Delta doping Technology for UV Photon Counting Detector Arrays

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Outline

- Motivation – UV photon counting detectors
- Silicon surface physics and back surface passivation
- Delta-doping – nanostructured silicon by MBE
- Delta-doping with high throughput and high yield
Detector Requirement:
Six cylindrically-curved ultraviolet photon counting detector array

Strategy:
Combine delta doping with avalanche gain CCDs and AR coatings, along with Curved FPA technology
Low-energy Molecular Ion Detection

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

Ion Image Data – Background Image Data = Spectrum Data

Iron Pentacarbonyl (196amu)
Silicon Imaging Arrays

“CCDs were born in the Si-SiO₂ revolution and created their own revolution in widespread imaging device applications.”
-- George Smith, co-inventor of CCDs* and Nobel Laureate


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Vertebrates and mollusks developed the camera eye independently.

*Vertebrate retina is less efficient than Mollusk retina.*
Silicon Imager Architectures: CCD vs. CMOS

Charge-coupled Device (CCD)
Serial readout device with charge transfer and one (or few) readout amplifiers.

CMOS Imaging Array
Parallel readout with few charge transfers and one readout amplifier per pixel.

CMOS APS

Scientific CMOS imagers are catching up with CCDs
– Jim Janesick, 2009
Thinning and back illumination can overcome limitations of silicon detectors:

- Quantum efficiency
- Fill factor
- Spectral range (especially in the blue-UV range)
UV Photon Absorption in Silicon

- High purity silicon detector thickness
- Conventional electrode thickness
- Shallow ion implant

Absorption Length (nm)

Wavelength (nm)

Delta-doping thickness ~1 nm
Between Physics and Chemistry

**Si-SiO₂ Surface States and Charging mechanisms**

- **Fast states / surface traps** – *QE hysteresis*
  - Acceptor-like – Neutral when empty, negative when filled
  - Donor-like – Positive when empty, neutral when filled
- **Slow states**
- **Surface charging**
  - *e.g.*, oxygen ions generated in UV flood
- **Fixed oxide charge**
  - Radiation damage
  - *e.g.*, positive charge from exposure to ionizing radiation (including UV light) flattens bands

**Surface Passivation**

- Reduce surface state density
- Control surface potential

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In 1984, *quantum efficiency hysteresis* was discovered during thermal vacuum testing of Wide Field Camera (WFPC-1).

**Quantum efficiency hysteresis** – CCD response depends on prior illumination history
- Unacceptable – Hubble needs stability to 1% over 30 days…
- Passivation of surface defects is necessary to solve the problem.
During the mid- to late-1980’s, WFPC-1 was plagued with stability problems. To help solve this problem, JPL formed a tiger team, which included MDL scientists. Hubble launched in 1990 with WFPC-1 on board. NASA installed WFPC-2 in 1993, with front-illuminated, lumogen-coated CCDs. In 1992, JPL’s Microdevices Laboratory demonstrated the first delta-doped CCD.
Quantum Efficiency Hysteresis in WF/PC 1 & 2

WF/PC2 (1992-2009) Front illuminated Loral CCDs with lumogen


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The Evolution of CCD Surface Passivation on Hubble

- **Unpassivated**
  - Doping by controlled thinning (*early WF/PC 1*)

- **Surface charging**
  - UV flood (*late WF/PC 1*)
  - Platinum flash gate (*WF/PC 2 – never flown*)
  - Chemisorption charging (*ACS HRC*)

- **Unthinned CCD**
  - Front-illuminated with phosphor (*WF/PC 2*)

- **Surface doping**
  - Ion implantation (*WFC3*)
Platinum Flash Gate

High work function metal induces surface charge
- Vulnerable to environmental contaminants (notably hydrogen)
- Encapsulation required for stability
- Passivation layer doubles as antireflection coating

Unlike MBE, surface charging methods provide poor control to environmental changes. Not suitable for high speed readout
Chemisorption Charging

Metal catalyst binds $O_2^-$ ions on the surface. Encapsulation / AR coating stabilizes the charge.

