Possibilities for Thick, Simple-Structure X-Ray Detectors Operated by Peltier Cooling and One High Voltage Bias

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OUTLINE

1. Problems on commercial SDD (Silicon Drift Detector)

A. The cost of SDD is expensive

B. The absorption of high-energy X-ray fluorescence is very low

2. How to reduce the cost

A. Proposal of simple-structure SDD, referred to as Gated SDD

B. Simulation of electric potential distribution in GSDD with 0.625-mm-thick, 10-kΩ·cm Si

C. Fabrication and experimental results of GSDD with 0.625-mm-thick, 10-kΩ·cm Si

3. How to make Si substrate thicker

A. Simulation of electric potential distribution in GSDD with thicker Si

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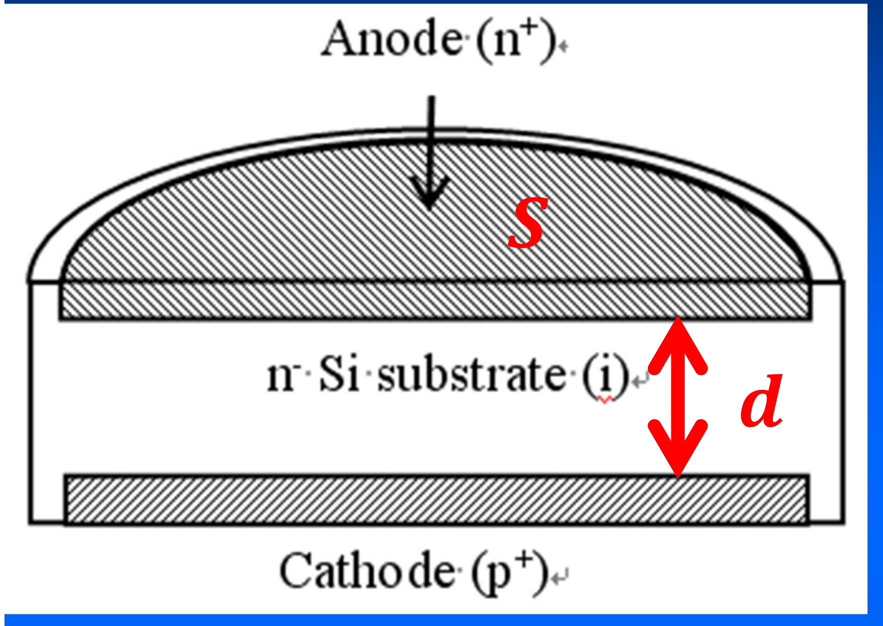
Pin diodes for X-ray detectors



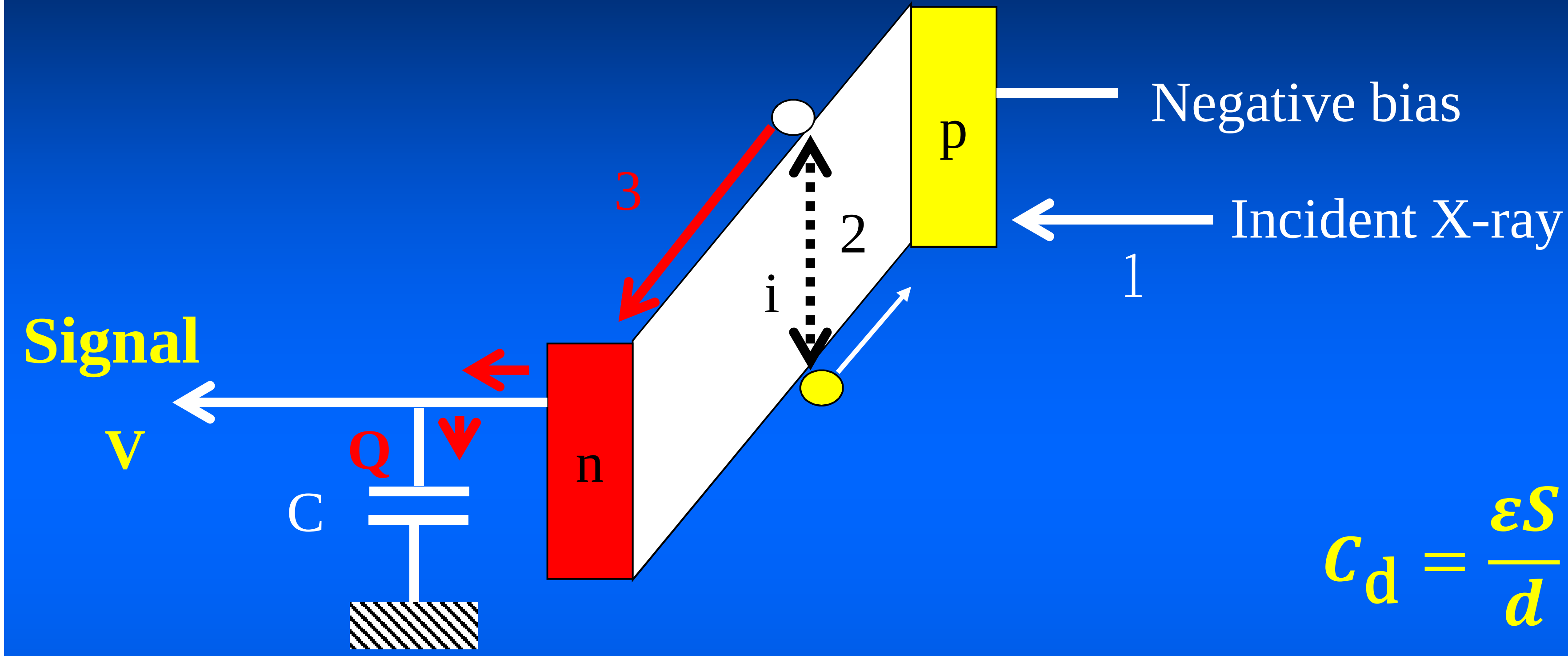
Anode area is the same as cathode area (S).
When active area is made larger,

$$C_{\mathrm{d}} = \frac{\varepsilon S}{d}$$

capacitance of diode becomes larger

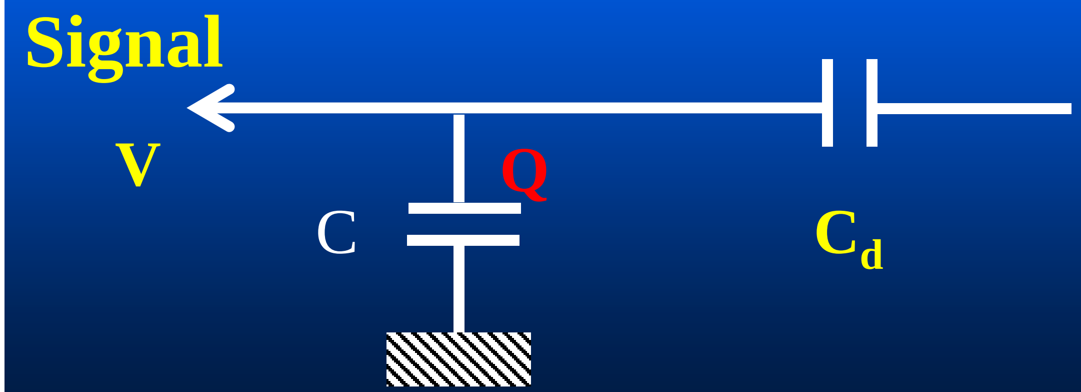
For high energy resolution, capacitance of detector should keep small.

Reason why the capacitance of detector should be small.



$$C_\mathrm{d} = \frac{\varepsilon S}{d}$$

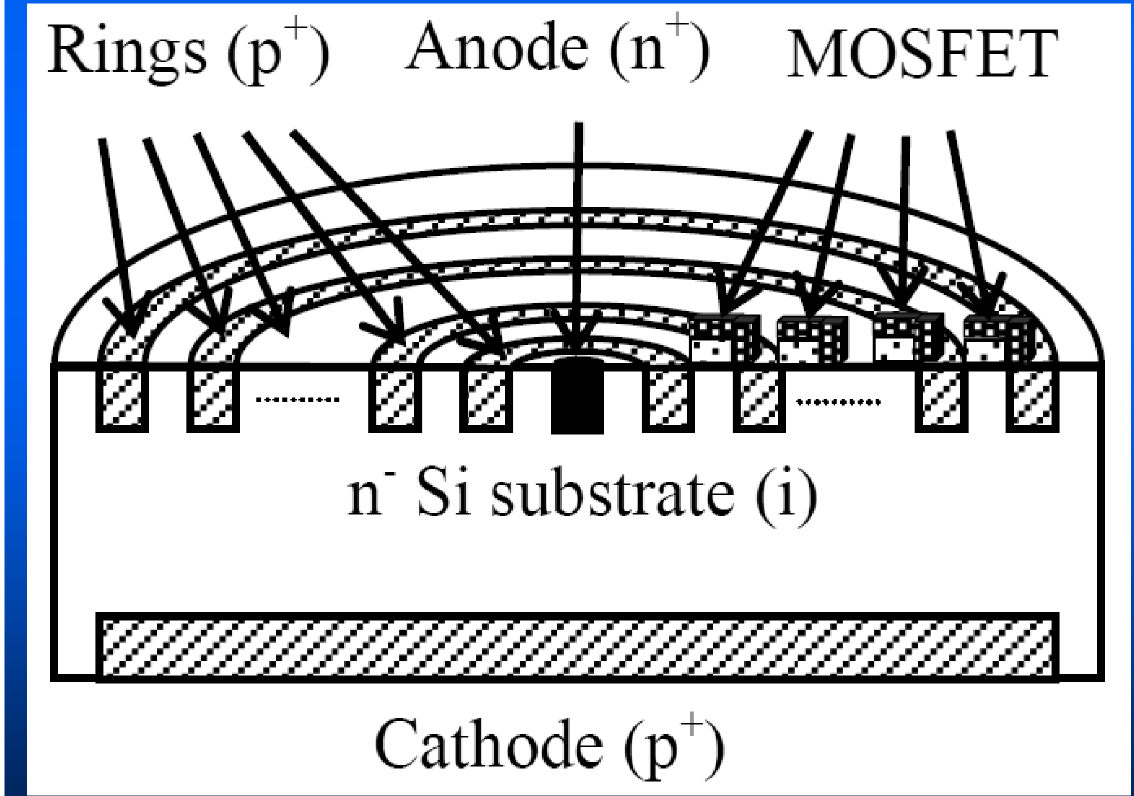
Equivalent circuit



$$V = \frac{Q}{C + C_\mathrm{d}}$$

Features of SDD

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



SDD currently in use

Si :

thickness: 0.3 – 0.5 mm

resistivity: 2 kΩ·cm

Applied voltages:

0.3-mm-thick case:

Cathode: - 50 V

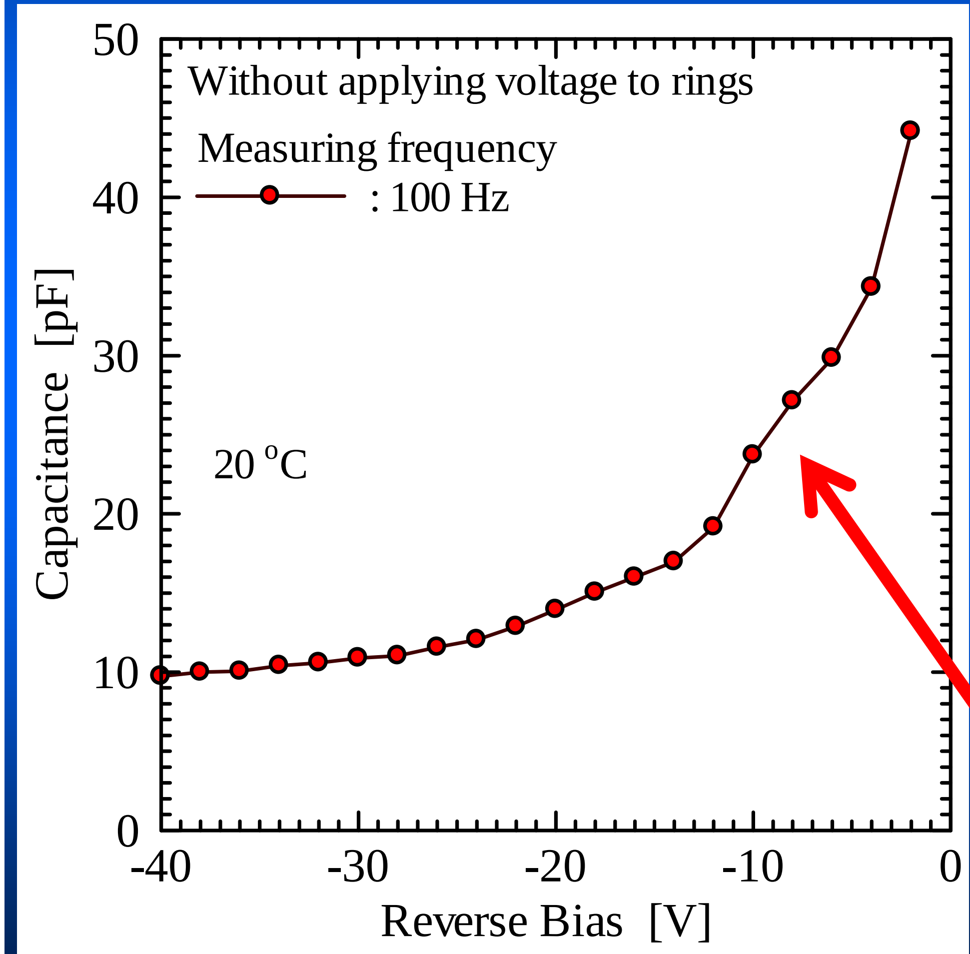
outermost p-ring: -100 V

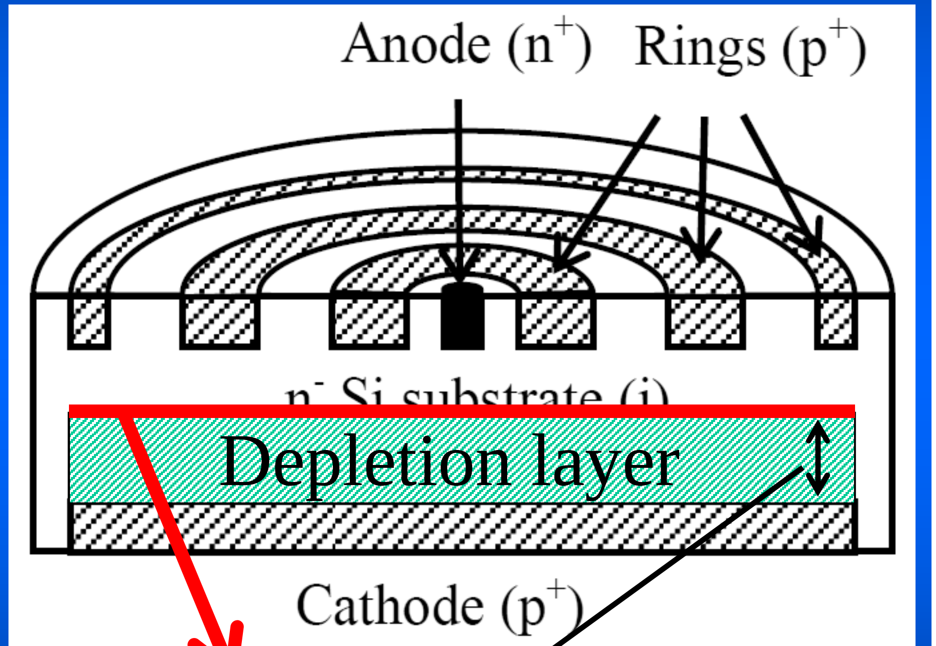
innermost p-ring: - 10 V

Reason why the capacitance is reduced

Capacitance-voltage characteristics

Without applying voltage to rings



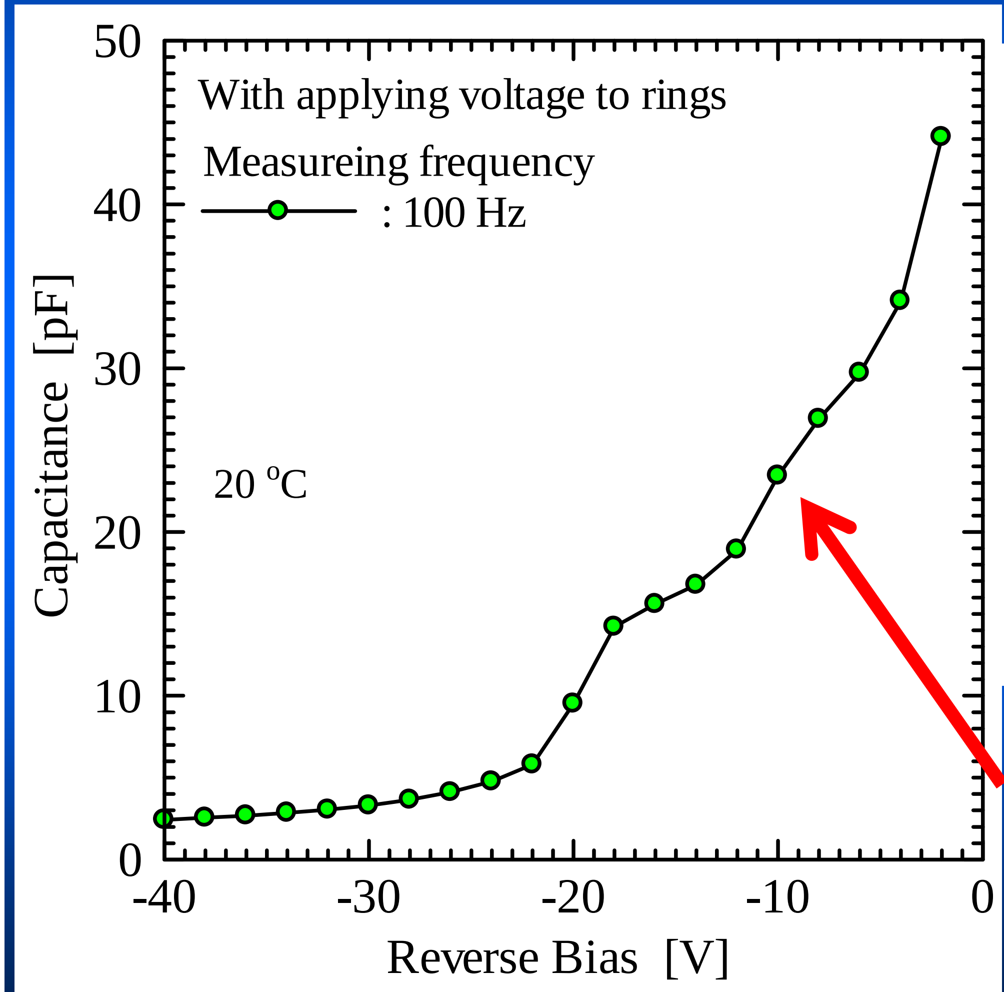


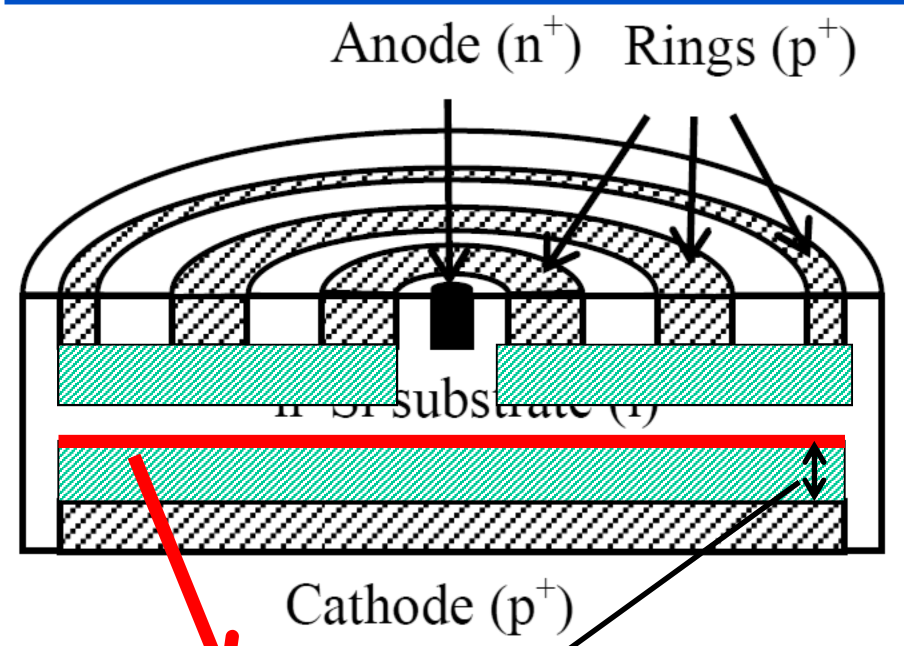
$$C = \frac{\varepsilon S}{d}$$

The capacitance of SDD is the same as that of pin diode.

Capacitance-voltage characteristics

With applying voltage to rings

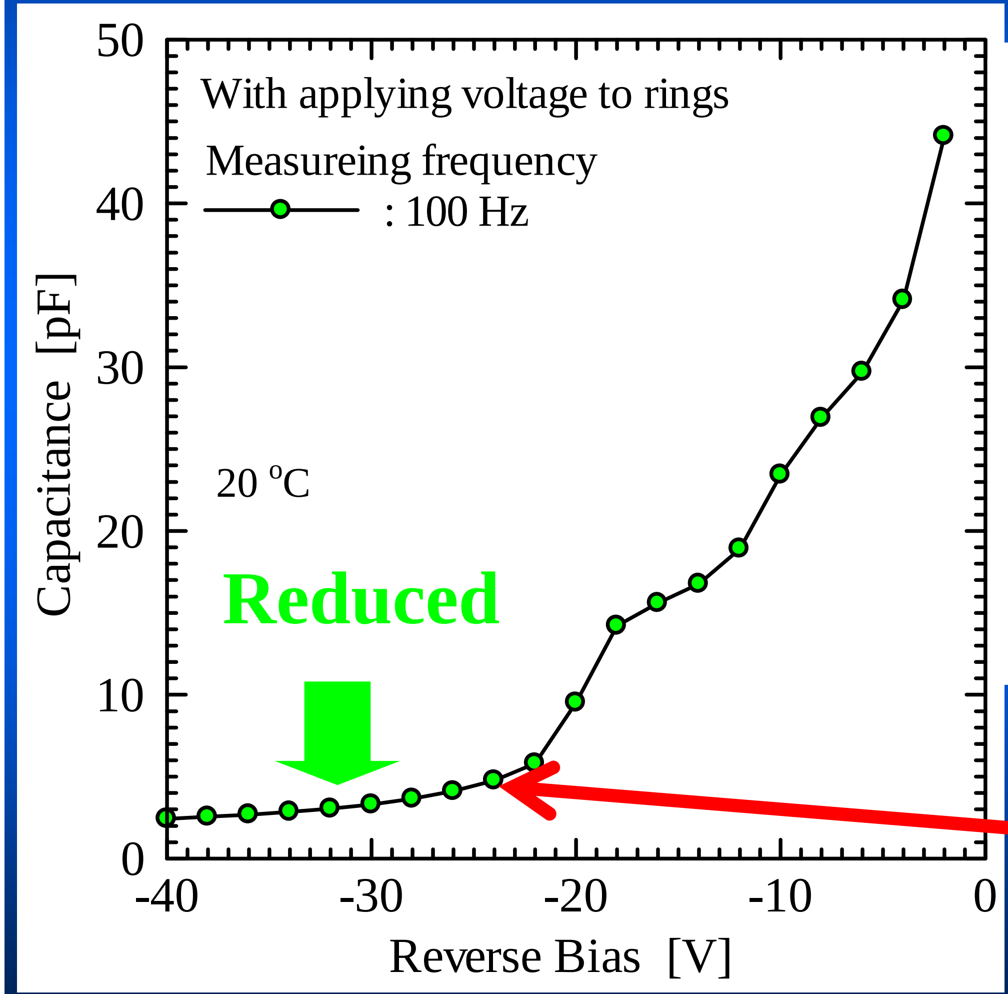


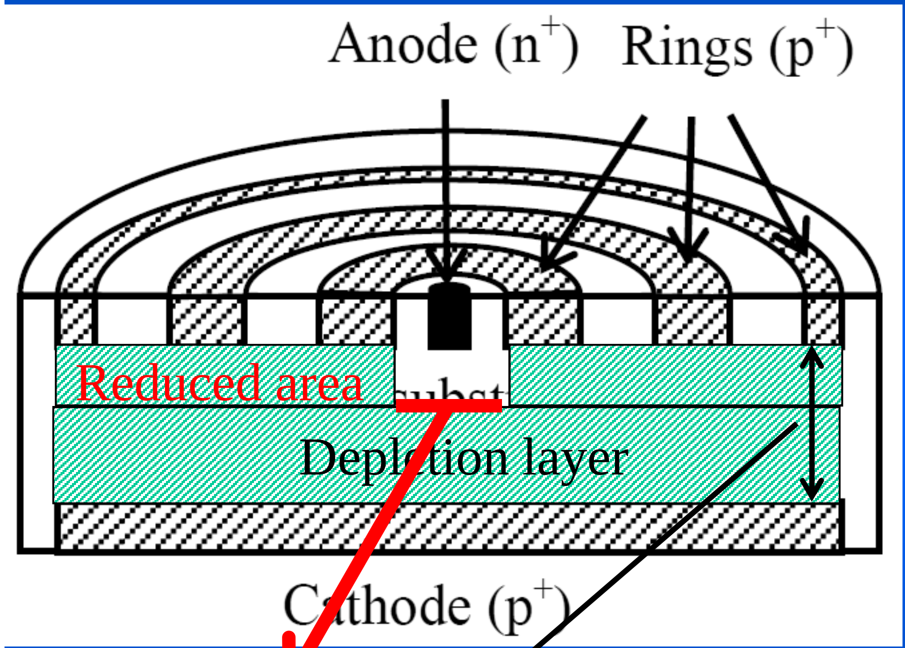


$$C = \frac{\varepsilon S}{d}$$

Capacitance-voltage characteristics

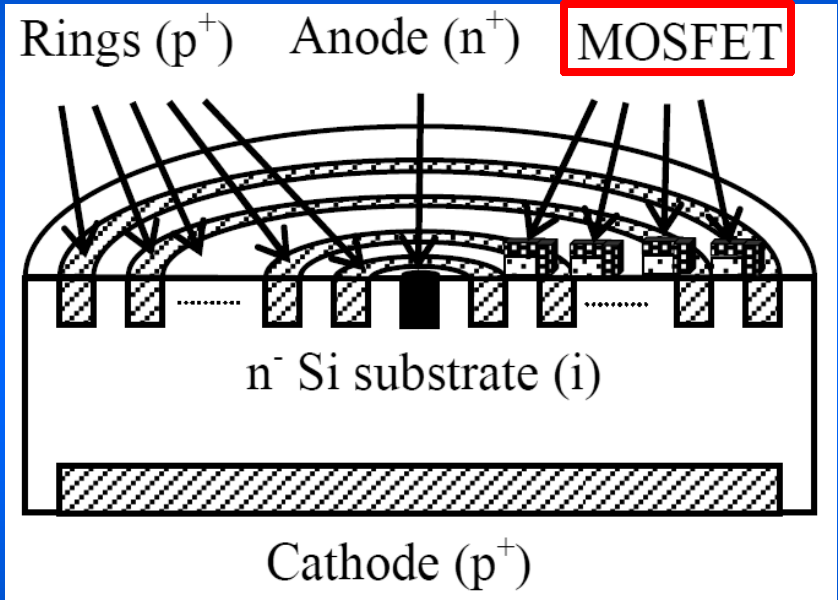
With applying voltage to rings

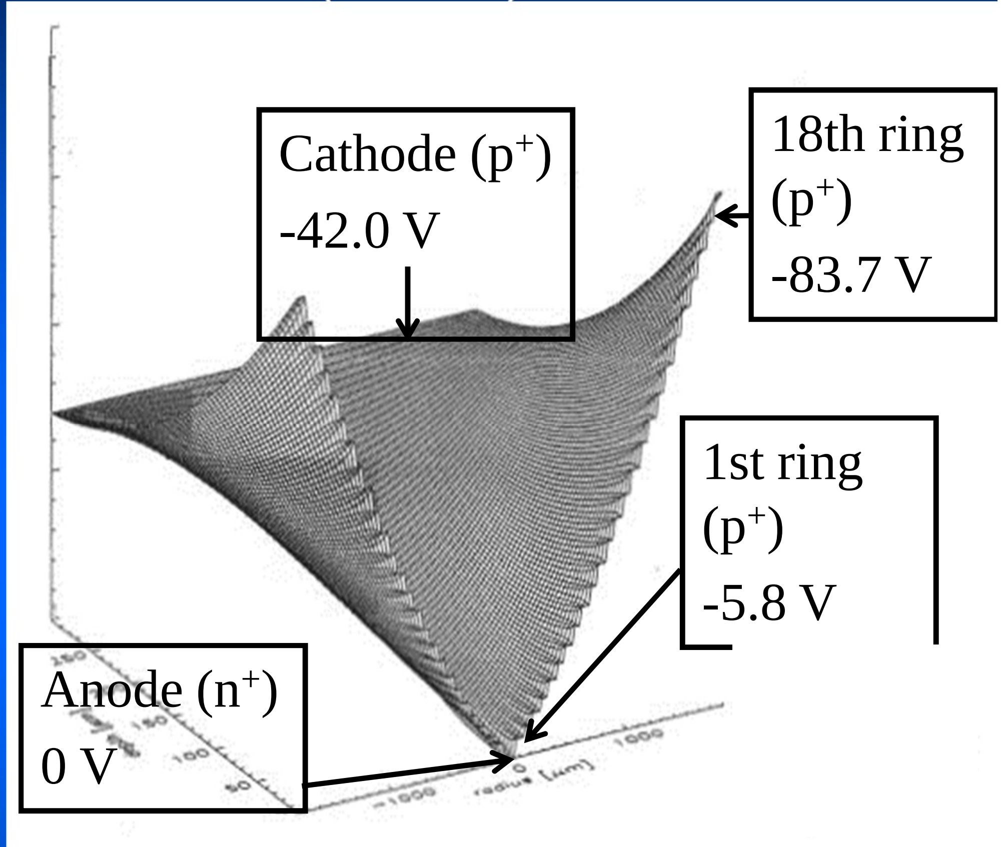




$$C = \frac{\varepsilon S}{d}$$

Silicon Drift Detector (SDD)





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

Fabrication processes of MOSFET are complicated.

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SDD is very expensive.

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A. Simulation of electric potential distribution in GSDD with thicker Si

4. Summary

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 a trace of atoms in materials, fluorescent X-rays of atoms are very useful.

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

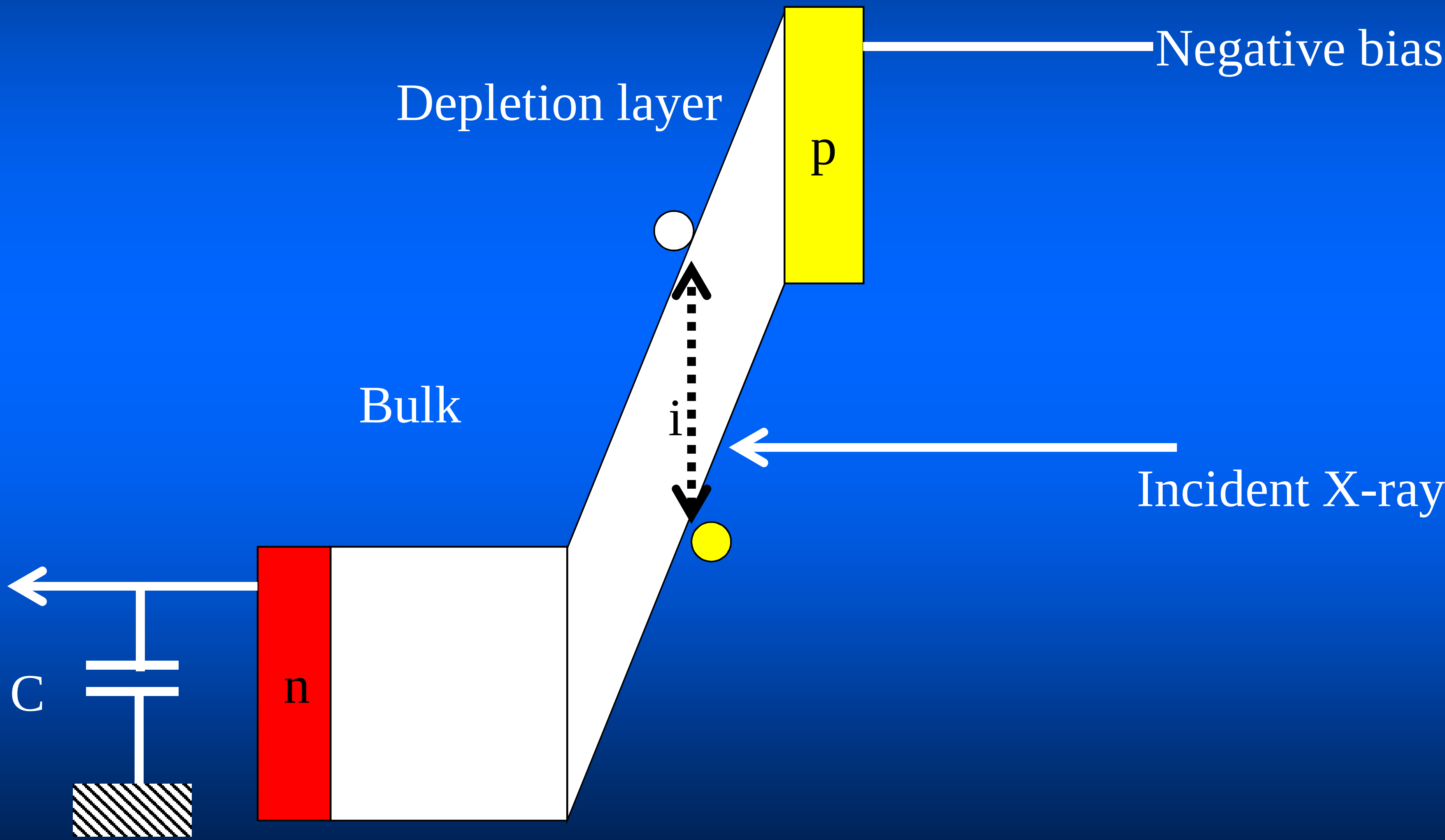
K-line X-ray fluorescence: ^{11}Na(1.0 keV) ～ ^{50}Sn(25.2 keV)

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

Reason why high reverse bias is required.

