Delta Doping High Purity CCDs and CMOS for LSST

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Outline

- **Overview of JPL's versatile back-surface process for CCDs and CMOS**
- **Application to SNAP and ORION missions**
- **Delta doping as a back-surface electrode for fully depleted LBNL CCDs**
  - Brief review of the technology and background on delta doping
  - Advantages of delta doping
  - Review of the process development for p-channel LBNL devices
- **Delta doping high purity CCDs for SNAP and ORION**
  - Optimized process
  - QE results
  - Dark Current results
  - Delta doping large format arrays
- **JPL CMP thinning process development**
- **Antireflection coating process development**
- **Summary**

Facilities for End-to-end Post-Fabrication Process

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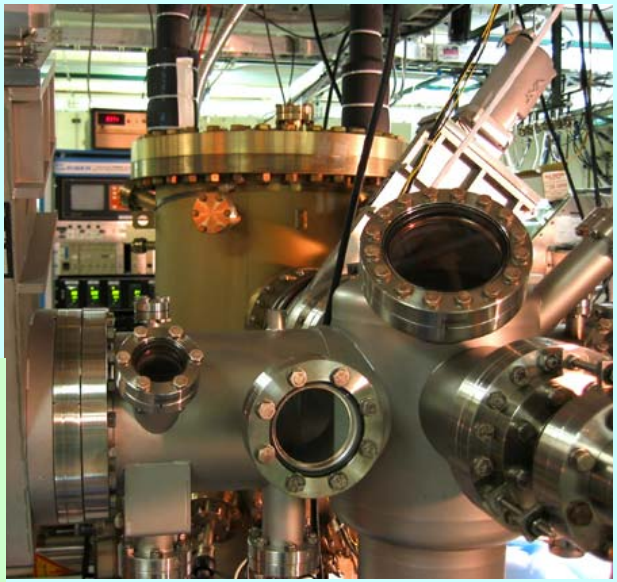
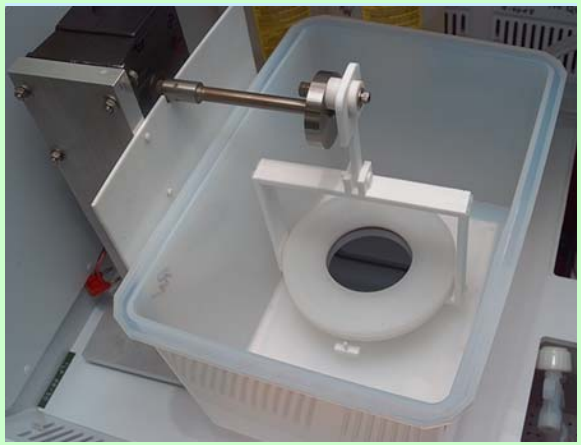
Fully-processed arrays fabricated at outside foundries are obtained.

Bonding

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



Chemical Mechanical Polishing (CMP)



Thinning

Excellent quality thinned CMOS and CCDs have been demonstrated.

Delta-doping

MBE is used to grow a delta-doped layer of Si on the backside of fully processed silicon arrays .

Response of detectors is enhanced to the theoretical limit.

Deposition of AR Coatings and Filters

Modeling capability, PECVD and sputtering system for deposition of Antireflection coatings

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

Large-Scale Astronomical Survey Missions

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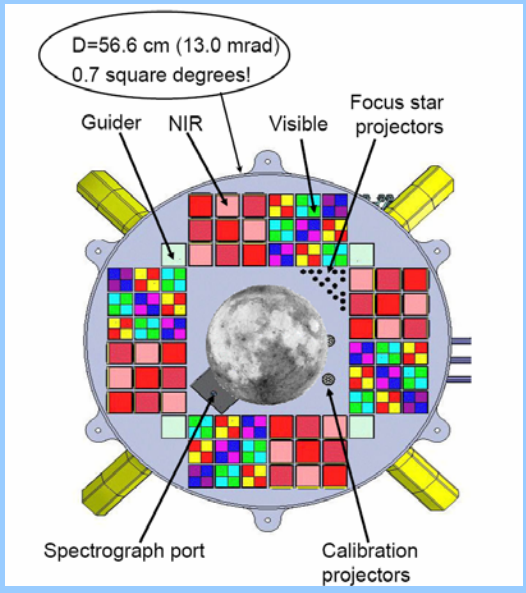
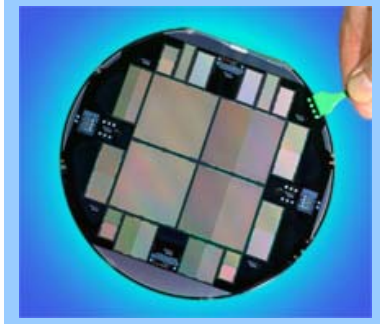
Delta doping under consideration for…

Supernova / Acceleration Probe (SNAP)

- High resolution survey of Supernovas and weak gravitational lensing, designed to reveal the nature of dark energy causing the acceleration of the expansion of the universe
- 2 M Optical – NIR telescope
- 350 – 1000 nm



Half billion pixel imager (equal CCDs and IR detectors)

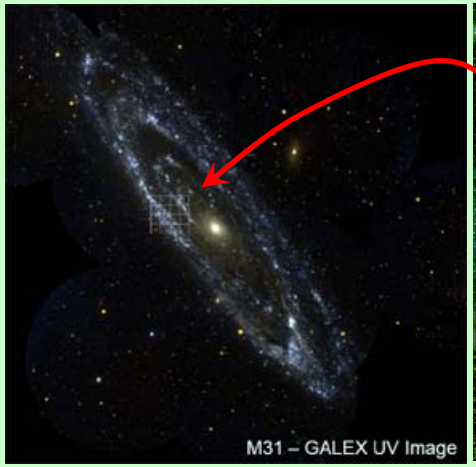


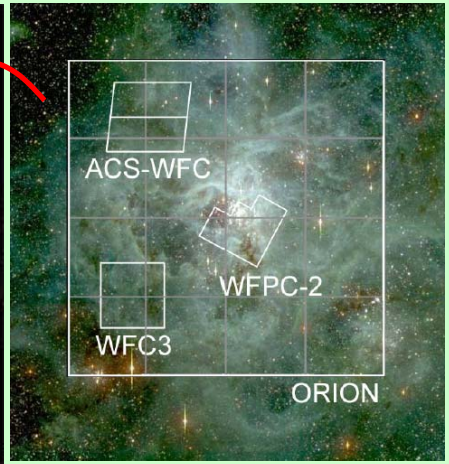
3.5Kx3.5K CCDs

Delta doping baselined for…

ORION (MIDEX)

- First ever high spatial resolution survey of statistically significant visible star forming environments.
- 1.2 M Optical-UV telescope
- 200 – 1000 nm
- Two channels with separate 8kx8k Mosaics (UV-blue and Red-NIR)
- ~ 200 sq arcmin FOV





Detector Objectives for SNAP and ORION

- 200 – 1000 nm range covered in a single detector
- High stable quantum efficiency over the entire range
  - SNAP: > 80% QE 400 – 800 nm
  - ORION: 80% QE @ 650 nm
    60% QE @ 370 nm
    50% QE in the UV
- Back-illuminated high purity silicon imagers (CCDs, hybrid arrays) meet these requirements
- Back-surface treatment required to get UV response

