Micro-Machined Silicon Detectors

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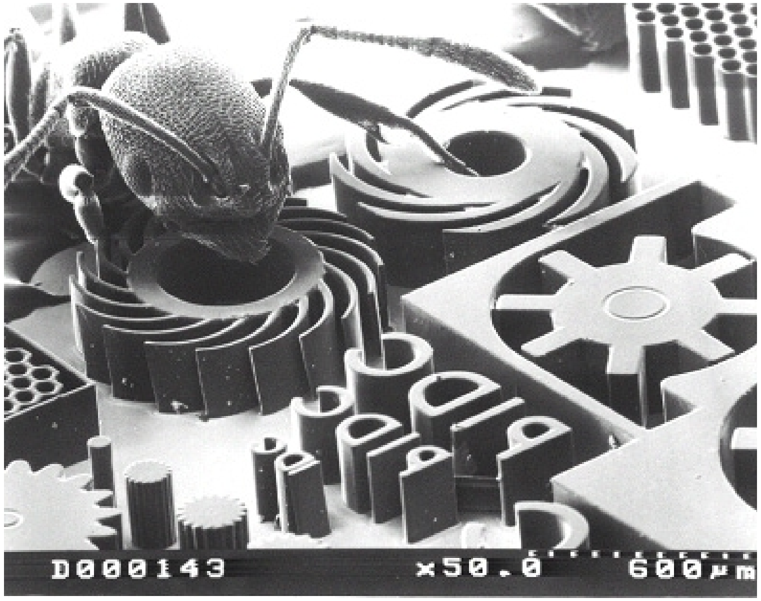
202-767-3572

MEMS

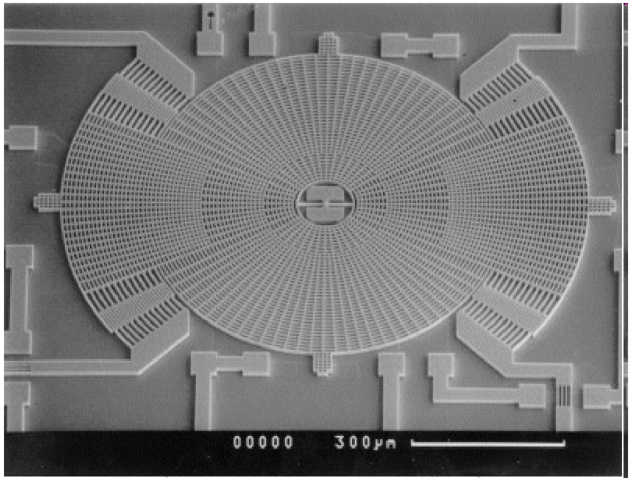
MEMS: Micro-Electromechanical Systems



Micrograph, ante with MEMS structures, developed ~ 10-15 years ago.

Evolution of MEMS

last 10 years

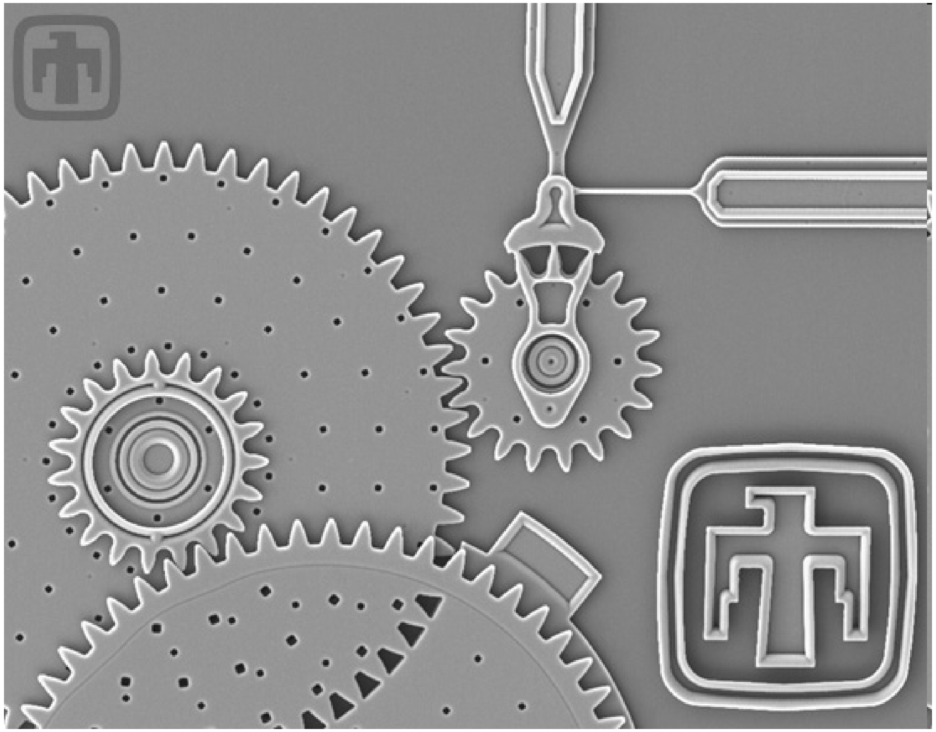


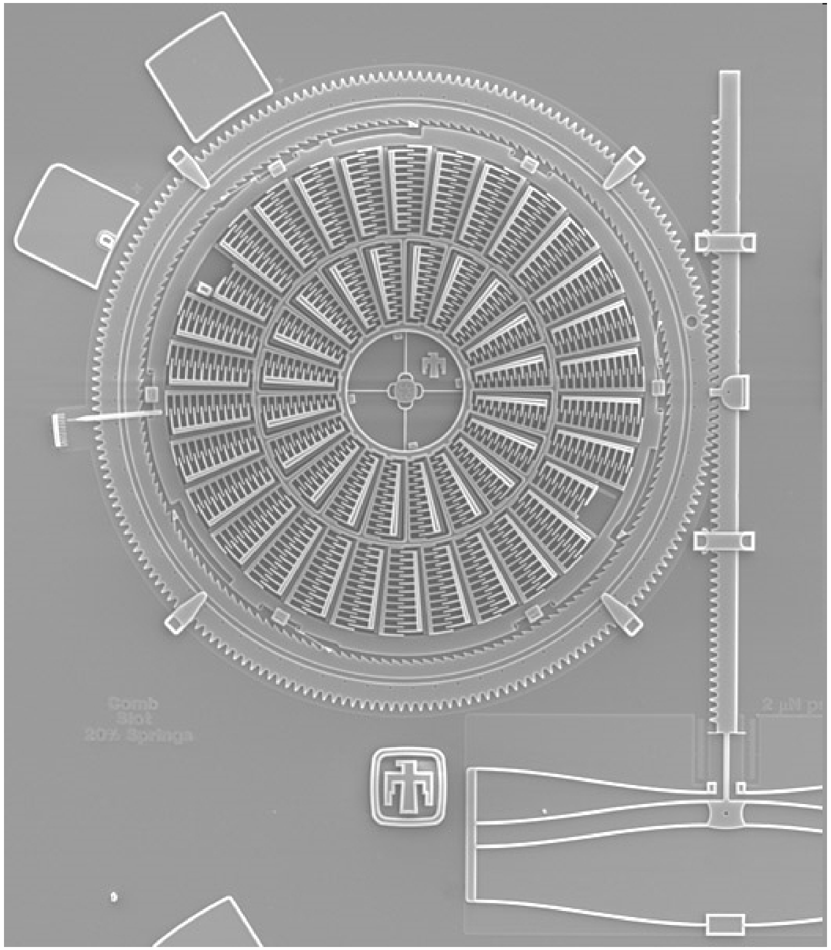
MEMS based gyroscope

images from Fraunhofer Institute and Apple

MEMS

MEMS: Micro-Electromechanical Systems

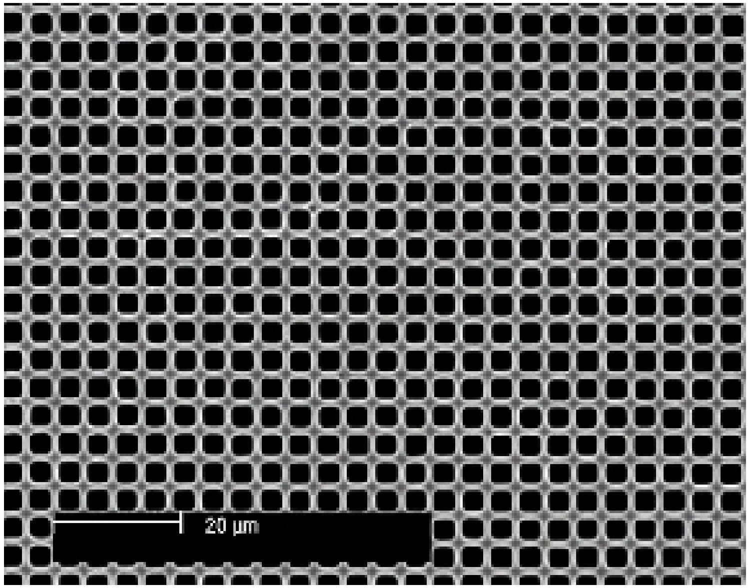


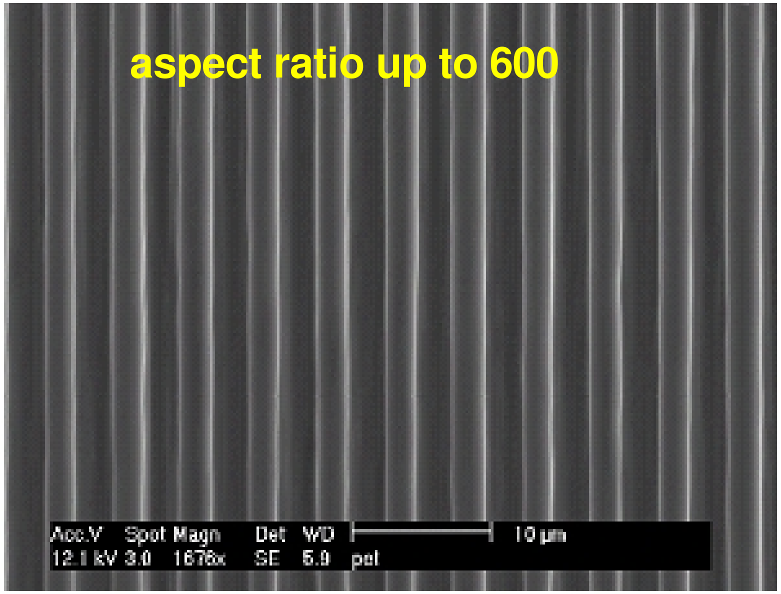


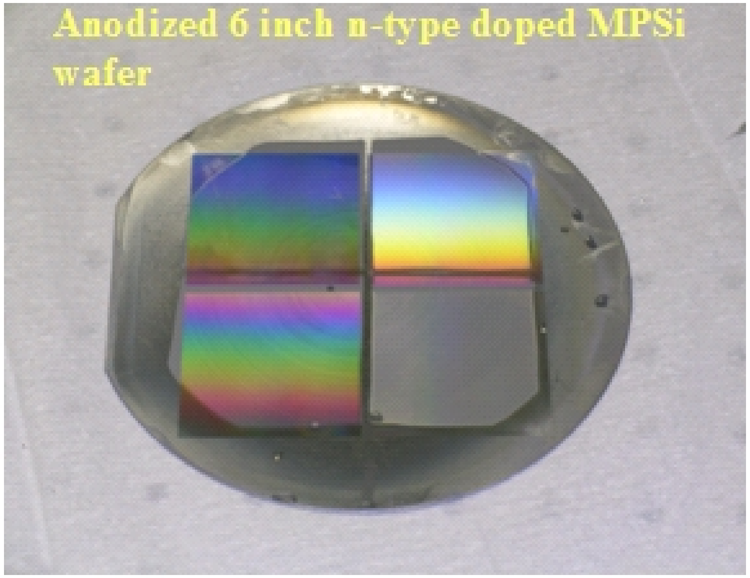
images from Sandia

High Aspect Ratio Structures

one enabling feature:
high aspect ratio structures



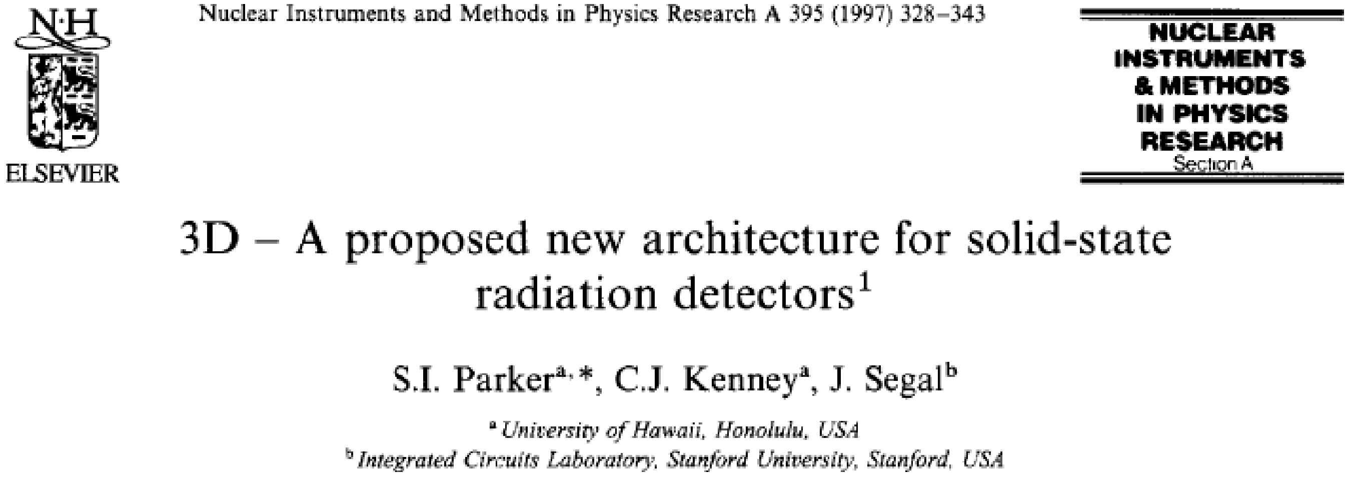

aspect ratio up to 600


Anodized 6 inch n-type doped MPSi wafer

Outline

- Trenched Gamma-Ray Detector
- Curved Radiation Detector

3-D Detectors



ELSEVIER

Nuclear Instruments and Methods in Physics Research A 395 (1997) 328–343

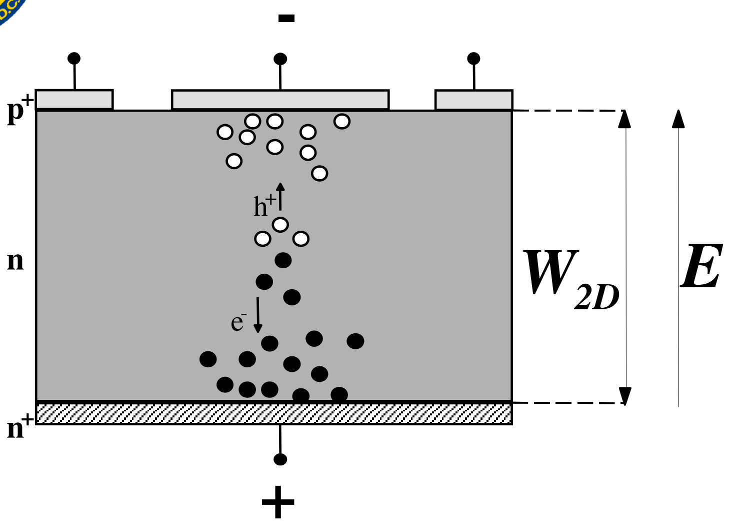
NUCLEAR
INSTRUMENTS
& METHODS
IN PHYSICS
RESEARCH
Section A

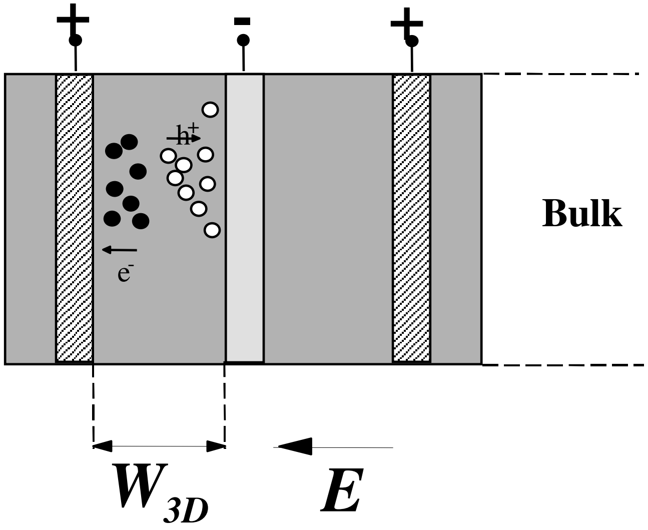
3D – A proposed new architecture for solid-state radiation detectors[1]

S.I. Parker[a,*], C.J. Kenney[a], J. Segal[b]

[a] *University of Hawaii, Honolulu, USA*
[b] *Integrated Circuits Laboratory, Stanford University, Stanford, USA*

