National Aeronautics and
Space Administration

Delta doping Technology for Back illuminated CMOS and CCD Imagers

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

Invited Presentation
2009 International Image Sensor Workshop
Back Illumination Symposium
Bergen, Norway

24 June 2009

Advanced Detector Arrays and Nanoscience Group and Affiliates

Future UV/Optical/NIR Missions Under Study

A bit of history…

Historically, UV sensitivity was the motivation for the development of back illuminated arrays and delta doping…….
….and it's still an issue…

- Current UV only detectors in missions are far from theoretical limits
  - Quantum efficiencies ~ 10%
  - Spatial resolution limited to 10 microns, spatial non-linearities
  - No energy resolution
  - Poor dynamic range (<100:1)

- Quantum efficiency enhancement over 0.1-0.3 micron band is critical.
  - Corresponds to x 3 telescope aperture improvement (e.g., HST 2.4 m -> 7 m)

Clearly, other factors have become important…

Back-illumination as key to high performance silicon imaging technology

Performance parameters

- Wide spectral range in one detector (e.g., UV, visible, NIR in silicon)
- High sensitivity, high fill factor

Realization of back illuminated devices

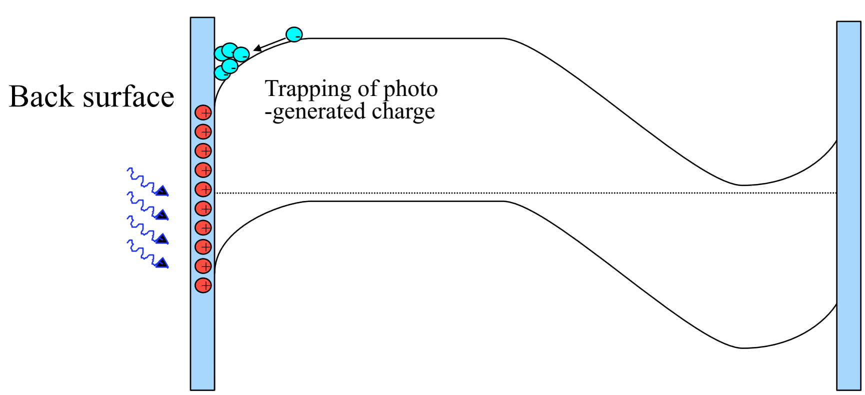
- Thinning, substrate removal
- Bandstructure engineering and end to end processing determine the performance

Other considerations

- Detector thickness and NIR response
- Thick fully depletable materials and detectors
- Radiation tolerance (CMOS and LBNL p-channel CCDs)
- Photon counting (L3CCDs, Impactron, APDs….)

BI device dilemma: Physics of Si / SiO2 Interface

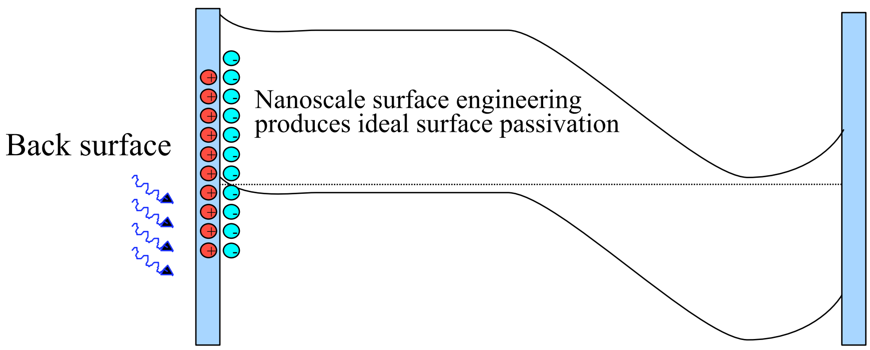
Si/SiO_2 interface charging produces spontaneous "self-bias":
- QE hysteresis: Low and unstable low quantum efficiency.
- Back illuminated silicon detectors are useless without surface passivation.



Using MBE to solve the BI device problem

In the late 1980's, JPL scientists Paula and Frank Grunthaner performed pioneering studies of Si/SiO2 interface and developed low temperature MBE process.

This work enabled epitaxial growth on fully fabricated (complete with metallization)



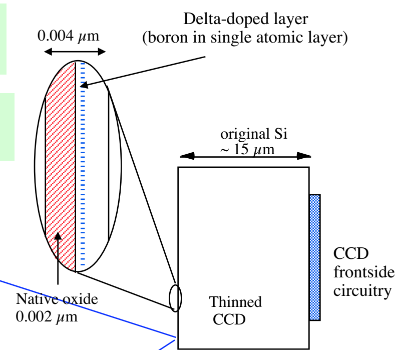
MBE enables atomic level control over charge distribution

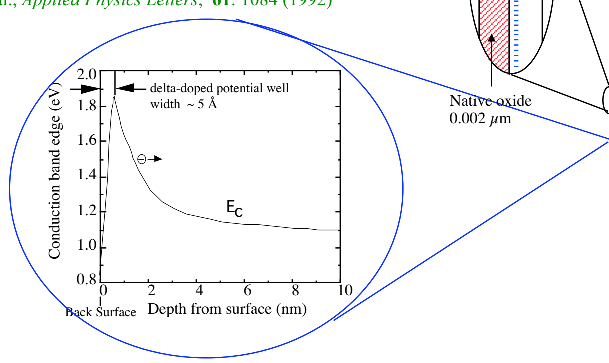
Delta doping technology as the ideal BI solution

Bandstructure engineering for optimum performance
Atomic layer control over device structure

Low temperature process, compatible with VLSI, fully fabricated devices (CCDs, CMOS, PIN arrays)

Hoenk et al., *Applied Physics Letters*, **61**: 1084 (1992)

