Solid State Ultraviolet Detectors

California Institute of Technology

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Sponsored by NASA Codes S and R

Workshop on
Innovative Designs for the Next Large Aperture Optical/UV Telescope
Space Telescope Science Institute, Baltimore, MD
April 11, 2003

Outline

UV Imaging Technology

Photoemissive, electron detection

Solid State Semiconductor Devices

Silicon Imaging Technology for UV/Optical

CMOS, CCD, high purity Si, hybrid, monolithic

QE Enhancement

Wide Bandgap materials and detectors

Silicon Carbide

Diamond

GaN

GaN and alloys for Solar-blind UV imaging

General Research

Focal Plane Arrays

Photocathodes

Status of the Technology

JPL Silicon-based Imaging Technology

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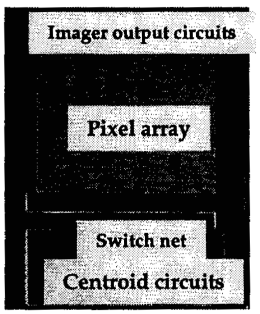
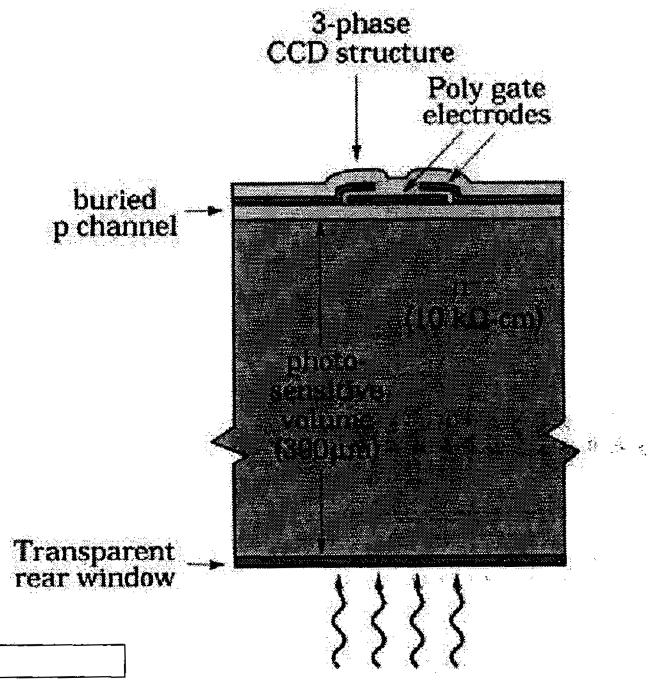
- Enormous investment has been made in the silicon imaging technology
- Innovative designs are developed in CMOS, high purity silicon arrays, and CCDs

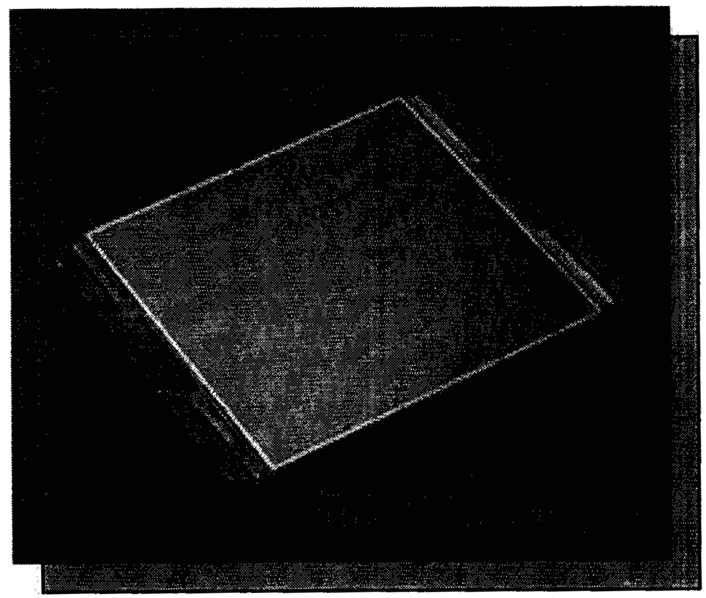


CMOS Imager with on-chip centroiding

(JPL, CMOS group)

High resistivity silicon imagers
Monolithic or Hybrid, LBNL





Advanced CCDs

- To achieve the highest quantum efficiency (and fill factor) back-illumination with proper surface treatment is required

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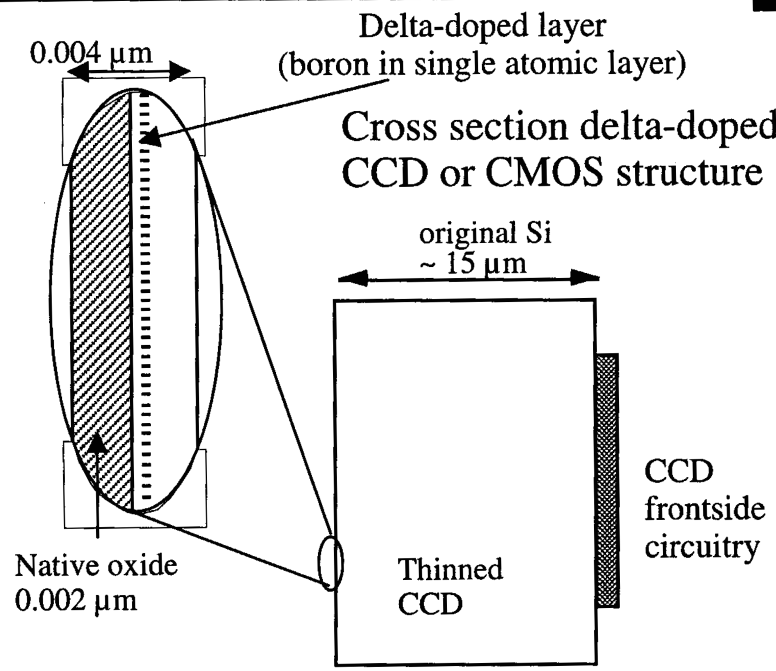
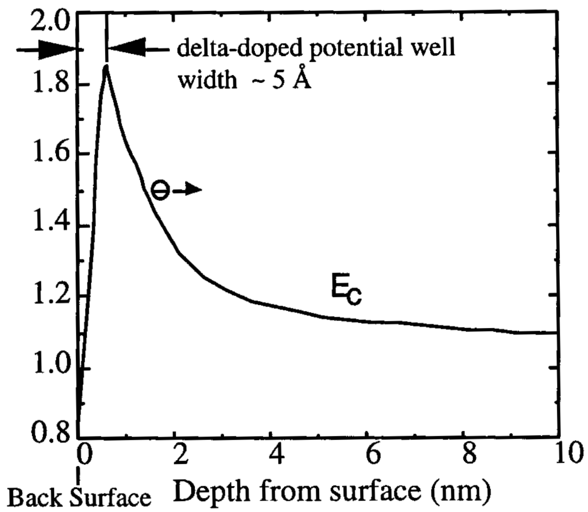
Delta doping