Standard 3-D Detectors





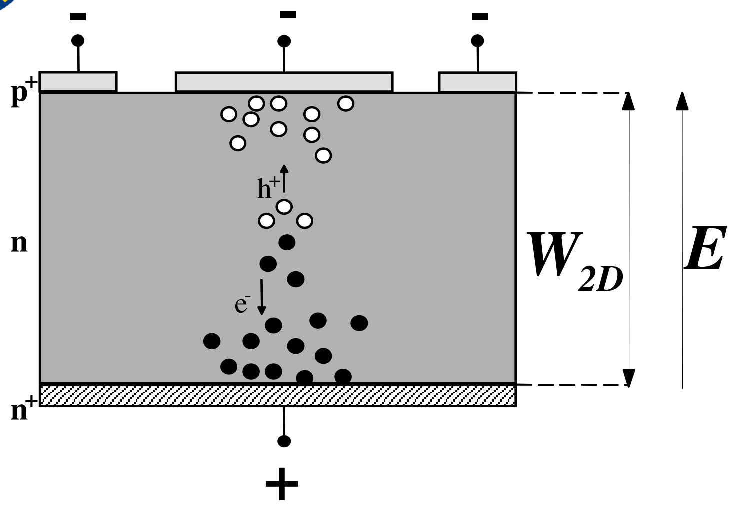
short distance between electrodes:

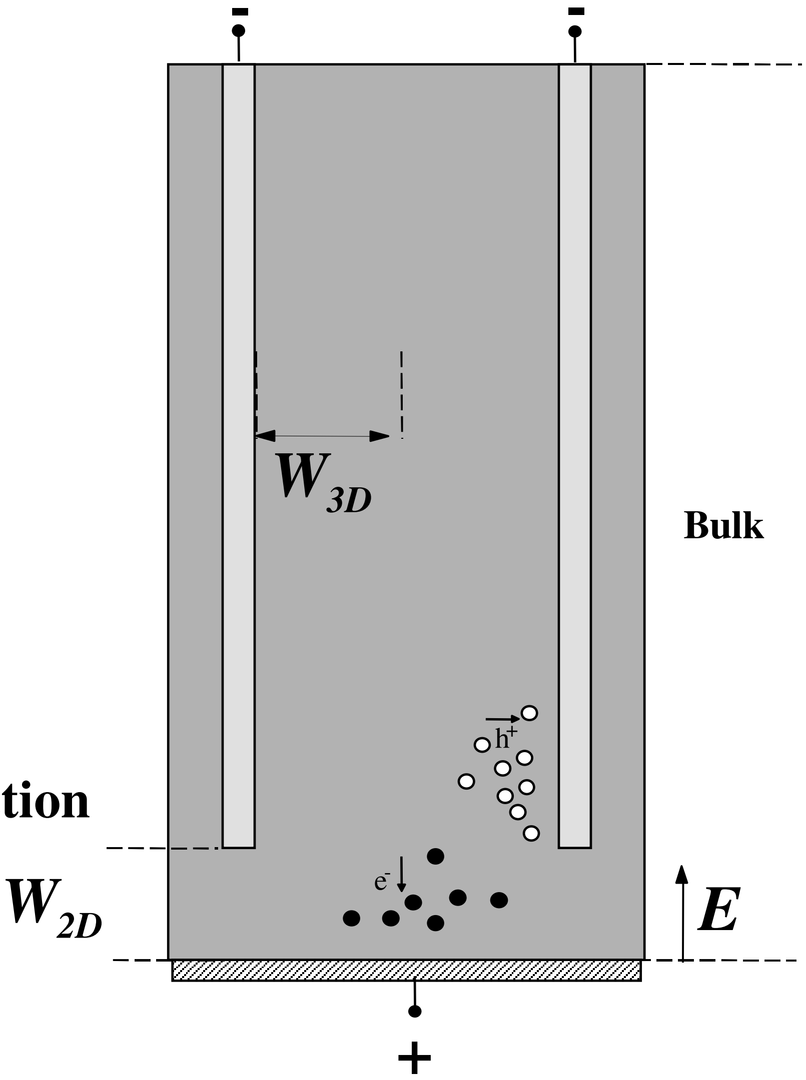
- **low full depletion voltage**
- **short collection distance**
  - ➢ **more radiation tolerant than planar detectors!**

DRAWBACK: Fabrication process of 3-D devices is not standard.

S.I. Parker, C. J. Kenney, J. Segal, *Nucl. Instr. Meth. Phys. Res. A* 395 (1997) 328

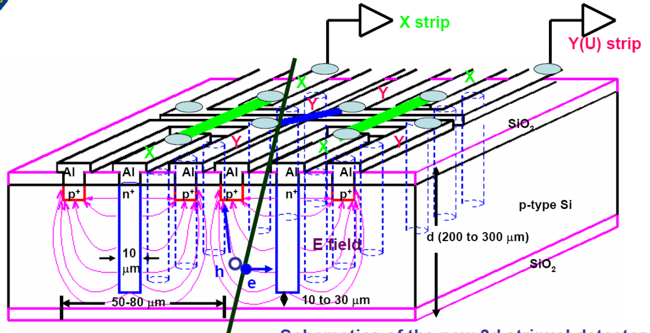
Trenched Gamma-Ray Detector - Concept





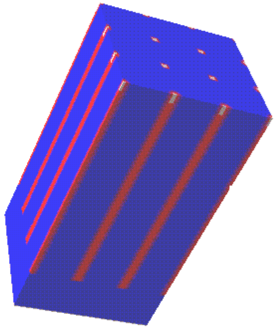
- mm thick detectors
- decoupling thickness and depletion voltage

Trenched Gamma-Ray Detector - Concept

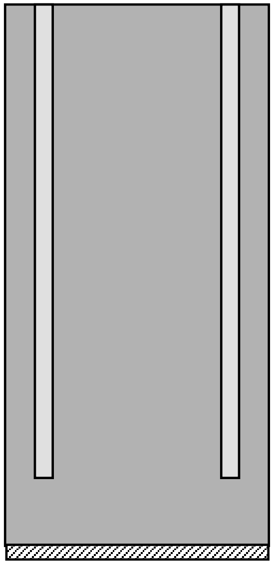


Schematics of the new 3d stripxel detector

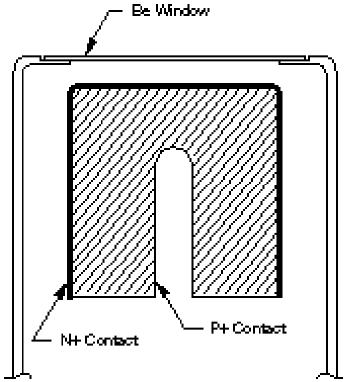
Z. Li, et al., *Nucl. Instr. Meth. Phys. Res. A* 139 (2007)



C. Piemonte, et al., *Nucl. Instr. Meth. Phys. Res. A* 541 (2005)



Trenched Gamma-Ray Detector



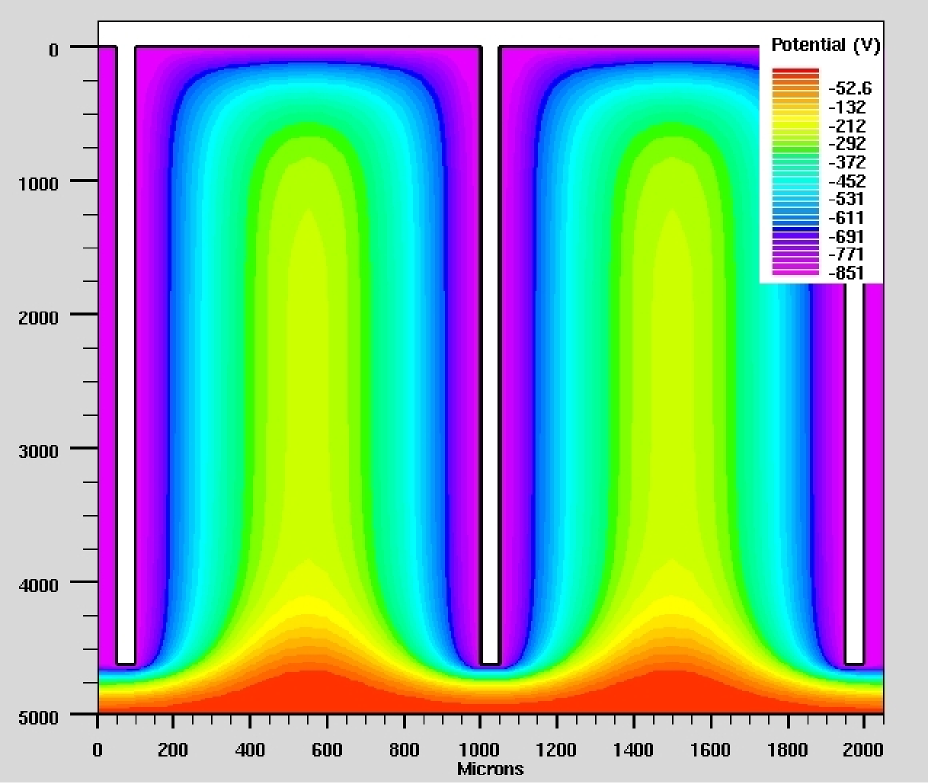
Coaxial Ge Detector

~ 0.3 – 0.5 mm

2-5 mm

~ 30 mm

Finite Element Simulations – Ideal Structure

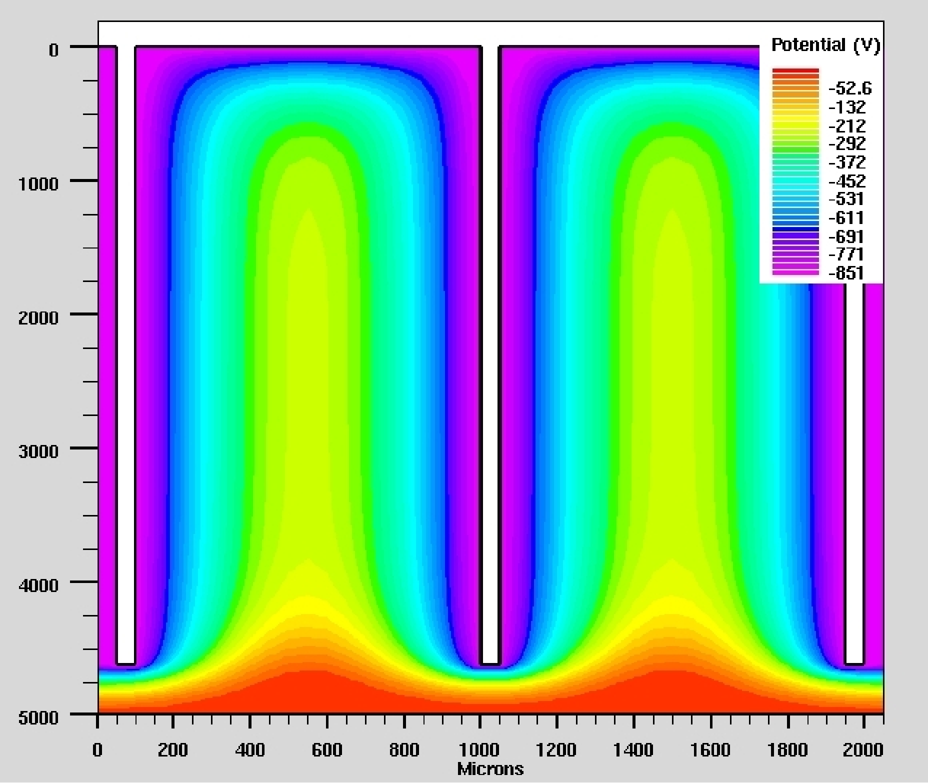


Silvaco® simulation result

Our goal:

5 mm thick trenched detector with near trenches for lateral depletion and charge collection.

Trenched Gamma-Ray Detector - Challenges



Silvaco® simulation result

Fabrication Challenges:

- ***microfabrication*** – high-aspect ratio trench/hole arrays, millimeters deep
- ***junction formation*** – homogeneous junction (no ion-implantation, I^2)
- ***leakage currents*** – maintain high minority carrier lifetime

Microfabrication

NRL Nanoscience Institute

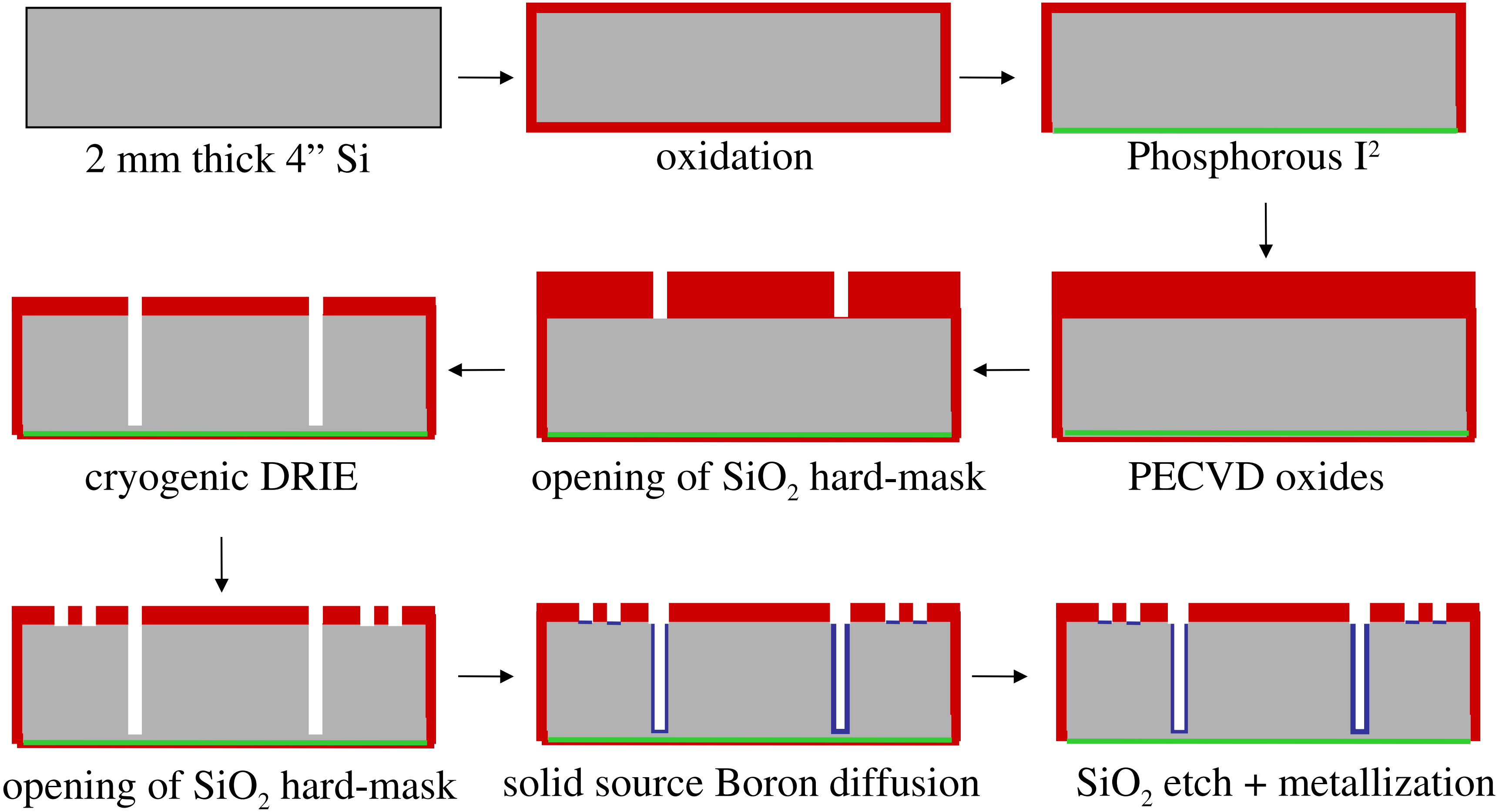
NSI Building
(2003)

- 5000 ft^2 laboratory space
- temperature controlled
- EM shielding
- vibration isolation
- acoustic isolation

Class 100 Cleanroom
5000 ft^2

- SEM (scanning electron microscope)
- pattern generator
- mask aligner
- reactive ion etcher (RIE) & DRIE
- e-beam evaporator