1. Produced electron-hole pair in depletion region



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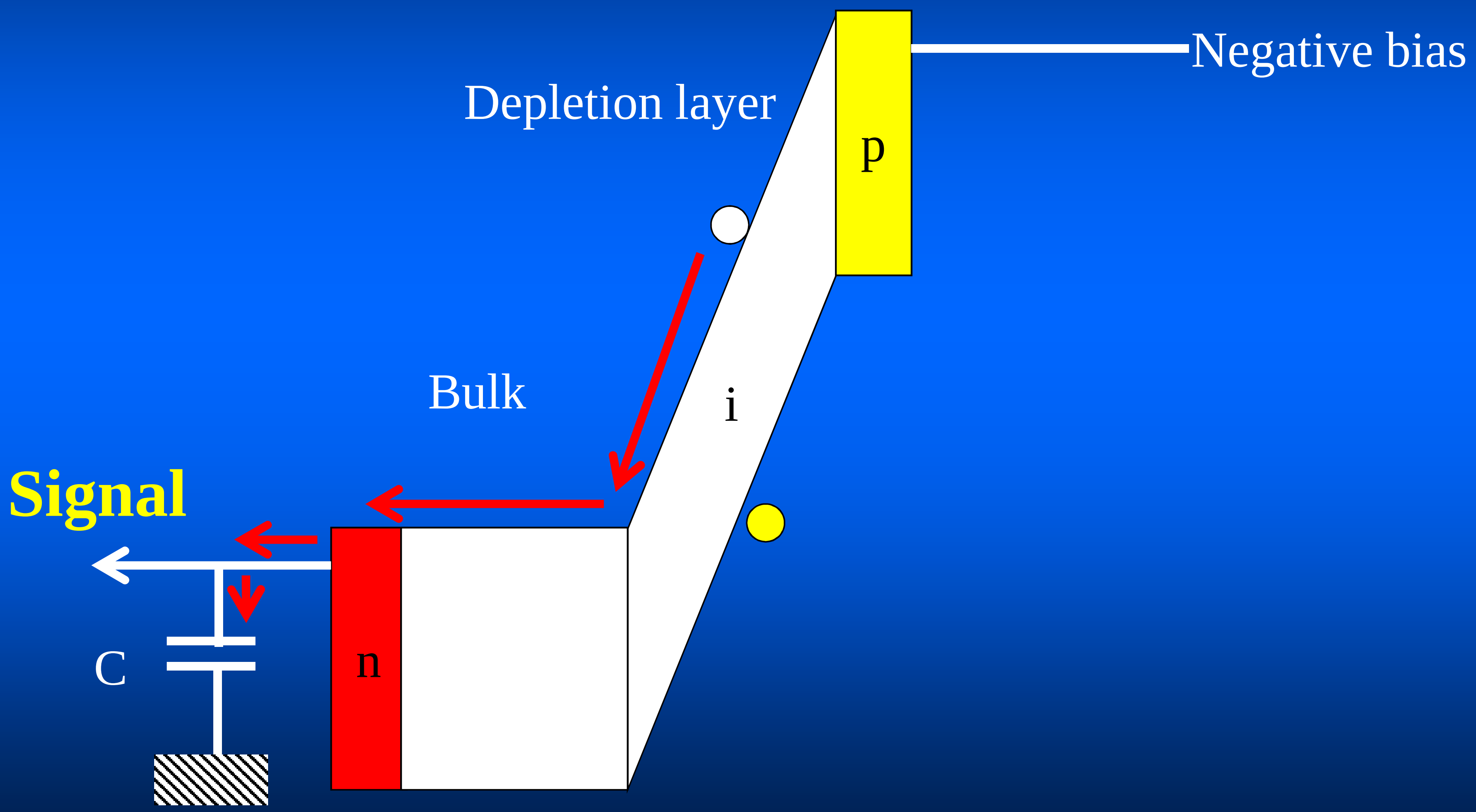
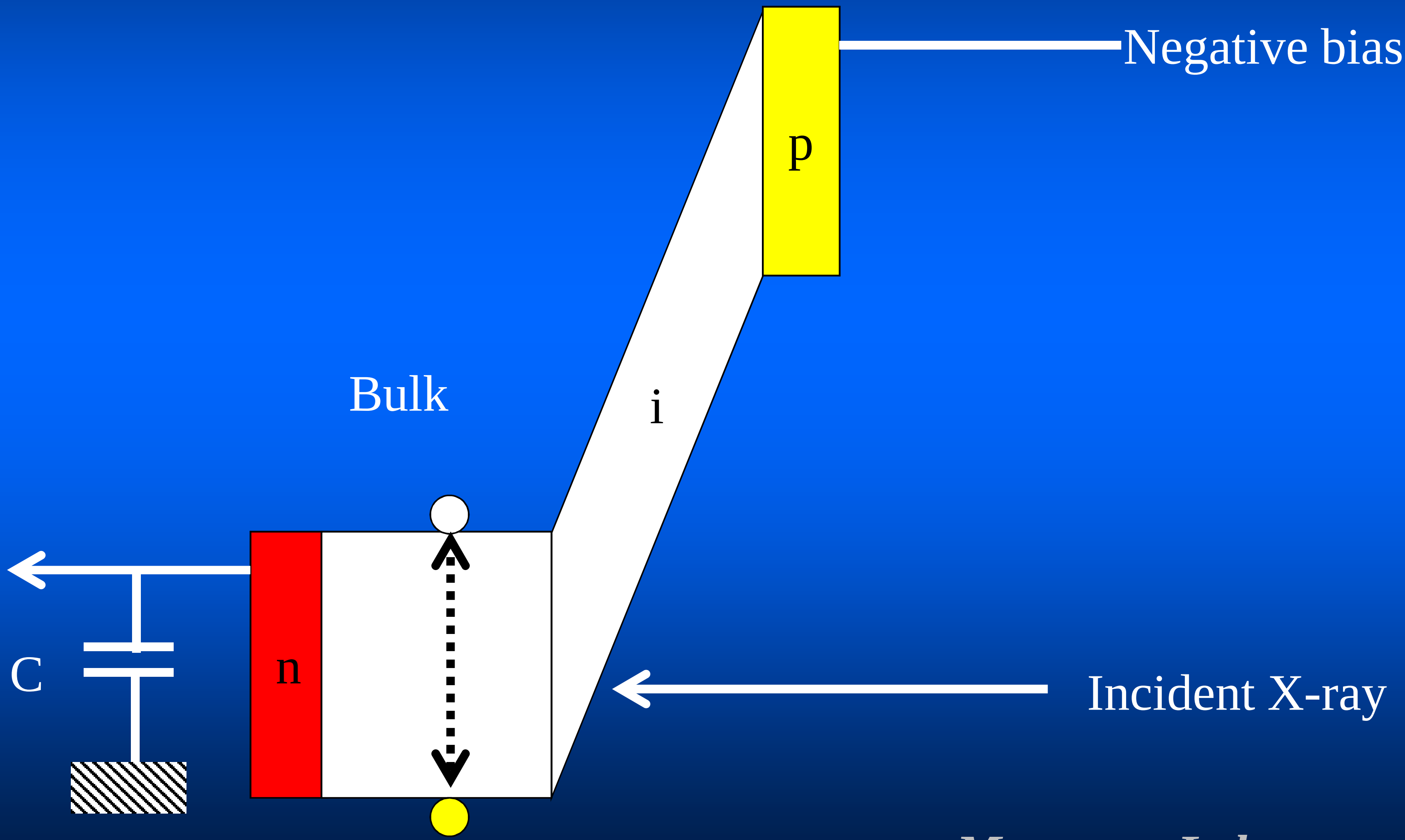


2. Produced electron-hole pair in bulk



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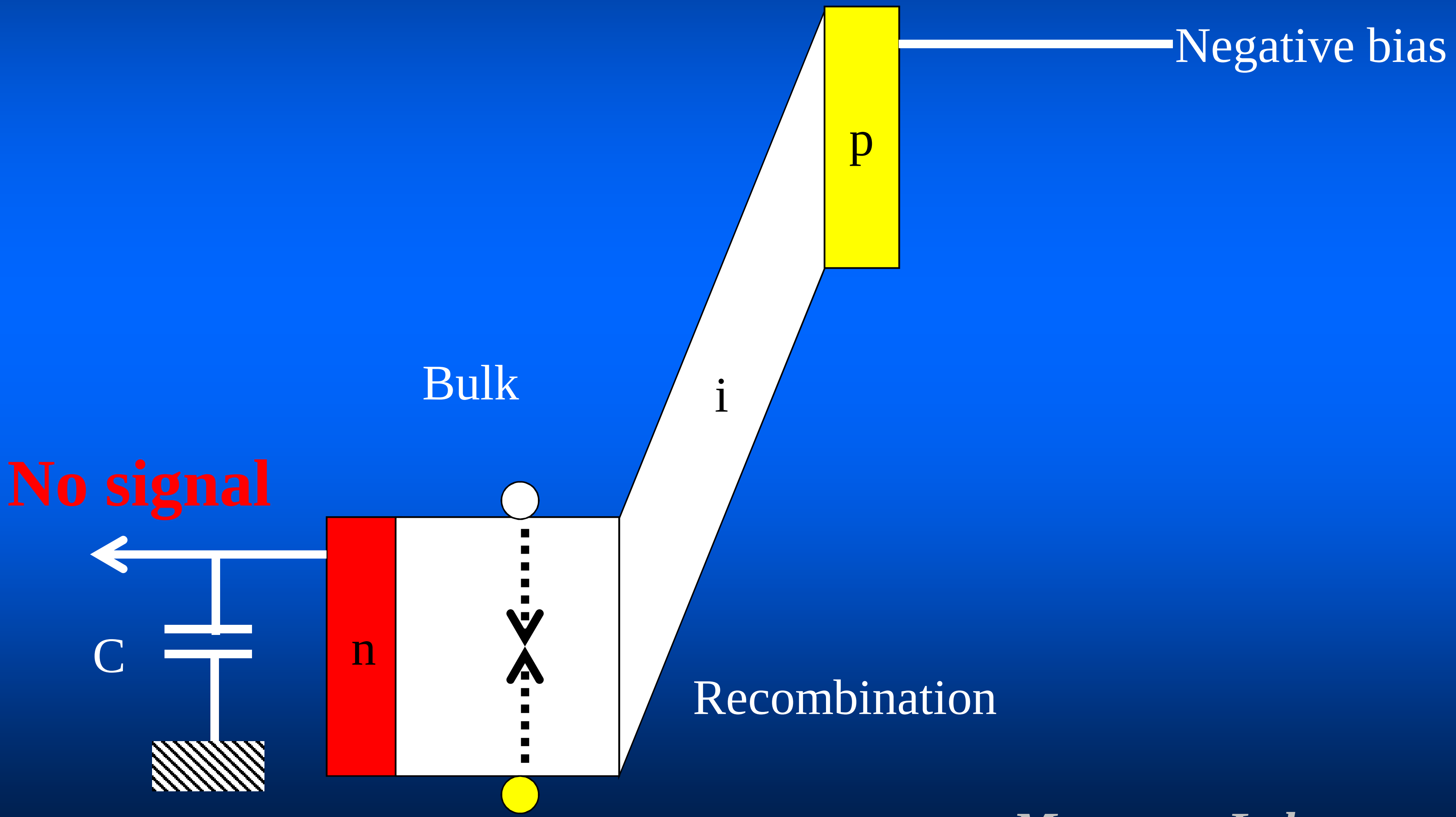
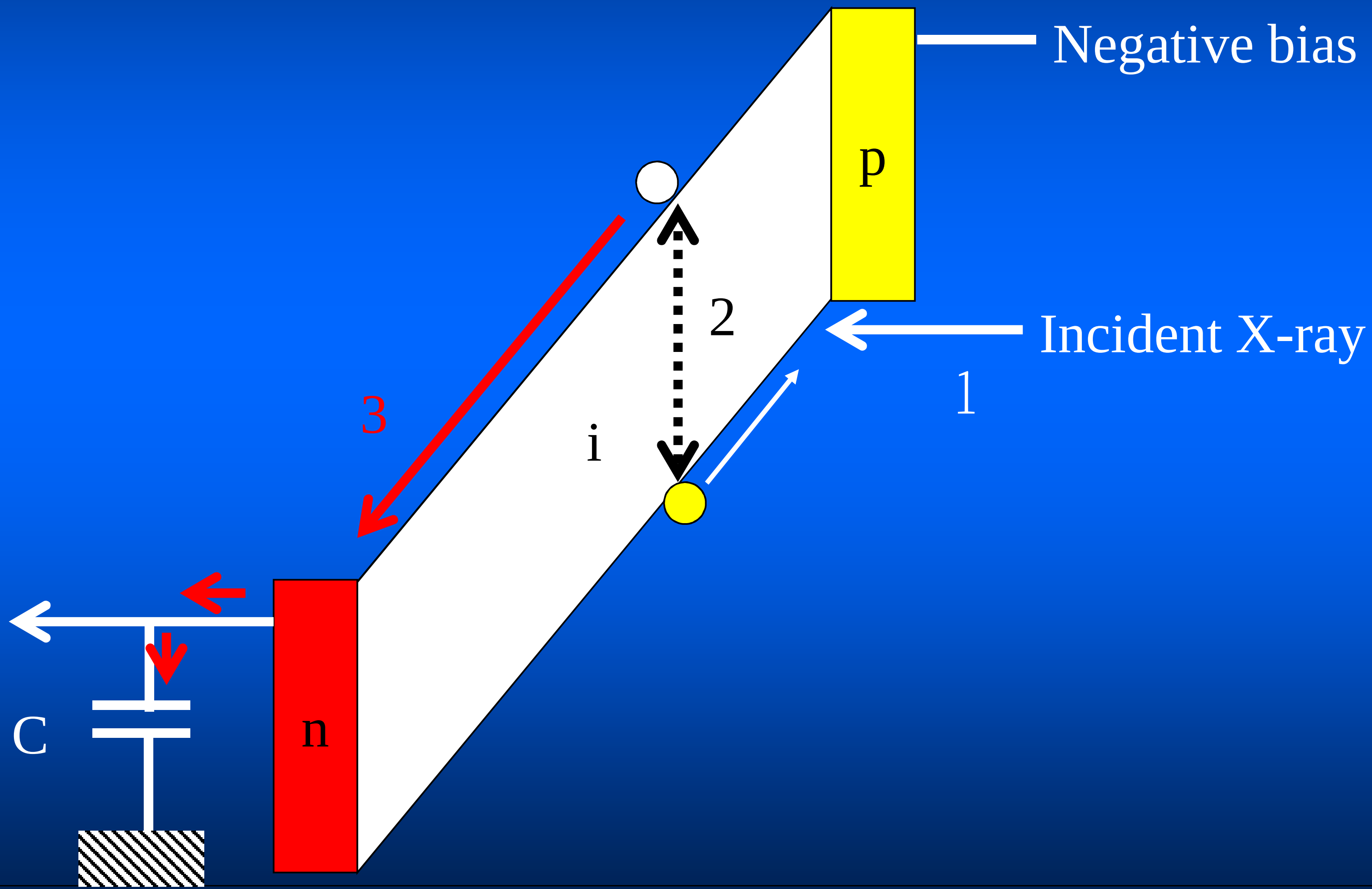