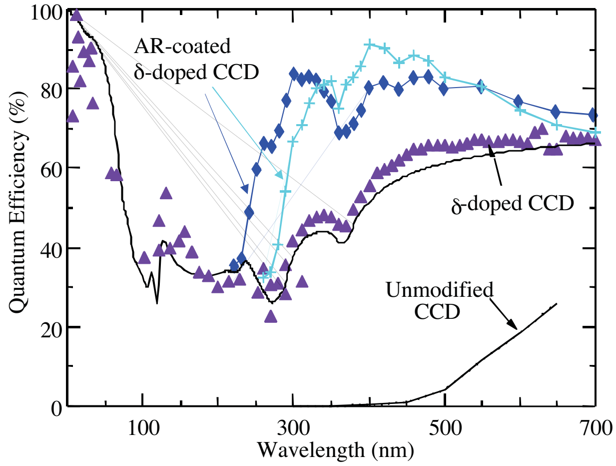




Fully-processed devices are modified using Molecular Beam Epitaxy (MBE)

Sensitivity with Delta doping technology

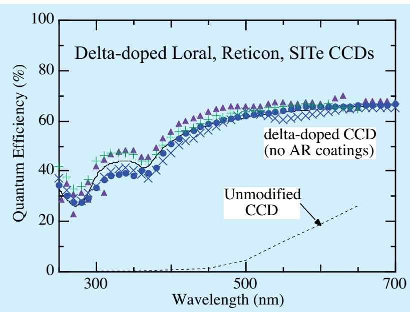
Quantum Efficiency of Delta doped CCDs

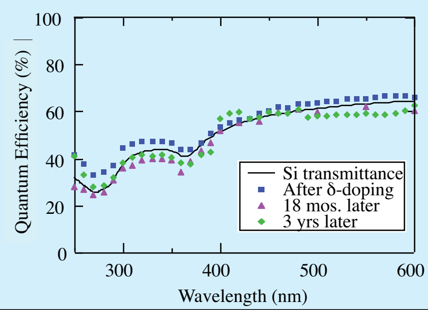


- 100% internal quantum efficiency, uniform, and stable (QY has been removed so maximum QE is 100%).
- Extreme UV measurements were made at SSRL
- Compatible with AR and filter coating: response can be tailored for different regions of the spectrum

Delta-doped CCD Stability and Reproducibility

- 100% internal QE is measured years after the MBE modification of the CCDs
- Reproducible and compatible with different formats and CCD manufacturing processes
- No hysteresis is observed in delta -doped CCDs
- Stable response over several years
- Precision photometric stability measured by the Kepler group

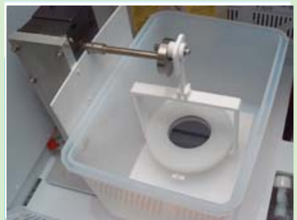




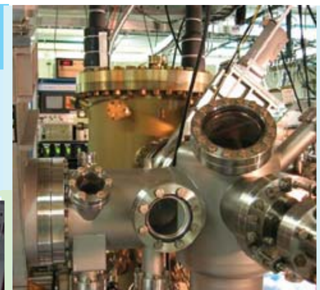
JPL Facilities for End-to-end Post-Fabrication Process

Fully-processed arrays fabricated at outside foundries are obtained.

Bonding: Thermocompression bonding or post MBE bonding is used for achieving flat, robust membranes



Chemical Mechanical Polishing (CMP)



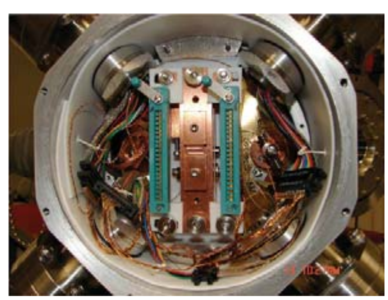
Delta doping MBE is used to grow a delta -doped layer of Si on the backside of fully processed silicon arrays .Response of CCD Si imager is enhanced to the theoretical limit.

Thinning: Excellent quality thinned CMOS and CCDs have been demonstrated.

AR Coatings and Filters Modeling capability and PECVD and sputtering system for deposition of filters and AR coatings

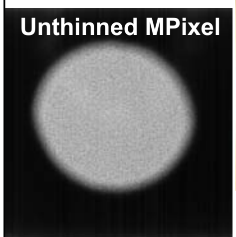
Versatile approach makes it possible to work with various imaging arrays and technologies

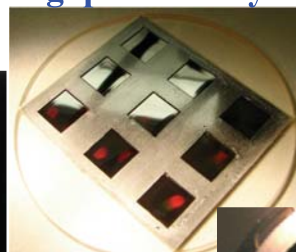
Characterization of Focal Plane Arrays



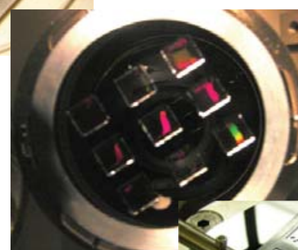
Tungsten and deuterium sources (indexable)
Clean system: minimum electronics circuitry inside
Tight temperature control (±1-2 degrees)
Leach controller
PC-based (control and data collection)
NIST-calibrated photodiode
Previously used for WF/PC and Cassini CCD characterization

Multimegapixel Array Processes and Images



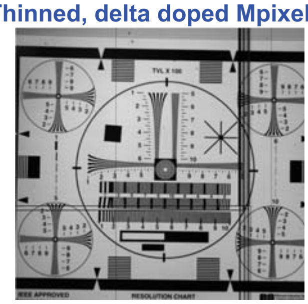


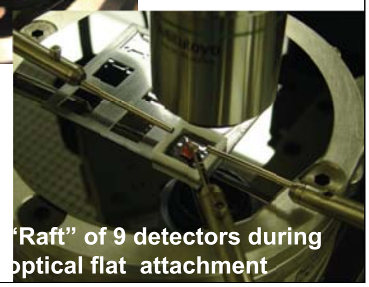
"Raft" of 9 thinned detectors



"Raft" of 9 detectors during delta doping

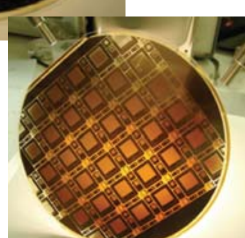
Thinned, delta doped Mpixel

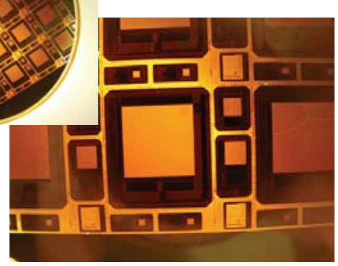


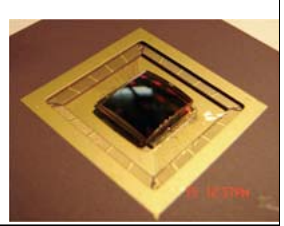


Delta doped Sparse Hybrid Megapixel CMOS Imager

High performance, buttable, high resolution UV/optical, sparse hybrid, vertically integrated arrays

