Introduction to Silicon Detectors

J. Lee
Center for High Energy Physics
Kyungpook National University

First School for Particle Detectors and Applications
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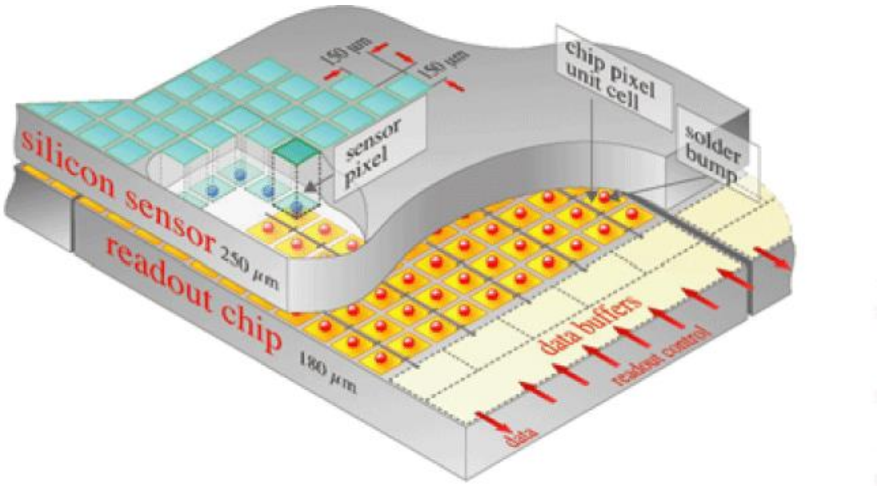
Outline

1. Introduction
    - Examples of silicon detectors
    - Interaction of particles with silicon
2. Properties of silicon
3. Silicon detectors for charged particle detection
4. Silicon detectors for photon detection
5. Summary

1. Introduction

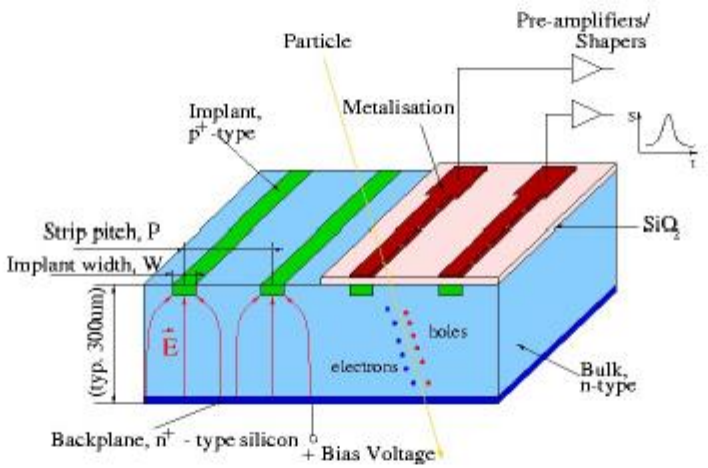
Examples of Silicon Detectors for Charged Particle Detection

Pixel sensor for CMS

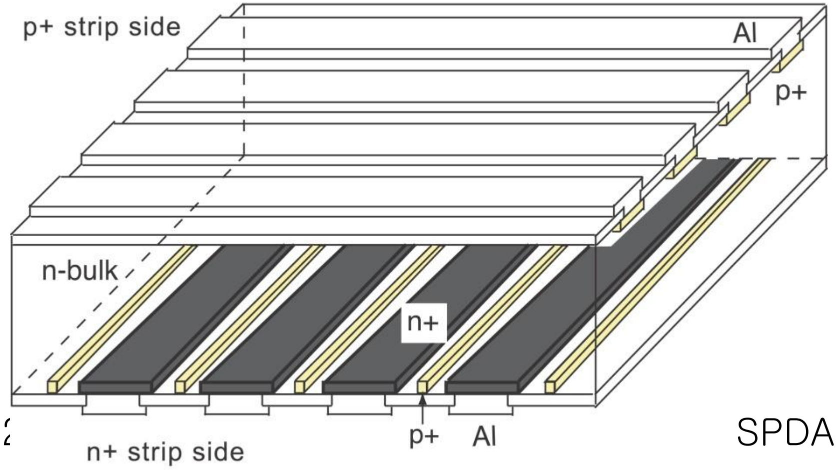


http://hep.fi.infn.it/CMS/sensors/Silicon_Detector.gif

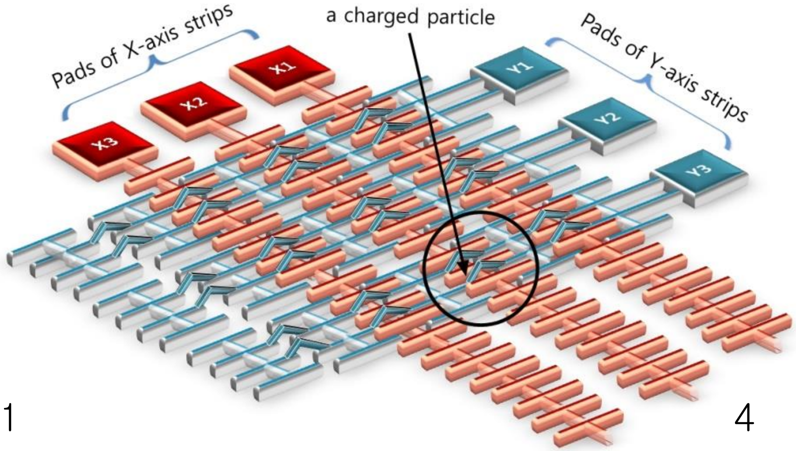
Single-side strip sensor



Double-side strip sensor



Strip-pixel sensor

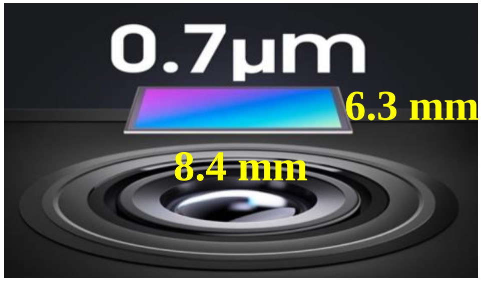


Examples of Silicon Detectors for photon detections

CCD

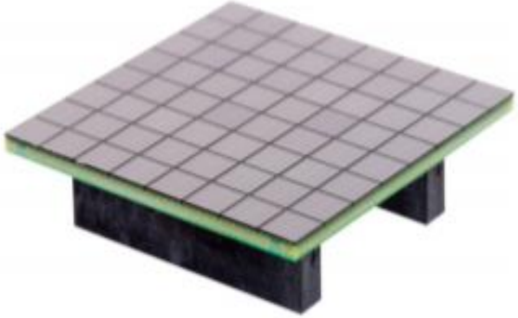
Sony ICX493AQA APS-C, 6.05 μm pixel size, 10.14 M pixels, 23.4 mm × 15.6 mm, CCD from digital camera Sony α DSLR-A200 or DSLR-A300, sensor side

CMOS



Samsung ISOCELL HM2 sensor, 0.7 μm pixel size, 12,000 × 9,000 (108 M) pixels, used in Xiaomi Redmi Note 9 Pro 5G and Xiaomi Mi 10i

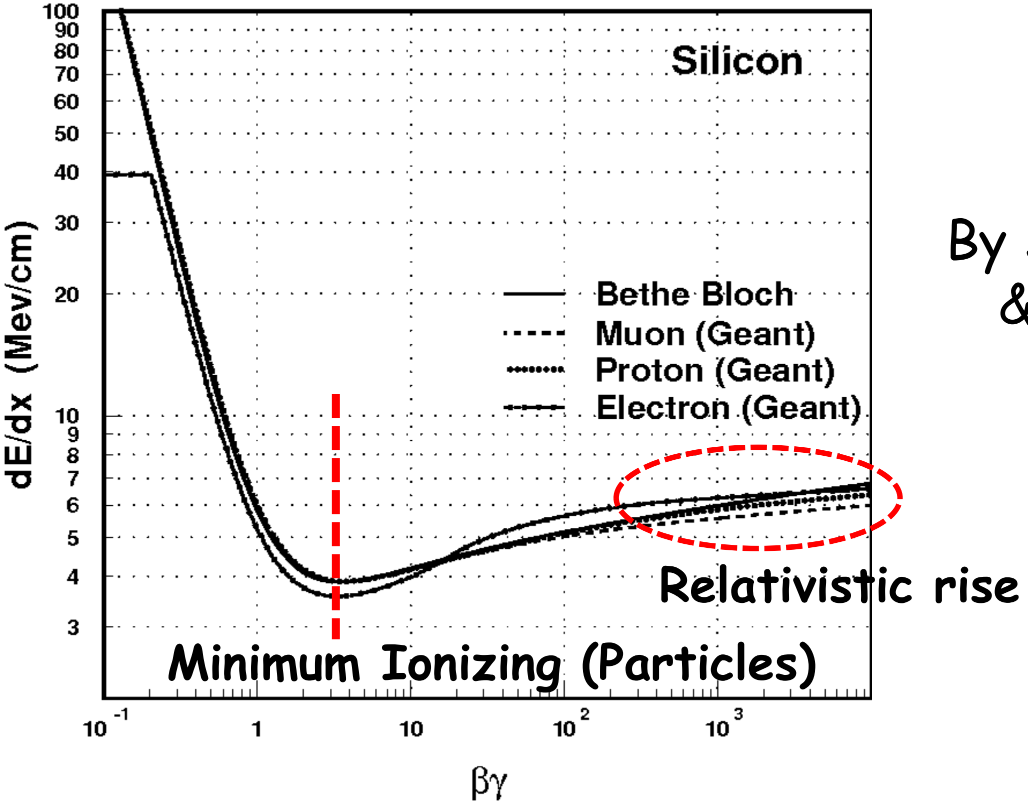
SiPM



Sensl SiPM pixel array, 8 × 8 pixels, 6 mm pixel size, 22,292 micro-pixels , 40 μm micro-pixel size

Interaction of charged particles with silicon

Energy loss by ionization



Relativistic rise

Minimum Ionizing (Particles)

By S. Banerjee
& A. Caner

We will not discuss about energy loss by radiation.