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

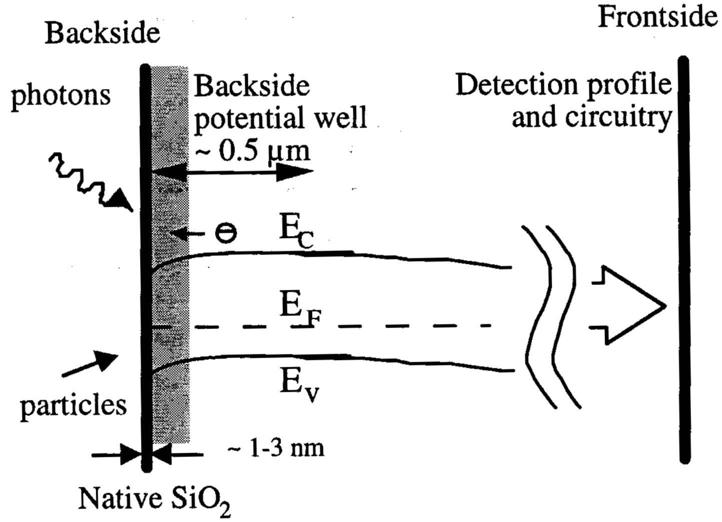
Cross section delta-doped CCD or CMOS structure



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



Band Structure of an untreated Back-illuminated Si Imager



Unfavorable bandbending prevents detection of low-energy particles as well as UV and EUV photons

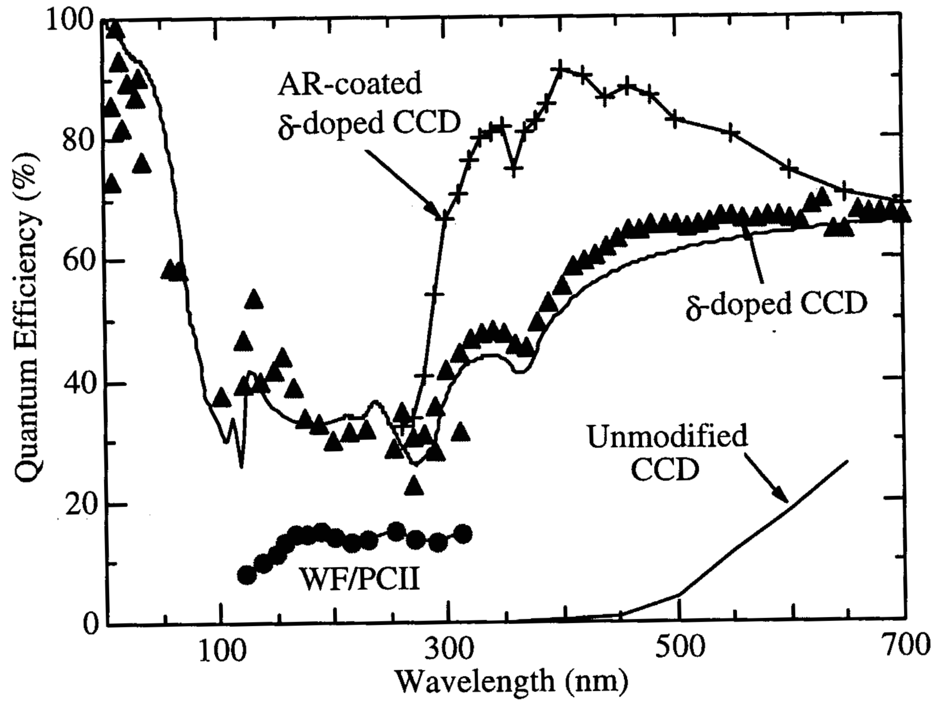
Quantum Efficiency

Back-illuminated devices can be treated by "delta-doping", where molecular beam epitaxy is used to grow a highly-doped capping electrode layer that is only a few atomic layers thick.

100% internal quantum efficiency is achieved.

The response is highly uniform, stable, and exhibits no hystheresis

No post process anneal is required



Quantum Efficiency of Bare (no AR coating) Delta doped CCD--purple triangles

QE with AR coating for 300-400 nm region

High-purity Silicon Imaging Technologies

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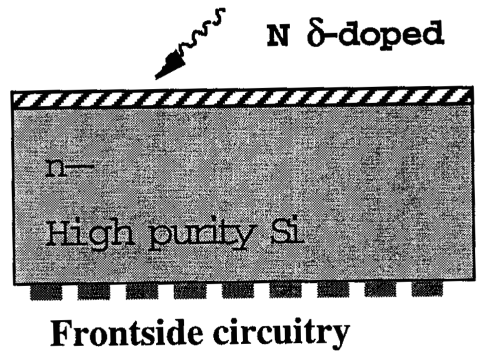
- Combines high purity and delta- doping technologies monolithically or in hybrid mode
- P-channel device, less prone to radiation damage
- Broad range of response (soft x rays to near IR)
- Fully depleted and no thinning requirement
- Low power, Rapid acquisition (hybrid)
- Low-temperature MBE process provides simplification of existing fabrication process



Collaboration with:
S. Holland and M. Levi at Lawrence Berkeley National Laboratory (SNAP)

High purity silicon PIN arrays, n-type & p-type

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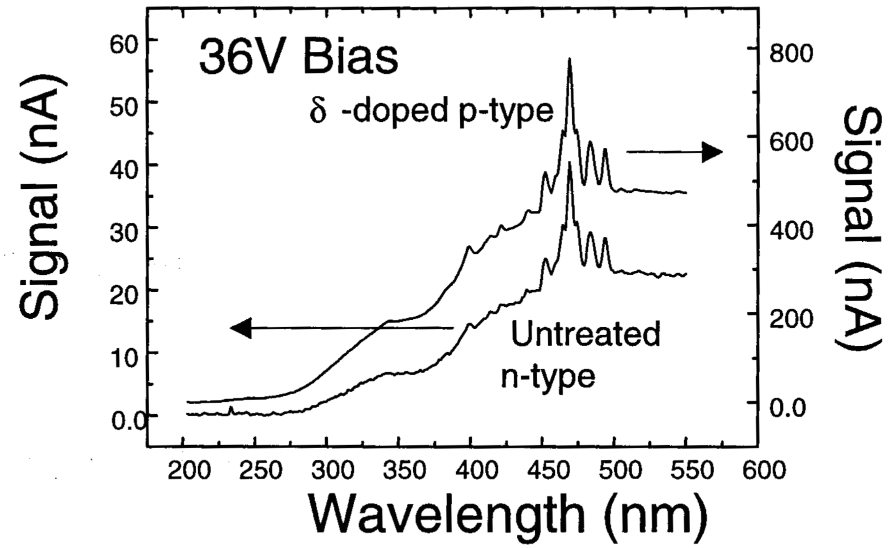
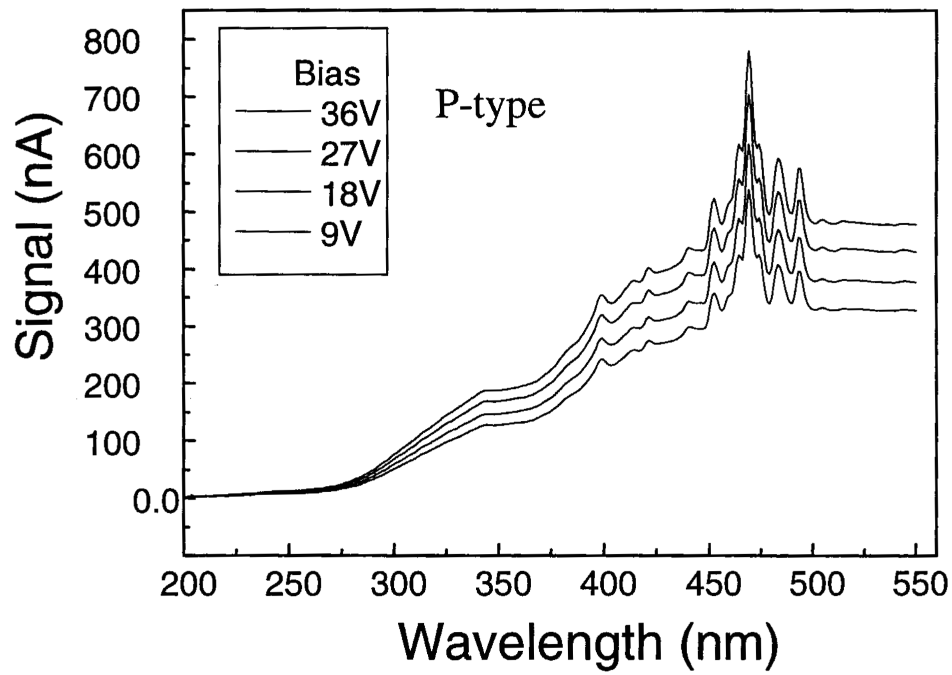
Optical and electrical measurements of p-type and n-type PIN diode arrays