P-channel High Purity CCDs and Delta doping

High purity silicon imagers
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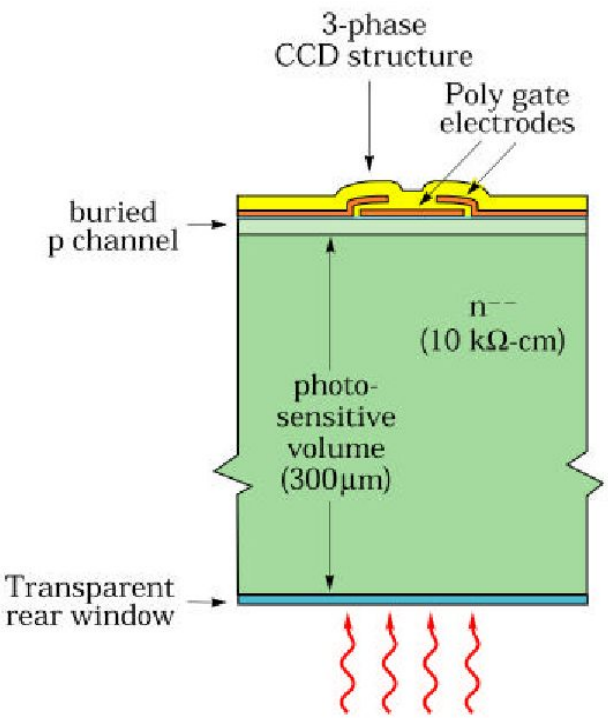
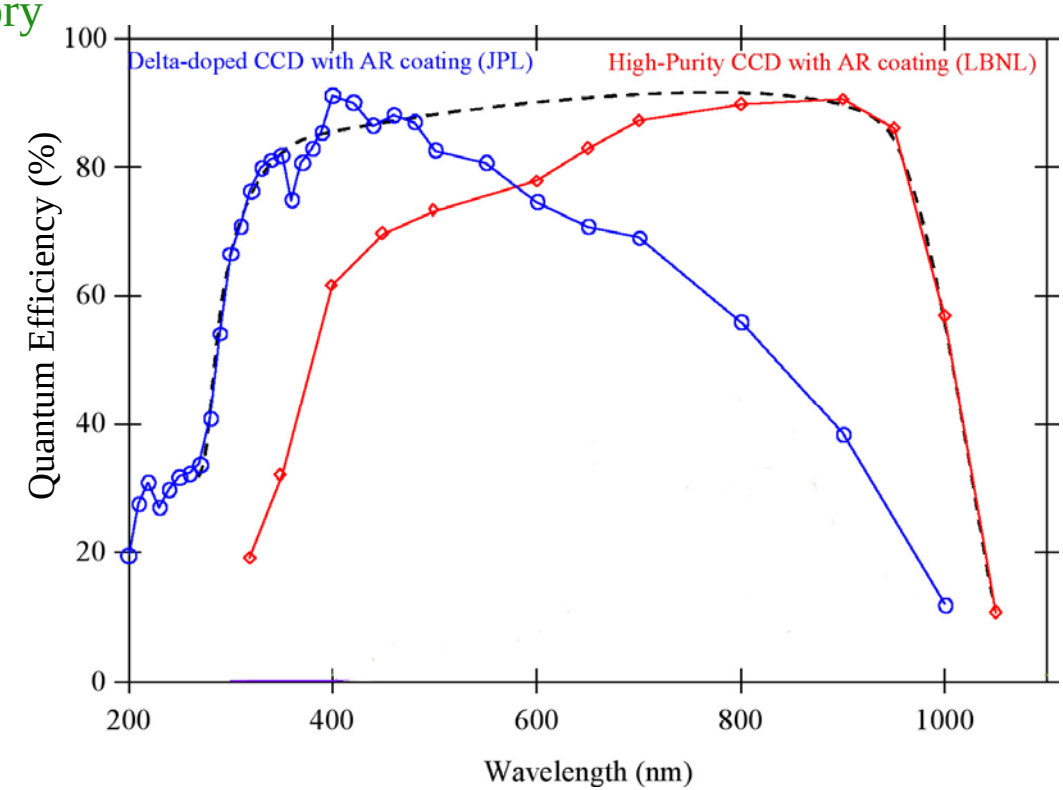
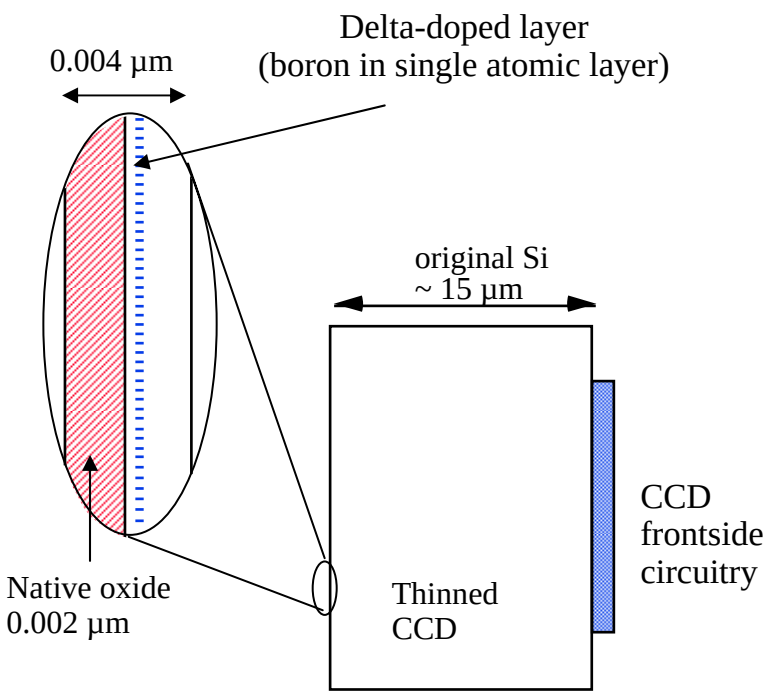




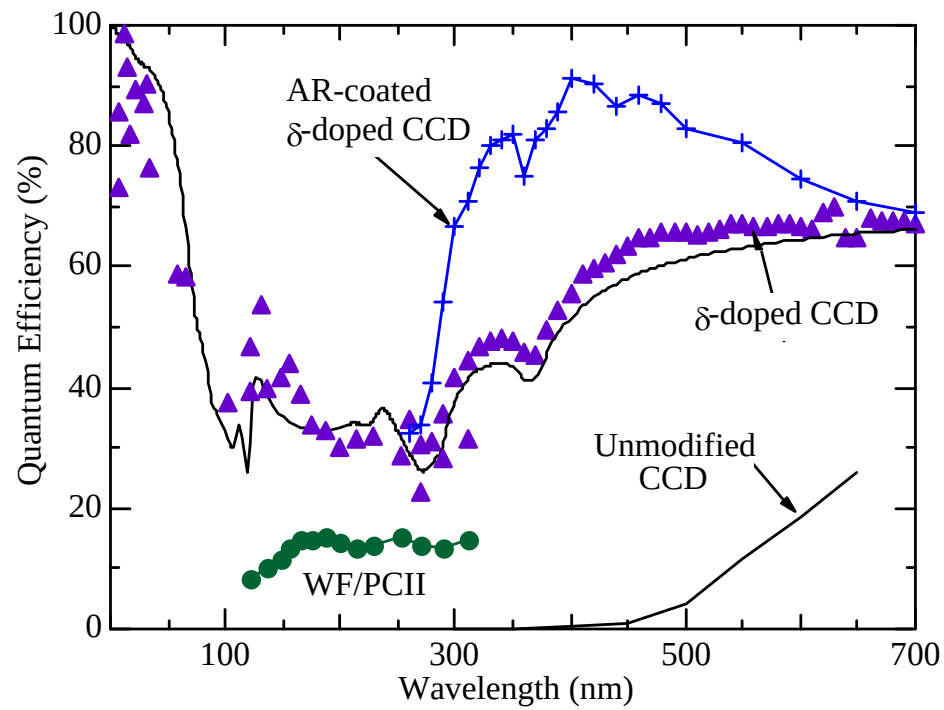
- The transparent electrode plays key role in: QE, dark current, spectral range, and fabrication
- Merge Delta doping with High purity Array Technology to achieve high QE& broadband response
- Allow streamlined fabrication because of the low temperature process of delta doping

Background on Delta doping

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



Cross section delta-doped CCD structure



Key Features

- *Low temp. growth (< 450 C)* Fully-processed devices
- *Ultrathin electrical contact* High and stable sensitivity
- *Surface passivation* Low dark current, full depletion

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

Delta-doped CCD Stability and Reproducibility

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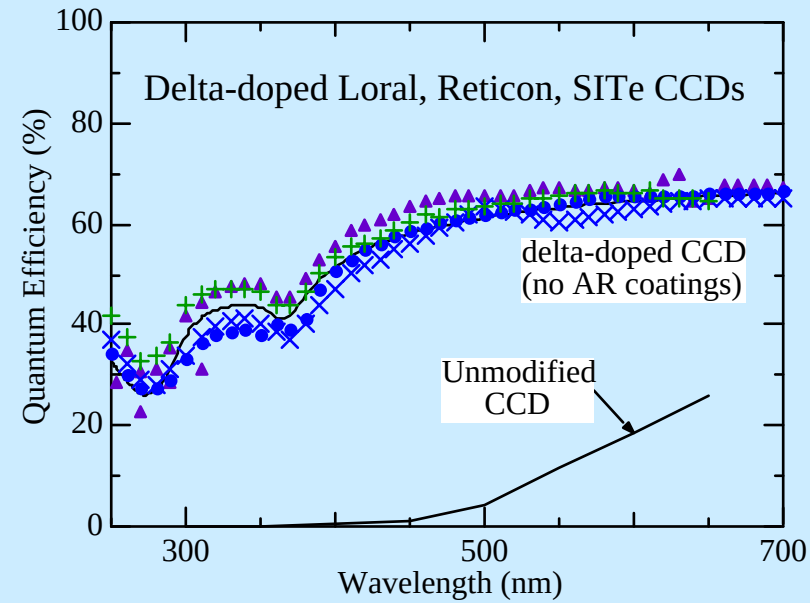
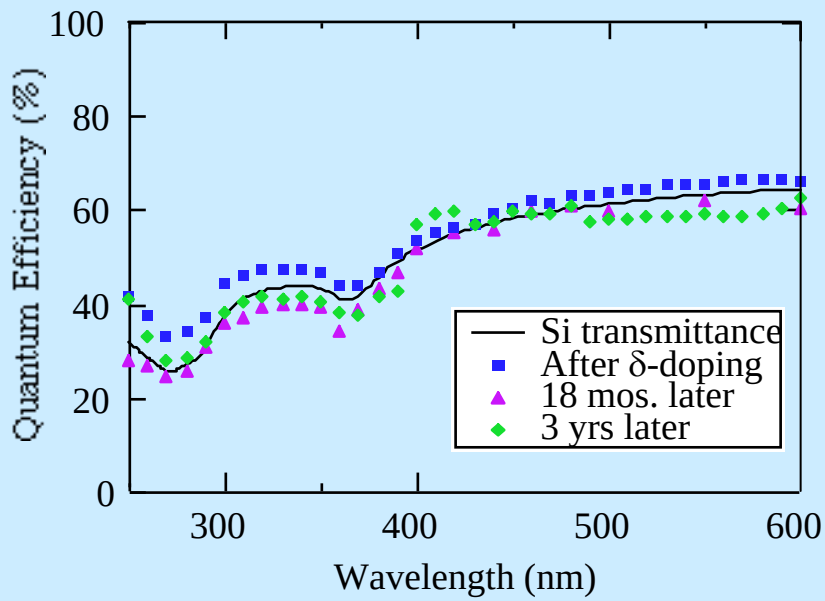
- 100% internal QE is measured years after the MBE modification of the CCDs
- Reproducible and compatible with different formats and CCD manufacturing processes
- No hysteresis is observed in delta-doped CCDs
- Stable response over several years
- Precision photometric stability measured by the Kepler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