Note that $\frac{dE}{dx}$(ionization) $\gg \frac{dE}{dx}$(radiation) for heavy particles.

Energy loss by ionization

z: charge of incident particle

Bethe equation

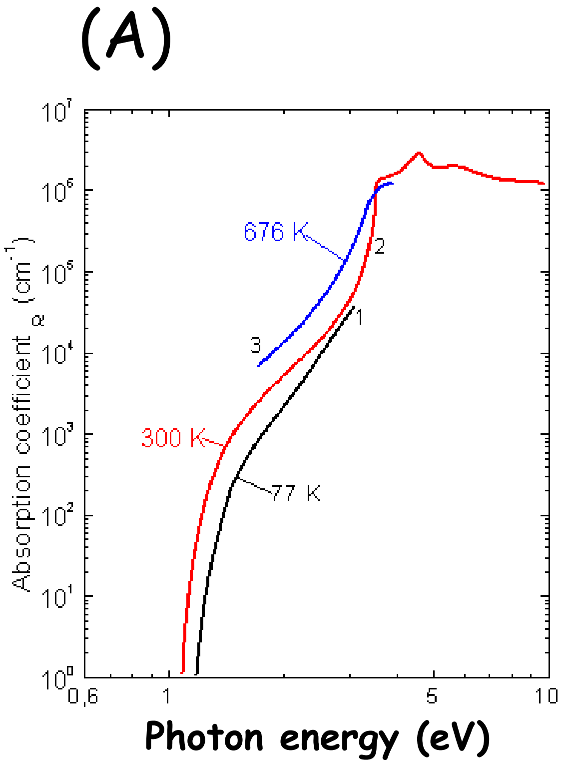
$$\left\langle \frac{dE}{dx} \right\rangle = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2 m_e c^2 \beta^2 \gamma^2 T_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$

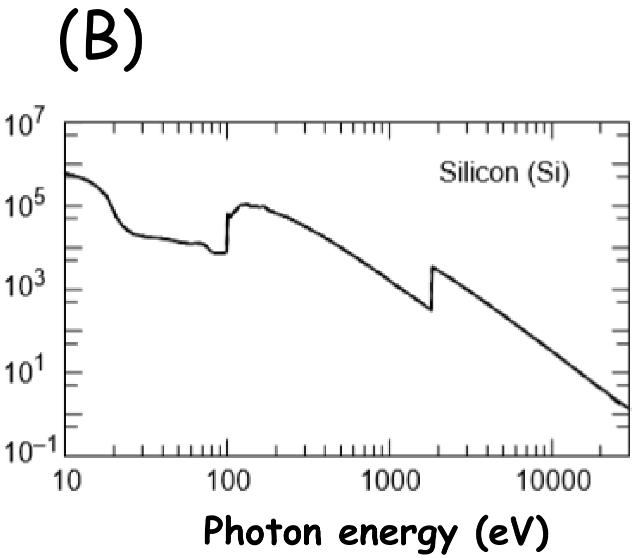
$$\left\langle \frac{dE}{dx} \right\rangle \propto z^2$$

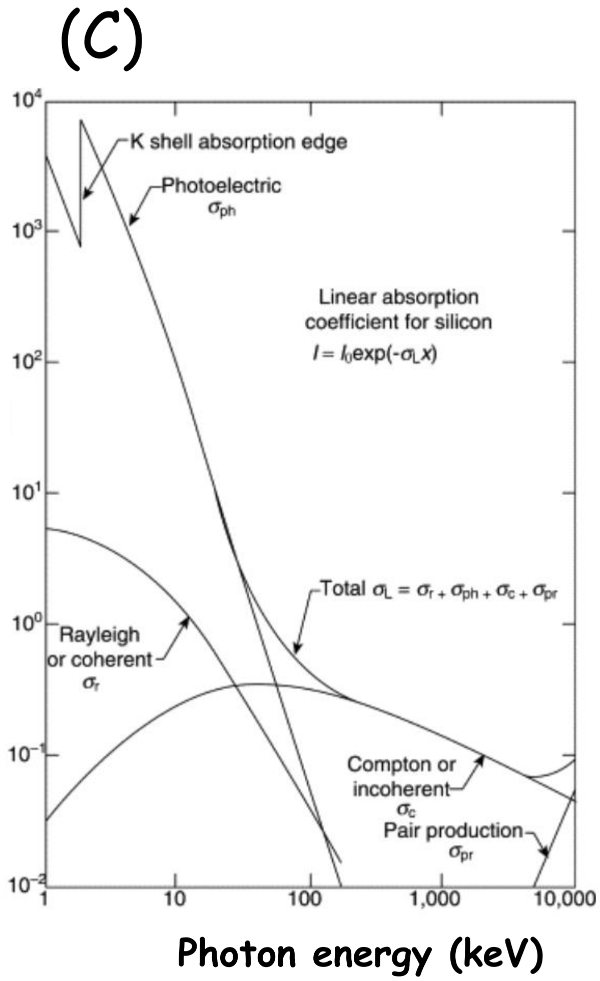
$\left\langle \frac{dE}{dx} \right\rangle \approx$ 40 keV / 100 μm in Si for minimum ionizing particles

3.6 eV required for producing a pair of e-h in Si
≈ 10,000 e-h pairs / 100 μm expected in Si

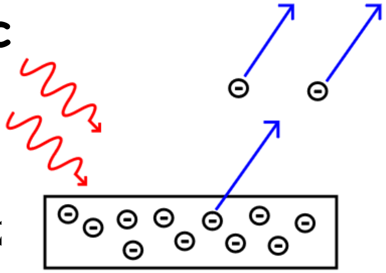
Interaction of photons with silicon



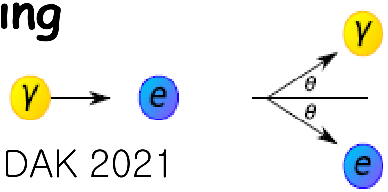




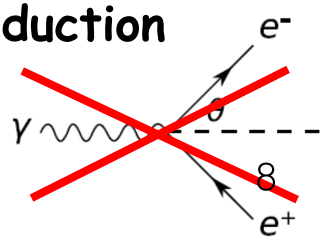
Photoelectric effect



Compton scattering



Pair production



References for the plots in Page 8

A. Sze, S. M., *Physics of Semiconductor Devices*, John Wiley and Sons, N.Y., 1981; Jellison, Jr., G. E. and F. A. Modine, *Appl. Phys. Lett*- 41, 2 (1982) 180-182.

B. X-RAY DATA BOOKLET, Lawrence Berkeley National Laboratory

C. Durini (Editor), “High Performance Silicon Imaging: Fundamentals and Applications of CMOS and CCD Sensors”, Woodhead Publishing, 2014 Particularly: Chapter 10 (p286) by R. Turchetta, STFC, UK

2. Properties of silicon

Band & bandgap

Isolated atoms brought together to form lattice → discrete atomic levels shift to form energy bands

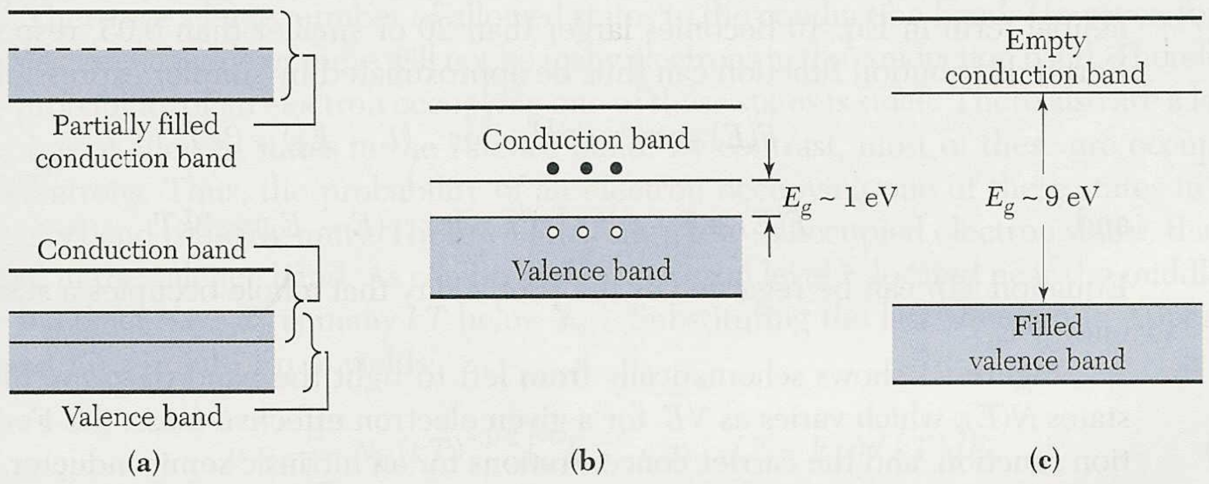


Fig. 19 Schematic energy band representations of (*a*) a conductor with two possibilities (either the partially filled conduction band shown at the upper portion or the overlapping bands shown at the lower portion), (*b*) a semiconductor, and (*c*) an insulator.

