Charge Coupled Device and Charge Injection Device Technology

George Lungu
Dr. Lynn Fuller
Motorola Professor
Microelectronic Engineering
Rochester Institute of Technology
82 Lomb Memorial Drive
Rochester, NY 14623-5604
Tel (585) 475-2035
Fax (585) 475-5041
LFFEEE@rit.edu
http://www.microe.rit.edu

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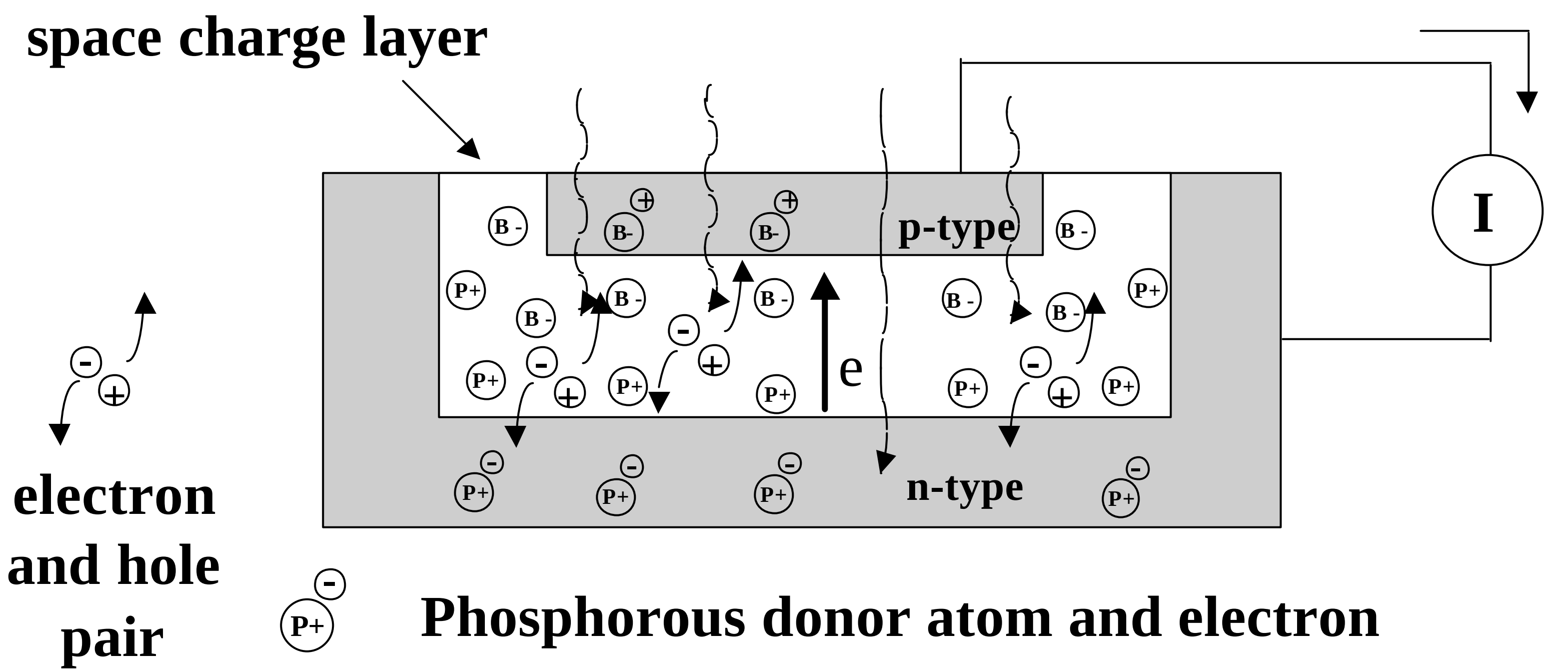
OUTLINE

- Charge Generation in Semiconductors
- Potential Wells and Barriers
- Charge Transfer
- CCD Readout
- Channel Stops
- Overflow Drains (anti-blooming)
- Clocking Schemes
- CCD Sensor Architecture
- CID's
- CID Sensor Architecture
- CID Readout
- Fabrication Processes for CCD's and CID's

CONVERSION OF LIGHT TO ELECTRIC CURRENT IN PN JUNCTION



- P+ with electron: Phosphorous donor atom and electron
- P+: Ionized Immobile Phosphorous donor atom
- B -: Ionized Immobile Boron acceptor atom
- B- with hole: Boron acceptor atom and hole

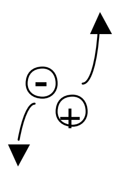
CHARGE COLLECTION IN MOS STRUCTURES

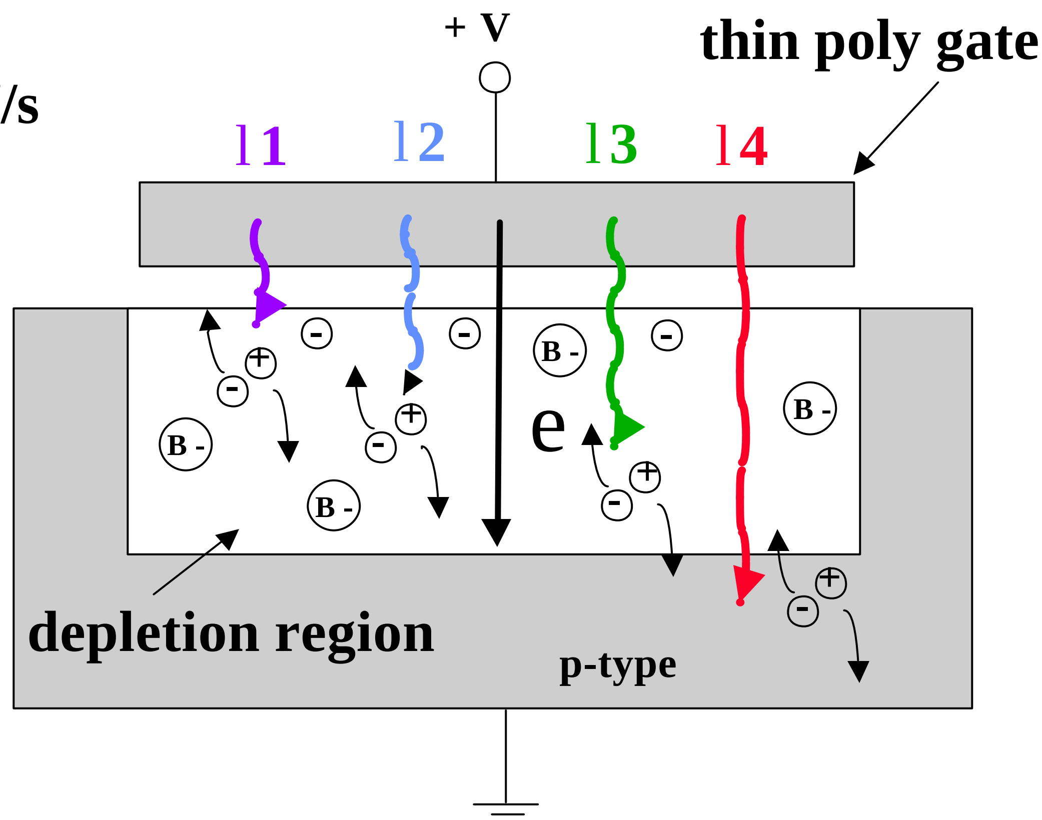
E = hn = hc / l

h = 6.625 e-34 j/s
  = (6.625 e-34/1.6e-19) eV/s

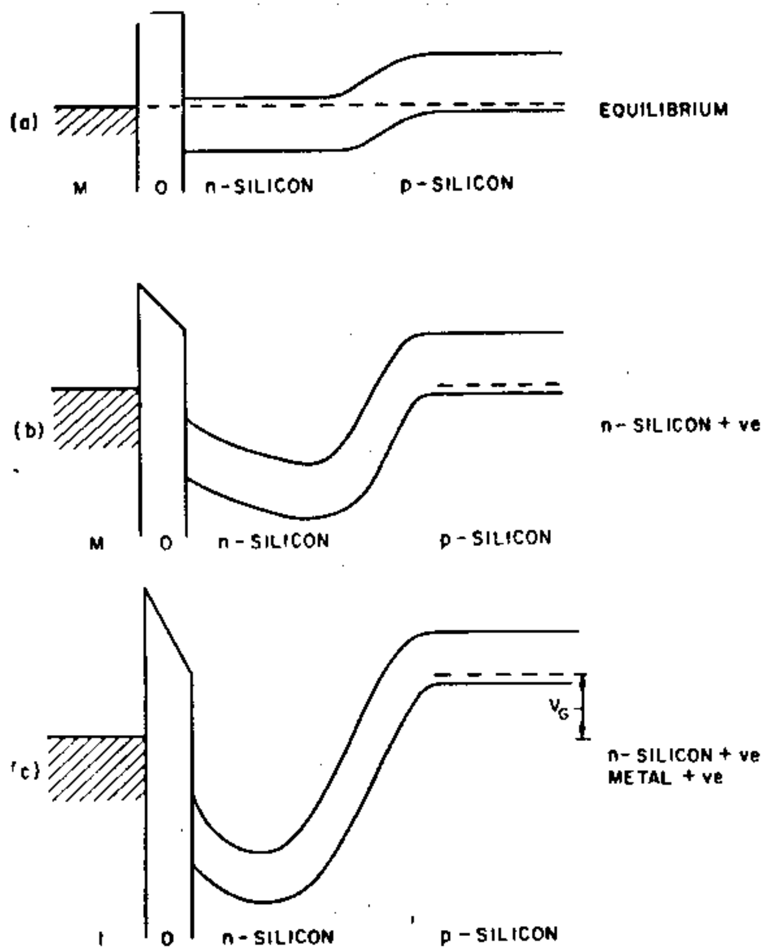
E = 1.55 eV (red)
E = 2.50 eV (green)
E = 4.14 eV (blue)

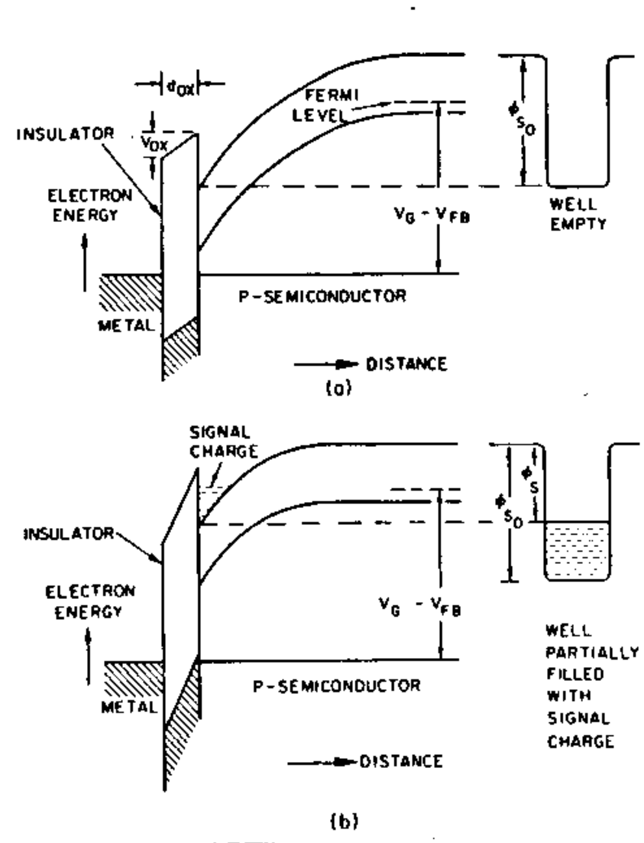
electron and hole pair



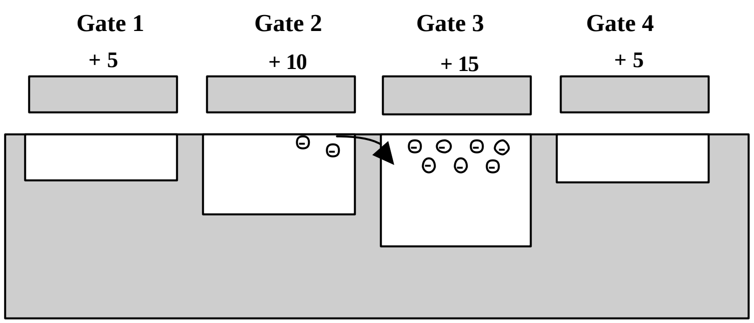


POTENTIAL WELLS AND BARRIERS

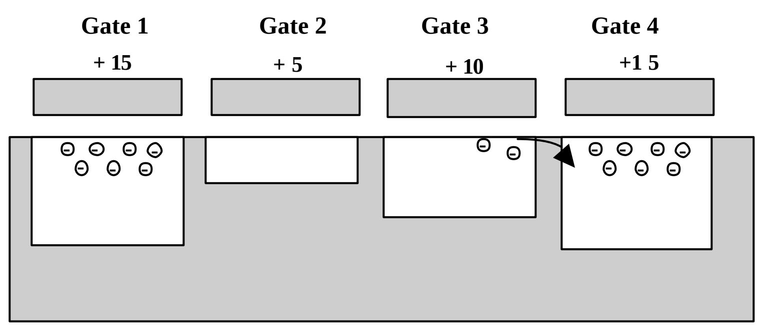


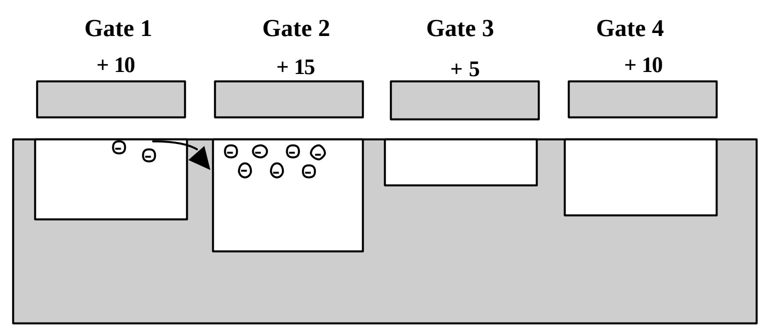


CHARGE TRANSFER



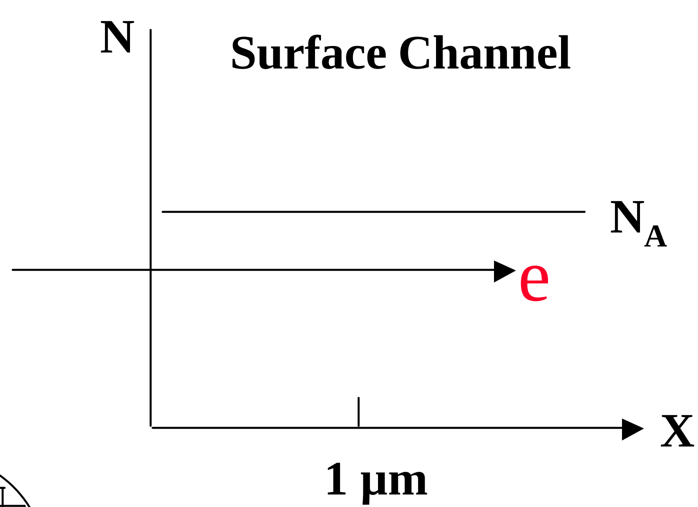
If a potential well is moved together with the surrounding barrier, most of the electric charge will move with it.