These measurement show that n-type devices require backside treatment

Hybrid Advanced Detector

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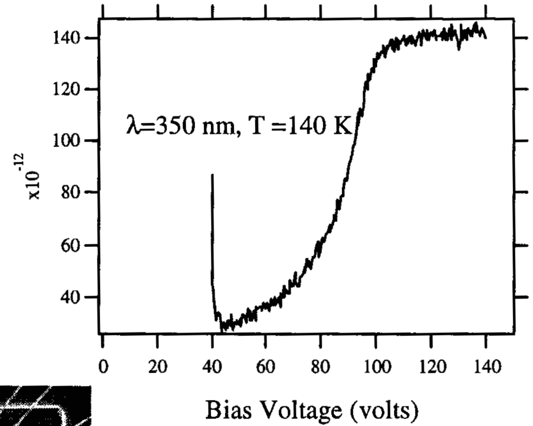
Vacuum-UV testing of δ-doped high-res Si diode array

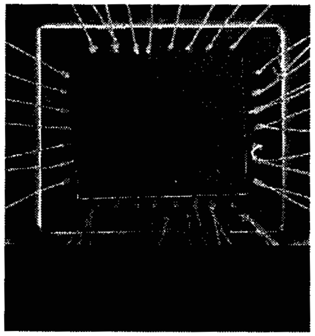


Features

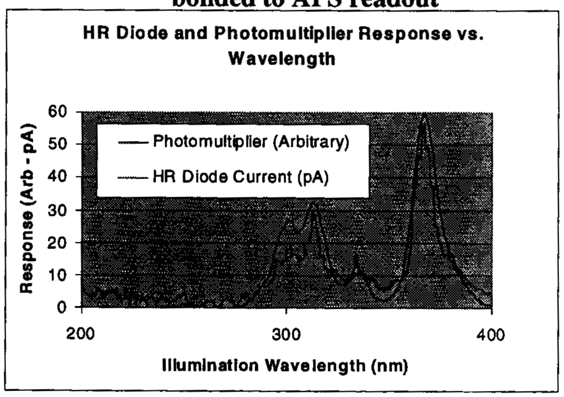
High resistivity silicon technology inherently sensitive to wide energy range for photons while leveraging the mature silicon technology

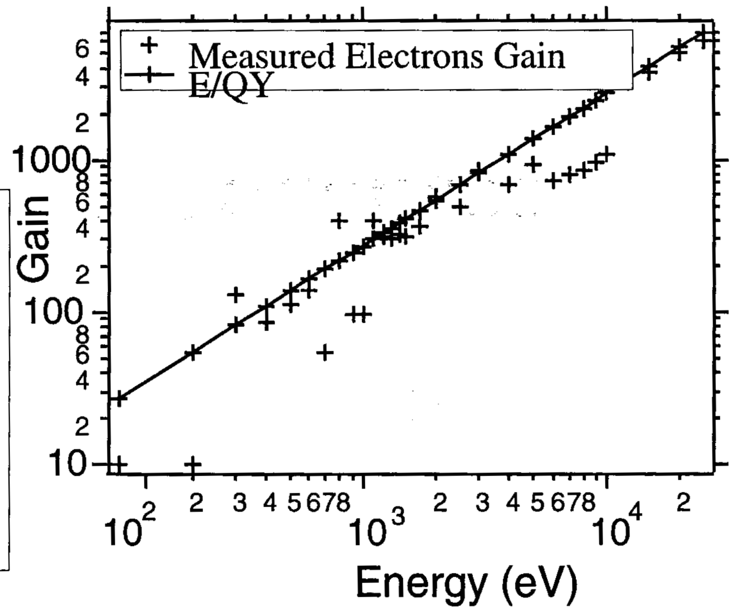
Rapid energy distribution acquisition (< 1 ms).
2D array allows full velocity distribution measurement
Simultaneous ion angular and energy characterization

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

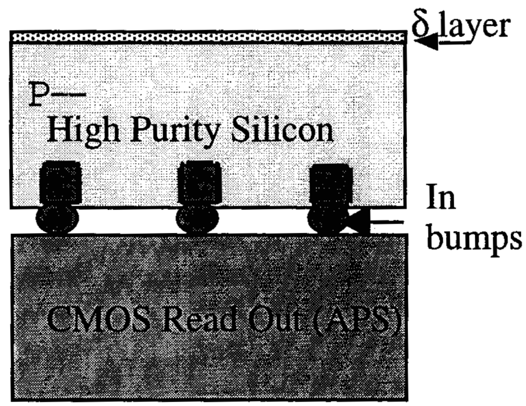


9x8 δ-doped diode array bump-bonded to APS readout

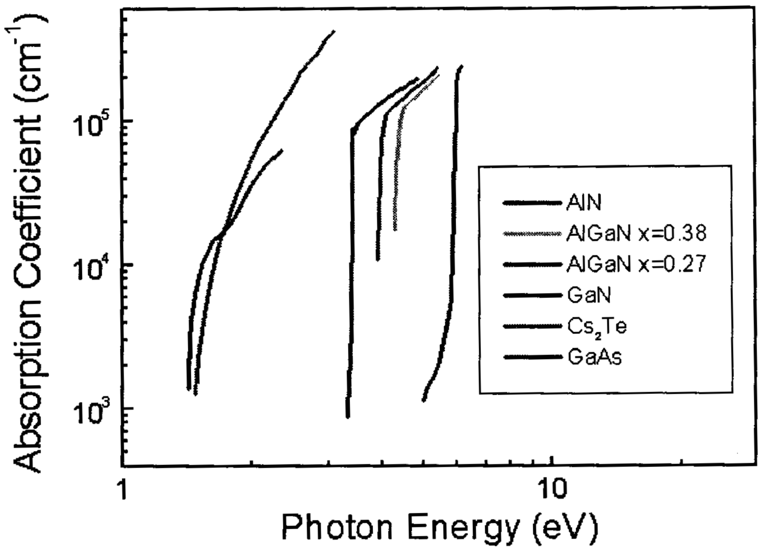


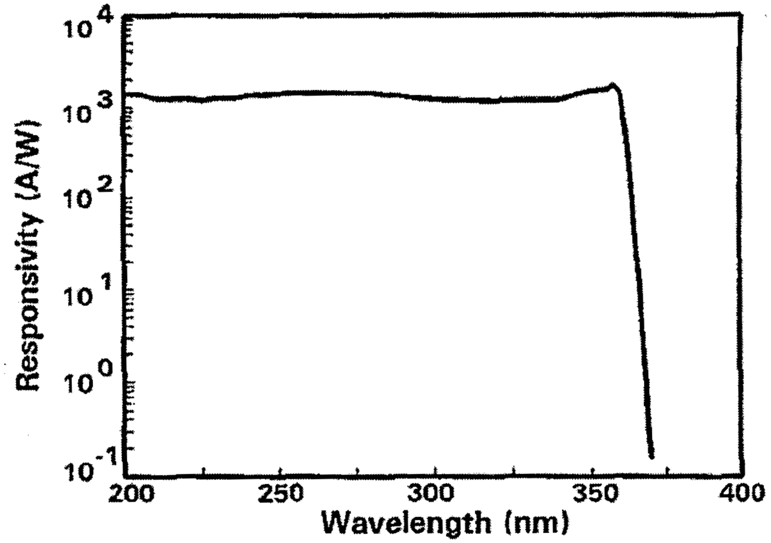


Hybrid Advanced Detector



III-N UV Detectors





- Extremely good intrinsic visible rejection
- Thermally and chemically stable
- Radiation tolerant, higher temperature operation
- Tunable energy response (bandgap engineering)