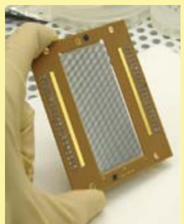




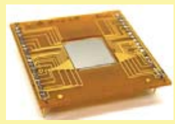


In collaboration with Tom Cunningham, JPL

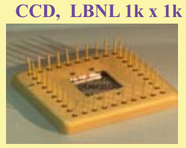
JPL Delta doped CCDs and CMOS Arrays



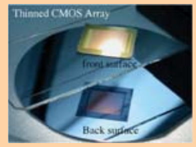
Delta-doped
p-channel CCD
LBNL 2k x 4k

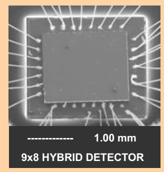


Delta-doped p-channel
CCD, LBNL 1k x 1k

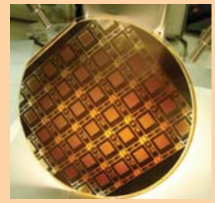


Delta-doped n-channel
CCD with structurally
supported membrane

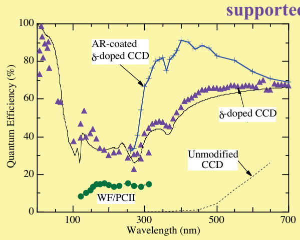




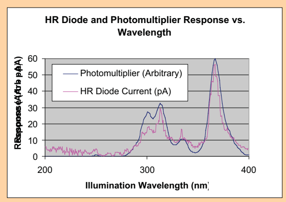
9x8 δ-doped diode array bump
-bonded to APS readout

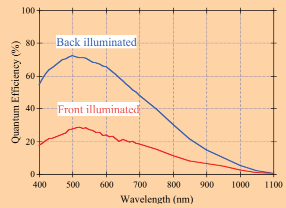


A thinned (6-μm thick) 6” wafer
containing 30 CMOS devices
supported by a quartz wafer.



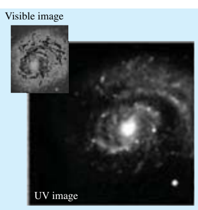
QE of delta doped CCDs
showing 100% internal QE





QE of a 1kx1k delta doped CMOS
-APS array

Sample Field Observations and Independent Evaluations

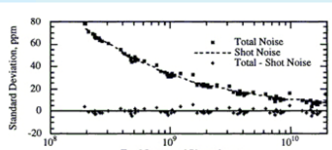


UV and violet image of
Galaxy 6137 at Palomar

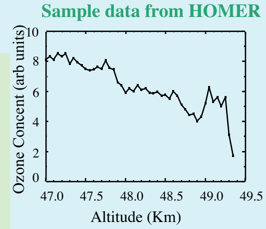
HOMER, a University of Colorado
sounding rocket experiment, used a
UV spectrograph equipped with a delta
doped CCD

A delta doped CCD was flown on a
sounding rocket experiment with Johns
Hopkins University

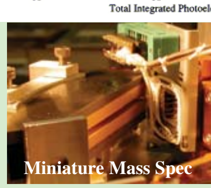
Precision photometry
with CCDs for *Kepler*
was proven by NASA
Ames, Kepler PI group
using a delta doped CCD



Sample data from HOMER



Tested by various groups and
incorporated in instruments
at JPL and other institutions
including NASA ARC,
Caltech, U of Michigan, SwRI,
etc

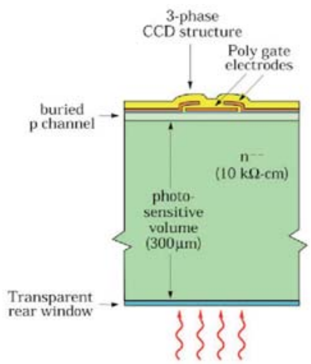


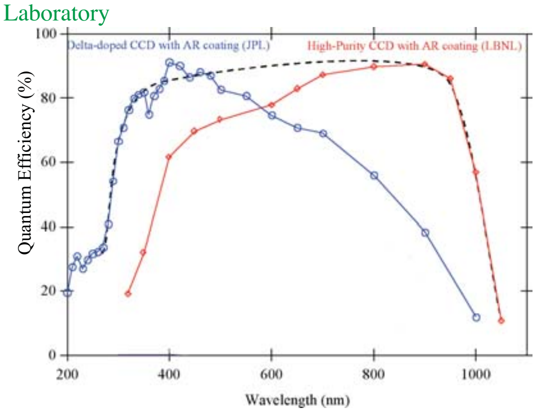
Miniature Mass Spec

Portable
UV camera

P-channel High Purity CCDs and Delta doping

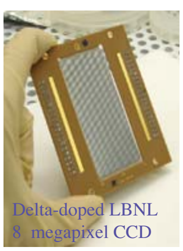
High purity silicon imagers
S. Holland, Lawrence Berkeley National Laboratory