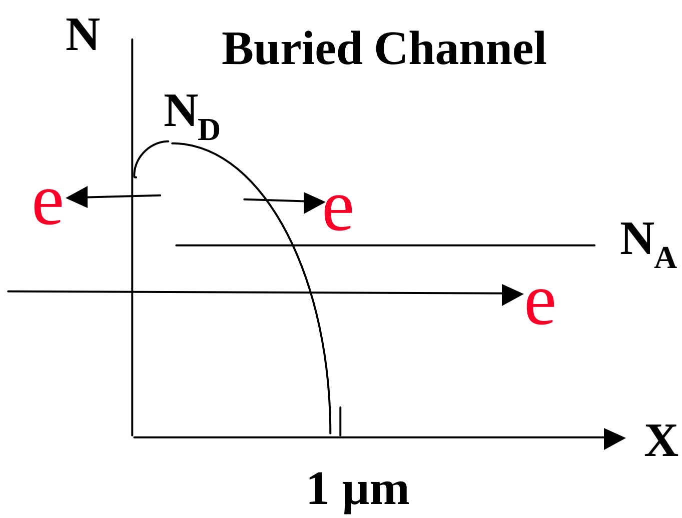




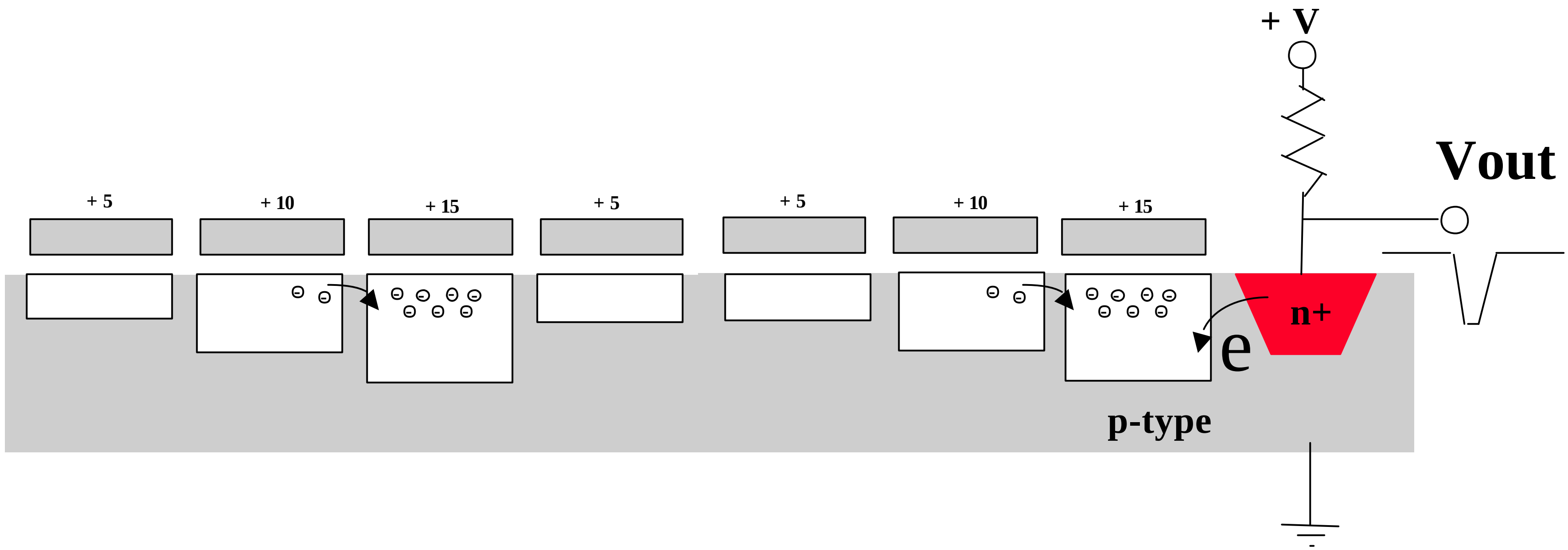
BURIED CHANNEL VS SURFACE CHANNEL CCD'S

Depending on the doping profile in the channel the electrons (p-type substrate) may be drawn toward the surface or tend to stay slightly below the surface in a lower energy channel. An n-type implant that has a peak slightly below the surface will result in a buried channel device. Buried channel devices are preferred because less electrons will be lost at traps at the surface interface.





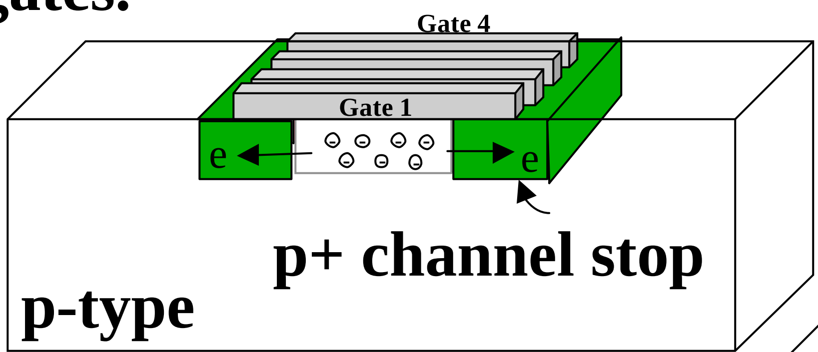
READOUT



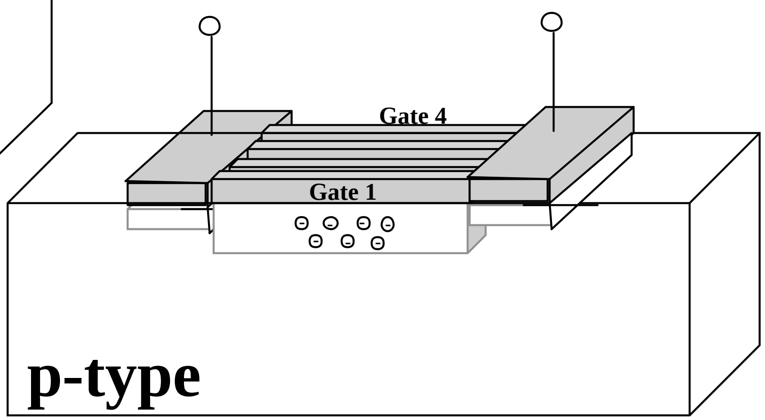
When electrons are emptied from the last gate the electric field associated with the pn junction collects electrons that move to +V and Vout will drop to a level proportional to the number of electrons in that packet.

CHANNEL STOP

The channel stop defines the width of the active region. The built in electric fields from pn junctions is such that electrons will be forced under the gates. Potential barriers created by Field Gate Electrodes can also keep electrons under channel gates.

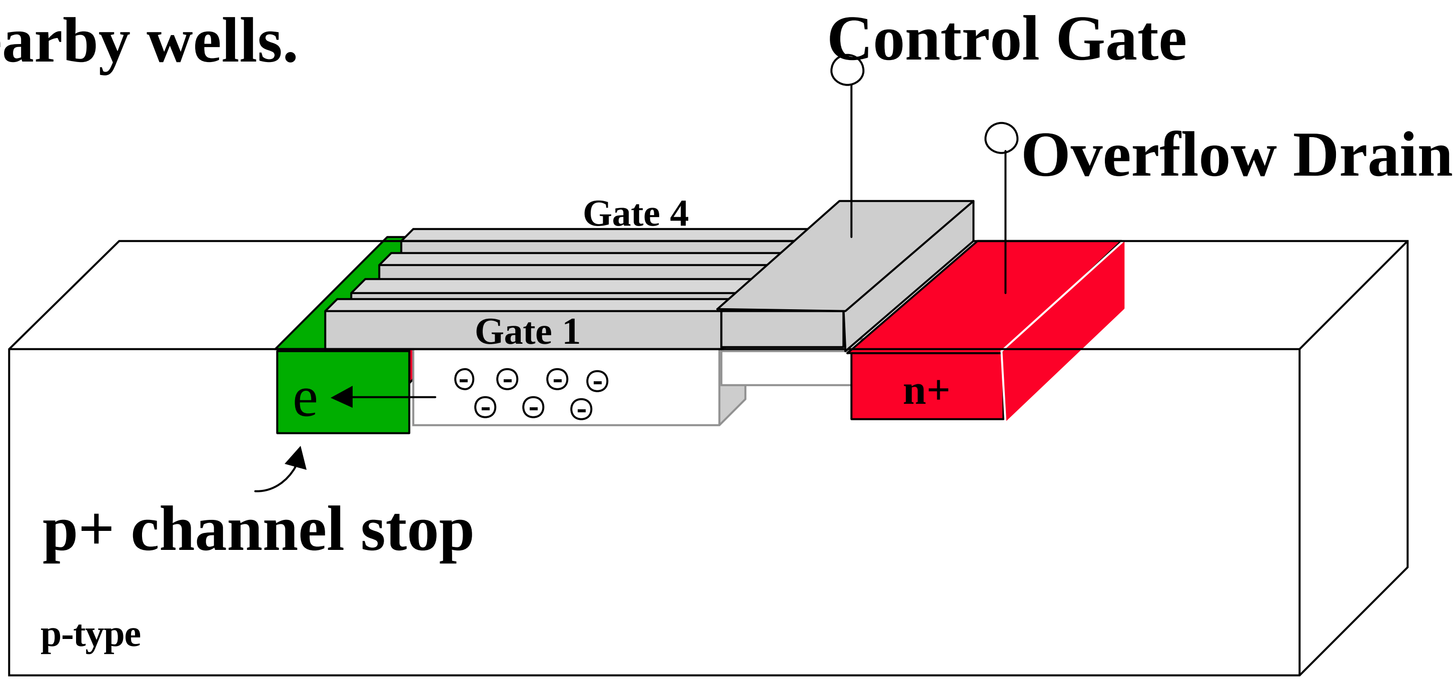


Field Gate Channel Stop

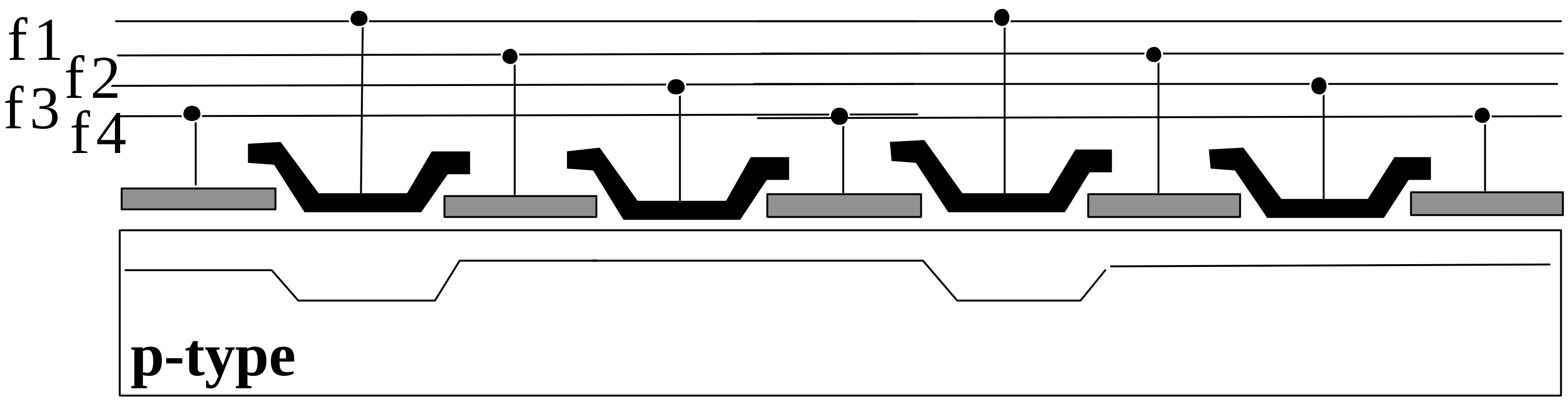


OVERFLOW DRAINS (ANTI-BLOOMING)

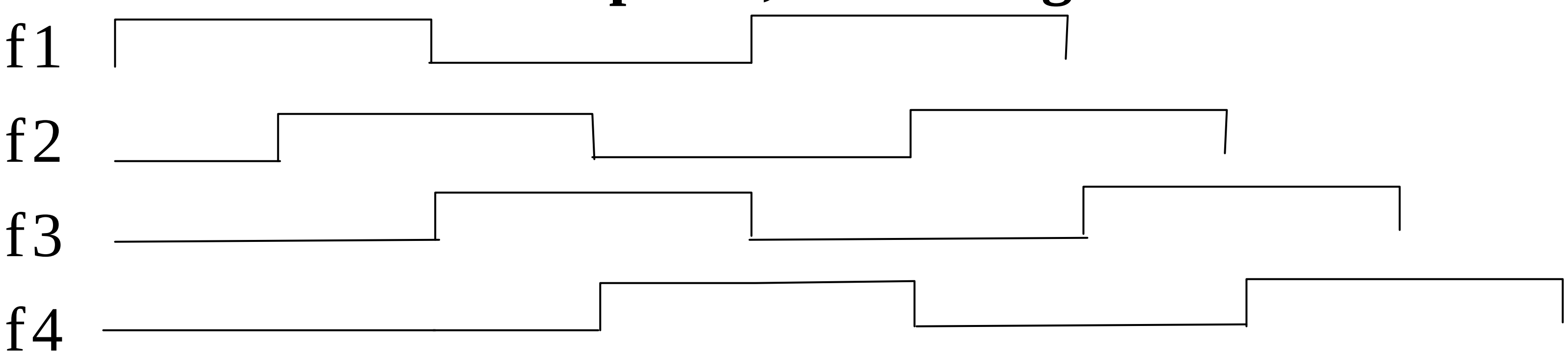
Potential well decreases as the well fills with electrons eventually electrons will spill into nearby wells.