A bit of History

GaN and its alloys have been of interest for quite some time

~1970's

Material improvement

Amano, H. et al. Applied Physics Letters, 48 353 (1986)

p-type doping

Amano, H. et al. Japanese Journal of Applied Physics, 28, L2112 (1989)

First Detectors were demonstrated

*Khan, et al Applied Physics Letters, **60,** 2917 (1992)*

Arrays began to be realized-- QE > 50% at zero bias

GSFC, MSM arrays, Huang, et. al. , Space Tech. And Applications International Forum-1998
*NCSU, 32 x 32 PIN array, J.D. Brown, et. al. MRS Internet J. Nitride Semiconductor Res. **4**, (1999)*
BAE system, M. Reine, et. al.Meeting of the Military Sensing Symposium, 2003, ...

DoD has funded the majority of work in III-nitrides growth and detector development

NASA's needs are different from DoD and DoD's interest in III-nitrides recently is focused on emitters and RF amplifiers

Quantum Efficiency/Visible rejection

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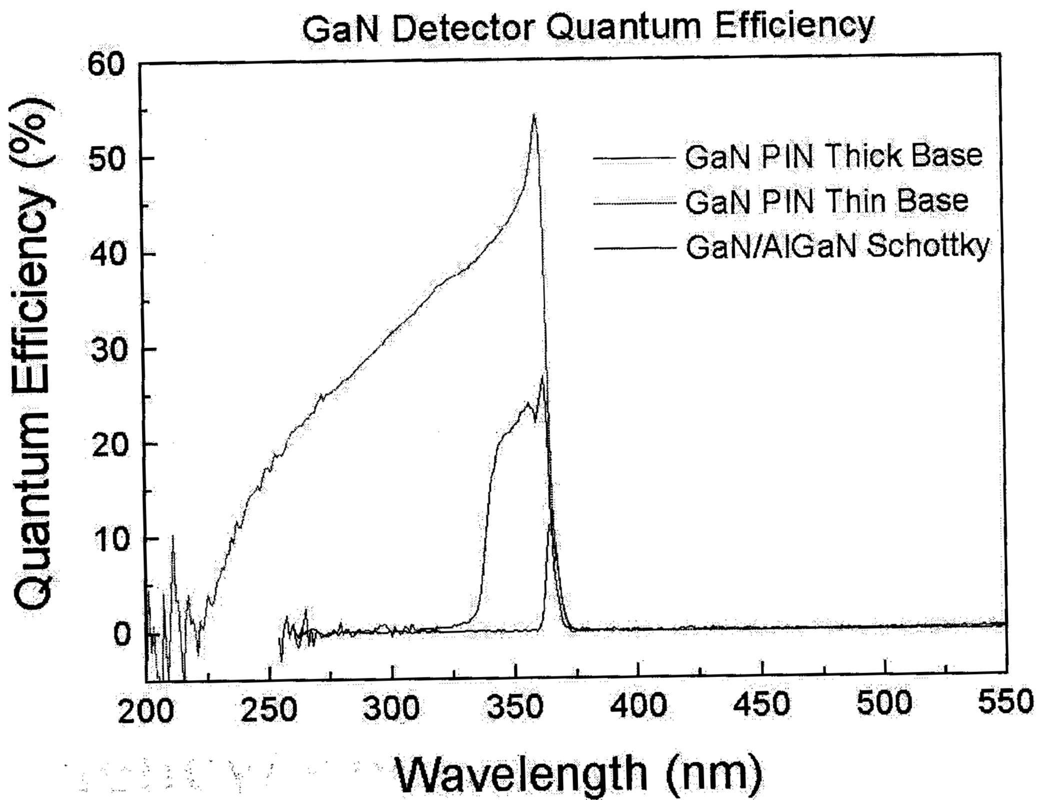
Quantum efficiency
peak at near bandgap ~55%

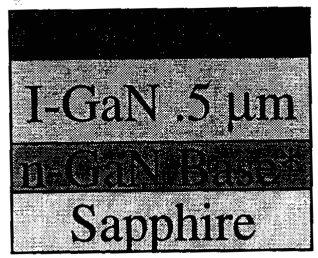
Visible rejection ratio > 5 orders of magnitude

Thin buffer (.1µm) allows response at short wavelength
Thick buffer-> limited near band gap response

AlGaN absorption region->
Less abrupt absorption edge



Thicker intrinsic region + larger Vbi-> higher PIN response observed
.5µm absorption region for PIN,
.3µm absorption region for Schottkys



*Thick Base ~0.6 µm
Thin Base ~0.1 µm

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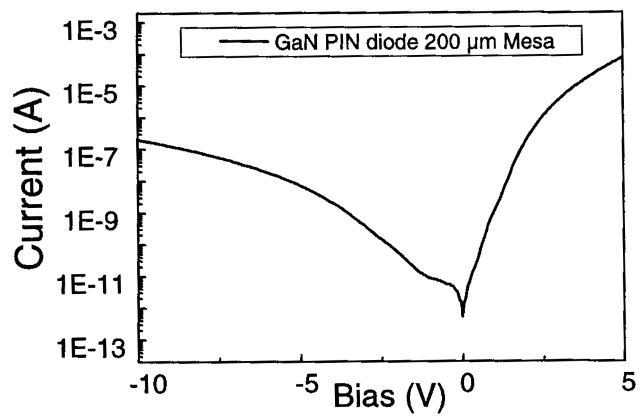
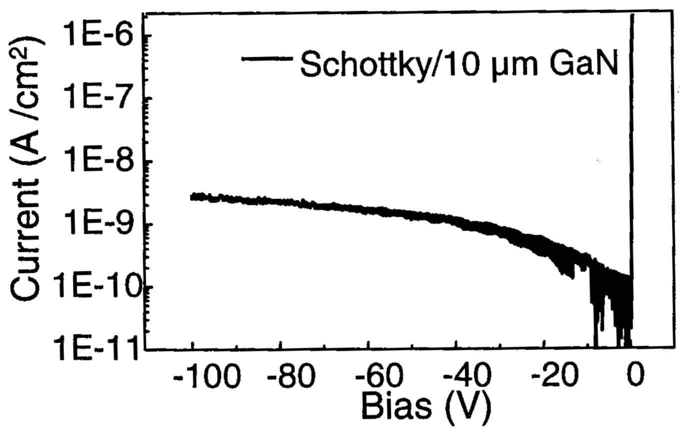
High-Performance far UV and UV Detector Hurdles

Standard Si readouts measure current
High leakage swamps signal
even at low bias

Some suppliers now work on special readout, e.g, BAE Systems



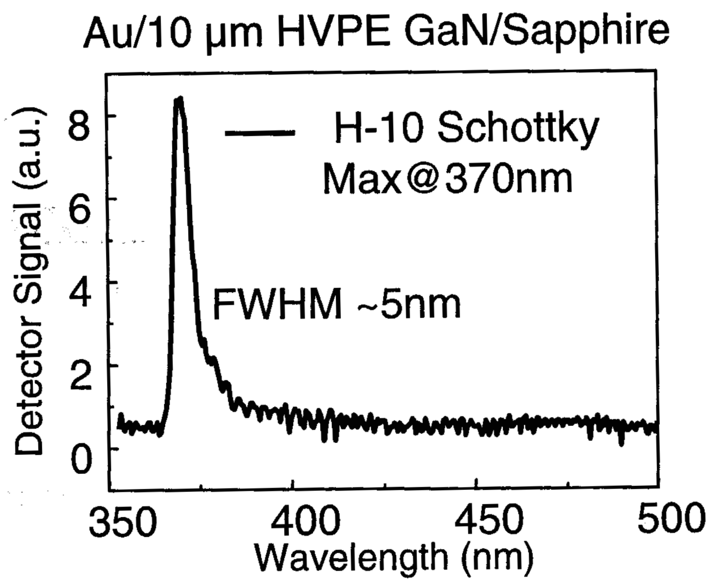


Thick dead layer near GaN/Sapphire interface leads to low far UV sensitivity

Sapphire->200nm cutoff, How to get FUV Substrates
GaN substrate now available

Hybridization for large format arrays

Readout for GaN (Leakage!)



