Possibilities for Thick, Simple-Structure Silicon X-Ray Detectors Operated by Peltier Cooling

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Requirement

Detection of a trace of hazardous atoms in materials

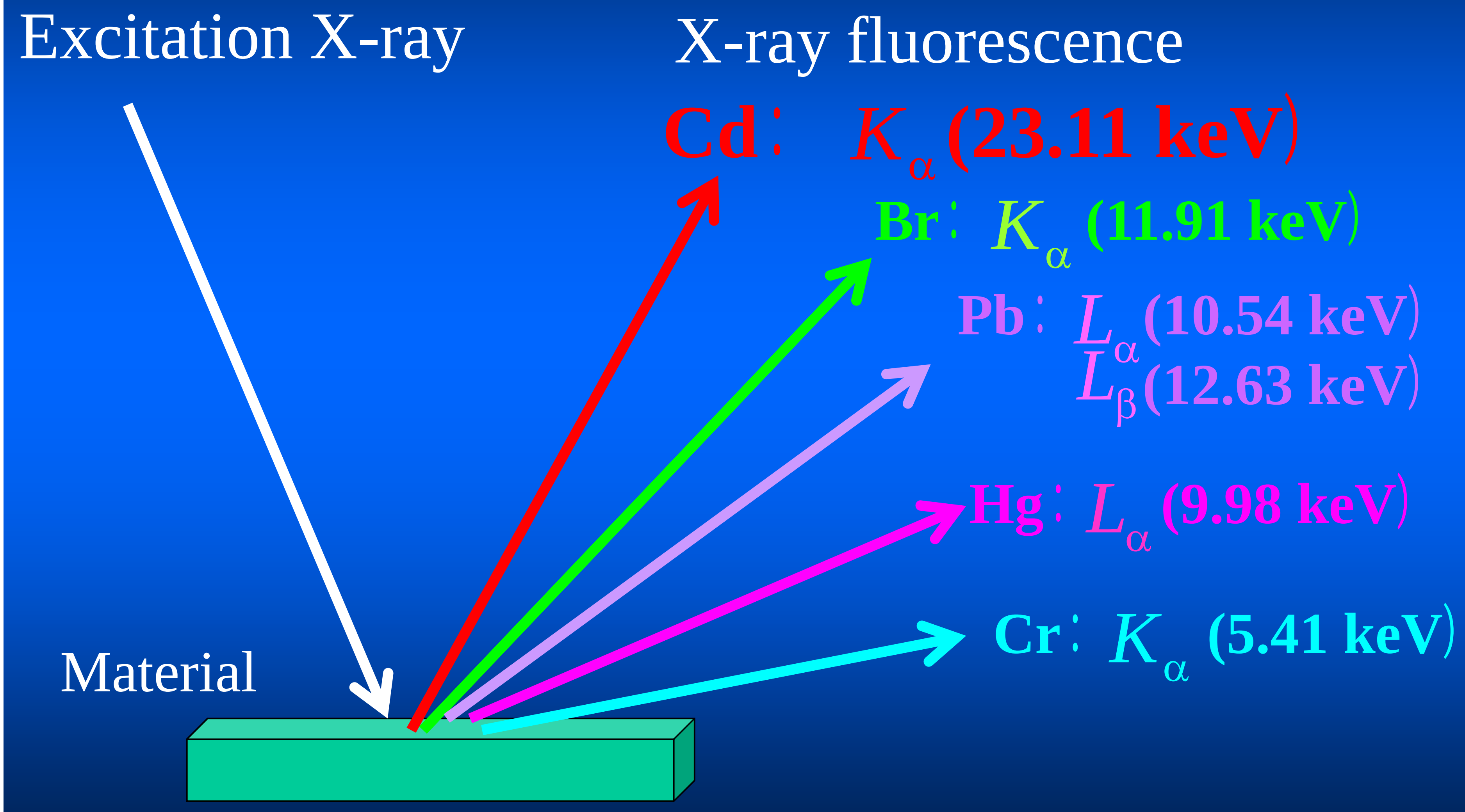
For examples;

A. Cd contamination in foods
   1. less than 0.4 ppm in rice
   2. less than 0.2 ppm in wheat

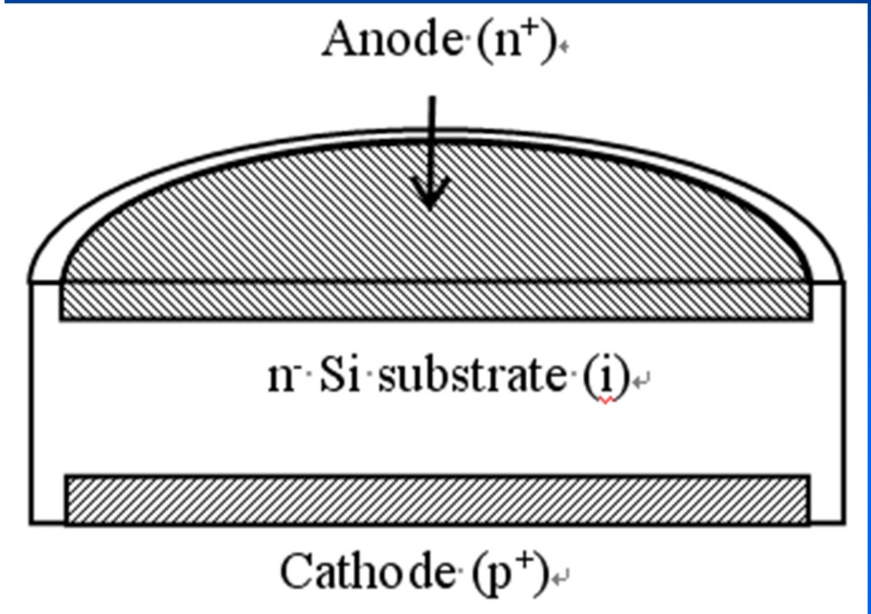
B. Hazardous elements in soil
   1. less than 150 ppm of cadmium
   2. less than 250 ppm of hexahydric chromium
   3. less than 150 ppm of arsenic
   4. less than 15 ppm of mercury

To detect fluorescent X-rays of atoms in materials is useful.

Energies of X-ray fluorescence of hazardous elements



Pin diodes for X-ray detectors



Larger active area (cathode)

↓

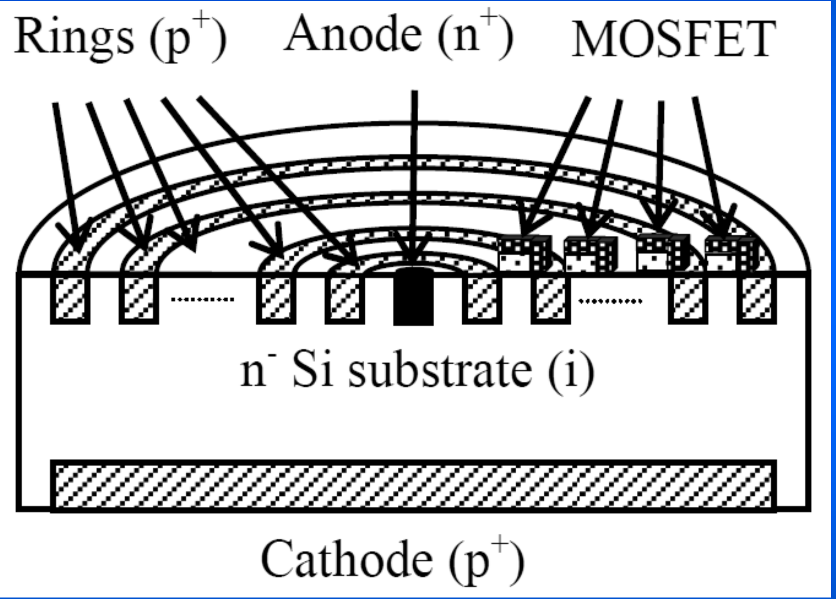
Larger capacitance of diode

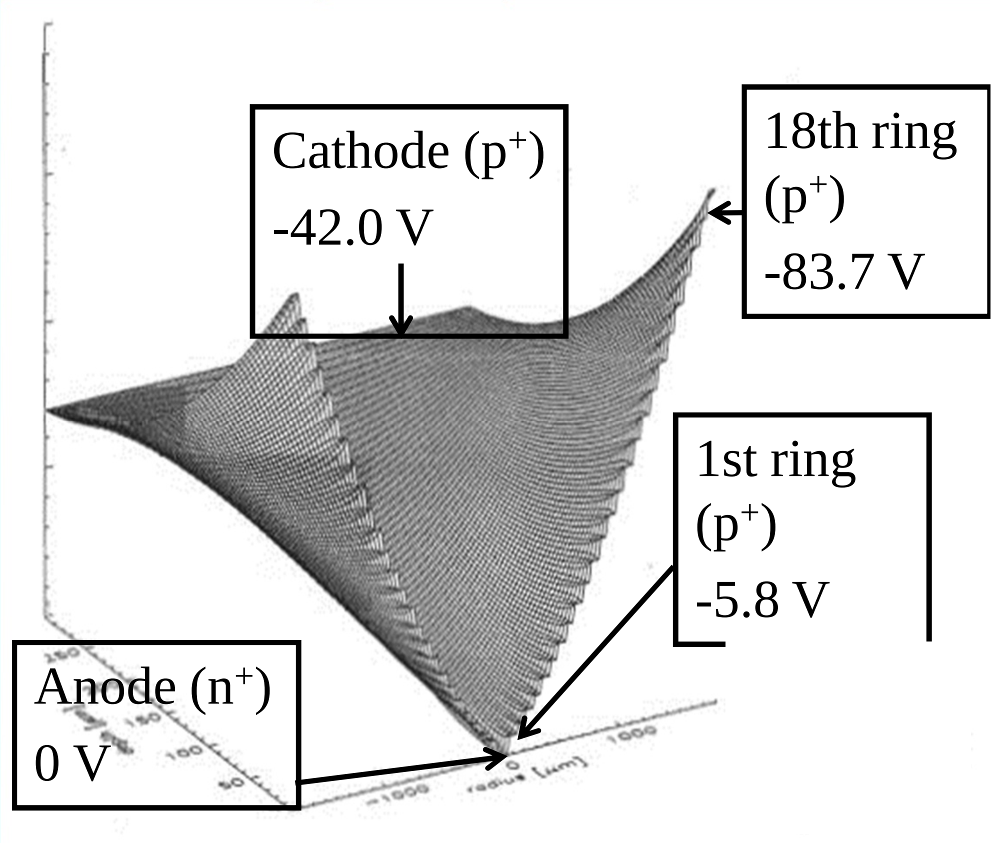
Transportable X-ray detectors require

1. **large active area for high sensitivity**
2. **small capacitance of detector for high energy resolution**
3. **operation by Peltier Cooling**

Silicon Drift Detector (SDD)

1. Large active area
2. Small capacitance of detector
3. Operation by Peltier cooling





The p-rings are electrically coupled using MOSFET to form an adequate electric field in SDD.

Fabrication processes are complicated.

SDD is very expensive.