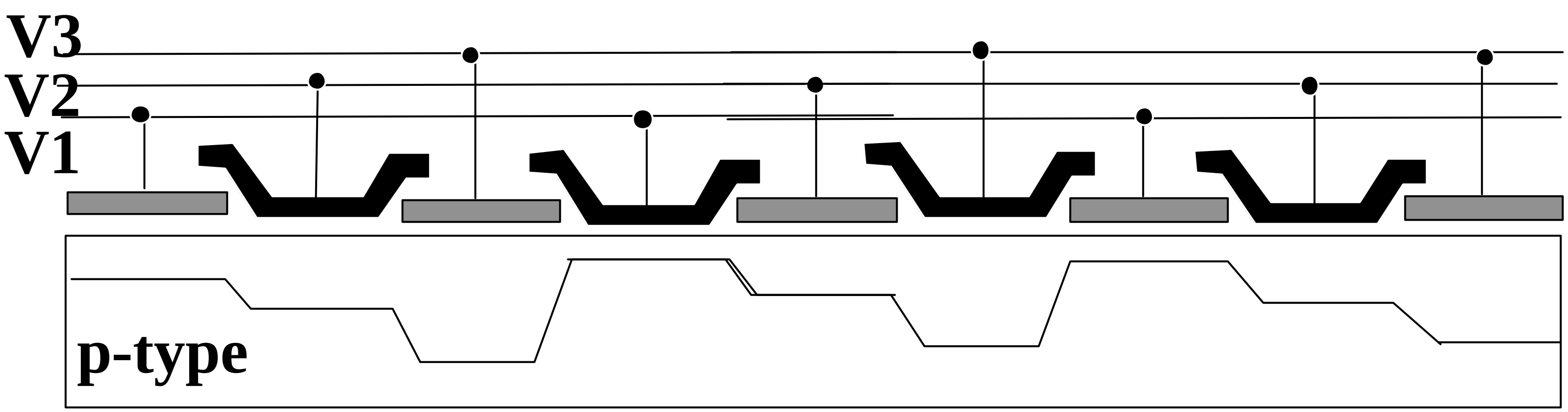
FOUR PHASE CLOCKING SCHEME



4-phase, two voltage levels



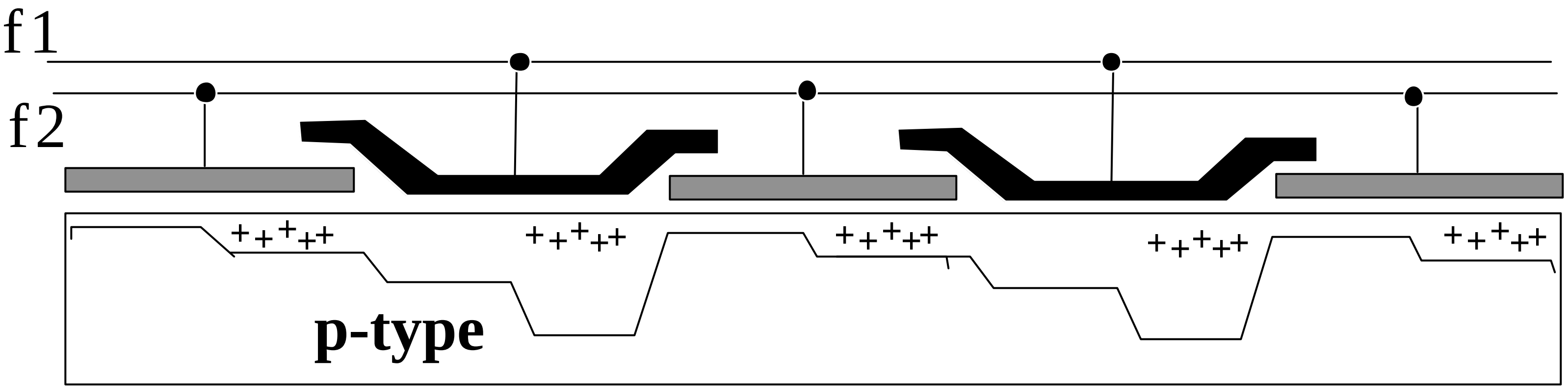
THREE PHASE CLOCKING SCHEME



3-phase, 3 voltage levels

TWO PHASE CLOCKING SCHEME

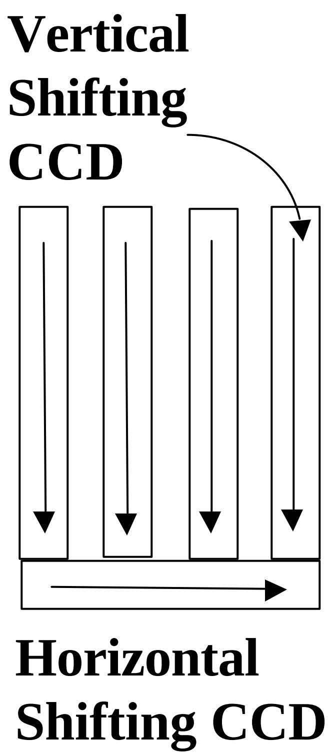
ion implant under 1/2 of each gate



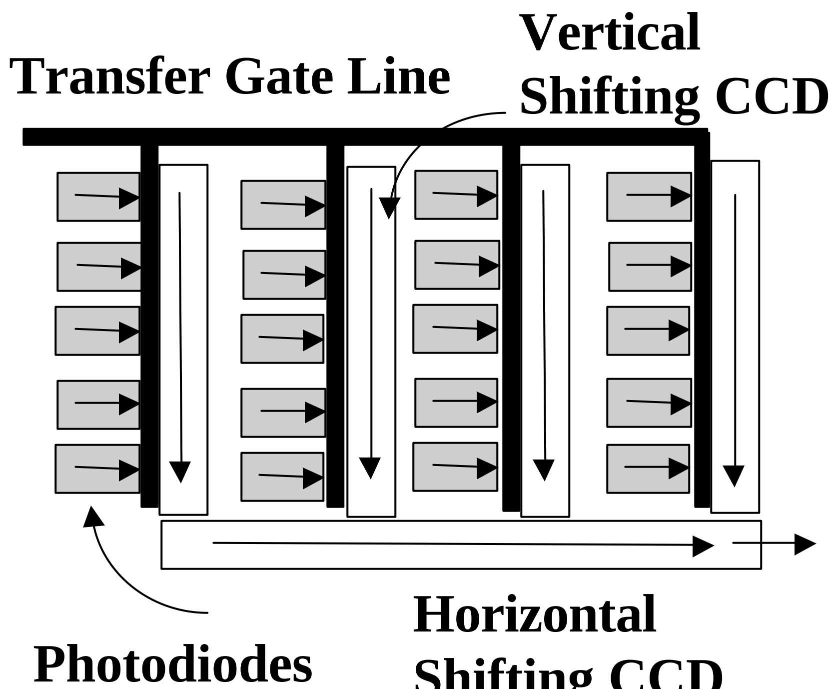
2-phase, 2 voltage levels

CCD SENSOR ARCHITECTURE

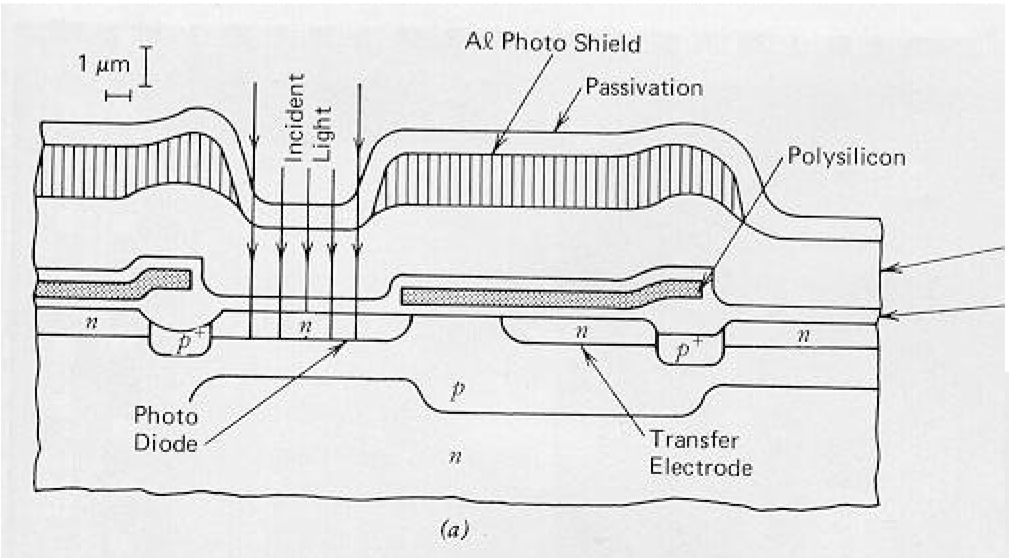
Line Addressed Organization



Interline Transfer Organization

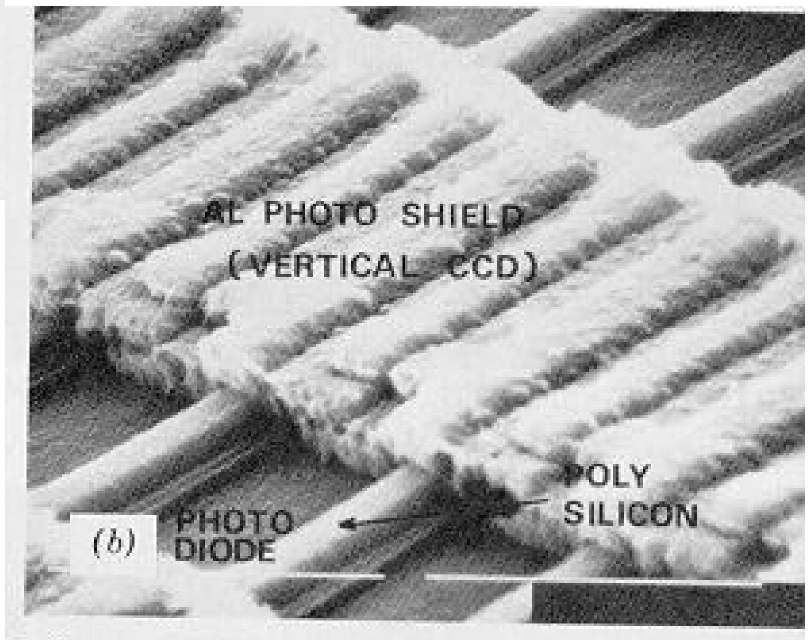


INTERLINE CCD



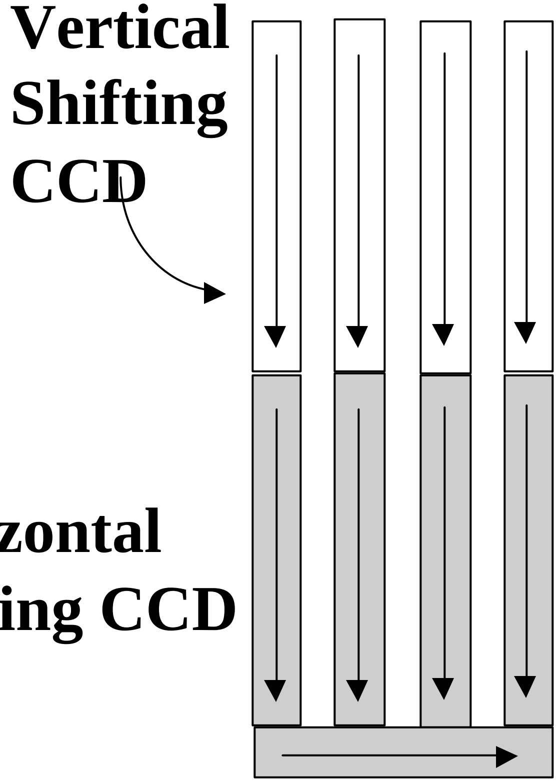
Unit cell cross section

Photo diode & photo shield



CCD SENSOR ARCHITECTURE

Frame Transfer Organization



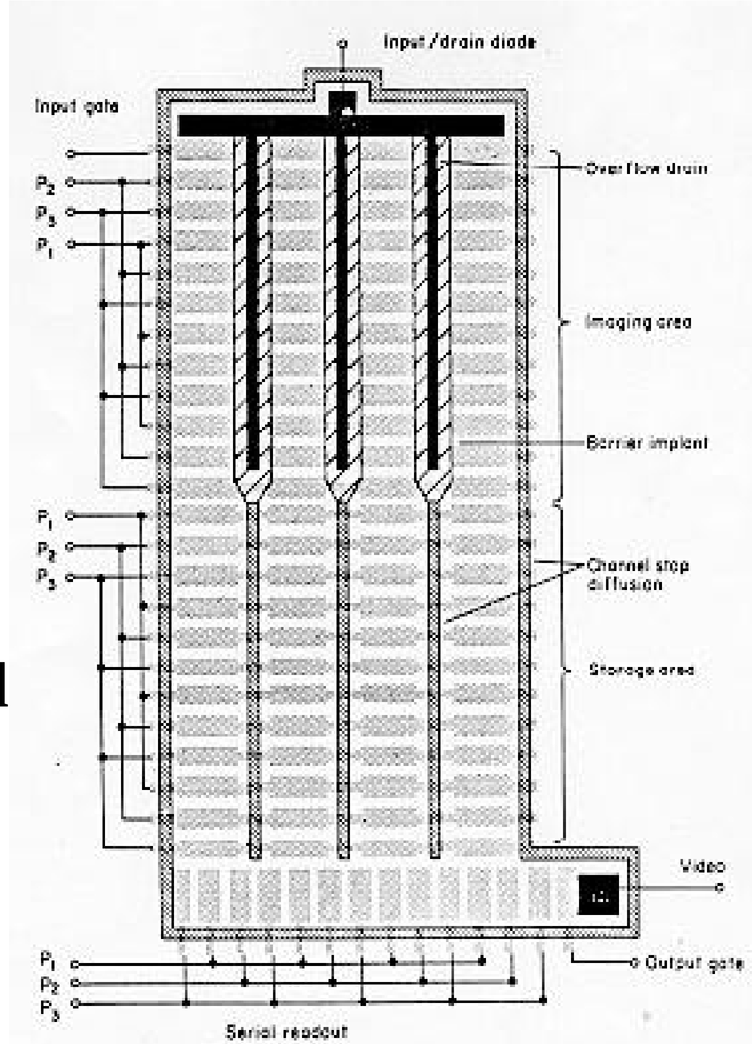
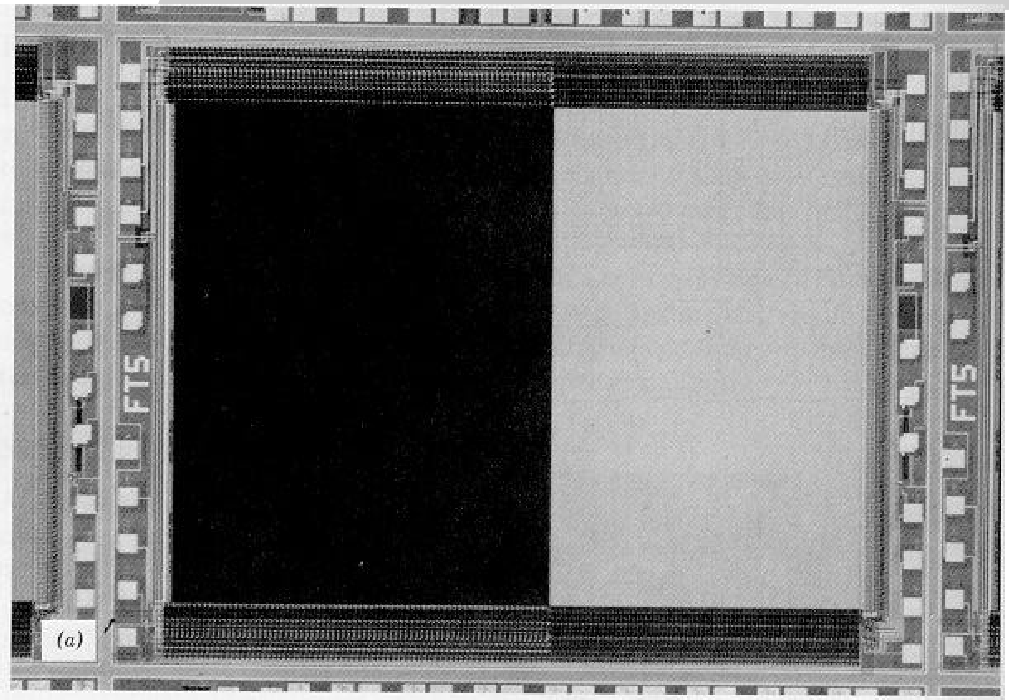


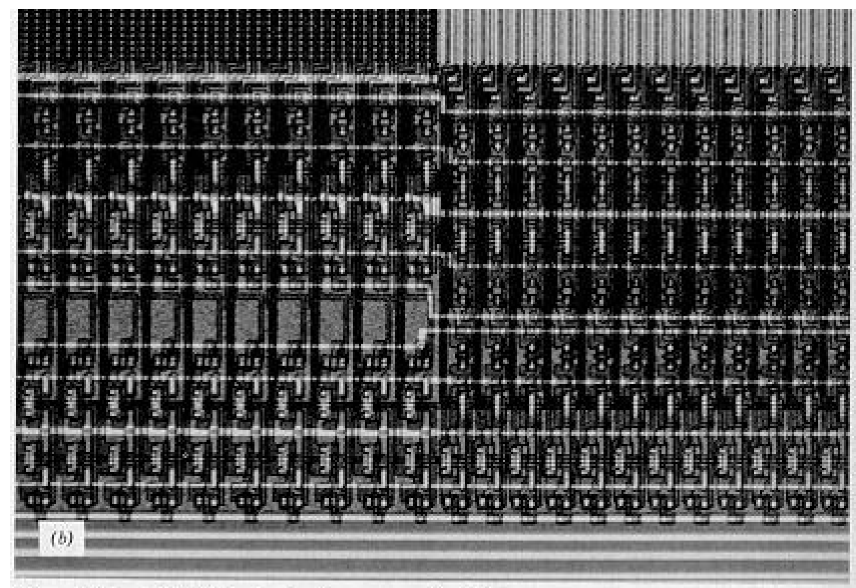
Fig. 18 Frame/field transfer organization of a charge-coupled area image sensor

FRAME TRANSFER CCD



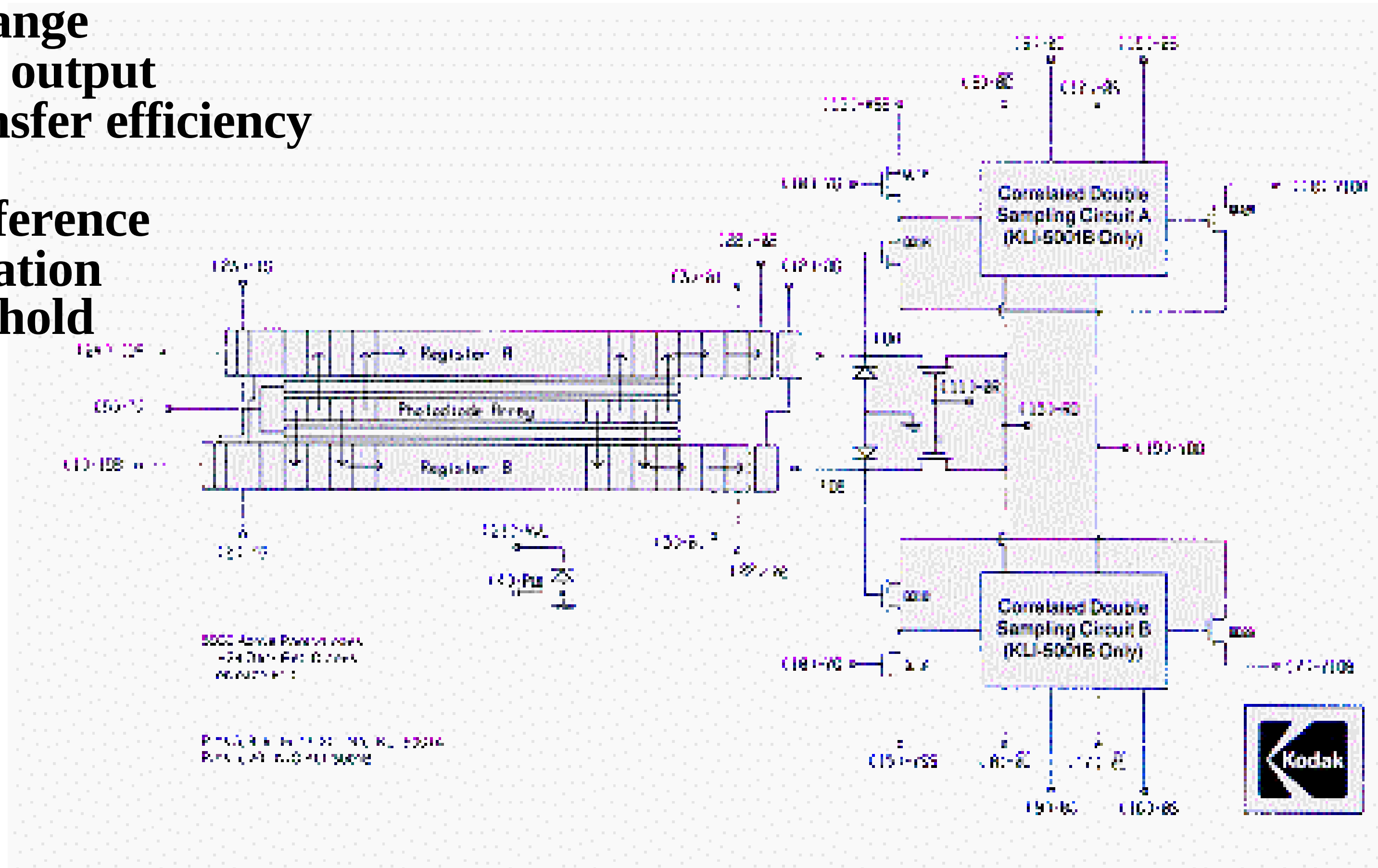
588 lines of 604 pixels, sensor area on left and light shielded storage area on right

CMOS circuits for CCD



5000 ELEMENT LINEAR CCD IMAGER

High resolution, 5000 elements
Wide dynamic range
2V peak-to-peak output
High charge transfer efficiency
2 phase clocking
On-chip dark reference
High speed operation
On-chip sample/hold

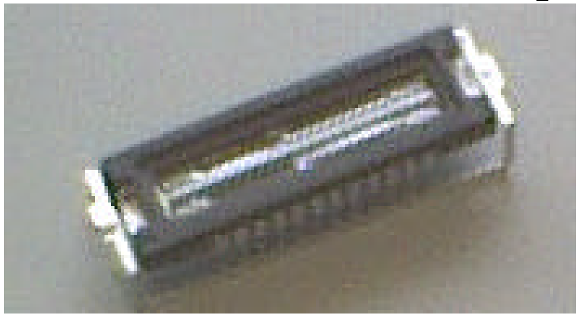


5000 ELEMENT LINEAR CCD IMAGER

The KLI-500 devices are high resolution linear arrays designed for scanned imaging applications. Each device contains a row of 5000 active photo elements, consisting of high performance diodes for improved sensitivity and lower noise. Readout of the pixel data is accomplished through the use of dual CCD shift registers, positioned on either side of the diode array.