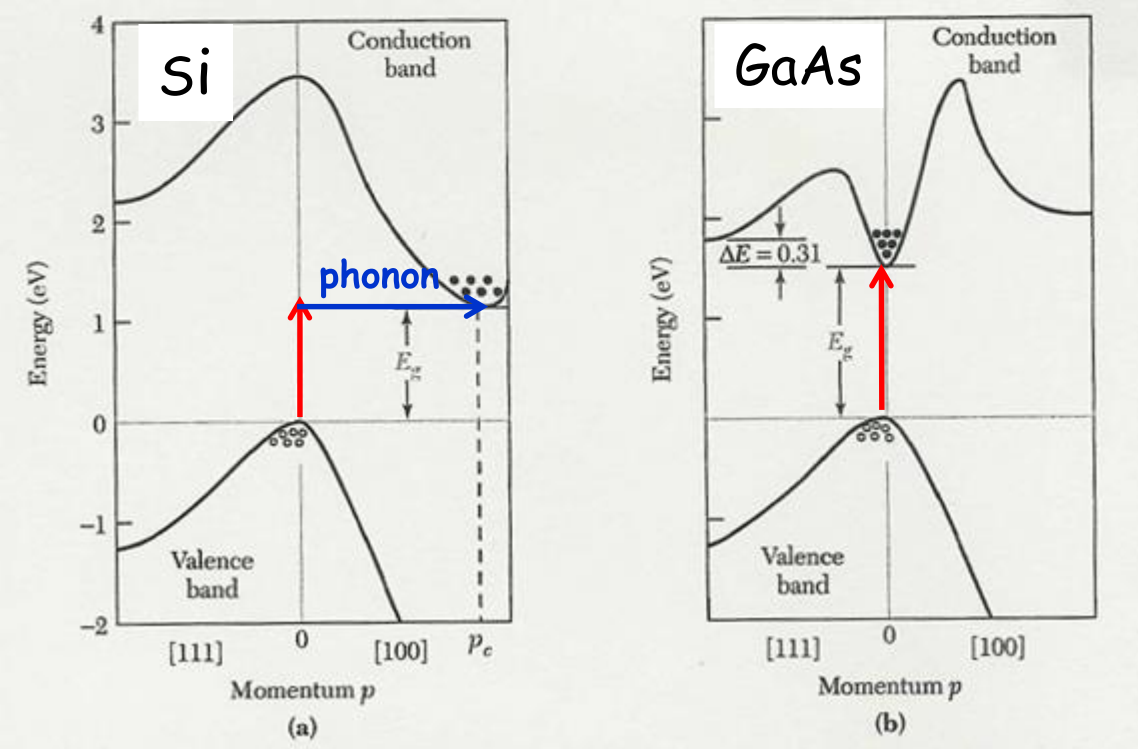
From 'Semiconductor Devices Physics and Technology Second Edition' by S.M. Sze

E_g: band gap (1.12 eV for Si)

Indirect vs Direct Bandgap Semiconductors

From 'Semiconductor Devices Physics and Technology Second Edition' by S.M. Sze

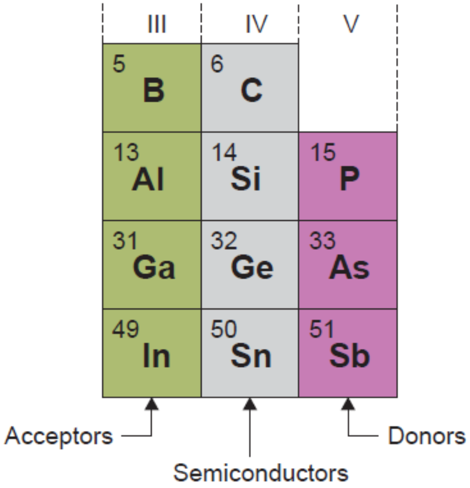
Indirect bandgap Direct bandgap



Excitation/De-excitation = E_g + E_{phonon}

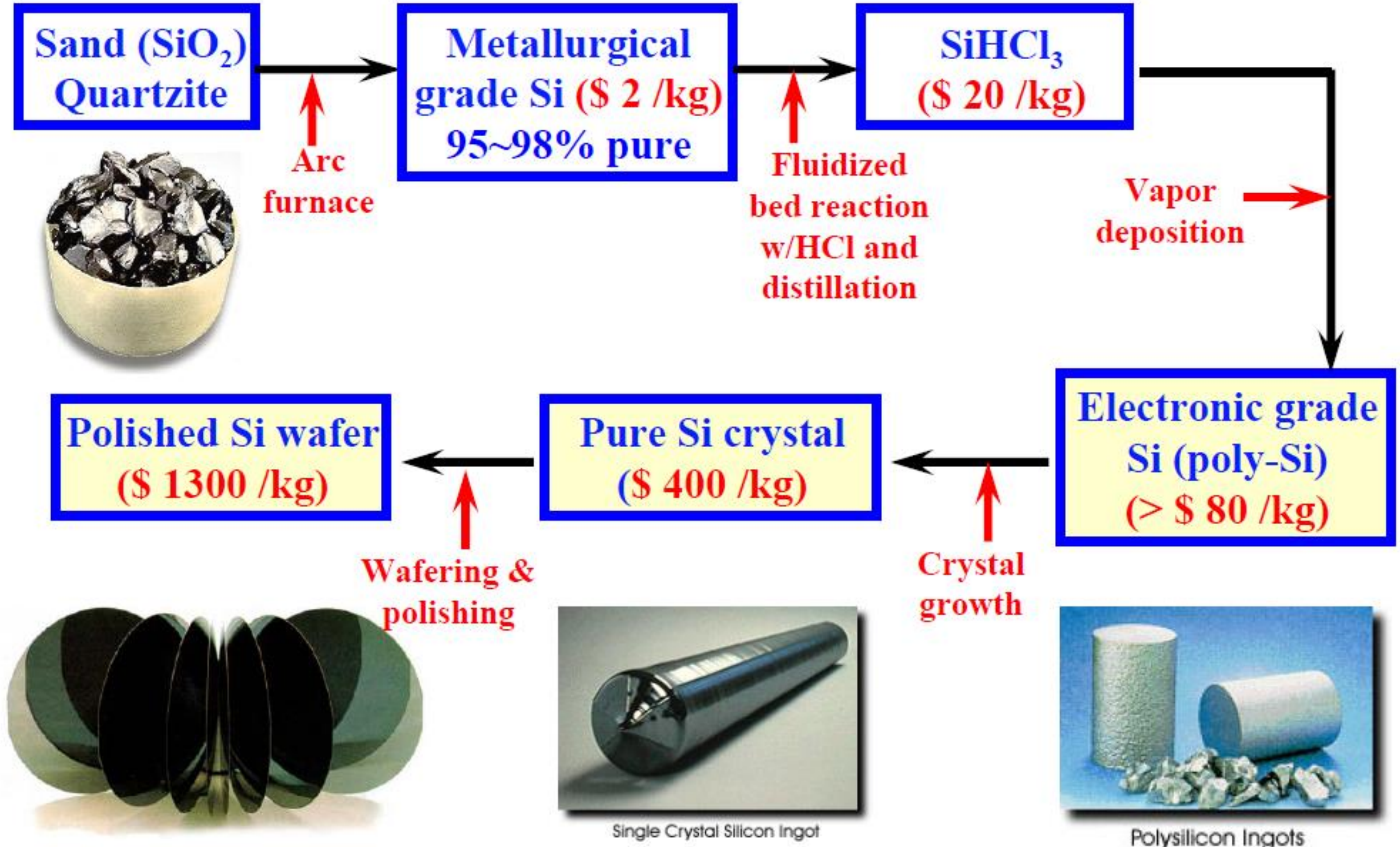
Excitation/De-excitation = E_g

Why Silicon?



- abundant --> cheap
- Lighter
- SiO_2 layer
  - Naturally or inexpensively formed
  - chemically and mechanically very stable
  - effectively passivates the surface states of the underlying silicon
  - forms an effective diffusion barrier for the commonly used dopant species
  - easily preferentially etched from the silicon, and vice versa, with high selectivity
  - By contrast, GeO_2 is a chemically unstable, poor electrical insulator that is 33 times more soluble in water than SiO_2, making it less suited to the photolithographic and wet chemical processes used to fabricate integrated circuits.

Sand to silicon wafer



Sand (SiO_2) Quartzite

Arc furnace

Metallurgical grade Si ($ 2 /kg) 95~98% pure

Fluidized bed reaction w/HCl and distillation

$SiHCl_3$ ($ 20 /kg)

Vapor deposition

Electronic grade Si (poly-Si) (> $ 80 /kg)

Crystal growth

Pure Si crystal ($ 400 /kg)

Wafering & polishing

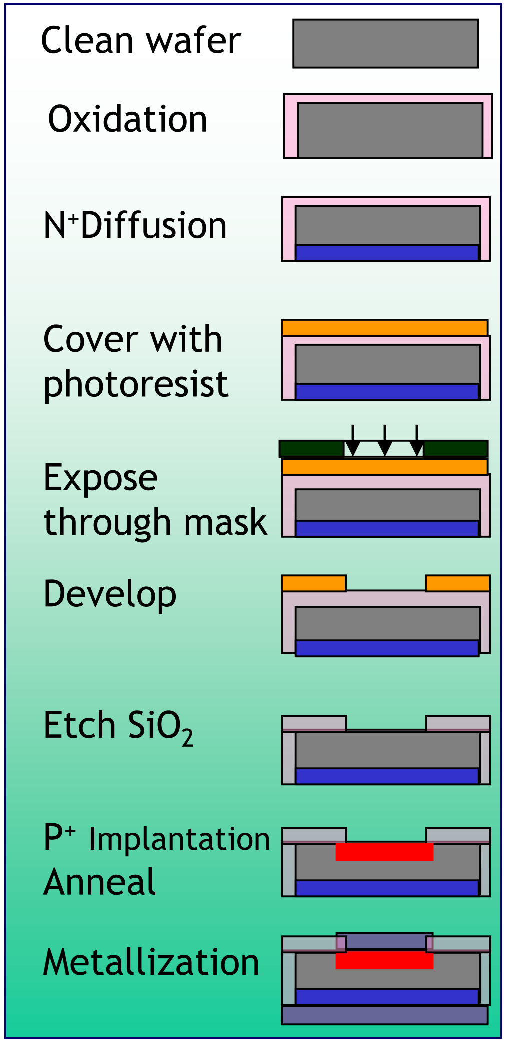
Polished Si wafer ($ 1300 /kg)