To deplete the whole i layer, high reverse bias is required

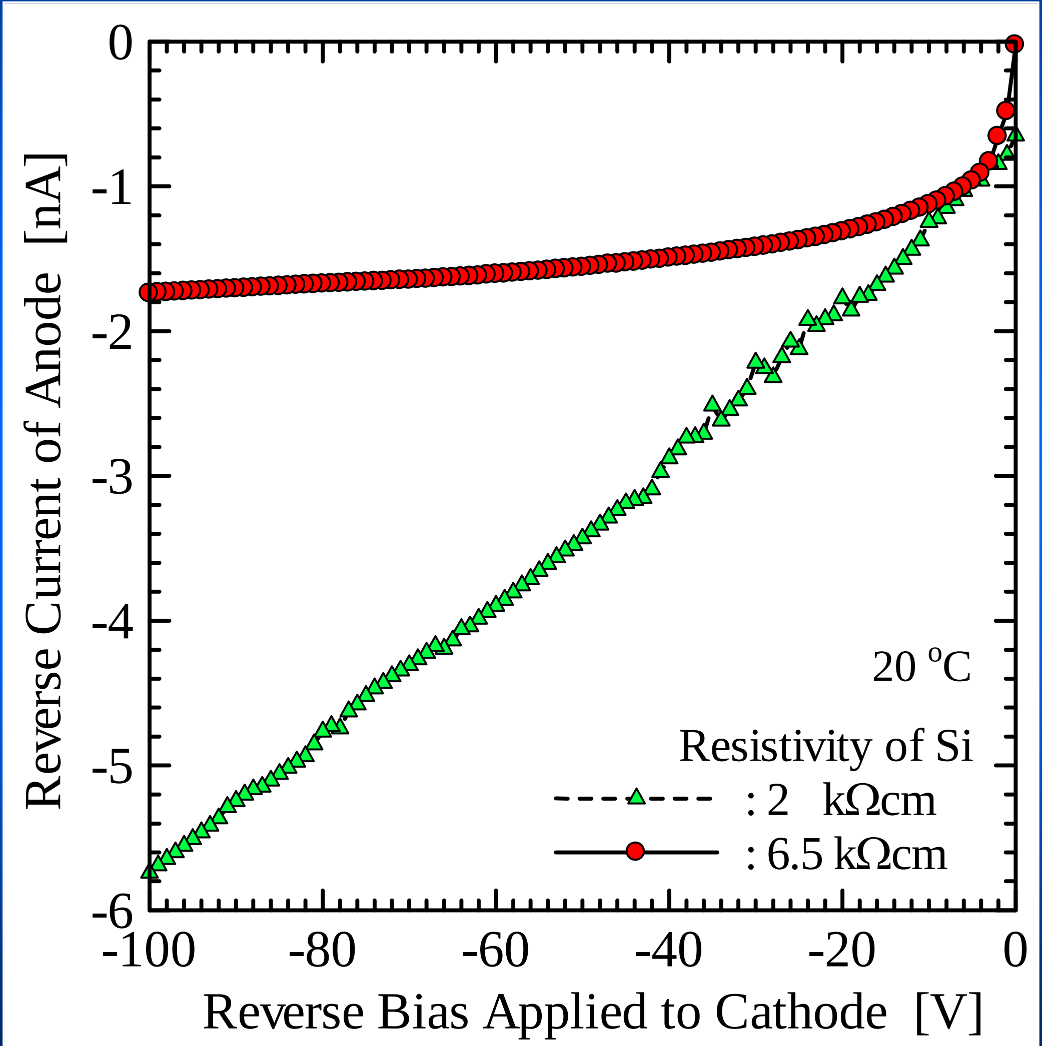


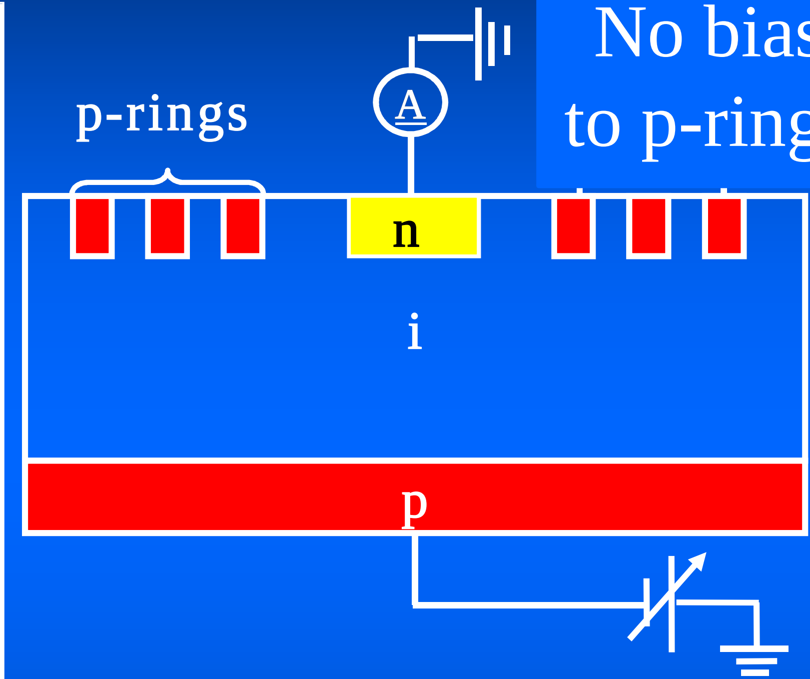
Reverse bias required to deplete a whole i layer of pin diode

Resistivity [kΩ·cm]	**2**	**10**	20	40
N_D [cm^{-3}]	2×10^{12}	4×10^{11}	2×10^{11}	1×10^{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**

To operate at reasonably low bias,
higher-resistivity Si substrate is required.

Dependence of Reverse Current of Anode on Si resistivity



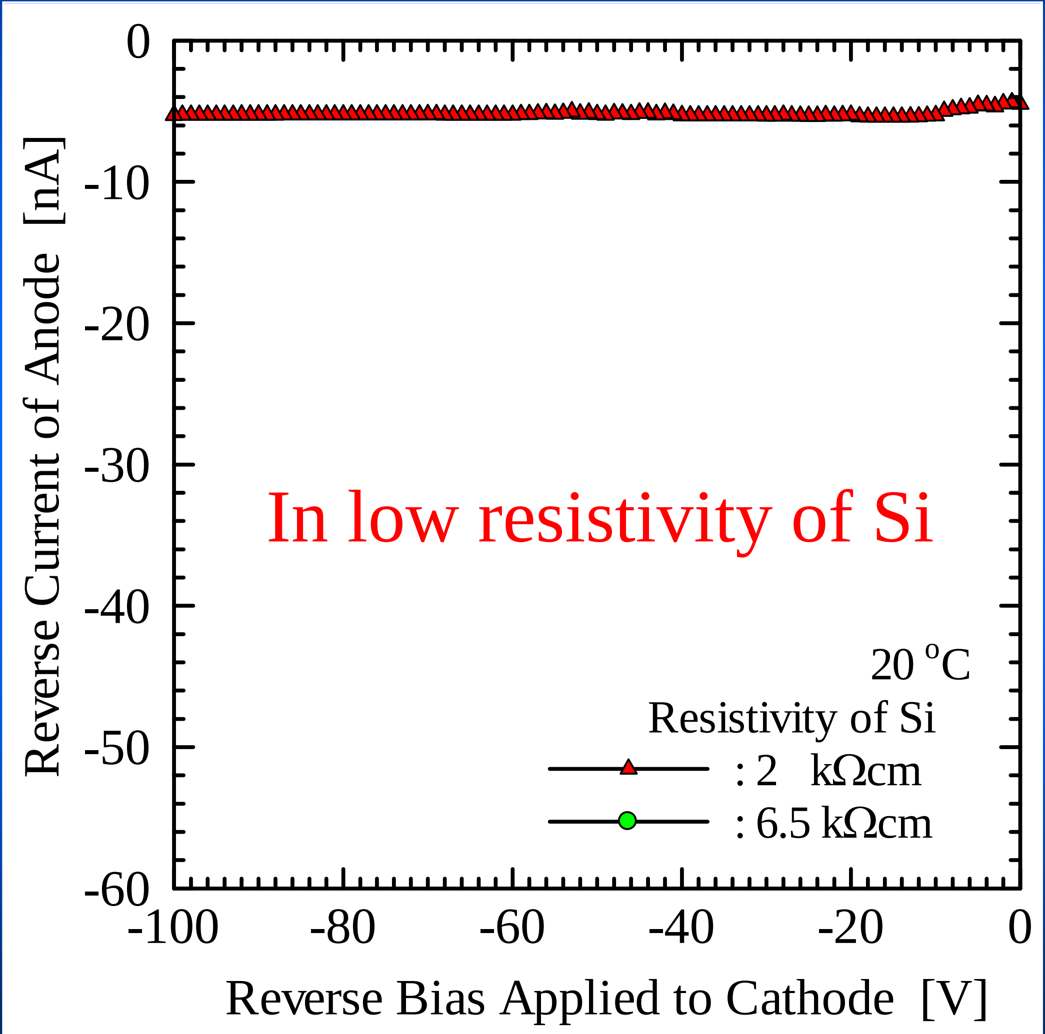


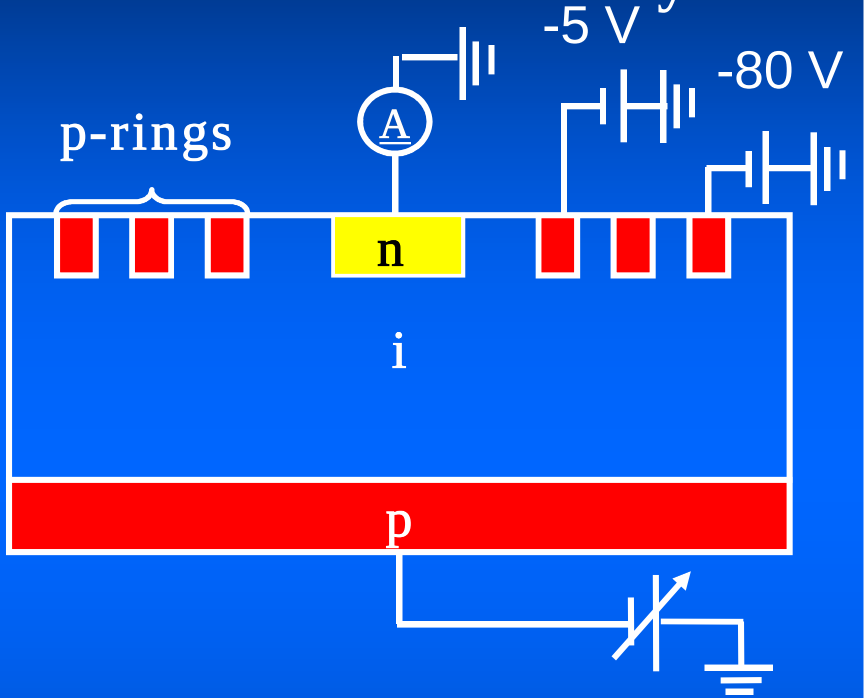
No bias to p-rings

The current for 6.5 kΩ·cm Si reduces compared with the current for 2 kΩ·cm Si.

Problem when bias is applied to p-rings

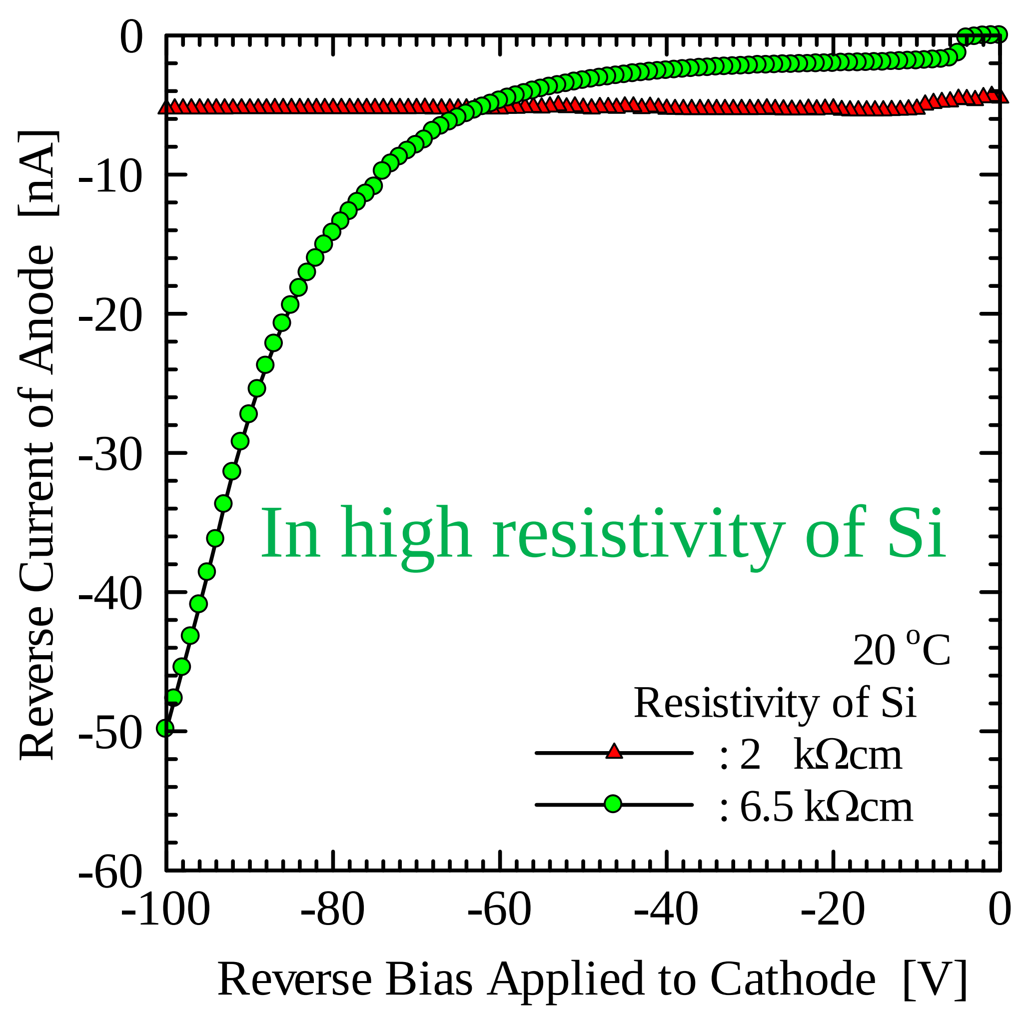
Dependence of Reverse Current of Anode on Si resistivity

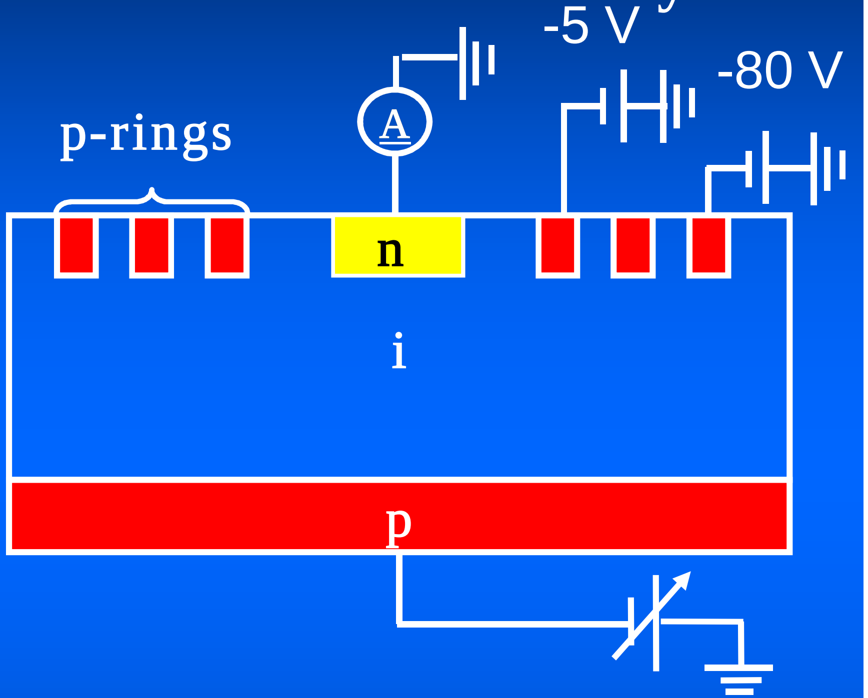




Problem when bias is applied to p-rings

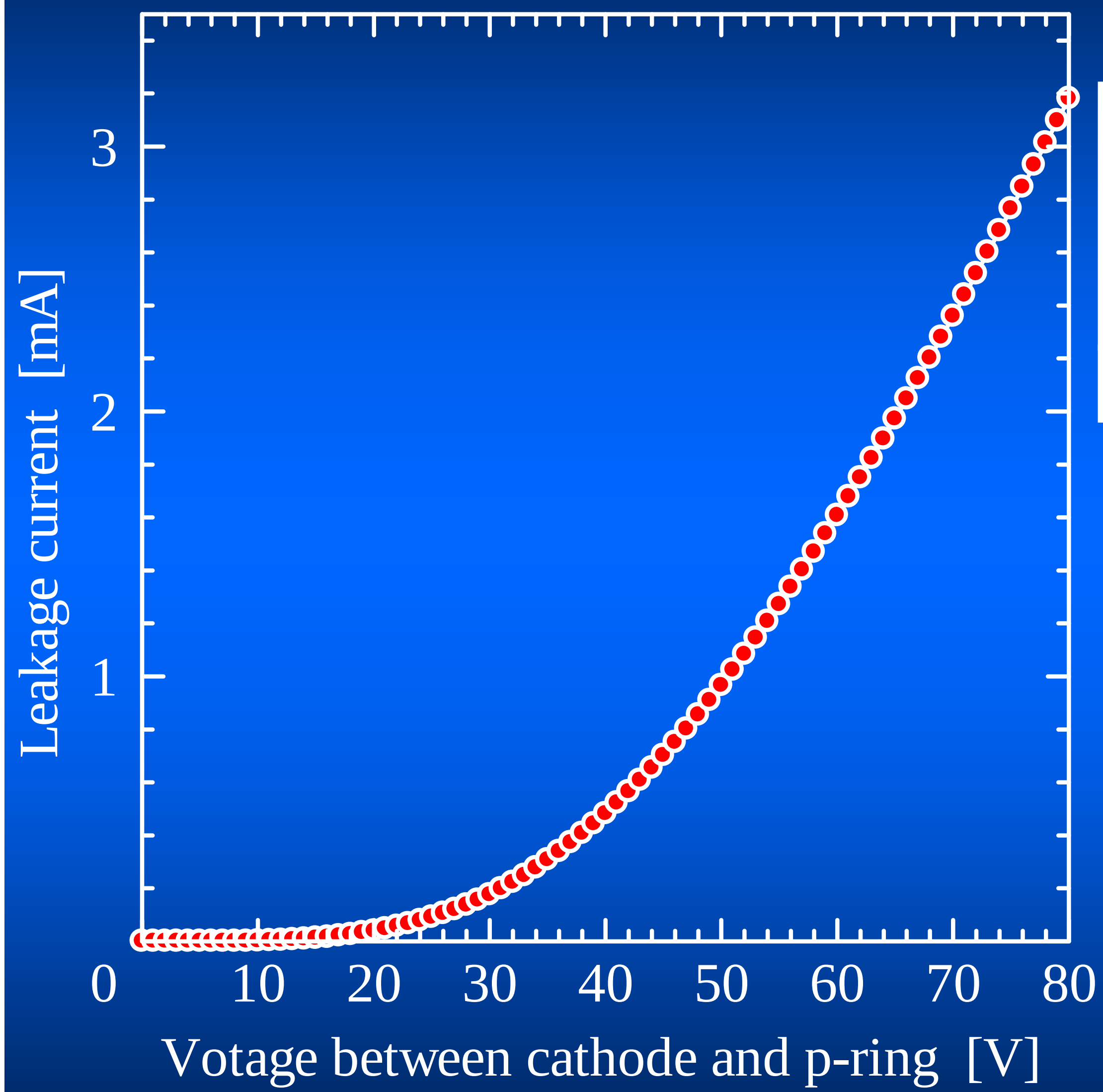
Dependence of Reverse Current of Anode on Si resistivity