Delta-doping High Purity P-channel CCDs

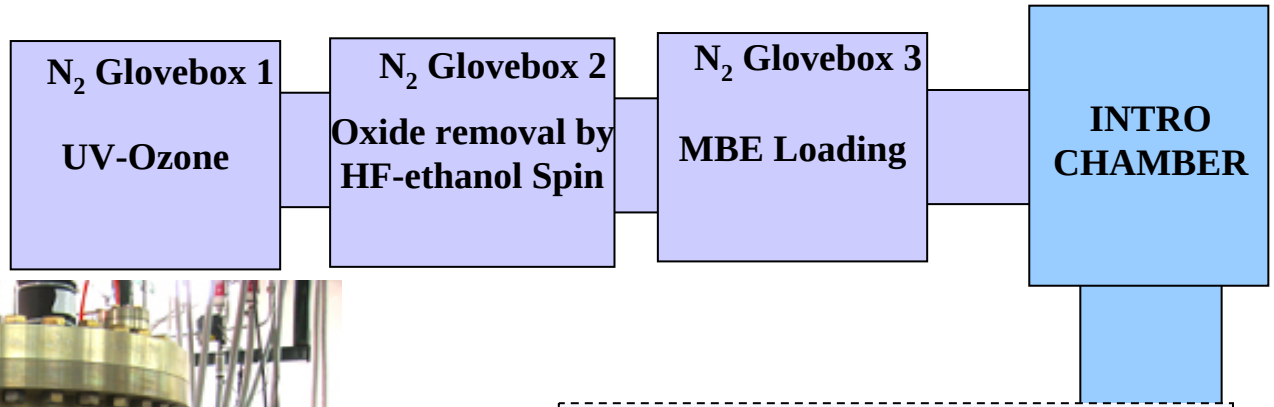
Advantages

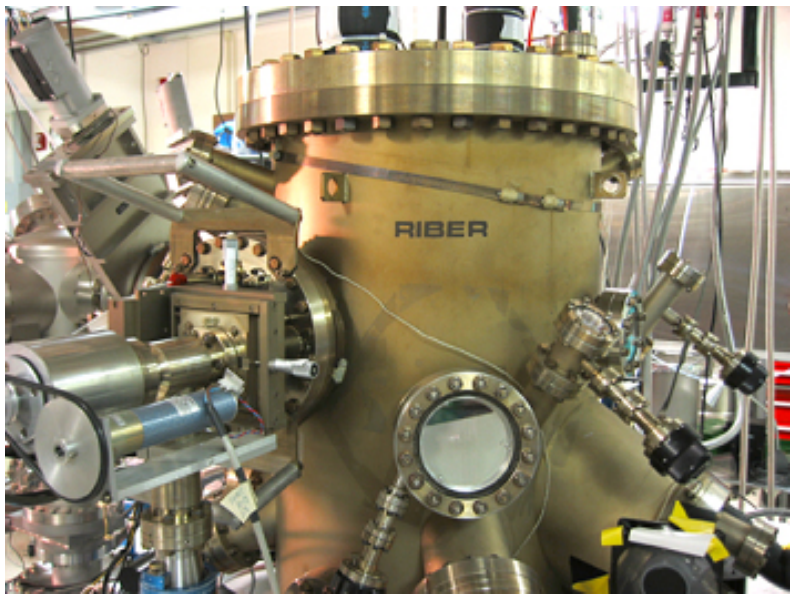
- Process available for both p-type and n-type silicon
- Delta doping enables high QE across the entire spectral range attainable with silicon
- Delta doping has been shown to offer excellent long-term stability
- Delta doping is a low temperature process and is compatible with fully-fabricated detector arrays.

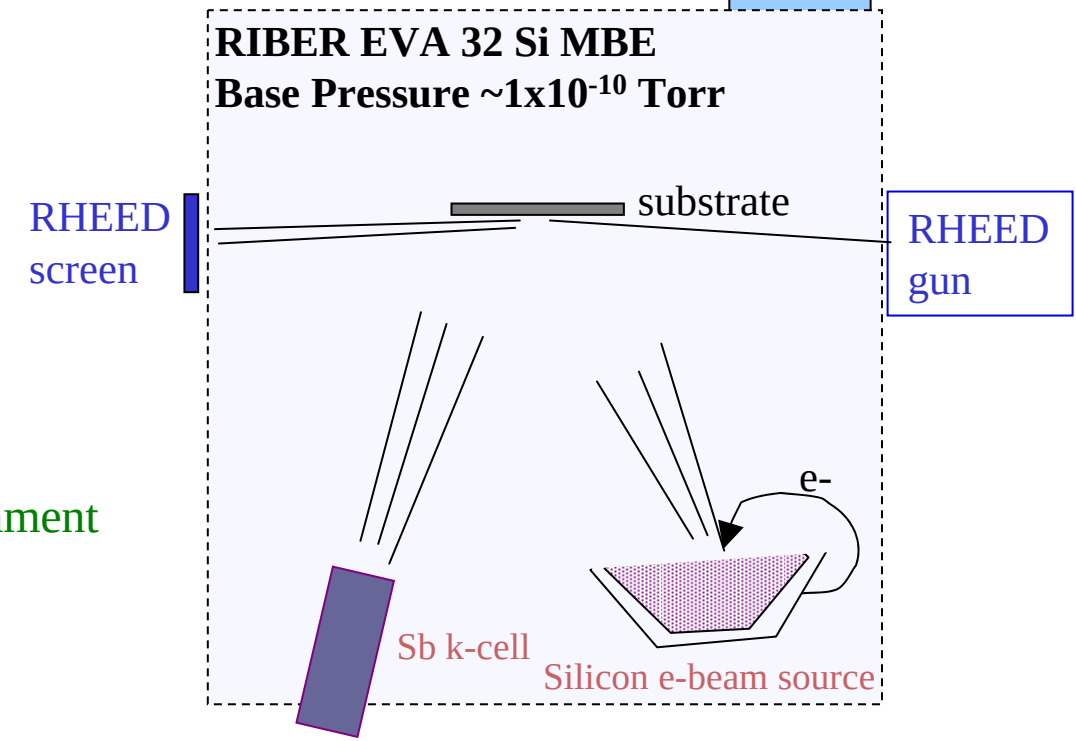
Recent Development

- *MBE techniques and processes had been developed for n-channel devices, i.e., p-type substrates with boron doped delta layers*
- *New epitaxial techniques and surface preparation techniques for delta doping with antimony and handling high purity silicon were developed for p-channel CCDs (n-type delta doping)*

Molecular Beam Epitaxy







- Surface preparation* under N_2 environment
- 3” rotatable substrate heater assembly
- Radiative substrate heating

*Grunthaner et al., Thin Solid Films **183**, 197 (1989)