Single Crystal Silicon Ingot

Polysilicon Ingots

Source: http://www.fullman.com/semiconductors/semiconductors.html

Recipe for fabrication process



Clean wafer

Oxidation

N^+Diffusion

Cover with
photoresist

Expose
through mask

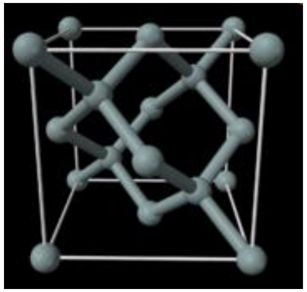
Develop

Etch SiO_2

P^+ Implantation
Anneal

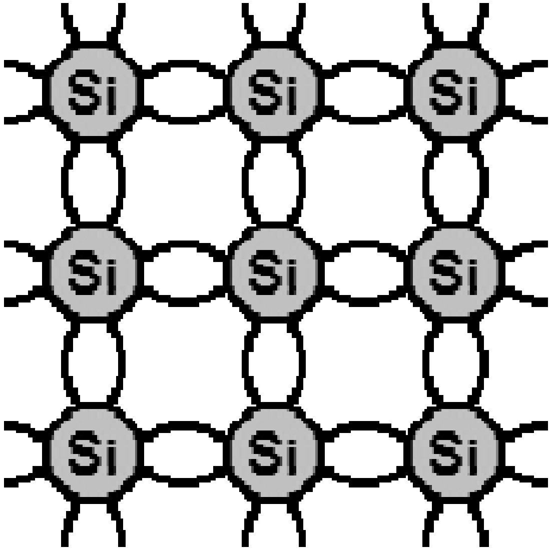
Metallization

Intrinsic Si semiconductor

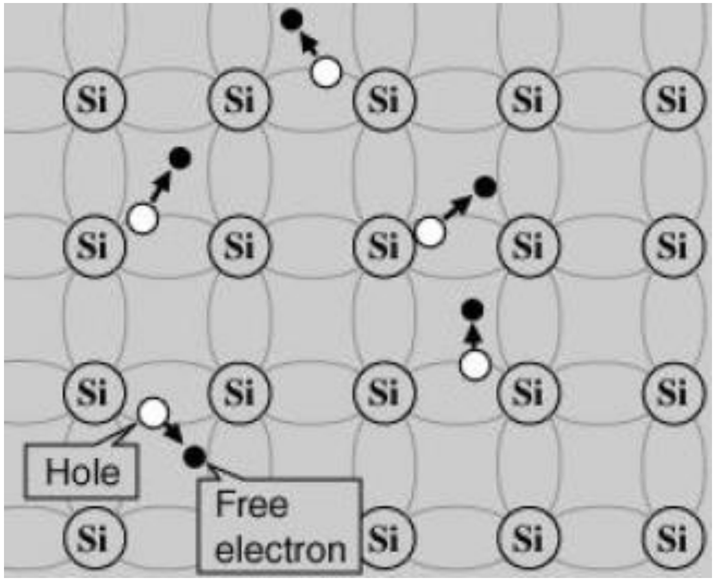


The crystalline structure is ***Diamond Cubic*** (FCC).
Bare wafers of <100> or <111> crystals are popular ones used for silicon detector fabrications.

low T : electrons bound in lattice



higher T : free electrons & holes



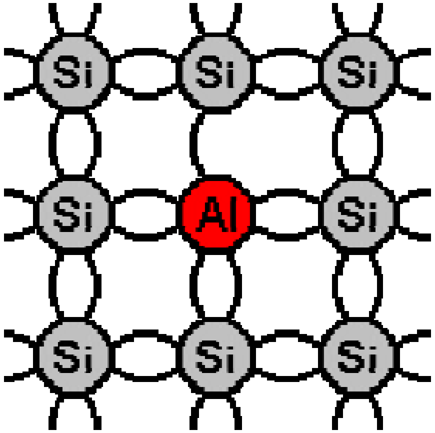
Impurities

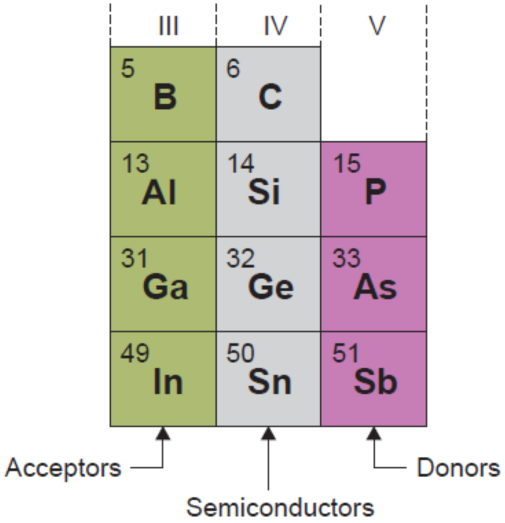
- Intrinsic semiconductor = pure, no impurities.
- Extrinsic semiconductor = impurities added.
- Some impurities always present.
- Turns out to be extremely useful to add impurities to control the properties of the semiconductor.

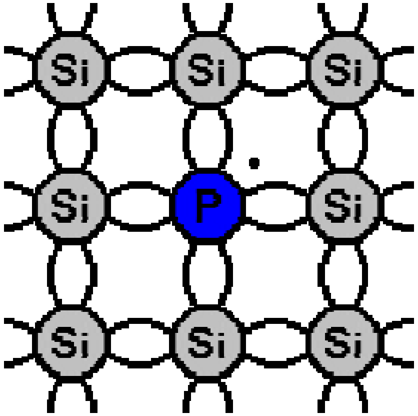
Jargons

- The heavily-doped pieces are called n^+-type or p^+-type; the lightly-doped pieces, simply n-type or p-type.

Doping: acceptors & donors





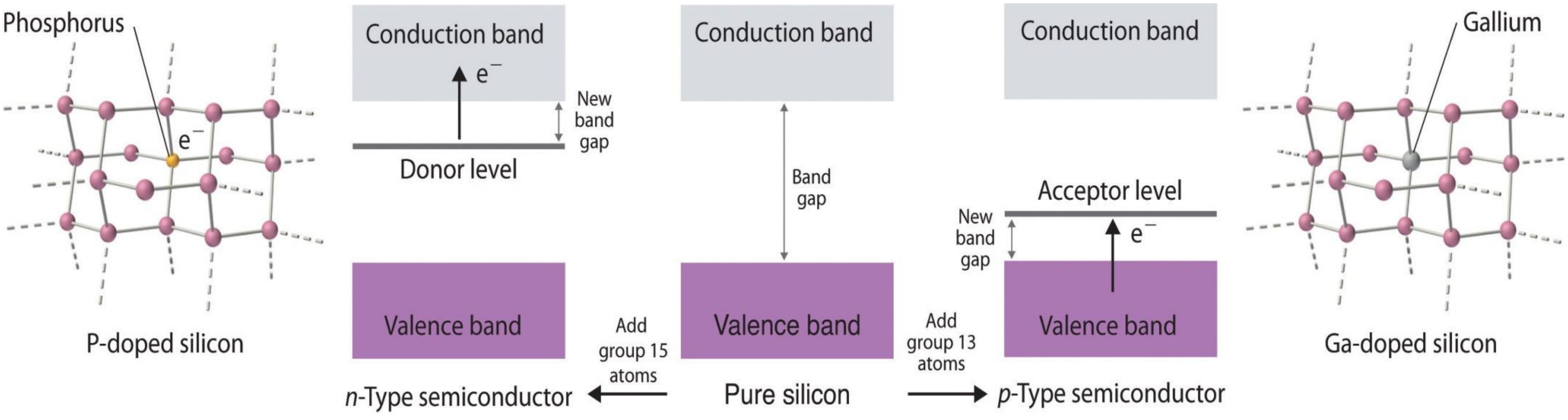


- Al or B impurities.
- 3 e^- in outer shell
- 3 e^- for bonds, one hole left-over (free)
- Acceptor impurity

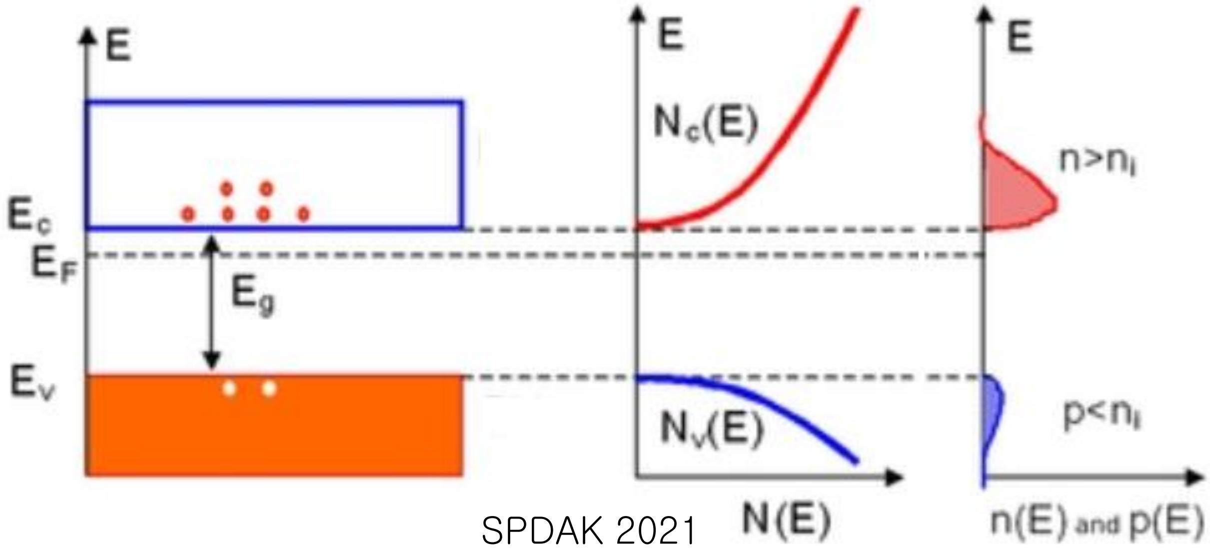
- P-type silicon

- P or As impurities.
- 5 e^- in outer shell.
- 4 e^- for bonds, one e^- left-over (free).
- Donor impurity
  - (donates e^-)
- N-type silicon