Simplified Process Sequence*



2 mm thick 4” Si → oxidation → Phosphorous I^2

↓

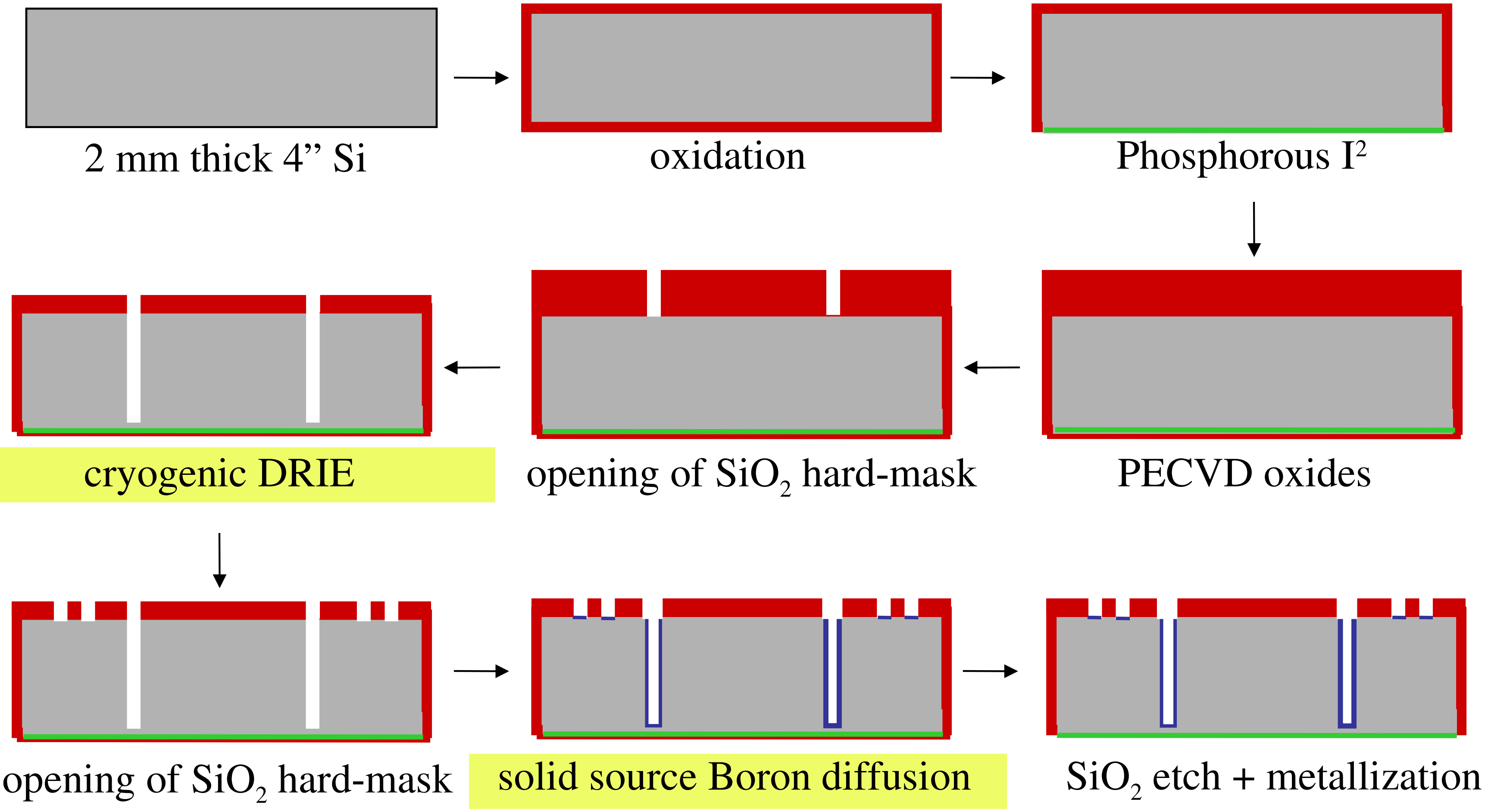
cryogenic DRIE ← opening of SiO_2 hard-mask ← PECVD oxides

↓

opening of SiO_2 hard-mask → solid source Boron diffusion → SiO_2 etch + metallization

* Does not include cleaning steps.

Simplified Process Sequence*



2 mm thick 4” Si

oxidation

Phosphorous I^2

PECVD oxides

opening of SiO_2 hard-mask

cryogenic DRIE

opening of SiO_2 hard-mask

solid source Boron diffusion

SiO_2 etch + metallization

* Does not include cleaning steps.

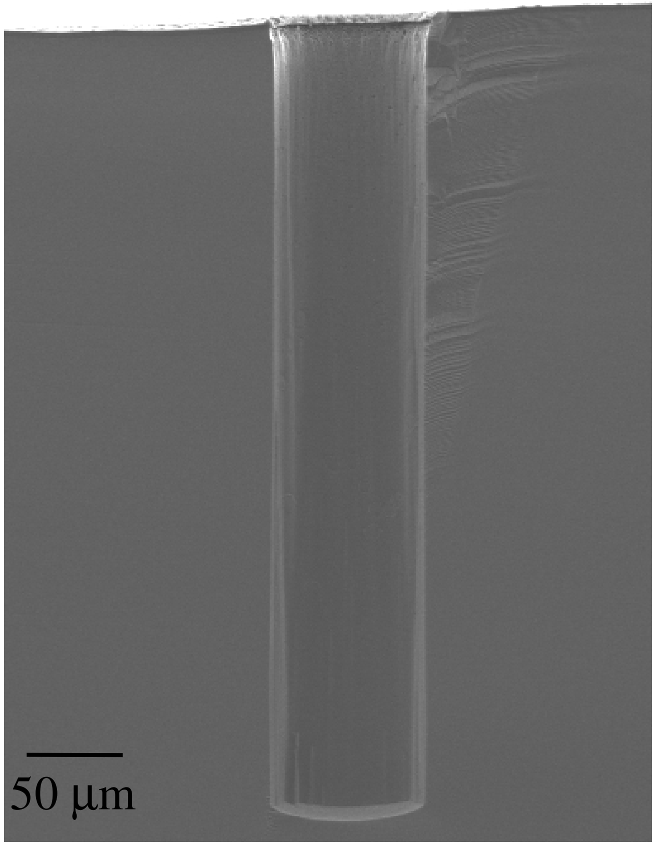
Silicon DRIE (Deep Reactive Ion Etching)

“types” of deep anisotropic plasma etching:

- Bosch process,
- room T continuous process,
- cryogenic process.

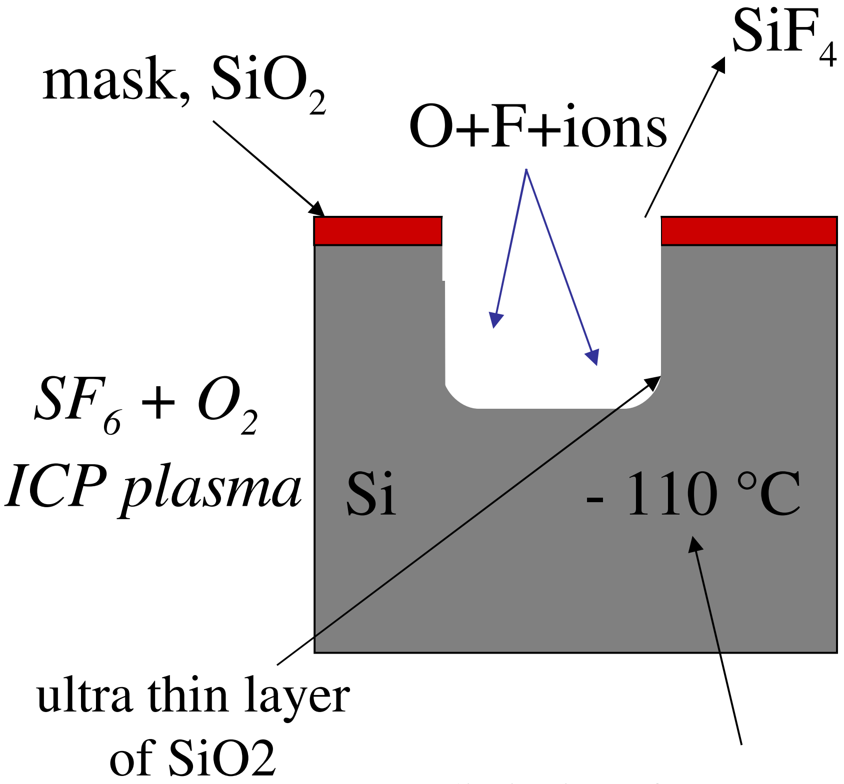
maximal reported depth 300 – 600 µm
(wafer through and via etching)

A. Ayon et al., *Sens. Act. A*, 91, 2001



SEM cross-section micrograph

Cryogenic DRIE



mask, SiO_2

SiF_4

O+F+ions

$SF_6 + O_2$

ICP plasma

Si

- 110 °C

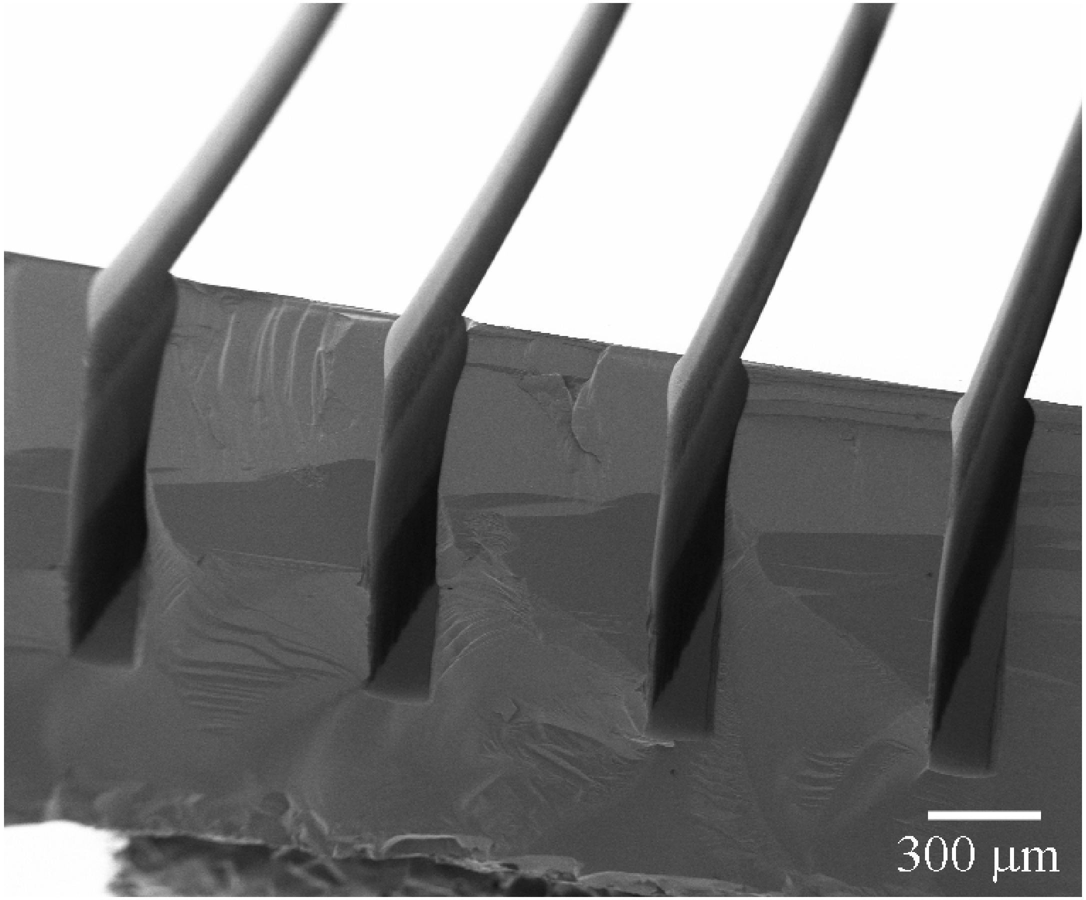
ultra thin layer
of SiO2

limitation of spontaneous chemical
reaction and improvement of O sticking

- no polymer contamination (reactor, substrate) in comparison to Bosch,
- low sidewall roughness,
- **DC bias < 10 V** (no silicon damage)
- **high etch selectivity** ~ 500 – 1,000 to SiO_2,

- BUT sensible process and not so flexible than Bosch process!

Cryogenic DRIE



SEM micrograph, bird's-eye-view.

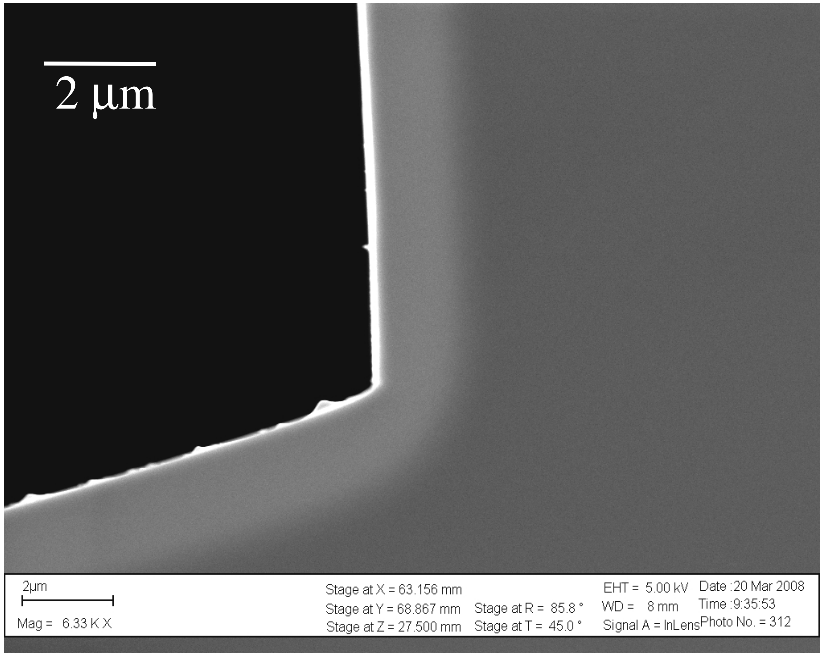
- aspect ratio ~ 12
- 1.75 mm deep

Final devices will have narrower trench arrays.

Boron Diffusion

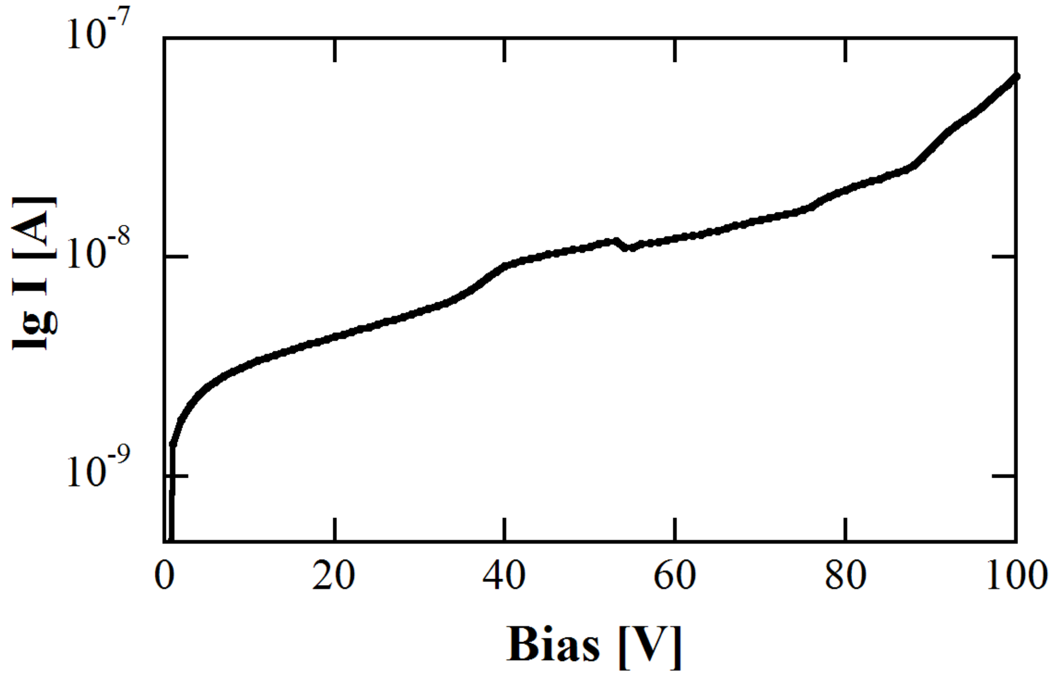
requirements:

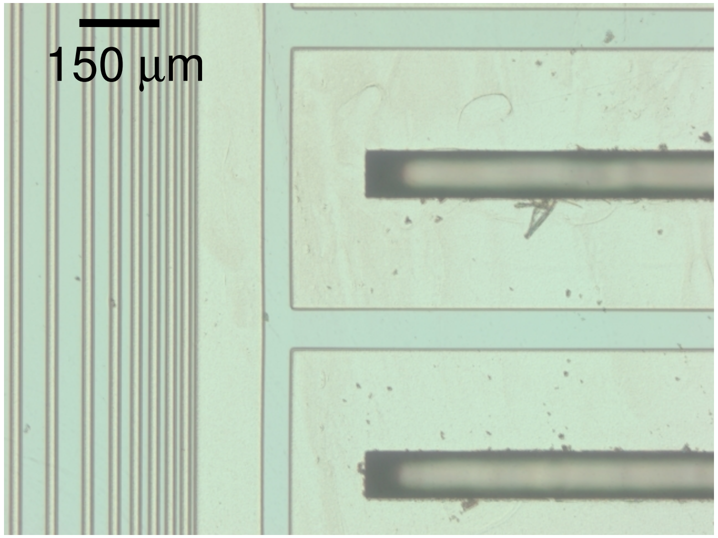
- penetrate trench array (no I^2),
- gaseous, spin-on, or solid source doping,
- no strong gettering effect (like Phosphorous).