Requirement of Si thickness

Element	^{48}Cd	^{50}Sn	^{51}Sb	^{53}I	^{55}Cs	^{56}Ba
	K_α	K_α	K_α	K_α	K_α	K_α
Energy [keV]	23.1	25.2	26.3	28.5	30.8	32.0
Si Thickness [mm]	Absorption [%]					
0.3	19	14	12	10	8	7
0.6	35	27	23	18	15	13
1.0	**51**	41	35	29	23	21
1.5	**65**	**54**	48	40	33	30
2.0	**76**	**64**	**58**	49	41	38

K-line X-ray fluorescence: ^{11}Na(1.0 keV) ～ ^{50}Sn(25.2 keV)

L-line X-ray fluorescence: ^{51}Sb(3.6 keV) ～ ^{92}U(13.6 keV)

Si thickness is required to be thicker than 1.5 mm

Aim of our study

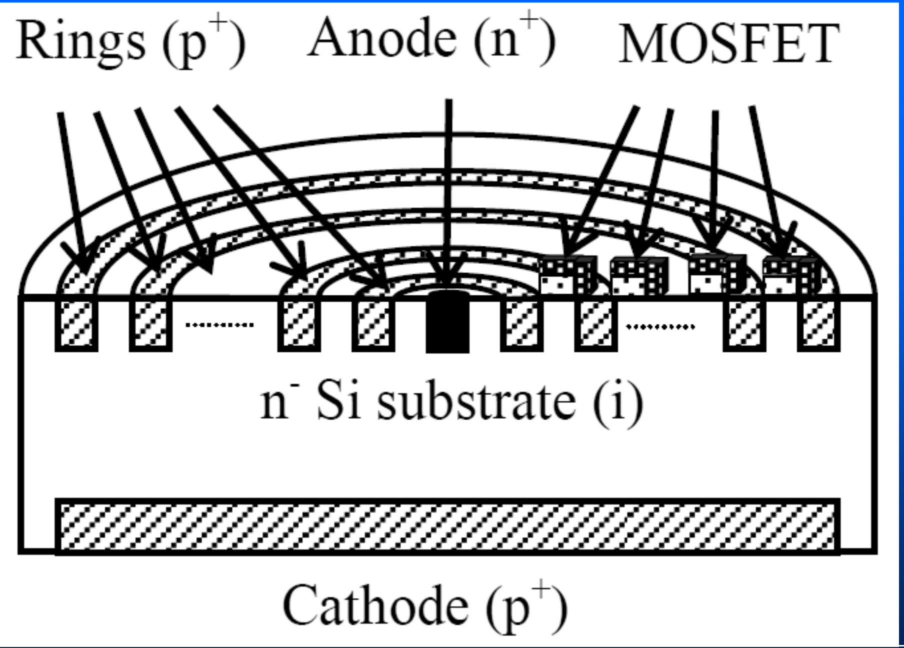
X-ray detectors that meet the following requirements are materialized.

1. **Large active area for high sensitivity**
2. **Small capacitance of detector for high energy resolution**
3. **Operation by Peltier Cooling for transportable unit**
4. **Simple structure for inexpensive detector**
5. **Thick Si wafer for high sensitivity of high energy X-rays**
6. **Only one high voltage bias for inexpensive unit**

Proposal of New X-ray detector

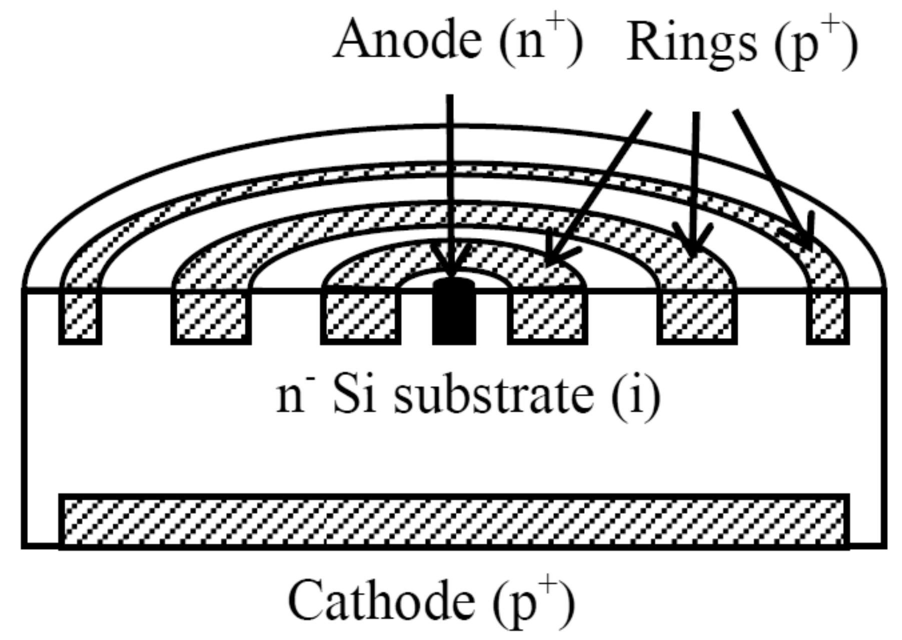
1. Large active area for high sensitivity
2. Small capacitance of detector for high energy resolution
3. Operation by Peltier Cooling for transportable unit
4. **Simple structure for inexpensive detector**

Prior art SDD

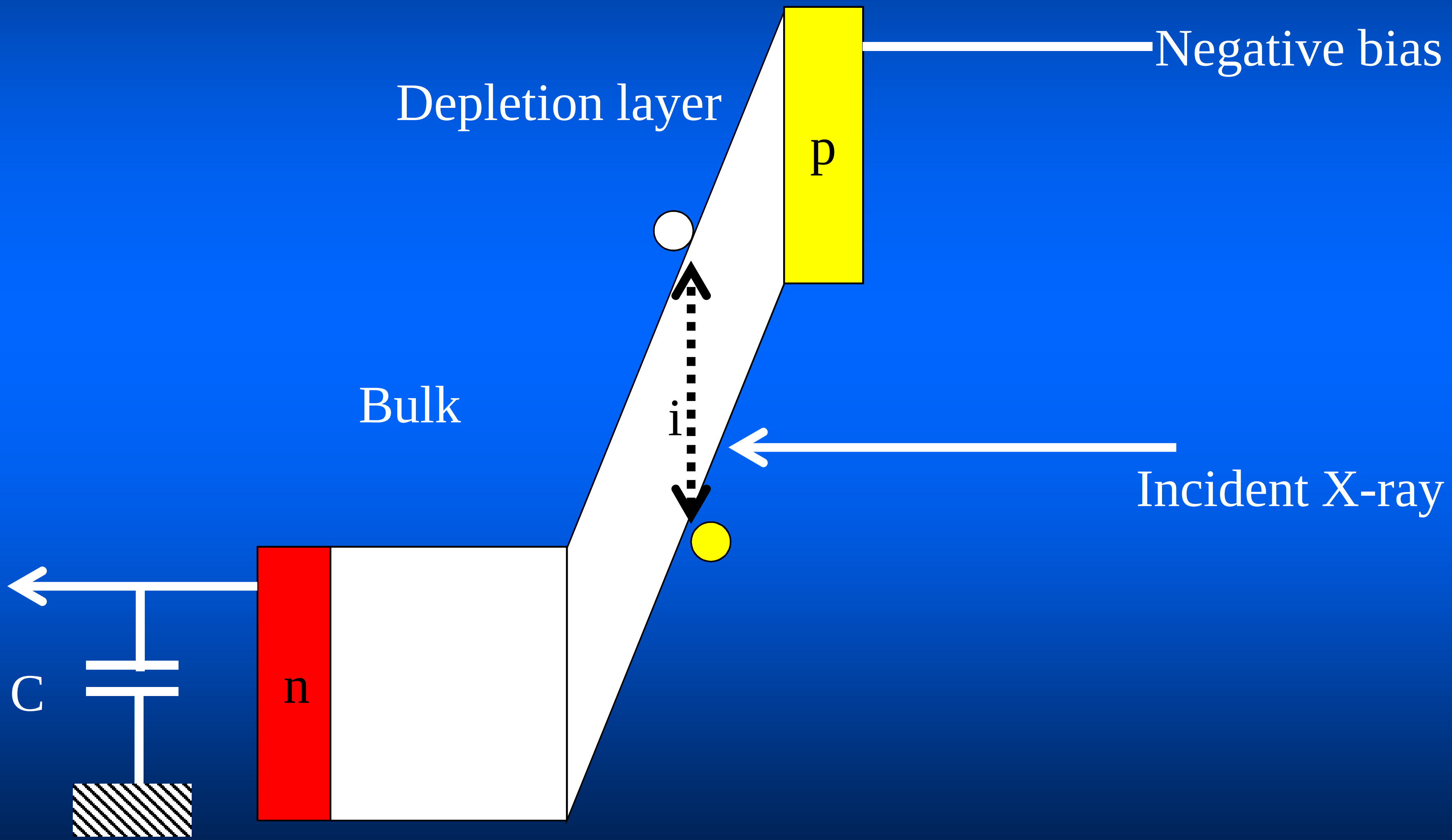


Simple-structure SDD (SSDD)