Effect of doping



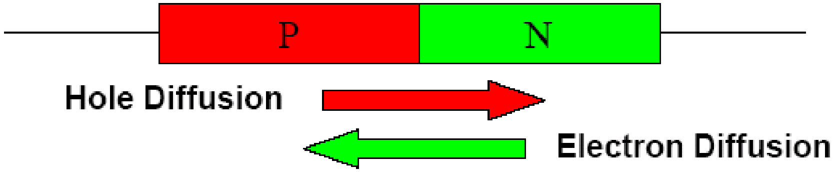
(a) Doping with a group 15 element **(b) Doping with a group 13 element**



3. Silicon detectors for charged particle detection

p-n junction (fundamental structure)

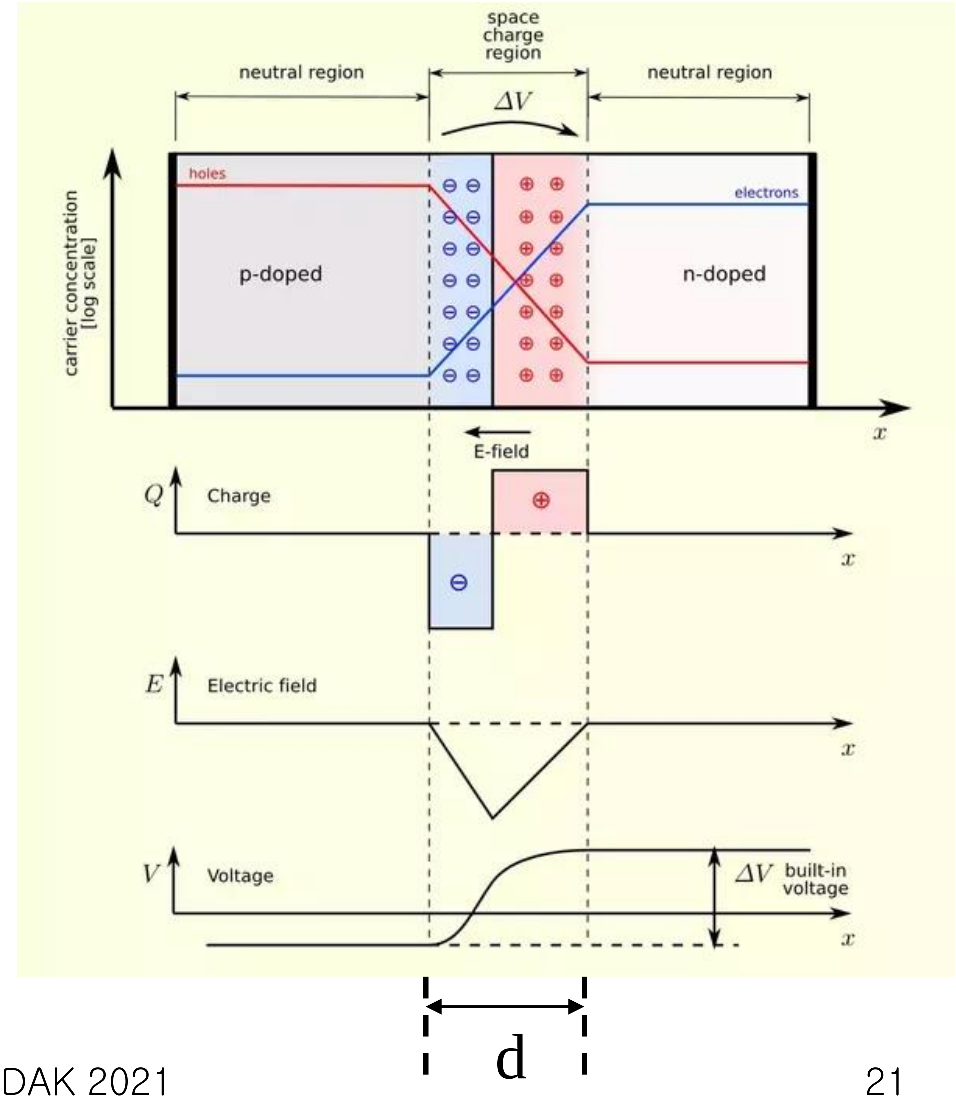
Bring p-type and n-type into contact:



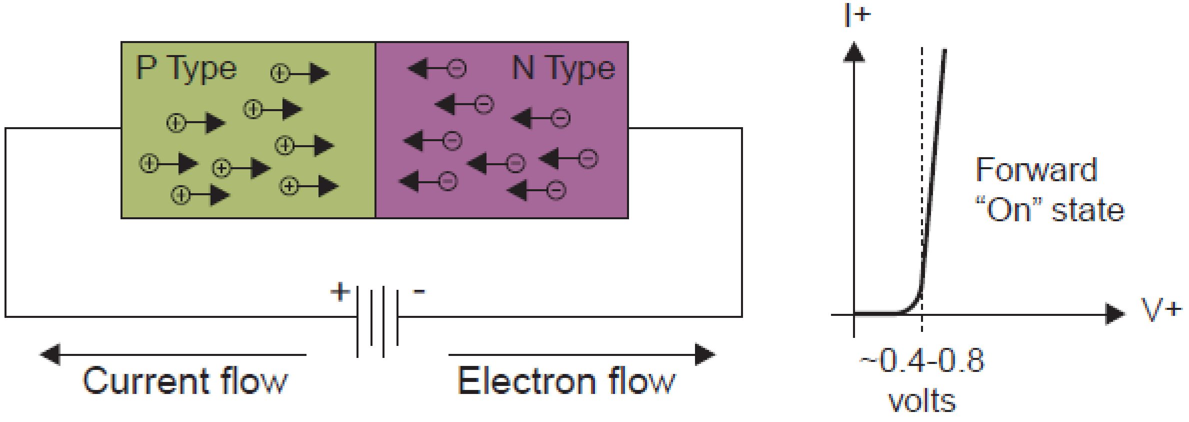
Hole Diffusion

Electron Diffusion

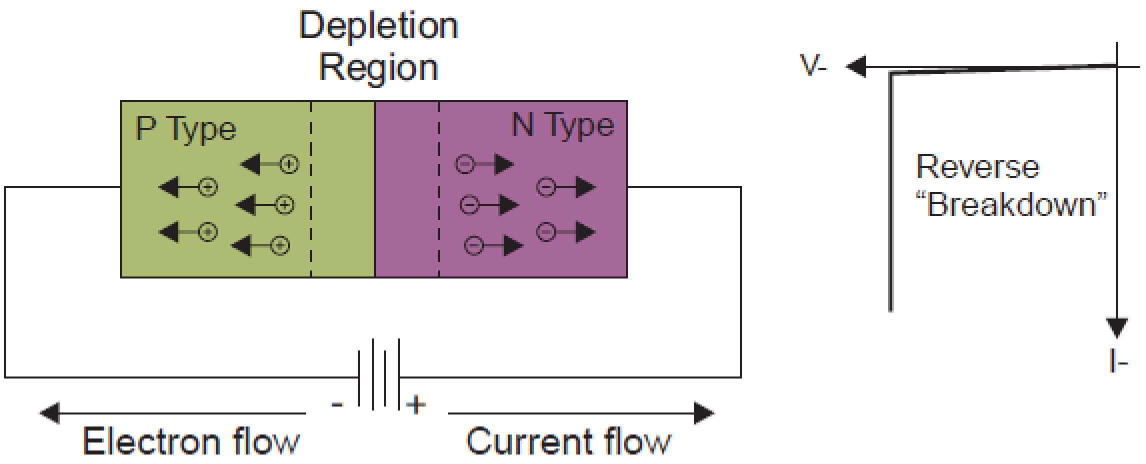
The depletion region d is a region with no charge carriers (with no free charges).



p-n junction



Forward Biased Junction



Reverse Biased Junction

Depletion depth

d= $\sqrt{\frac{2\epsilon}{e}\,\frac{N_A+N_D}{N_A N_D}\,(V_{bi}+V)}$

V_{bi} : potential difference due to barrier field

d= $\sqrt{\frac{2\epsilon(V_{bi}+V)}{eN_B}}$

In many cases, $N_A \gg N_D$ or $N_D \gg N_A$
N_B is the smallest of N_D and N_A

d= $\sqrt{2\epsilon\mu\rho(V_{bi}+V)}$

An exercise :
p-type Si
ρ ~ 10 kΩ cm
d ~ 300 μm
→ V ~ 110 V

d= $0.5\mu\text{m}\sqrt{\rho(V_{bi}+V)}$ (n-type)
d= $0.3\mu\text{m}\sqrt{\rho(V_{bi}+V)}$ (p-type)

