JPL

Ultraviolet Imaging Arrays, Particle Detector Arrays, and Quantum Dots

Shouleh Nikzad
Jordana Bandaru, Robert Beach, Tom Cunningham, April Jewell, Todd Jones

Nanoscience and Advanced Detector Arrays Group
Jet Propulsion Laboratory, California Institute of Technology

Presentation in

NASA Advanced Sensors Symposium:
New Directions in Advanced Sensor Technology
Baltimore, MD

July 30, 2002

Sponsors: NASA and BMDO

Outline

UV Imaging Technology (Silicon Based)

Applications in UV

Challenges of UV detection

Delta-doped arrays for UV detection

Low energy particle detectors

Delta-doped arrays for low-energy charged particle detection

Applications

Hybrid Advanced Detector

GaN and alloys for visible-blind UV imaging

Focal Plane Arrays and Photocathodes

Curved Focal Plane Arrays

Applications

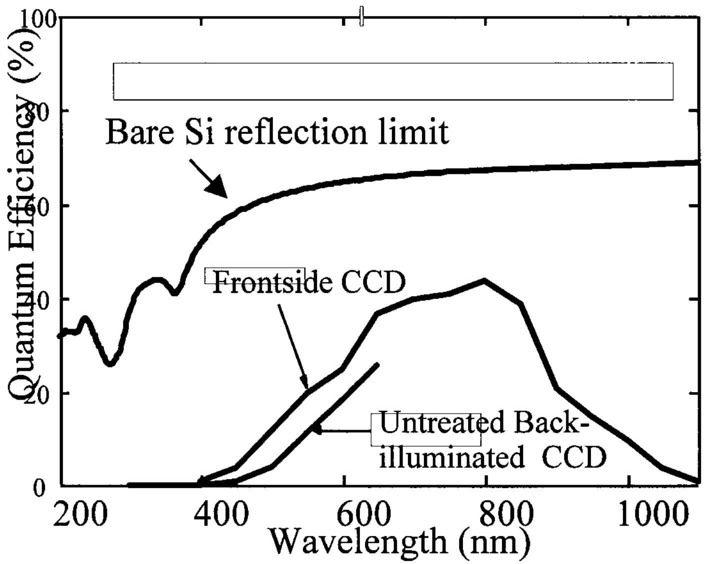
Curved High resistivity Arrays

Curved thinned FPAs

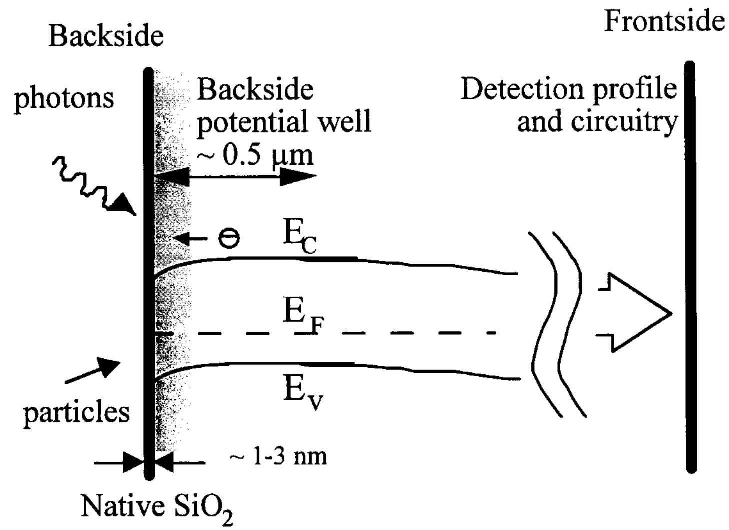
Status of the Technology

Challenge : Ultraviolet Detection in Silicon Imagers

UV Response of Standard CCDs or CMOS Arrays



Band Structure of a Back-illuminated Si Imager



Ultraviolet has applications in many fields: defense, biomedical, criminology, astrophysics, life detection, industrial sites, semiconductor process control, security/identification, etc.

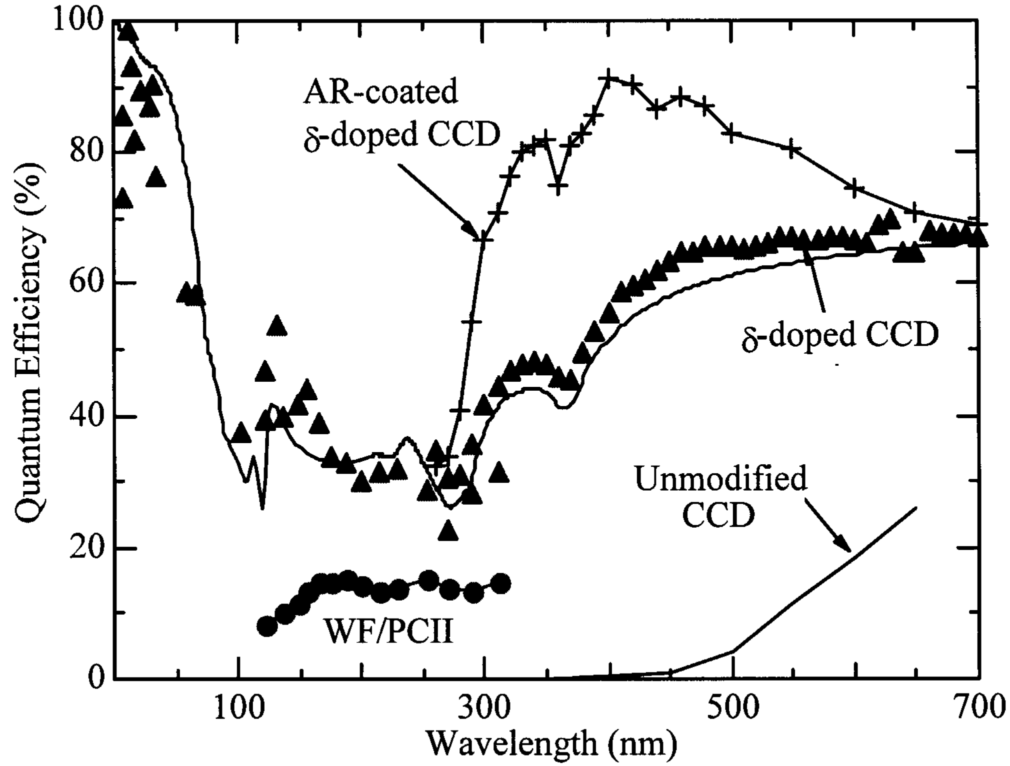
Silicon CCDs and CMOS arrays are attractive imagers for their high resolution, lownoise, and maturity of technology

Back-illuminated imagers potentially have the highest quantum efficiency (bare Si transmittance) in silicon arrays

However, untreated thinned, back-illuminated imagers (or conventrioan frontside) are blind to UV**due to short absorption profiles (<10 nm for1 -400 nm and unfavorablebandbending induced by the oxide interface states**

Delta doping technology

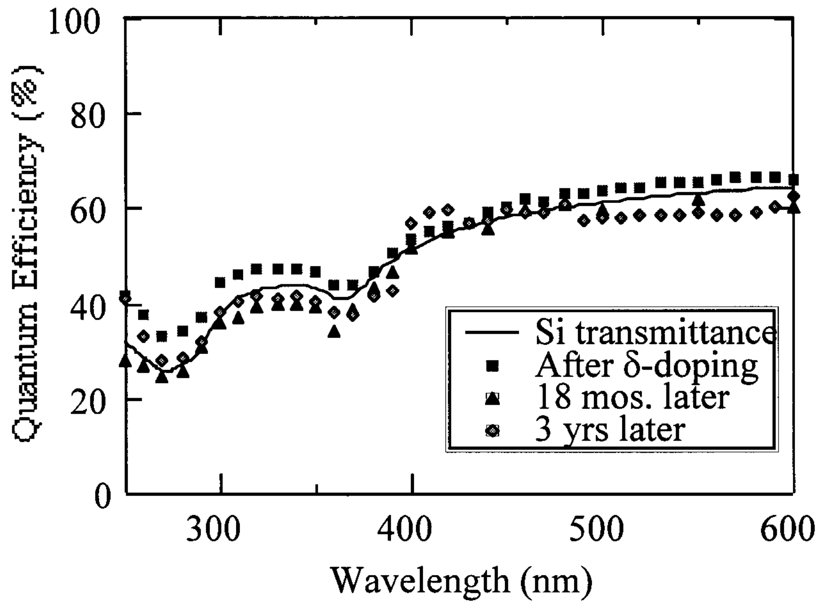
Quantum Efficiency of Delta doped CCDs



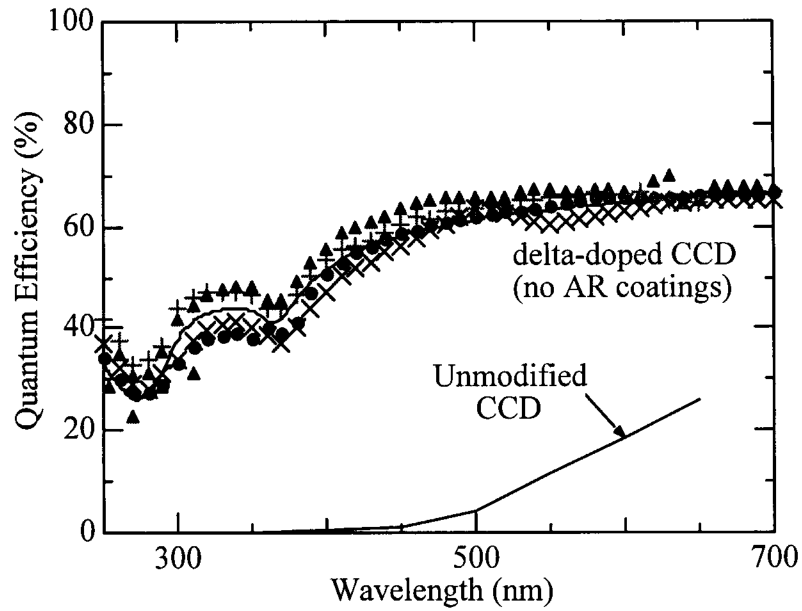
- 100% internal quantum efficiency, uniform, and stable
- Extreme UV measurements were made at SSRL
- Compatible with AR and filter coating: response can be tailored for different regions of the spectrum