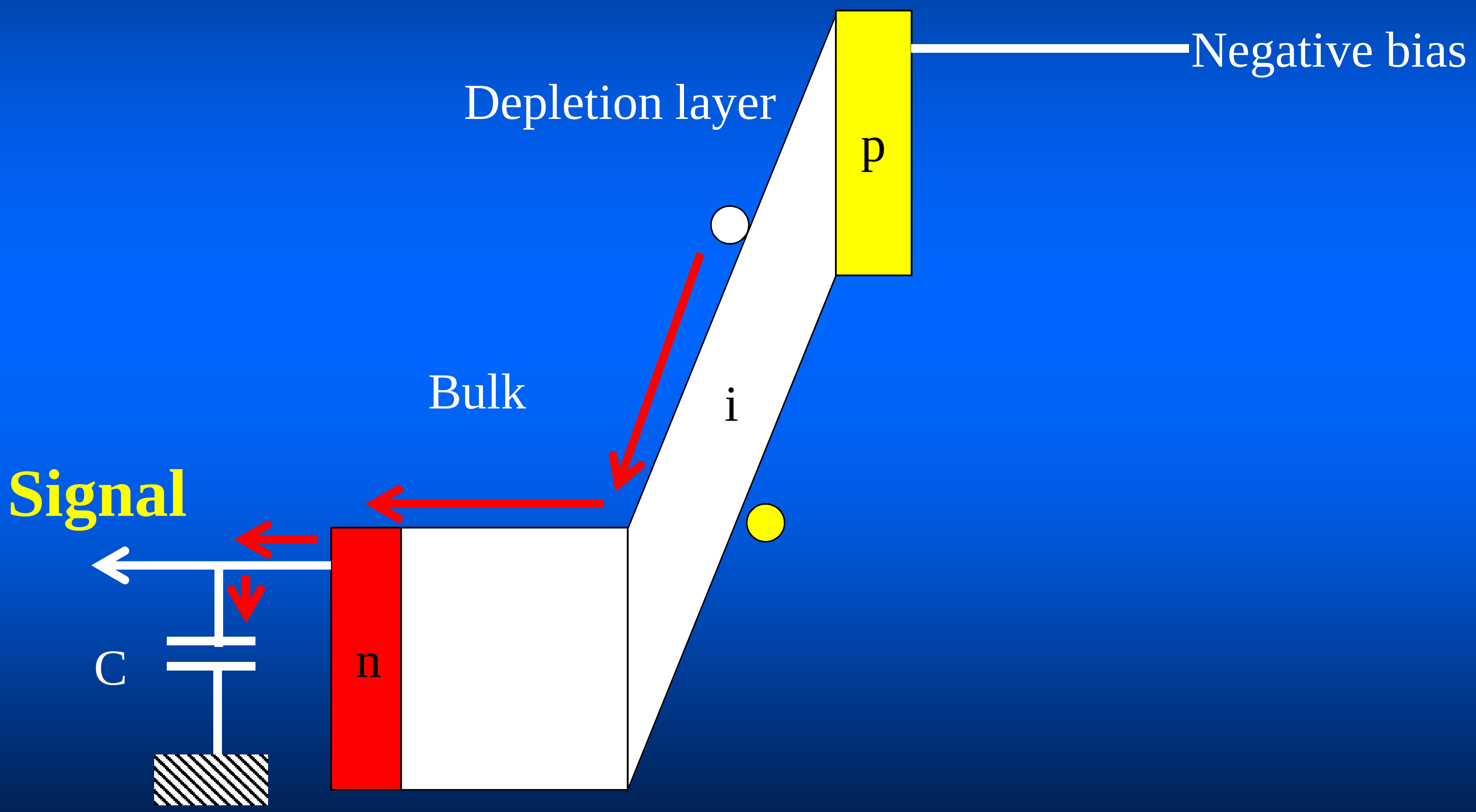
Without MOSFET



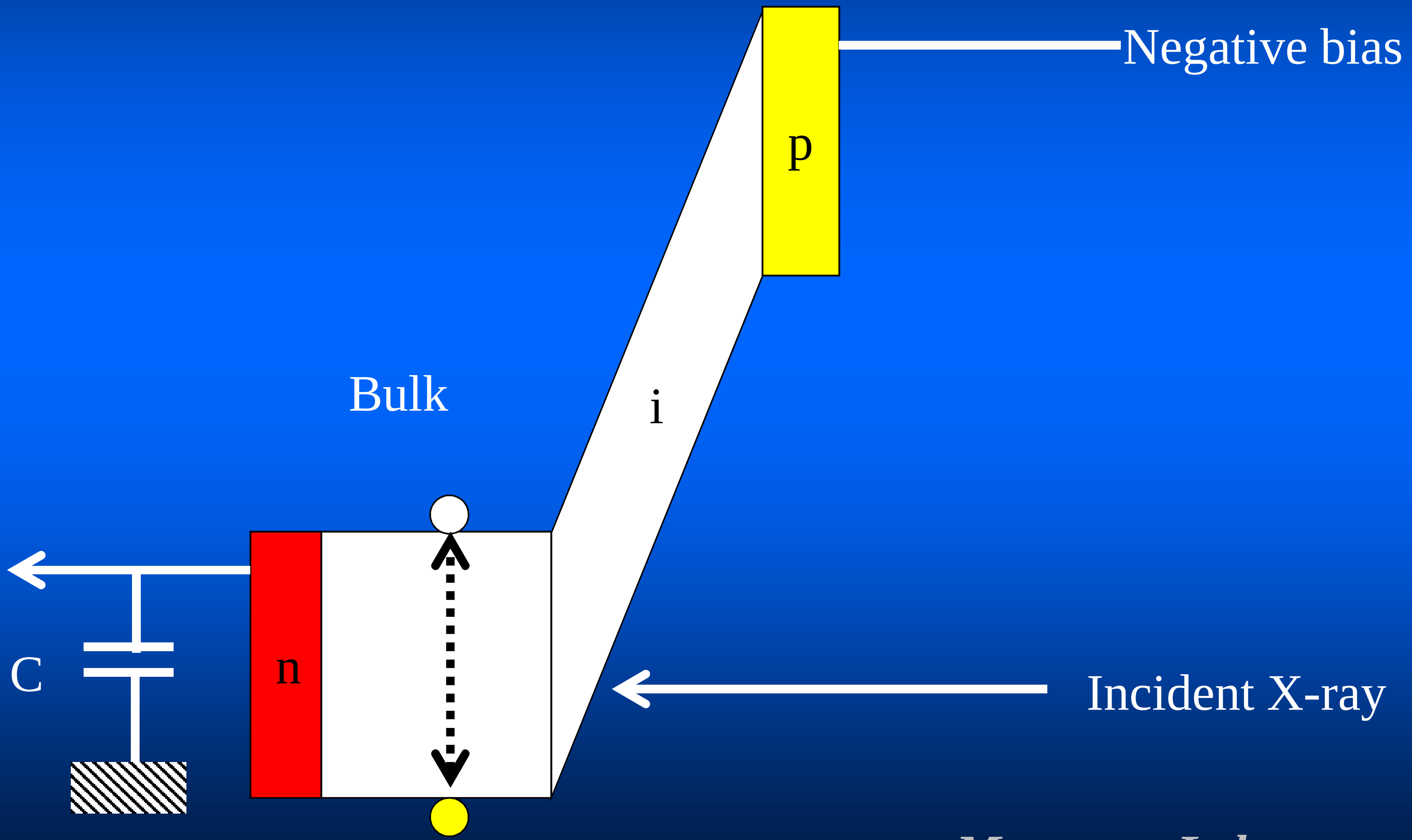
Produced electron-hole pair in depletion region



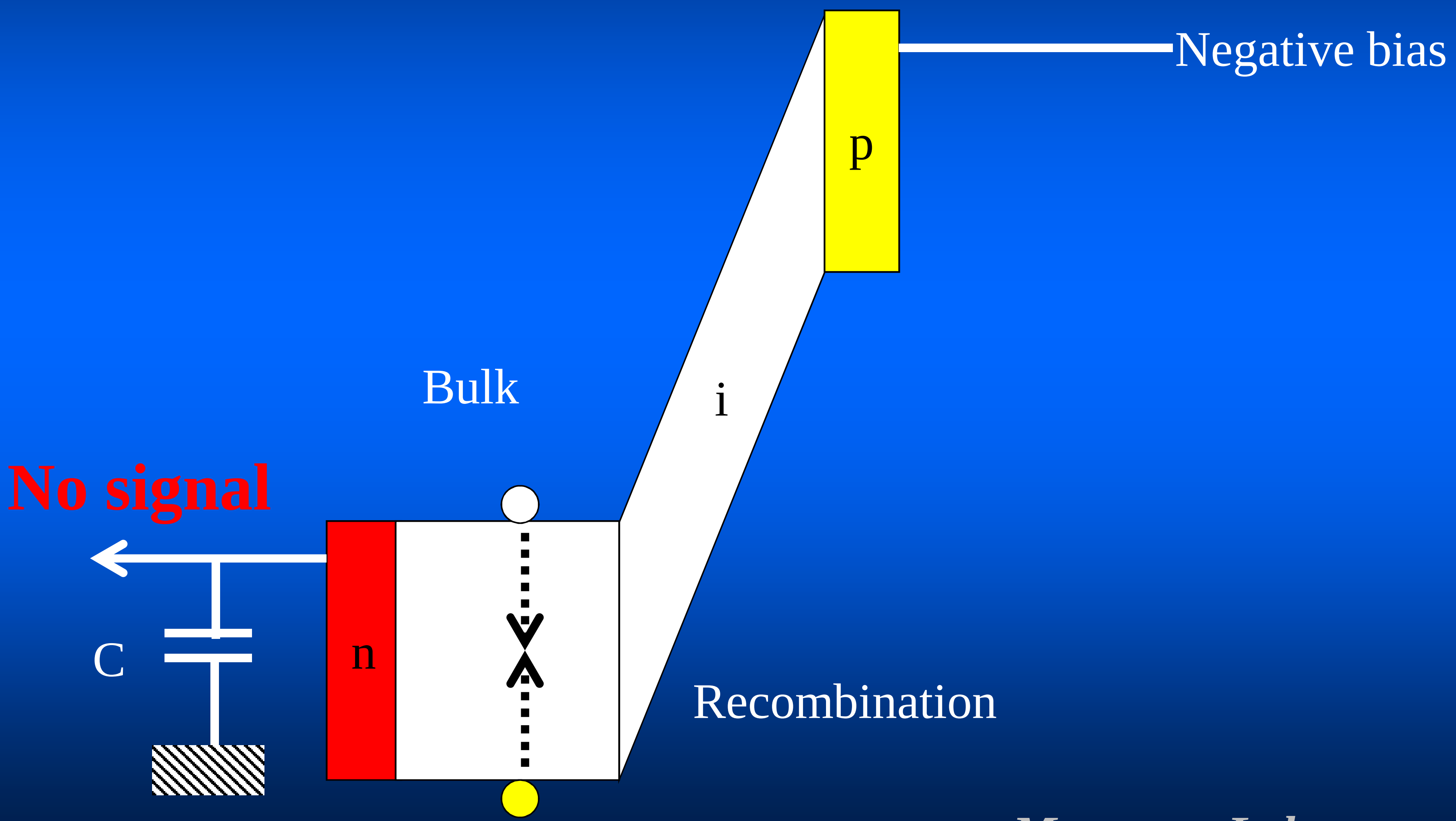
Produced electron-hole pair in depletion region



Produced electron-hole pair in bulk



Produced electron-hole pair in bulk

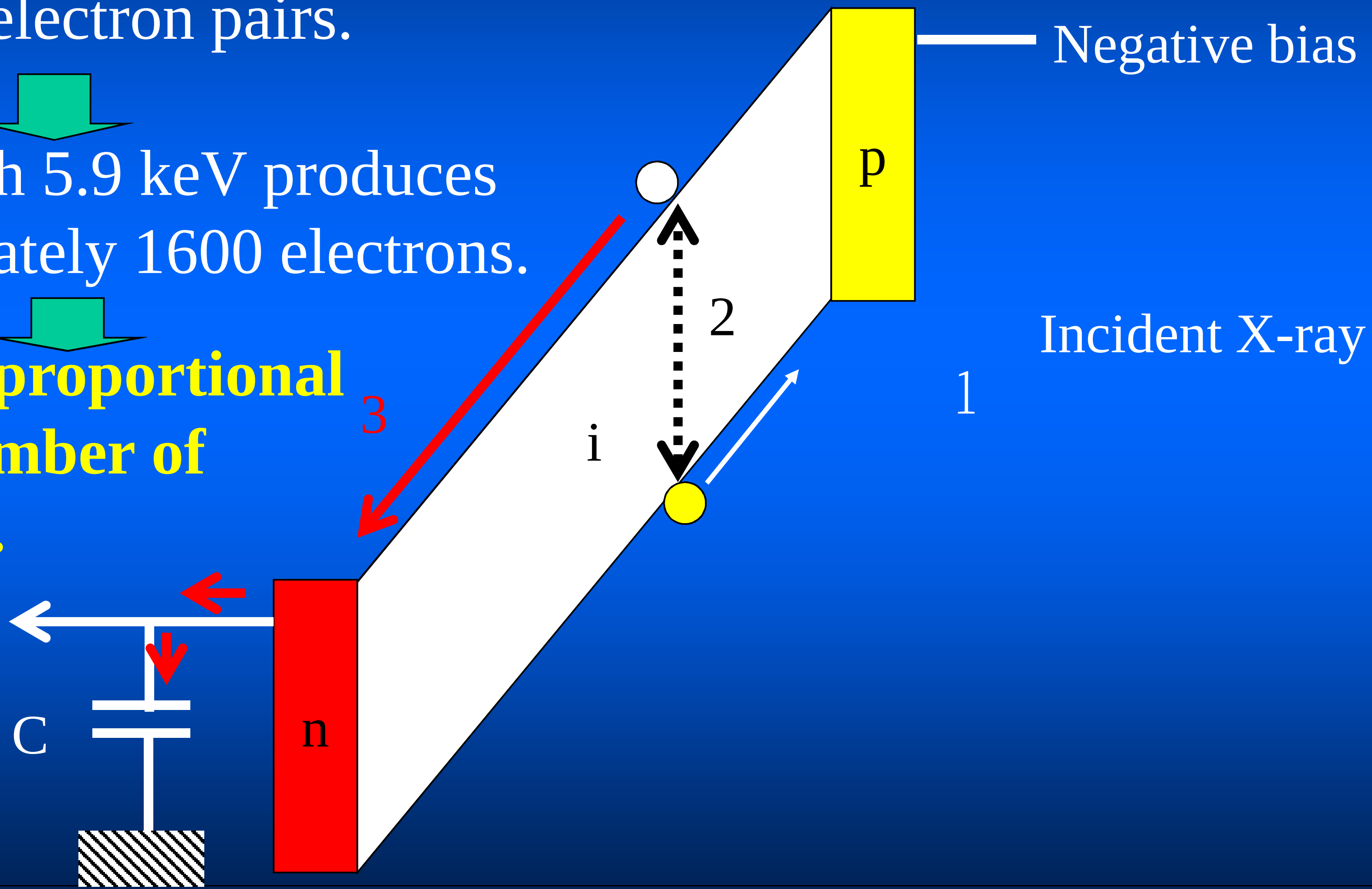


To deplete the whole i layer is required

In Si, 3.6 eV of X-ray produces one hole-electron pairs.

X-ray with 5.9 keV produces approximately 1600 electrons.

Signal is proportional to the number of electrons.