SEM cross-section micrograph stain etched Boron junction

Leakage Current

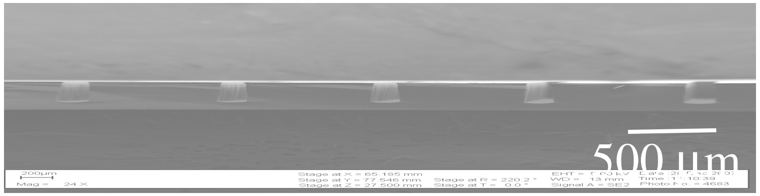


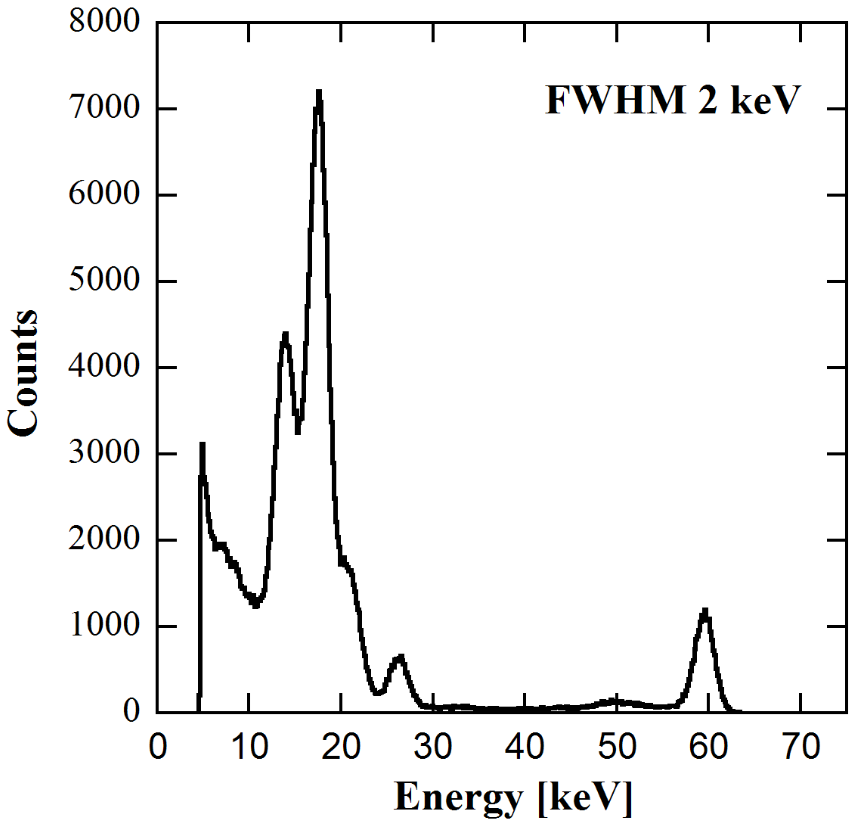


optical micrograph, top-view

- IV curve of trenched 3-D gamma-ray detector (0.5 mm thick silicon substrate)
- low leakage current
- strip dimensions: 0.85 x 7.1 mm

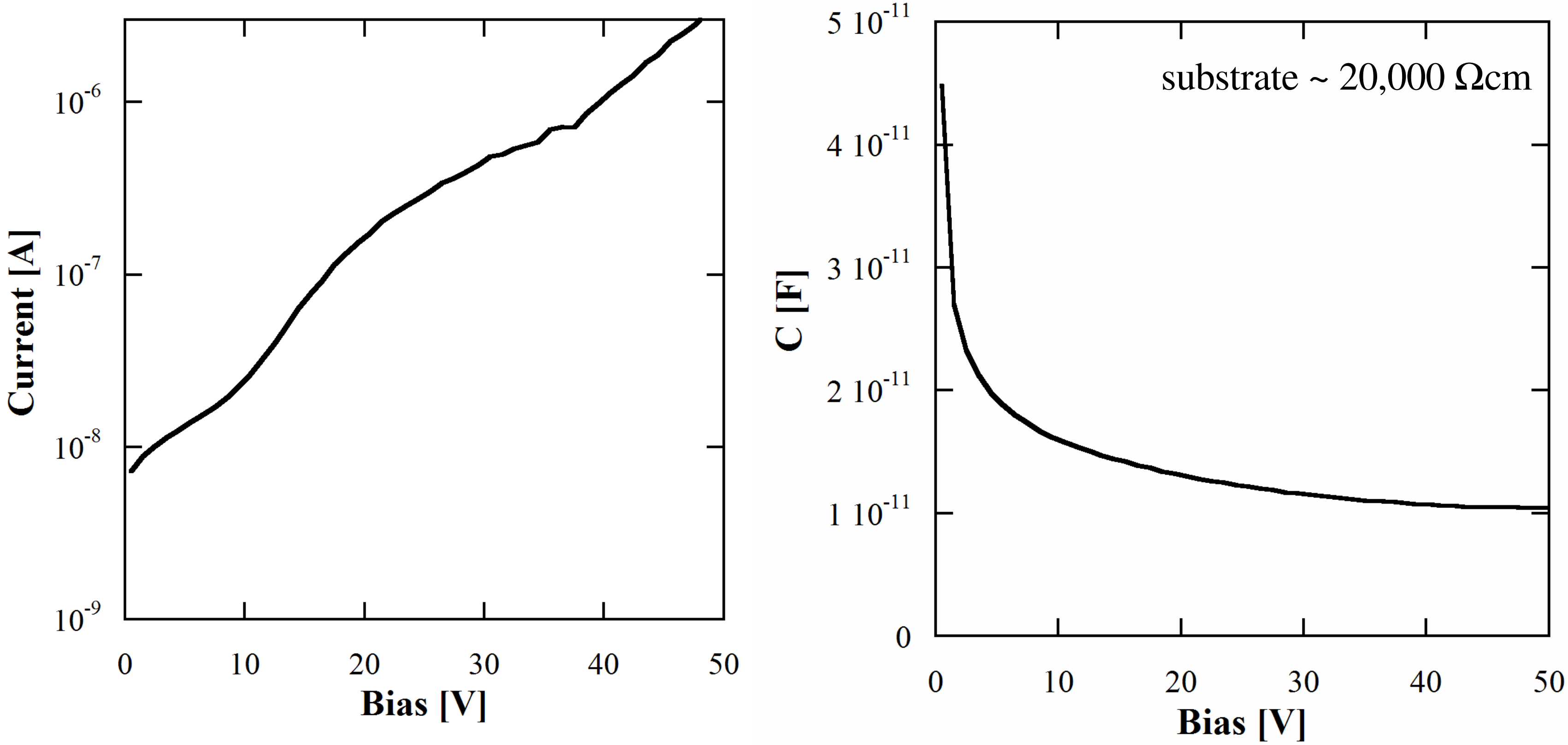
Am-241 Spectrum





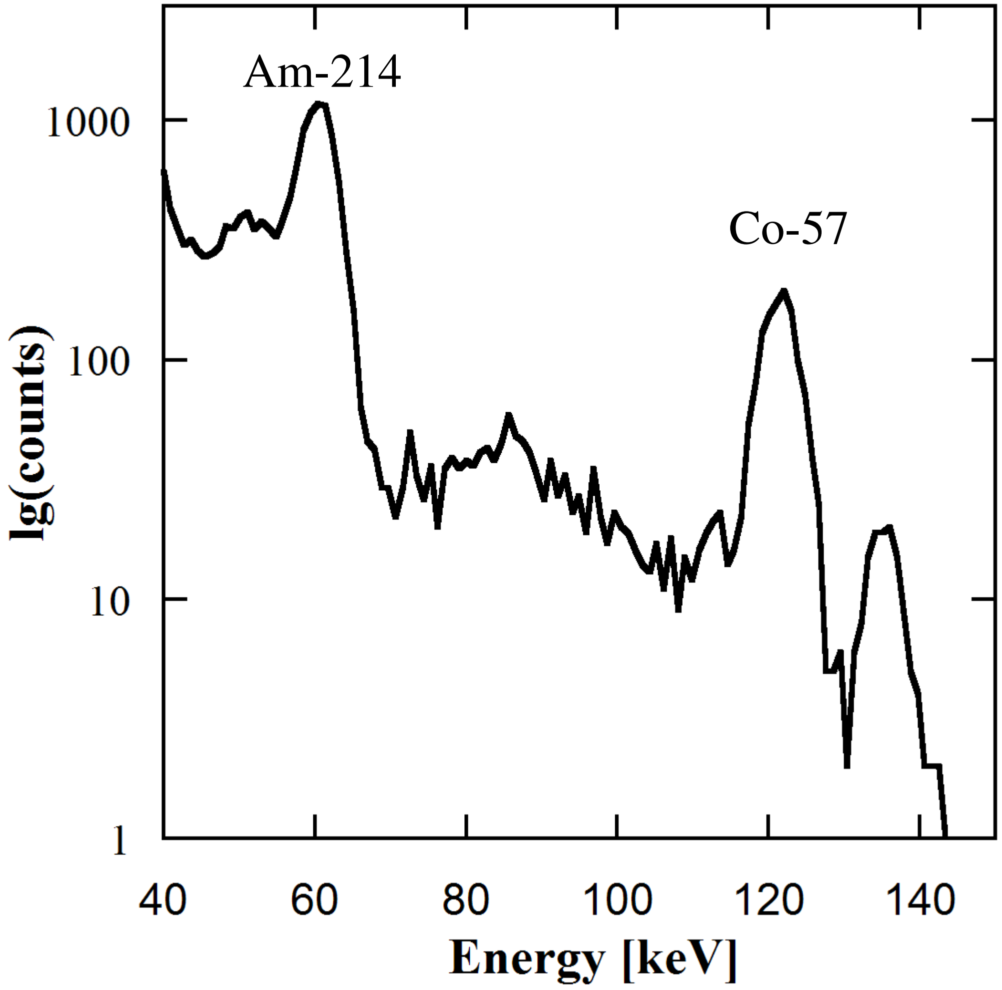
- Am-241 source
- energy resolution is ~ 2.3 keV FWHM at 59.5 keV
- excellent charge collection

2 mm Thick Wafer



- high leakage current due to back-side damage,
- **full depletion at 50 V**.

2 mm Thick Wafer



Am-241 & Co-57 sources

energy resolution: 3.0 keV FWHM at 60 keV

Discussion - Trenched Gamma-Ray Detector

The quest for *millimeter* deep trenches in silicon …

- anisotropy (vertical sidewall),
- mask material (SiO_2…),
- roughness and slope sidewall,
- charge collection inside trenches,
- junction formation,

under control

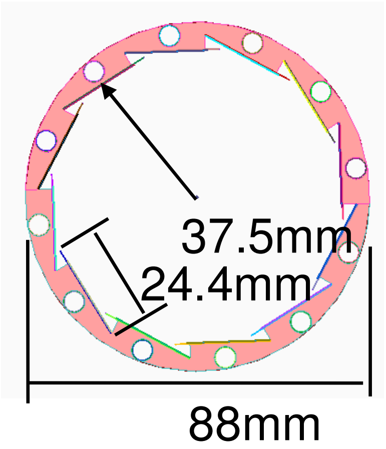
- selectivity SiO_2:mask (O/F, pressure, DC bias),
- etch rate (1-2 µm/min),
- increase the aspect ratio.

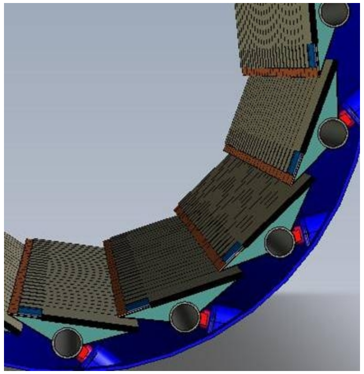
challenges

Outline

- Trenched Gamma-Ray Detector
- Curved Radiation Detector

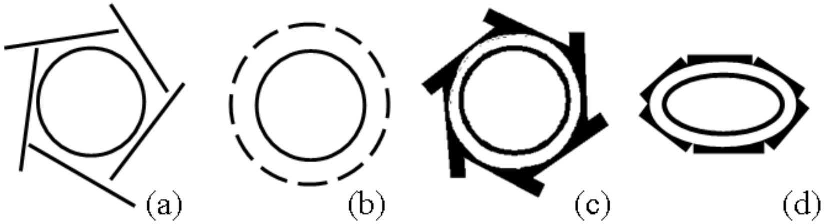
Particle Physics Vertex Detectors





Current

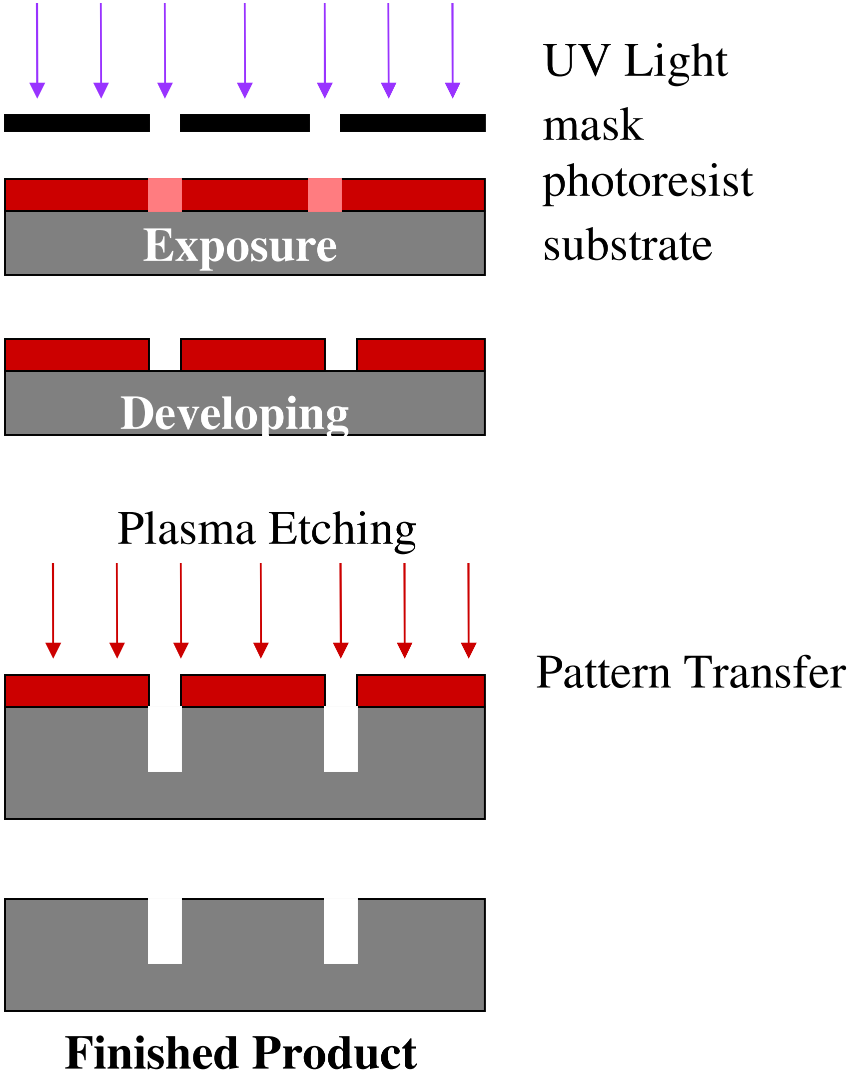
Proposed



- need to shape surfaces
- need high precision
- preserve silicon quality
- no “machining”
- clean room processes only

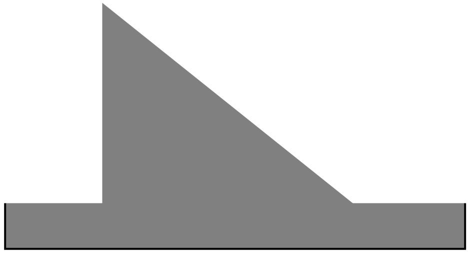
Standard Lithography

- The layer of resist is exposed in specific areas through a mask.
- Development washes away exposed resist.
- A plasma etch step transfers the resist pattern into silicon.
- In the final step, resist is removed.



Gray-Tone Lithography

- Photo-sculpting the photoresist (or other photosensitive materials) by spatially variable exposure.
- The thickness of the photoresist after development depends on the local dose of UV irradiation
- Local dose is adjusted to take into account the non-linear photo-response of the particular photoresist and proximity effects.
- The 3-D resist profiles can be transferred into different etch depths or used for molding. The combination of reactive ion etching and gray-tone lithography is called *gray-tone technology*.