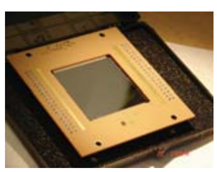




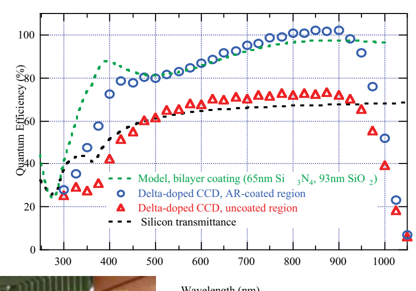
- The transparent electrode plays key role in: QE, dark current, spectral range, and fabrication
- Merge delta doping with high purity array technology to achieve high QE, stability, & broadband response
- Allow streamlined fabrication because of the low temperature process of delta doping

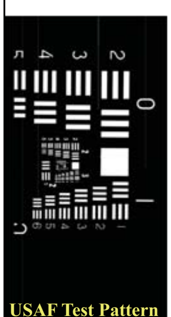
Delta doped Large Format P channel CCDs

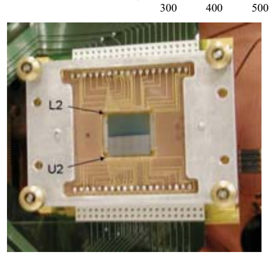

Delta-doped LBNL 8 megapixel CCD


Delta-doped LBNL 10 megapixel CCD

MBE Growth on P-channel High Purity CCDs



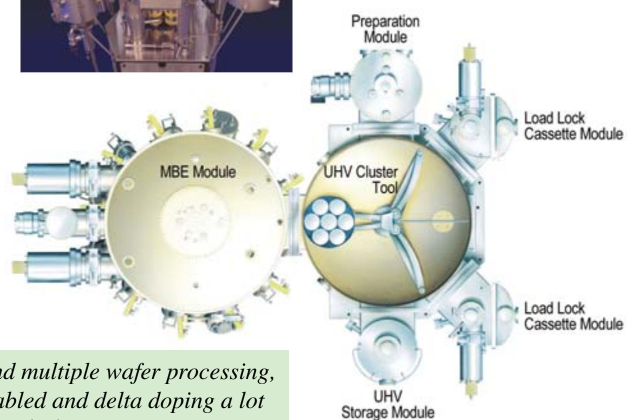

USAF Test Pattern



Collaboration with Steve Holland, Chris Bebek, Natalie Roe, Lawrence Berkeley National Laboratory

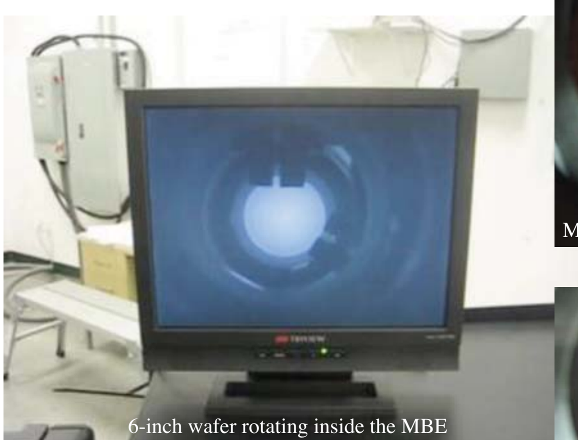
Dark current ~ 1 e-/pixel/hr

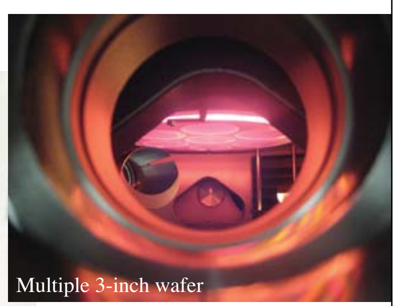
8-inch Wafer Silicon MBE

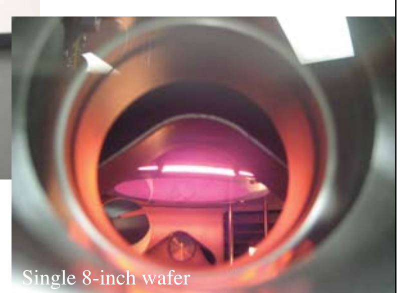


With large size wafer capacity and multiple wafer processing, high throughput processes is enabled and delta doping a lot run can be achieved in short period of time

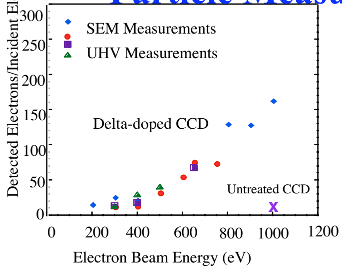
Photograph of Wafers heating inside MBE

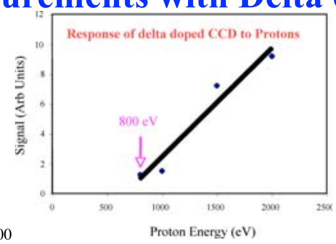


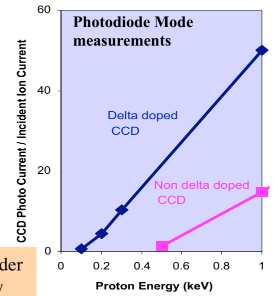




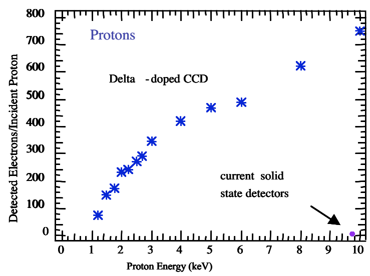
Spinoff:
Particle Measurements with Delta doped Arrays