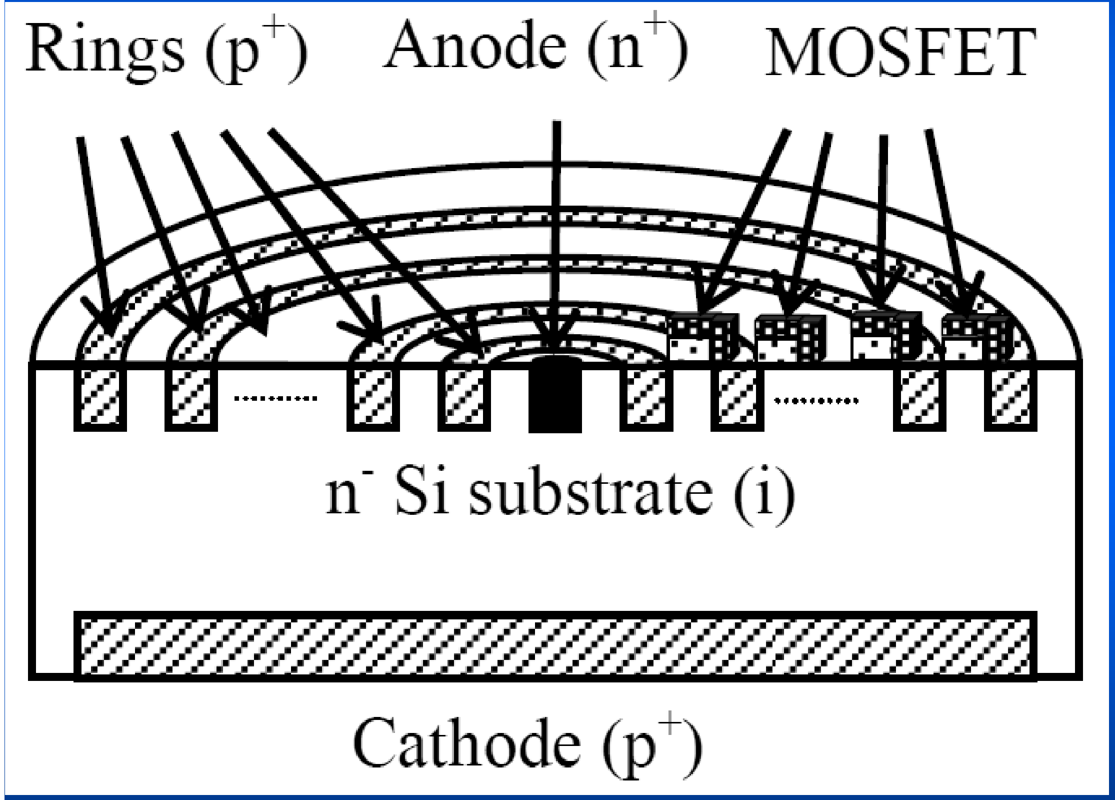


Reverse bias required to deplete a whole i layer of **pin diode**

Resistivity [kΩcm]	2	10	20	40
N_D [cm^{-3}]	$2x10^{12}$	$4x10^{11}$	$2x10^{11}$	$1x10^{11}$
Si Thickness [mm]	Applied voltage required to deplete i layer [V]			
0.3	**137**	**27**	**14**	**7**
0.6	**547**	**109**	**55**	**27**
1.0	1519	**304**	**152**	**76**
1.5	3417	**683**	**342**	**171**
2.0	6074	1215	**607**	**304**

Higher-resistivity Si substrate is required to operate at adequate high reverse bias.

Conditions of the prior art SDD



SDD currently in use

Si

thickness: 0.3 – 0.5 mm

resistivity: 2 k Ωcm

Applied voltages

0.3-mm-thick case

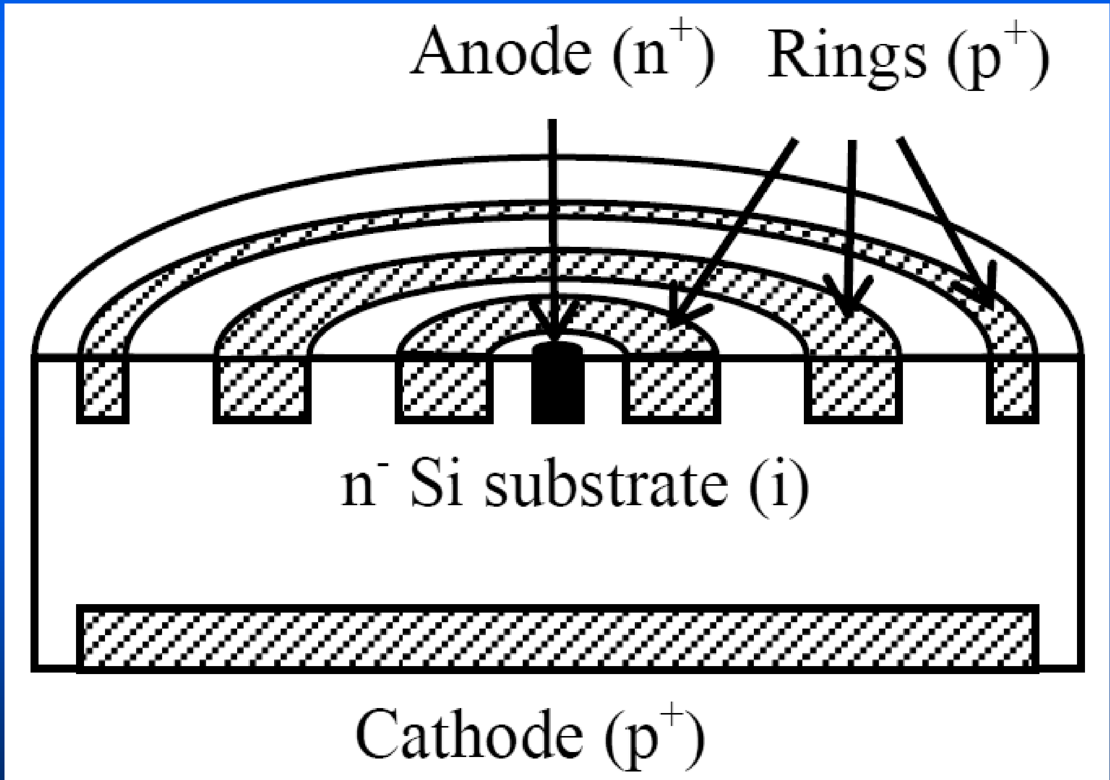
Cathode: - 50 V

outermost p-ring: -100 V

innermost p-ring: - 10 V

Fabrication of SSDD

To investigate a possibility of use of higher-resistivity Si substrate.