Optimizing n-type delta layers as backsurface Electrode

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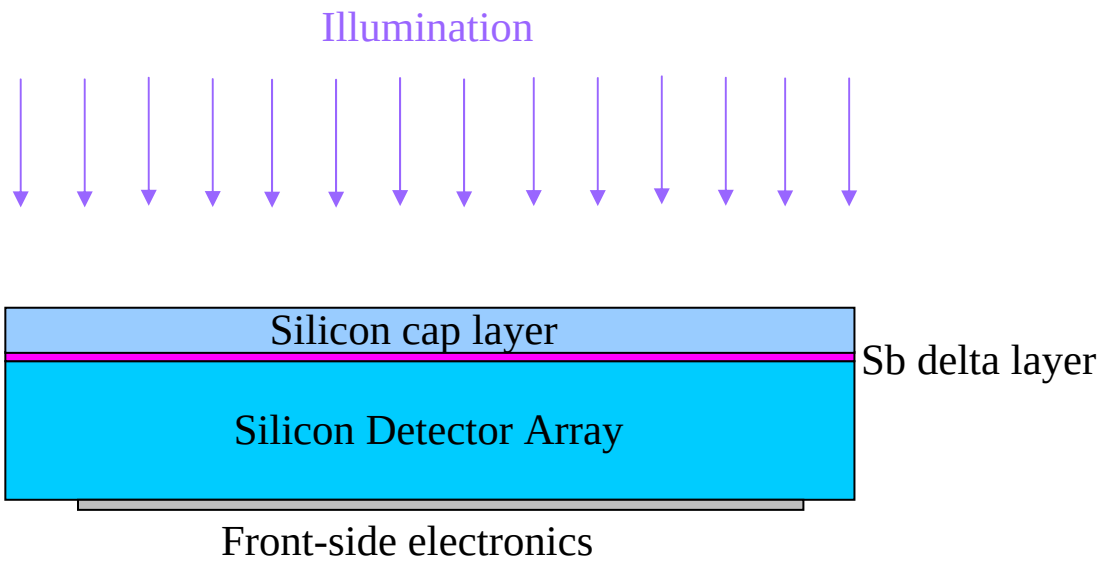
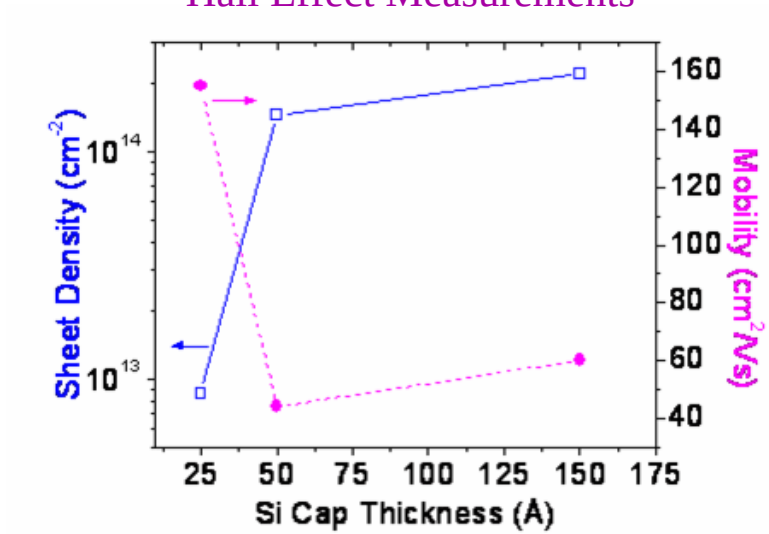


Hall Effect Measurements



- **High concentration of electrically activate Sb in the delta layer is important.**
- **A thin silicon cap layer is required to prevent oxidation of the delta layer**
- **The silicon cap layer thickness determines the short wavelength detection limit and the stability of the response.**

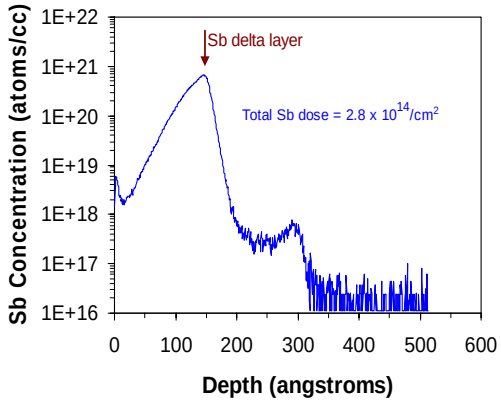
$2x10^{14}$ cm^{-2} electrically active Sb is achievable.

MBE Growth on Si substrates and Fully-processed Devices

- Demonstrated an *entirely ultra low temperature MBE process for thin, highly (Sb)-doped epitaxial layers on n-type high purity wafers*.

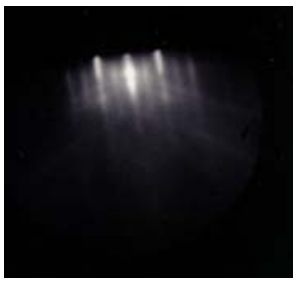
Reflection High Energy Electron Diffraction (RHEED)

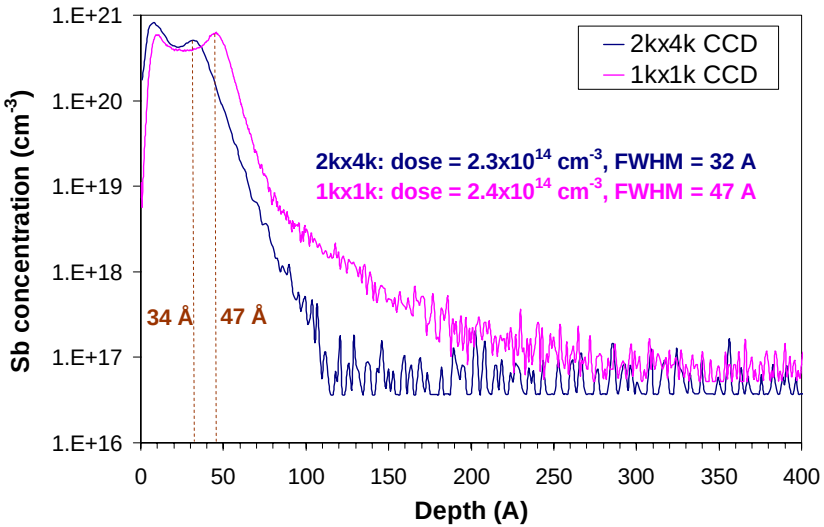
Secondary Ion Mass Spectrometry (SIMS)

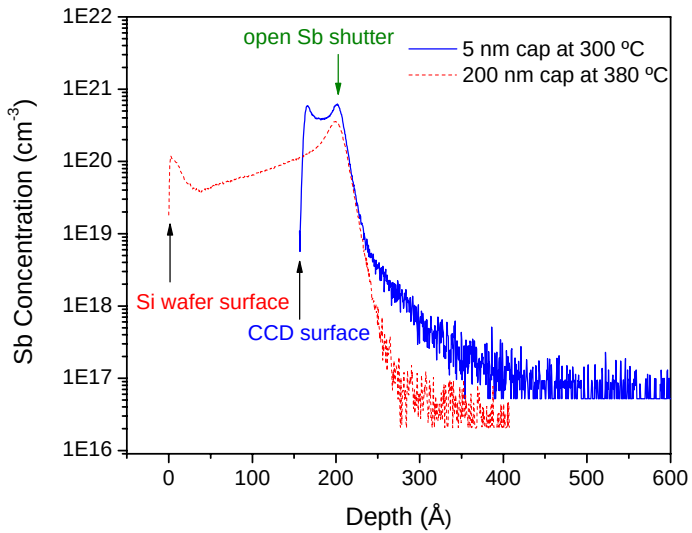


- Successfully extended the process to PIN diode test arrays, and CCDs…….

RHEED

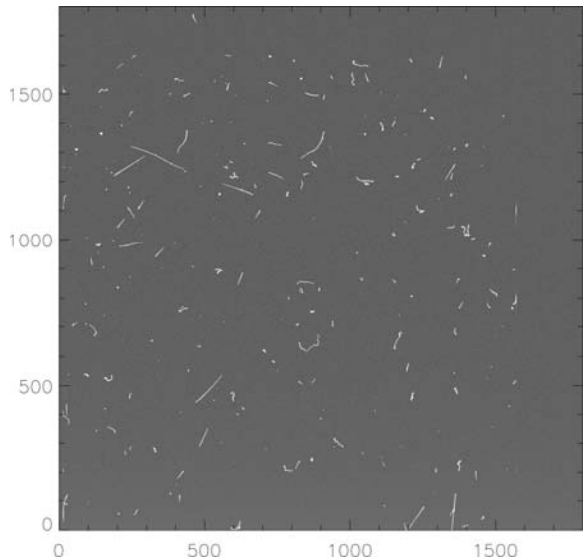




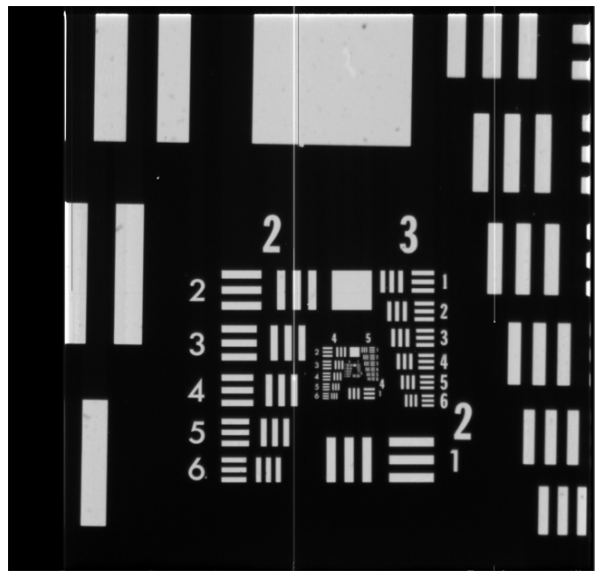


High Resolution and Excellent Point Spread Function

- *Successfully extended the process to 1K x 1K CCDs (~ 1.6 K x 1.5 K CCDs). Demonstrated high resolution, low dark current.*