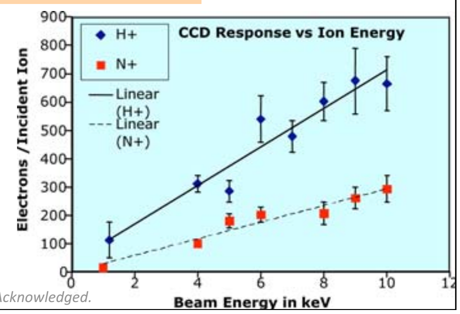






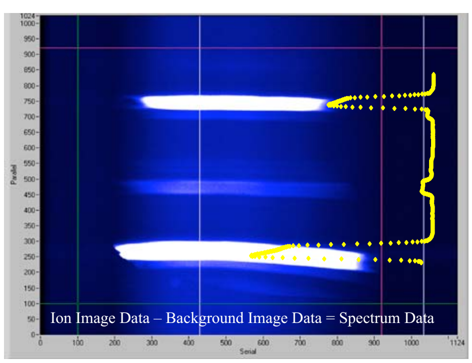
Demonstrated approximately an order of magnitude improvement in low -energy detection threshold





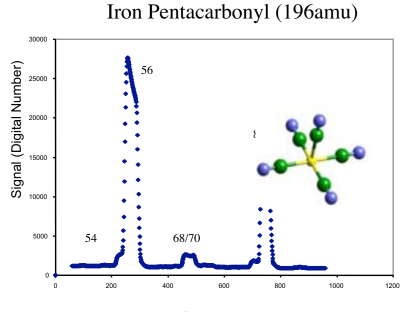
Enabling Compact Instruments:
Delta doped array at focal plane of a miniature mass spec

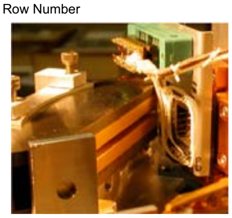
5000-10000dn shown – 60s exposure /80amu centered



Direct Detection of Low Energy Molecular Ions with 700 eV energy!!

Iron Pentacarbonyl (196amu)





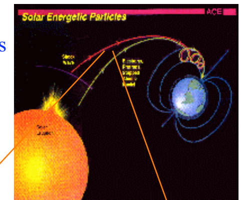
In collaboration with M. Sinha for Miniature Mass Spectrometer

Motivation for Low-energy Particle Detectors

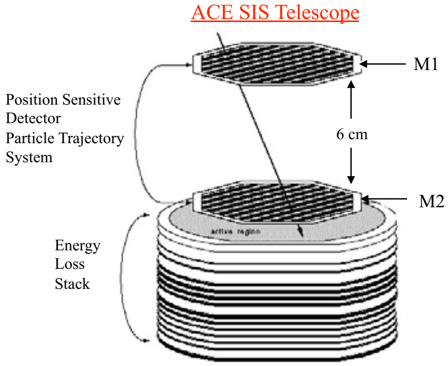
• Compact, low-power, low-mass, and highly-sensitive space plasma instruments are enabled by solid-state low-energy particle detectors

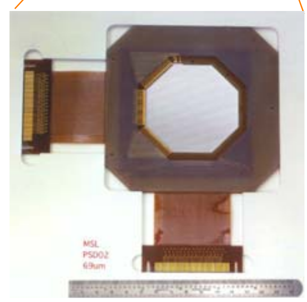
• SOA: MCPs or Telescoping strip detectors:

• E.g., ACE uses a telescope of 2-D arrays for the measurements that can be made by a single, energy-resolving, mid to high-energy particle detector



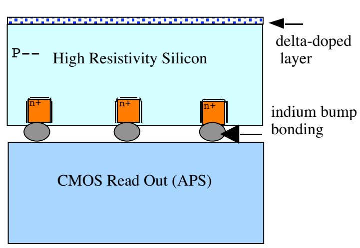
ACE SIS Telescope

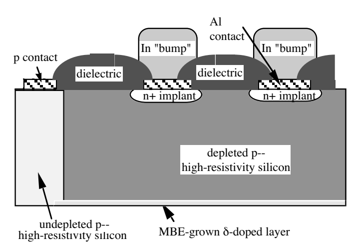


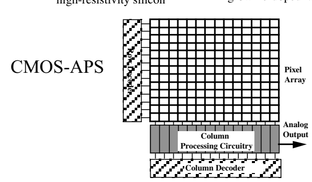


Position Sensitive Detector
M (active region:34 cm^2)

Hybrid Advanced Detector



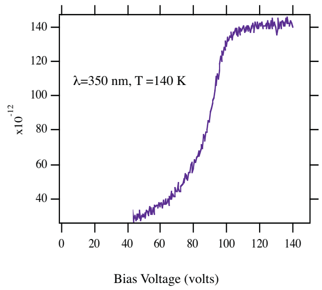


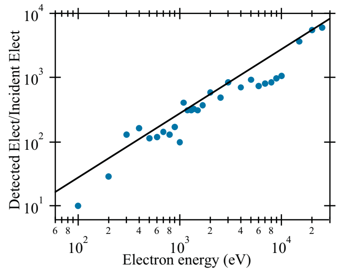


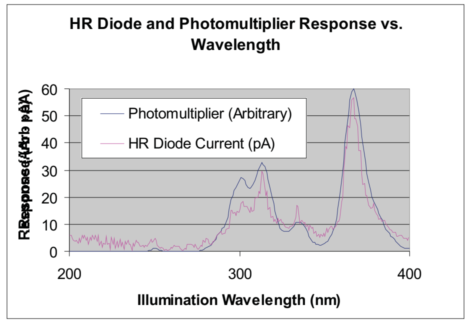
In collaboration with Tom Cunningham, JPL

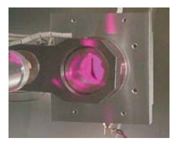
• Direct detection of low-energy ions and electrons (eV-10 keV)
• Rapid acquisition (< 1 ms)
• 2-D array
• Simultaneous ion angular and energy characterization