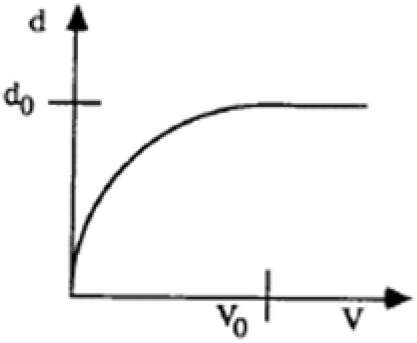
(V in Volts & ρ in Ω cm) for Si

p-n junction reverse bias characteristics

d = depletion layer depth

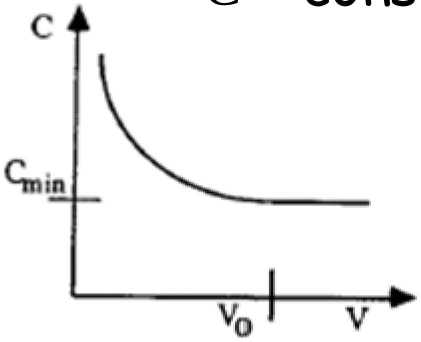
$d \propto \sqrt{V}$ for $V < V_0$

$d = d_0$ for $V > V_0$



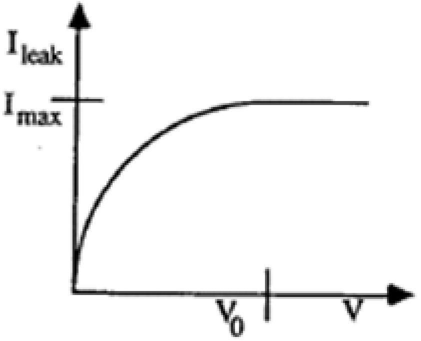
$C \propto 1/\sqrt{V}$ for $V < V_0$

$C = \text{const.}$ for $V > V_0$



$i \propto d \propto \sqrt{V}$ for $V < V_0$

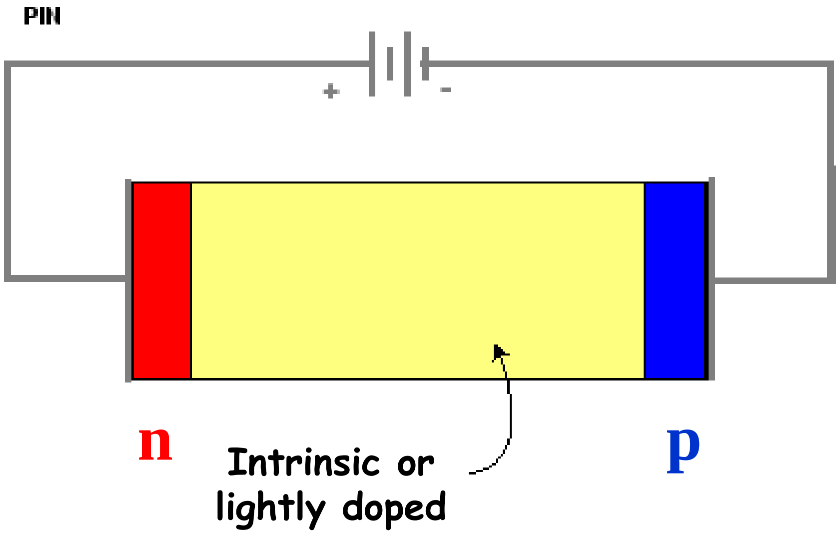
$i = \text{const.}$ for $V > V_0$

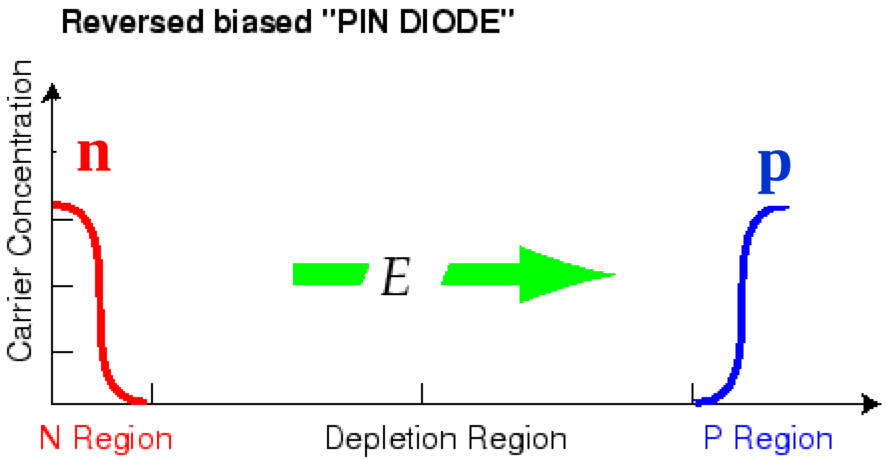


V_0 = full depletion voltage

d_0 = junction thickness

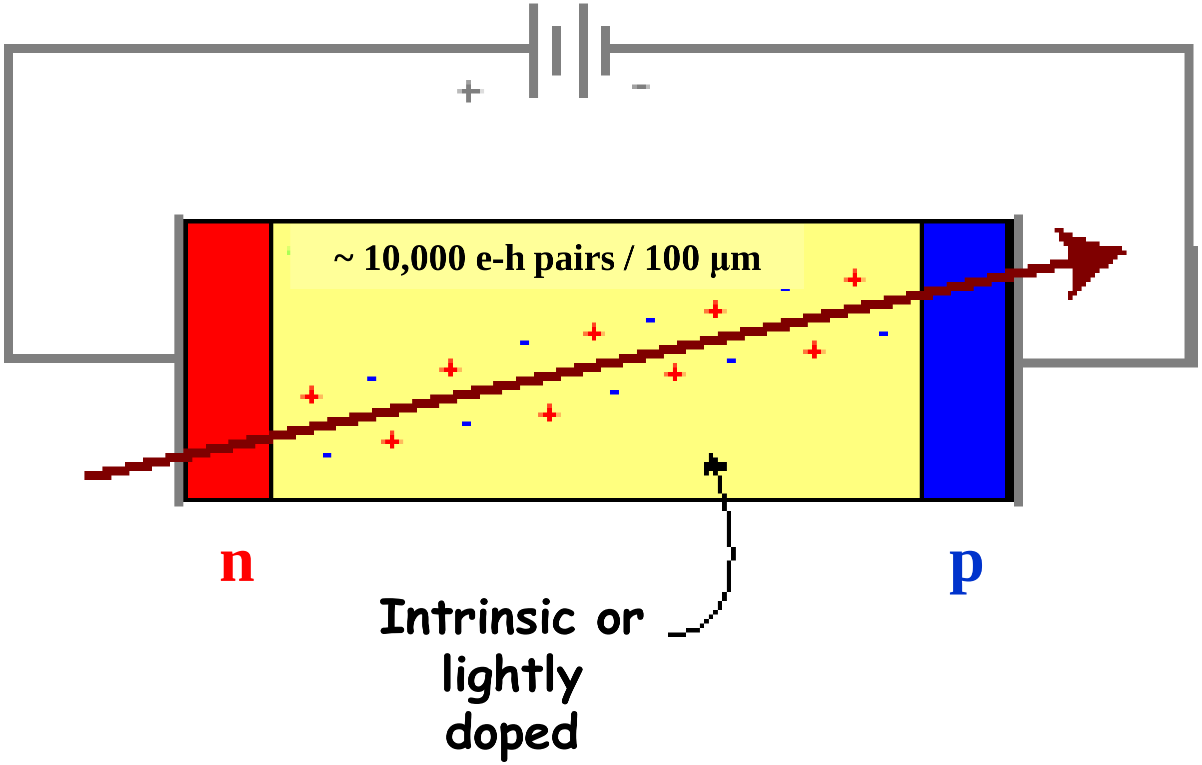
PIN Diode


PIN
+
-
n
Intrinsic or
lightly doped
p


Reversed biased "PIN DIODE"
Carrier Concentration
n
p
E
N Region
Depletion Region
P Region

When a charged particle traverses the depletion zone

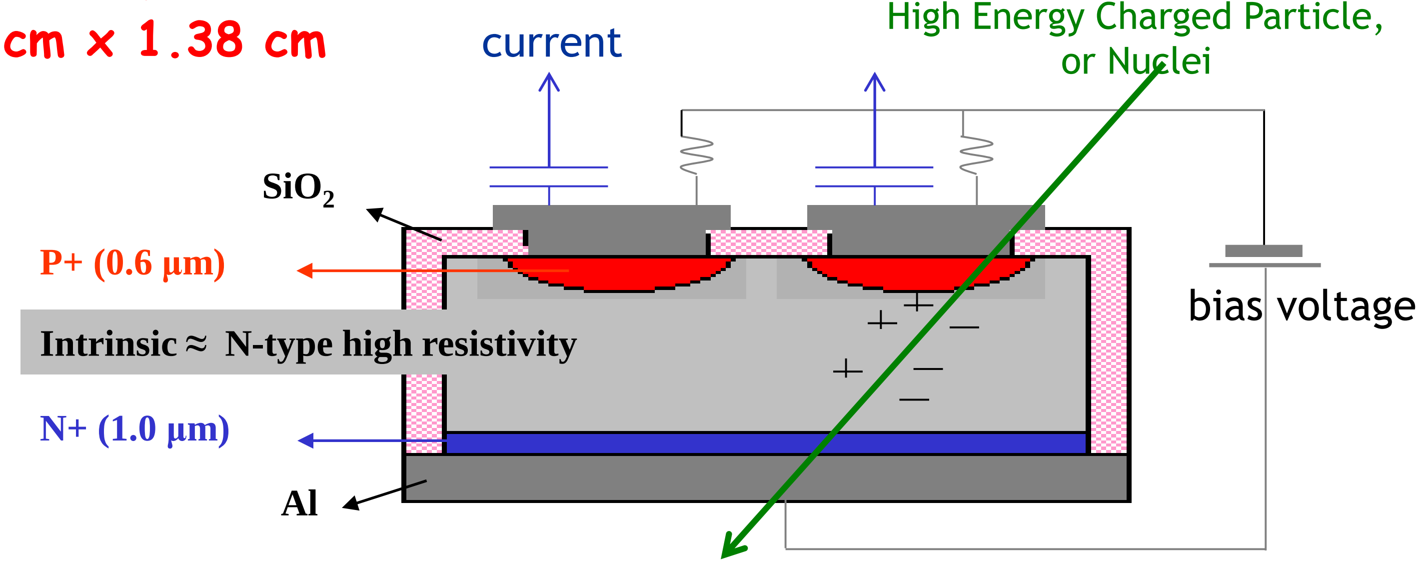
Simple detector



Silicon pixel sensor

- PIN diode, DC type
- Wafer: 5 inch, 525 μm in thickness, double polished side, N-type high resistivity (>5 kΩ-cm), (111) orientation

