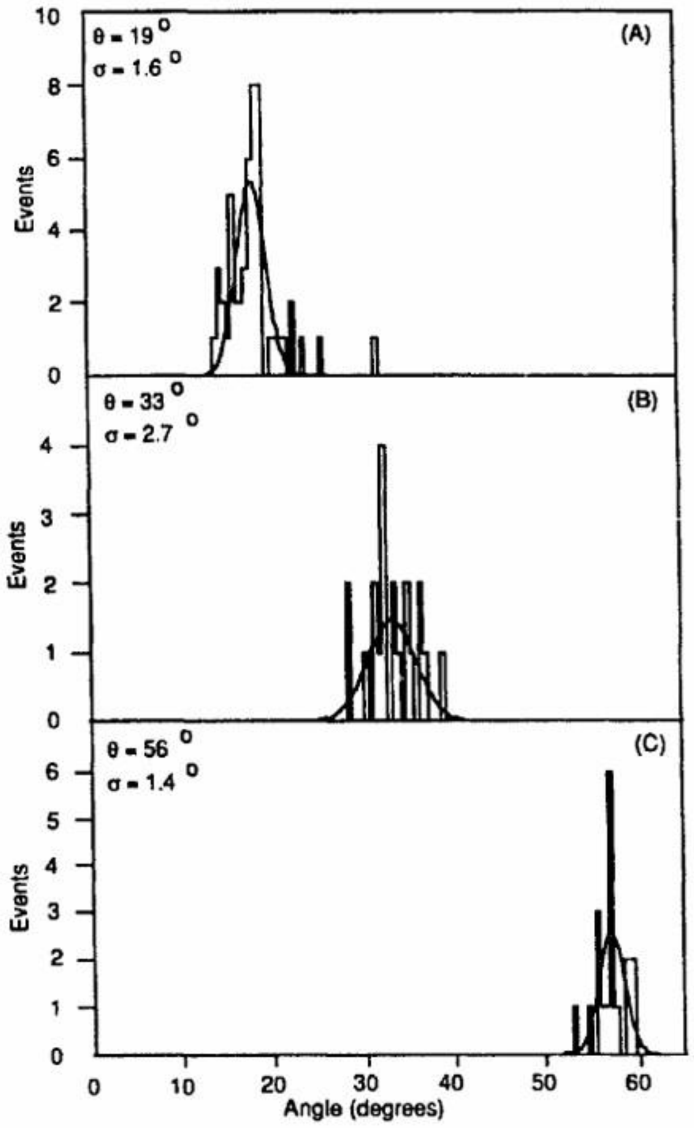
Beam Test – Angled Tracks





Beam Test – Angled Tracks

- Three angles
- 19, 33, and 56 degrees
- Could **measure the track angle to with an RMS of about 2 degrees**



ig. 20. Track angle determined from cluster width for 19°, 33°, and 56° tracks.

Beam Test – The Competition

- Hybrid imaging detectors were also a nascent technology
- Hughes was at the forefront
- SLAC (Steve Shapiro) and LBL's Space Sciences Lab (Arens and Jernigan) collaborated with Hughes
- On same beamline about 10 feet away

Design	Array Size	Pixel Size (μm)	Year
CRC–171	10 × 32	120 × 120	1980
CRC–198	10 × 64	120 × 120	1981
CRC–228	58 × 62	75 × 75	1983
CRC–234	128 × 128	50 × 50	1984
CRC–304	256 × 256	30 × 30	1985
CRC–350	256 × 256	30 × 30	1986
CRC–352	244 × 400	24 × 24	1986
CRC–365	256 × 256	30 × 30	1986
CRC–389A	244 × 400	24 × 24	1987
CRC–389B	512 × 512	20 × 20	1987
CRC–412	488 × 640	20 × 20	1988

Pixel detector workshop

On January 25, 1990 a SLAC/SSRL/LBL workshop was held with the objective of assessing the application of X-ray pixel detectors to present and future synchrotron light experiments. Organized by Steve Shapiro, a SLAC high energy physicist, and with the cooperation of Herman Winick, deputy director of SSRL, and Brian Kincaid, deputy project director of the Advanced Light Source (ALS) project at Lawrence Berkeley Laboratory, more than twenty active X-ray researchers participated in lectures and discussions with representatives of the Hughes Aircraft Company.

Hughes Aircraft Co. has been a pioneer in the development of hybrid arrays. These hybrids are characterized by having the detector array and the readout electronics constructed as two separate chips, each optimized for its specific function. Then the two arrays are indium bump bonded together, each pixel of the detector array having its mate on the readout structure. Such arrays have been developed for the detection of infrared radiation for over 13 years and, during this same time, hybrids useful for the detection of charged particle and X-rays have also been de oped.

The workshop beg presentation by Bo Hughes describin ties of the Hughes c o meet technical ch examples, Bob de number of succe s which utilized sta VLSI technology in comb with signal processing power easured in billions of operations per second. Bob was followed by Gordon Kramer, also from Hughes, who described the development of a vertex detector for the SSC. These devices emphasized the detection of charged particles with good signal to noise (100:1) and good time resolution (15 nsec.). They would be read out in a few microseconds, and would be radiation hardened to a few MRad.

Steve Shapiro of SLAC then gave a short review of the properties of the present generation of arrays now being used as particle detectors (see Figure1 and Figure 2). A 256 x 256 array having 30 micron square pixels was described. The detector chip is a 300 micron thick array of silicon PIN diodes. Minimum ionizing particles produce a signal of 25,000 electrons. They are stored within the pixel on the 40 femtofarad gate capacitance of the sense FET, re sulting in a signal size of a 0.1 Volt. A spectrum of electrons from Bismuth displayed, along with urement of less th ons rms at 200 deg s mentioned that Silicon of this thickness was an efficient detector for X-rays up to about 10 KeV. Thicker silicon diodes could be hybridized to this readout structure, or Germanium diode arrays could replace the silicon for increased detection efficiency for X-rays in the 30 - 40 range.