Long-term Stability, Quantum Efficiency Hysteresis, and Reproducibility

QE stability



QE reproducibility:
Delta doped Loral, SITe, and Reticon CCDs



- 100% internal QE is measured 1-3 years after the MBE modification of the CCDs
- Reproducible and compatible with different formats and CCD manufacturing processes (demonstrated on Loral, SITe, and Reticon CCDs)
- No hysteresis is observed in delta-doped CCDs (tested by John. Trauger's group)
- **Book Chapter**: "*Delta-doped CCDs* ", S. Nikzad, in "Charge-Coupled Device" by J.R. Janesick, SPIE PRESS VOL. PM83.

JPL

δ-doped CCD with a structurally supported membrane, essential for robustness and applications using fast optics

UV and violet image of Galaxy 6137 at Palomar

Advantages:

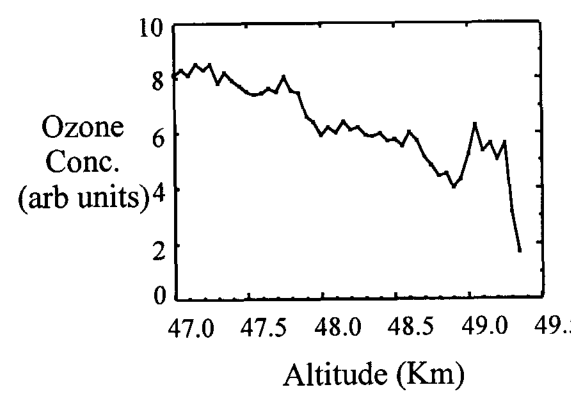
- 100% internal quantum efficiency
- No hysteresis
- Stable (years)
- Direct deposition of anti reflection coatings
- Original electrical device performance (ie., noise, CTE, etc.) is not affected by delta doping

Applications:

- Ground and space-based astronomy
- Spectroscopy
- Space plasma physics
- Biomedical applications
- Plume and bow-shock observations

HOMER
(High altitude Ozone Measuring and Educational Rocket)

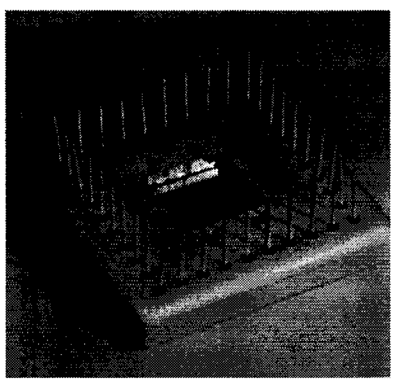
Sample data from HOMER



Tested by various groups at JPL and in the country including NASA ARC, Caltech, and Pixel Vision (Janesick).

Portable, “high”-frame rate UV camera

Portable UV CCD camera



δ-doped CCD with a structurally supported membrane, essential for robustness and applications using fast optics

Features:

- 100% internal quantum efficiency
- No hysteresis
- Stable (years)
- 1024x1024, frame transfer or full frame
- 1-30 frames per second (electronics capability)
- 1-10 frames per second (current chip capability)
- Digital control and digital output
- c-mount UV lens and visible-blind filter
- Room temperature and thermoelectric cooling

Applications:

- Ground and space-based astronomy
- Plume and bow-shock observations
- Spectroscopy
- Space plasma physics
- Biomedical applications

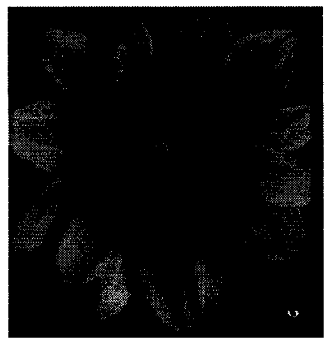
Bio-signature detection using ultraviolet

Insects can see ultraviolet. Eurema lisa butterflies can detect one another and distinguish their gender in a visually crowded field.

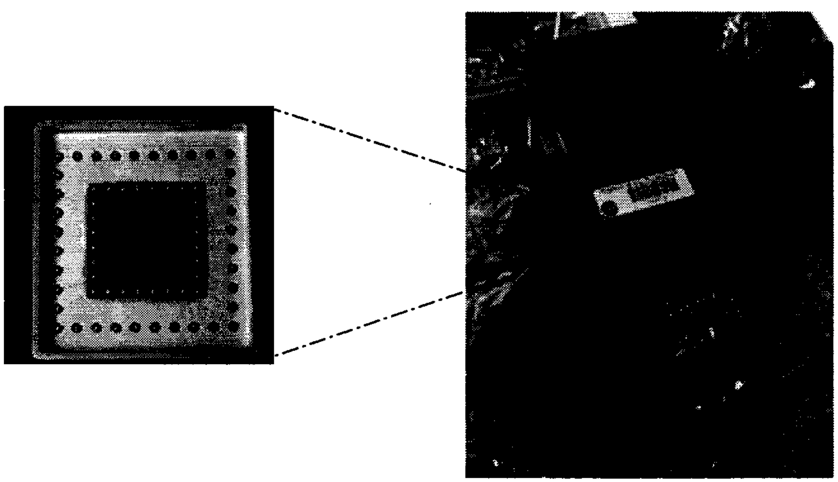
UV Signature of Black-eyed Susan Helps signal Pollinators

Visible Image

UV Image



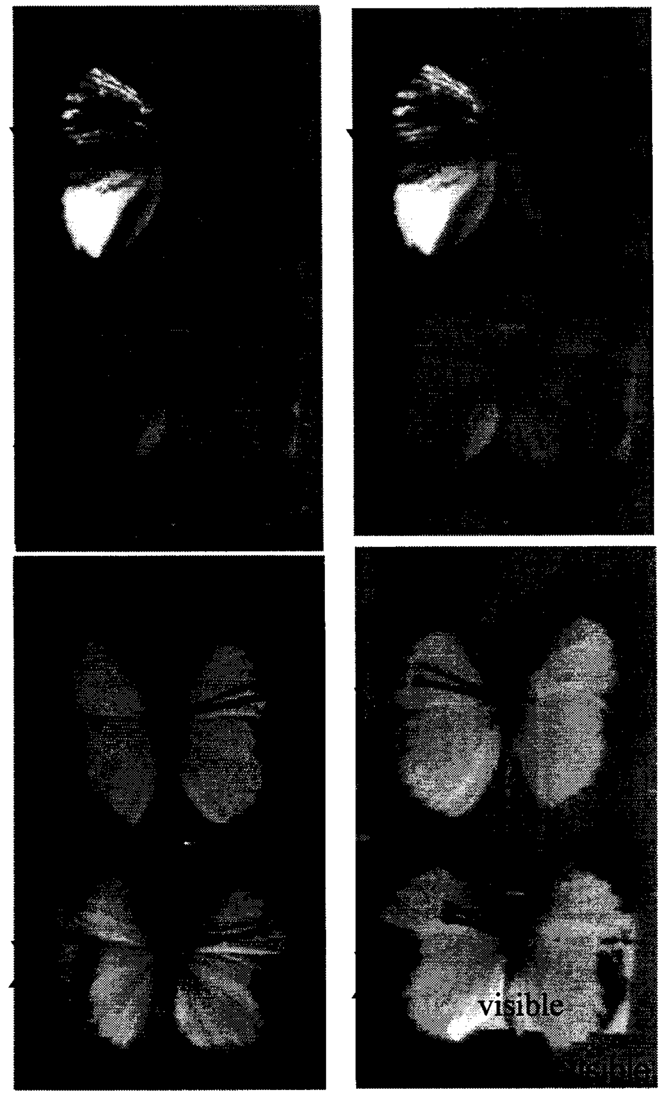
- Black-eyed Susan has a "bullseye" in the UV image due to the strong absorption of the petals in the 340-380 nm range.