Two type of SSDD

Si

resistivity: 2 kΩcm

6.5 kΩcm

thickness : 0.3 mm

Applied voltages

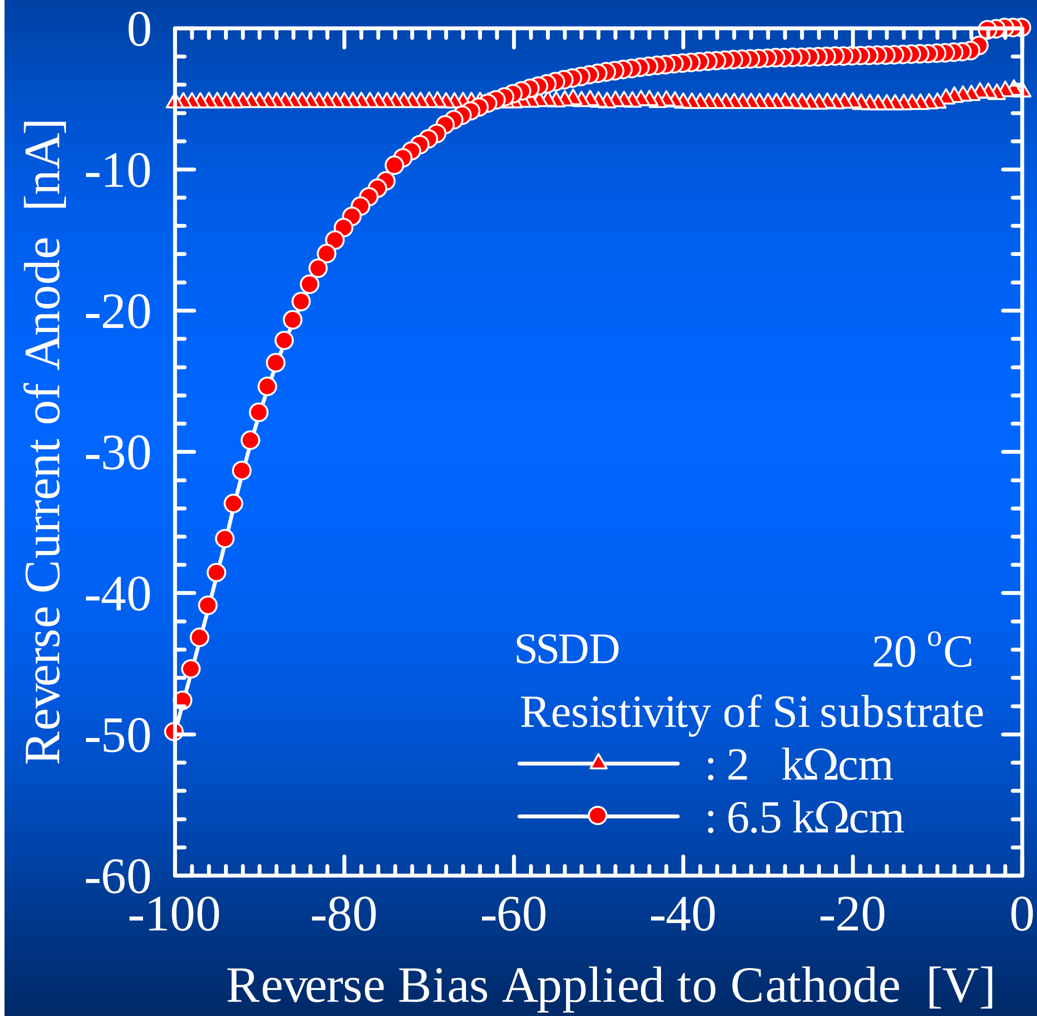
cathode : -80 V

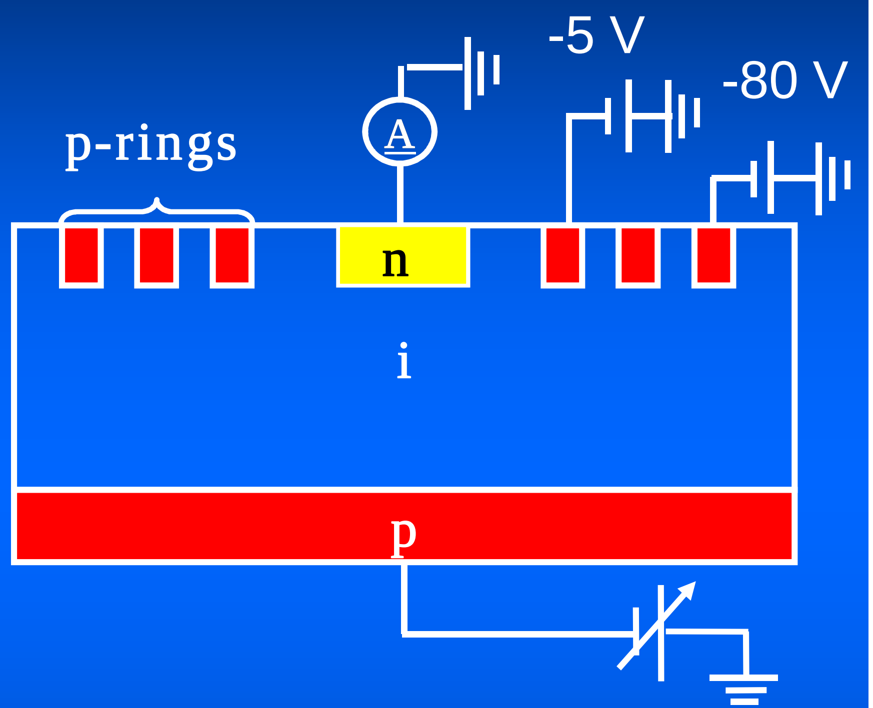
outermost p-ring: -80 V

inner p-ring: -42.5 V

innermost p-ring: -5 V

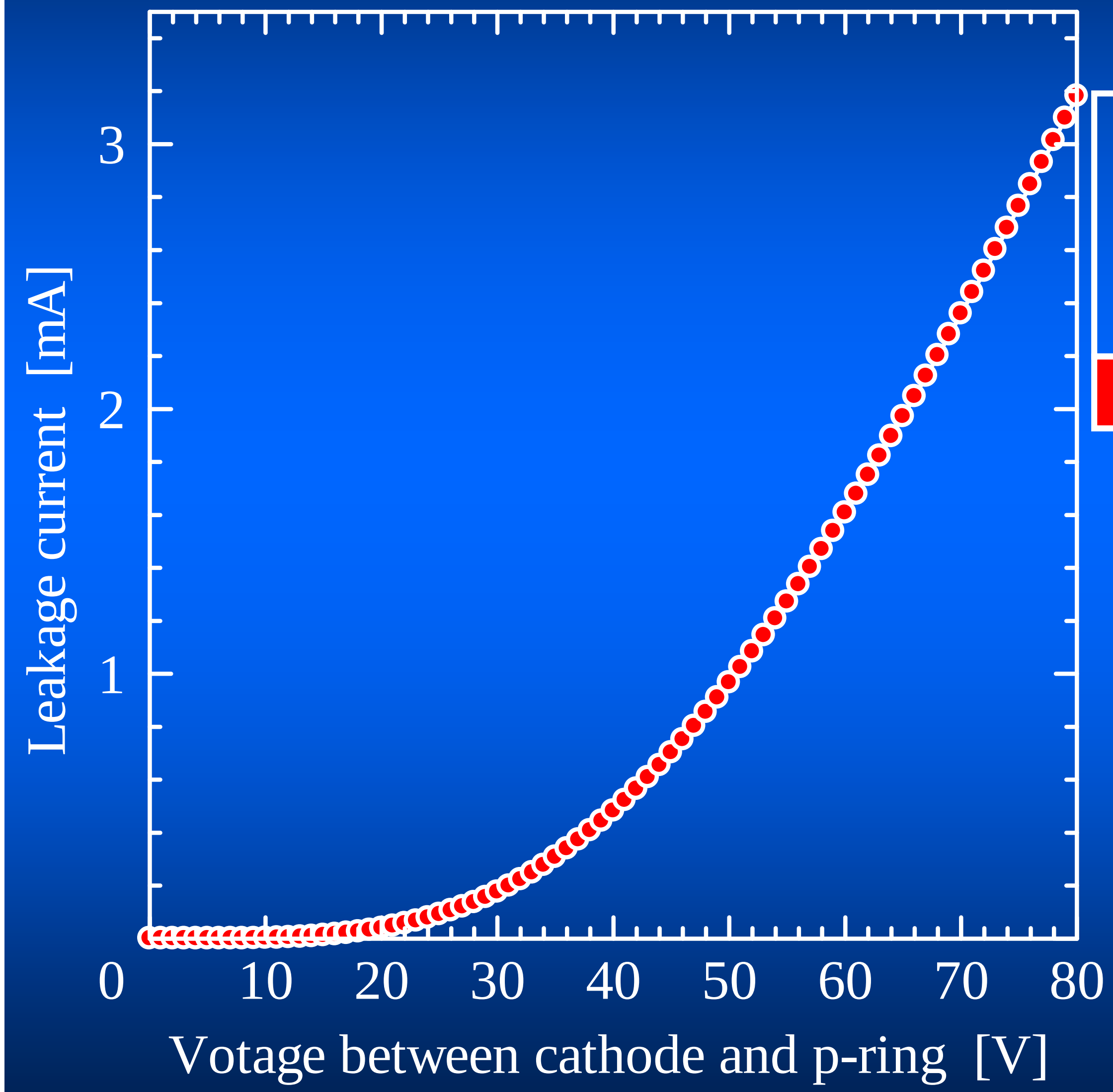
Reverse Current of Anode

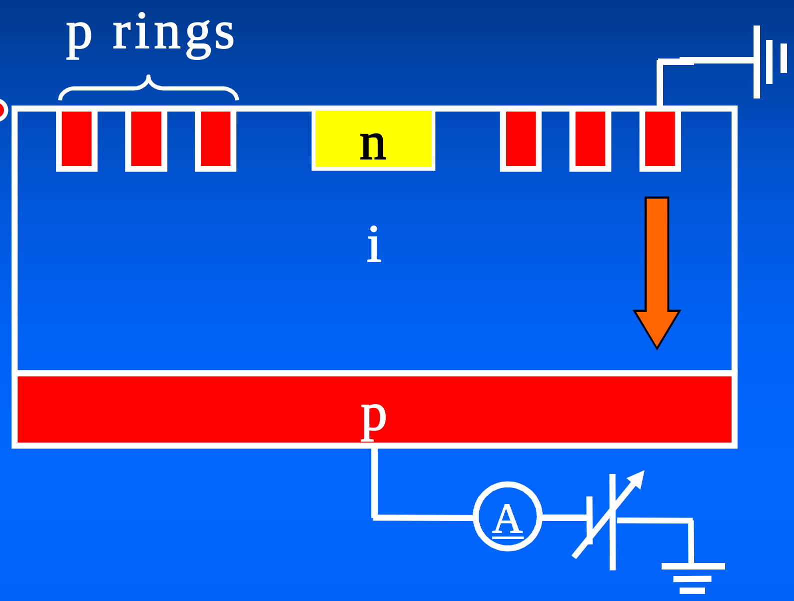




Unfortunately, the current for 6.5 k Ωcm Si increased with bias, and exceeded the current for 2 k Ωcm Si.

Leakage current between cathode and p-ring





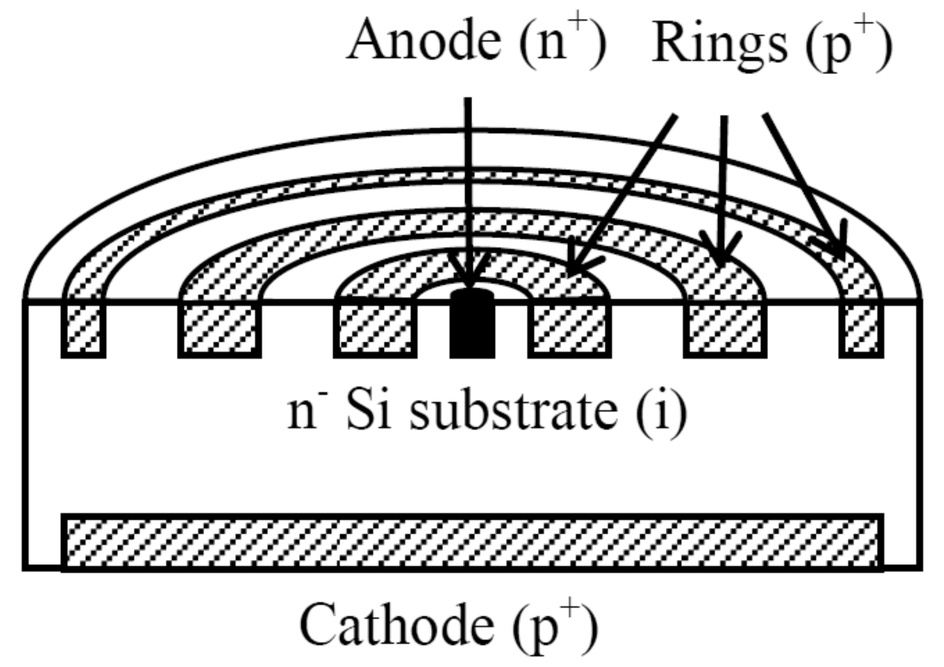
The current between cathode and p-ring became of the order of mA.

This occurred due to the difference in voltage between cathode and p-ring.

To operate SSDD using high-resistivity Si

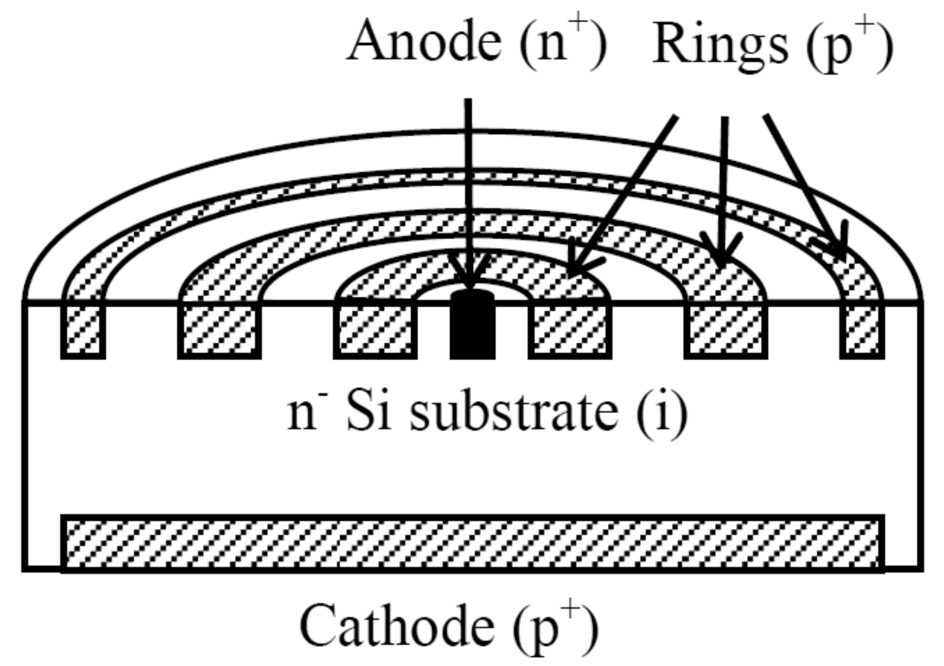
the same voltage should be applied to the cathode and p-rings, that is,

1. **Outermost p-ring is applied to a negative bias that is the same as the cathode.**
2. **Inner p-rings are floating.**