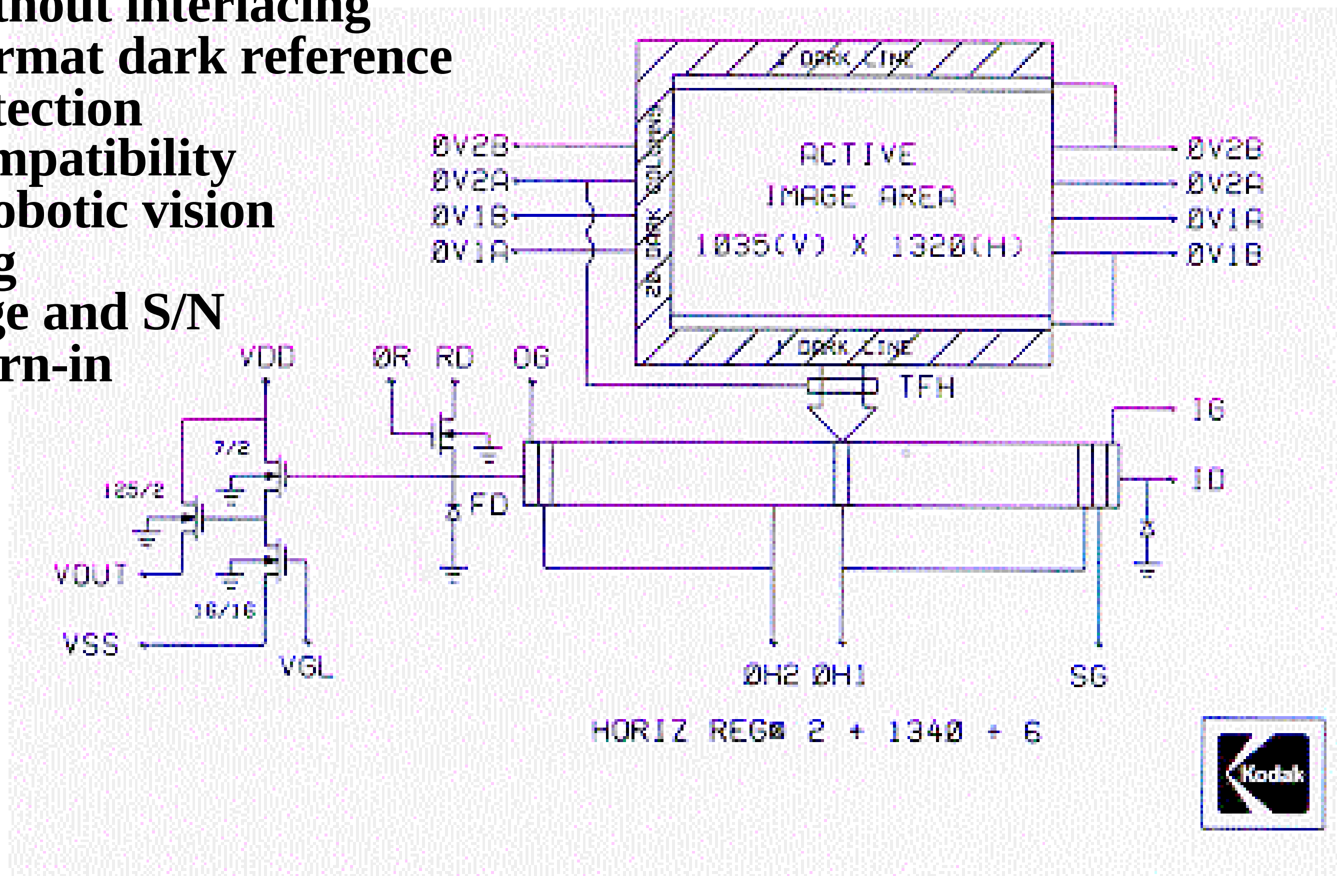
The sensors are positioned on 7 µm centers with an associated 7 µm aperture which spans the length of the array. A dark reference consisting of 24 light shielded elements is also located on each end of the array. The architecture and operation of the A and B versions are similar except the B device contains on-chip, correlated double sampling circuitry.

The devices are manufactured using NMOS, buried channel processing, and utilize dual layer polysilicon and dual layer metal technologies. The die size is 36.00mm x 1.12 mm and the chip is housed in a 24-pin 0.600” wide, dual-in-line package.



1320 (H) x 1035 (V) ElEMENT FULL FRAME CCD IMAGER

1,366,200 Pixels without interlacing
On-chip column format dark reference
Anti-blooming protection
2/3 Inch format compatibility
Square pixels for robotic vision
Two-phase clocking
High dynamic range and S/N
No image lag or burn-in
4.3 Aspect ratio



1320 (H) x 1035 (V) ELEMENT FULL FRAME CCD IMAGER

The KAF-1400 is a 1320(H) x 1035(V) element, solid state charge-coupled device, full frame imager. It is designed for high resolution monochrome imaging and has square pixels for robotic vision applications. The devices optically active area measures 8.98(H) x 7.04(V) mm. Each element in the array measures 6.8µm by 6.8µm.

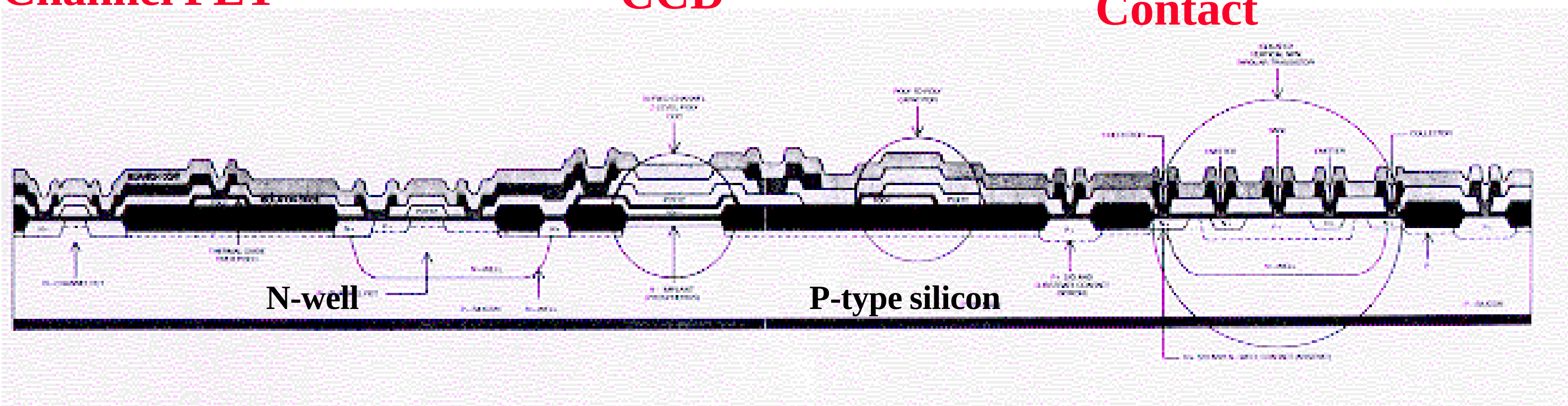
An image is obtained by collecting the electrons generated when incident image photons create electron hole pairs within the silicon. The amount of charge stored per pixel is a linear function of the localized light intensity and the integration time, and a non-linear function of wavelength. The signal charge is then transferred out of the image area by two-phase complementary clocking. The dark reference consists of 20 columns, each spanning the entire height of the image area, and is located at the left side of the sensor. The first and last row is also dark. During integration the rows are shifted vertically and read out horizontally.

CMOS-I/CCD PROCESS CROSS-SECTIONAL VIEW

N-Channel FET

Buried Channel
2 Level Poly
CCD

P+ Source
Drain, Substrate
Contact



P-Channel FET
N-Well

Poly-to-Poly
Capacitor

Isolated Vertical NPN
Bipolar Transistor

CID'S

Charge Injection Devices

Random readout of image information is possible

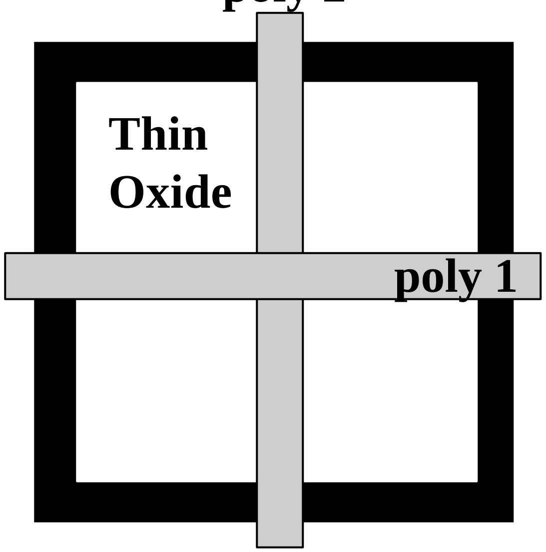
Nondestructive readout is also possible

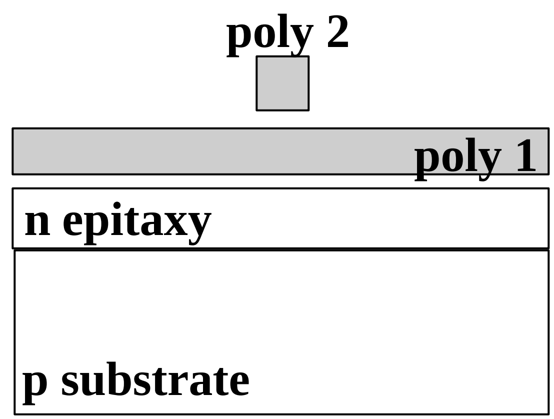
Suitable for use in pattern recognition, target tracking and other forms of image processing

PHYSICAL STRUCTURE

Each pixel consists of a pair of MOS capacitors

The two capacitors run perpendicularly to each other and are know as collection and sense pads



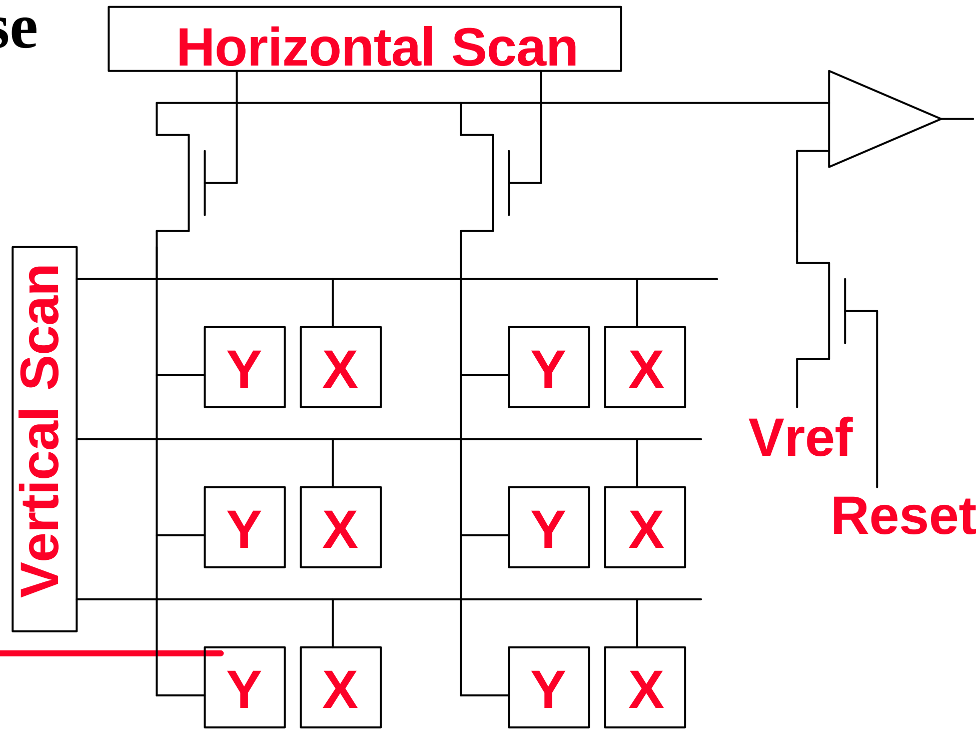


CID ARCHITECTURE

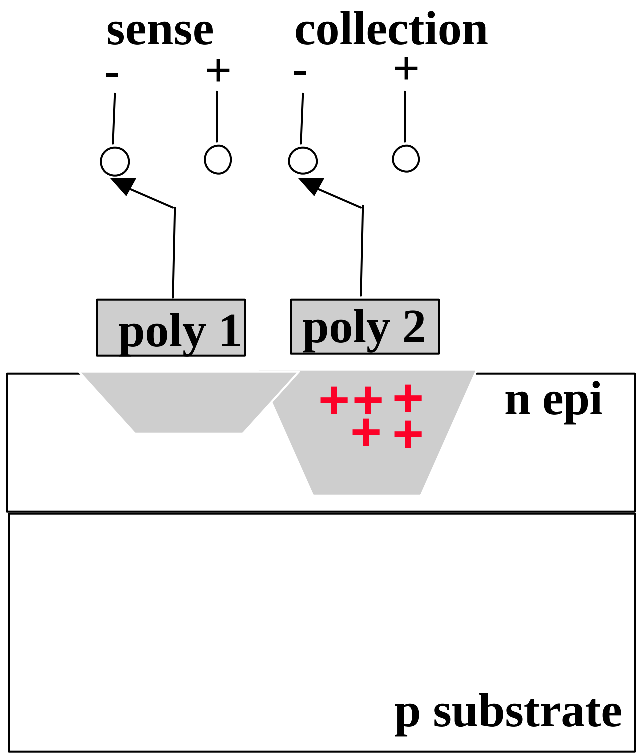
The collection pad is common for all the pixels in a row.

The sense pad is common for all the pixels in a column.

Both collection and sense pads are controlled by demultiplexers or shift registers.