Gender-dependent UV Signature of Eurema lisa Butterfly

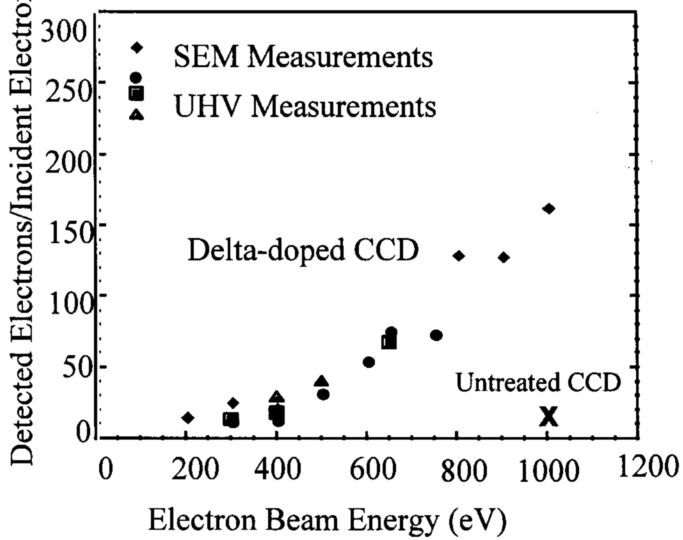
Illuminated from left

Illuminated from right

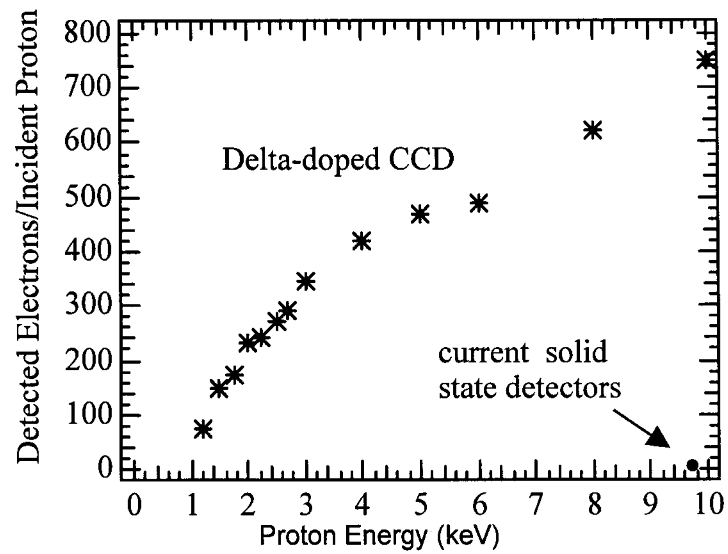


Low-energy Particle Detection with Delta-doped CCDs

Low-energy Electron Detection



Low-energy Proton Detection



• Delta-doped CCDs for particle detection outperform all other solid state detectors in terms of low-energy detection threshold (~ order of magnitude) and gain.

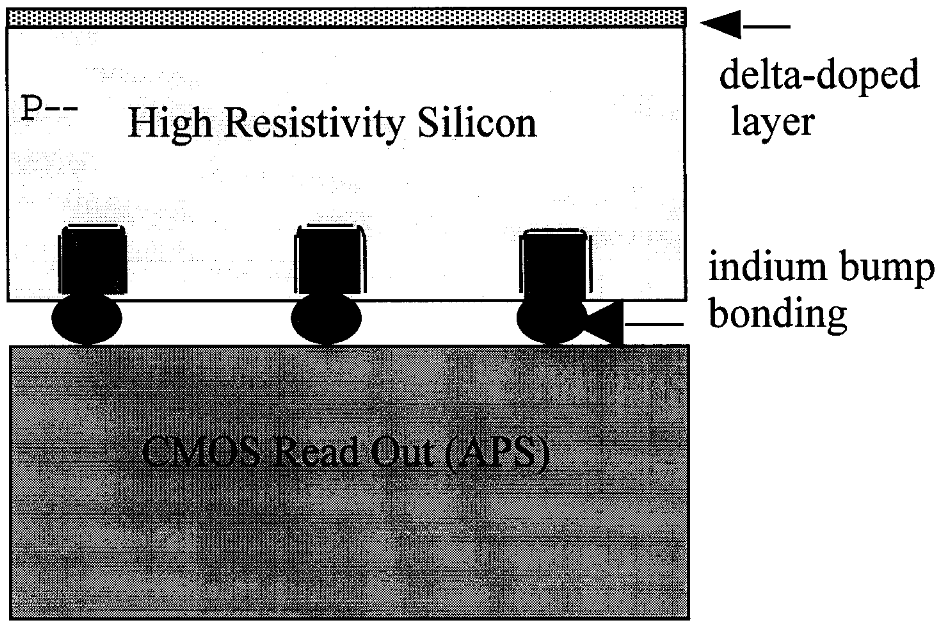
• Replacing microchannel plate systems with single monolithic particle detectors:

- reduces components
- increases reliability
- reduces mass and power requirements

• Applications:

- low-energy plasma detection (e.g., for Space Physics)
- visible-blind UV detection (combined with photocathodes for DOD and NASAapplications, image tubes, goggles)
- electron imaging for commercial use

Hybrid Advanced Detector



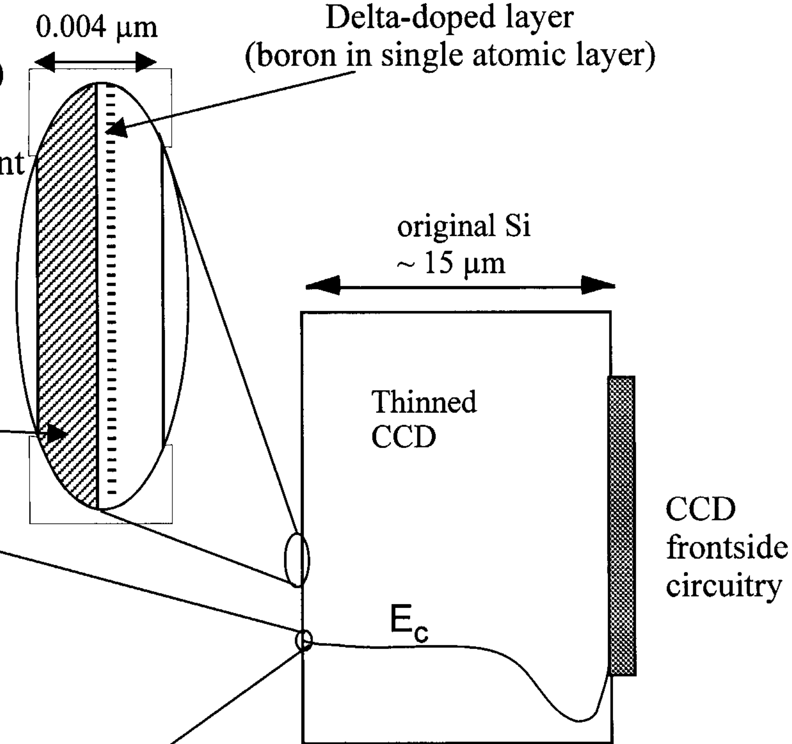
- Direct detection of low-energy protons and electrons
- Rapid acquisition (< 1 ms)
- 2-D array
- Simultaneous ion angular and energy characterization

Solution: Delta doping technology

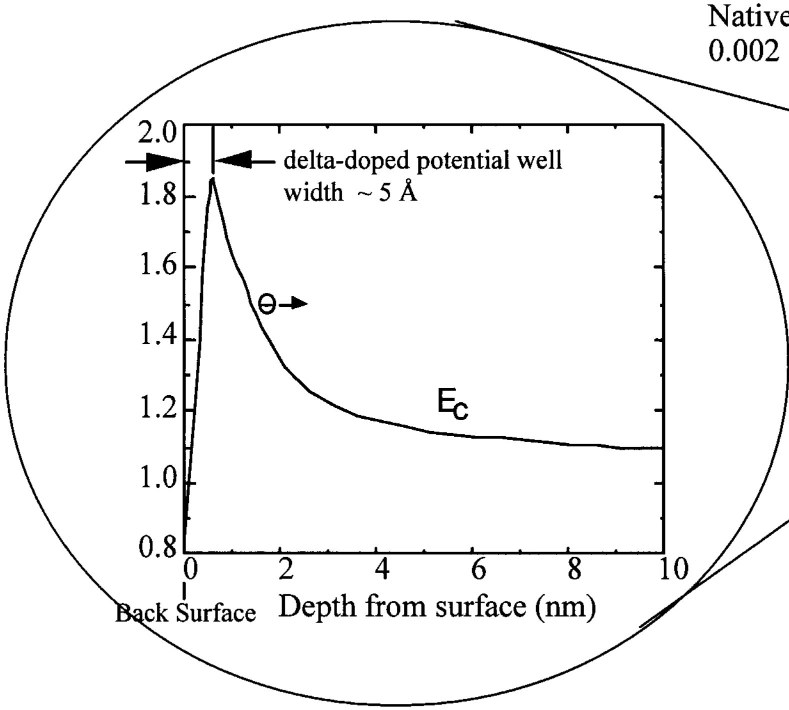
Cross section delta-doped CCD structure

- Fully-processed devices are modified using molecular beam epitaxy (MBE) to modify the back surface bandstructure and effectively remove the backside potential well (deadlayer)

- Process enabled by low-temperature MBE growth development at JPL (P. Grunthaner, et. al. '88)