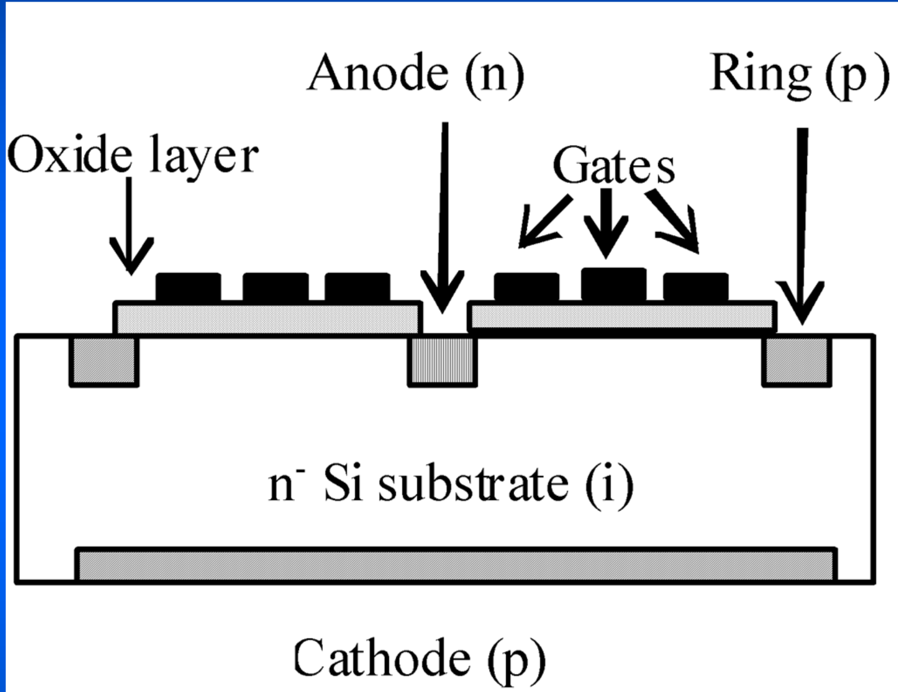
Proposal of second new structure

SSDD



1. Outermost p-ring is applied to a negative bias that is the same as the cathode.
2. Inner p-rings are floating.

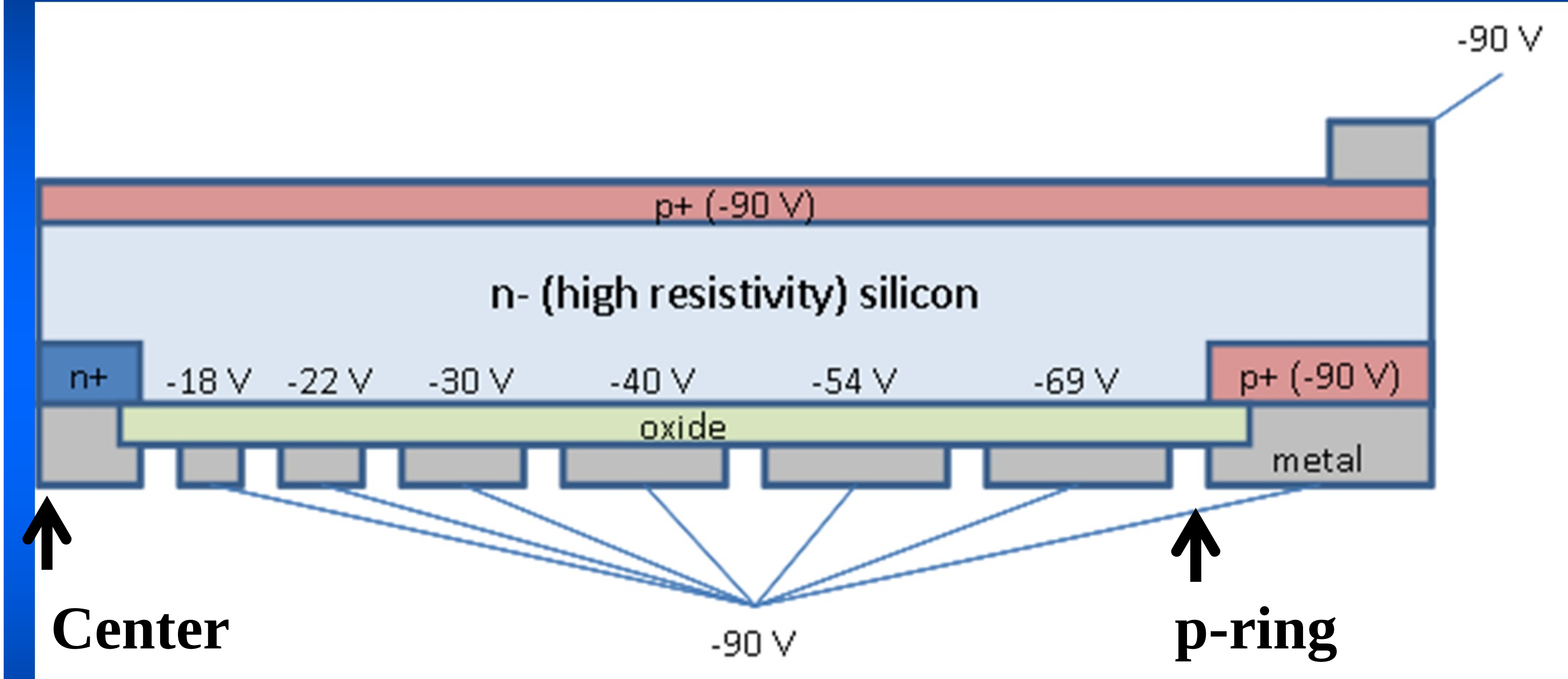
Gated SDD (GSDD)



P-ring and all the gates are applied to a negative bias that is the same as the cathode.

SSDD and GSDD require only one high voltage bias

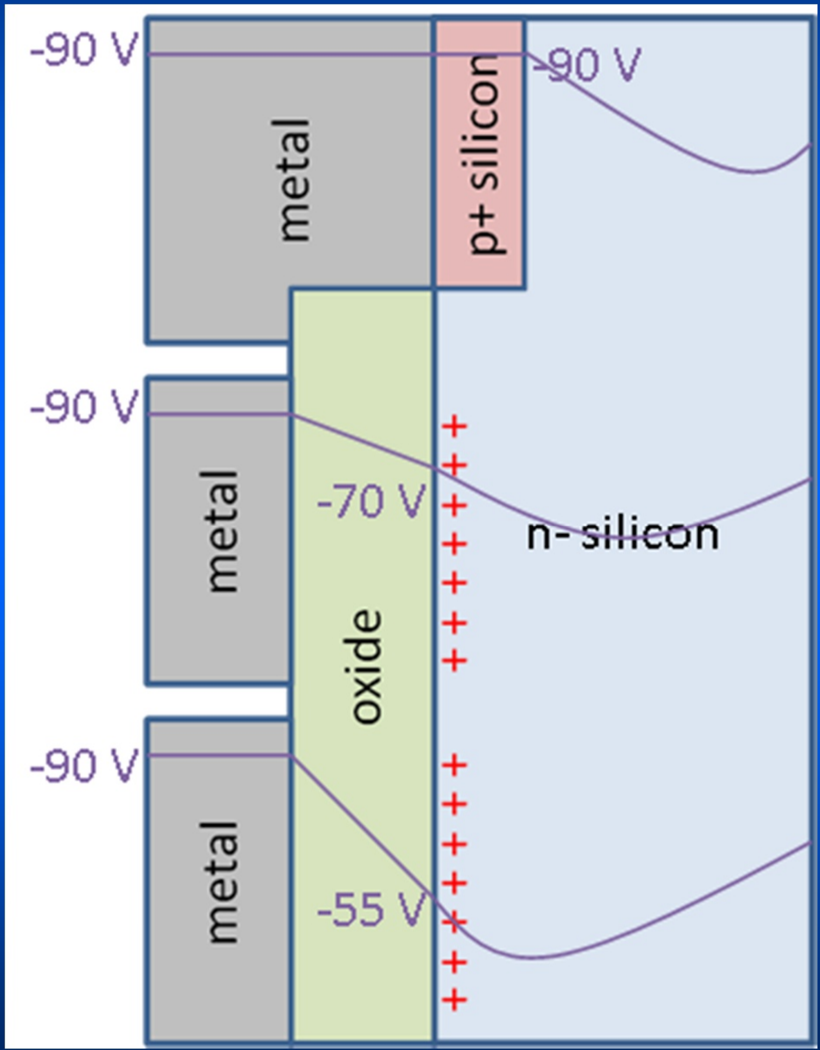
Simulation and Fabrication of GSDD



Si resistivity: 10 kΩcm
Si thickness: 0.625 mm

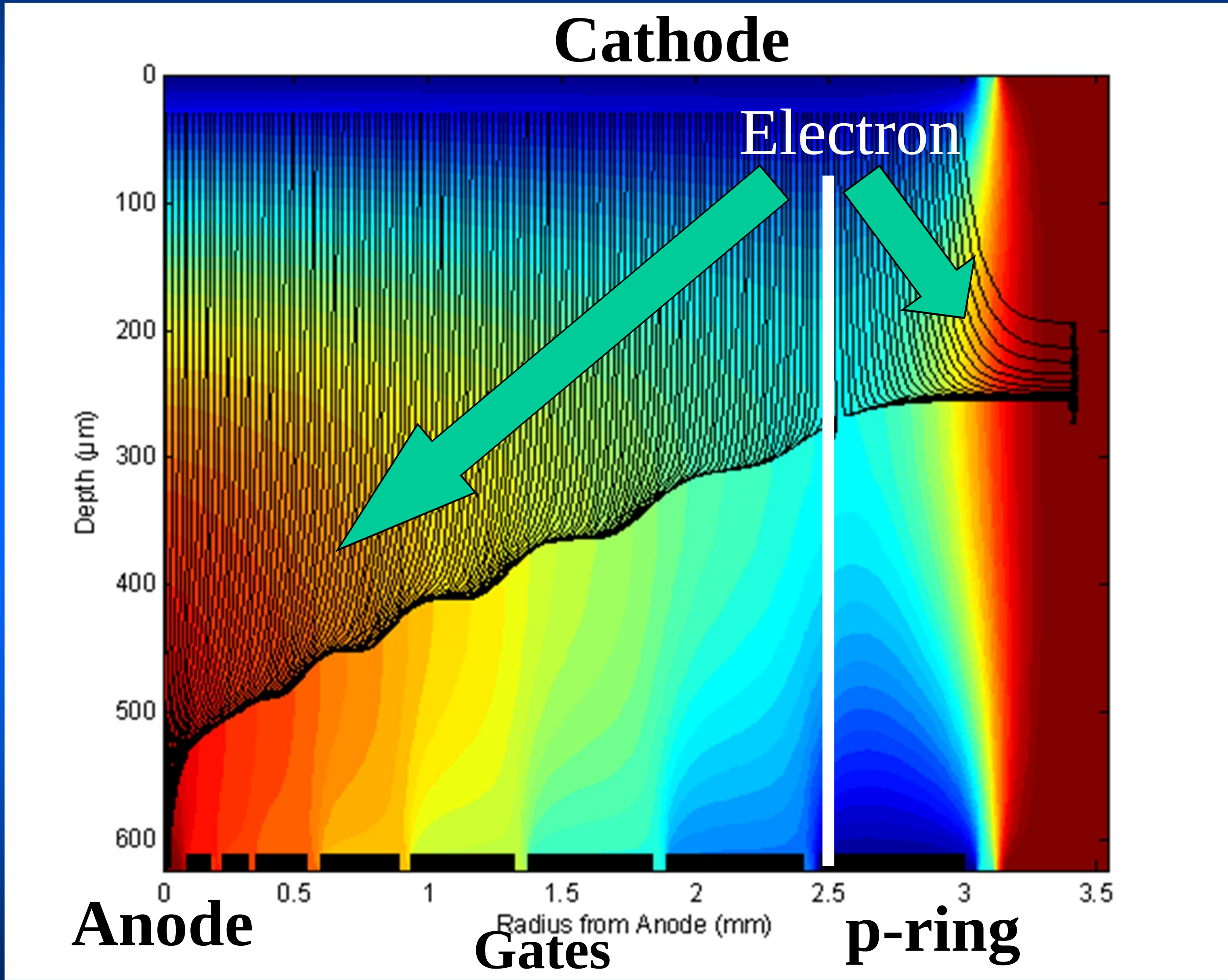
Distance between center and p-ring:
2.455 mm

Potential at SiO_2/Si interface



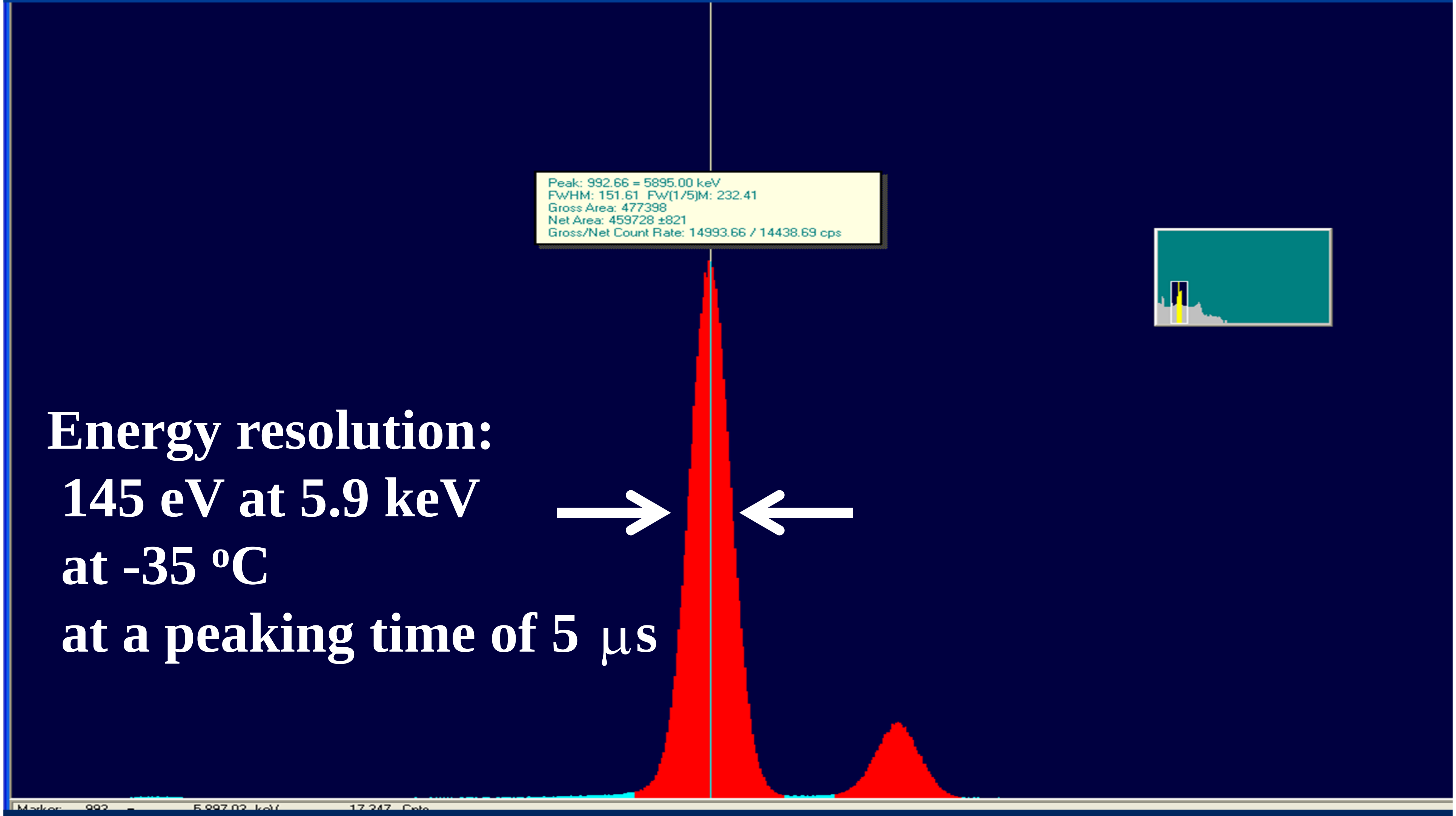
The potential at the SiO_2/Si interface is strongly dependent on the fixed oxide charge and the gap between the gates.