Garrett Jernigan of Sciences Laboratory a gave a brief descr use of a silicon pixe ect X-ray bursts usion of deuteriu the Lab for Laser Rochester, NY. Eri lso of the Space o, discussed the use of hybrid arrays in infrared omy.

Herman Winick of SSRL then presented an overview of the synchrotron radiation activities worldwide. He pointed out that there are about 45 storage rings in operation, construction, or design and

Stephen Shapiro proposes using hybrid detectors for synchrotrons

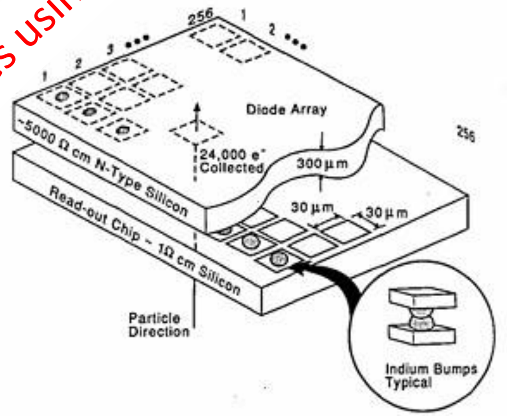
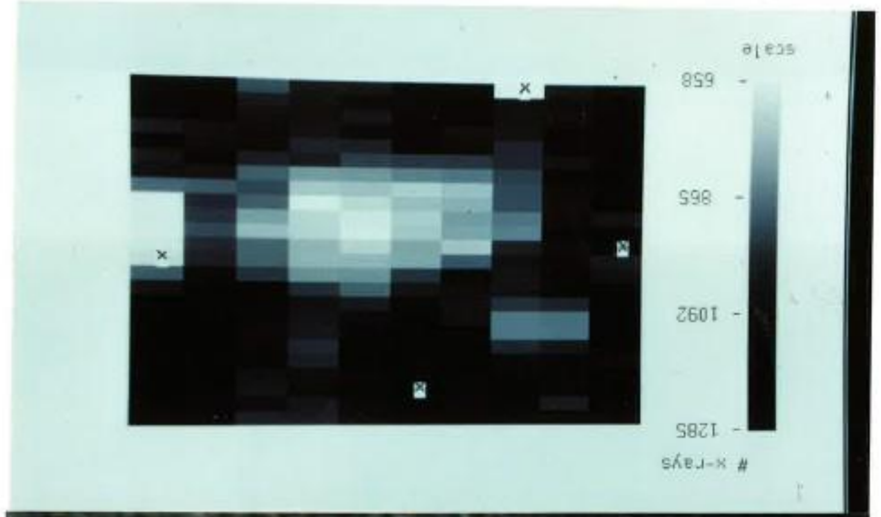
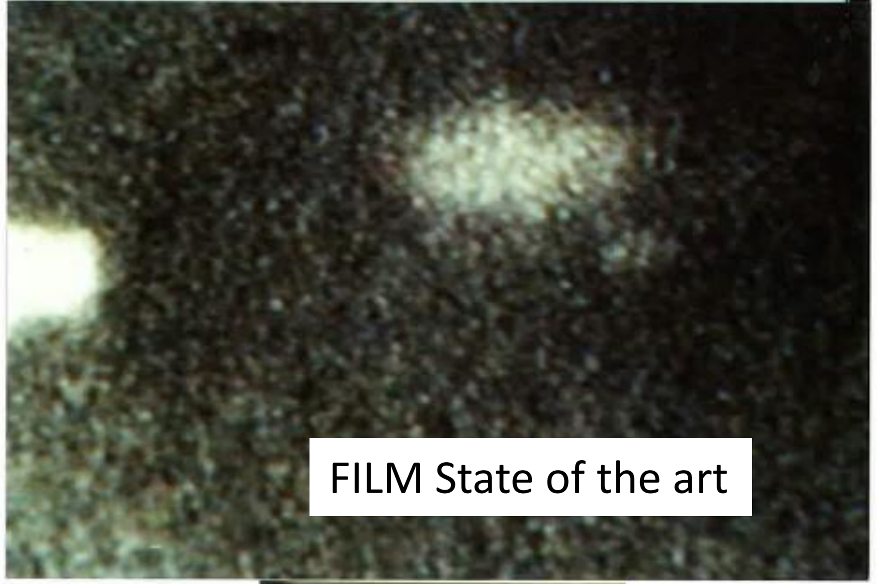


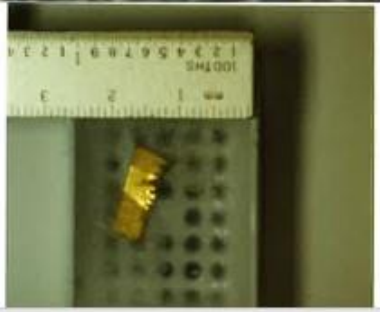
Figure 1 Silicon PIN Diode Hybrid Array used for Charged Particle Detection. The array is 256x256 with each pixel being 30 µm on a side. The hybrid is comprised of a silicon PIN array and a readout array which are connected together with an array of indium bumps - 65,536 in all. This PIN Diode array is 300 µm thick, but for the detection of other particles, e.g., X-rays, the PIN array can be changed to germainum of thicker silicon.