pixel size
= 1.55 cm x 1.38 cm

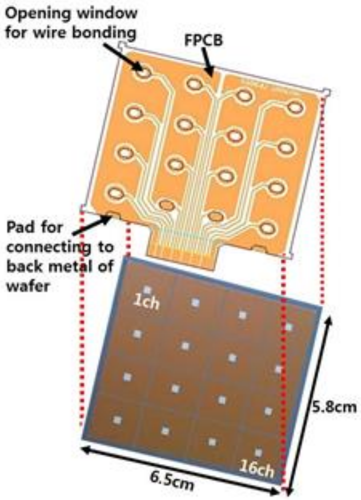


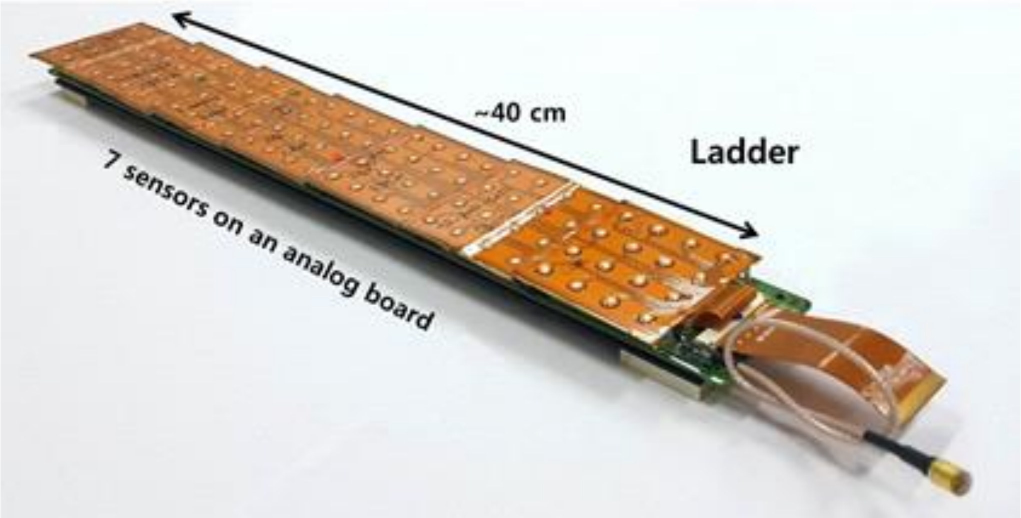
$$<\frac{dE}{dx}> \propto z^2$$

Measure the ionization energy loss in silicon sensor
-> Determine the charge of the incident particle

Silicon Pixel Sensor & Ladder for SCD

Built by SKKU group

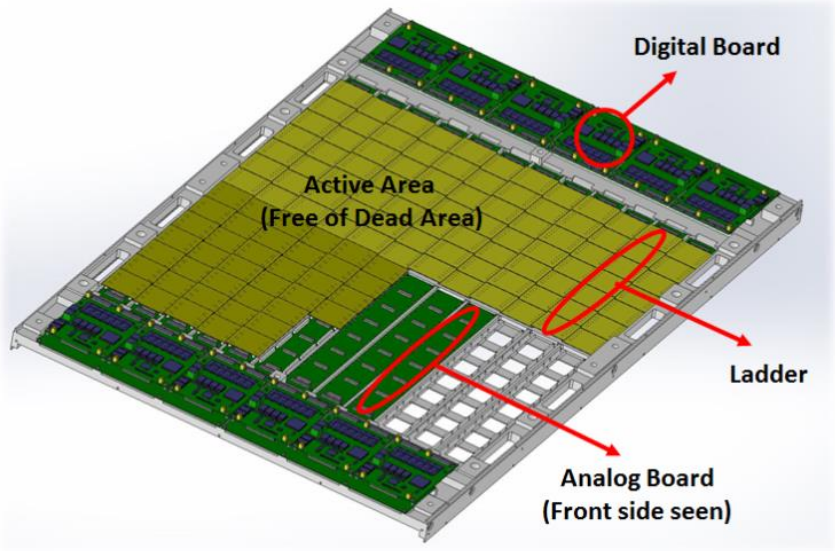


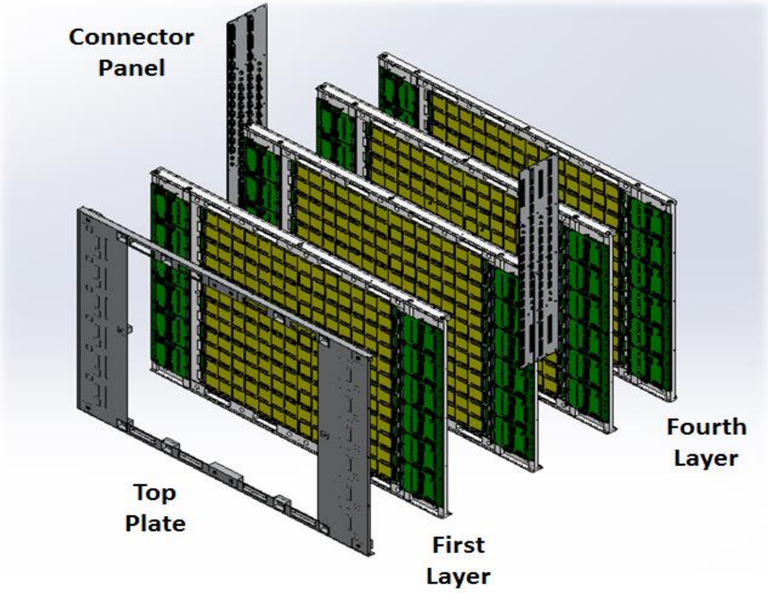


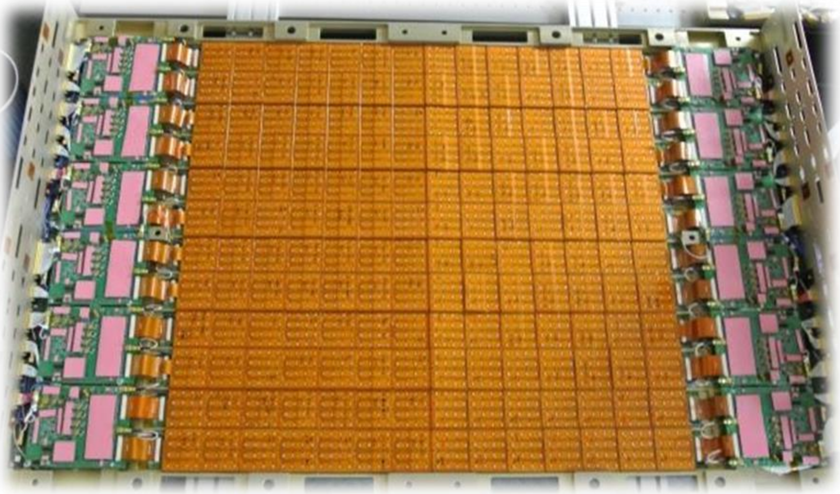
pixel size = 1.55 x 1.38 cm^2

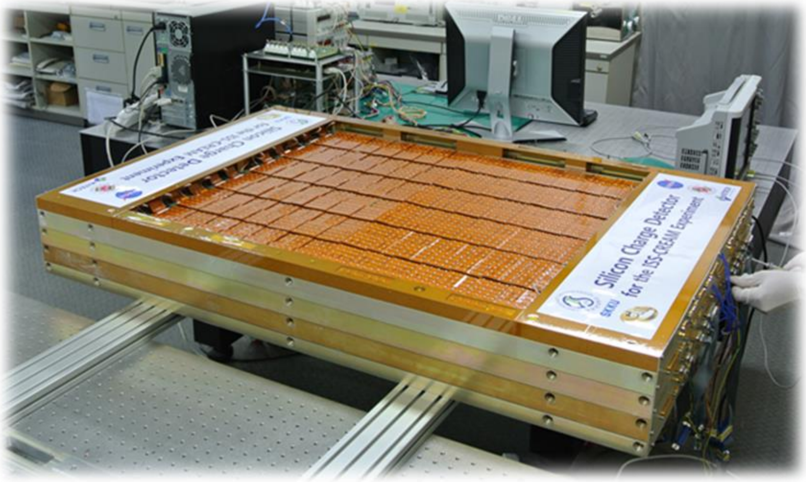
Silicon Charge Detector (design, fabrication & assembly