PHOTON COLLECTION AND READOUT IN A CID

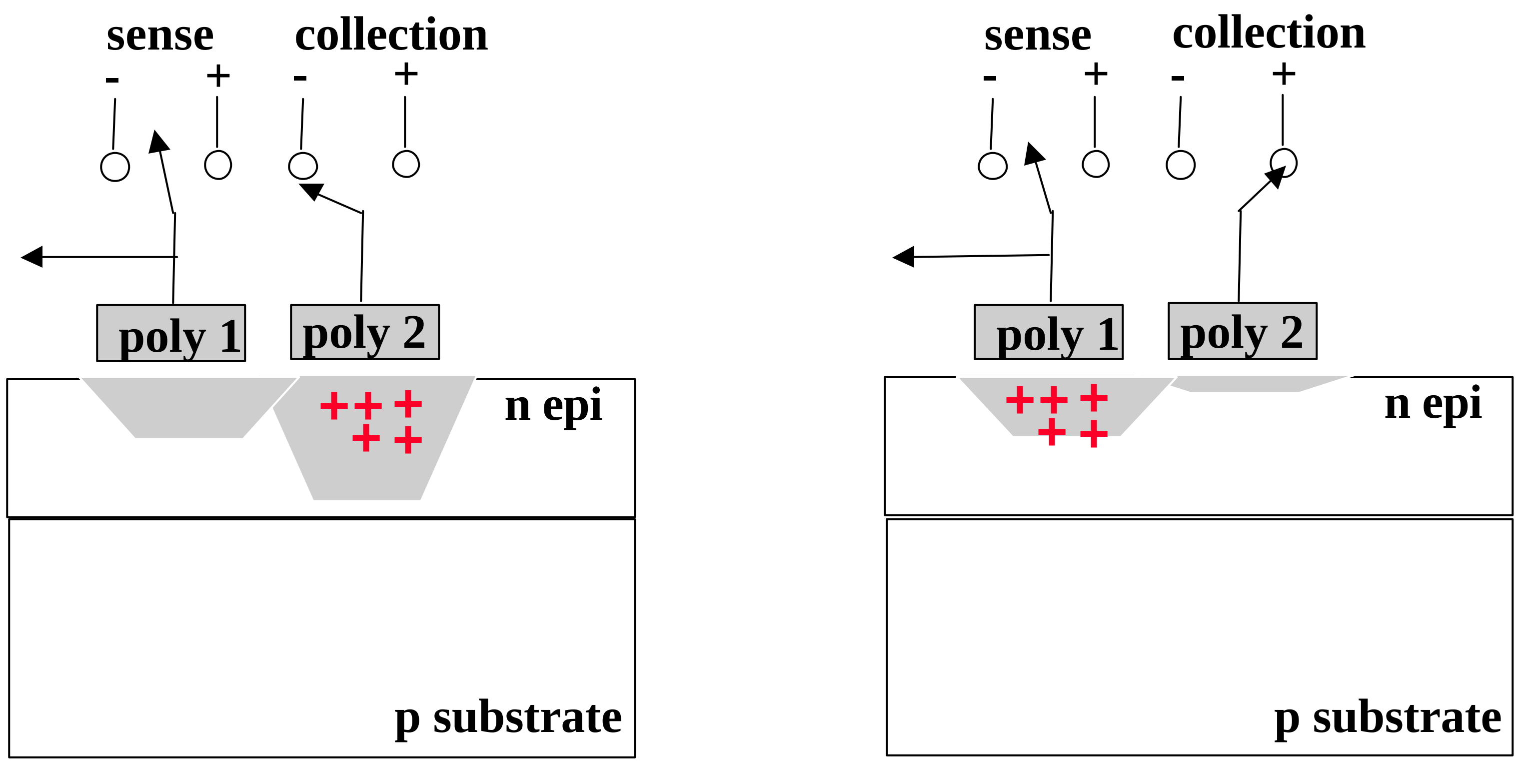


Accumulation

Photons generate electrons and holes. Holes are collected in the depletion region (potential well) under the poly2 gate.

Sense at -5, Collection at -7

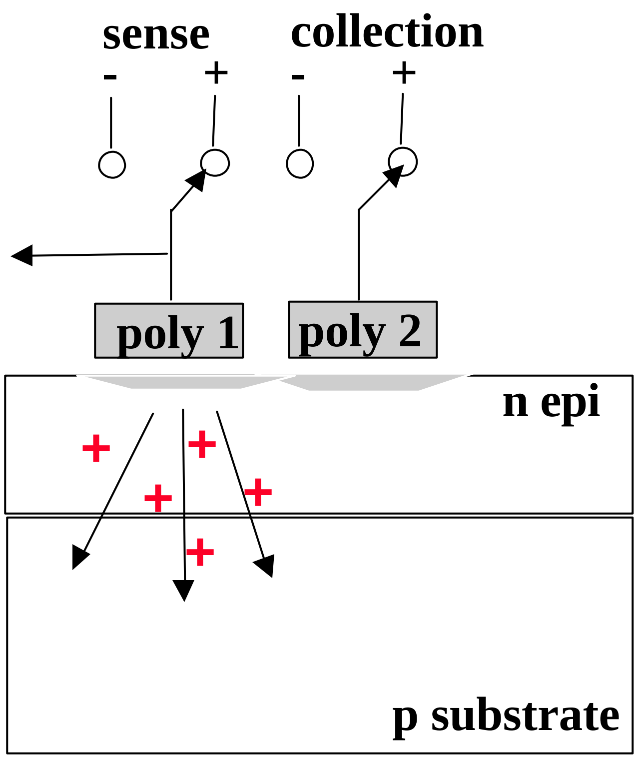
ZERO LEVEL SENSE AND SIGNAL SENSE



Zero Level Sense
(floating gate readout)

Signal Sense
V = Q/C

INJECTION (DESTRUCIVE READOUT)



Injection

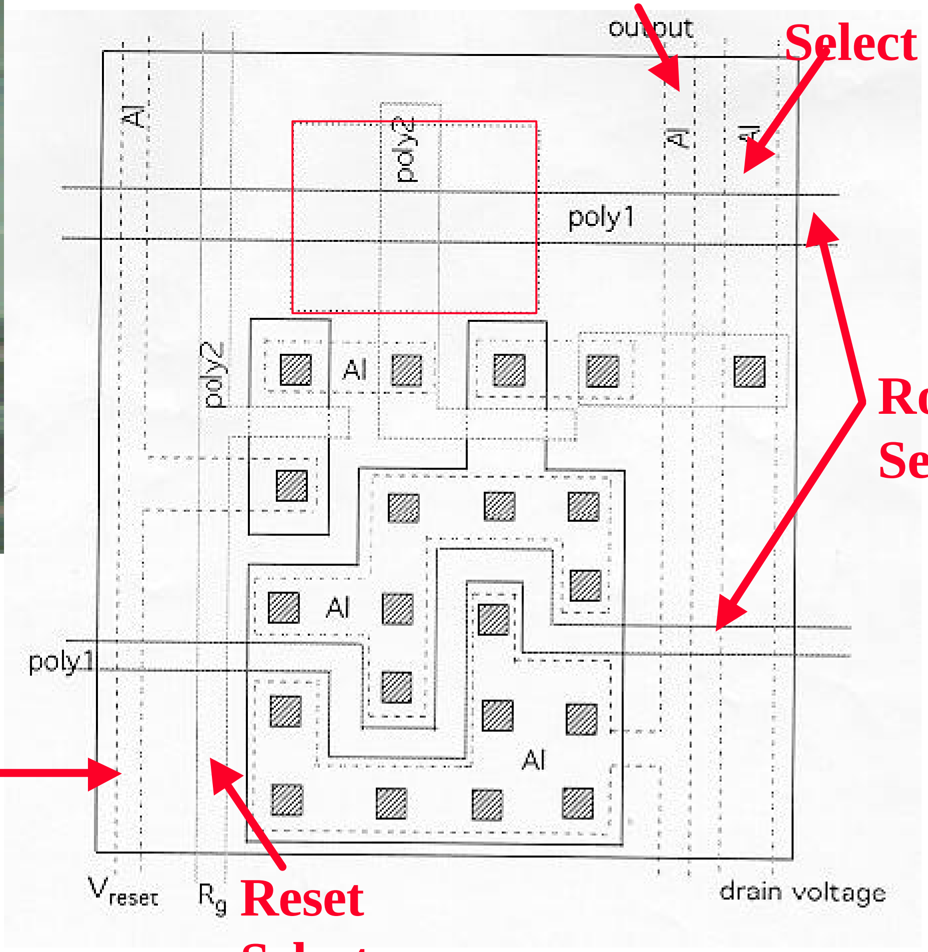
RIT CID PROCESS

PMOS on n-type epitaxial substrate
6 micron gate, 4 micron contact cut
Double poly-silicon, one metal level
15 V process, 50 nm gate oxide

8 Photo levels

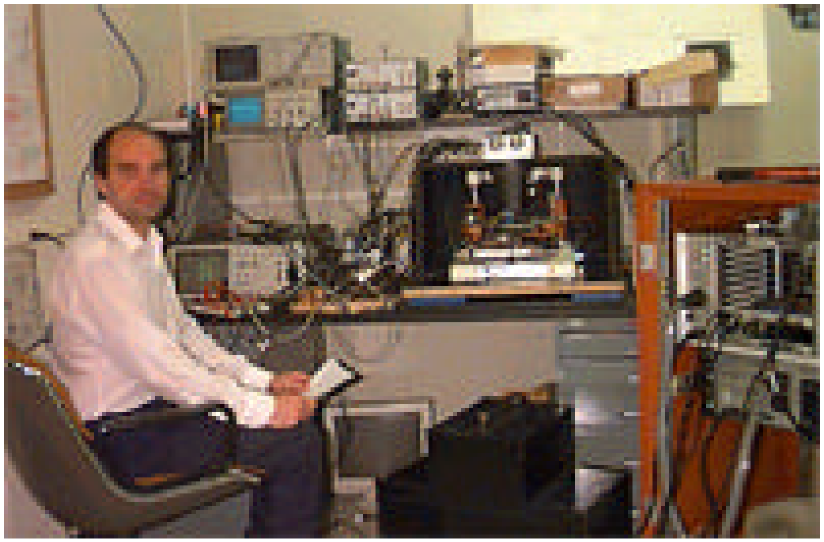
- **Active**
- **Poly-1**
- **Poly-2**
- **p+ D/S Implant**
- **n+ Substrate Contact**
- **Pinning Implant**
- **Contact Cut**
- **Metal**

CELL LAYOUT



Vreset
-5 to collect
+5 to reset

TEST BLOCK DIAGRAM



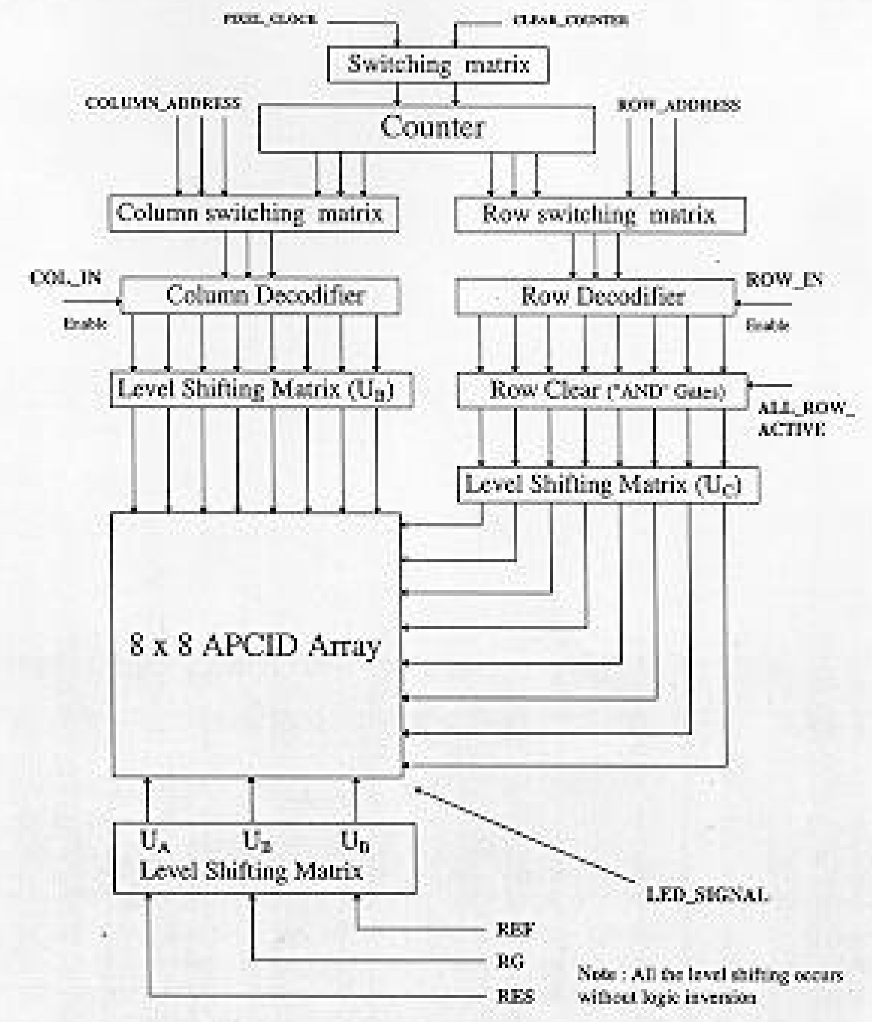
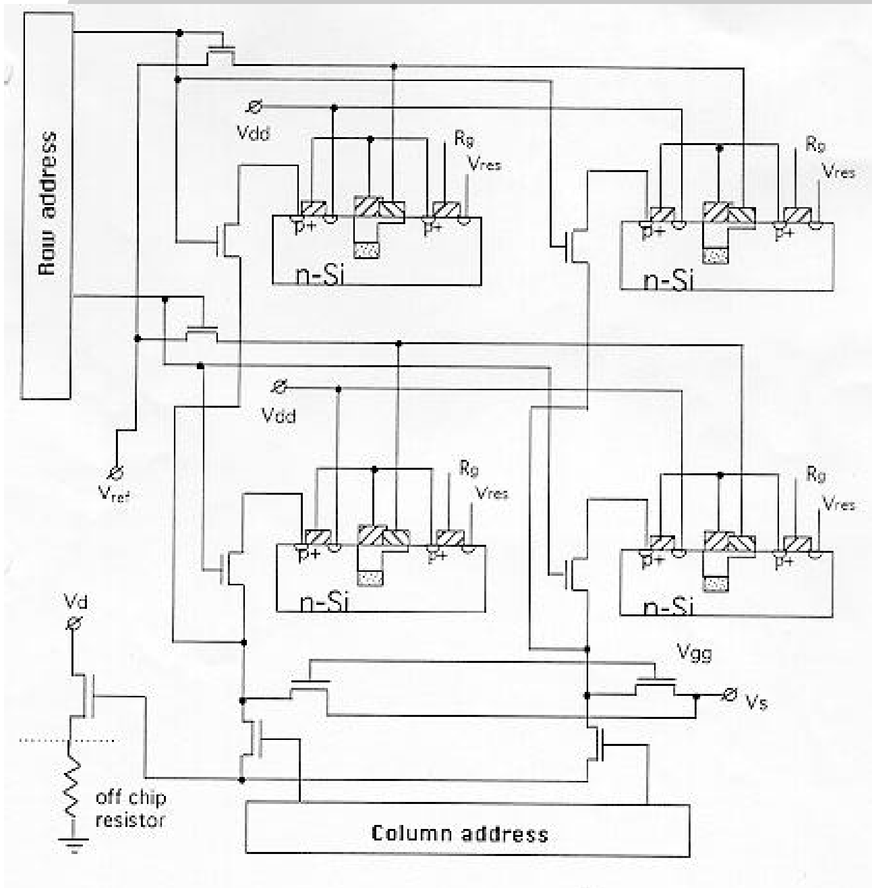
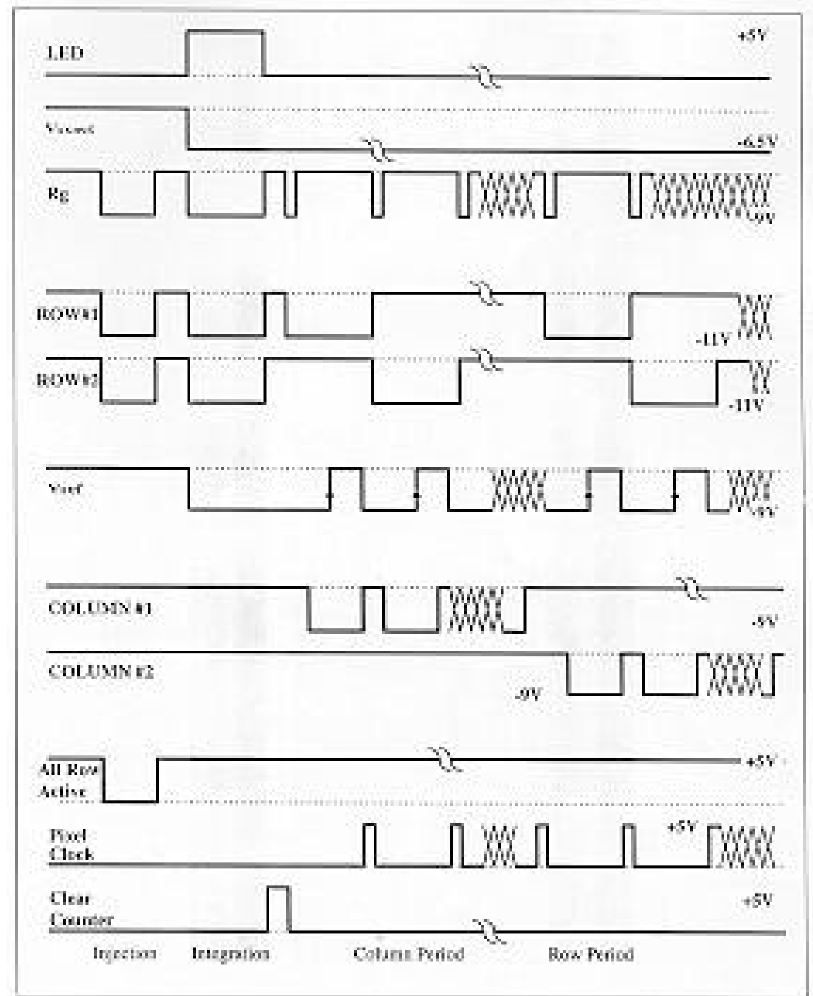


Fig 2 The complete block schematic of the driver.