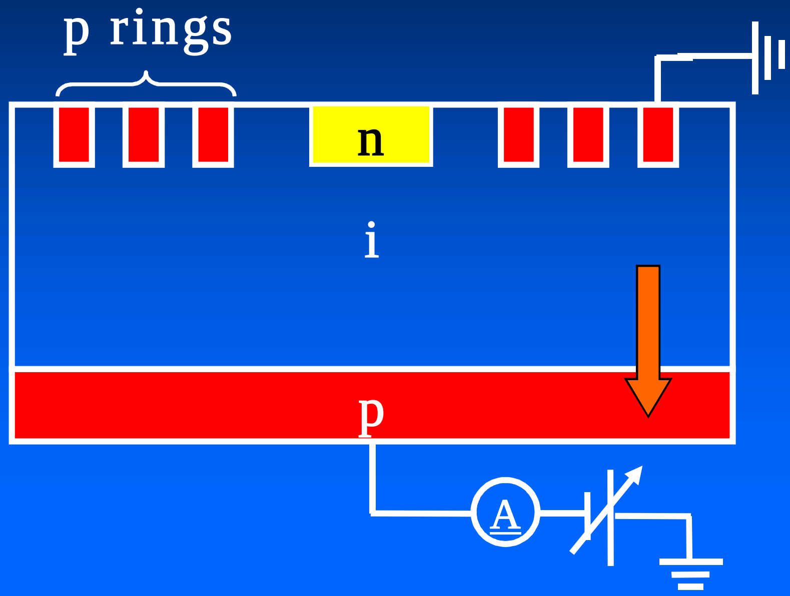




Unfortunately, the current for 6.5 kΩ·cm Si increased with bias, and exceeded the current for 2 kΩ·cm Si.

Leakage current between cathode and p-ring for higher-resistive Si





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.

High-resistive Si is not used for SDD.

SDD has the following features;

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

Moreover, our proposed detector has the following features.

4. **Simple structure for inexpensive detector**
5. **Thick Si substrate for high sensitivity of high energy X-rays**
6. **Only one high, but reasonably low, voltage bias for inexpensive unit**

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   C. Fabrication and experimental results of GSDD with 0.625-mm-thick, 10-kΩ·cm Si
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   A. Simulation of electric potential distribution in GSDD with 1.5-mm-thick Si
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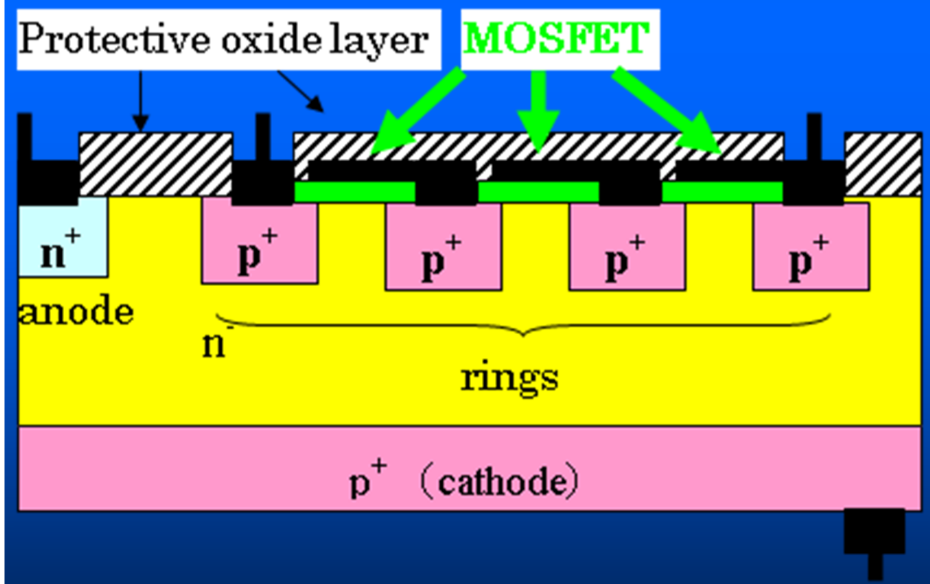
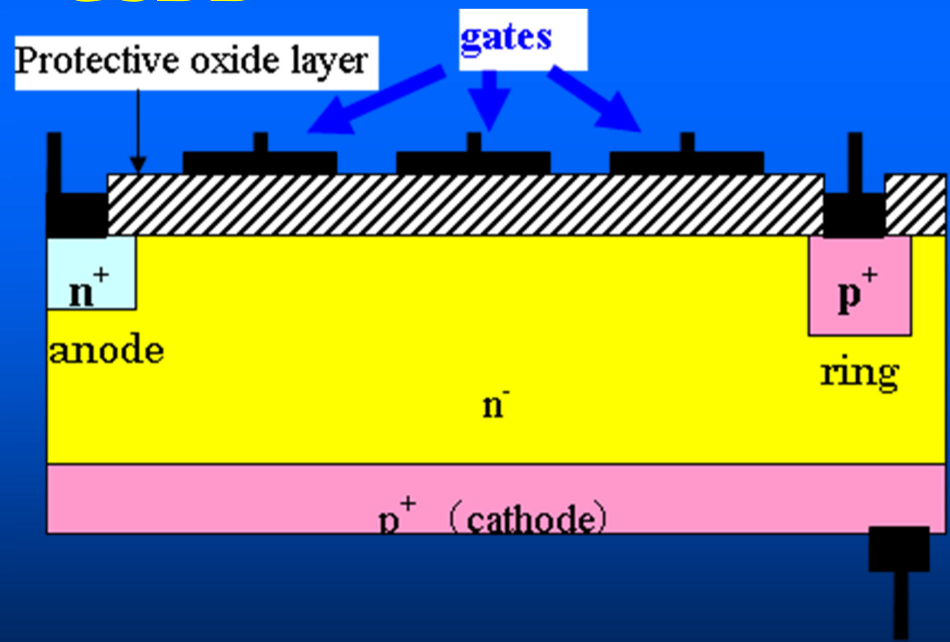
Proposal of New X-ray detector

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**
5. One high voltage bias

SDD



GSDD



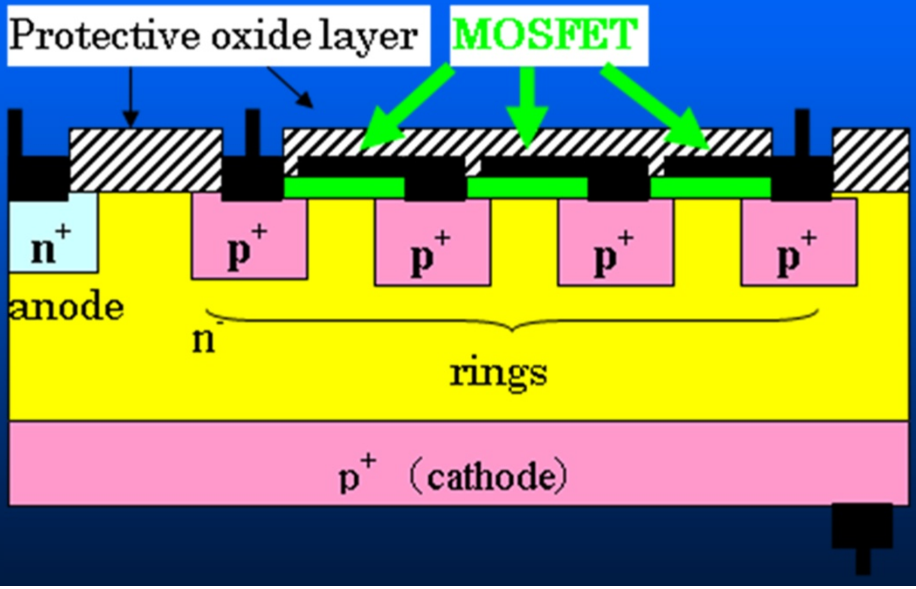
Comparison of fabrication processes of SDD and GSDD

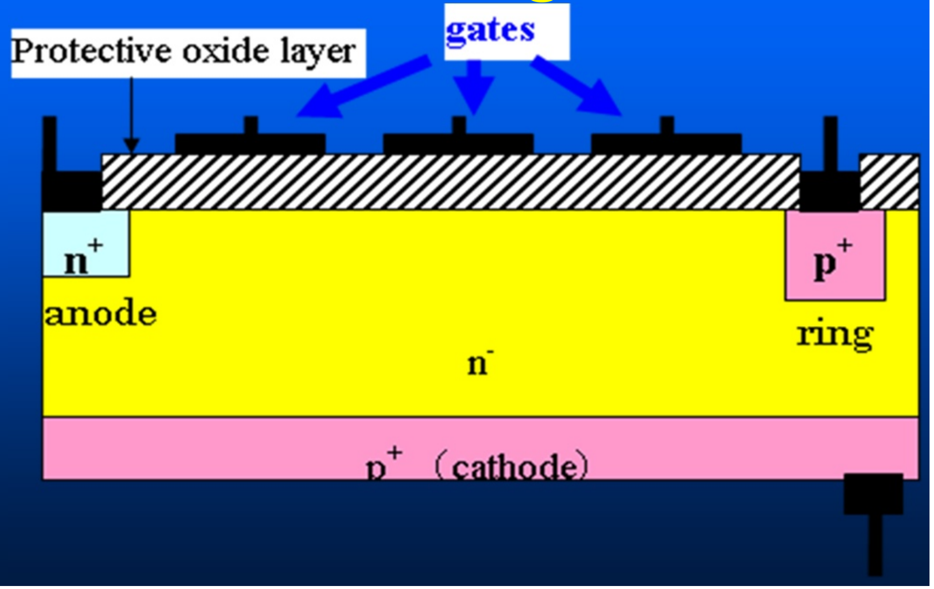
SDD

1. p-rings and guardrings
2. Anode
3. Cathode
4. **MOSFETs or resistors between p-rings**
5. Protective oxide layers
6. Metallization

GSDD

1. p-rings and guardrings
2. Anode
3. Cathode
4. Protective oxide layers
5. Metallization and **gates**





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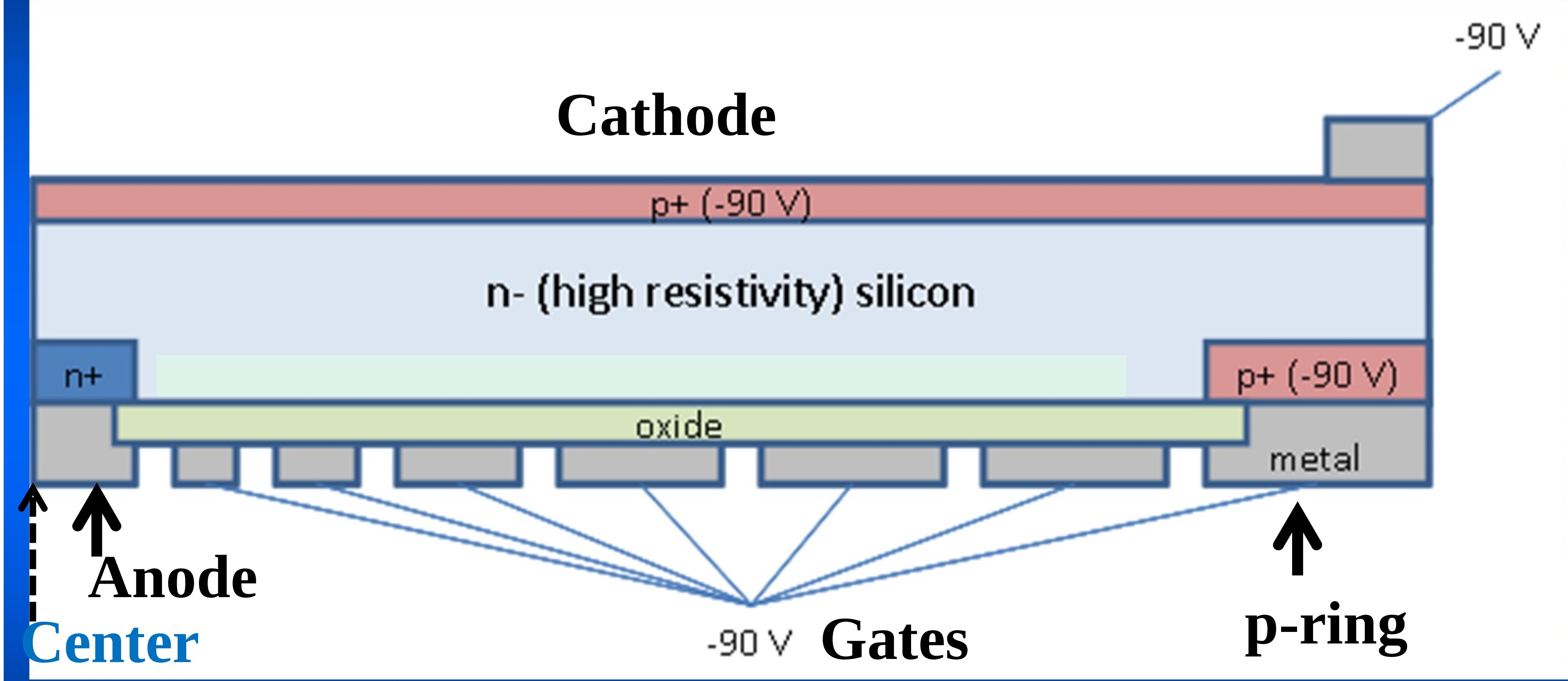
Simulation of GSDD

