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

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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…
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/SiO₂ 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

Back surface

Nanoscale surface engineering produces ideal surface passivation

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)


Fully-processed devices are modified using Molecular Beam Epitaxy (MBE)
Sensitivity with Delta doping technology

- 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.
- 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

Unthinned MPixel

Thinned, delta doped Mpixel

“Raft” of 9 thinned detectors

“Raft” of 9 detectors during delta doping

“Raft” of 9 detectors during optical flat attachment

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

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

QE of a 1k x 1k delta doped CMOS -APS array

Sample Field Observations and Independent Evaluations

UV and violet image of Galaxy 6137 at Palomar

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

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

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

Sample data from HOMER

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

MBE Growth on P-channel High Purity CCDs

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.

**Spinoff:**

**Particle Measurements with Delta doped Arrays**

- SEM Measurements
- UHV Measurements

- Delta-doped CCD
- Untreated CCD

**Delta-doped CCD**

**Response of delta doped CCD to Protons**

- 800 eV

**Photodiode Mode measurements**

- Delta doped CCD
- Non delta doped CCD

**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

Hybrid Advanced Detector

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

In collaboration with Tom Cunningham, JPL
Electrical, Optical and Particle Detection

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

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

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**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

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

In collaboration Prof. A. Khan, U South Carolina

**Unexpected spinoff:**

**Curved Focal Plane Arrays**

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.

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**Large Curved Focal Plane Arrays, Spherical Arrays, Cylindrical Arrays**

Delta doping technology was invented at JPL for modifying silicon imaging arrays to achieve ultrastable 100% internal quantum efficiency. A transportable delta-doped CCD camera has been developed to obtain UV and visible images at a few frames per second. Working with scientists from the Los Angeles Natural History Museum, we are detecting the gender-specific UV signature in Eurema lisa. In UV the brightness of the male Eurema Lisa wings vary as the angle of illumination changes. In the visible the male and female Eurema lisa appear identical as the angle of illumination changes (same two butterflies are imaged in all the photographs). Increased directional reflectivity of the male wings in the UV which appears as flickering in flight is due to protein layers on the male wings. This phenomenon assists the courtship of Eurema lisa.

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.
Partial List of References