Potential distribution in the detector



Active area: 18 mm^2

Experimental result: ^{55}Fe spectrum



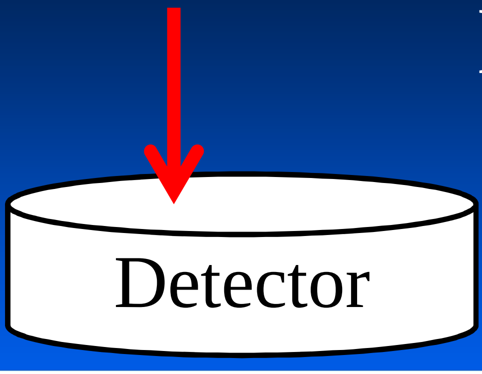
Energy resolution:

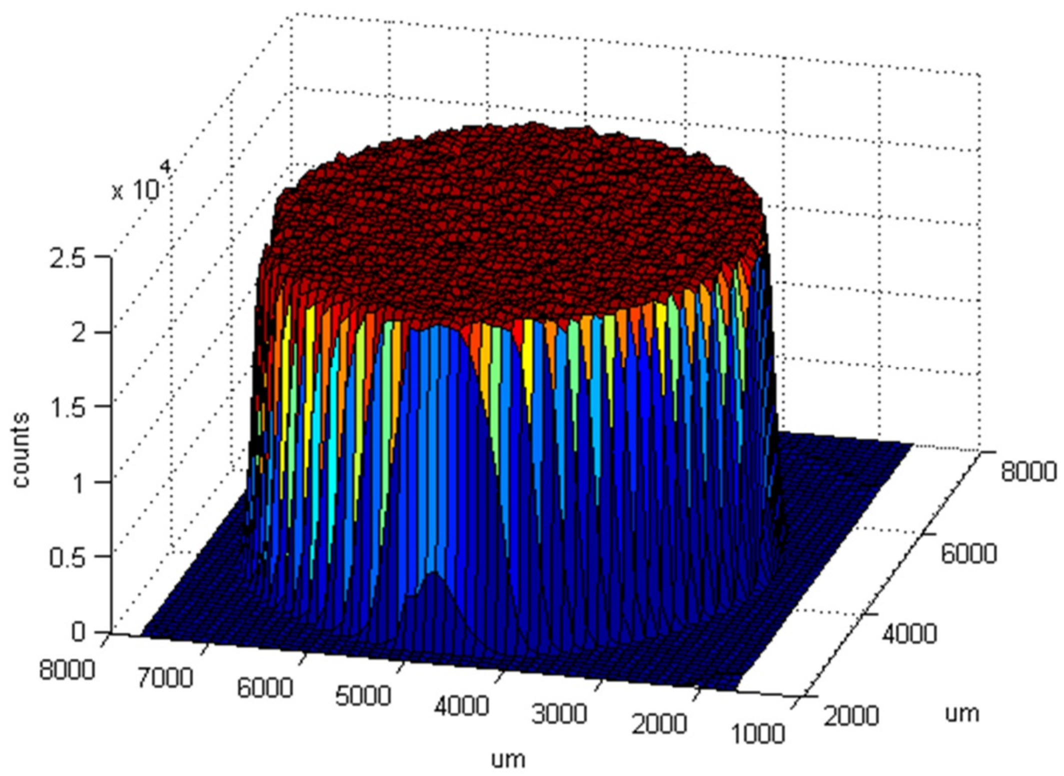
145 eV at 5.9 keV

at -35 ^{o}C

at a peaking time of 5 μs

Mapping of counts



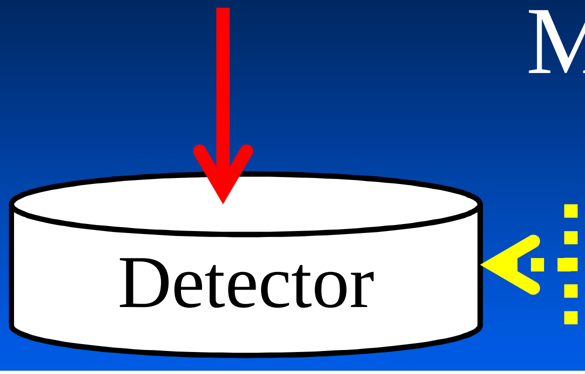


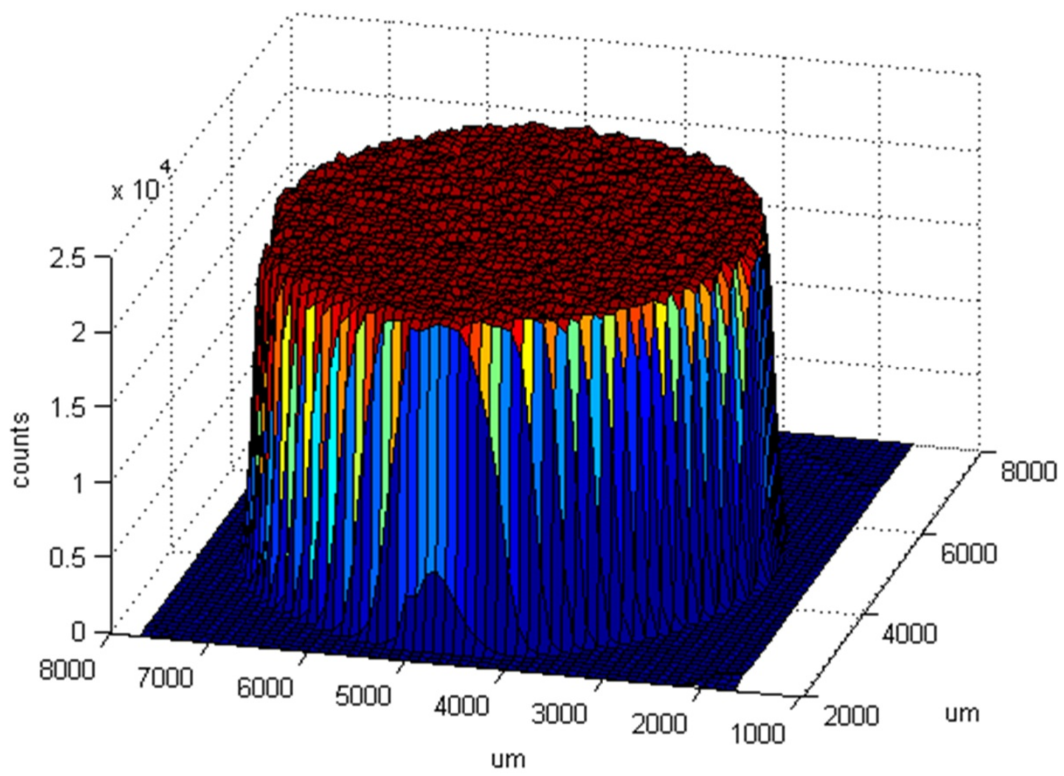
Experiment:

1. **X-rays were incident through 100- μm-diameter pin hole.**

Active area: 18 mm^2

Mapping of counts



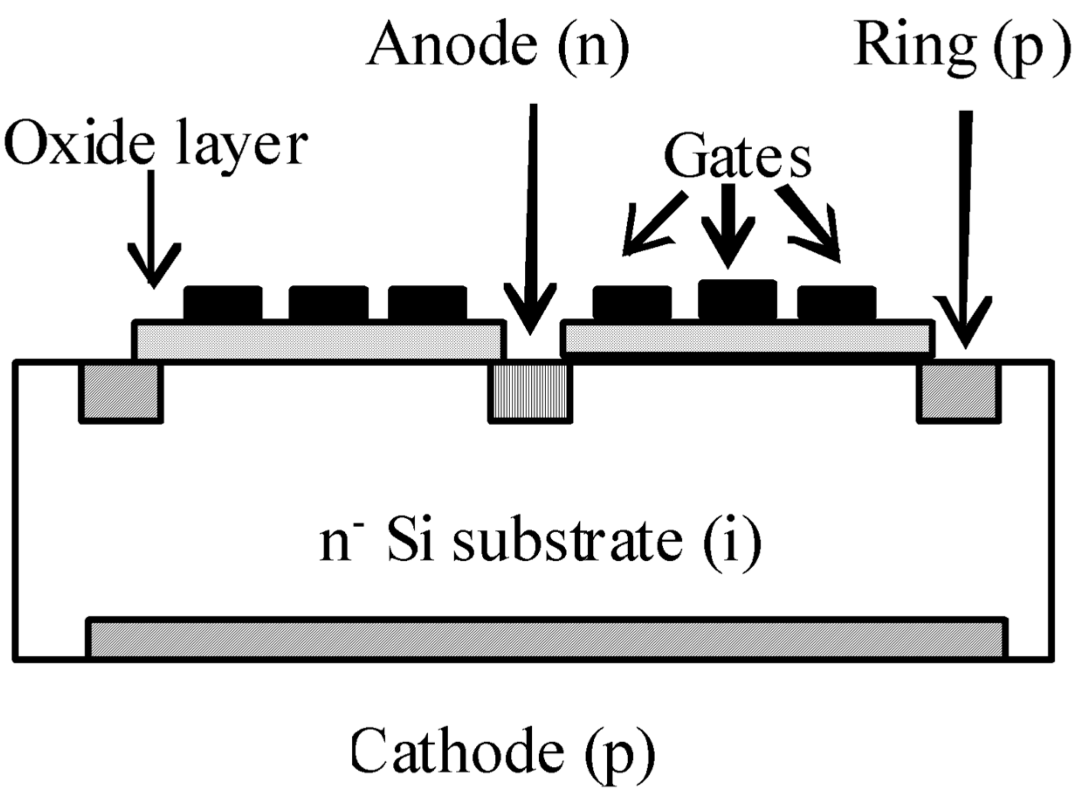


Experiment:

1. **X-rays were incident through 100- μm-diameter pin hole.**
2. **Detector was moved in 100- μm increments.**

Active area: 18 mm^2

Simulation of GSDD with 1.5-mm-thick Si



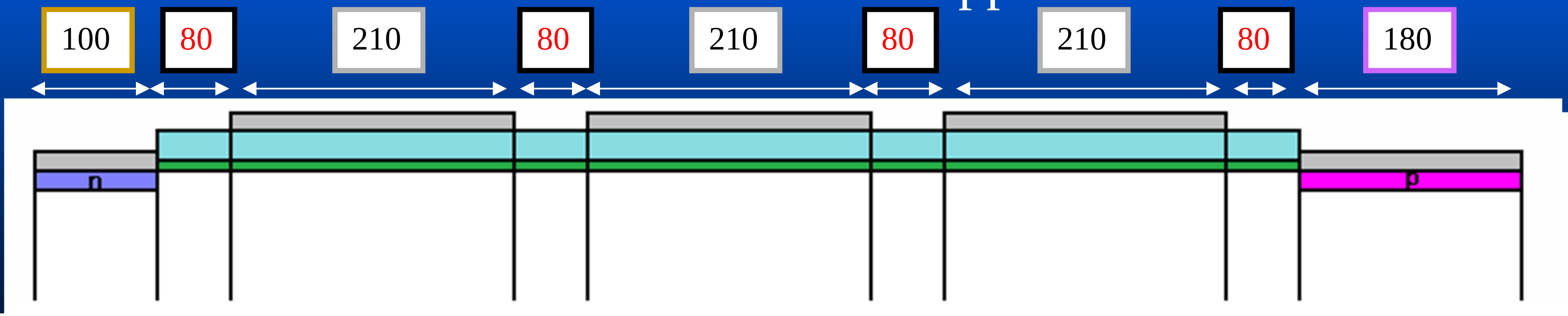
Si
- thickness: 1.5 mm
- resistivity: 10 kΩcm