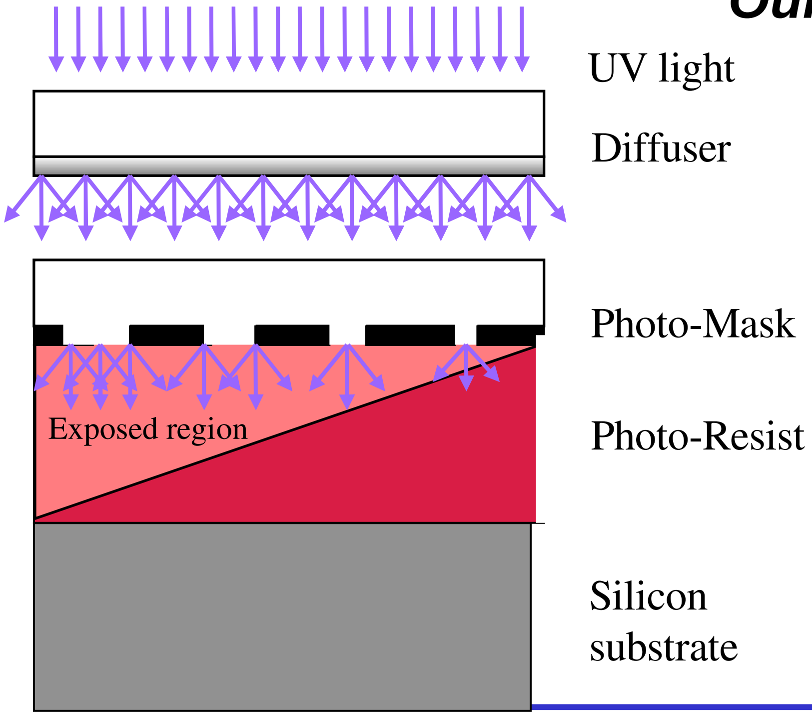
Pattern Transfer - Etching

Gray-Tone Lithography

Traditional Gray-tone Lithography

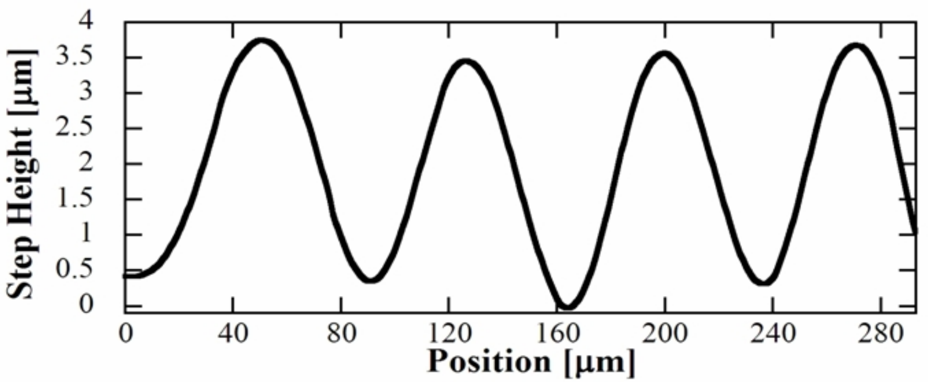
- Stepper exposure: Binary pattern arrays with sub-micrometer resolution on standard chrome-on-glass masks (expensive masks), patented by Gal 1994.
- High Energy Beam Sensitive (HEBS) Glass: Different Ag$^+$ ion concentrations generated by exposing the HEBS-glass , patented and commercialize by Canyon Materials, Inc.,1994.

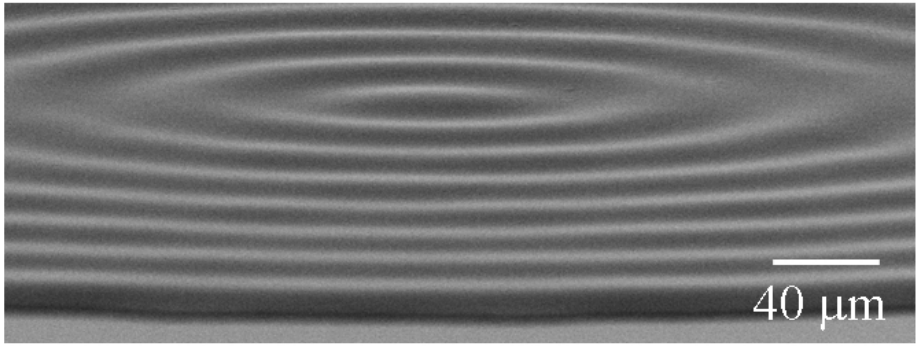
Our Approach



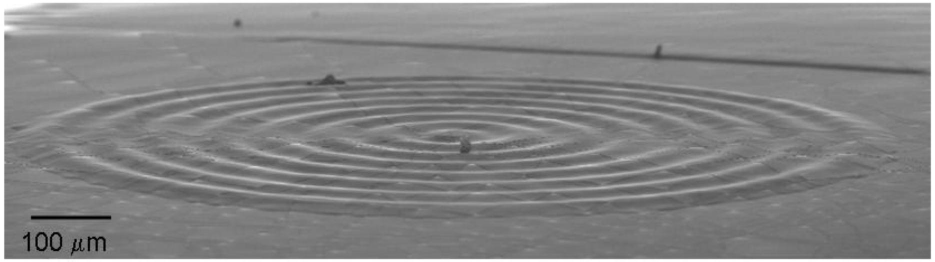
- Our approach presents true gray-tone lithography by using simple contact lithography with an optical diffuser. These contact lithography aligners are widespread in microelectronics laboratories and industry.
- The main idea is to randomize the collimated light using an optical diffuser to generate uniform, controllable intensity distributions in the photoresist.

Gray-Tone Lithography





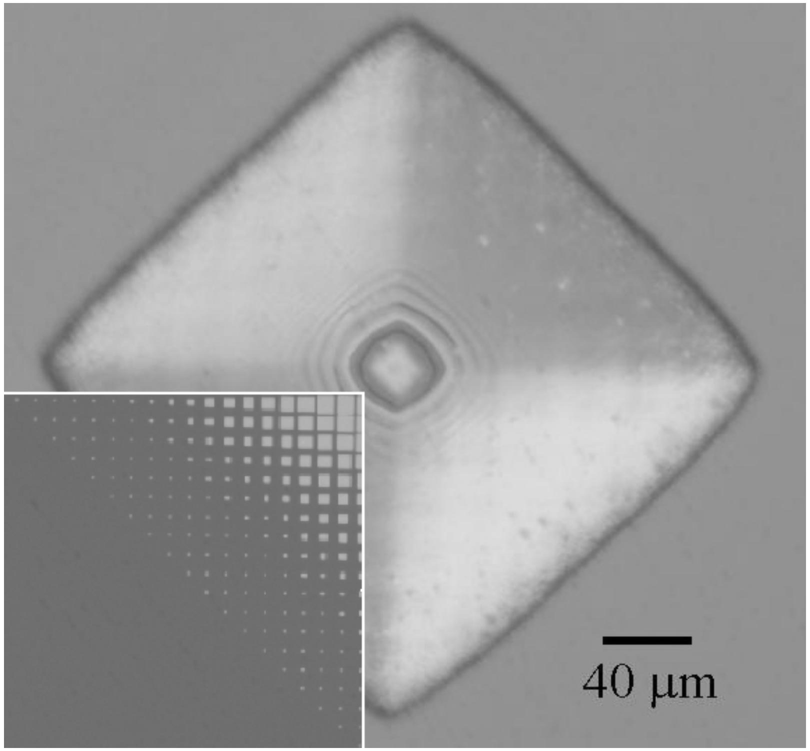
3D sinusoidal resist profile



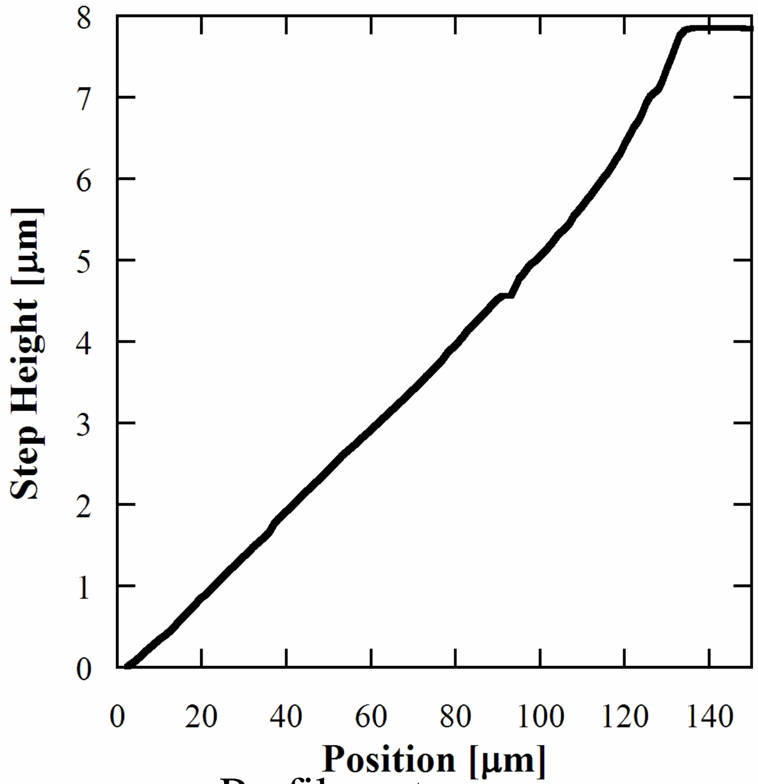
3D molded replica

We successfully have shown complex 3-D resist profiles. PDMS (polydimethylsiloxane) replica structures have been obtained.

Gray-Tone Lithography

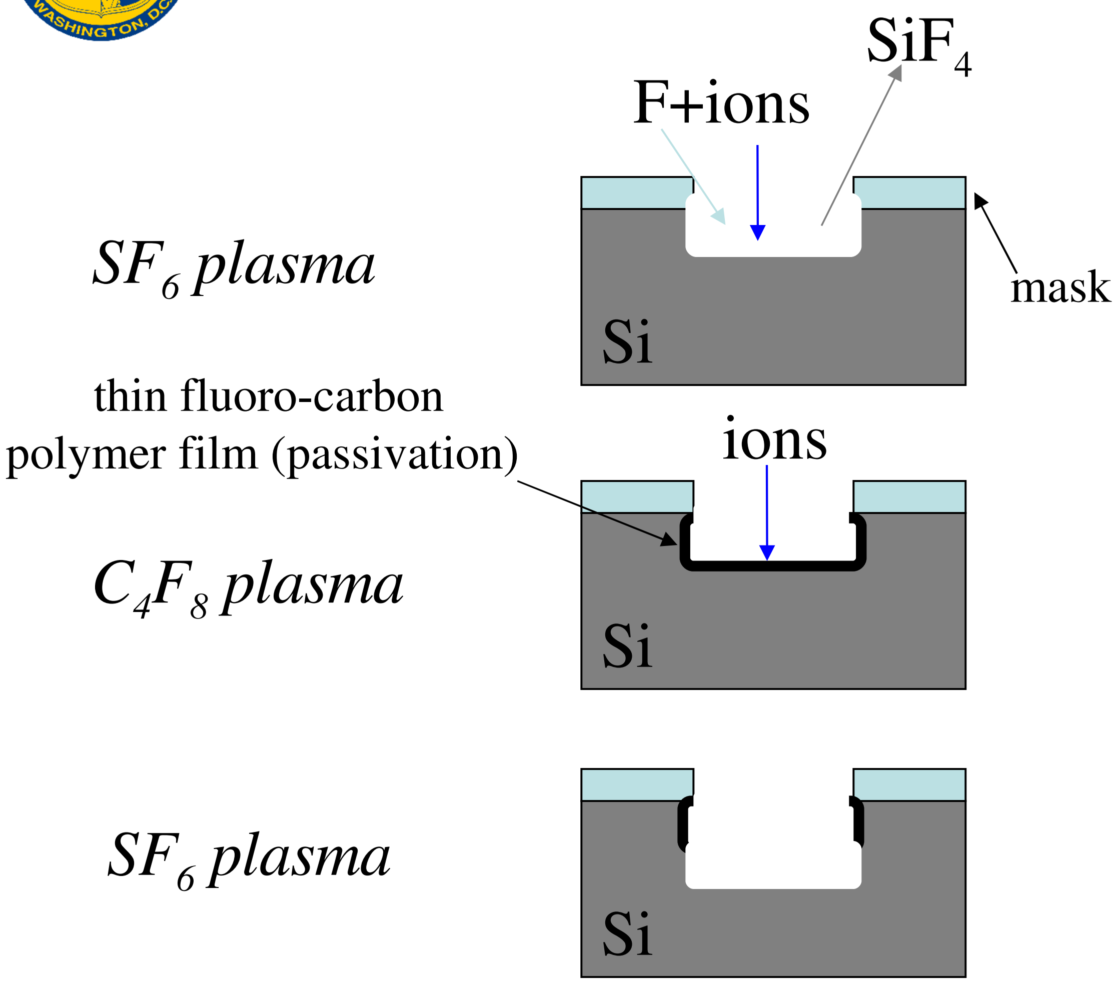


Optical micrograph, top view



Profilometer scan

Deep Reactive Ion Etching



SF_6 plasma

F+ions

SiF_4

mask

Si

thin fluoro-carbon polymer film (passivation)

C_4F_8 plasma

ions

Si

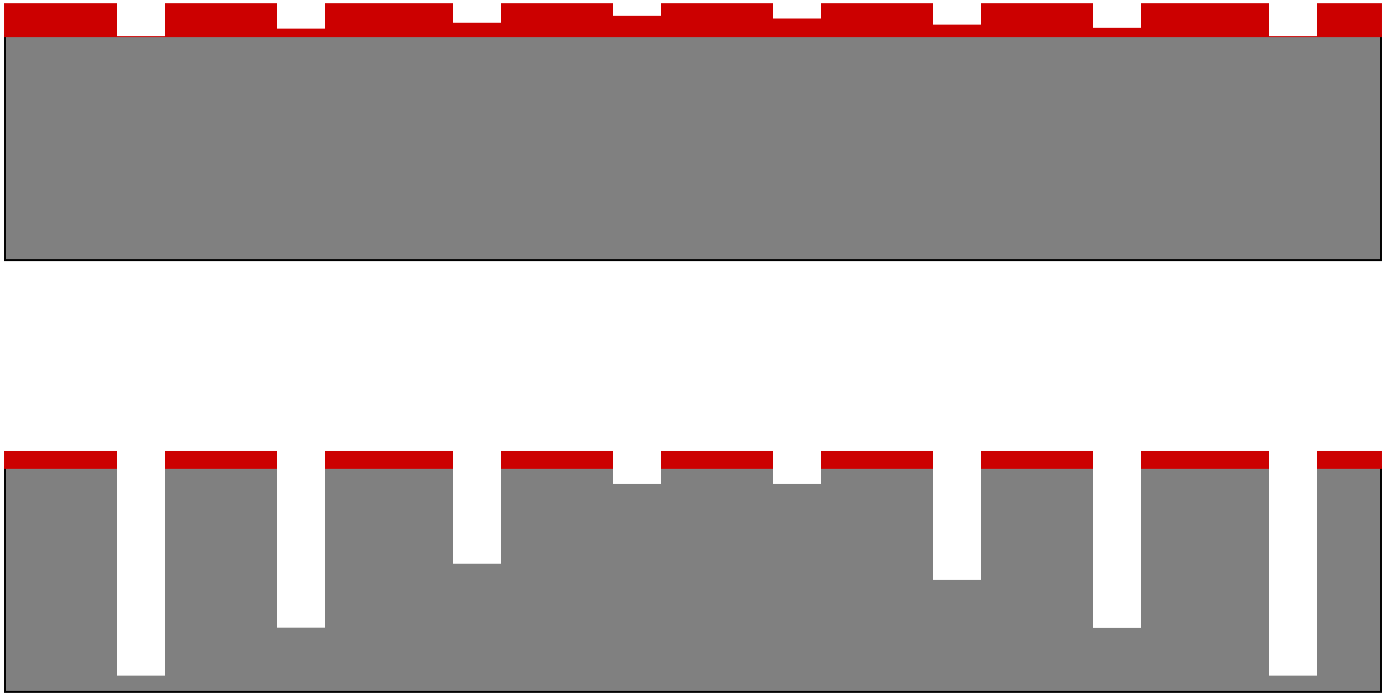
SF_6 plasma

Si

etch selectivity (etch rate silicon vs. photo-resist): 70
sufficient etch rate of photo-resist needed for pattern transfer