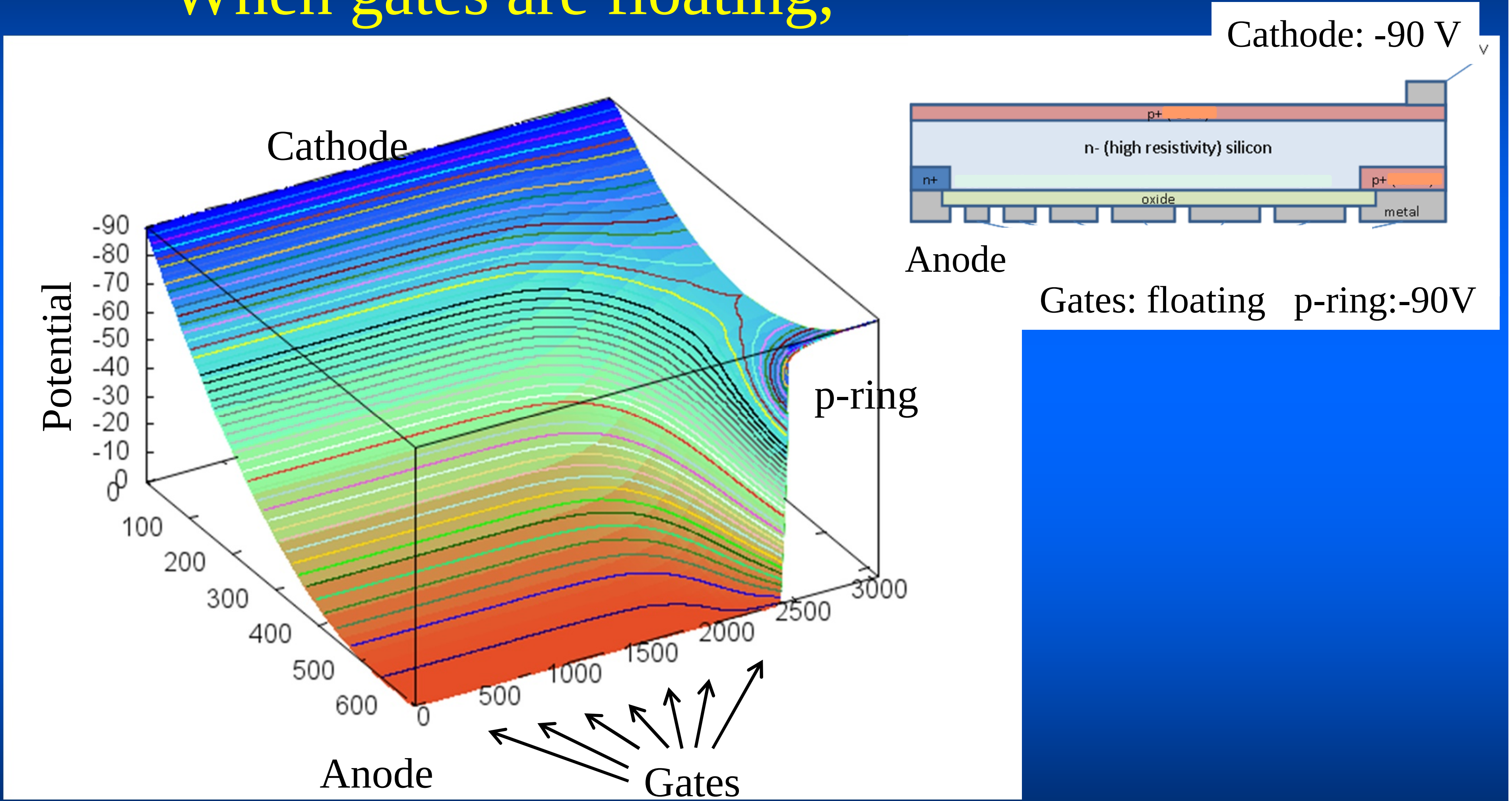


Si resistivity: 10 kΩ·cm
Si thickness: 0.625 mm

Distance between center and p-ring:
2.455 mm

Simulated Electric Potential Distribution within GSDD

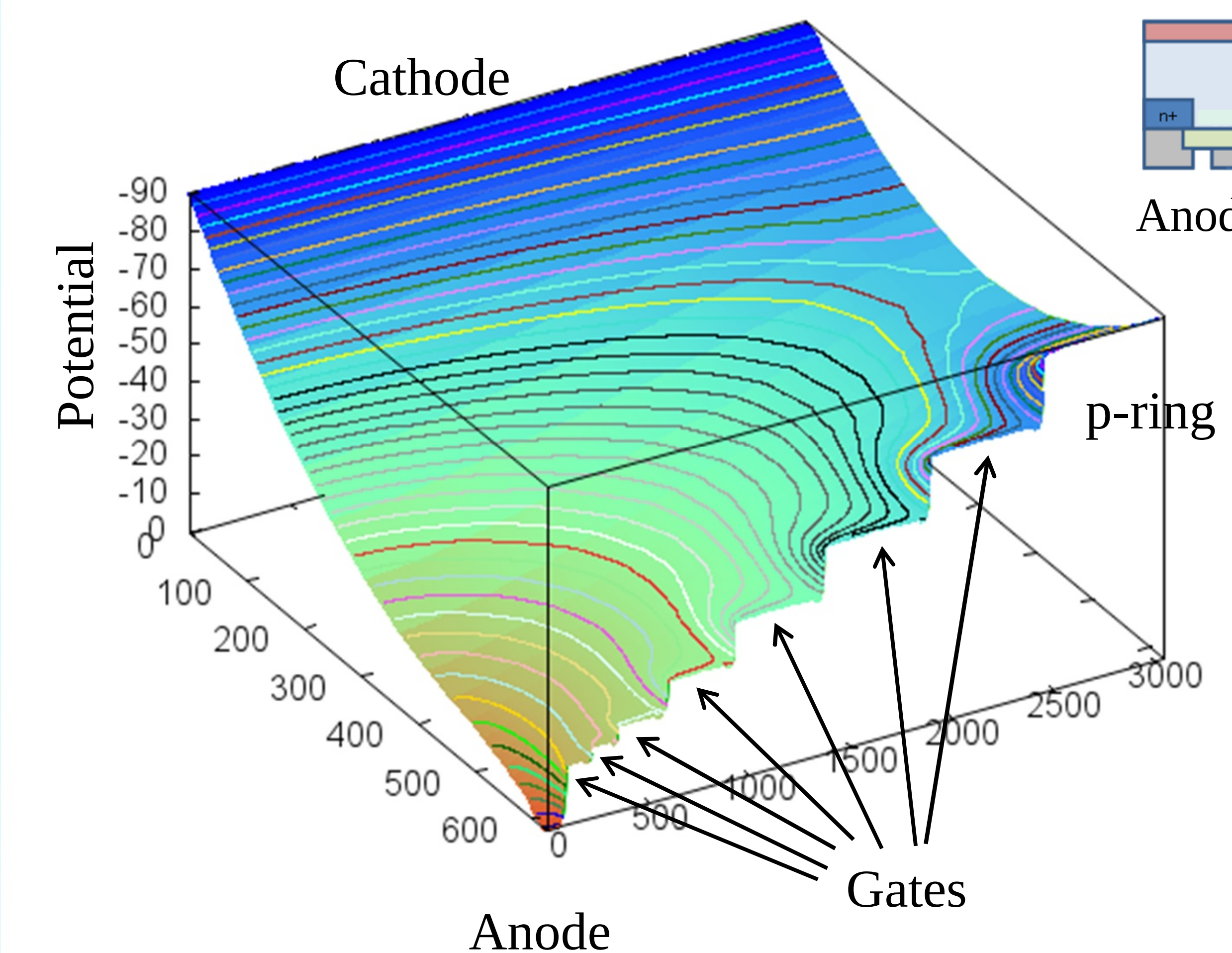
When gates are floating,

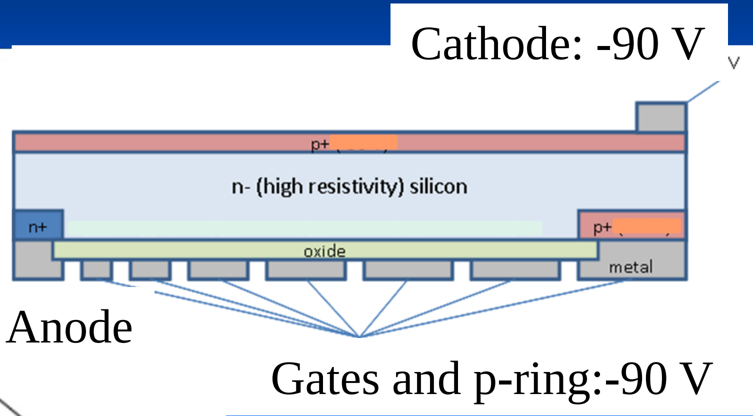


Electrons flow to interface, not to anode.

Simulated Electric Potential Distribution within GSDD

When gates are biased,





Applying the same bias to gates is very effective.

Influence of fixed oxide charges near SiO_2/Si interface on electric potential distribution

In SiO_2 near SiO_2/Si interface, there are positive fixed oxide charges of $3 \times 10^{10}\ \mathrm{cm}^{-2}$ for current fabrication conditions.

However, the density of positive fixed oxide charges is influenced by the fabrication process conditions and operating environmental atmosphere.

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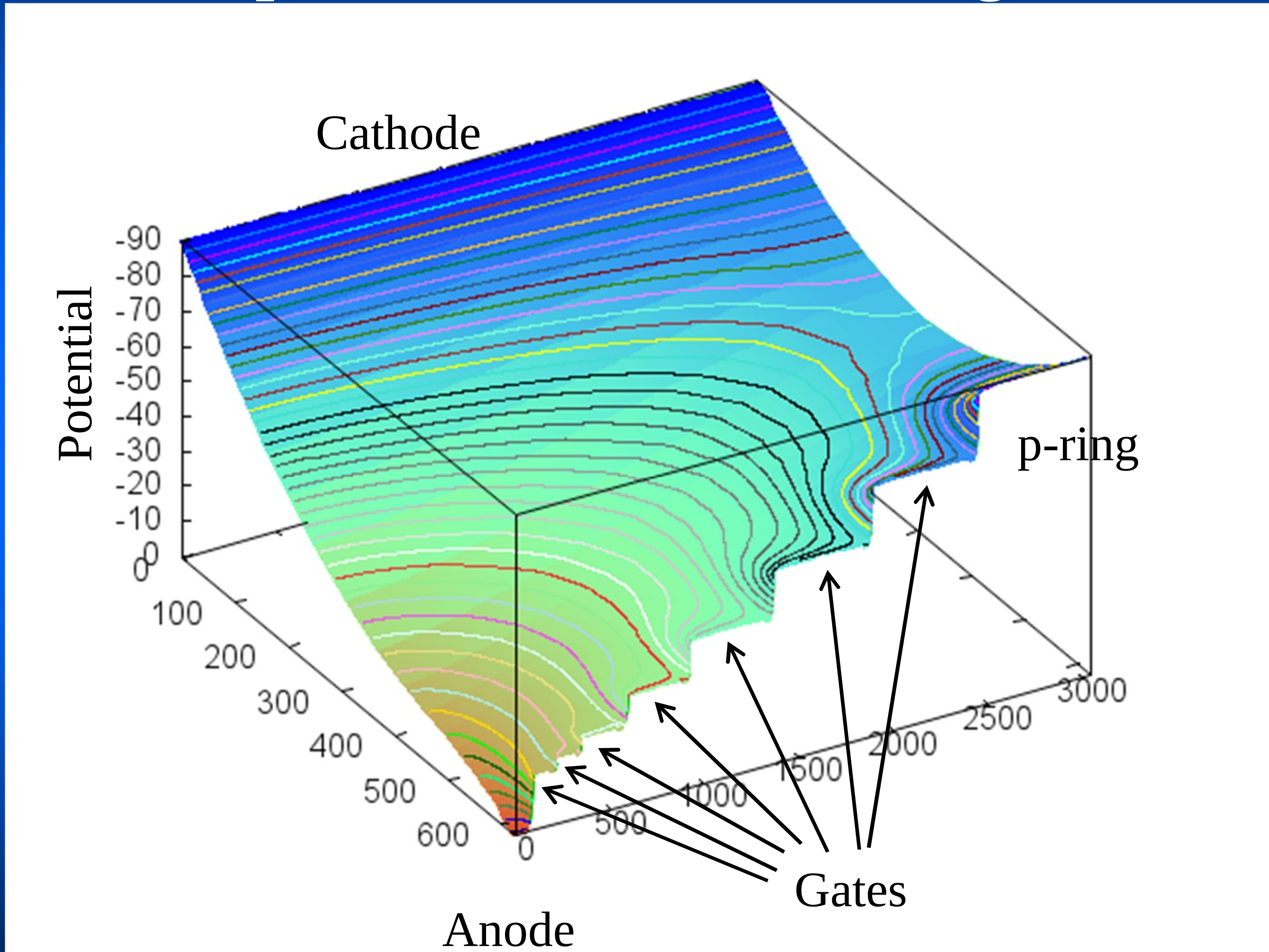
The design of GSDD is feasible for various positive fixed oxide charges.

Simulated Electric Potential Distribution within GSDD

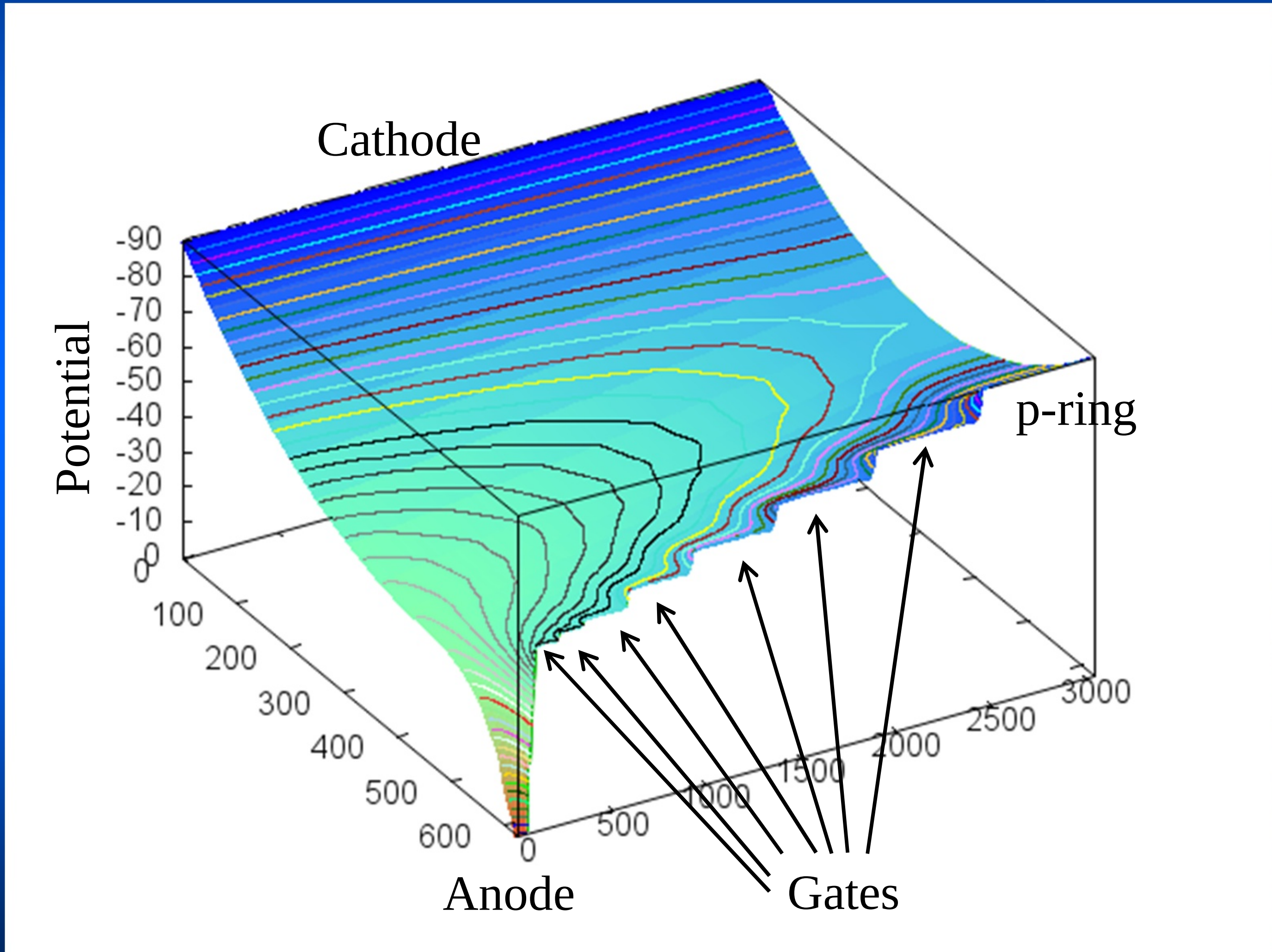
In the case of positive fixed oxide charges of 3×10^{10} cm^{-2}



Excellent electric potential distribution

Simulated Electric Potential Distribution within GSDD

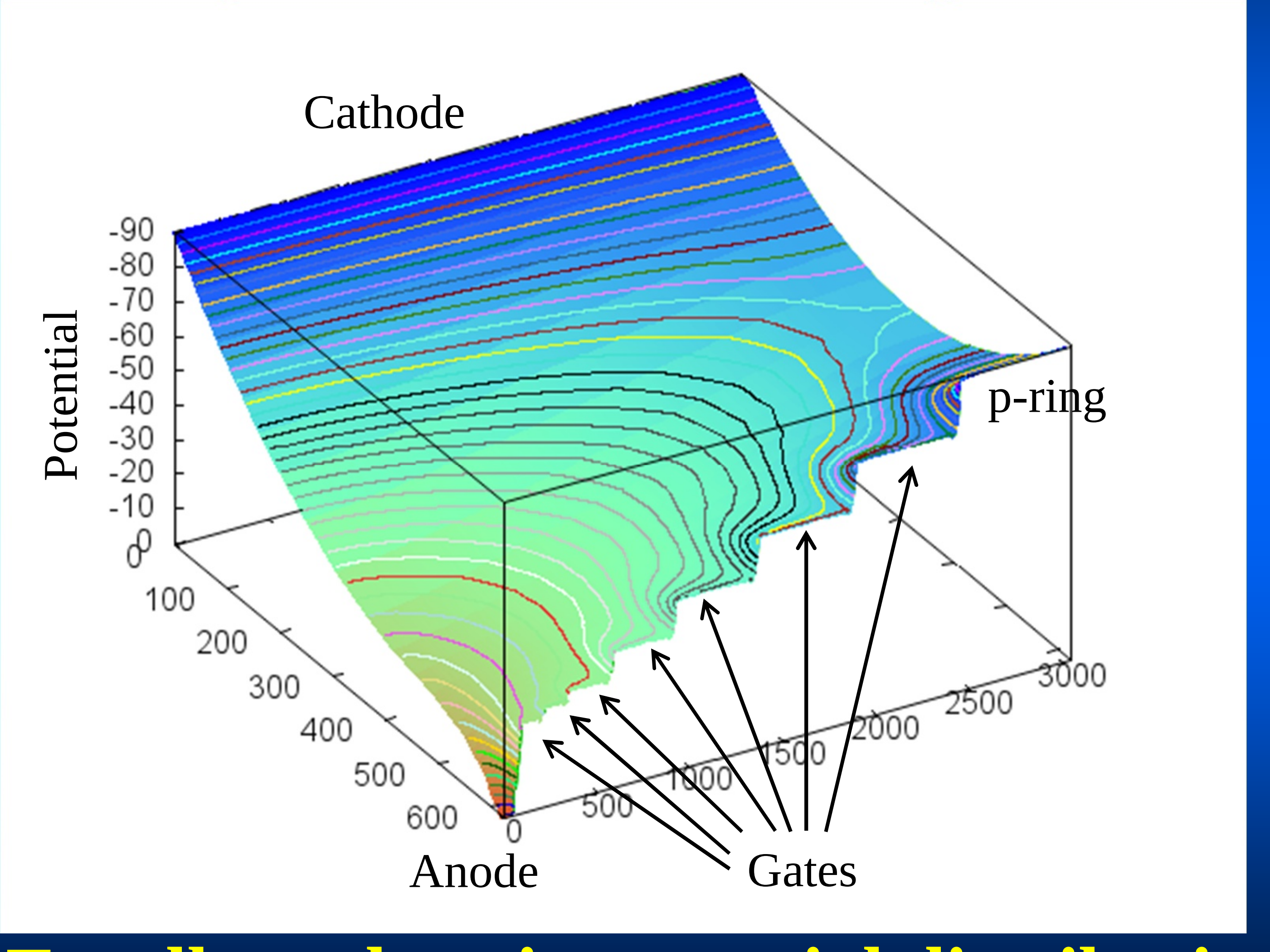
In the case of positive fixed oxide charges of 0 cm^{-2}