MAPS for Medical Imaging

- Collaborated with Debi Ikeda at Stanford Medical Center
- Took care of by baby daughter during the day
- Took mammography data at night
- **First use of MAPS for medical imaging?**
- Tumor tissue
- **Could easily observe 50 micron calcification**
- Medipix was later started to address mammography using hybrids

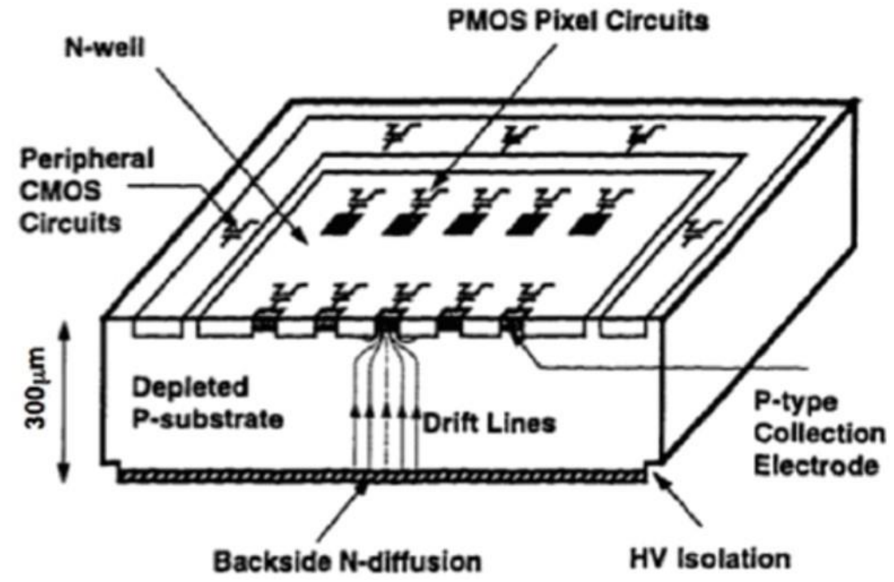