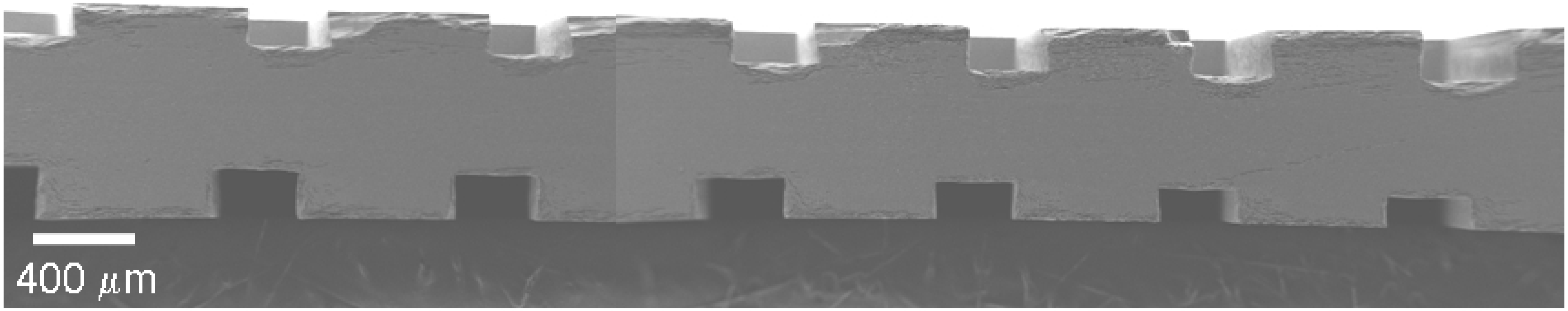
Gray-Tone Lithography

gray-tone resist

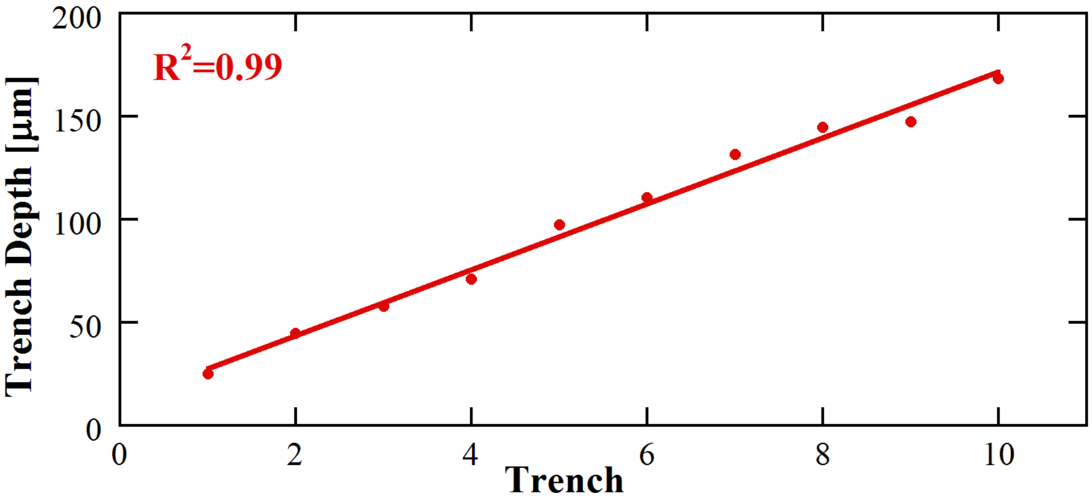


Pattern Transfer - Etching

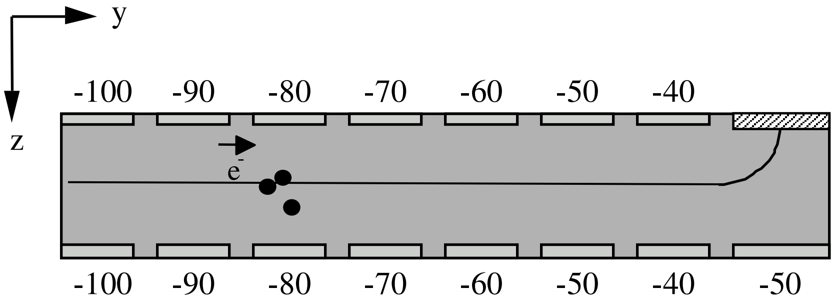
Trench Etching

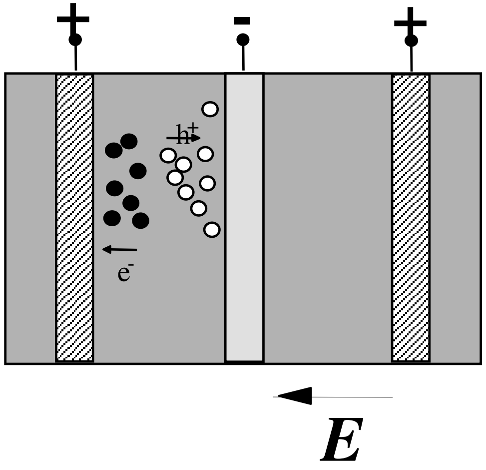


cross section, SEM micrograph



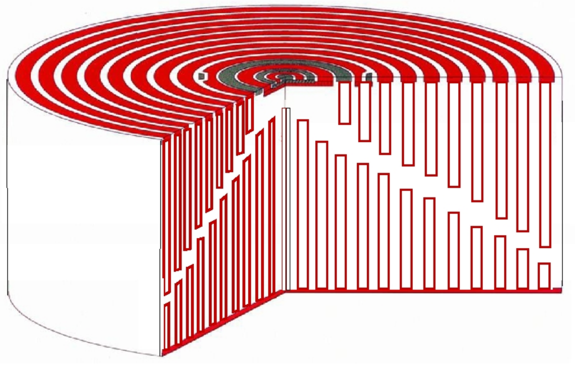
Trenched Gamma-Ray Detector - Concept



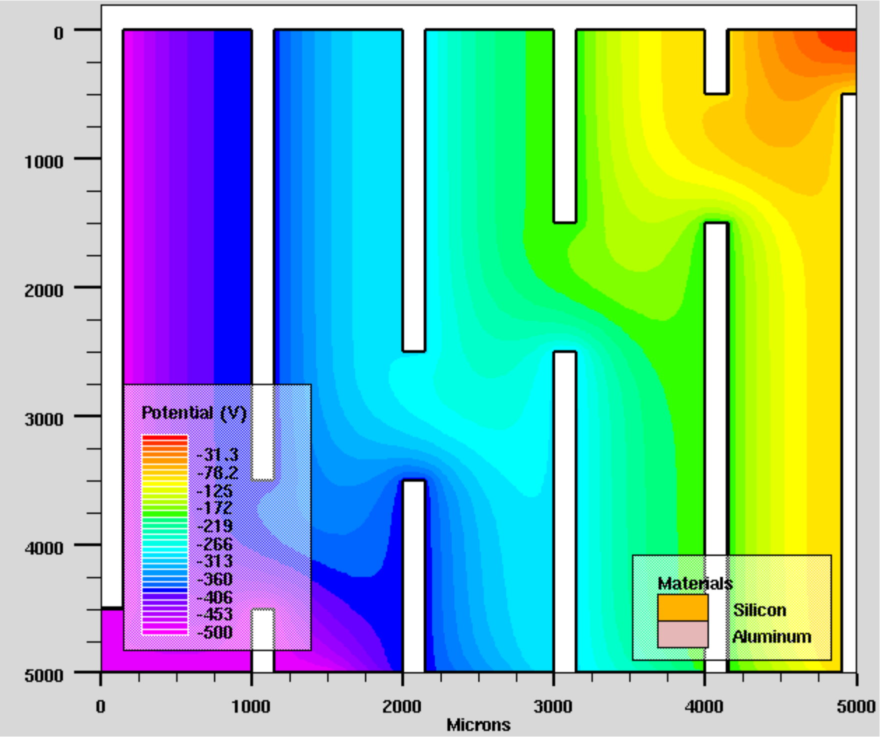


E. Gatti, P. F. Rehak, *Nucl. Instr. Meth. Phys Res. A* 225 (1984) 608

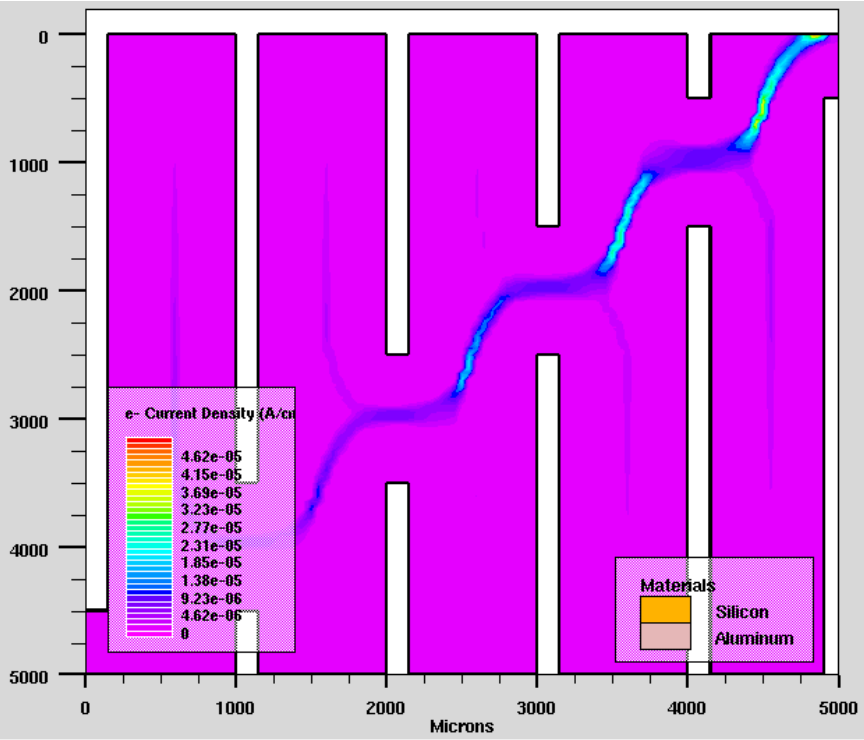
S.I. Parker, C. J. Kenney, J. Segal, *Nucl. Instr. Meth. Phys. Res. A* 395 (1997) 328



Finite Element Simulation

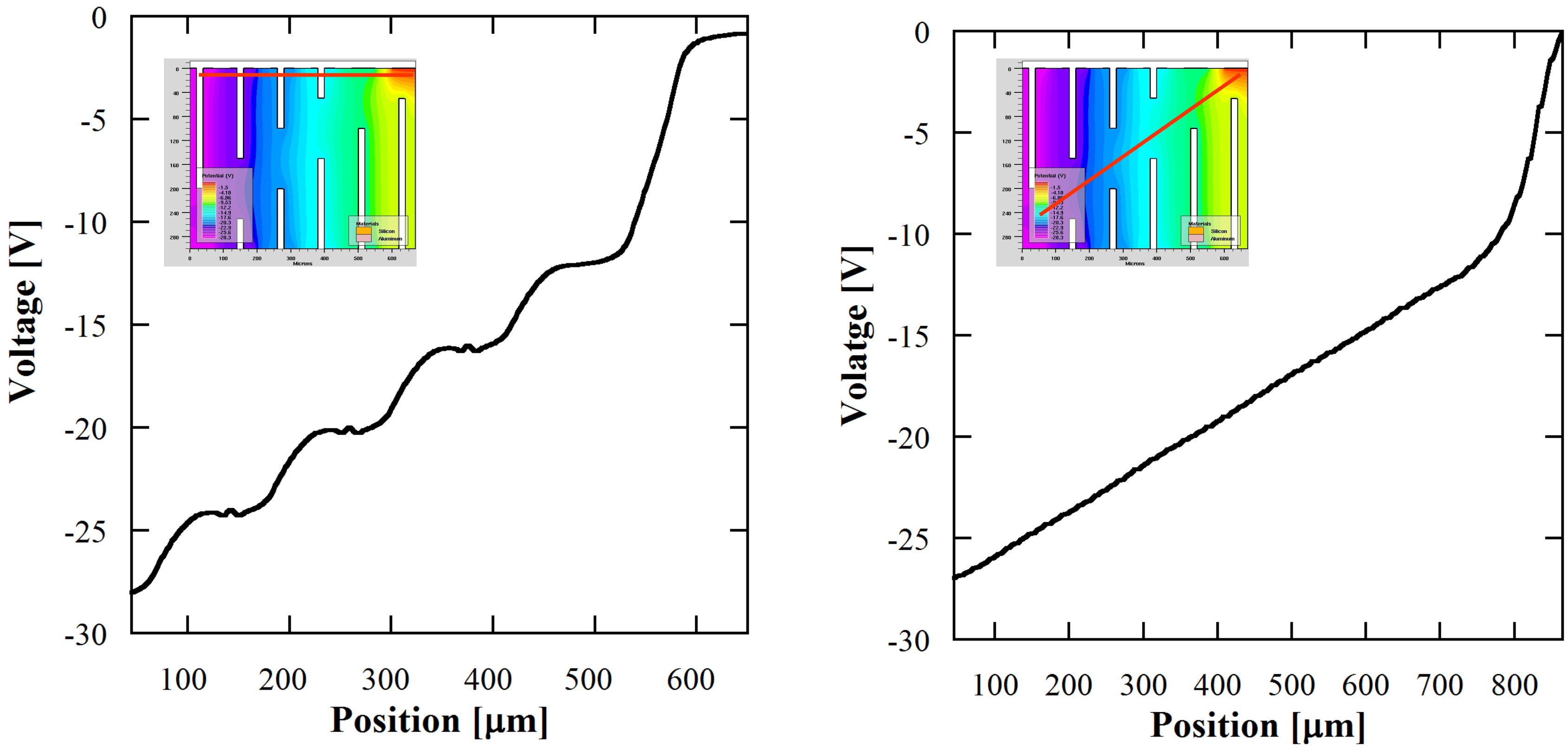


potential distribution



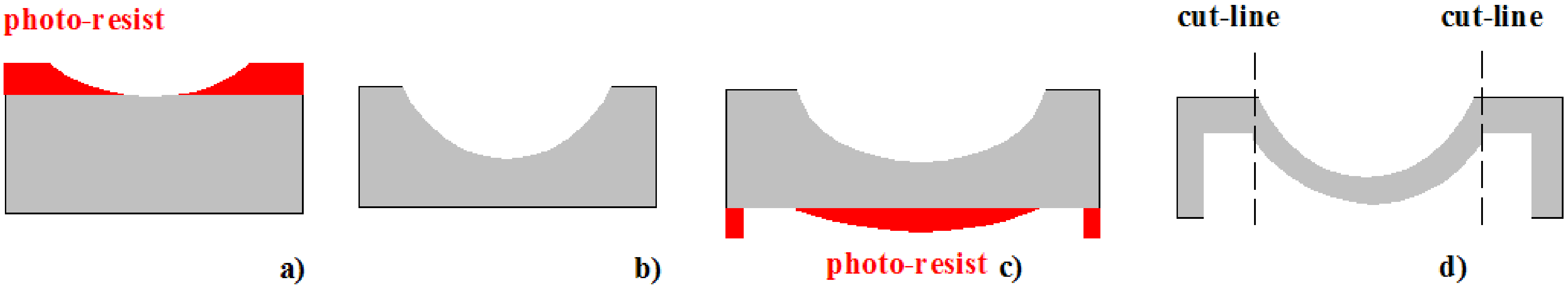
thermal electron leakage current

Finite Element Simulation

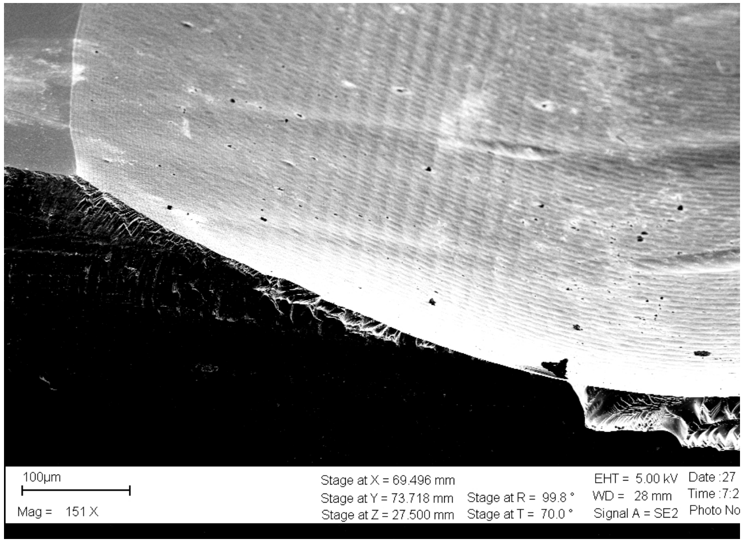


potentials along red lines

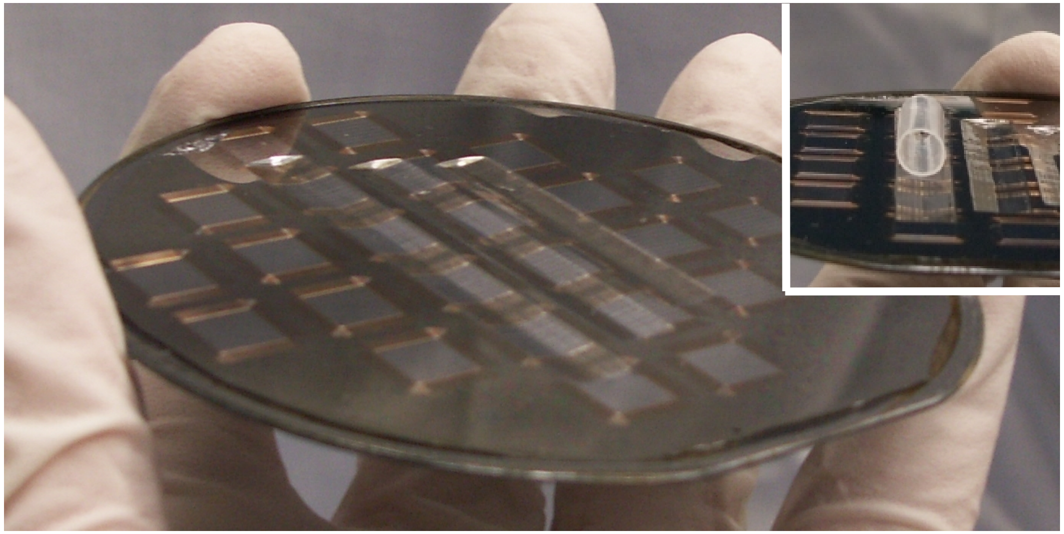
Gray-Tone Lithography – Curved Detector



Curved Detector

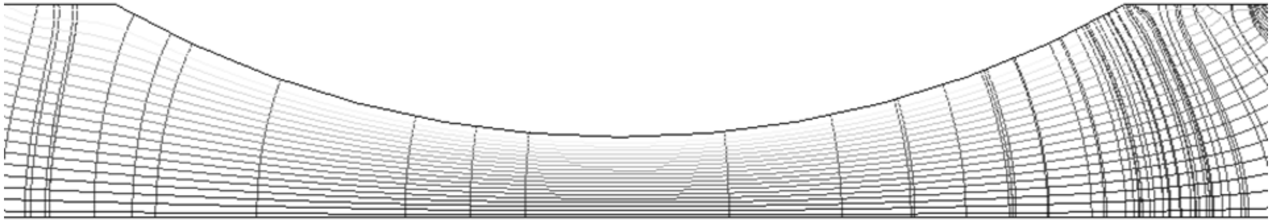


SEM micrograph
mechanical sample



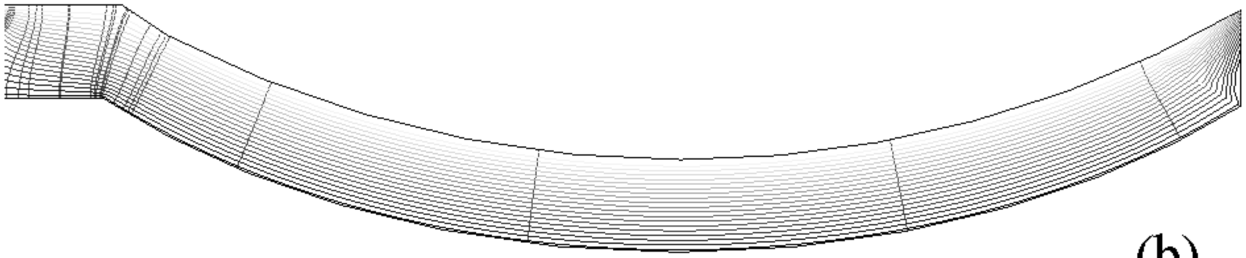
photograph

Curved Detector



single-sided etched

(a)