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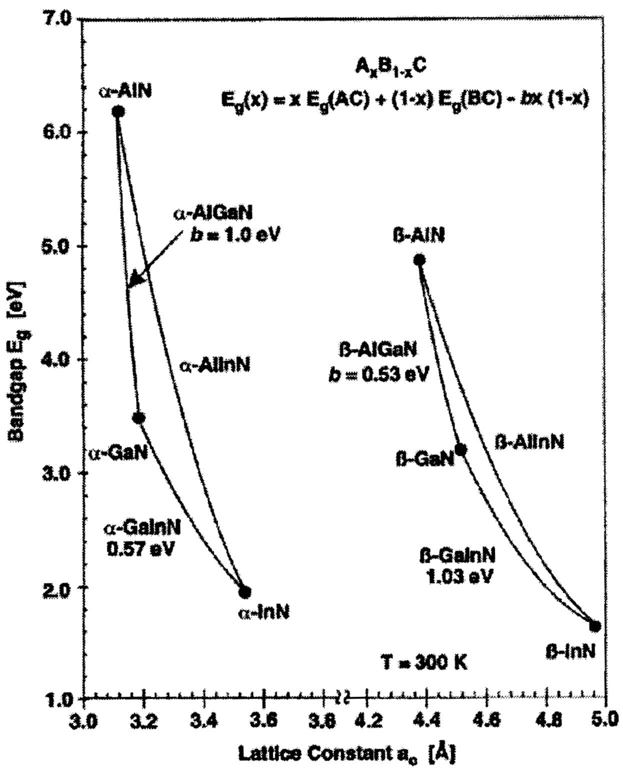
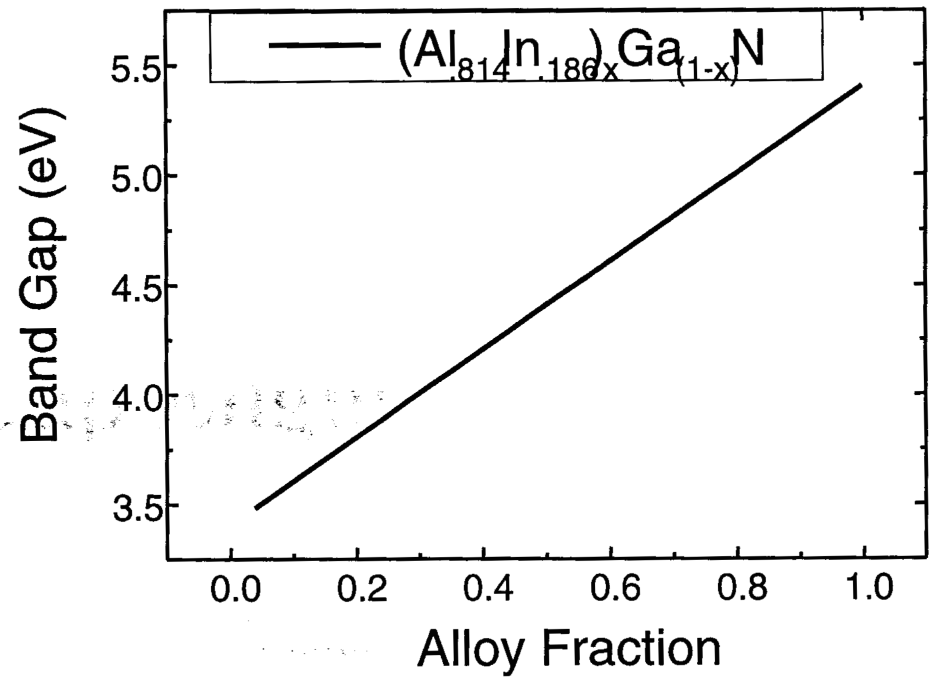
Band Gap Engineering

NASA

Reduces dislocations at optical window/absorption region interface
Reduces leakage current
Increases breakdown voltage

Quaternary AlInGaN
Lattice match to GaN
Band gap (3.4-5.4eV)



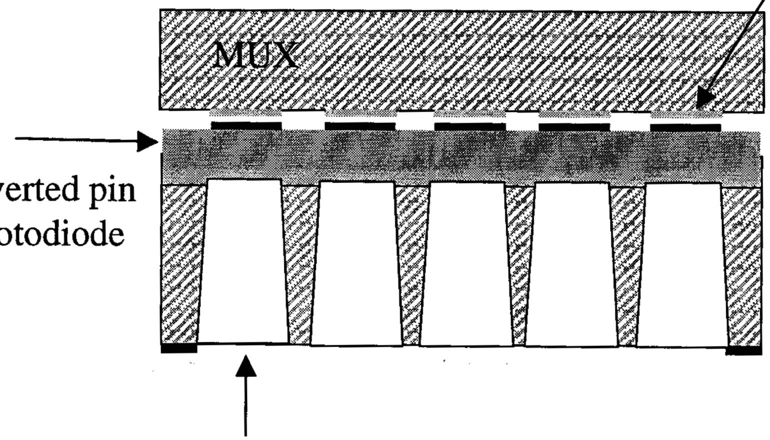


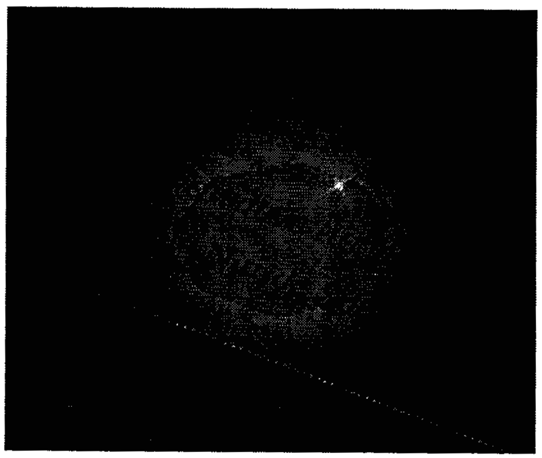
Collaboration with Prof. A. Khan, U of South Carolina

Solution

Optimize fabrication for leakage
Back side thinning of detectors grown on GaN substrates

Device Goal





GaN substrates now available
ATMI
Kymatech
Sumitomo Electronics

Key Features:
Use of quaternary AlInGaN layers
Back illumination
Front side hybridization
Deep UV response