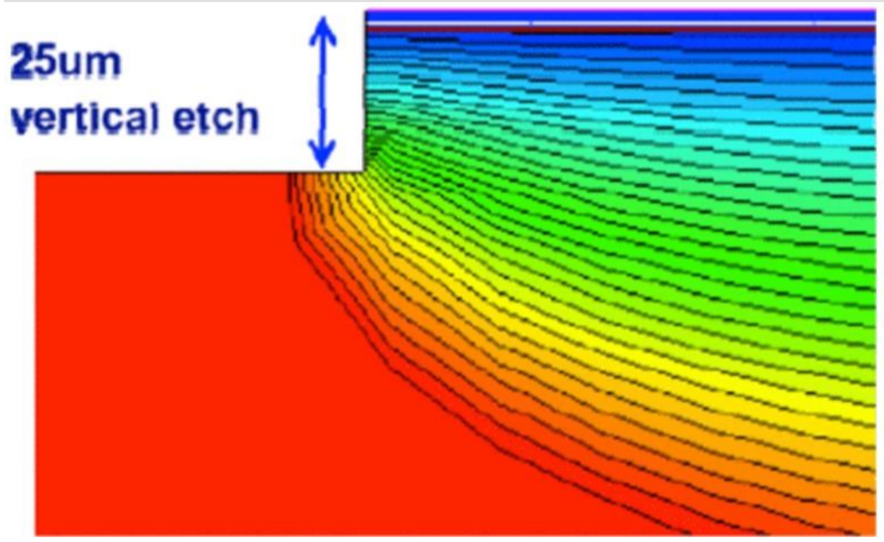




HEP MAPS – 2nd Generation

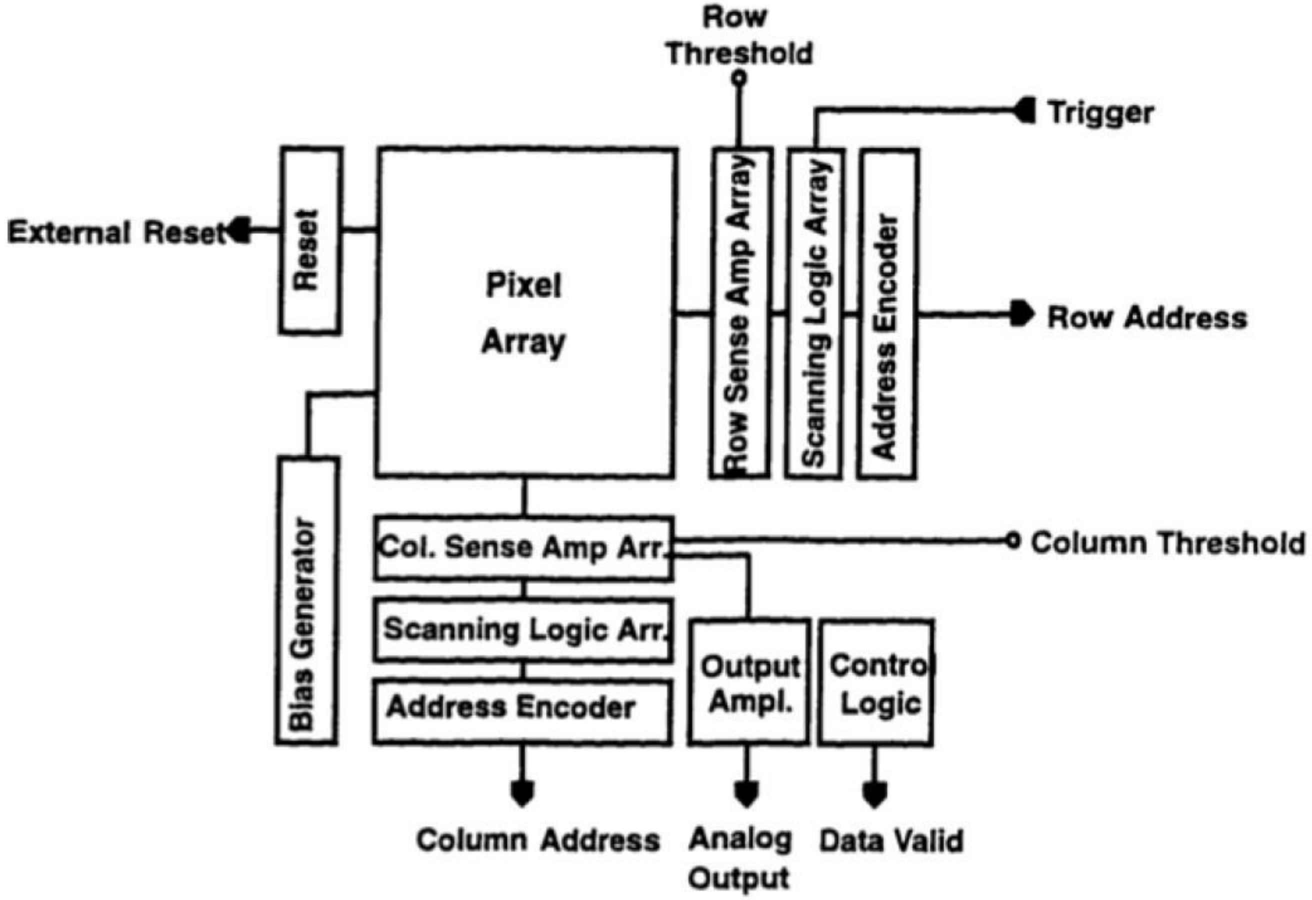
- Fabricated at Stanford by Julie Segal
- Still 3 micron design rules
- Larger array ~ 1 cm2
- 60 micron pixels
- Advanced backside process with reduced masks using a MEMS-like method
- Replaced guard rings





HEP MAPS – 2nd Generation