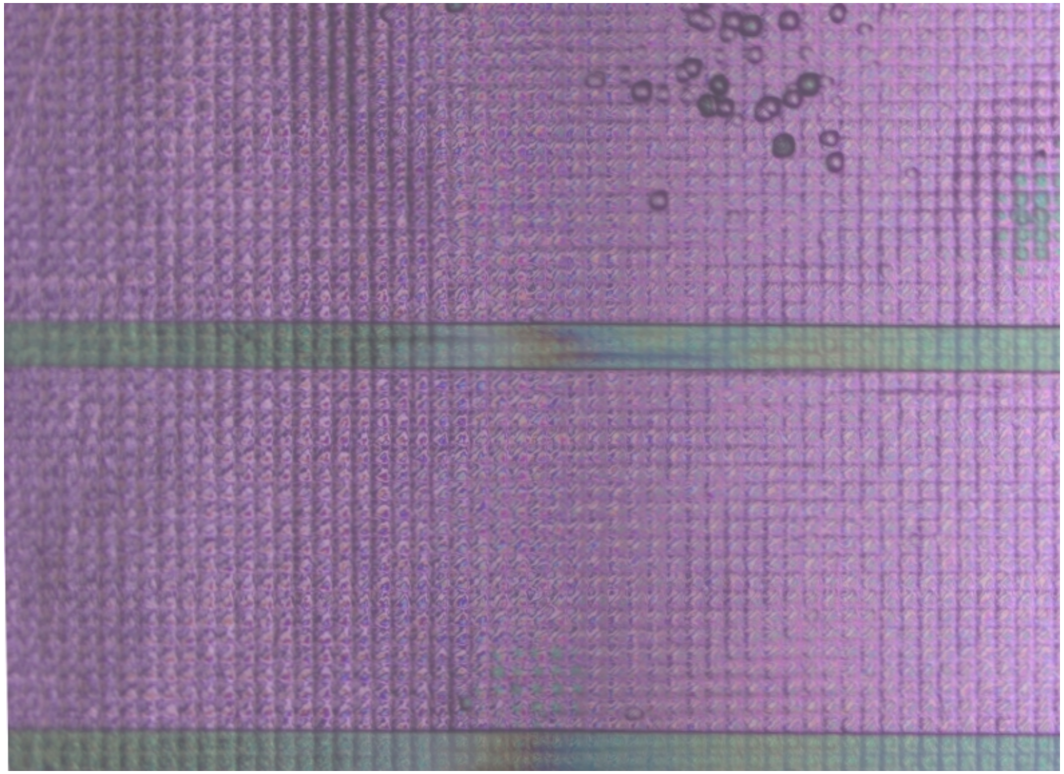


double-sided etched

(b)

- Equipotential and field lines for a partly curved (a) and curved detector (b).
- For the partially curved detector the collection time depends on the position due to thickness variations.

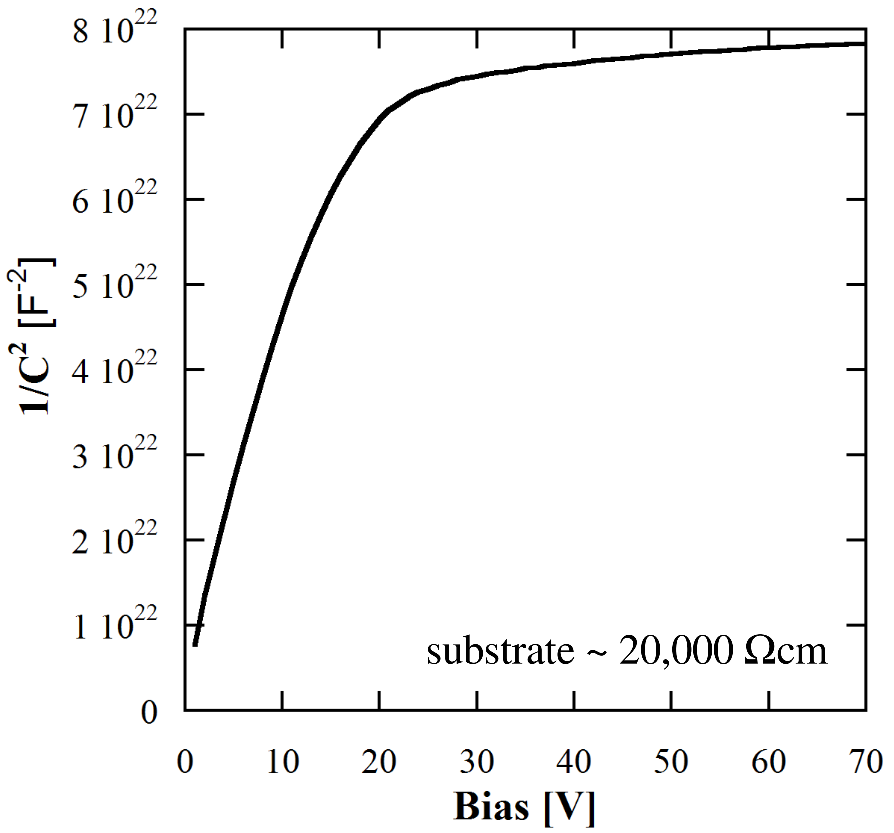
Curved Detector – Strip Detector

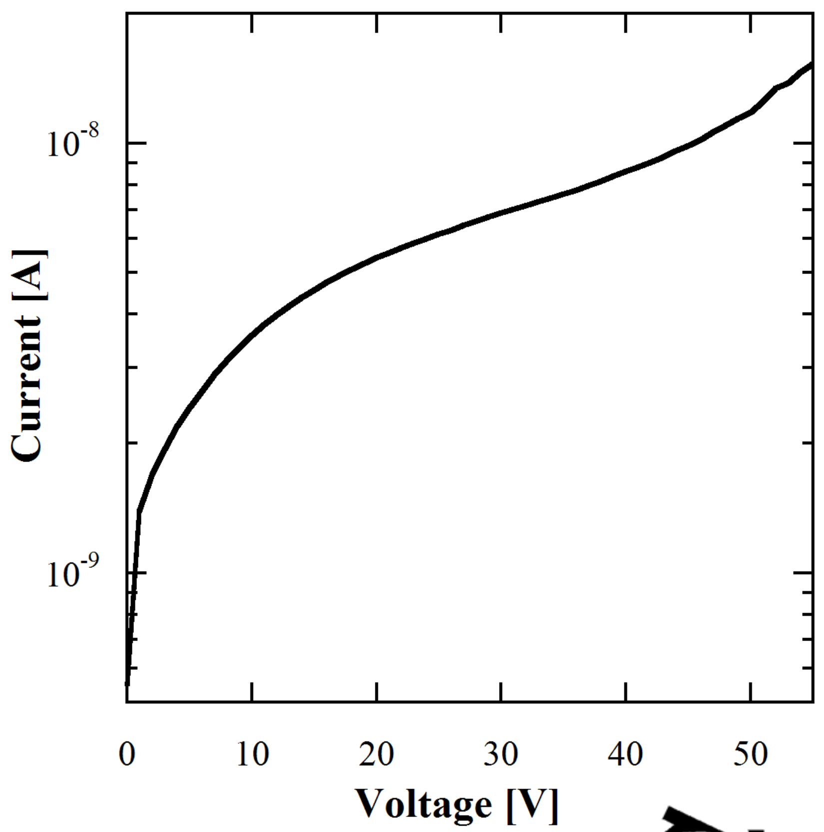


Optical micrograph, top view, strip dimensions 14 x 0.8 mm

- some surface roughness due to Bosch DRIE-etching
- modified lithography on curved surface

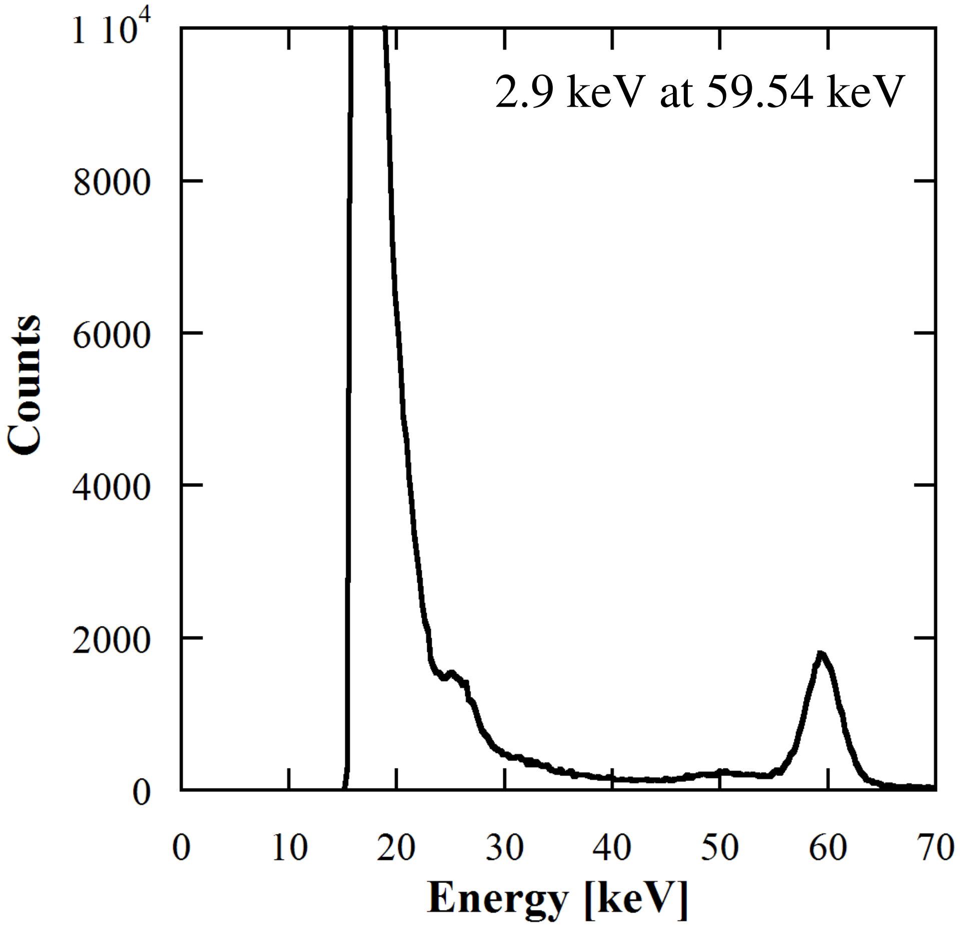
Curved Radiation Detector – IV, CV Curve





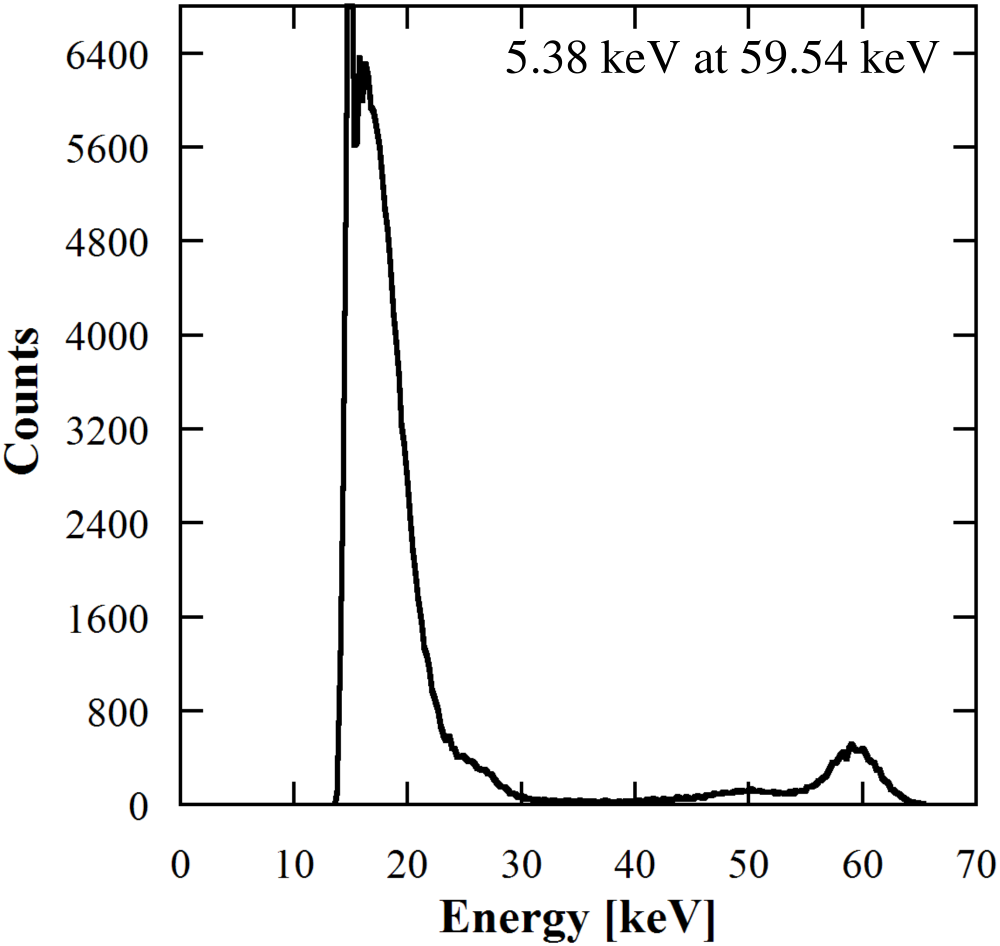
- single-sided strip detector
- half-pipe detector, under reverse bias

Curved Radiation Detector



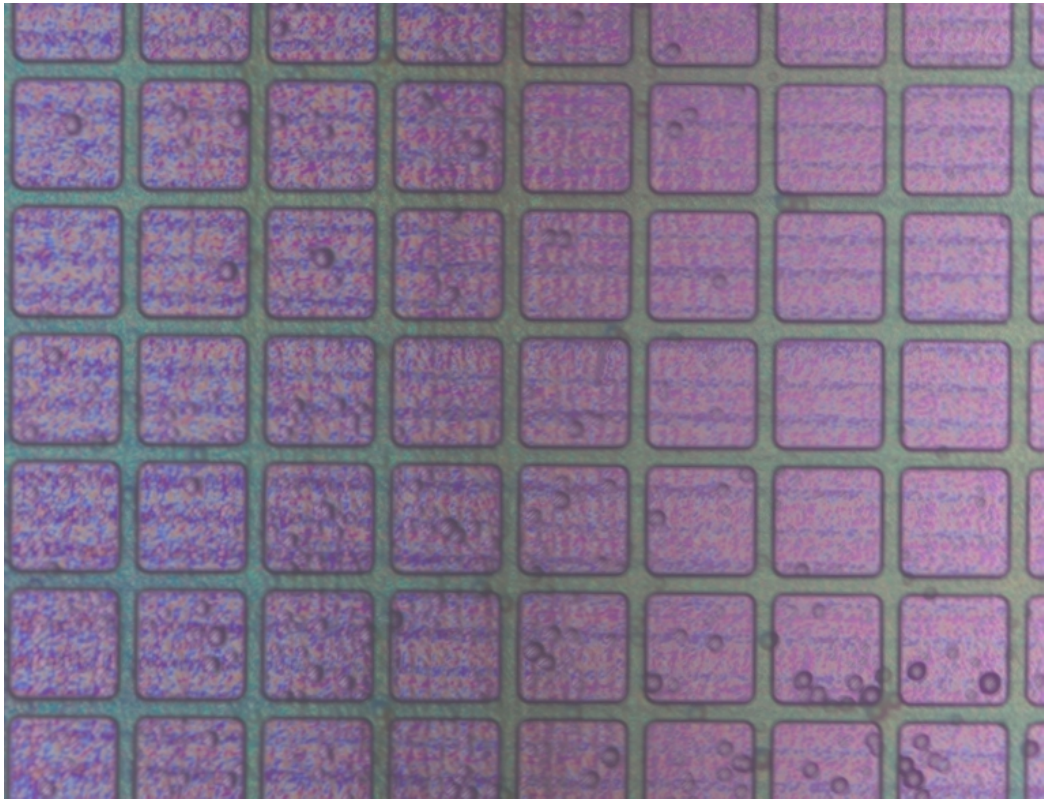
- single-sided strip detector
- half-pipe detector, fully depleted