Cosmic ray tracks
showing full depletion



250 μm thick,
back-illuminated
1kx1k, 12 μm pixel CCD
45 V, -140 °C

Quantum Efficiency of Delta-doped 1kx1k LBNL CCDs

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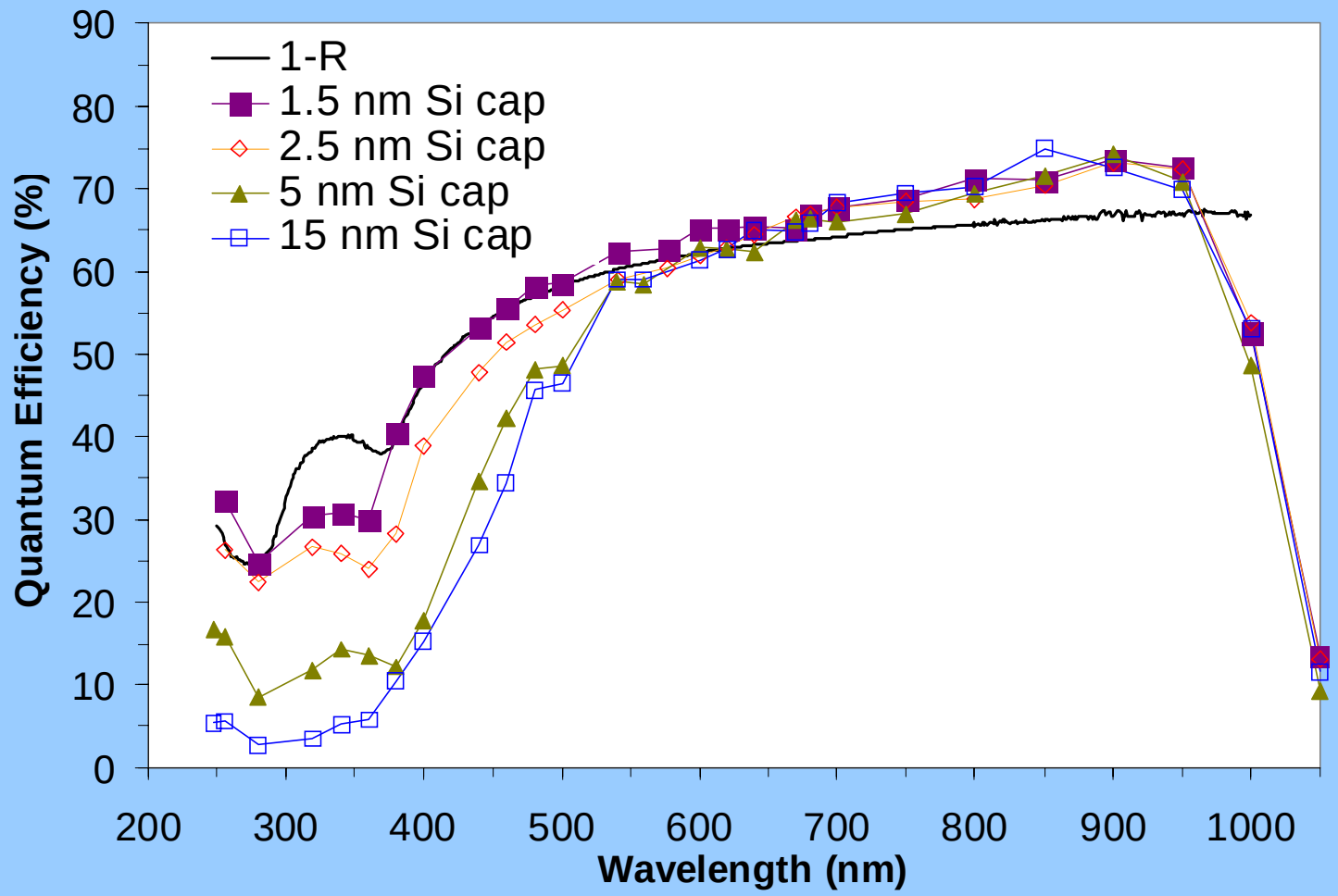
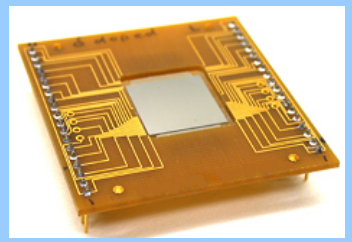
Near 100% Internal QE with Optimized MBE Layers

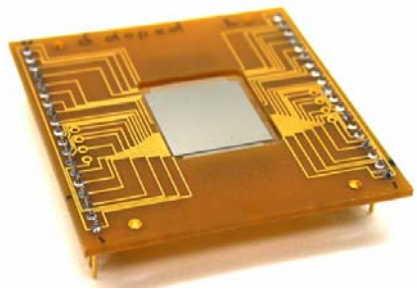


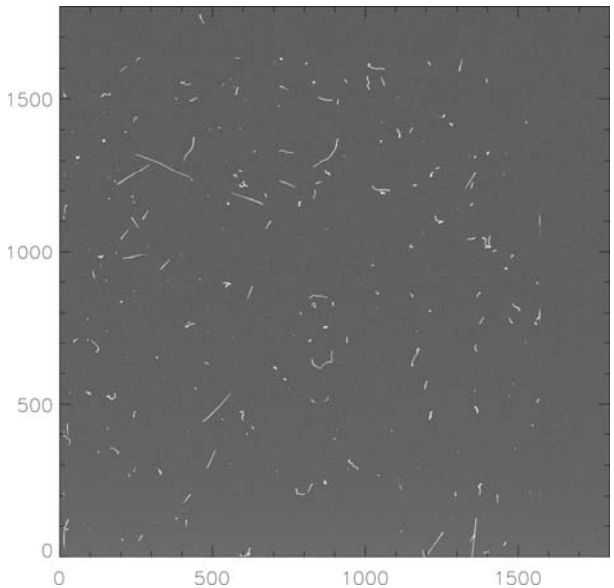


1K x 1K CCDs

Dark current in Delta doped 1kx1k CCDs

- SNAP requirements: < 3.6 e-/pixel/hr
- Measured on delta doped CCDs @ -135 C:
- Achieved 0.52 e-/pixel/hr ($3x10^{-17}$ A/cm^2)
- Dark current is within specifications for SNAP





1800 s. dark exposure, L-amp. Measured dark current was 0.53 e-/h/pixel. Overscan read noise for same amplifier was 6.79/1.86 = 3.6 e- rms.

Delta doping large arrays - uniformity

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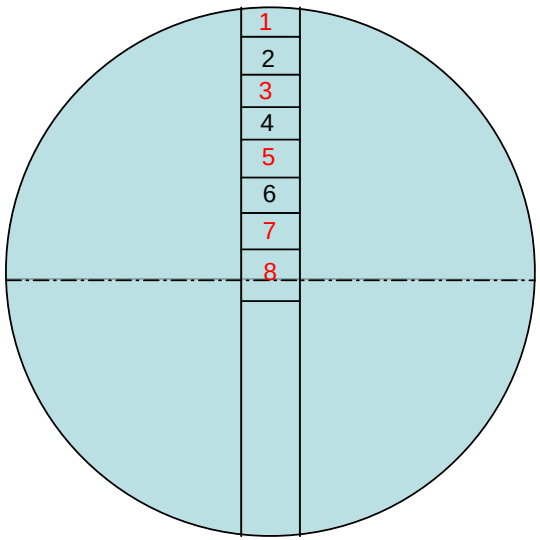
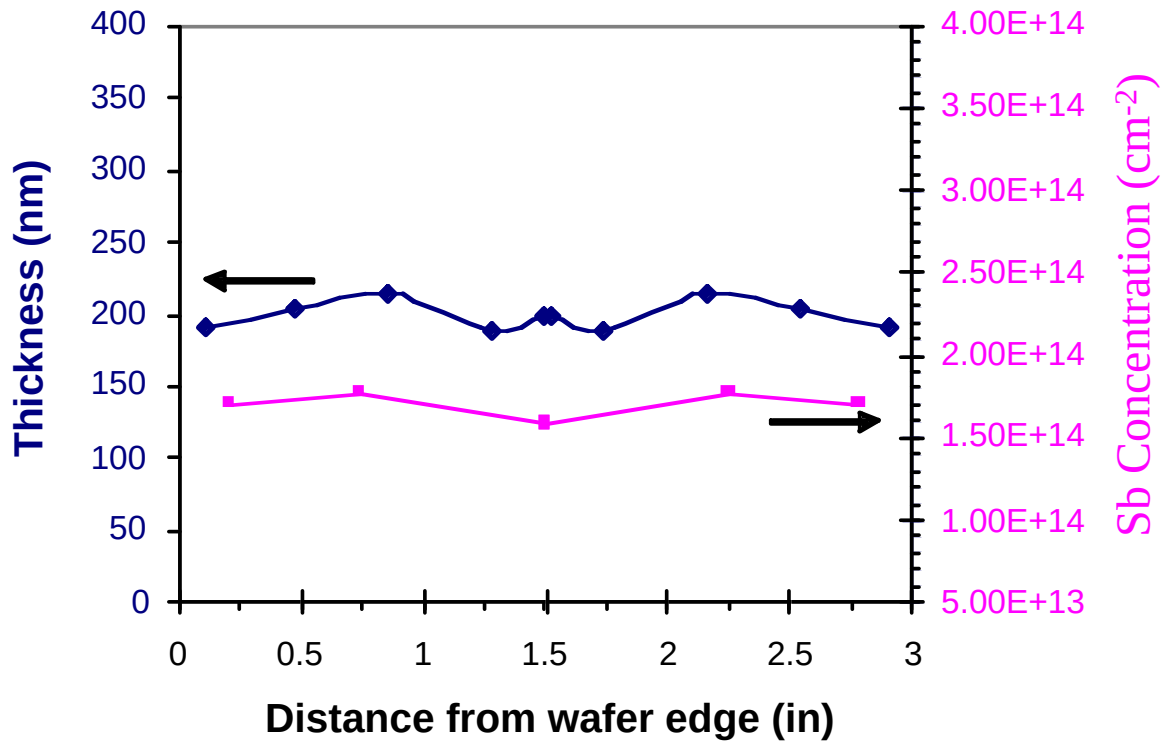
Silicon Wafer



Silicon thickness and Sb doping uniformity



Uniformity of thickness and dopant incorporation was examined across a silicon wafer

Variation of the order of <10% was achieved.