- Sparse readout – first for MAPS?



Modern iPhone CMOS Imager taking picture of its great, great grandparent

HEP MAPS – 2^{nd} Generation

- Sparse readout – first for MAPS?
- End-of-column and row discriminators

Am-241
59 keV gammas

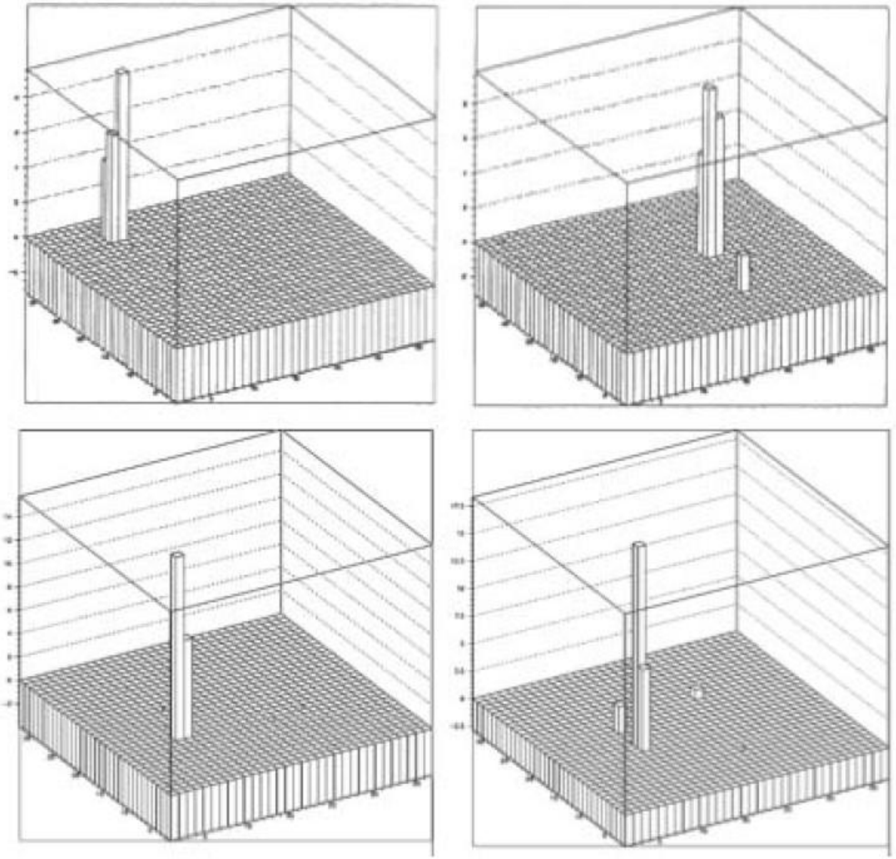
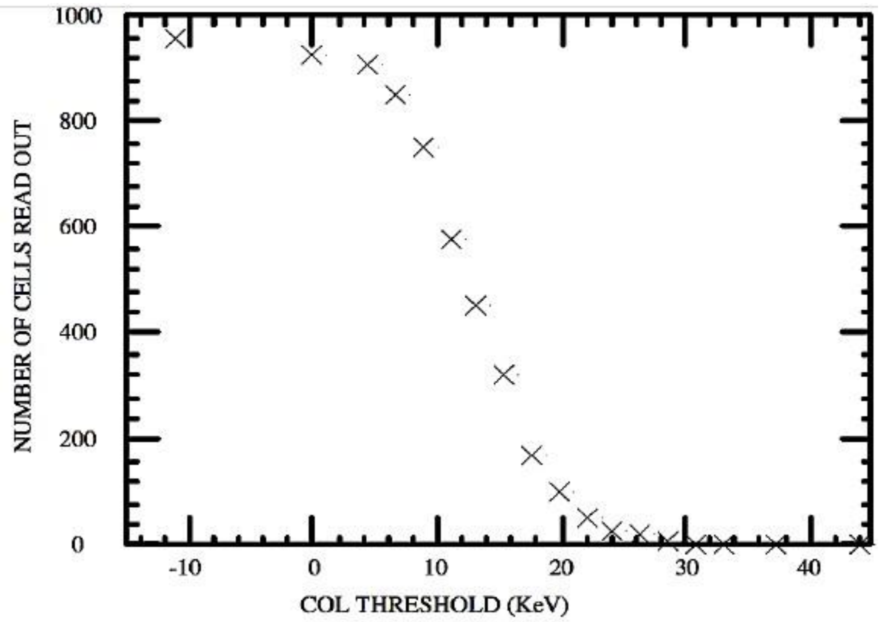
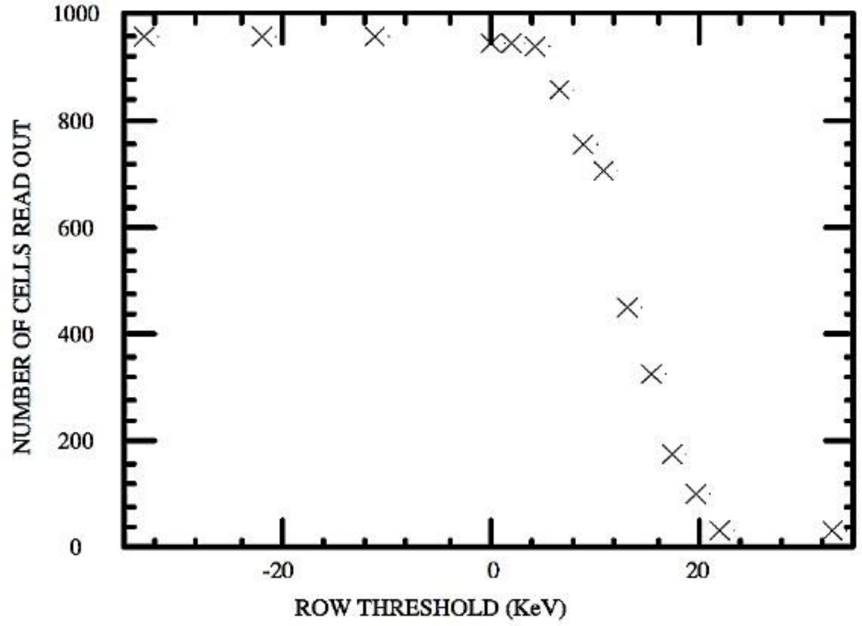