Not bad electric potential distribution

Simulated Electric Potential Distribution within GSDD

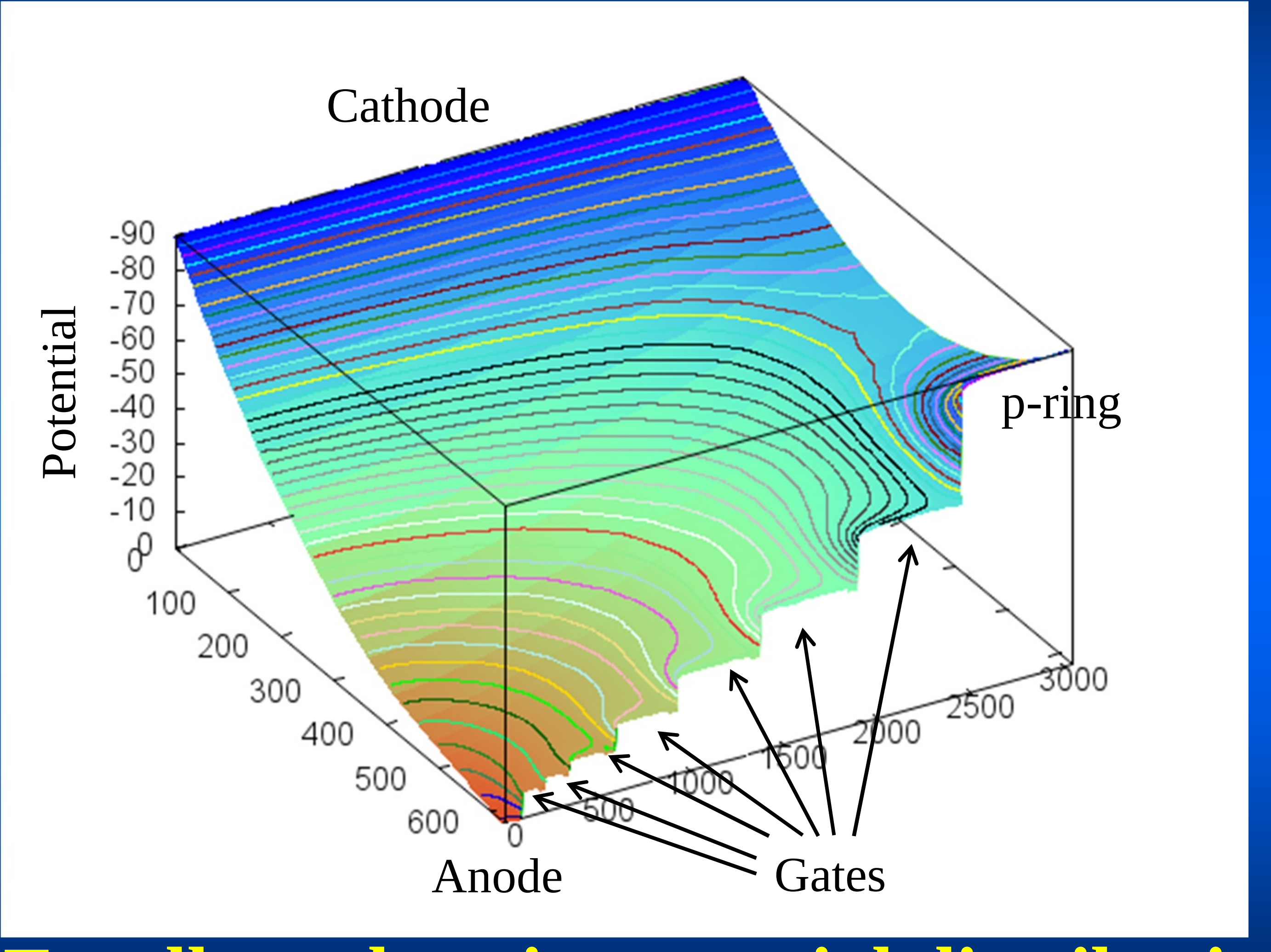
In the case of positive fixed oxide charges of $1x10^{10}$ cm^{-2}



Excellent electric potential distribution

Simulated Electric Potential Distribution within GSDD

In the case of positive fixed oxide charges of $1x10^{12}$ cm^{-2}



Excellent electric potential distribution

The proposed GSDD with 0.625-mm-thick Si works well.

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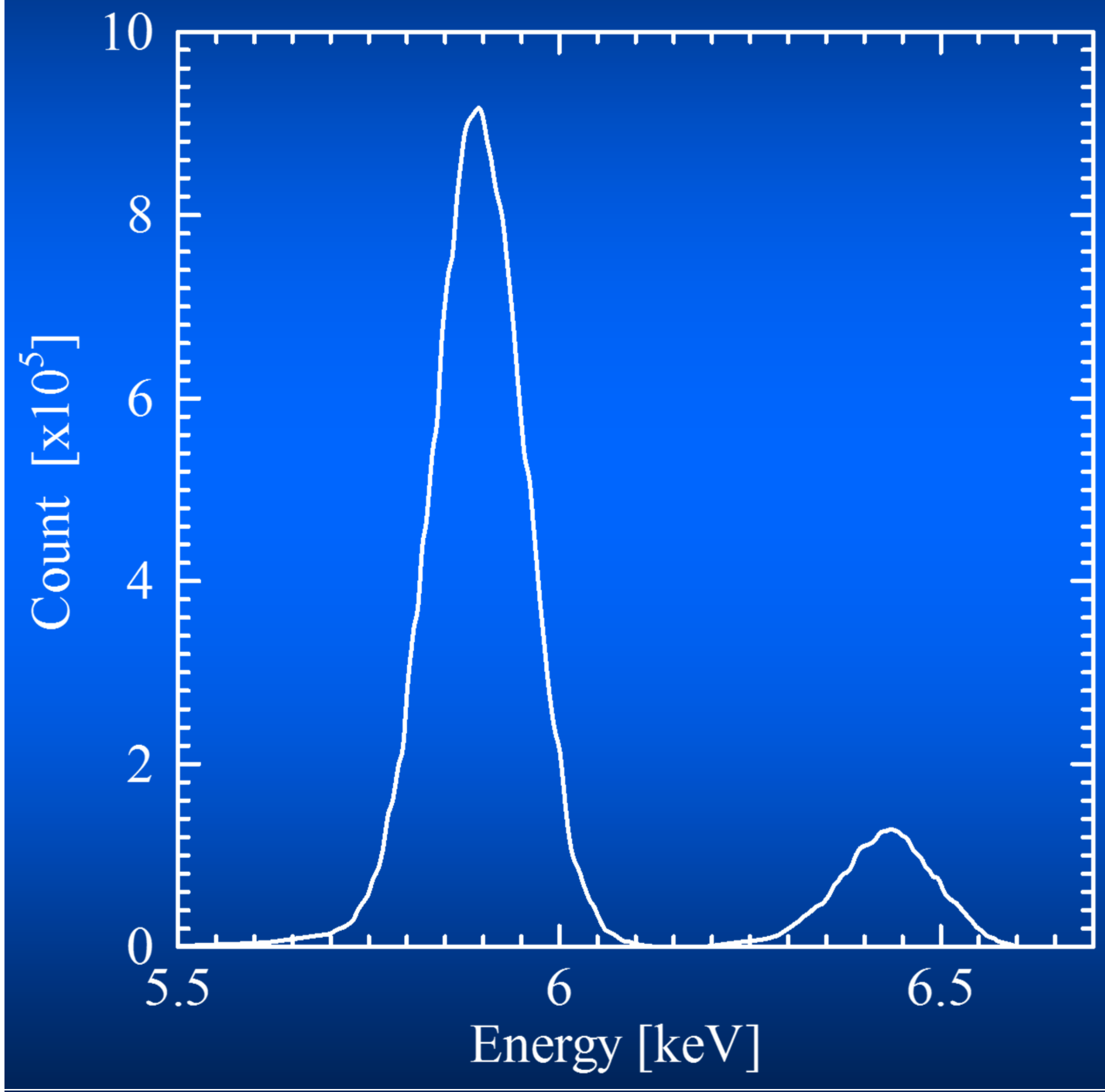
Experimental result: ^{55}Fe spectrum

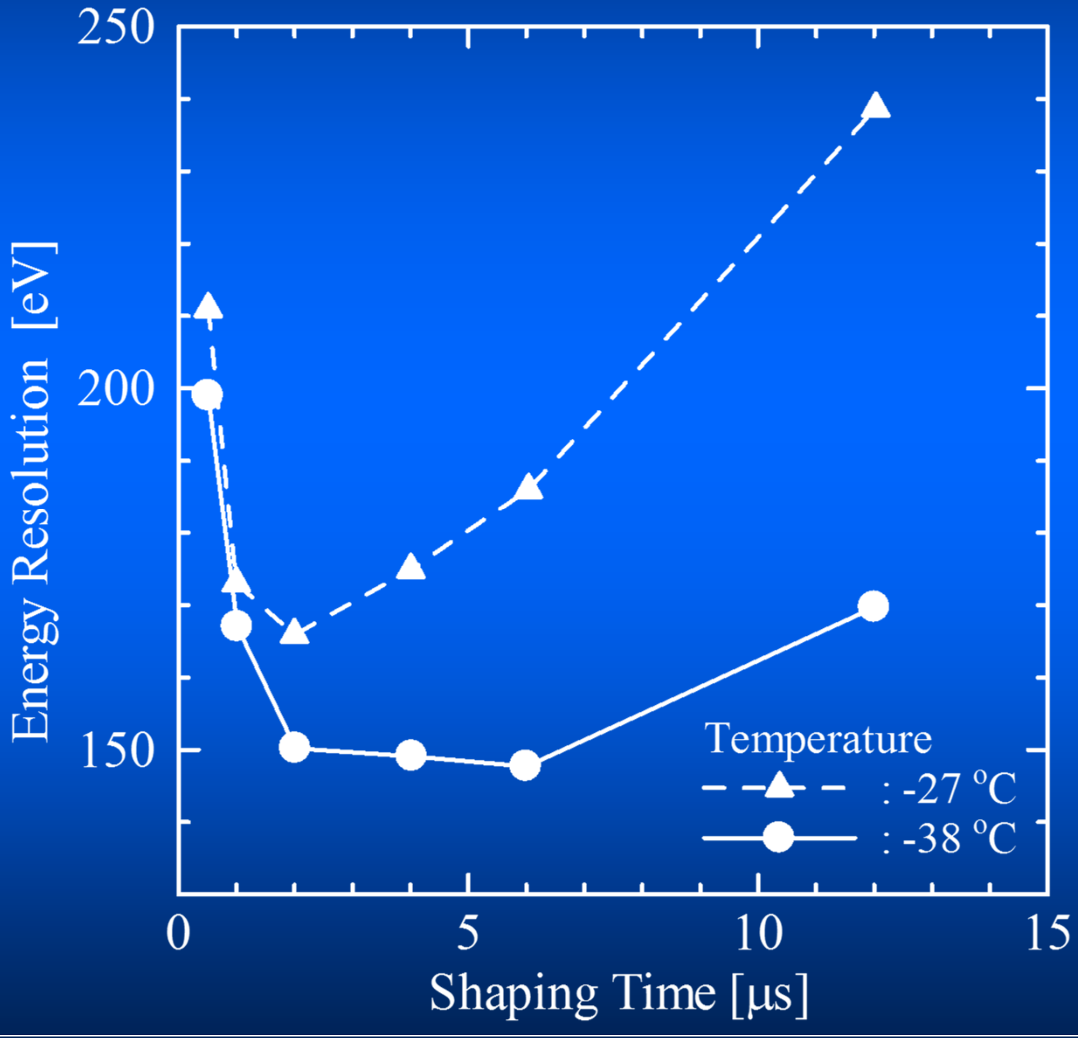


Energy resolution:
151 eV at 5.9 keV
at -38 ºC
at a shaping time of
2.5 μs

GSDD is comparable to SDD.

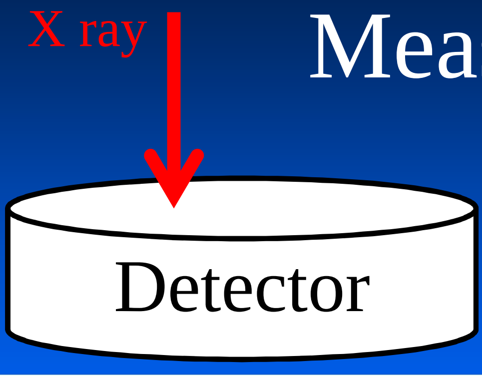
Experimental result: ^{55}Fe spectrum

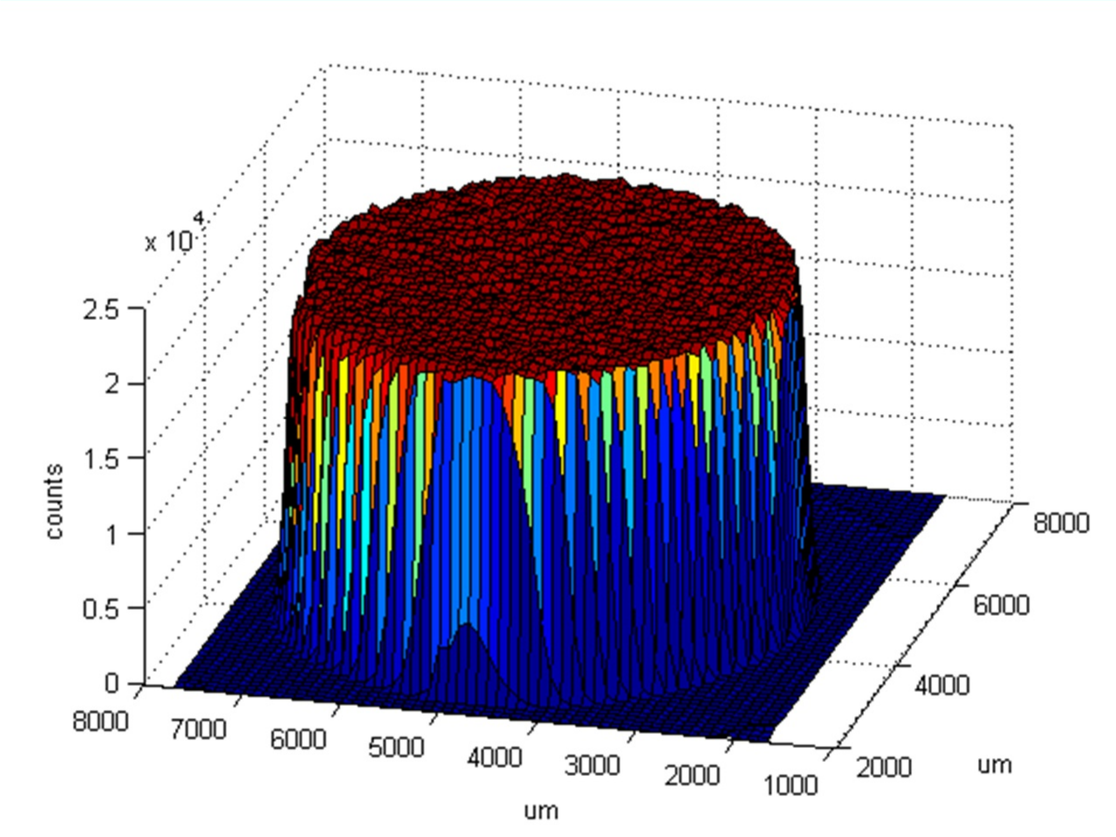
Shaping-time dependence of energy resolution



Even by Peltier cooling (-38 °C), the good energy resolution can be obtained.