Photo-Electrochemical (PEC) Etching of GaN

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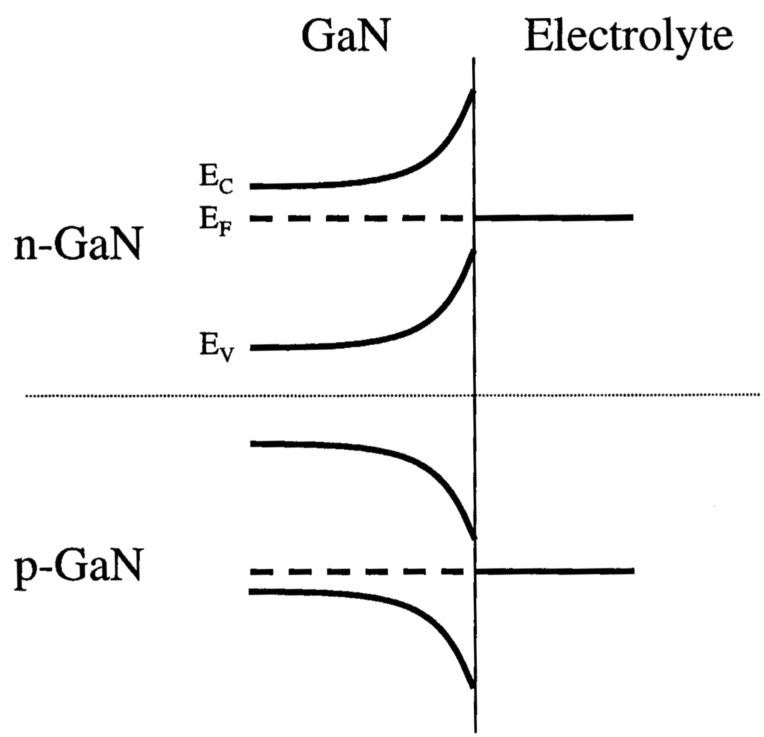
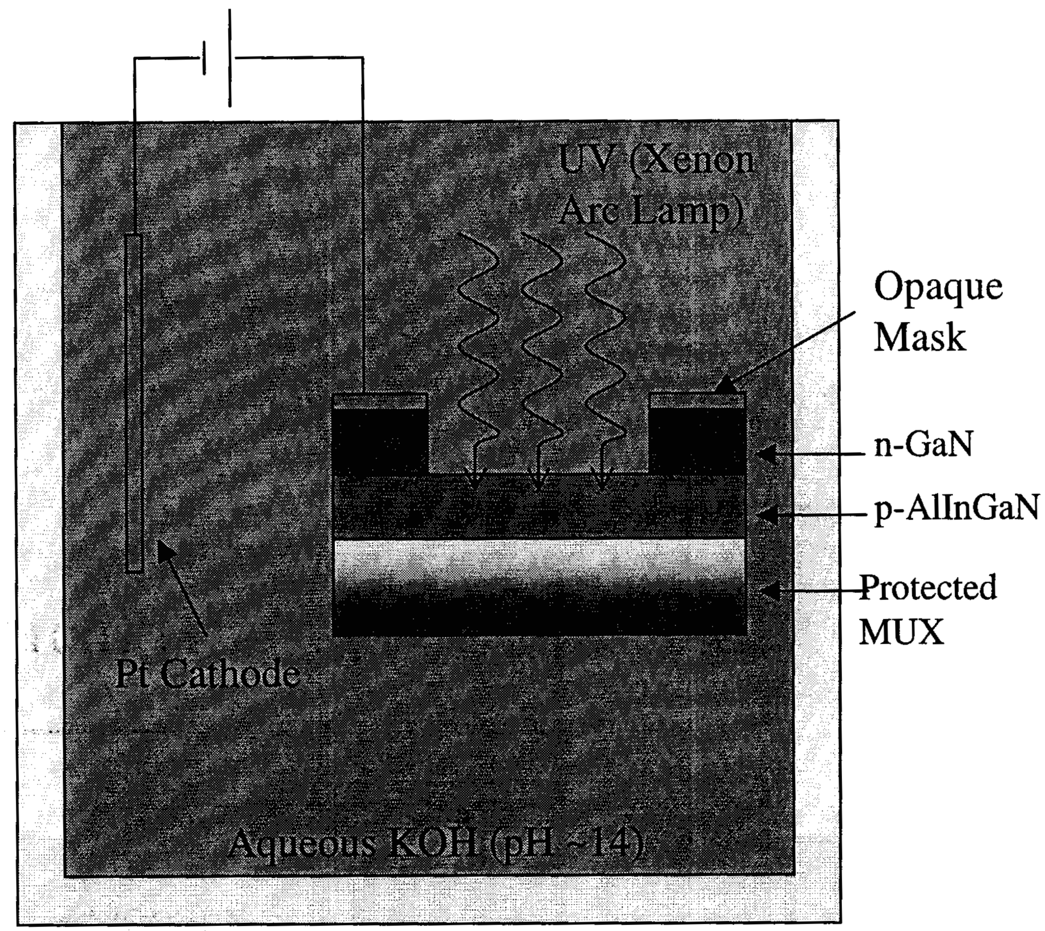
Holes created by UV light are swept away from surface in p-type, towards surface in n-type -> n-type etching

- Bandgap Selective
- Dopant Selective





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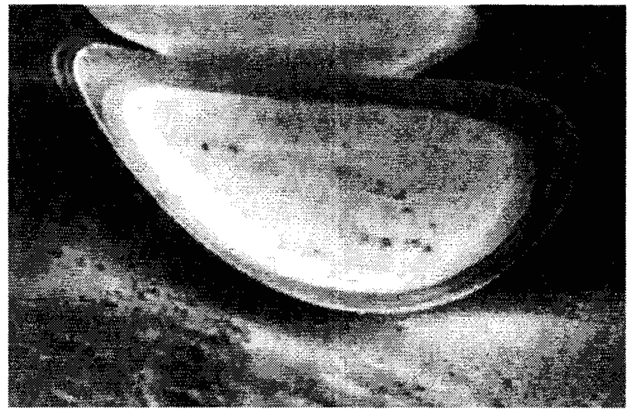
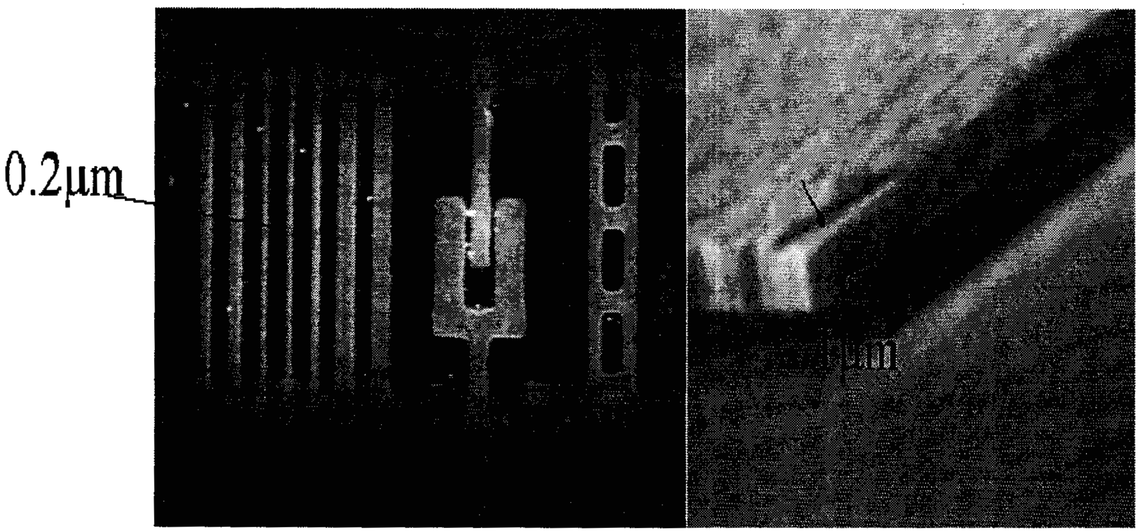
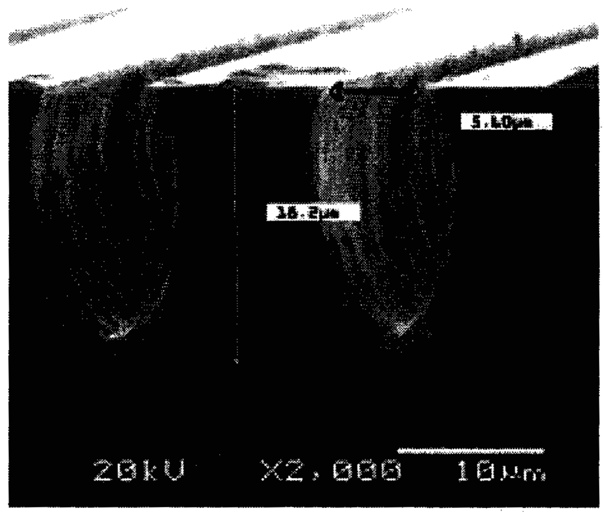
Substrate Etching