Fig. 11. Examples of single event γ-ray read-outs in sparse field mode



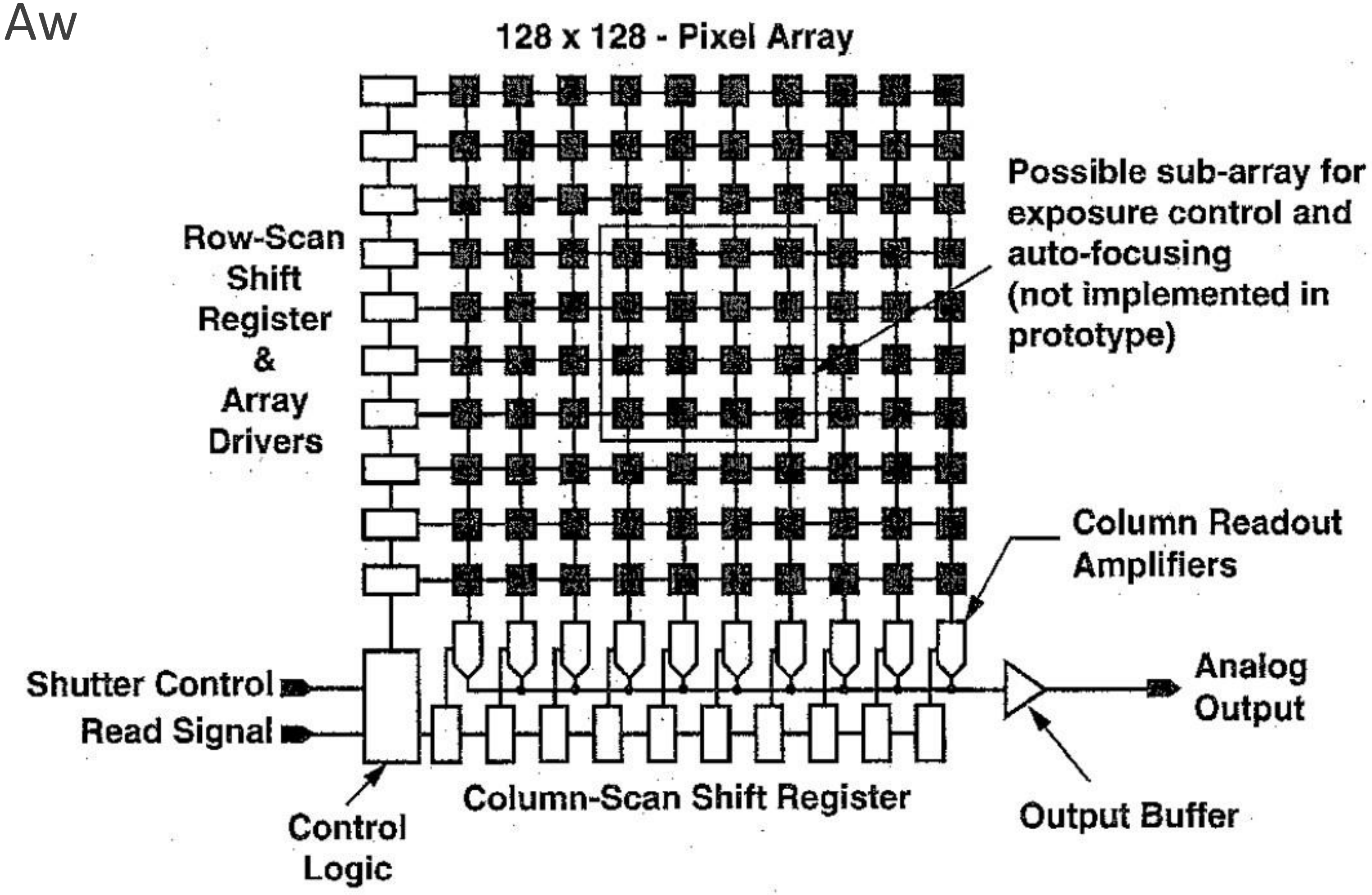


Early MAPS – JPL/CalTech Effort (Fossum et al.)

- COMMERCIAL FOUNDRY
- 2 um CMOS
- 40 micron pixels
- 128 x 128 array
- 30 Hz
- 2 e- noise
- Fill factor of about 26%

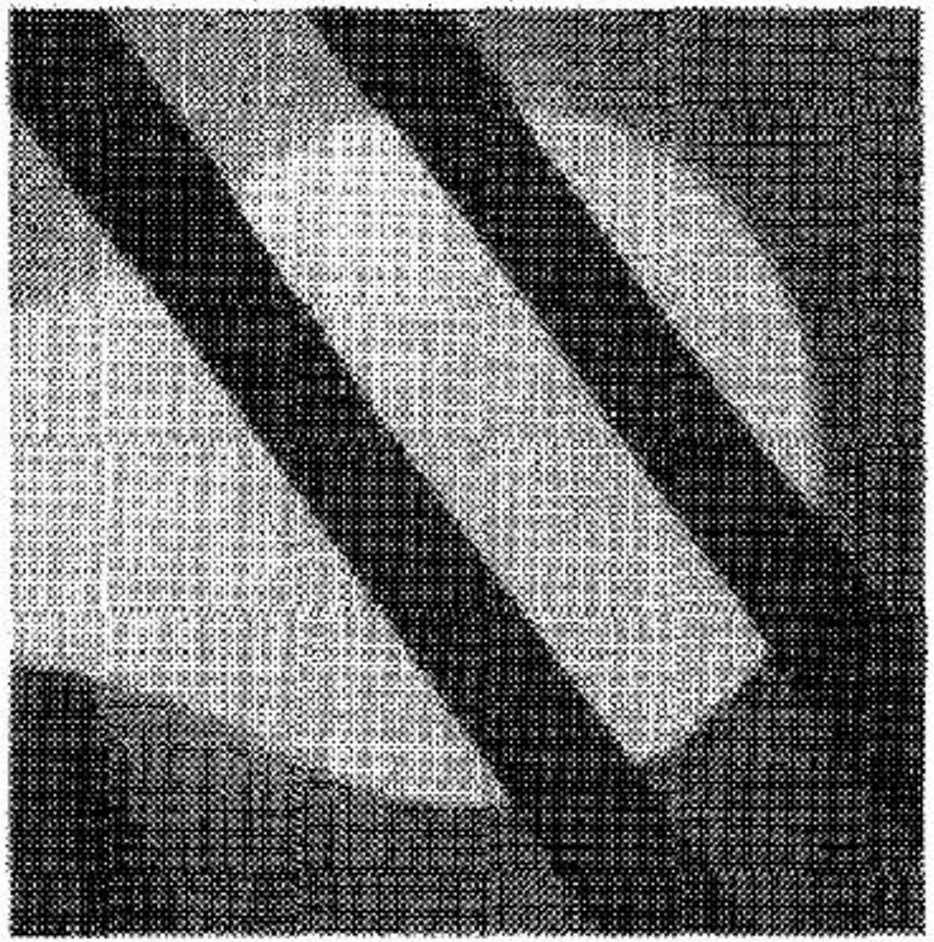
Early MAPS for Optimized for Visible Light