Electrical, Optical and Particle Detection

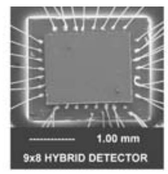








Vacuum-UV testing of δ-doped HP Si diode array

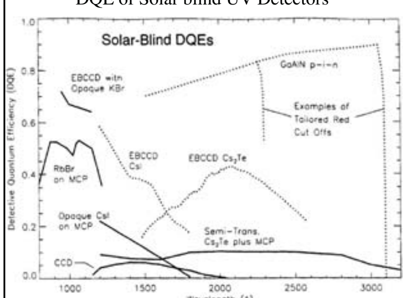


9x8 δ-doped diode array bump -bonded to APS readout

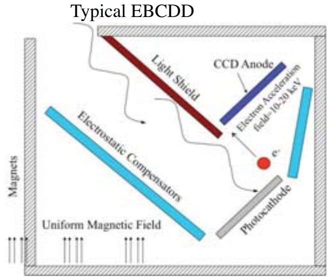
Sensitivity to UV shows removal of the deadlayer
Full depletion demonstrated for 350 nm photons (absorption length ~ 50 Å)
Sensitivity to electrons with a wide energy range demonstrated

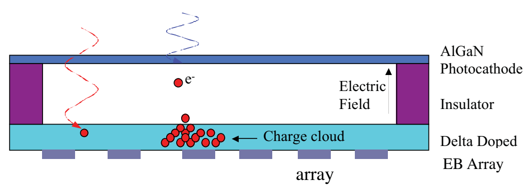
Advanced Electron Bombarded Arrays

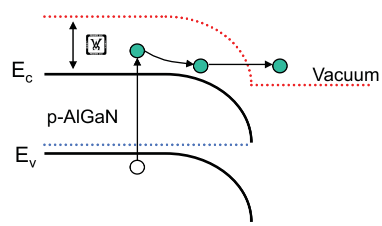
DQE of Solar blind UV Detectors



Typical EBCDD







Under development in collaboration with Professor Chris Martin, Caltech

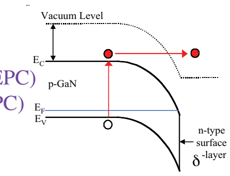
Novel Cs-free Photocathodes

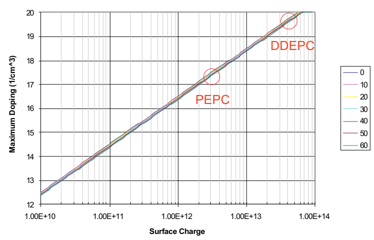
Photocathode

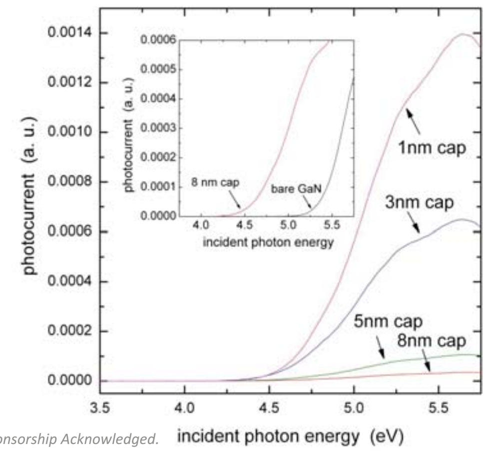
Piezoelectrically-Enhanced Photocathode (PEPC)
or Delta-doped Enhanced Photocathode (DEPC)
are stable with exposure to air

High sensitivity, tailorable, and air stable

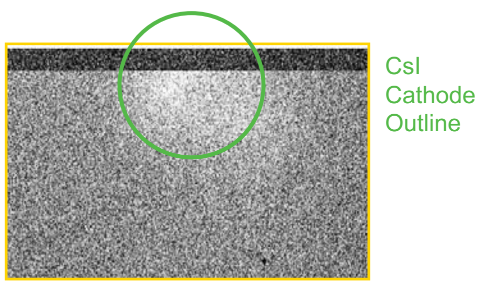
Under development in collaboration with
Prof Chris Martin, Caltech
& Prof. S. Shahedipour SUNY-Albany



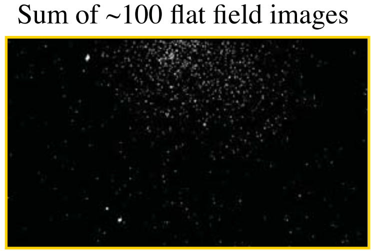




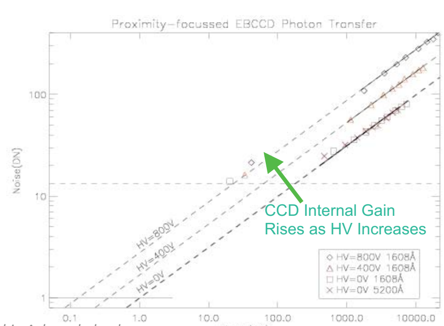
Preliminary Results with CsI Photocathode



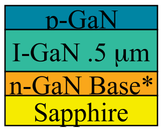
Sum of ~100 flat field images

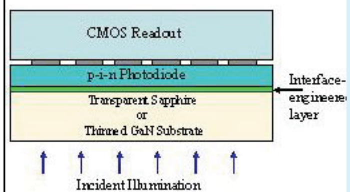


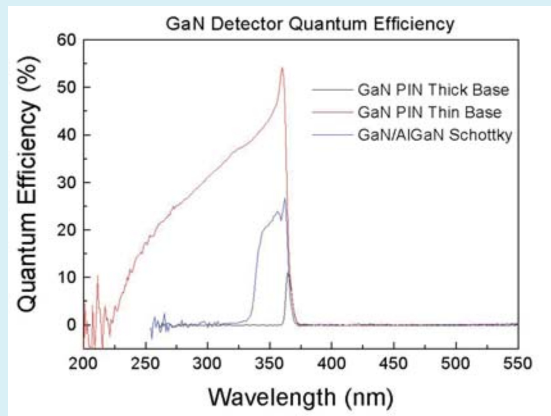
Accumulated events above software threshold corresponding to gain of 60-100.