SiO_2
- thickness: 3 μm

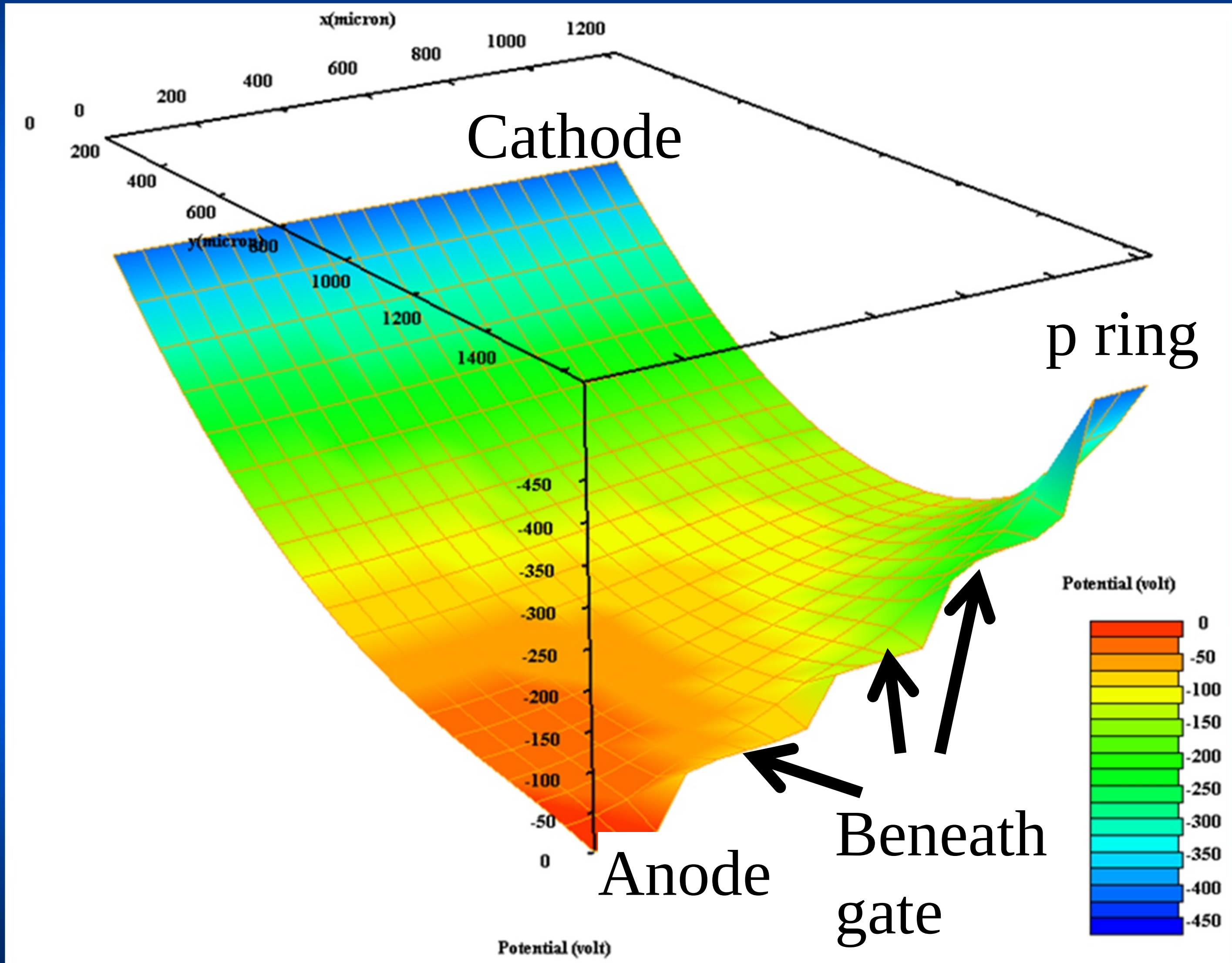
SiO_2/Si interface
- fixed charge: 1×10^{10} cm^{-2}

Cathode
- radius of area: 1.23 mm

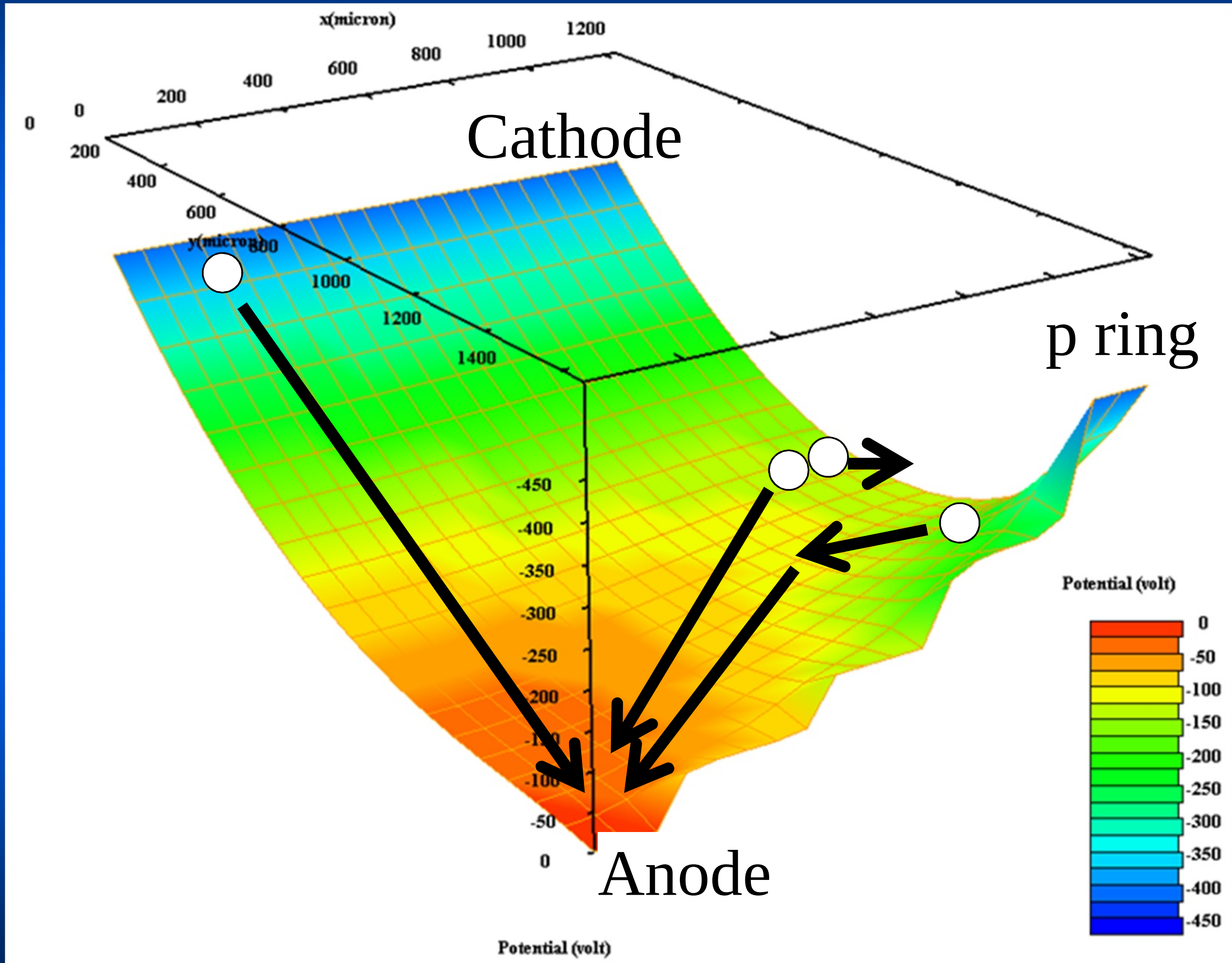
P-ring and all gates are applied at -400 V



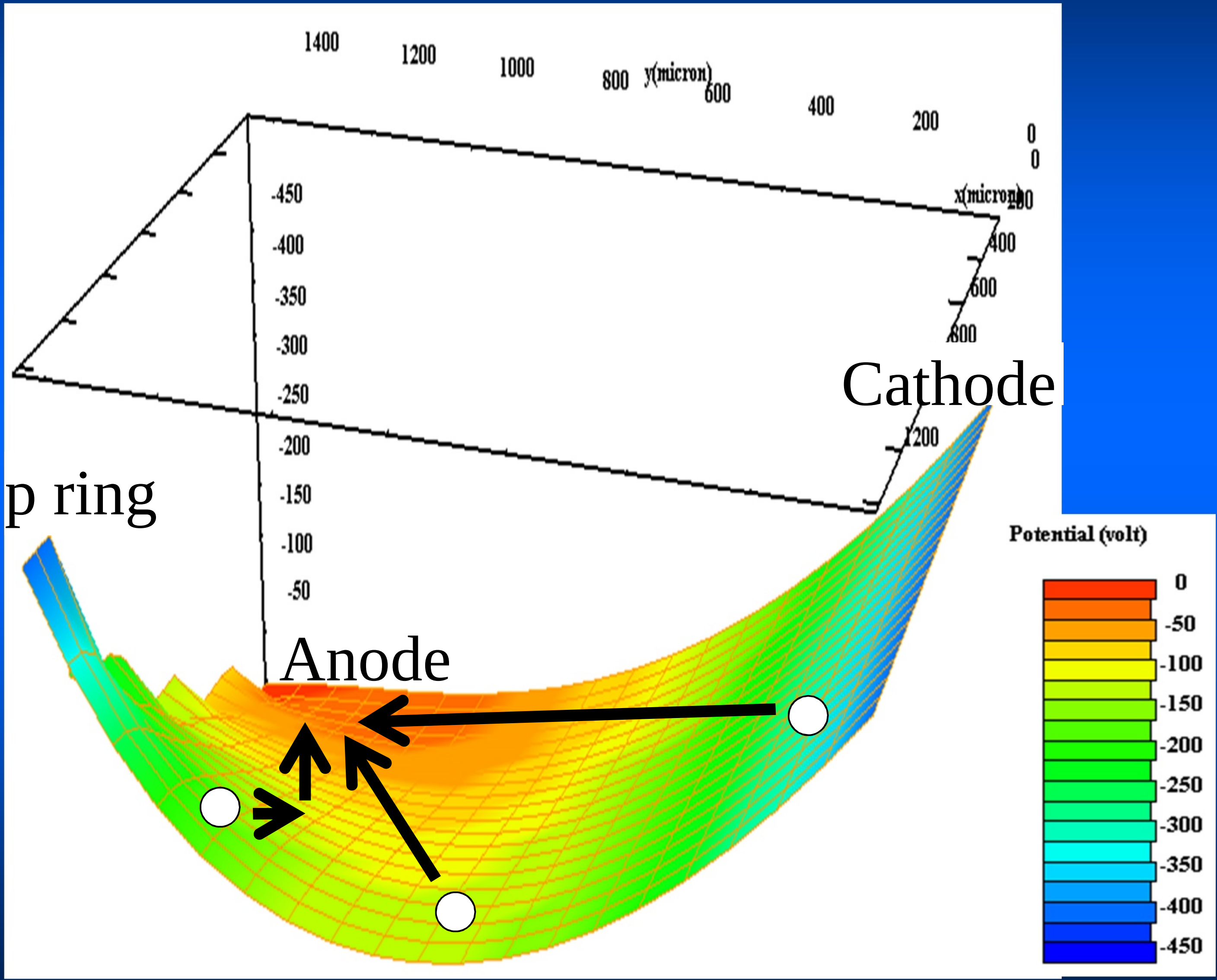
Potential Distribution in Si



Potential Distribution in Si



Potential Distribution in Si



Electrons produced by X-rays can flow smoothly to the anode.

Summary

From experimental results and simulations, we showed the possibilities for Si X-ray detectors satisfied with the followings.

1. **Large active area for high sensitivity**
2. **Small capacitance of detector for high energy resolution**
3. **Operation by Peltier Cooling for transportable unit**
4. **Simple structure for inexpensive detector**
5. **Thick Si wafer for high sensitivity of high energy X-rays**
6. **Only one high voltage bias for inexpensive unit**