Delta doping Large-format High purity Arrays

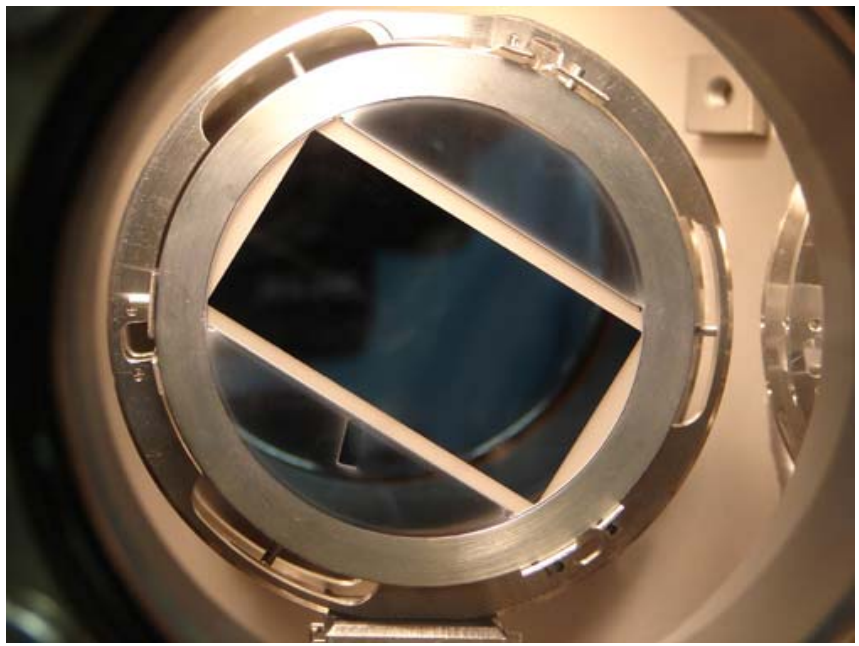
Thickness and dopant incorporation was examined across a 3-inch silicon wafer shown uniform

Two 2K x 4K, 15 micron pixel CCDs have been delta doped.

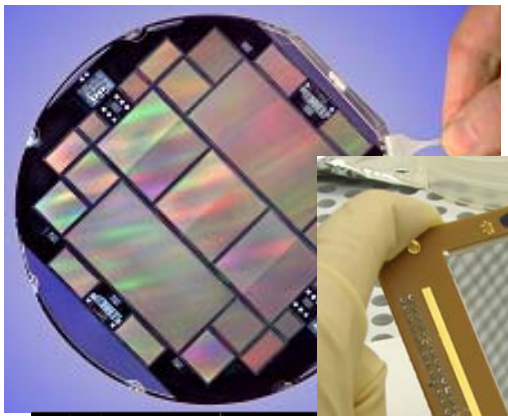
First device was used for development

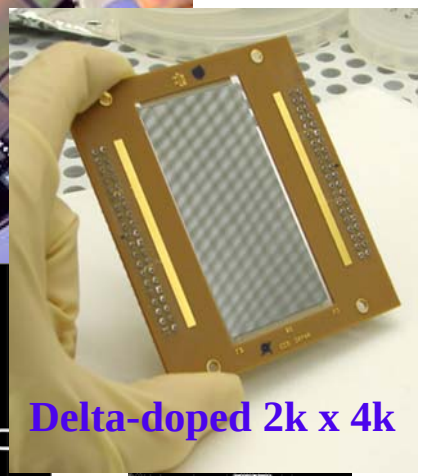
Second device was successfully delta doped and tested at LBL and JPL

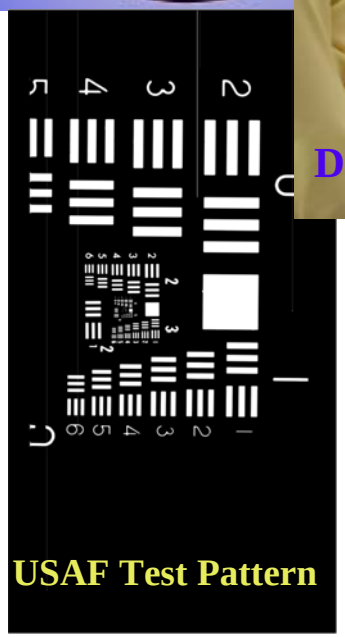
Close-up of 2K x 4K Array in the MBE chamber

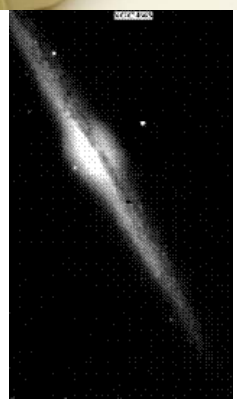


Delta doped Large-format CCDs

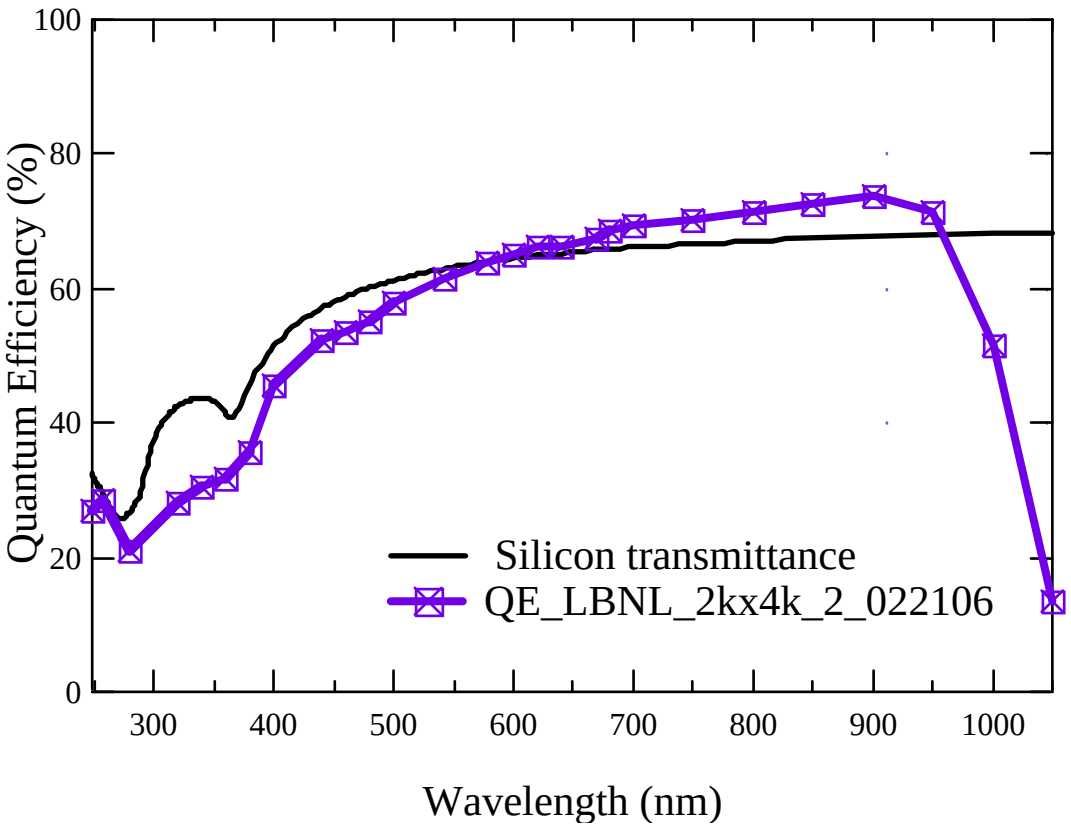






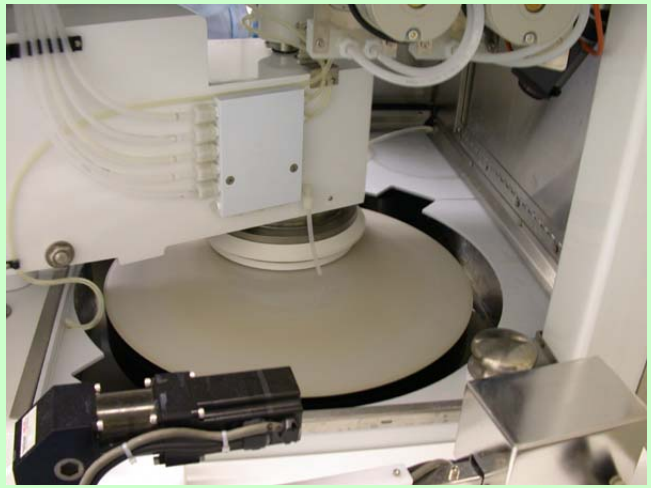


MBE Growth on 2k x 4k P-channel HP CCDs (No AR coating)



MBE modification using the thinnest delta layers were applied to 2k x 4k p-channel high purity CCDs. High resolution, low dark, and near 100% internal QE was demonstrated.