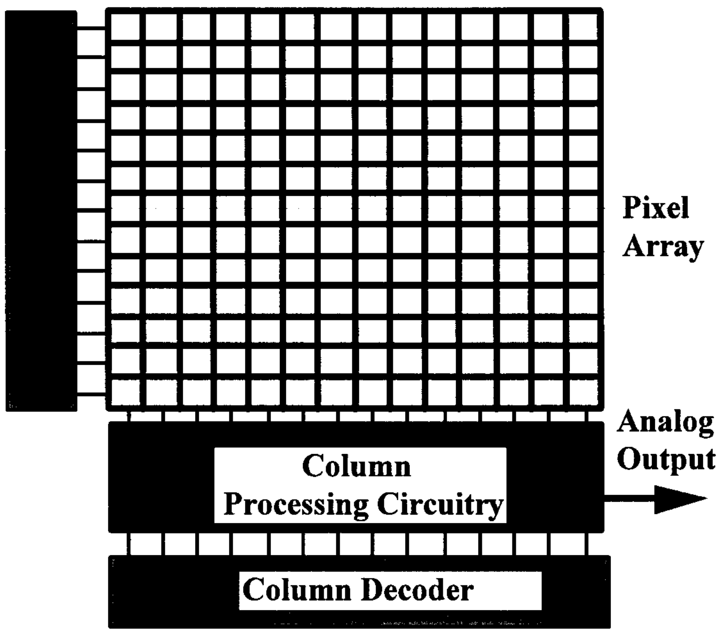


Close up of bandstructure edge after delta doping exhibits no unfavorable bandbending

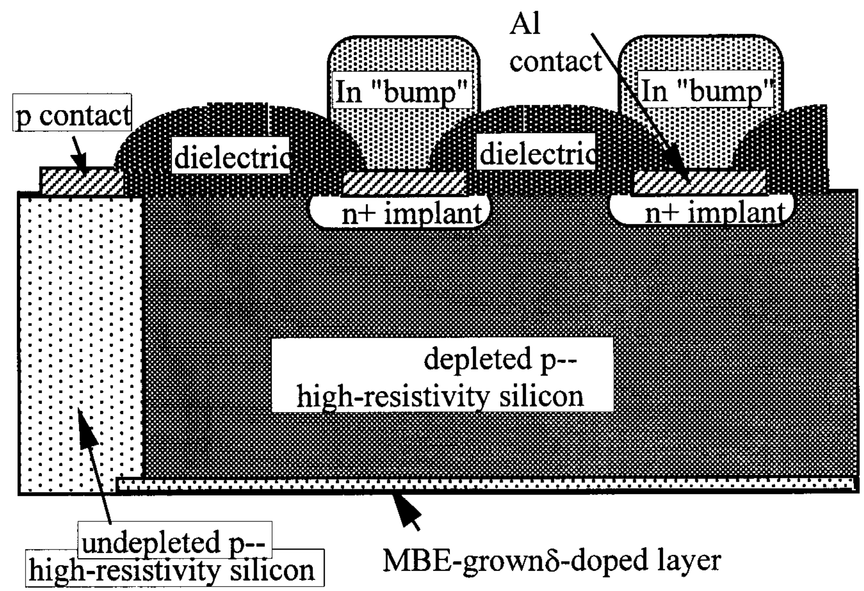


Readout arrays and High resistivity p-type detector arrays were designed and fabricated

CMOS Readout Technology



High resistivity PIN diode array

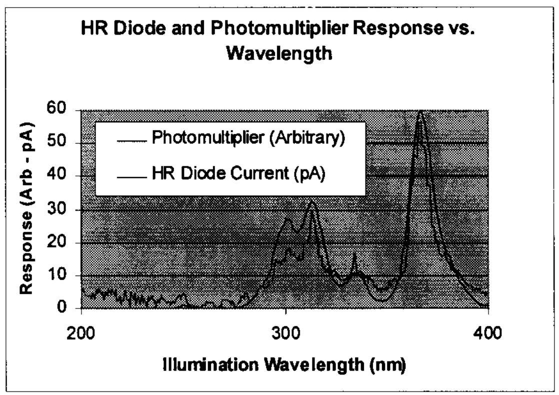


- Fast readout
- Low power
- Sparse readout is potentially possible

- PIN diode array designed at JPL and fabricated at LBNL (custom p-type fab run)
- Full depletion (over 300 μm) is possible with 140 volts

Hybrid Advanced Detector

Vacuum-UV testing of δ-doped high-res Si diode array

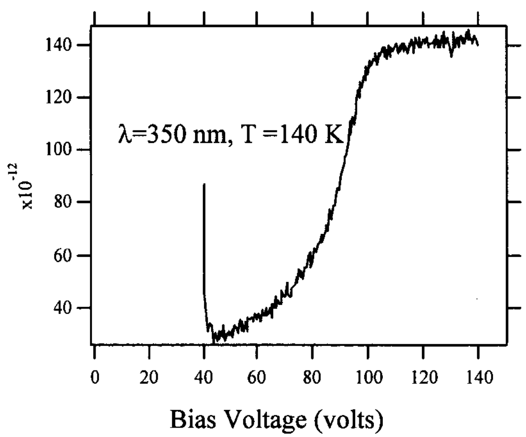


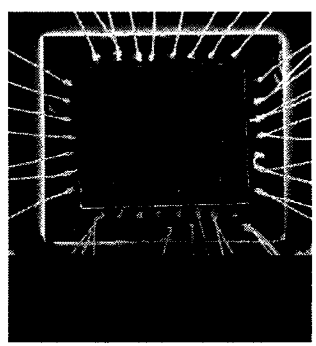
Features

High resistivity silicon technology inherently sensitive to wide energy range for photons while leveraging the mature silicon technology

Rapid energy distribution acquisition (< 1 ms).
2D array allows full velocity distribution measurement
Simultaneous ion angular and energy characterization

Direct detection of low-enregy electrons make it possible for high sensitivity, compact, solar blind UV detectors without requiring high voltage





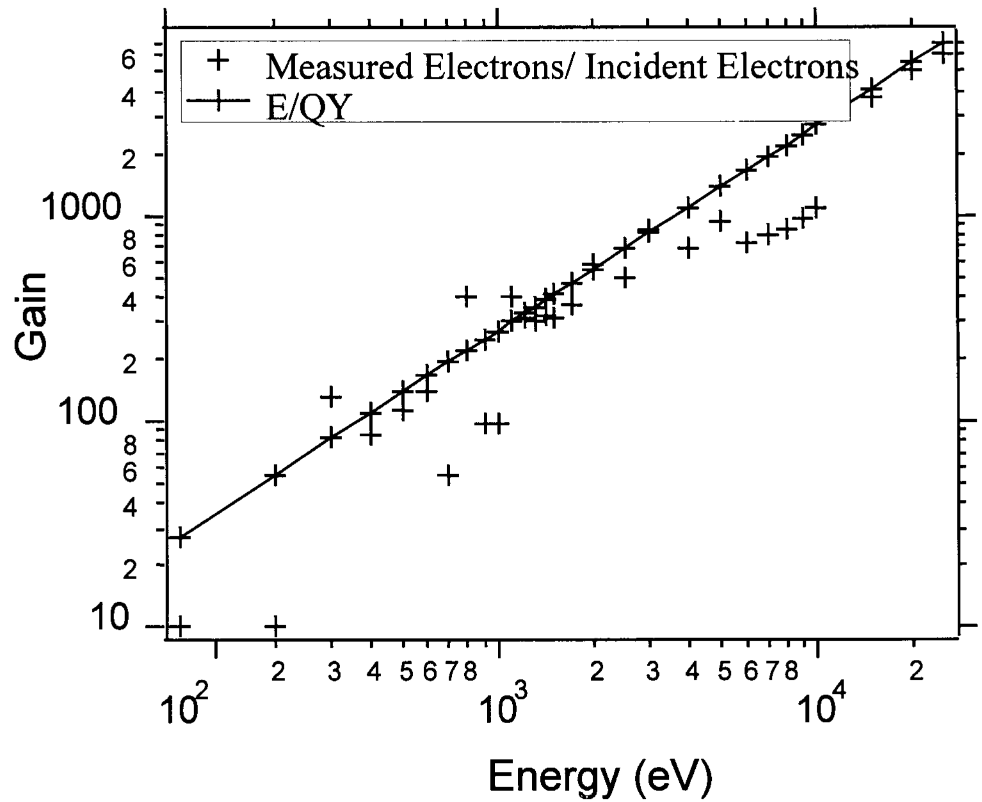
9x8 δ-doped diode array bump-bonded to APS readout

Status

Detection of UV radiation demonstrates sensitivity of thick (300μm) δ-doped detector confirming proof-of-concept functionality of device.