- Developed highly selective etching
- Shown small features to be robust
- Will allow back side thinning of GaN substrates





Undercut p on n sample

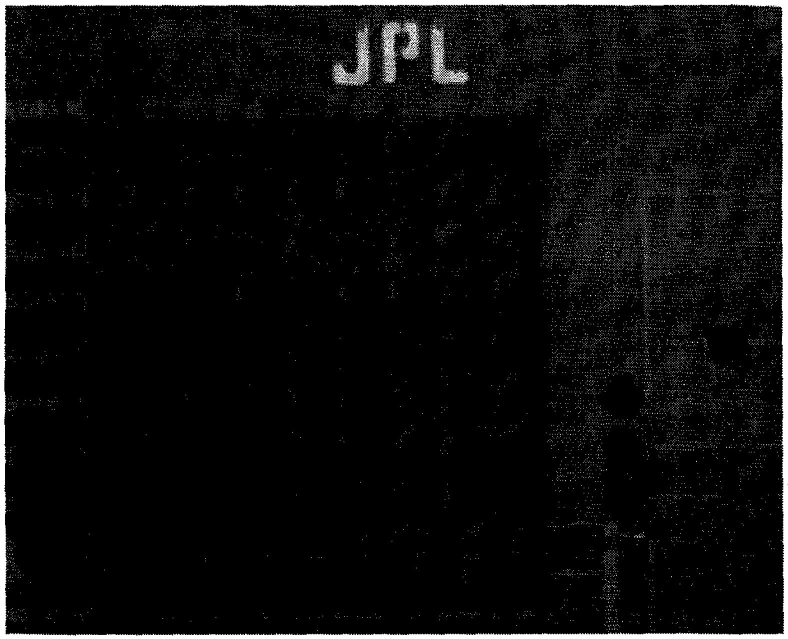


Electro-chemical etching of bulk GaN (SEM Image)

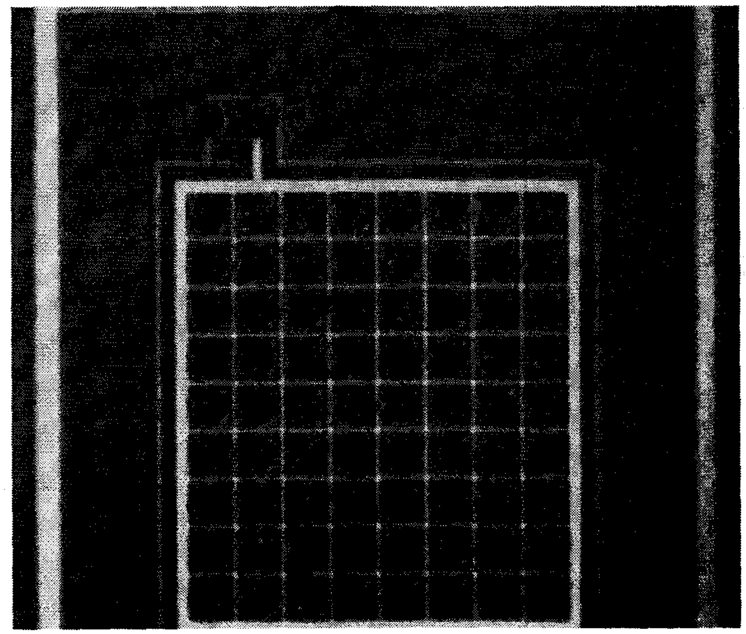
Readout Development &Hybridization

- Developed lithography and bump deposition process
- Processed and hybridized small format test arrays

JPL Designed Readout array with
In bumps prior to Hybridization



Detector Array prior to Hybridization



Piezoelectric Enhancement of AlGaN Devices

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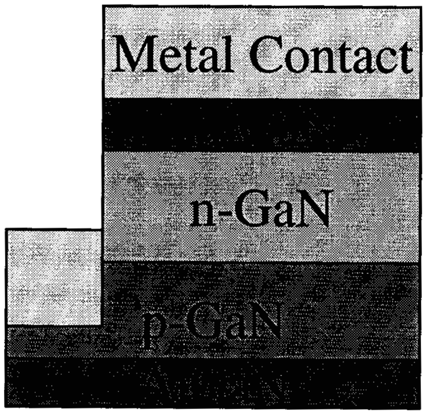
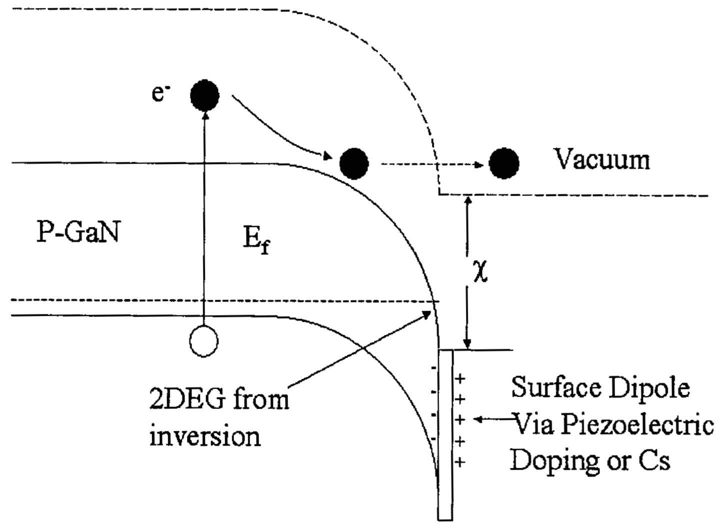
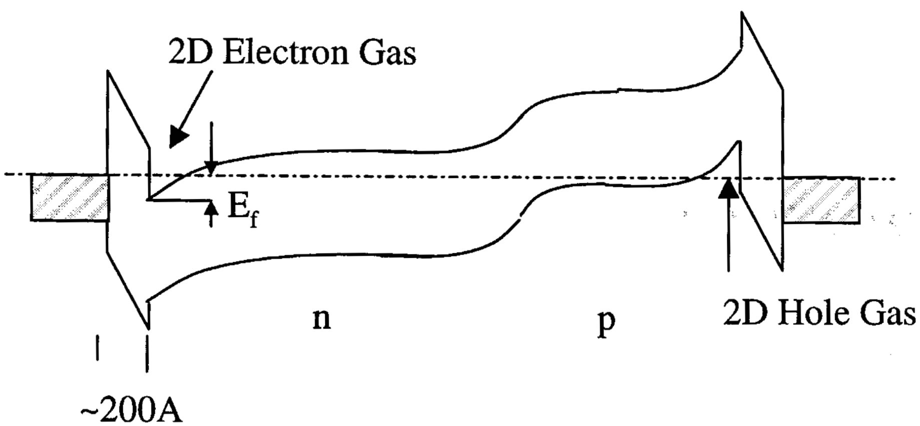
Photodetector