Polishing and Thinning Wafers



- In house CMP provides mirror finish surfaces
- Complete thinning down to 11-micron epi layer produced excellent quality surfaces
- MBE layers have been grown on the polished and thinned surfaces of fully-fabricated CMOS devices showing excellent quality surface finish and 100% internal QE

CMP and Back-Surface Quality

- A high quality back surface without defects and traps is important in achieving low dark current and good CTE.

- N-type high purity silicon presents additional challenges
  - Non-uniform chemical etching of n-type Si
  - Slow etch rates

- Future work will sort out processes to produce a high quality back-surface by CMP.
  - Investigate and compare wafers after the JPL CMP process as well as polished surfaces from various vendors.

Maximizing QE with Antireflection Coatings

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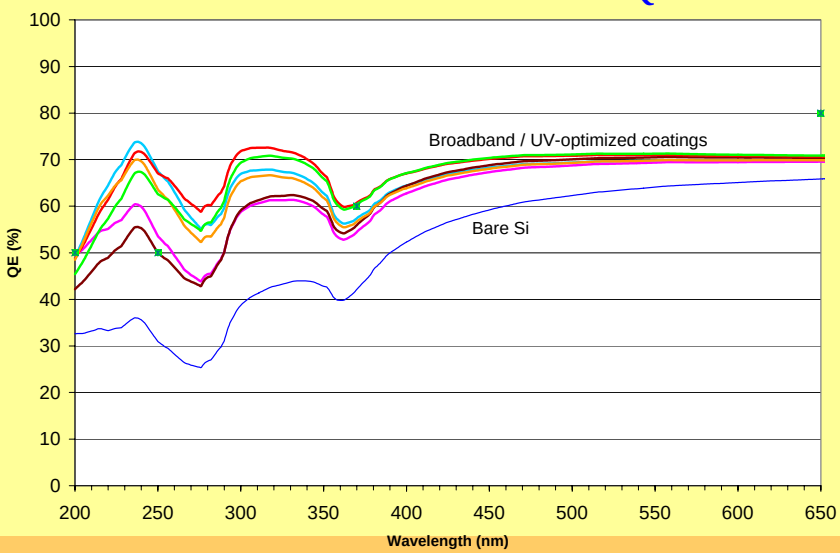
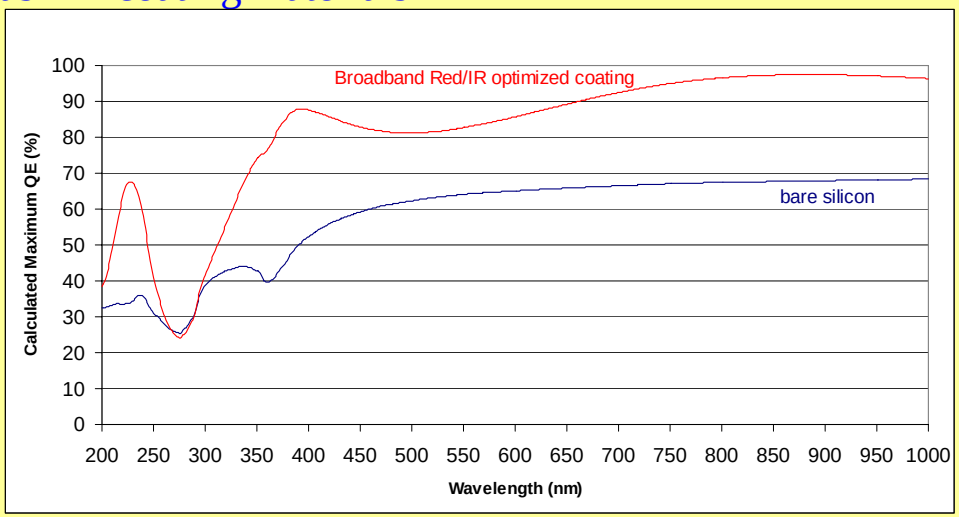
Antireflection (AR) Coating Modeling

Wavelength	Silicon	SiO_2	Si_3N_4	Al_2O_3	MgO	MgF_2	ITO	HfO_2
200	0.97	1.55	2.50	1.83	1.90	1.42		2.50
250	1.56	1.50	2.20	1.83	1.80	1.40	2.35	2.30
300	4.77	1.47	2.15	1.80	1.78	1.40	2.31	2.12
350	5.53	1.47	2.10	1.80	1.75	1.40	2.21	2.10
400	5.43	1.47	2.07	1.79	1.74	1.39	2.11	2.02
600	3.89	1.46	2.02	1.77	1.73	1.38	1.97	1.98
800	3.66	1.45	2.00	1.76	1.72	1.38	1.88	1.96

Index of refraction Vs. Wavelength for AR coating materials

Calculated QE with various AR coating materials





AR coatings for silicon were modeled for UV and broadband response

Single and multilayer designs were investigated

New deposition systems at JPL expand options for multilayer coating design

Antireflection Coatings

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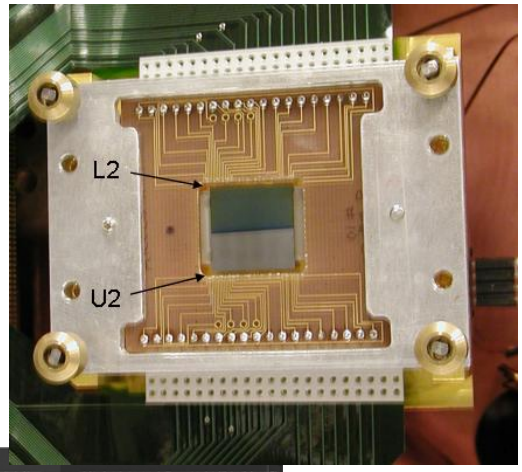
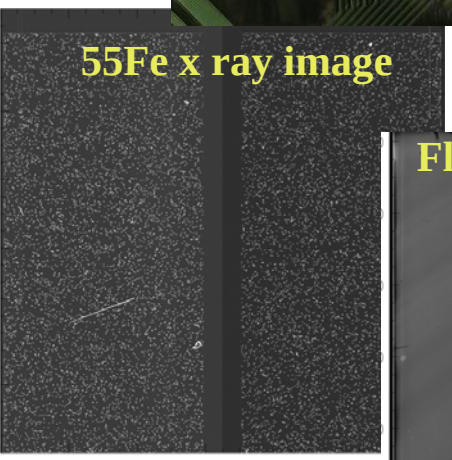
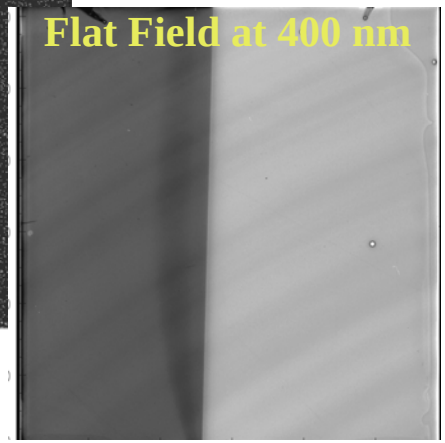
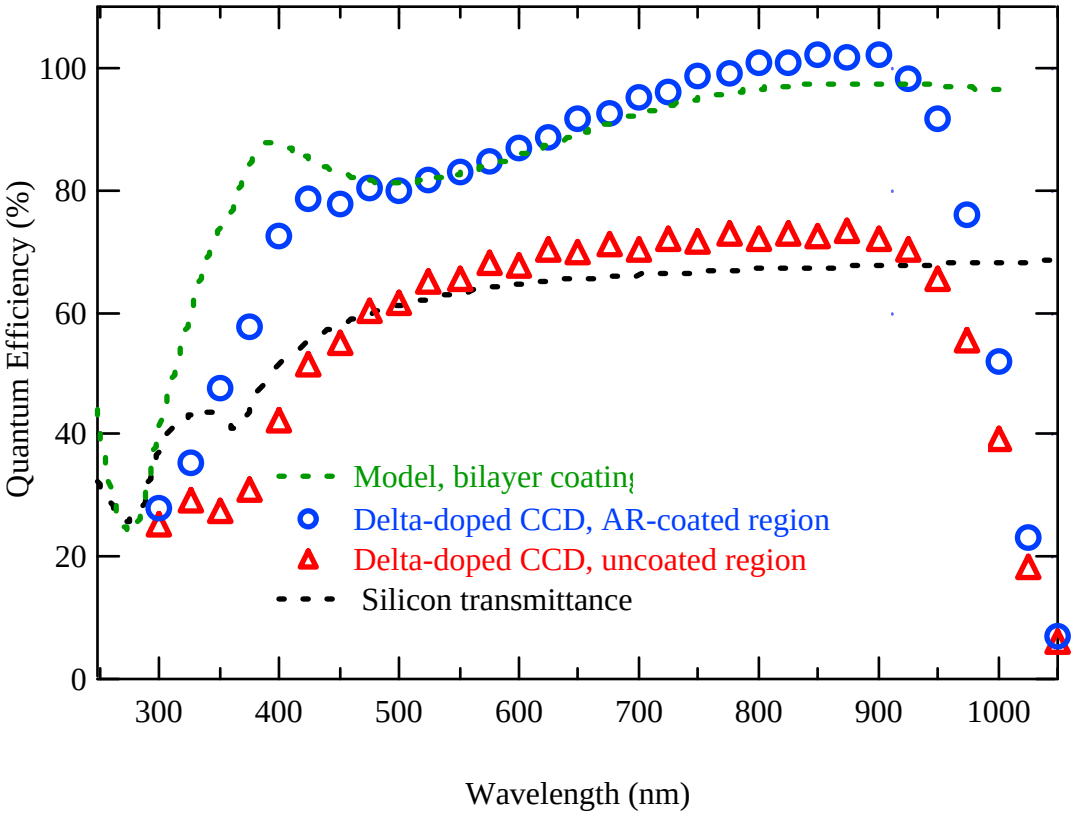