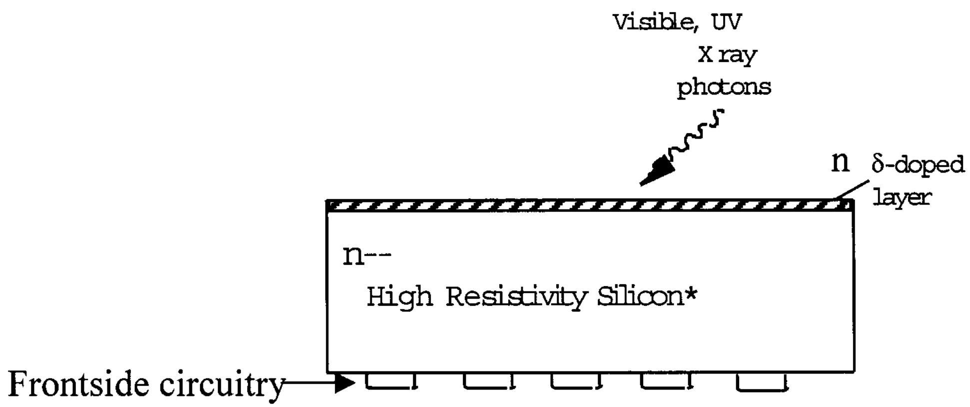
9x8 HR diode device has been hybridized (bump-bonded)

Response of wire bonded DDHR p-type PIN diode array to electrons



- Signal increases with increasing incident energy due to quantum yield effect
- At higher energies the response of the device follows the quantum yield-dictated numbers
- At low electron energies, the device exhibits lower gain than dictated by quantum yield (3.65)

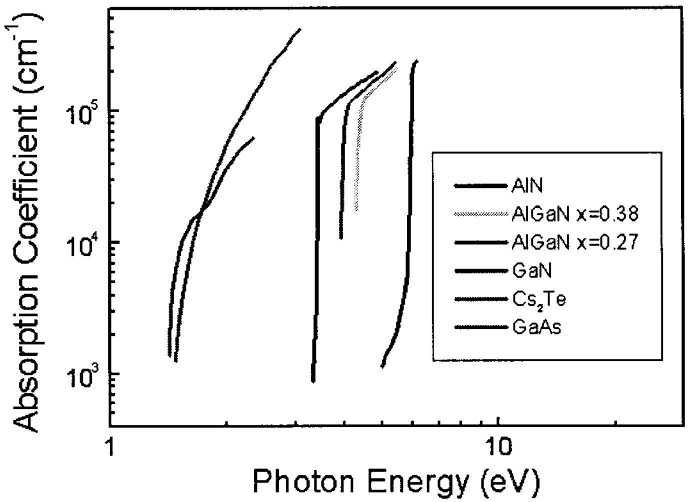
Monolithic n-type Imager

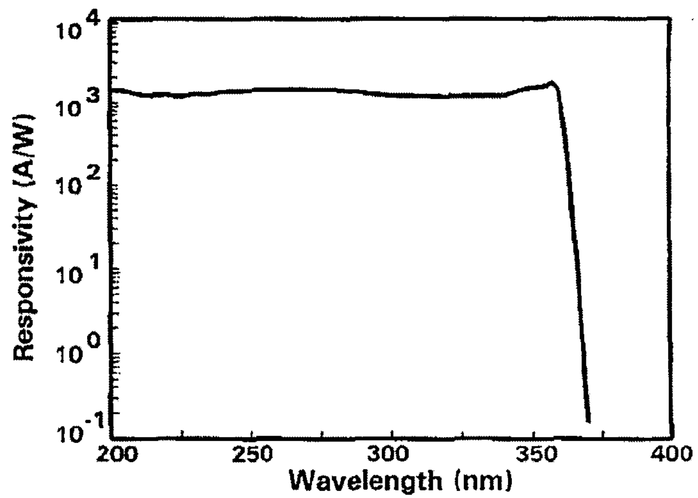


- Combines high resistivity and delta- doping technologies monolithically
- Less prone to radiation damage.
- Broad range of response (soft x rays to near IR)
- More versatile since compatible with the n-type high purity silicon technology
- Fully depleted and no thinnning requirement

* High-resistivity silicon detectors are fabricated at Lewrence Berkeley National Laboratory (Collaborators: S. Holland and M. Levi)

III-N UV Detectors



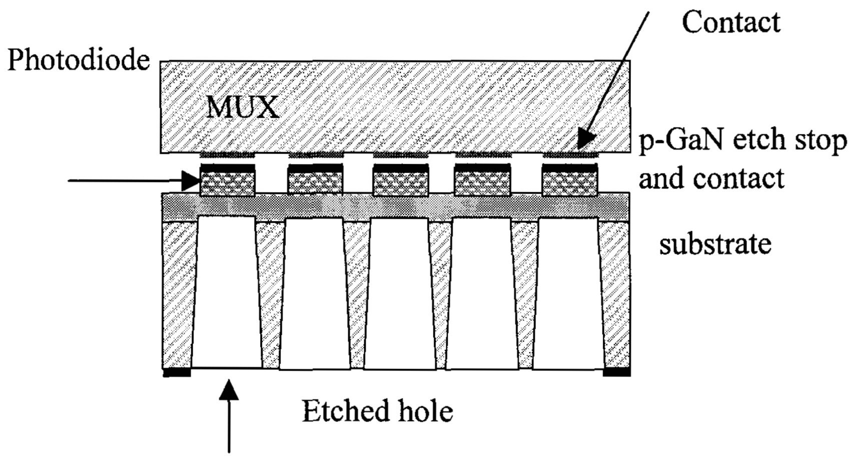


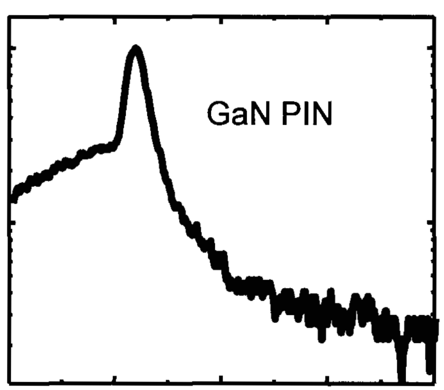
Objective: Design and fabricate III-N solar blind focal plane array for UV imaging.

Motivation: Extremely good intrinsic visible rejection, thermally and chemically stable, radiation tolerant, and tunable energy response.

UV Detector Technologies Under Development

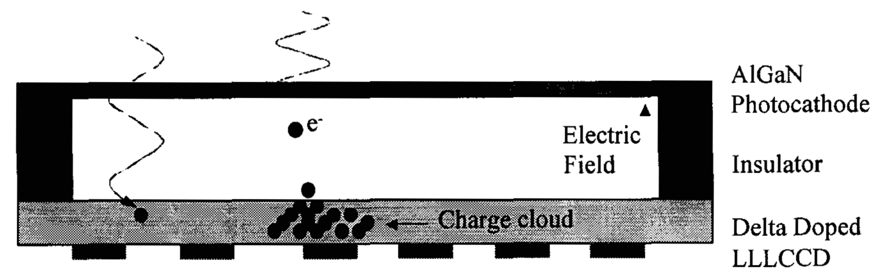
III-N based Solar-blind UV Focal Plane Array





Collaboration with Prof. A. Khan, USC

Novel Electron-Bombarded CCD Design with PEPC

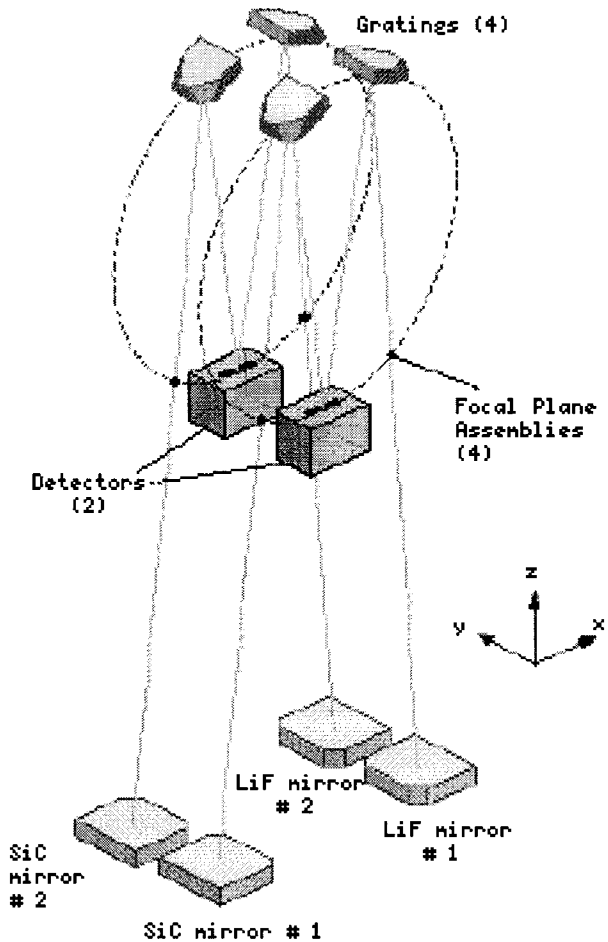


- **High-efficiency, high-resolution, high-gain, and low-noise**
- **Low-voltage operation**the *10-15 kV to 0.5-1 kV*
- **Easy fabrication, no sealed tube requirement**
- **Potentially two-color device**
- **Perfect match for image tube application**
- **Low mass, magnet-free operation**

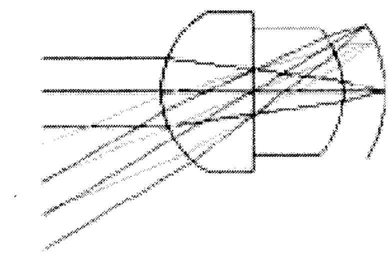
Collaboration with Prof. Chris Martin, Caltech