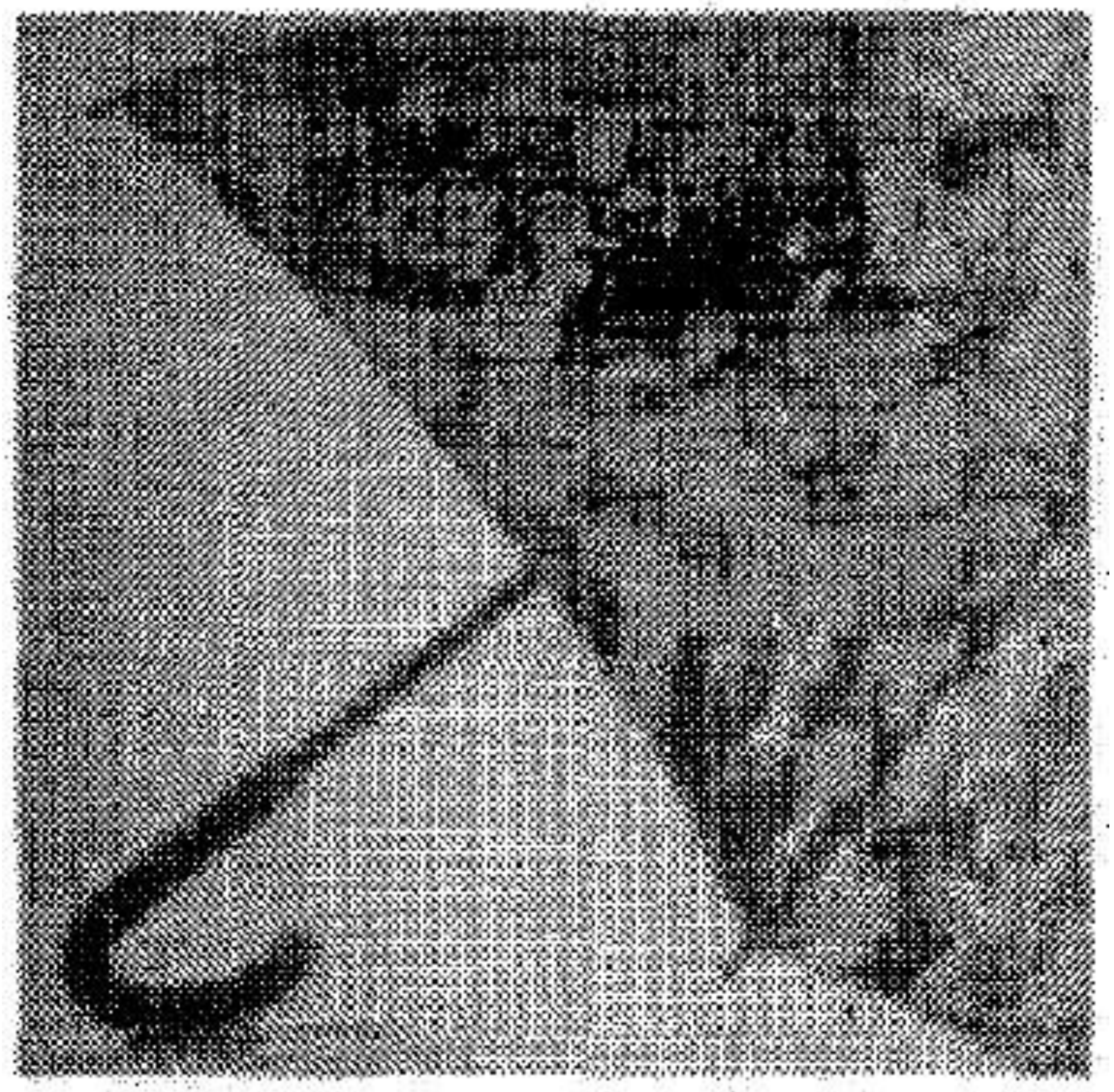
- Stanford B. Wooley and C. H. Aw
- 24 micron pixels
- 1.2 um CMOS process
- COMMERCIAL FOUNDRY!
- 500 Hz frame rate
- Correlated Double Sampling
- 4T in pixel



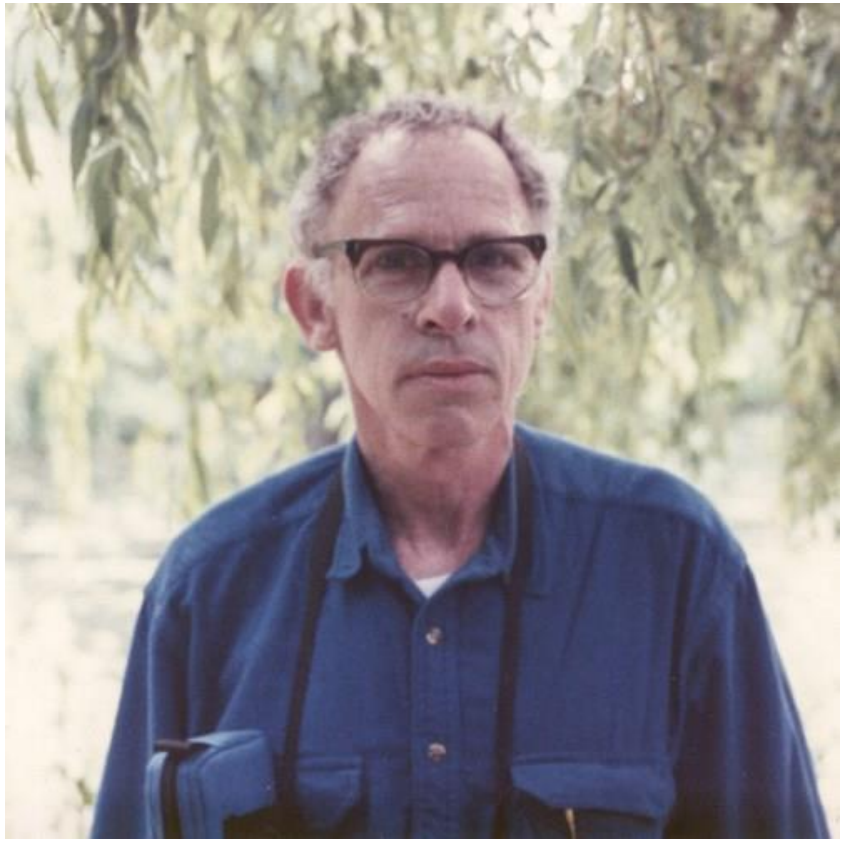
Early MAPS for Optimized for Visible Light