Deposition of Broadband AR coating
on Delta Doped P-channel CCDs

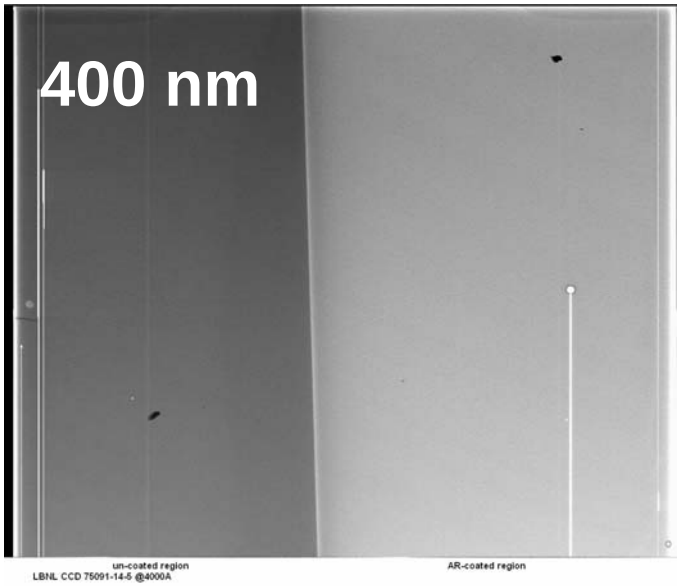


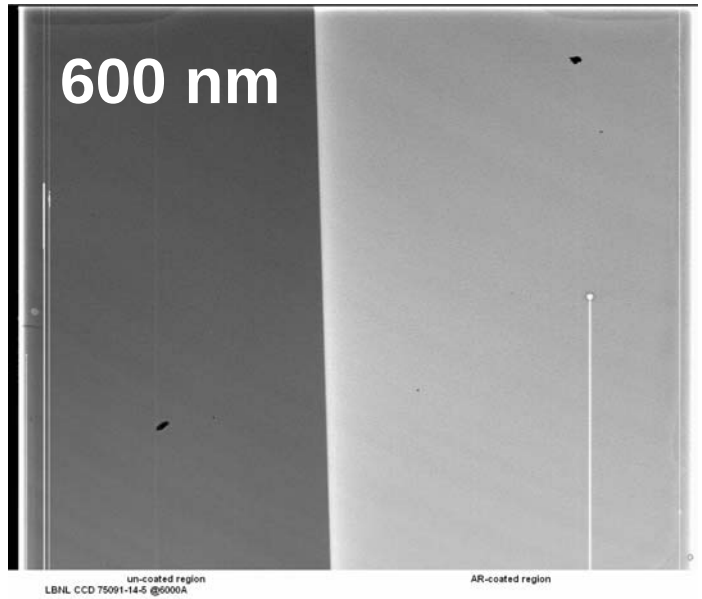
Broadband two layer coating (SiN_x/SiO_x) was deposited on 1/2 a 1k x1k Delta doped CCD by PECVD

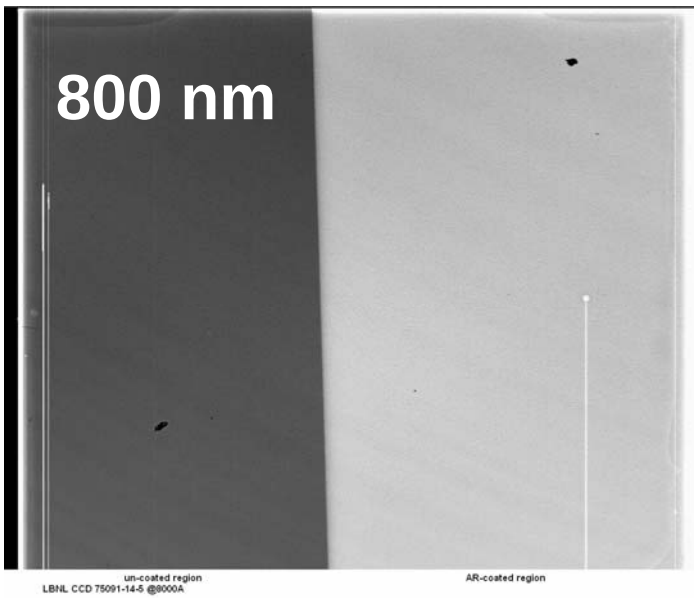
Excellent QE enhancement was observed. Flat Field at 400 nm shows grind marks from CMP.

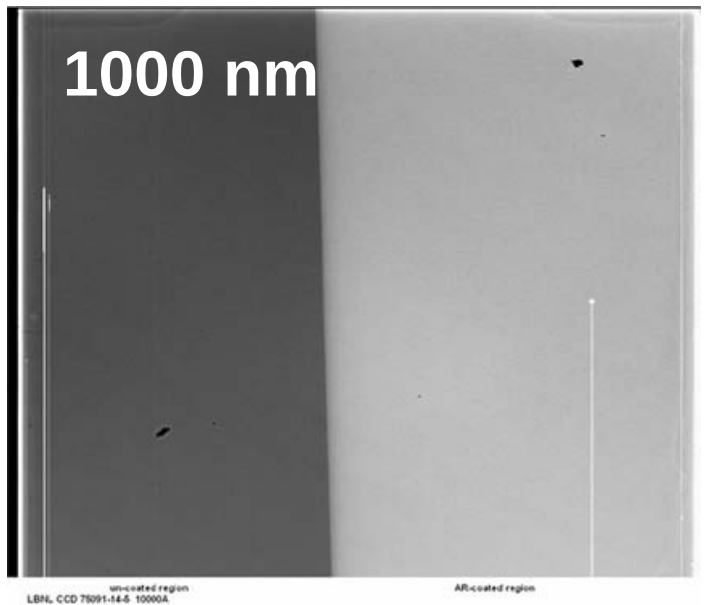
X ray data showed that both amplifiers function properly.

Flat fields at various wavelengths









Summary and Plans

•A complete end-to-end back-side process has been developed at JPL and can be applied to both CCD and CMOS arrays

•We have developed and demonstrated a delta doping process applied to fully-fabricated p-channel CCDs (complete with Al metallization).

•High QE and low dark current is demonstrated with delta doped p-channel CCDs.

•Delta doping process was successfully demonstrated on large format (2k x4k) CCDs. We will continue delta doping and fully characterizing 2k x 4k CCDs.

•We have received 3.5k x 3.5k SNAP CCDs and will begin delta doping.

•JPL in-house AR coatings have been demonstrated on masked 1k x 1k CCDs.

•We are developing a JPL in-house CMP process for wafer-level thinning.

•Work on obtaining a large-capacity MBE underway

Publications

Publications

"Ultra-low temperature homoepitaxial growth of Sb-doped Silicon",
Jordana Blacksberg, Michael E. Hoenk, and Shouleh Nikzad
Journal of Crystal Growth, 285(4) pp. 473-480, December 15, 2005.

"Enhanced quantum efficiency of high purity silicon imaging detectors by ultra-low temperature surface modification using Sb-doping"
Jordana Blacksberg, Michael E. Hoenk, Steve E. Holland, S.Tom Elliott, and Shouleh Nikzad, *Applied Physics Letters*, December 19, 2005.

“Delta-doped fully depleted, high-purity silicon p-i-n diode arrays for direct detection of 0.1-20 keV electrons”,
Shouleh Nikzad, Thomas J. Cunningham, Ronald Ruiz, Steve E. Holland, David Soules, *Applied Physics Letters*, submitted.

Presentations

SPIE, Orlando, FL, May 24-31 2006

Materials Research Society, Boston, MA November 28- December 2 2005

American Physical Society, Los Angeles, CA March 2005