learning from silicon
III-N FPAs for Solar Blind, UV Imaging



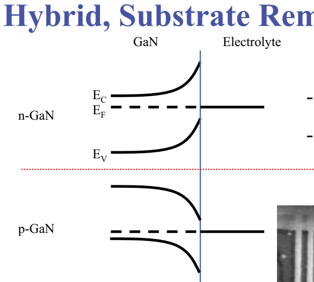




In collaboration Prof. A. Khan, U South Carolina

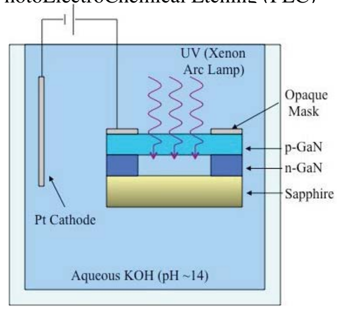
High QE and low leakage can be obtained using epitaxial growth techniques including delta doping for interface engineered devices

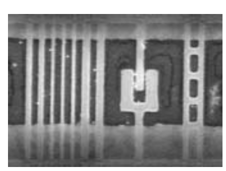
Hybrid, Substrate Removed, and Monolithic III-N FPAs

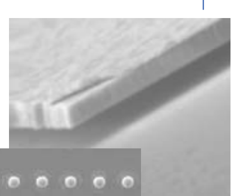


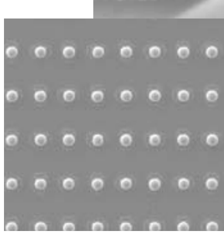
- Bandgap Selective
- Dopant Selective

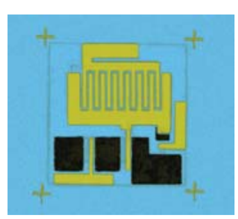
PhotoElectroChemical Etching (PEC)

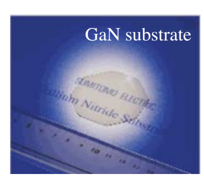






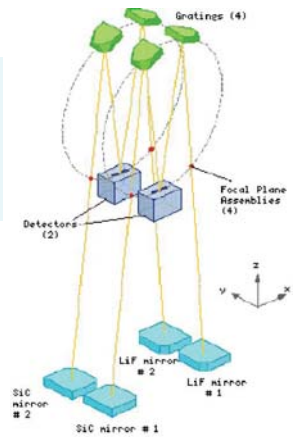






Unexpected spinoff: Curved Focal Plane Arrays

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



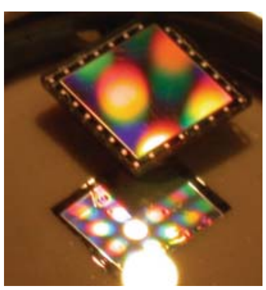
Allowing the focal plane to be curved enables improved:
- Throughput
- Efficiency
- Field of view (factor of 2)
- Image quality (aberration is introduced by each field flattener)
- Simplicity………

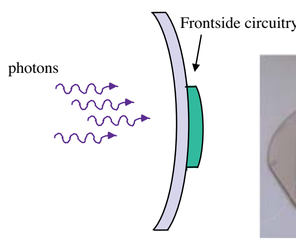
Examples:
Rover Panoramic Camera, a CFPA removes 3-4 elements

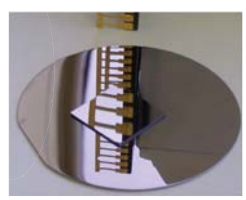
• DoD and commercial applications

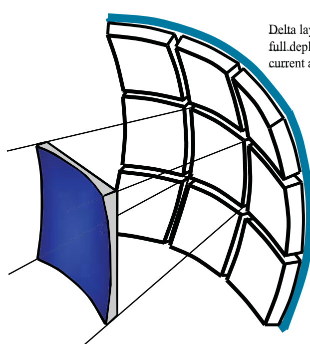
Curved MCPs have been used to enable missions such as FUSE and Rosetta, *however, curved solid state detectors will have clear advantages*

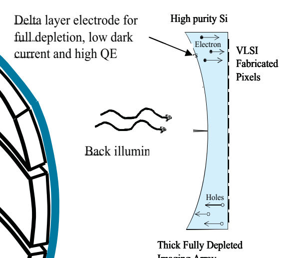
Large Curved Focal Plane Arrays, Spherical Arrays, Cylindrical Arrays



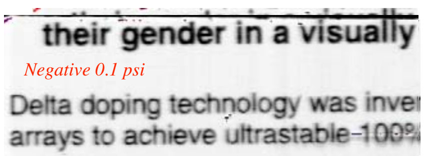


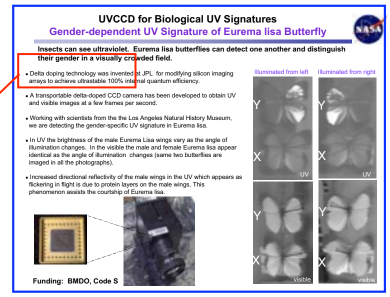


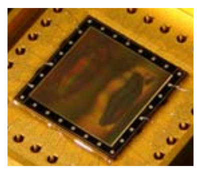




Imaging Results of Thinned CFPA







Summary

Back illumination is key for achieving the highest performance in Silicon imagers

Delta doping was invented at JPL enabling stable and high QE solution for BSI silicon imagers

JPL's BI end-to-end post fabrication processing including thinning, delta doping, AR coating, and packaging is applied to fully fabricated CCD, CMOS, or PIN array wafers

P-type and n-type delta doping has been developed for n-channel and p-channel CCDs

Delta layers are highly conductive and can be used as an electrode for full depletion

New techniques and applications have been developed both in silicon imagers and in other materials and devices. Spinoffs such as curved FPAs have been developed.

Delta doped arrays have been used for charged and neutral particle detection

Similar physics and bandstructure engineering is extended to other materials and devices such as III-N devices for hybrid FPAs and photocathodes

New equipment and infrastructure has been incorporated at JPL enabling both p and n-type delta doping at wafer level with batch processing for high throughput delta doping and quick turn around processing of lot runs

Copyright 2009 California Institute of Technology. Government Sponsorship Acknowledged.