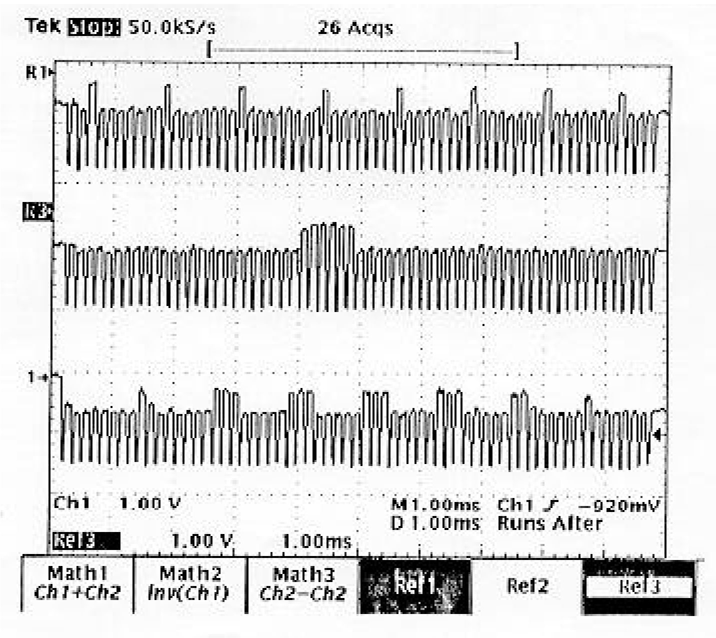
ARRAY and CLOCKING WAVEFORM



3. Clocking diagram for the AP-CID



OUTPUT WAVEFORM

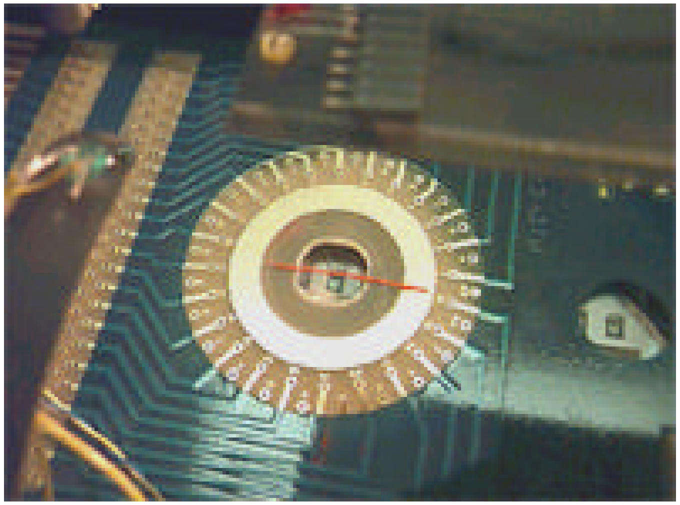


Output of vertical slit illumination

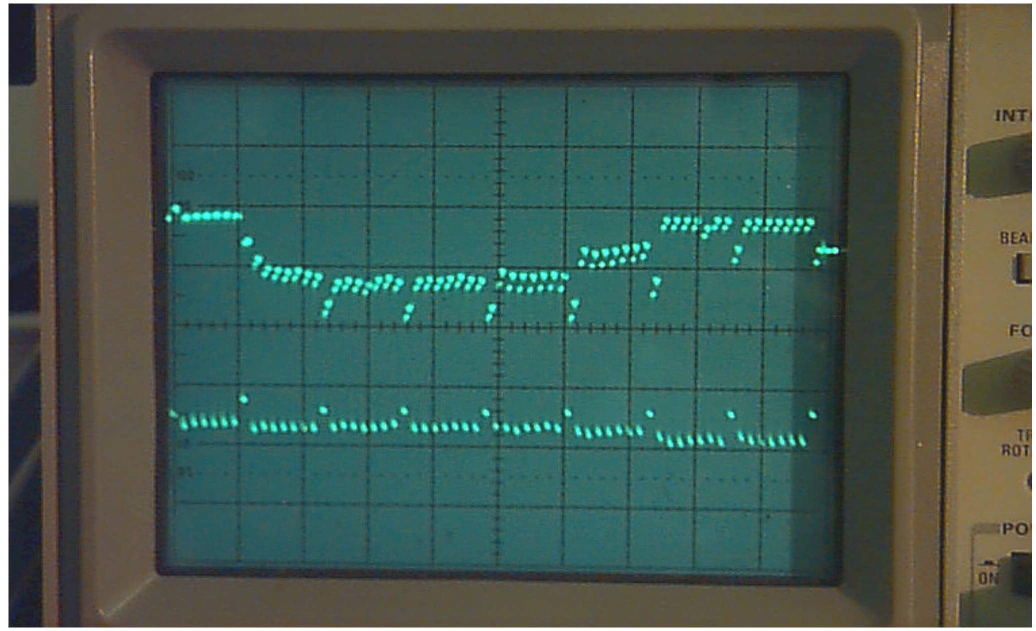
Output for horizontal slit illumination

Output for point illumination

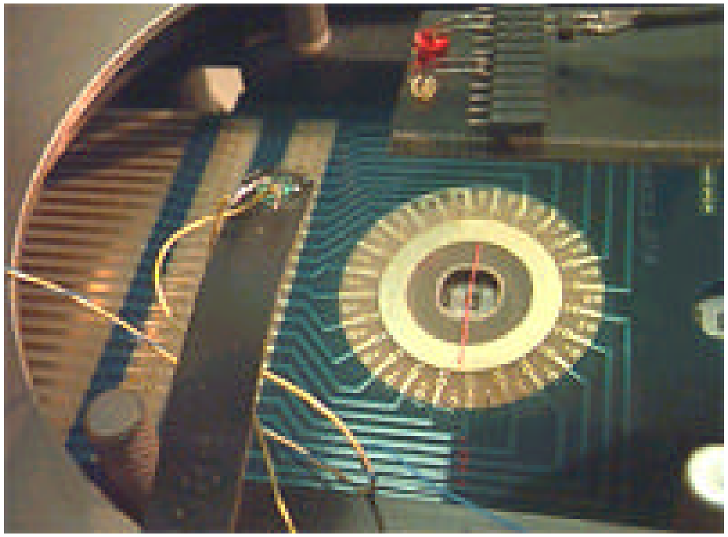
DISPLAY OUTPUT BY COLUMN



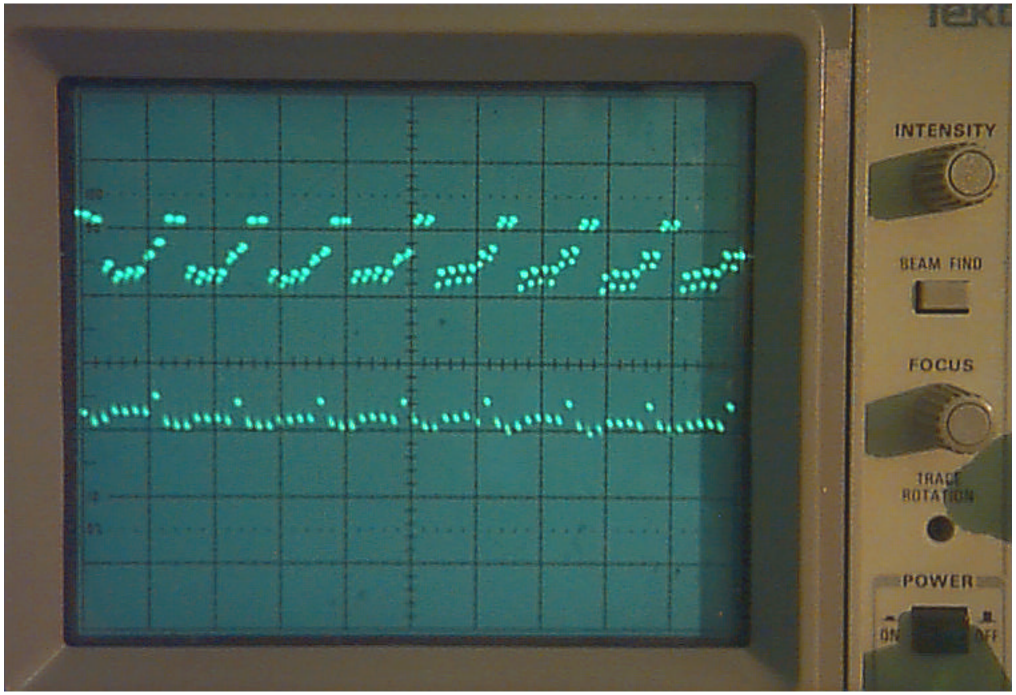
Wire blocking rows in array



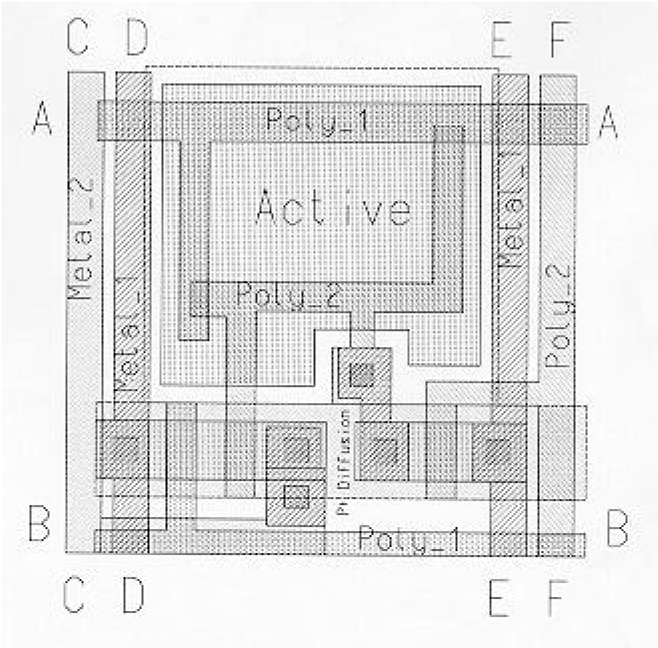
DISPLAY OUTPUT BY COLUMN



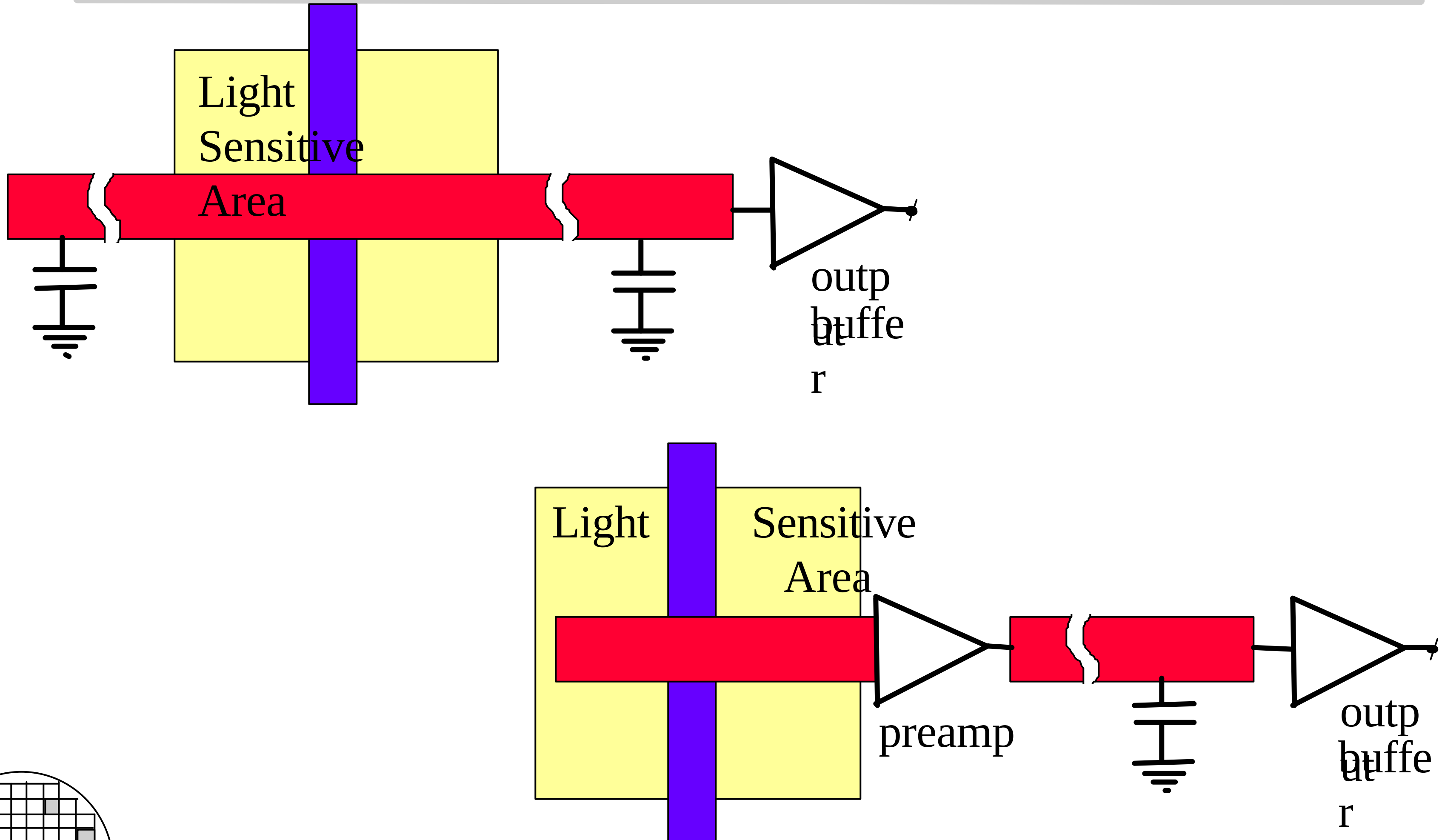
Wire blocking columns in array



NEW PIXEL DESIGN

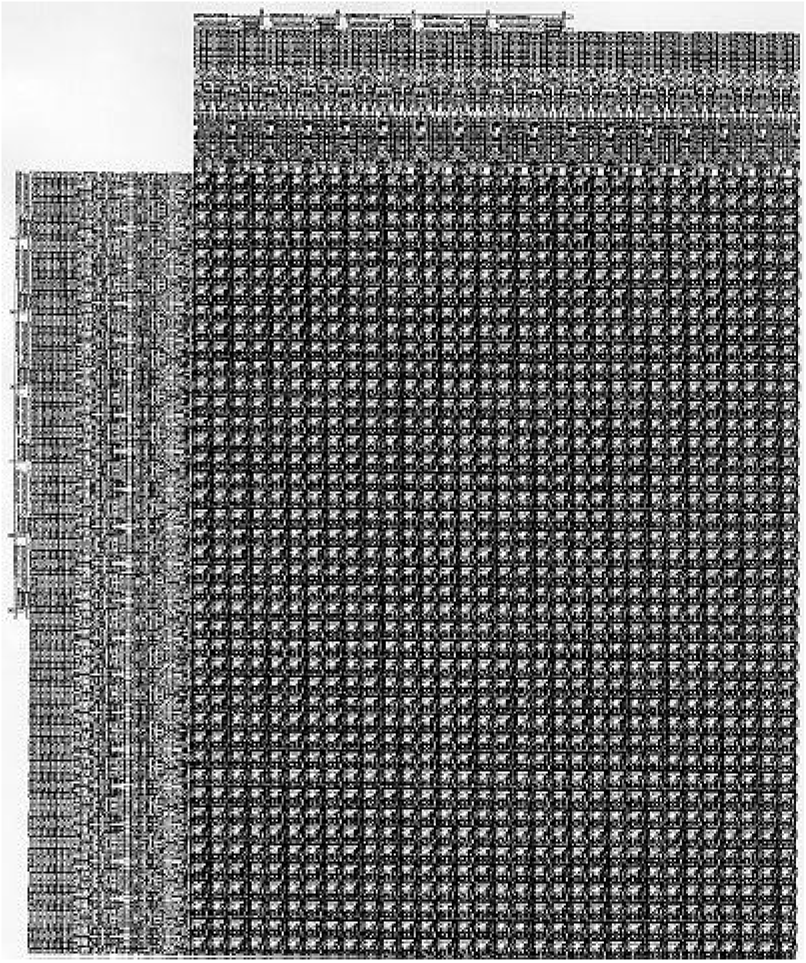