“Chemisorption charging can be a permanent charging process if there are no other processes which either chemically react to remove the oxygen or contribute significant positive charge to produce a net positive charge on the surface.”

Ion Implantation and Laser Anneal

Doping the surface introduces fixed charge into the silicon lattice

- Dopant profiles are generally broad – thinner is better, but problems with traps
- Damaged lattice creates traps & dark current
- “Brick wall” pattern in flat field images from laser anneal process

Hubble’s Wide Field Camera 3 uses ion-implanted CCDs.
Quantum efficiency hysteresis is still a problem.

“The WFPC2 CCDs are **thick, front-side illuminated devices** made by Loral Aerospace. They support multi-pinned phase (MPP) operation which eliminates **quantum efficiency hysteresis**. They have a Lumogen phosphor coating to give UV sensitivity.”

http://www.stsci.edu/instruments/wfpc2/Wfpc2_hand4/ch1_introduction2.html
Quantum Efficiency Hysteresis in WFC3

Wide Field Camera 3

- Instabilities on the order of a few percent
- Mitigated by on-orbit flooding with visible light to fill surface traps


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Delta doping

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)

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Delta doping produces ideal surface passivation in back-illuminated CCDs.
Electric Field

- Delta-doped
- MBE
- Ultrashallow ion implant
- Ion implant
Quantized States in Delta-doped Detectors

![Graph showing energy levels vs depth with labeled bands and levels.]

- **Quantized electronic "ground state"**
- **Conduction band (bulk)**
- **Quantized valence band**
- **Valence band (bulk)**
- **Fermi level**

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Quantum Confinement in Delta-doped Surface

• Quantized states in delta-doped surface
  – Holes form 2DEG with quantized subbands
    • High conductivity surface
    • Quantum-confinement enhanced potential and fields
      – Strongly peaked potential at delta-layer
  – Electrons
    • Width of potential well ~1.5nm
    • Electrons isolated from surface by high fields
    • Quantized subbands with few quasi-bound states

• Passivation by Delta-doping
  – MBE creates abrupt interfaces, electric field ~10^7 V/cm
  – Buried electronic “surface” confines electrons to bulk
  – Surface dark current suppressed by quantum confinement
Quantum Efficiency of Delta-doped CCDs

![Graph showing quantum efficiency vs. wavelength for Delta-doped CCDs with and without anti-reflective coating, and a front-illuminated CCD.]
Delta-doped CCD Stability and Reproducibility

- Near 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
Uniformity

E2v CCD ion implant/laser anneal

Delta doped CCD
Delta doped CCDs and CMOS Arrays

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

Delta-doped n-channel CCD with structurally supported membrane

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

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

QE of delta doped CCDs showing 100% internal QE

QE of a 1kx1k delta doped CMOS-APS array
Fully-processed arrays fabricated at outside foundries are obtained.

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

**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.

**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.

Versatile approach makes it possible to work with various imaging arrays and technologies.
AR Coating Systems

Deposition uniformity with A330-XP (5)

Source Cluster Flange featuring in-situ tilt focused on rotating, 6.0" diameter, Si Wafer.

SiO(2) deposition shows +/- 1.17% uniformity.
Full Wafer Processing with 8” MBE

Raft of 9 thinned CMOS Imagers
Mounted in 3” MBE

Thinned 6” wafer with 32 CMOS Imagers

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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.
MBE Installation in JPL’s Microdevices Laboratory

MBE after Initial Hook-up at JPL

MBE under bake
Photographs of wafers heating inside MBE

Multiple 3-inch wafer

6-inch wafer rotating inside the MBE

Single 8-inch wafer

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Conclusions

• Delta-doped single photon detectors for UV astronomy
  **ISTOS Mission**: Chris Martin, David Shimonovich, Patrick Morrissey, Shouleh Nikzad

• Silicon surface physics and passivation
  *Requires atomic scale control of dopant profile*

• Delta-doping
  *Nanostructured surface by MBE*
  *Strong electric field (107 V/cm) and quantum exclusion*
  *Proven performance*

• Future
  Delta-doped L3CCDs for UV photon counting
  Delta-doping at wafer level for high yield and throughput