Partial List of References

“HYDROEGEN-TERMINATED SILICON SUBSTRATES FOR LOW-TEMPERATURE MOLECULAR-BEAM EPITAXY”, P.J. Grunthaner, et al., Thin Solid Films, ’89

“Growth of a Delta-Doped Silicon Layer By Molecular-Beam Epitaxy On a Charge-Coupled Device For Reflection-Limited Ultraviolet Quantum Efficiency,” M.E. Hoenk, P.J. Grunthaner, F.J. Grunthaner, M. Fattahi, H.-F. Tseng and R.W. Terhune, *Appl. Phys. Lett.,* **61**, 1084 (1992).

"Delta-doped CCDs for High and Stable in the UV and Visible", S. Nikzad, M.E. Hoenk, P.J. Grunthaner, F.J. Grunthaner, R.W. Terhune, R. Winzenread, M. Fattahi, and H-F Hseng, *Proceedings of the SPIE*, *Instrumentation for Astronomy VIII*, **2198**, 907 (1994).

"Delta-doped CCDs for Enhanced UV Performance", S. Nikzad, M.E. Hoenk, P.J. Grunthaner, F.J. Grunthaner, R.W. Terhune, R. Winzenread, M. Fattahi, and H-F Hseng, *Proceedings of the SPIE, X-ray and UV Detectors*, **2278**, 138 (1994).

“High Precision Photometry with Back-Illuminated CCDs,” J.M. Jenkins, W.J. Barouki, E.W. Dunham, and J.S. McDonald, in ASP Conf. Ser. 119, Planets Beyond our Solar System and Next Generation of Space Missions, Ed. D. Sodarblum, 277-280 (1997).

“Direct Detection and Imaging of Low-energy Electrons with Delta-doped Charge-coupled Devices”, S. Nikzad, Q. Yu, A.L. Smith, T.J. Jones, T.A. Tombrello, and S.T. Elliott, *Applied Physics Letters*, **73**, 3417 (1998).

“Single-event, keV Proton Detection using a Delta-doped Charge-coupled Device”, S. Nikzad, D. Croley, S.T. Elliott, T. Cunningham, W. Proniewicz, G. Murphy, and T.J. Jones, *Applied Physics Letters*, **75**, 2686 (1999).

“Delta doped CCDs with integrated UV coatings”, P. Deelman, S. Nikzad, and Morley Blouke, *Proc. Of SPIE*, **3965**, 462 (2000).

"Ultrastable and Uniform EUV and UV Detectors", S. Nikzad, T.J. Jones, S.T. Elliott, T.J. Cunningham, A.B.C. Walker, H.M. Oluseyi, *Proc. of SPIE*, **4139**, 250 (2000).

“Delta doped CCDs” In *Scientific Charge Coupled Devices*, J.R. Janesick, SPIE Publications, 2001.

“Enhanced quantum efficiency of high purity silicon imaging detectors by ultra-low temperature surface modification using Sb-doping”, J. Blacksberg, M.E. Hoenk, T. Elliott, S. Holland, Shouleh Nikzad, *Applied Physics Letters*, **85** 254101, (2005).

“Simultaneous direct detection of sub keV molecular and atomic ions with a delta-doped CCD at the focal plane of a miniature mass spectrometer”, A.D. Jewell, T.J. Jones, M.P. Sinha, and S. Nikzad, *Applied Physics Letters* **88** 043501 (2006).

“Response of a delta doped charge-coupled device to low energy protons and nitrogen ions”, S.T. Lepri, Shouleh Nikzad, T. Jones, J. Blacksberg, and T.H. Zurbuchen, *Review of Scientific Instruments*, **77**, 053301 (2006).

Partial List of References, cont.

Response of a delta doped charge-coupled device to low energy protons and nitrogen ions”, S.T. Lepri, Shouleh Nikzad, T. Jones, J. Blacksberg, and T.H. Zurbuchen, *Review of Scientific Instruments*, **77**, 053301 (2006).

“Delta-doped, fully depleted, high-purity silicon p-i-n diode arrays for direct detection of 0.1-20 keV electrons”, S. Nikzad, T.J. Cunningham, M.E. Hoenk, R. Ruiz, D. Soules, S.E. Holland, *Applied Physics Letters*, **89** 182114 (2006).

“A Novel Low Voltage Electron Bombarded CCD Readout”, Patrick Morrissey, Steve Kaye, Chris Martin, Shouleh Nikzad, Todd Jones, Michael Hoenk, and Jordana Blacksberg, and Douglas Bell, SPIE proceedings 2006.

“Curved Focal Plane Arrays”, S. Nikzad, M.E. Hoenk, A. Jewell, T.J. Jones, R. Mcmillan, 2003 *IEEE Workshop on Advanced Image Sensors*

“EUV measurements with a delta-doped CCD at Stanford Synchrotron Radiation Laboratory”, Shouleh Nikzad, Tom Elliott, H. Oluseyi, Geoff James, *Optical Engineering, in preparation.*

"Band Anticrossing in Sn_xGe_{1-x}," K. Alberi, J. Blacksberg, L. D. Bell, S. Nikzad, K.M. Yu, O.D. Dubon, W. Walukiewicz,, Physical Review B, 77 073202 (2008).

“Calibration and flight performance of the long-slit imaging dual order spectrograph”, R. Lupu, S. McCandliss, B. Fleming, K. France, Shouleh Nikzad, Astro-Ph, June 10 2008.

“Near-100% quantum efficiency of delta doped large-format UV-NIR silicon imagers”, J. Blacksberg, Shouleh Nikzad, M.E. Hoenk, S.E. Holland, W.F. Colbe, *IEEE Transaction on Electron Devices, **55**, 3402* (2008).

“Curved Focal Plane Arrays: Imaging in spherical and cylindrical shapes with Si and III-N Arrays”, S. Nikzad, T. Jones, M.E. Hoenk et al. *Applied Optics*, to be submitted.

Copyright 2009 California Institute of Technology. Government Sponsorship Acknowledged.