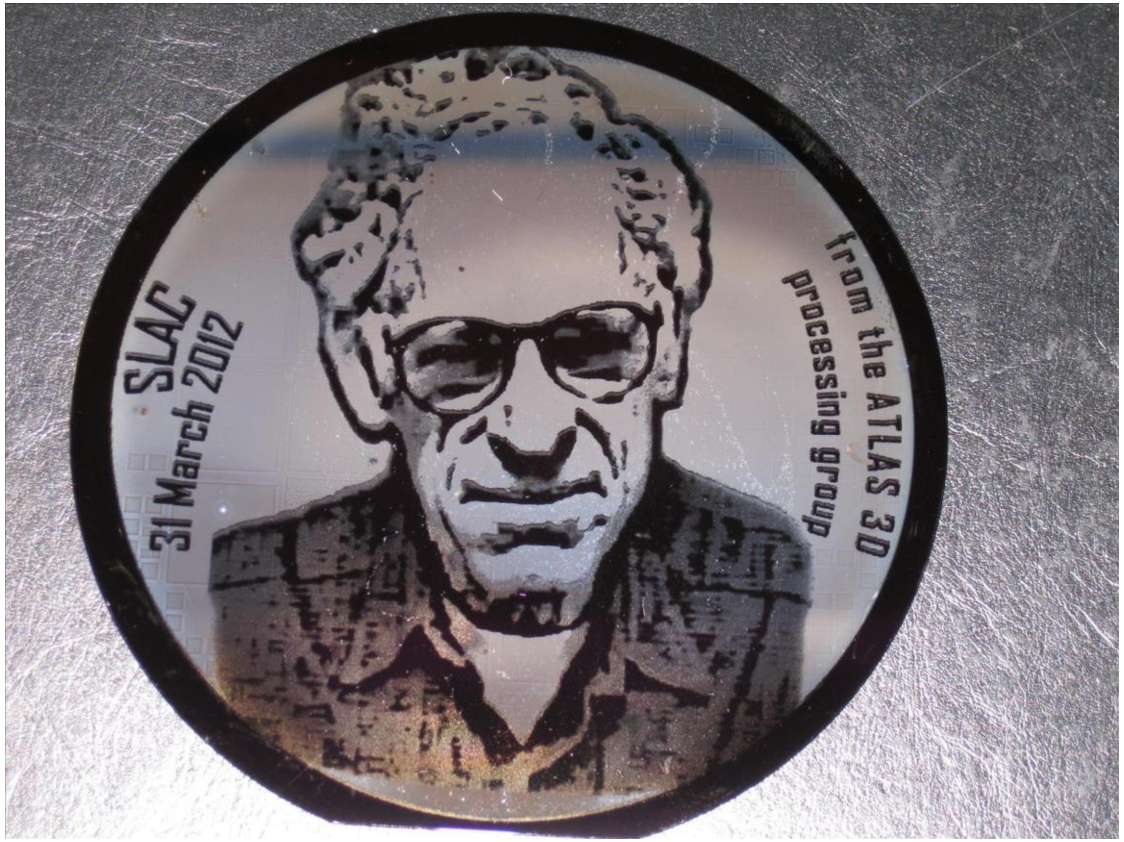
- Incorporated an anti-blooming technique





People – Sherwood Parker





First to conceive of and realize monolithic pixel detectors for HEP, Medical, etc.

Hawaii, SLAC, and **The Rad Lab**

People – Stanford EE Students

Walter Snoeys

Initial Imager -

Designed, Fabricated, Testing

Julie Segal

Process Design,
Fabricated, Testing

Chye Huat Aw

2^{nd} Generation Imager -

Circuit Design & Testing

Geert Rosseel

1^{st} Generation Imager – amplifier design

People – Faculty

Jim Plummer

Walter's and Julie's advisor

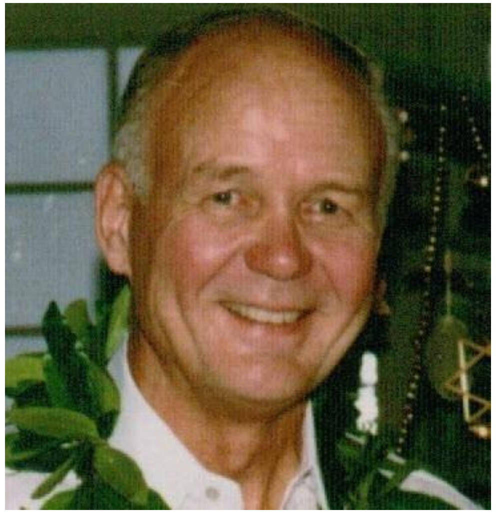
Director of CIS / SNF

Bruce Wooley

Chye Huat's and Geert's advisor

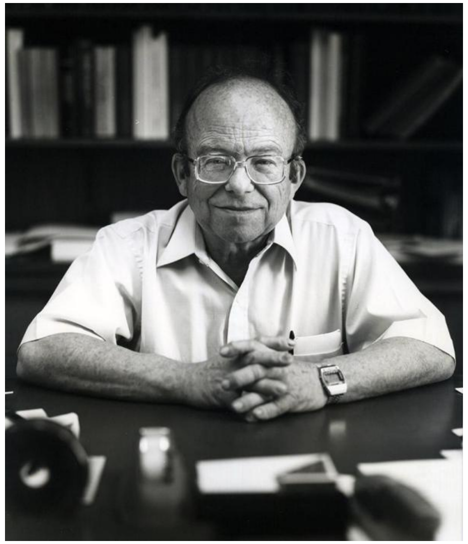
(and Gunther's)

Vince Peterson



Head of Hawaii HEP Group

Pief Panofsky



Supported effort at SLAC