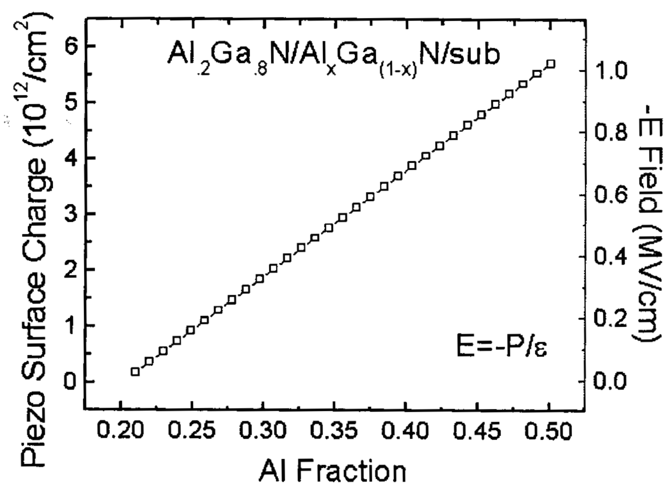


Photocathode

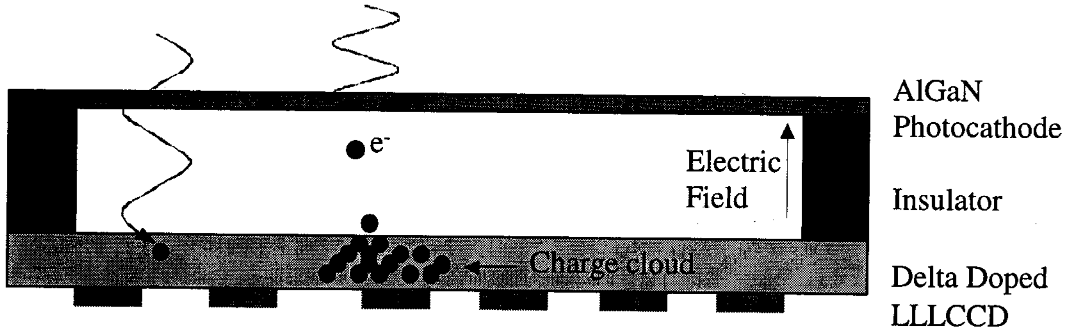


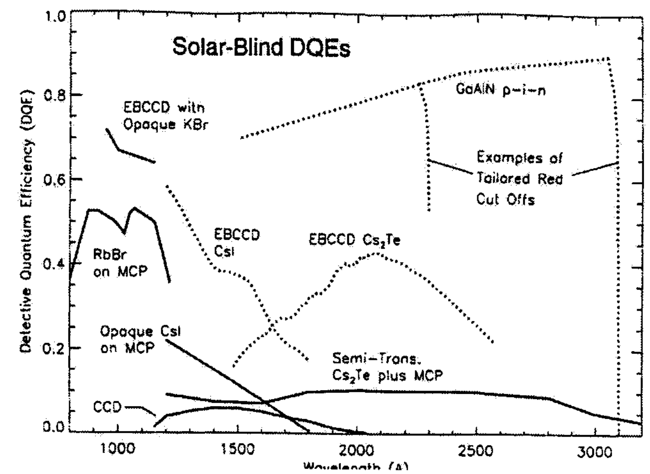


Reduce dead layer by 1 order of magnitude



Novel Electron-Bombarded CCD

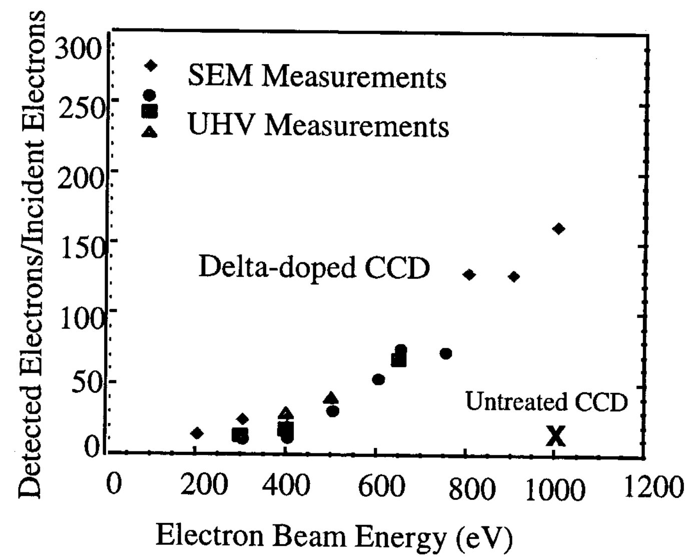




Joseph, *Proc. SPIE* **3764**, 246 (1999).

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

Low-energy Electron Detection



"....an innovative, perhaps revolutionary, ..detector", PIDDP program review

Collaboration with Prof. Chris Martin, Caltech

Further in the future....

How to take full advantage of III-Nitrides?

Will take full advantage of high Temperature and radiation hardness of III-Ns

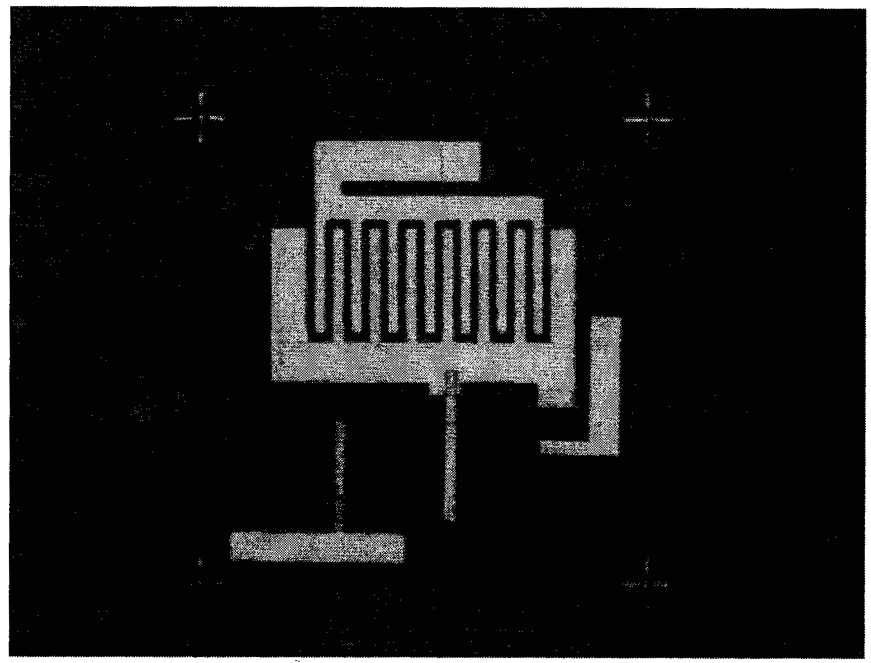
Simple Schottky Detector

GaN FET for readout

A simple Active Pixel Sensor

No silicon readout

NAPS (Nitride APS) Detector



Future

- High sensitivity, high resolution, large format, low noise silicon devices
- High purity silicon devices
- III-nitride stable photocathodes
- Growth on GaN substrates
- Detector optimization
- Substrate thinning using PEC after growth and hybridization
- Hybridizing large area arrays
- Monolithic III-nitride devices