ACTIVE PIXEL ARRAY

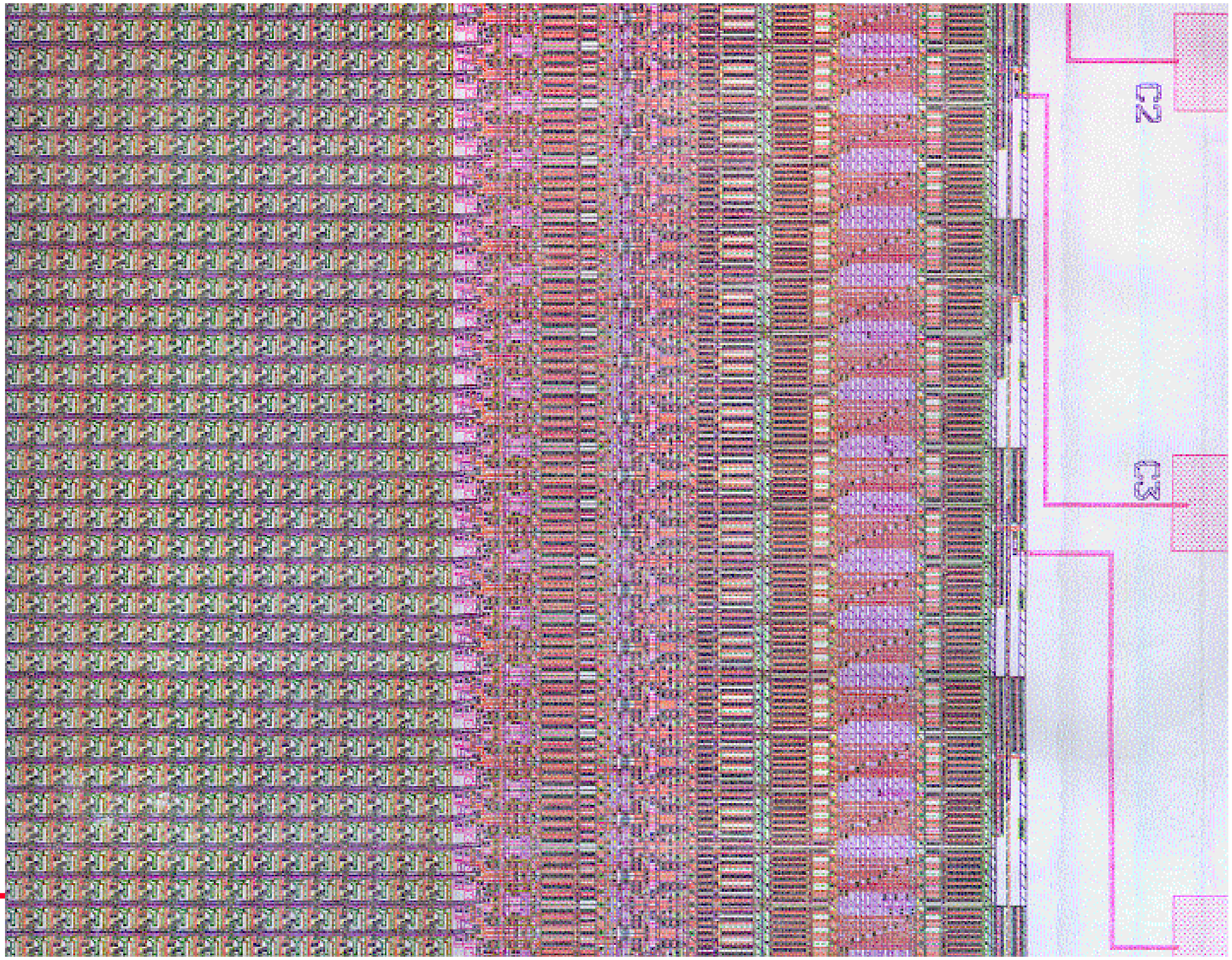


32 X 32 PIXEL ARRAY

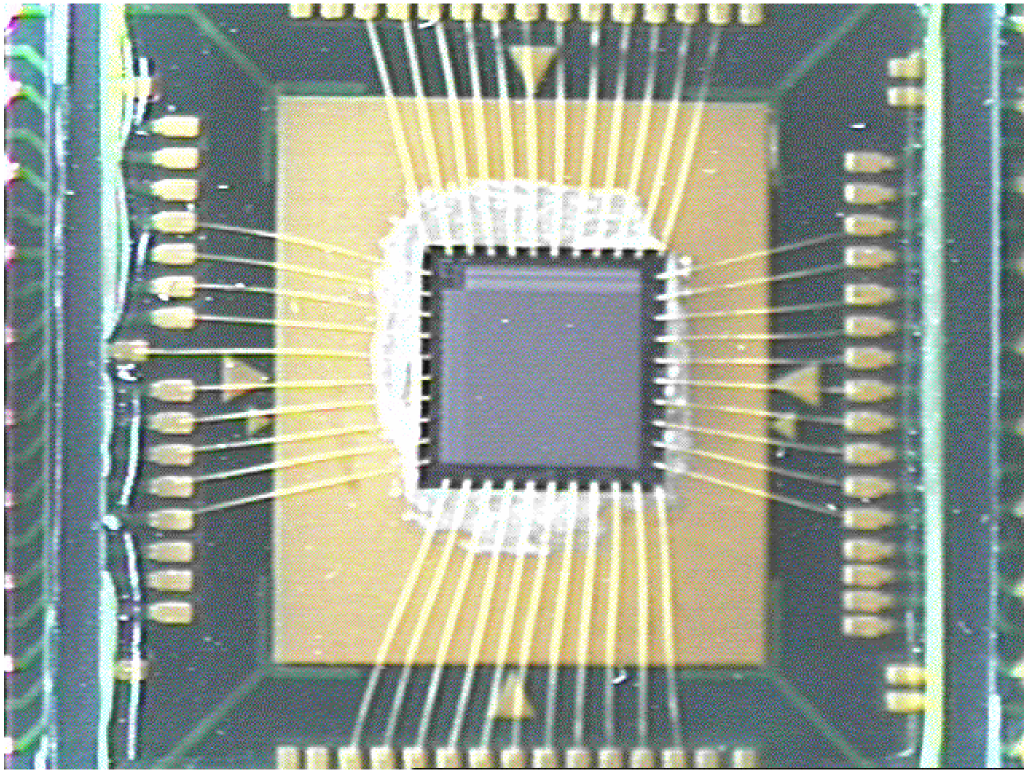
32 X 32 Array Fabricated at RIT



128 x 128 PIXEL DESIGN

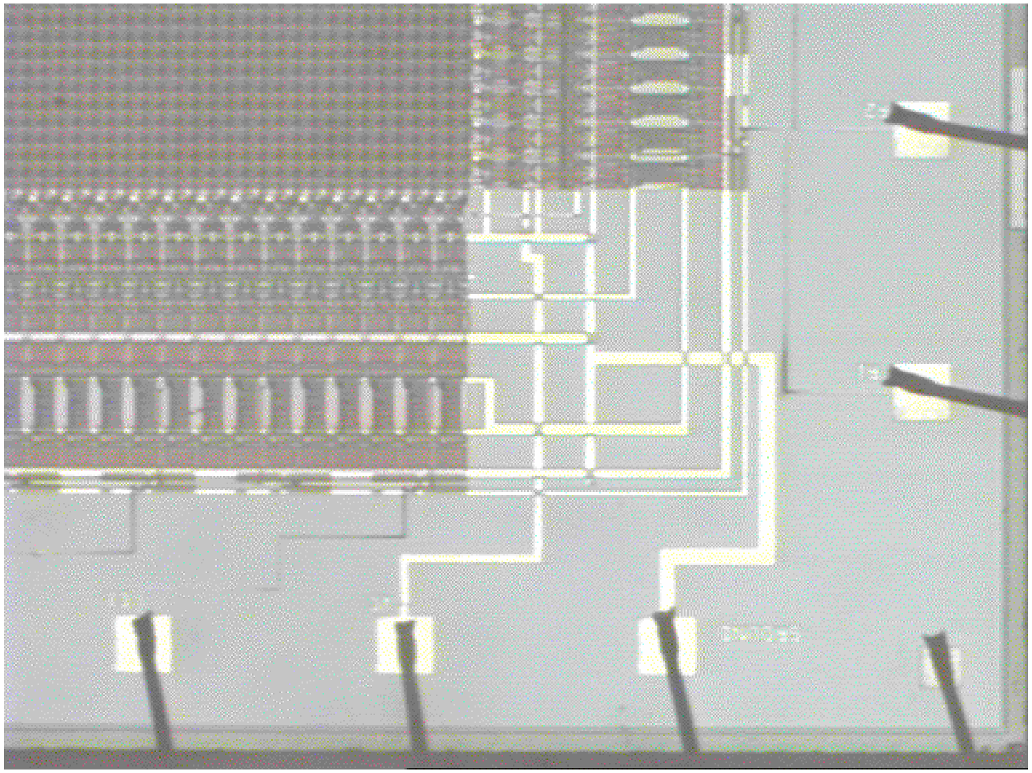


RESULTS

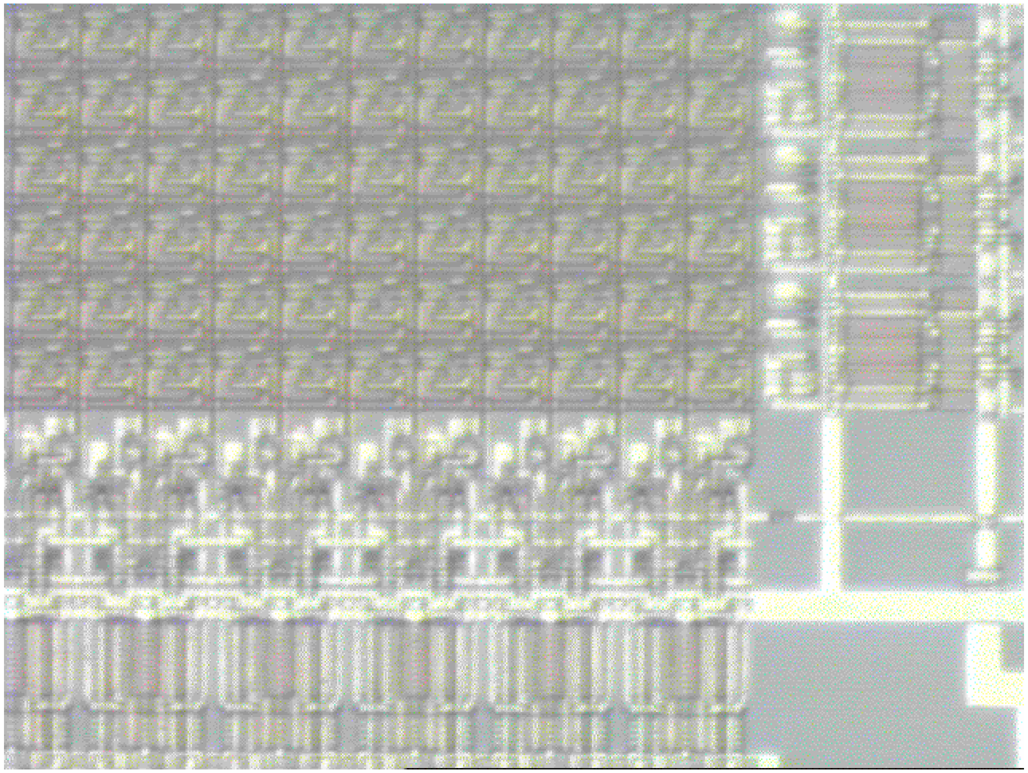


128 x 128 Array Fabricated at Orbit Semiconductor Includes on Chip Electronics for Addressing

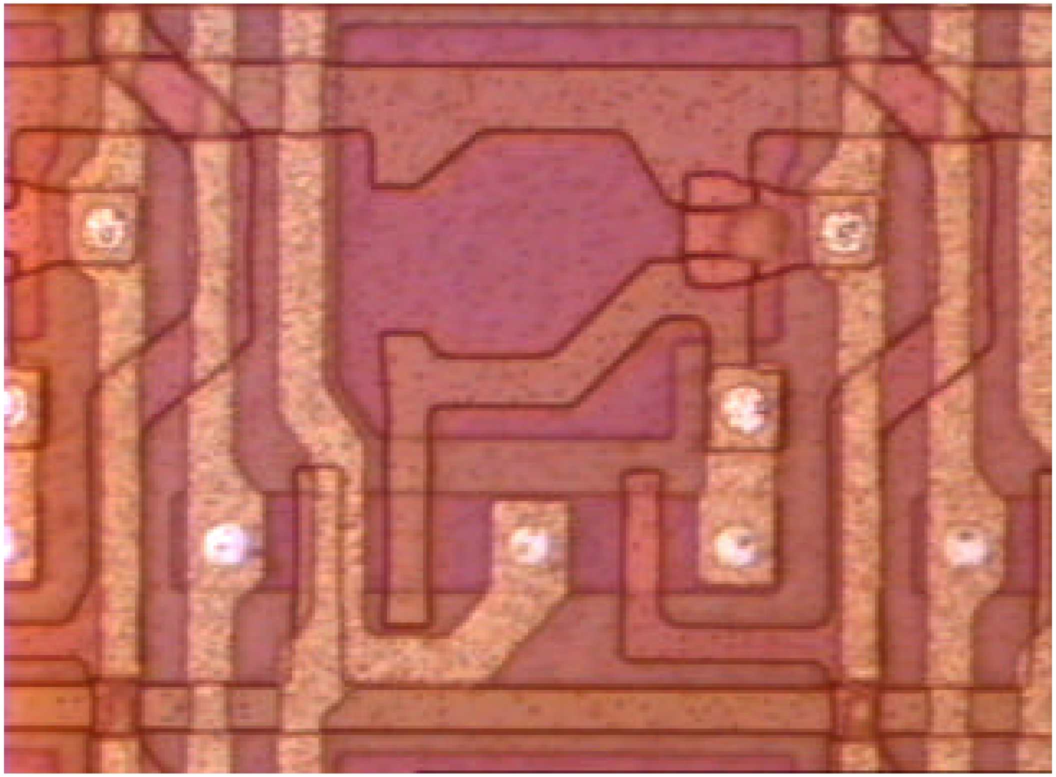
RESULTS



RESULTS



RESULTS



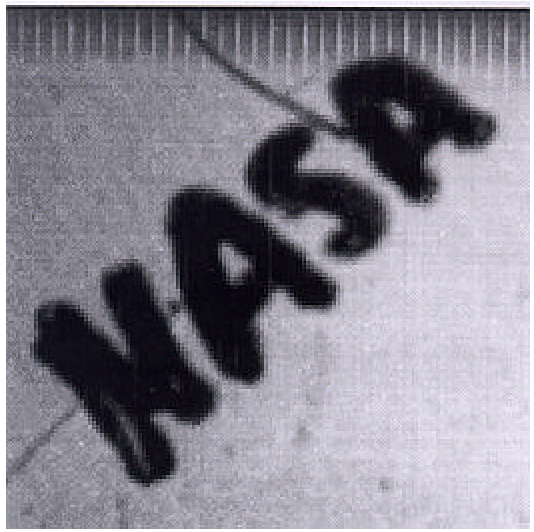
FIRST PICTURES FROM RIT 128 X 128 CID

April 16, 1999

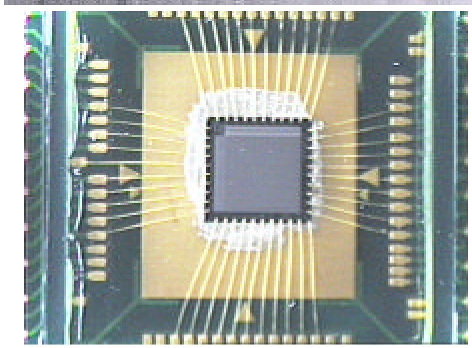
Objects were placed directly on the glass cover over the CID chip