Curved Detector Focal Plane Arrays

Optical layout of FUSE instrument showing curved MCPs on the Rowland circle



Two-element simplification of optical design (elimination of field flatteners)

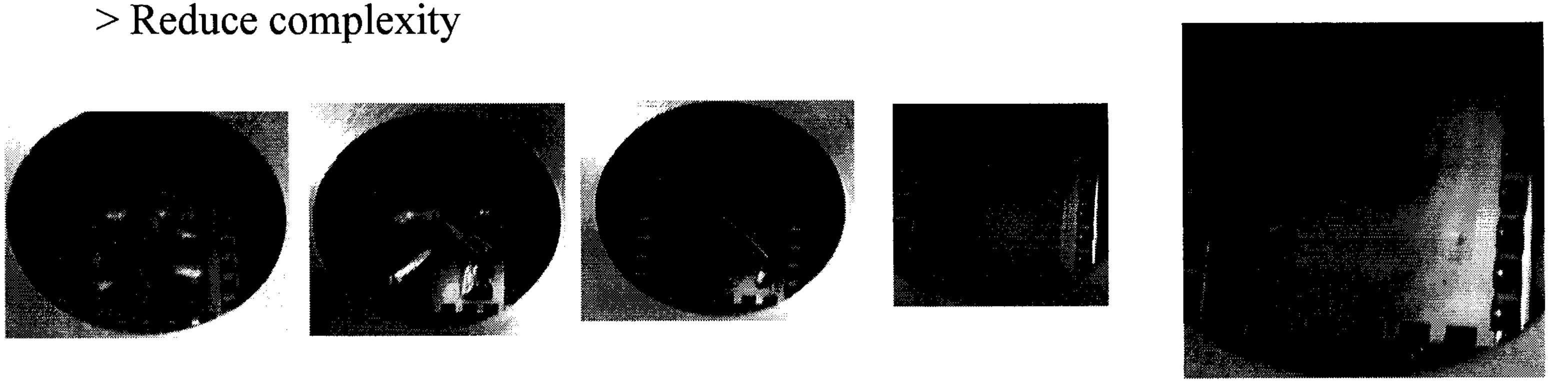


Typical Application	F.L. (mm)	f#	FOV (deg)	Image Surface Curvature (mm)	Number of Optical Elements (Complexity)
Miniature Startracker	25	2	60	25	2
Miniature Startracker	25	5	28	53	3
Rover Panoramic Camera	25	3	28	117	6
Miniature Startracker	25	2	60	846	11
Spacecraft Camera Optics	1600	10.6	1	238	2
Spacecraft Camera Optics	1752	11.6	1	30000	4

Flat and Curved Focal Plane Arrays

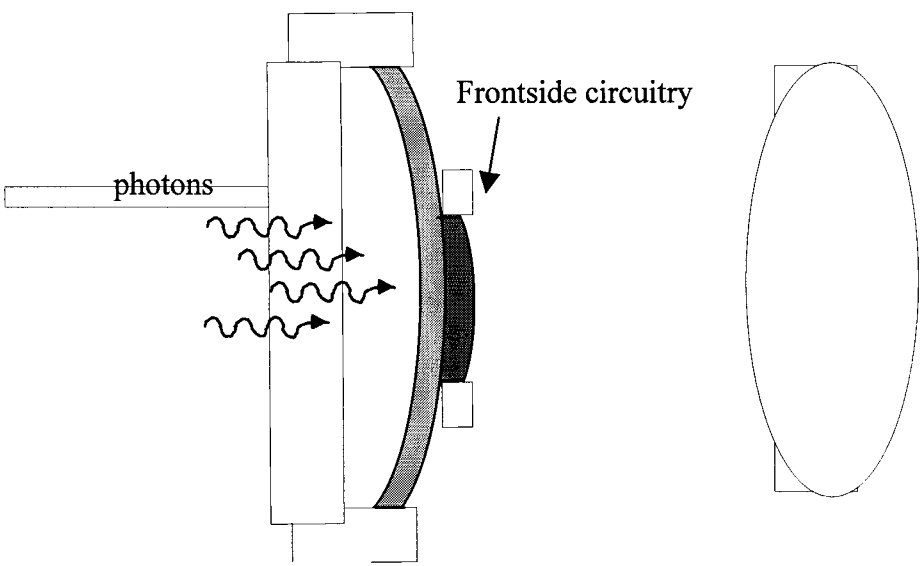
- Thinned membranes can be conformed to substrates for flat or curved focal planes
- Eliminate optical elements:
  - > Reduce mass
  - > Reduce complexity