Measurement of active area

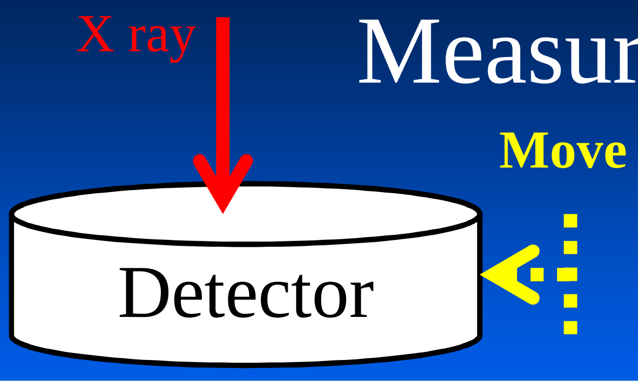


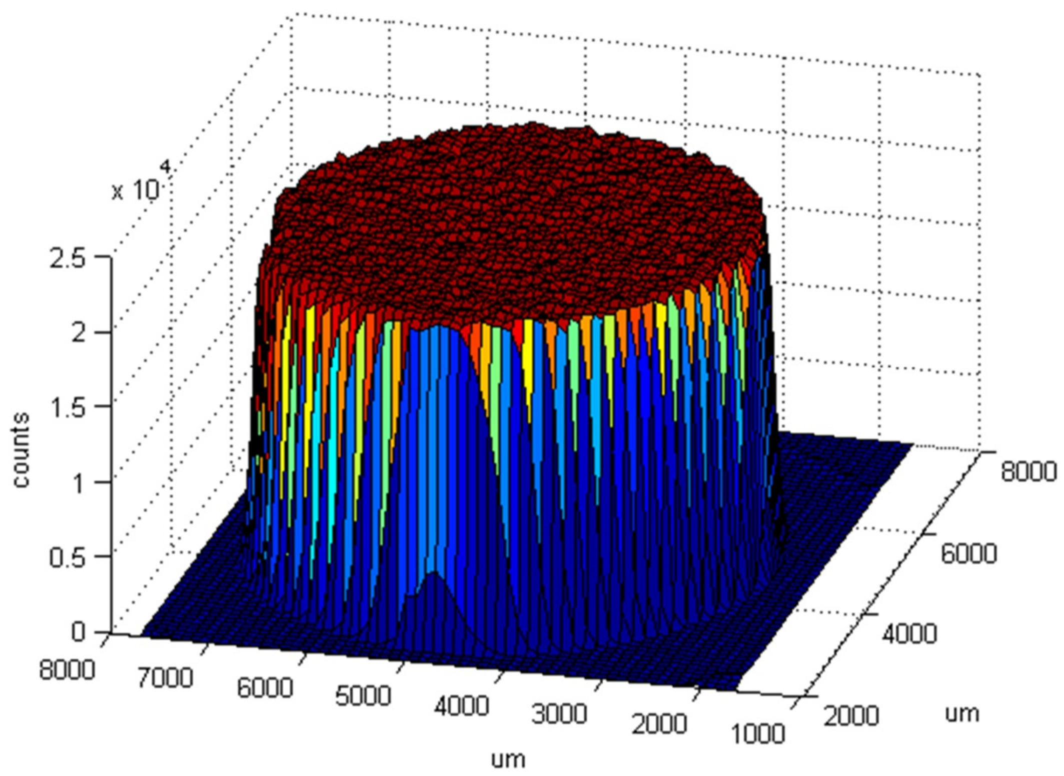


Experiment:

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

Measurement of active area



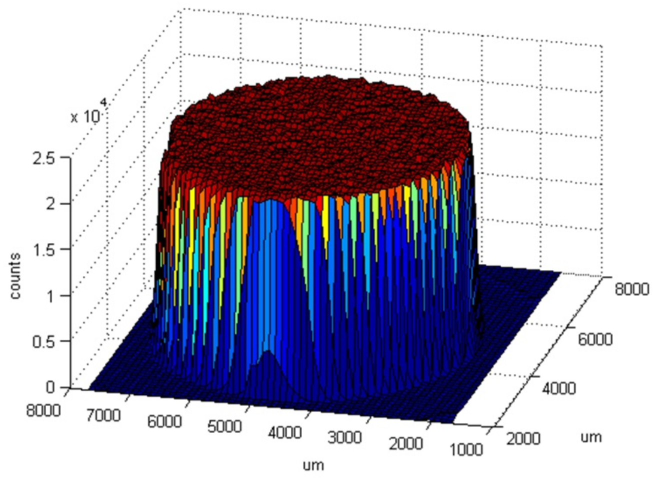


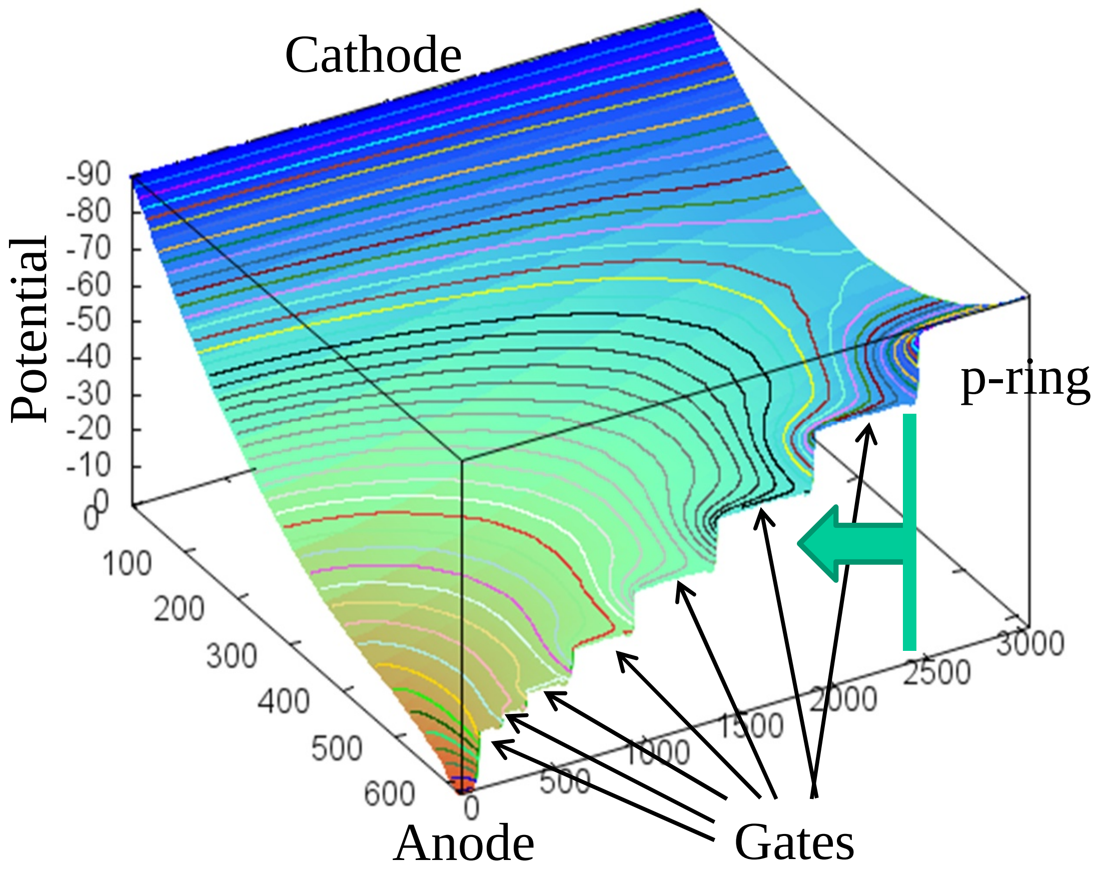
Experiment:

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

Active area: 18 mm^2

Is the active area of 18 mm² reasonable?





Estimation:

$$S = \pi \times (2.4)^2$$
$$= 18.1\ \mathrm{mm}^2$$

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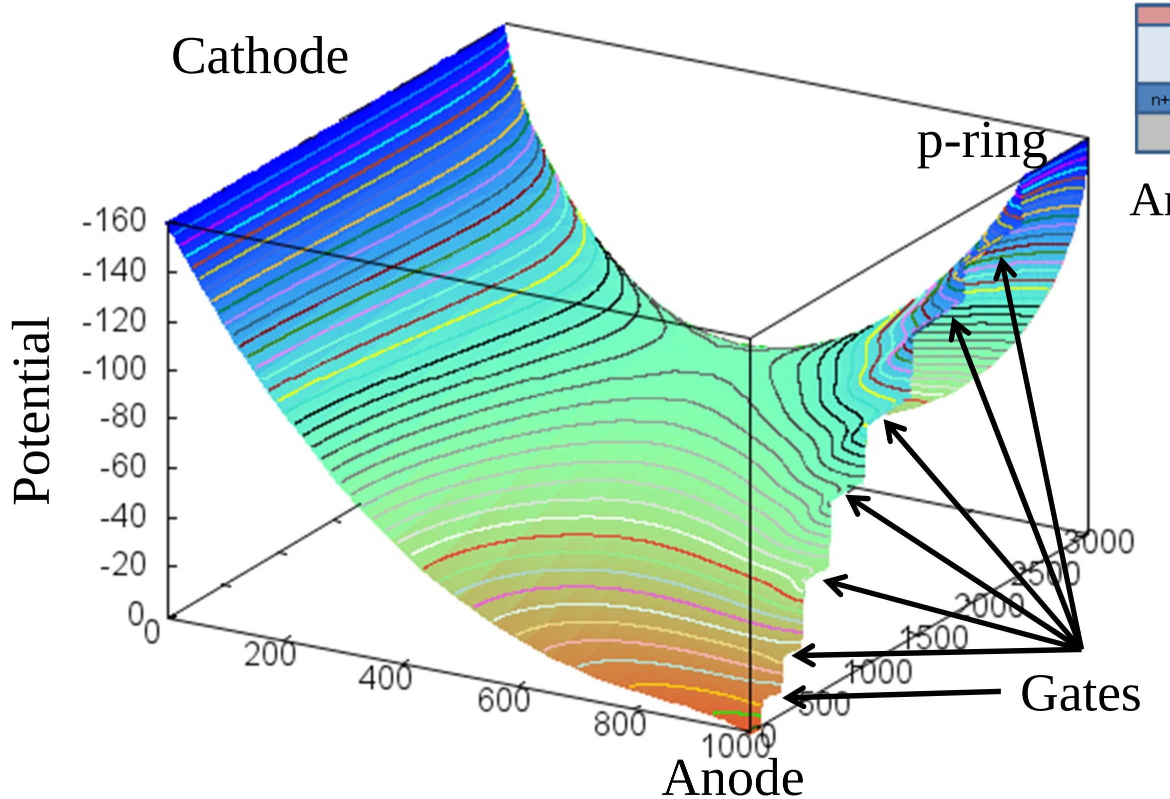
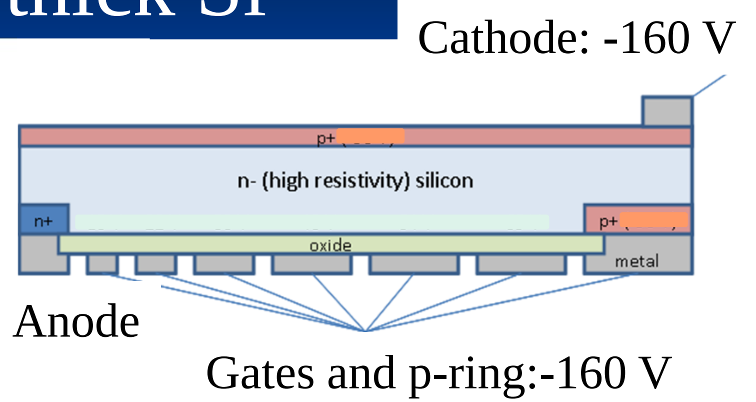
1. Problems on commercial SDD (Silicon Drift Detector)
    A. The cost of the SDD is expensive
    B. The absorption of high-energy X-ray fluorescence is very low
2. How to reduce the cost
    A. Proposal of simple-structure SDD, referred to as Gated SDD
    B. Simulation of electric potential distribution in GSDD with 0.625-mm-thick, 10-kΩ·cm Si
    C. Fabrication and experimental results of GSDD with 0.625-mm-thick, 10-kΩ·cm Si
3. **How to make Si substrate thicker**
    A. Simulation of electric potential distribution in GSDD with thicker Si
4. Summary

GSDD with 1-mm-thick Si





Excellent electric potential distribution

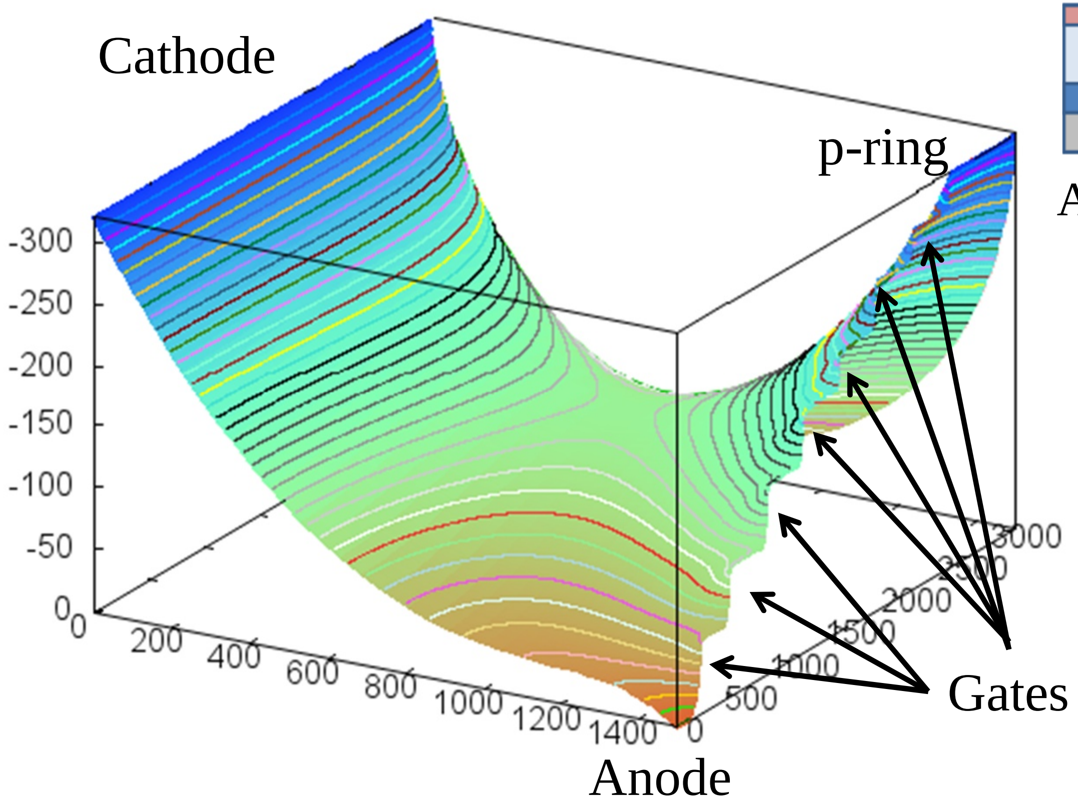
Thickness of SiO_2: 1.5 μm

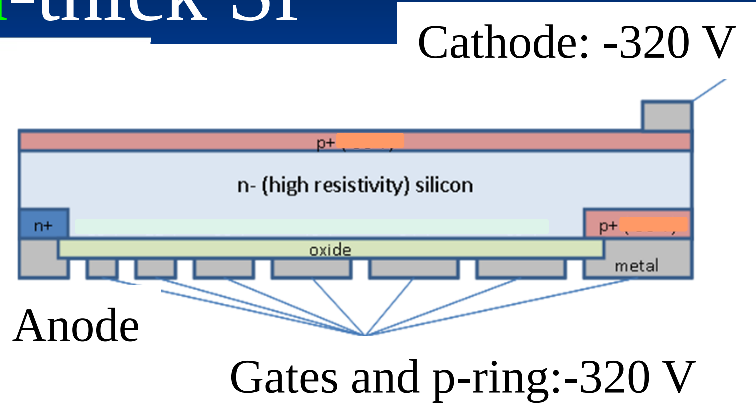
Applied voltage to cathode and gates: -160 V

To deplete i-layer in pin diode, -300 V is requited.

On the other hand, only -160 V is required in GSDD.

GSDD with 1.5-mm-thick Si





Excellent electric potential distribution

Thickness of SiO_2: 1.5 μm

Applied voltage to cathode and gates: -320 V

To deplete i-layer in pin diode, -700 V is requited.

On the other hand, only -320 V is required in GSDD.

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 substrate for high sensitivity of high energy X-rays**
6. **Only one high, but reasonable low, voltage bias for inexpensive unit**

Thank you for your attention