0.3 msec timed exposure from a red LED

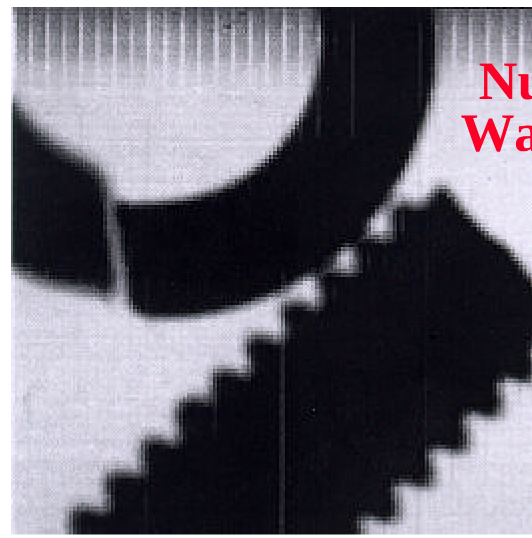
CID output stored in gif format and then printed



Cleanroom Fly



RIT CID chip 128 x 128



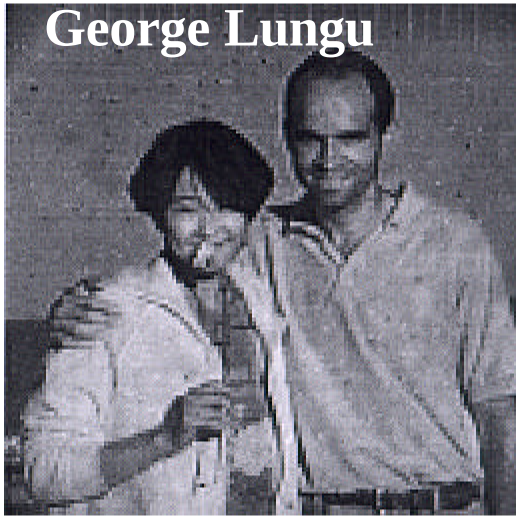
Nut & Washer

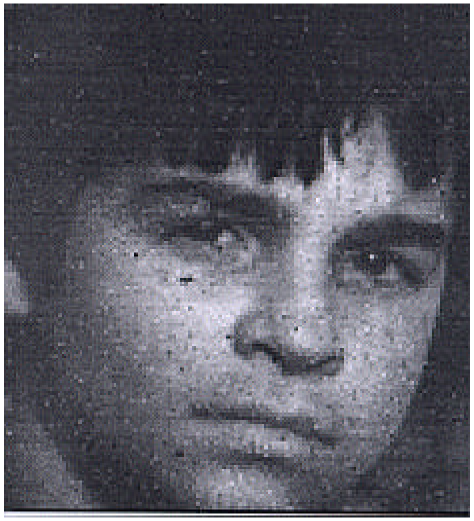
FIRST PICTURES FROM RIT 128 X 128 CID

April 16, 1999

Images projected onto CID from a 35 mm slide using a 50 mm lense 100 msec timed exposure from a red LED

CID output stored in gif format and then printed





ROCHESTER
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RIT boosts space imaging

■ Work improves on technology to protect satellite-mounted cameras from radiation.

BY STAFF WRITER
CORYDON IRELAND

When George Eastman invented stable film and the box camera to go with it, the idea flew around the world.

A new imaging technology being developed in Rochester may soon fly around the world as well — literally.

It would provide improved imaging devices that would protect satellite-mounted cameras from the intense radiation of outer space.

An off-the-shelf version of such a "radiation-hardened" device could be ready in as little as two years, said Zoran Ninkov, a professor of imaging science at the Rochester Institute of Technology.

"Hardening" such a device ensures that it will operate normally when placed in the intense radiation fields found in outer space or in nuclear reactors.

A prototype will be in hand this spring, said Ninkov. NASA has put about $350,000 a year into the RIT project and related improvements for less than a decade.

Radiation-hardened imaging sensors are already available; the basic technology is 30 years old. But the RIT work could be a significant leap forward. The new radiation-hardened devices would not only protect the sensors from radiation, but be cheaper and lighter and require less metal shielding, which adds to the weight of a spacecraft.

"The less (weight) you have to launch, the cheaper your mission becomes," said Ninkov, one of NASA's chief advisers on imaging sensor technology. One sensor being developed at RIT is about the size of a nickel.

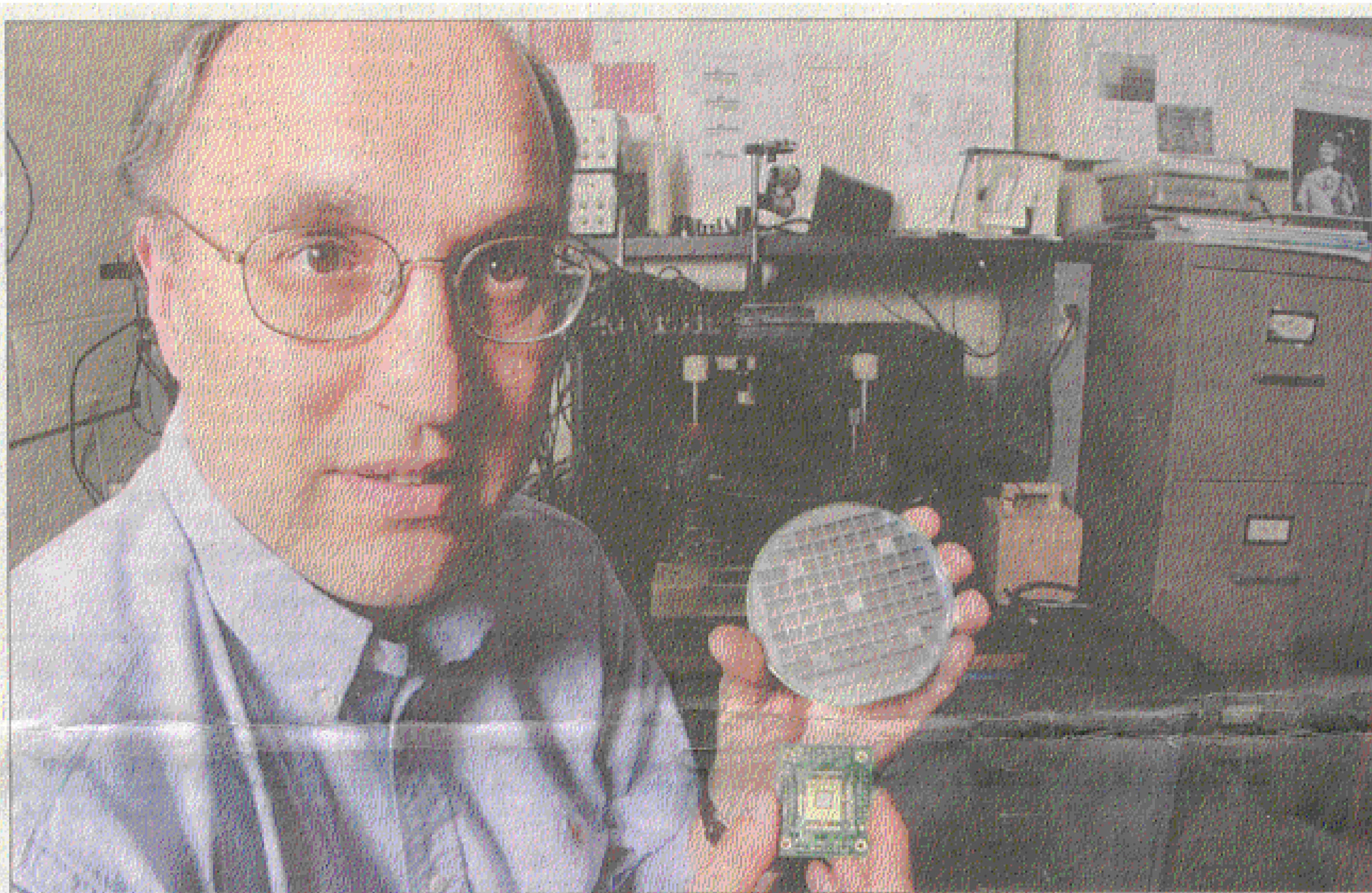
The RIT device also allows

RADIATION, PAGE **10A**

Hub of science

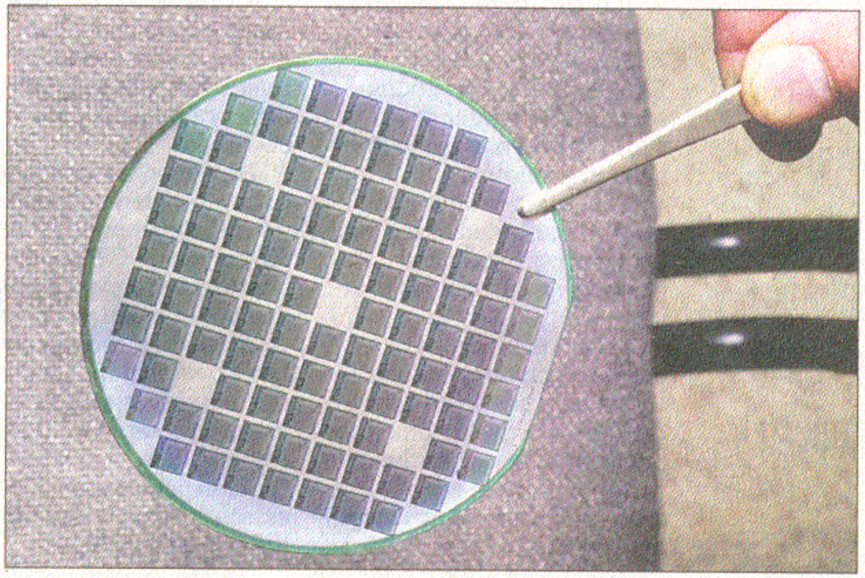
RIT is "a key player" in developing technologies used to capture images in outer space, says NASA chief Daniel Goldin. RIT has eight projects pending worth $2.5 million, including one to study forest fires via satellite images.

RIT also gets funding from New York's Centers for Advanced Technology program, which helps about 20 high-tech research programs in the area. Others involved: the University of Rochester, Xerox Corp., Eastman Kodak Co. and Bausch & Lomb Inc.



ANDREA MELENDEZ staff photographer

Clearer picture Zoran Ninkov, an RIT imaging science professor, displays a silicon wafer that may eventually help scientists get a better view of outer space. "Our area of the country is a kind of hotbed" for such research, he says.



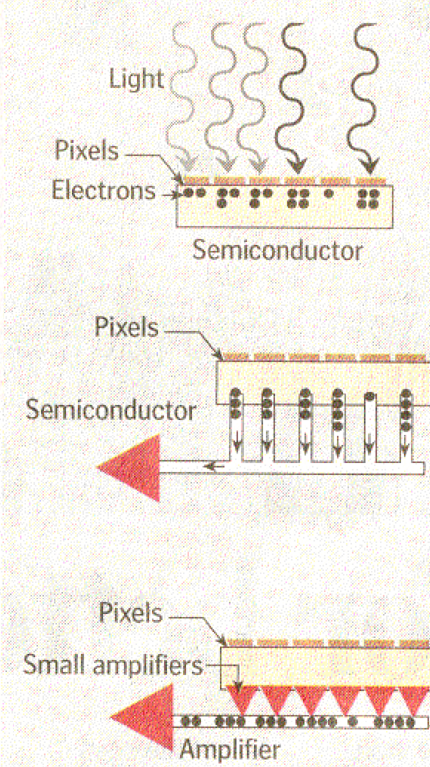
ANDREA MELENDEZ staff photographer

Small, powerful The technology for the development of this silicon wafer, fabricated at RIT, has been possible only since 1995.

Improving images sent from outer space

On Earth, digital cameras are protected from intense radiation by the atmosphere. In outer space, that radiation degrades digital images captured by telescopes and other satellite-mounted hardware. So radiation-hardened sensor arrays are being designed at the Rochester Institute of Technology and elsewhere.

The normal digital camera, based on a charge-coupled device that gathers light, works this way:



Light falls on a semiconductor, producing a charge and creating electrons proportional to the intensity of light. The electronic charge is isolated in tiny, square like "pixels," or picture units, which are millionths of a meter across.

Each pixel gives up its electric charge, which moves through a grid of other pixels to an exitlike amplifier. The movement is orderly, like spectators leaving a movie theater. In outer space, radiation damages the bucketlike structure of the pixels and interrupts the orderly flow of electrons to the amplifier. Result: a distorted or destroyed image.

At RIT, several strategies are being explored to provide detector arrays that are impervious to the effects of radiation. In one of them, researchers add an amplifier to each pixel. This eliminates the need for vulnerable electrons to travel long distances. Result: reduced chances of radiation damage.

SOURCE: Rochester Institute of Technology

HERM AUCH staff artist

Radiation

FROM PAGE 1A

a camera to zoom in on a fast-moving object in space, by employing a limited array of picture elements, called pixels. Current digital imaging sensors can only take pictures using the whole pixel array.

"Things keep getting better," said Dona Flamme, who oversees similar technology development for Eastman Kodak Co.

Kodak is the largest manufacturer of digital imaging sensors of all kinds in North America. Most are used in digital cameras, which require no film and are available for as little as $100.

Kodak had its own radiation-hardened imaging sensors in cameras that were mounted on the Mars Rover, the wheeled exploring device that successfully rambled over the surface of Mars in 1997.

Ninkov — teaming with graduate students, other universities and local industry — has been working since 1991 on ways to develop radiation-hardened imaging sensors.

Existing sensors are called charge-coupled devices, known as CCDs. They are the electronic heart of digital cameras and camcorders. Steady improvements now allow CCDs — thin cookies of imprinted silicon — to produce images comparable in quality to 35mm film.

But in outer space, such picture quality is degraded by intense ionizing radiation, the same potent energy that makes nuclear fuel dangerous and X-rays powerful.

Radiation-damaged CCDs on the Hubble Space Telescope had to be replaced by a space shuttle crew, like eye doctors changing a pair of million-dollar glasses.

"CCDs will not take that level of (outer space) radiation," said digital imaging expert Joe Carbone, engineering vice president for CID Technologies Inc. near Syracuse.

And future space missions will need radiation-hardened imaging devices more than ever.

The next generation of space telescopes, to be launched by NASA within a decade, will hover deep in space, well out of range of repair crews. The Hubble Space Telescope orbits a modest and accessible 385 miles above Earth.

And within just a few years, NASA will launch a deep space probe to Europa, a frozen moon of the planet Jupiter. Europa may harbor water under its outer surface of ice — making it one day a sort of wet oasis for outer space travelers.

To get to Jupiter, the probe will need radiation-hardened sensors as "star trackers," to triangulate its trajectory, much the way a sailor navigates by stars. And once in orbit, the space probe will take pictures to beam back to Earth — while baking for a month in Europa's unusually intense radiation.

NASA has bids out for the probe's star tracker and digital imaging devices, said Carbone, who works with Ninkov.

He called the RIT scientist "a resource person for NASA, someone they use to screen technologies."

Competition to make the NASA devices is intense, and the Rochester area appears to have an edge in technology that provides sensors impervious to radiation in space.

"Our area of the country is a kind of hotbed" for working on radiation-hardened imaging devices, said Ninkov.

A normal CCD, found in commercially available cameras, is vulnerable to radiation.

Light from an image falls on a semiconductor, producing an electric charge. The resulting electrons, whose relative intensity represents shadings in the image, gather under the pixels. These tiny rectangular areas are just a few millionths of a meter across. The electrons move "like water flowing into a series of buckets," said Ninkov.

move in straight lines to a common amplifier, which converts the electron information to a complex series of numbers. A computer converts the numbers into an image, in gradations of gray or color.

Outer-space radiation puts holes in the buckets, and turns the dominolike line of flowing electrons into a diffuse stutter of impulses.

One RIT strategy for making CCDs radiation-hardened adds an amplifier to each pixel. These microtechnology products — dubbed by RIT "active pixels sensors" — have only been even theoretically possible since about 1995. Before then, said Ninkov, CCD makers — laboring in what insiders call silicon "foundries" — worked on a coarser scale. "We only had big hammers," said Ninkov.

Since the Hubble and Chandra space telescopes use conventional CCDs, they are still vulnerable to radiation.

"Both (telescopes) work, just not as well as everyone imagined," said Ninkov. "We want detectors in space to work as well as the ones on the ground do." ❑

REFERENCES

1. "Imaging Devices Using the Charge-Coupled Concept", David f. Barbe, Proceedings of the IEEE, Vol.63, No. 1, January 1975.
2. "B.S.T.J. Briefs, Charge Coupled Semiconductor Devices", W.S. Boyle and G.E. Smith, January 29, 1970, The Bell System Technical Journal, Vol.49, April 1970.
3. "Solid State Image Sensors Using the Charge Transfer Principle", J.G. van Santen, Proceedings of the 8th Conference on solid State Devices, Tokyo, 1976, Japanese Journal of Applied Physics, Volume 16 (1877) Supplement 16-1, pp 365-371.
4. Eastman Kodak Company, Electronic Imaging, Microelectronics Technology Division, Products Literature.

HOMEWORK - CCD'S AND CID'S

1. **Describe how charge is generated in a CCD.**
2. **How is charge transferred in a two phase CCD.**
3. **How does a CID work?**