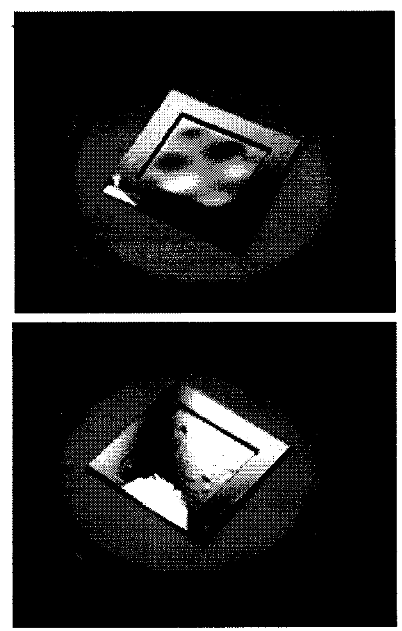
Evolution of CCD flatness

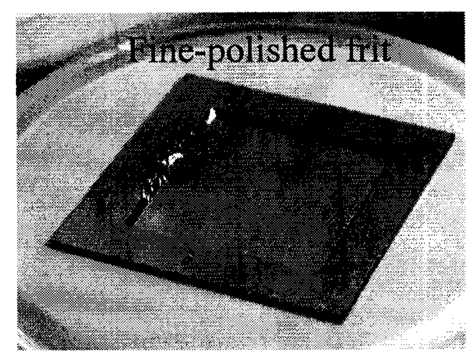


Curved focal plane arrays

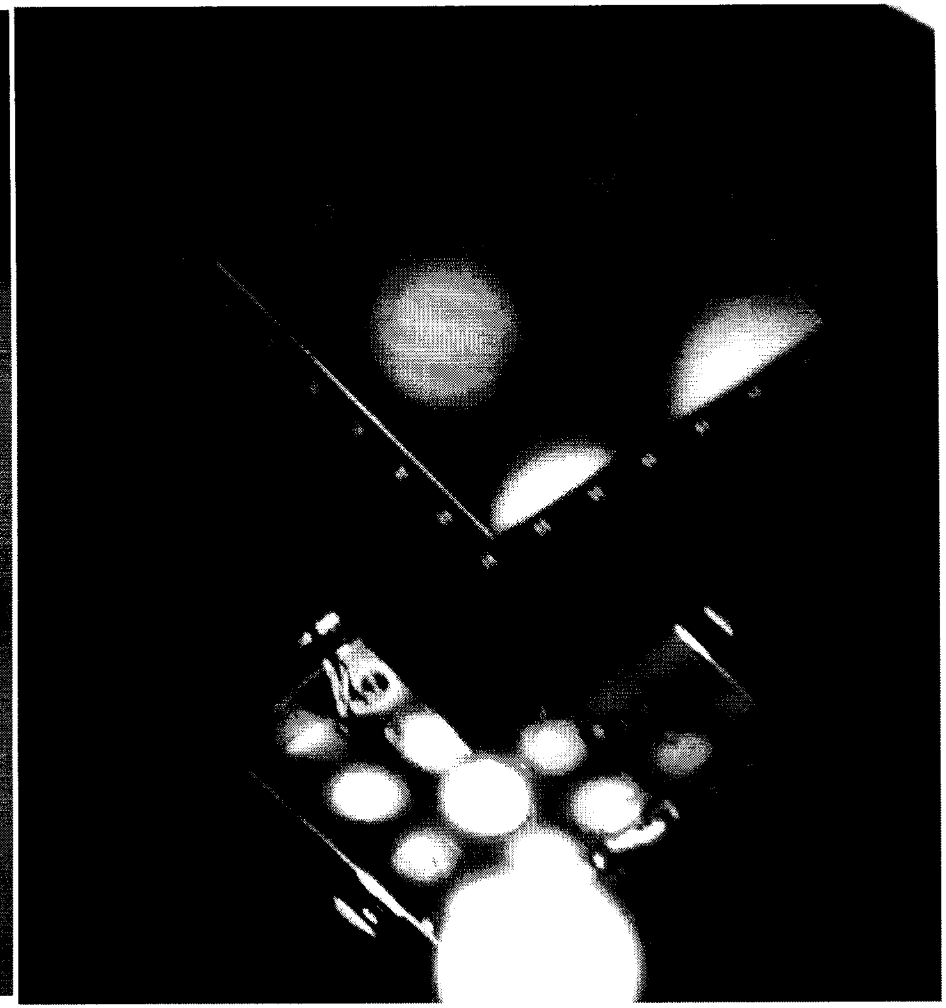
Thinned curved FPA



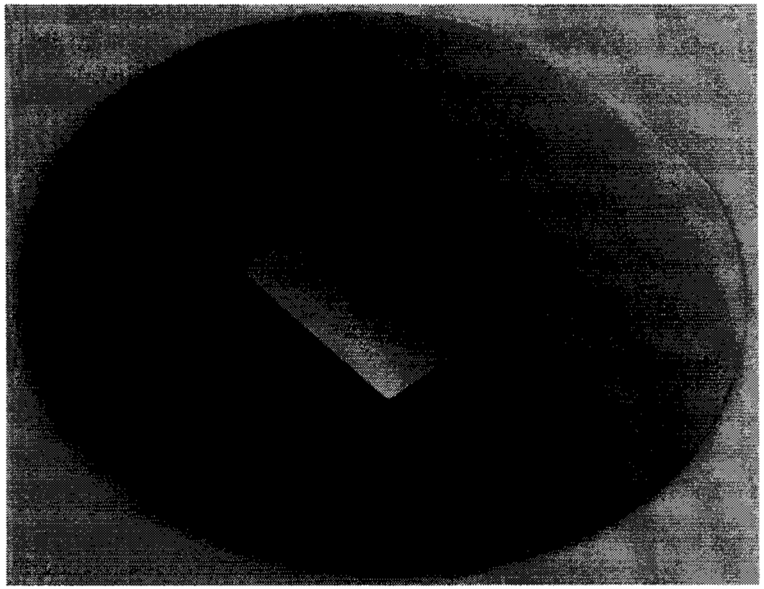


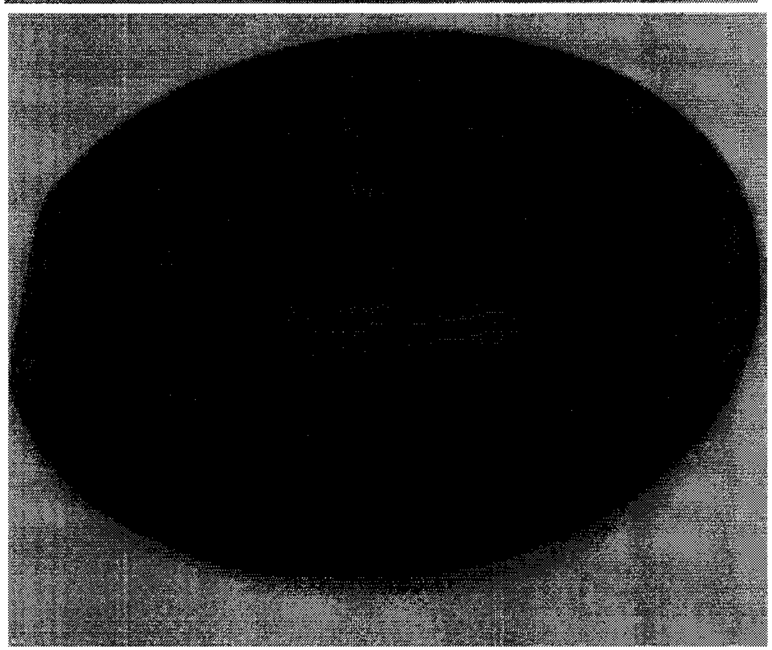


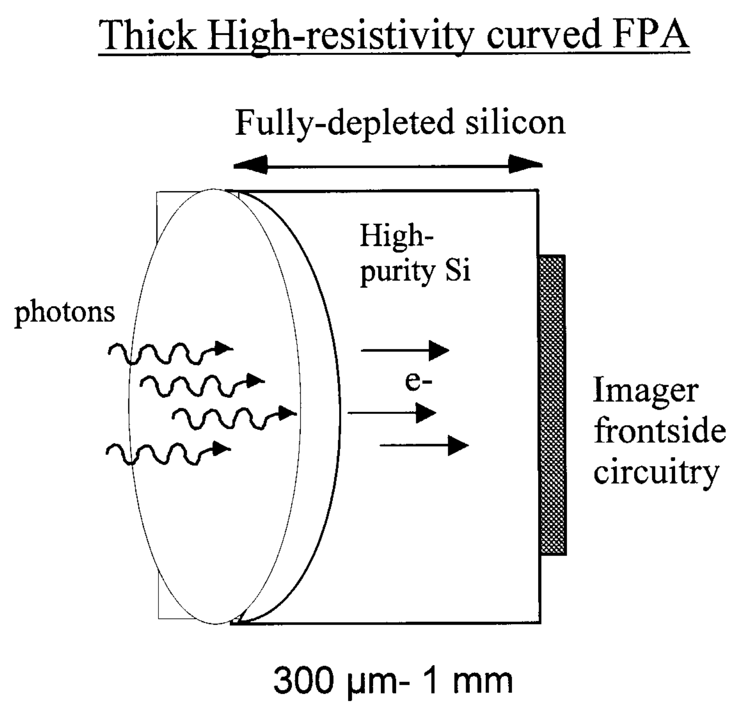
Thinned Membrane Curved and Flat Focal Plane Arrays



Curved Focal Plane Arrays using High-resistivity Silicon Arrays



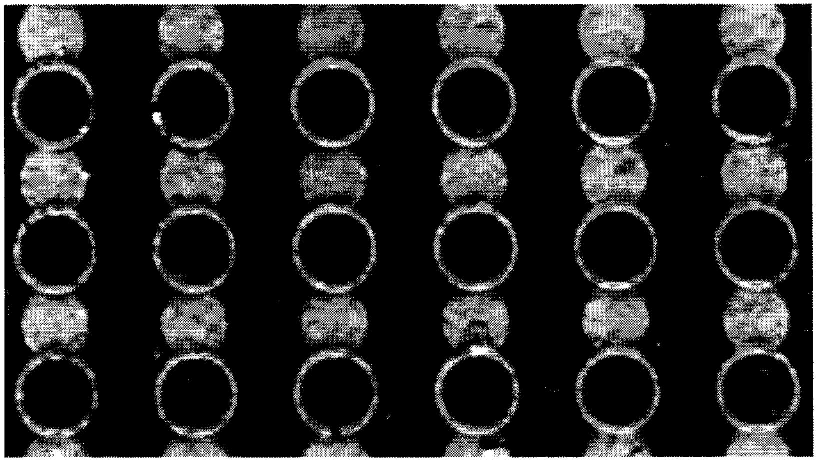


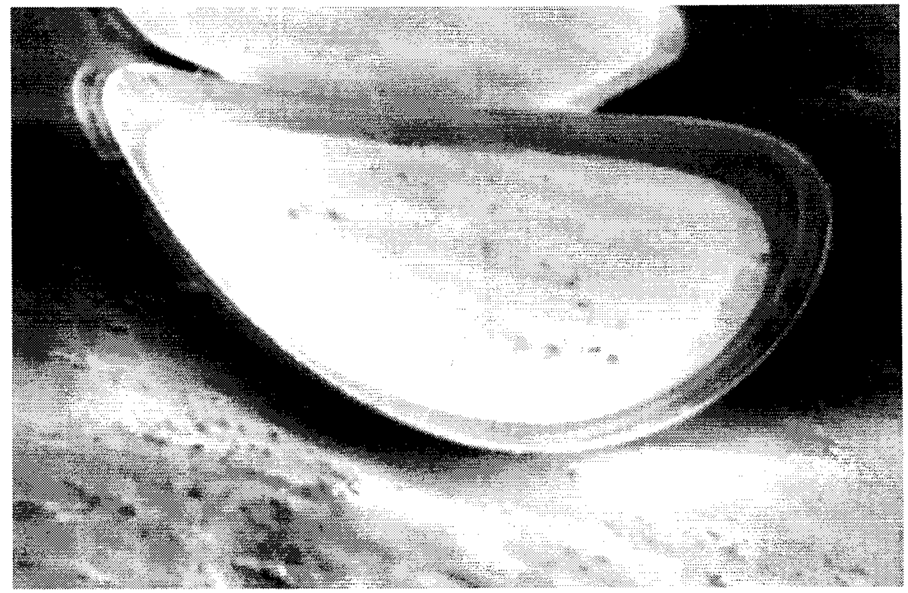


- High-resistivity imagers are fully depleted, don't require thinning, and can be polished to shape
- Back illumination is essential for these enabling technologies