Curved Radiation Detector



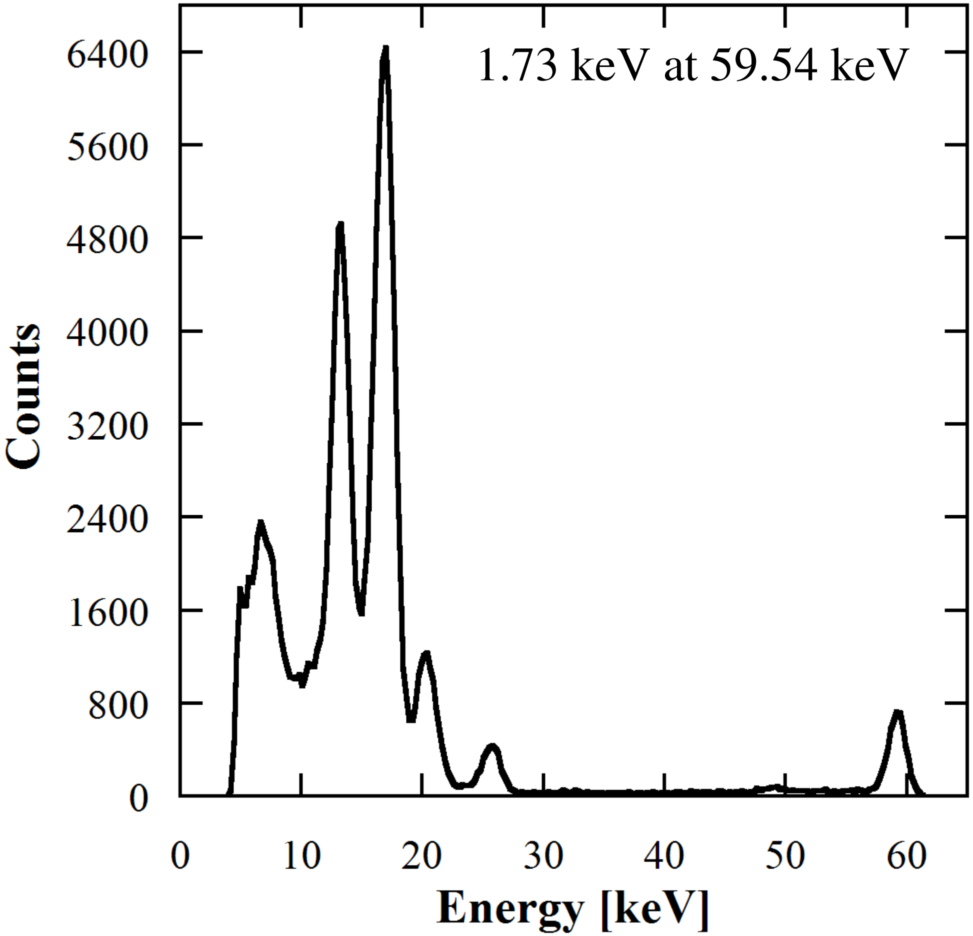
- single-sided strip detector
- double-sided etched detector, fully depleted

Curved Detector – Pixel Detector



Optical micrograph, top view, pixel dimensions 150 x 150 μm

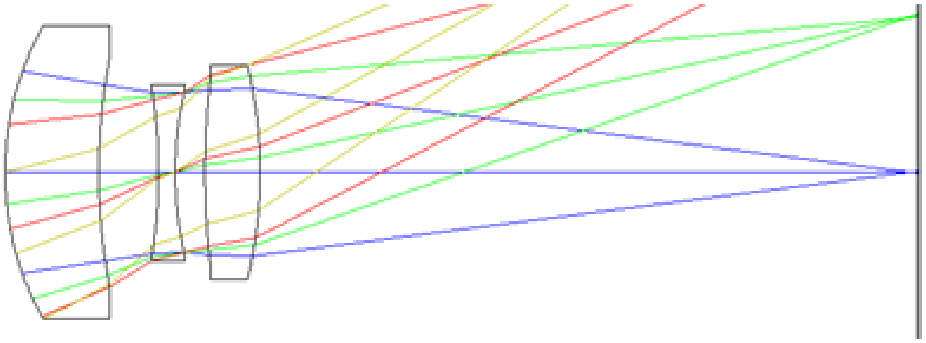
Curved Radiation Detector



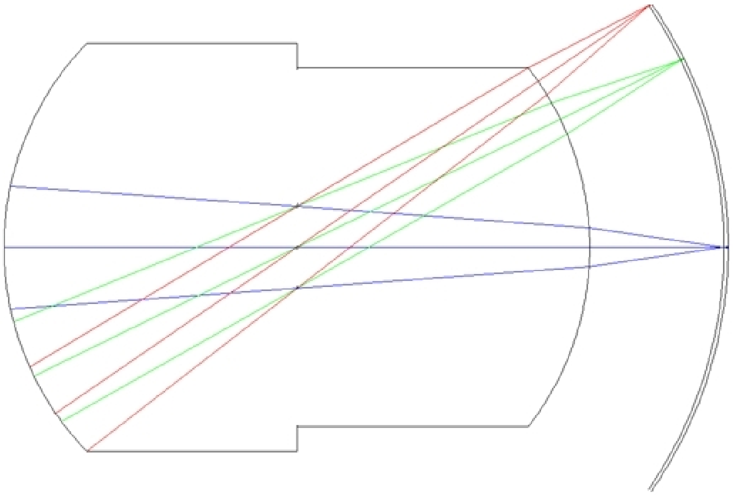
- pixel detector
- half-pipe detector, fully depleted

Outlook – Wide Field of View Camera

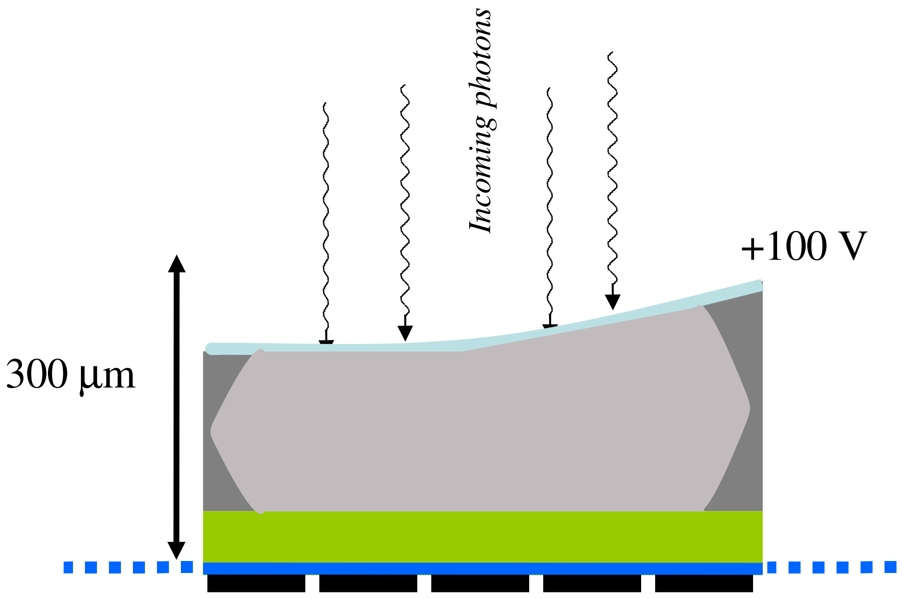
- regular setup
  - 3-element lens
  - planar focal plane array



- curved focal plane array
  - 1-element lens
  - curved focal plane array



Outlook – Wide Field of View Camera



▬ Backside electrode for depletion, ITO (Indium Tin Oxide)

■ p-type silicon

■ depleted

🟩 n-type silicon

▬ Silicon dioxide insulating layer

▬ Polysilicon electrodes

- The use of a high-resistivity substrate permits fully depleted operation at reasonable bias voltages.
- This electric field extends essentially all the way to the backside contact, hence the term full depletion.

No Effect on CCD Fab line. Final curvature already present.

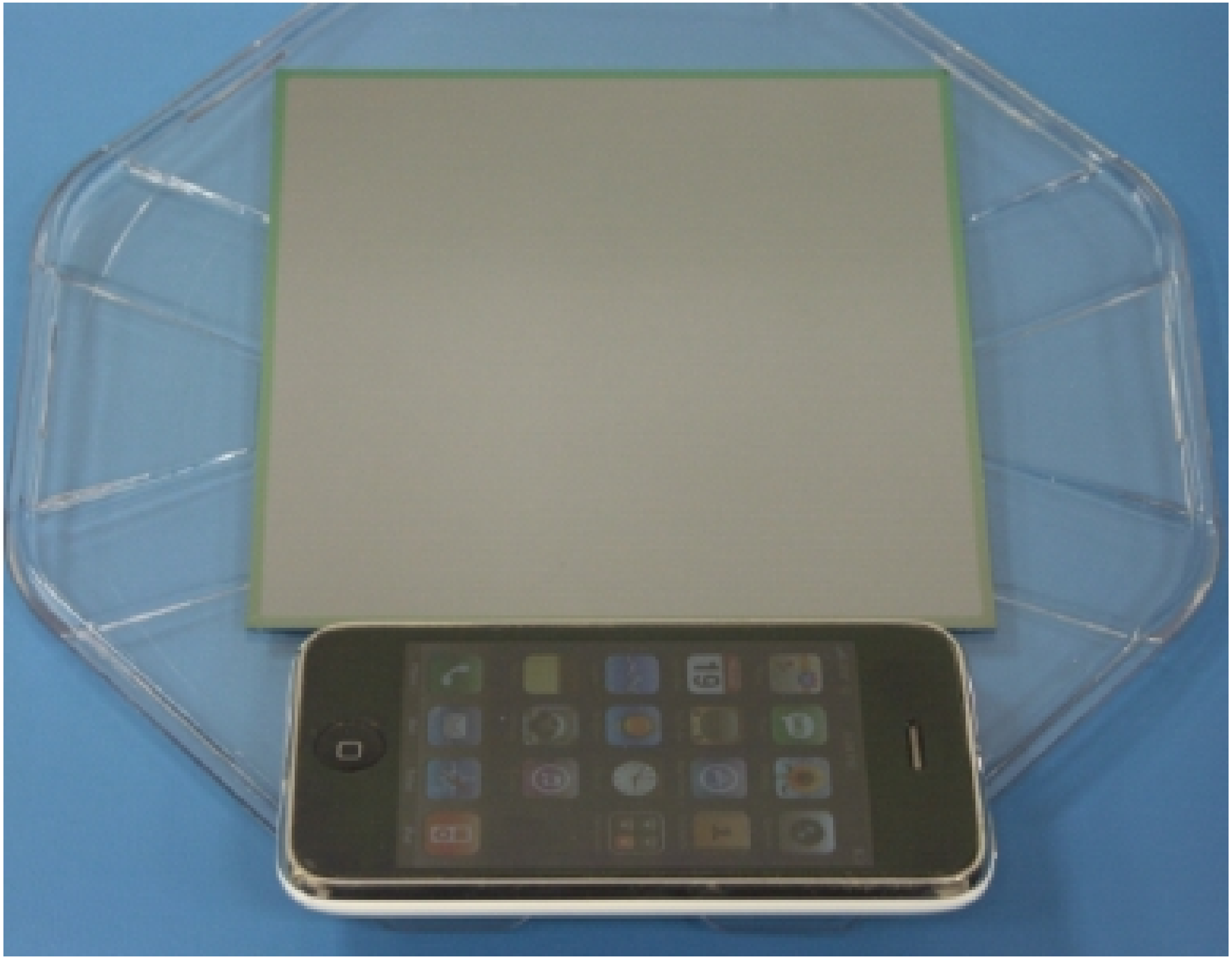
Conclusions

- The basic structure of a thick gamma-ray detector based on trenched substrates has been shown. These detectors have low leakage currents and have an energy resolution of ~ 2.3 keV FWHM at 59.5 keV.
- 2 mm thick silicon fully depleted at ~ 50 V.

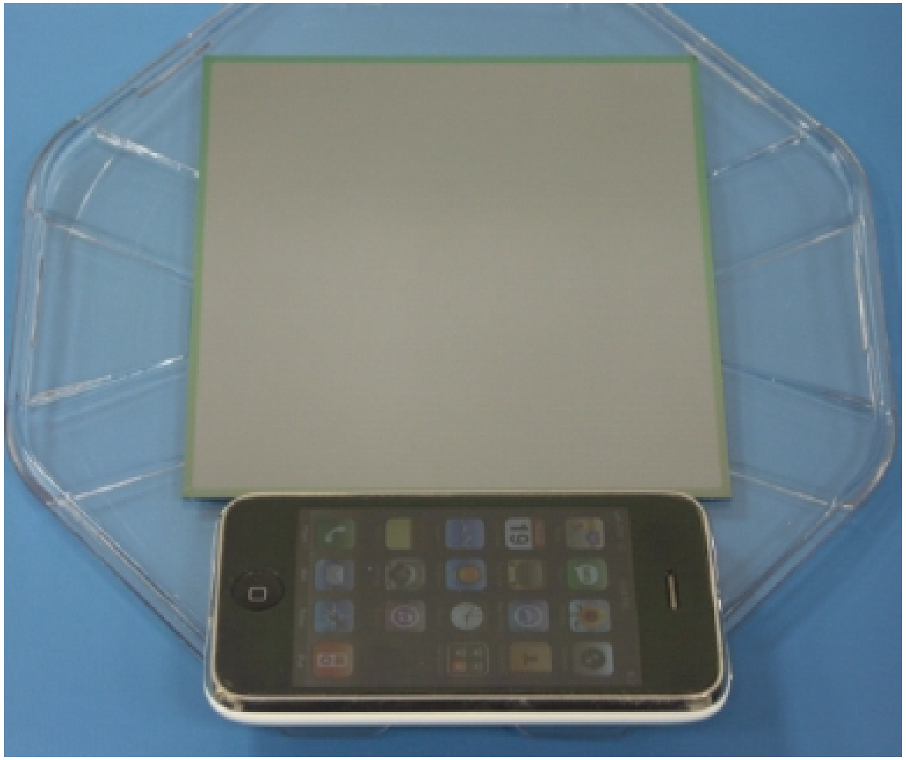
- Curved radiation detector due to “gray-tone technology”.
- Pixel and strip detector on single- and double-sided etch detectors.

⚠ Wide field of view camera based on curved back-sided illuminated CCD.

200 mm Wafer Processing

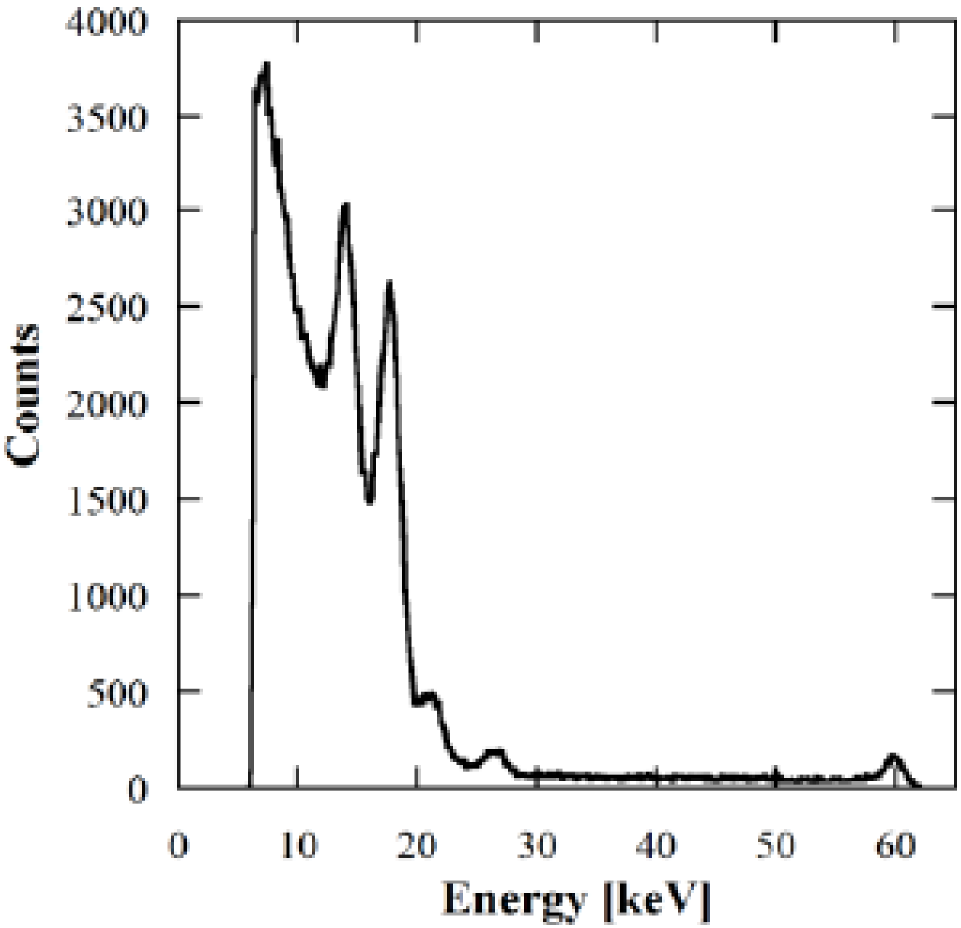


200 mm Wafer Processing



- ~ 9k Ohmcm FZ material
- 725 µm thickness
- single side strip detector, 128 strips, 0.97 mm wide and 125 mm long

200 mm Wafer Processing



- Am-241 source
- energy resolution is ~ 2.6 keV FWHM at 59.5 keV (0.7 x 7 mm strip)