Curved Focal Plane Arrays using III-nitrides

Pre-Etch

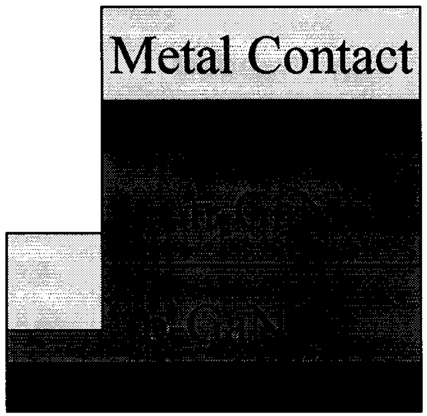


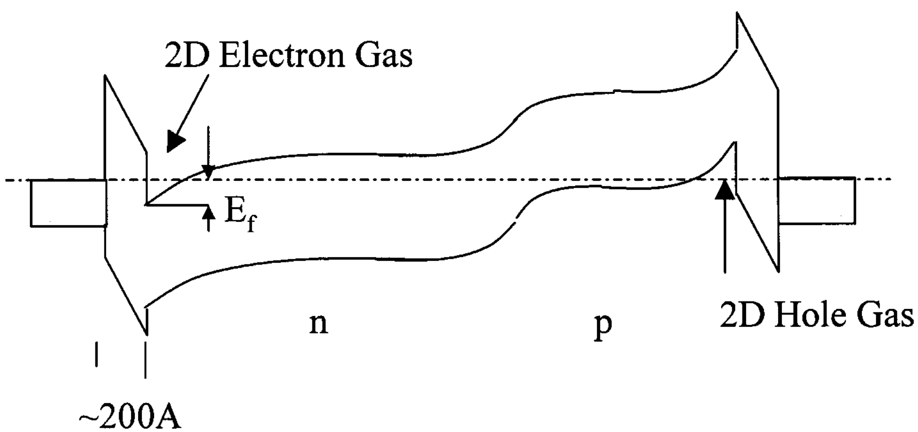


- MEMS-type structures have been demonstrated at Caltech/JPL
- Robust structures can be made out of GaN and alloys thinned membrane
- Curved focal plane array concept can be potentially made in III-N arrays
- GaN micron-size features fabricated using photoelectrochemical etching

Piezoelectric Enhancement of AlGaN Device Application

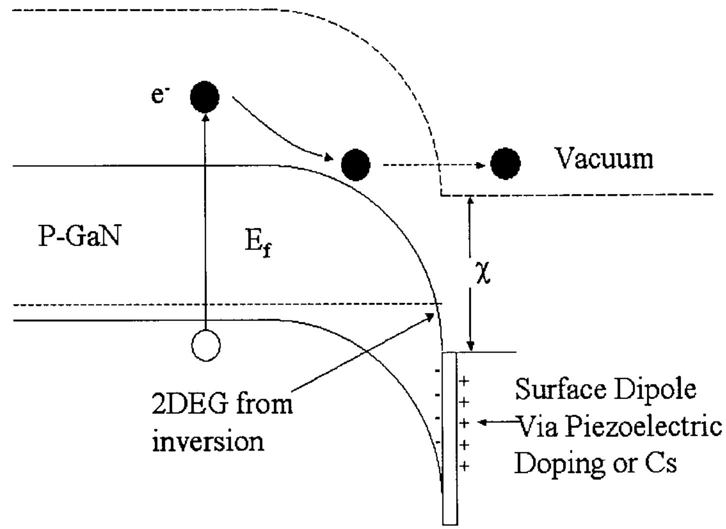
Photodetector

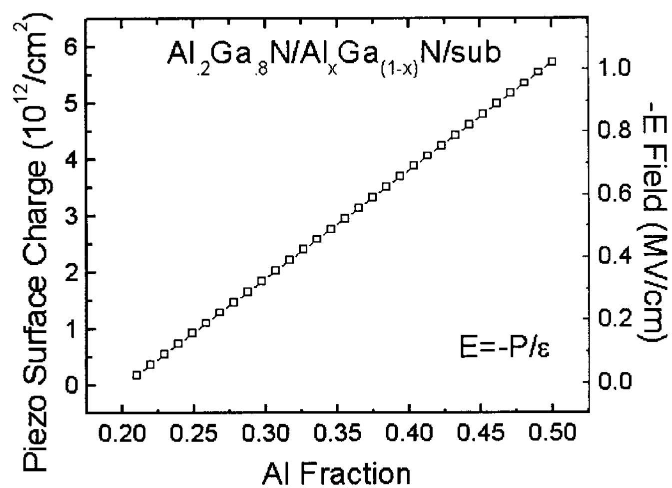




Reduce dead layer by 1 order of magnitude

Photocathode

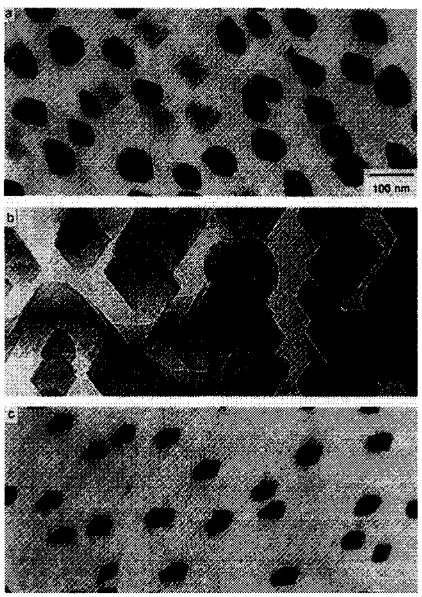




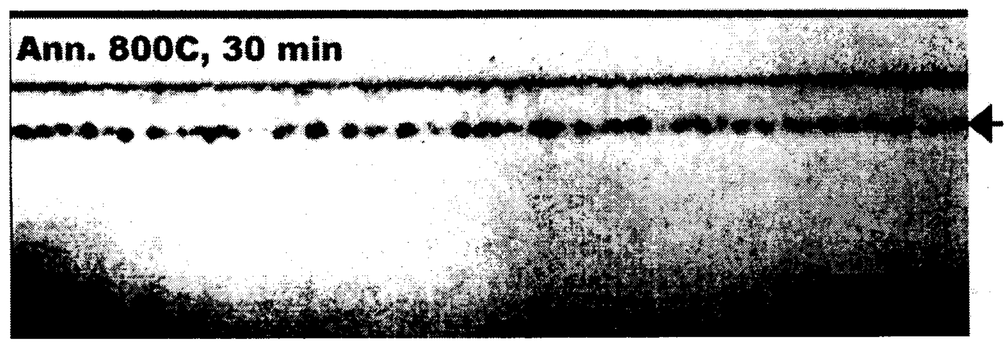
Self-Assembled Group-IV Quantum-Dot Arrays

$120K (1-year JPL DRDF)

- Most work to date has been based on the III-V semiconductor materials system.
- Group-IV materials offer the advantage of direct integration into CMOS.
- Possible materials candidates: $CoSi_2$, α-Sn
- Quantum size effects, in small quantum dots of group-IV-compatible materials such as α-Sn, are expected to produce a transition to direct-bandgap semiconductor band structure.
- End product: Development of a reliable fabrication process for self-assembled arrays of group-IV QDs by in-situ MBE growth.



Plan-view TEM micrographs of CoSi2 QDs grown on Si at 700°C with Co fractions of approximately 8%, 20%, and 2%



Sn QDs formed from a 2nm 10% Sn:Si layer grown at 170°C

Prepared by L. D. Bell 12 March 2002

Novel Sn-IV (SnSi, SnGe) Alloys and Applications

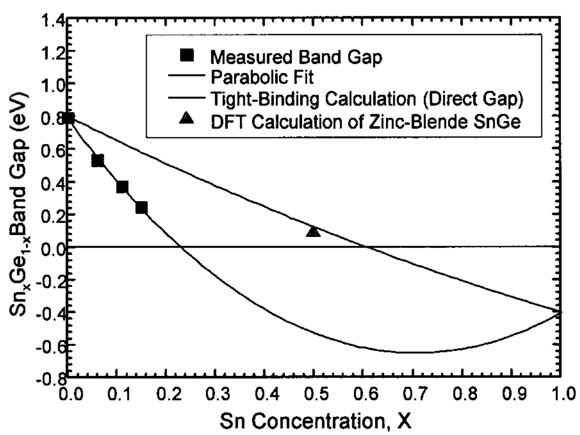
Motivation

- Ge_xSn_{1-x} and related alloys offer potential for developing completely group IV-based optoelectronic devices [1,2]

- Si_xSn_{1-x} offer possibilities for low-dimensional structures such as quantum dots

Background

- Direct bandgap can be engineered in the range 0.6-0.35 eV (2.0-3.5 μm).
- Optical absorption measurements have shown direct bandgap for Ge_xSn_{1-x} alloy [2]
- Nanostructures of SnSi have been fabricated



[1] After M. Rojas, et.al., J. Appl. Phys., 84, 2219, (1998).
[2] After G. He and H.A. Atwater, PRL, 79, 1937 (1997)

Potential Applications

- High-speed, tailorable, inexpensive IR detectors
- Integrated optoelectronics systems
- Thermophotovoltaics: microminiature power sources, space- borne energy systems
- Quantum dots in silicon-based systems

Advantages of SnGe

- Direct bandgap, very high absorption coefficient in the IR: high energy conversion efficiency
- Group IV material, consistent with dominant group IV growth, processing, and microelectronics technology:
- Simple binary alloy: Simplified fabrication method
- Direct bandgap can be engineered (2.0-3.5 μm IR absorption)
- Inexpensive Ge or Si substrates: 100 times less Substrate cost
- Contact technology in Ge is mature: Low development cost

Challenges

- Growth of thick (several μm) optical quality material
- Doping of SnGe material

Status of The Technology

Delta-doped UV Imaging Arrays

Mature--Ready for licensing

Delta-doped Particle Detectors

Can be licensed (for night vision/image tubes, EBCCDs, etc.)
Further development on HAD can be done collaboratively

III-Nitrides Focal Plane Arrays

Early stages of development (looking for partnership)

Curved Focal Plane Arrays

Early stages of development (and concept)

Quantum Dots

Concept