Built by SKKU group

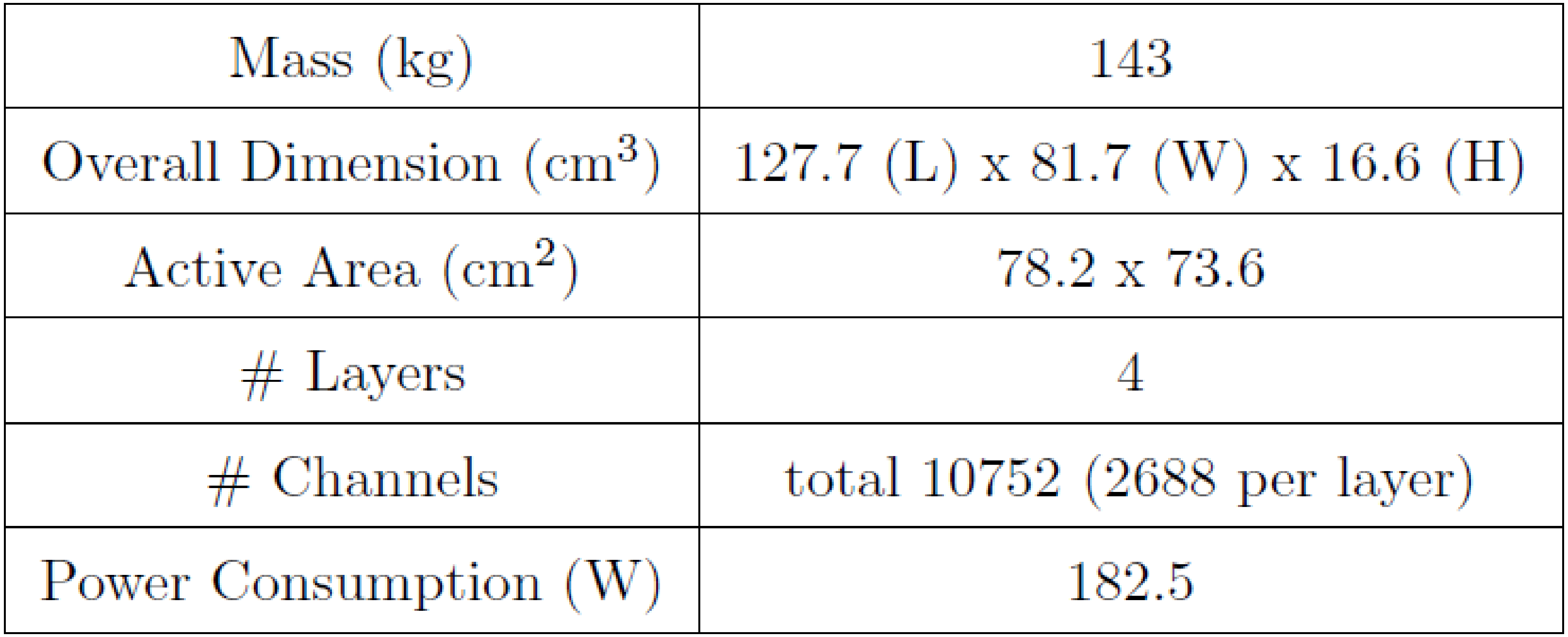








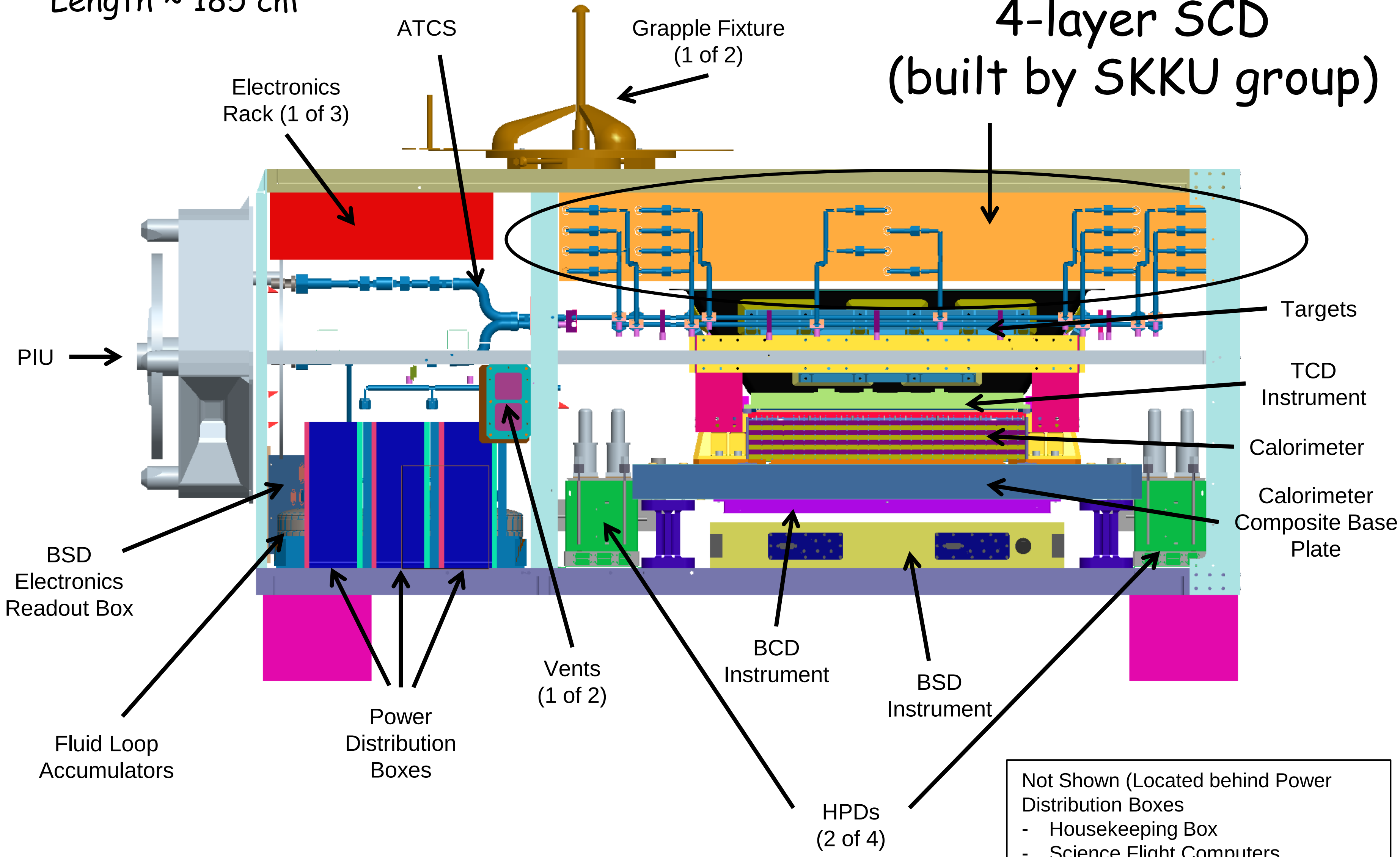
Silicon Charge Detector (specification)



Mass (kg)	143
Overall Dimension (cm^3)	127.7 (L) x 81.7 (W) x 16.6 (H)
Active Area (cm^2)	78.2 x 73.6
# Layers	4
# Channels	total 10752 (2688 per layer)
Power Consumption (W)	182.5

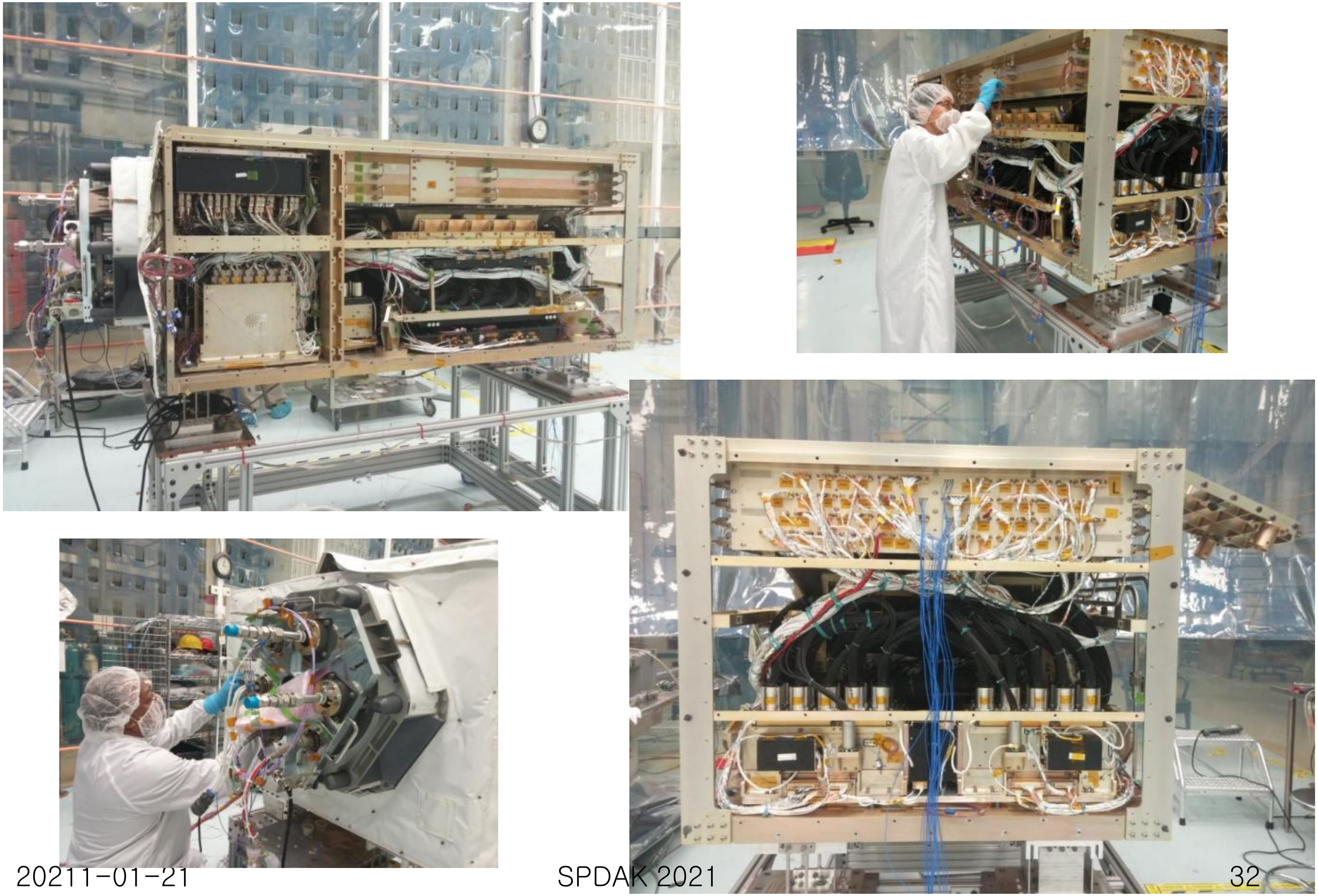
ISS-CREAM payload

Mass ~ 1258 kg
Power ~ 415 W
Length ~ 185 cm

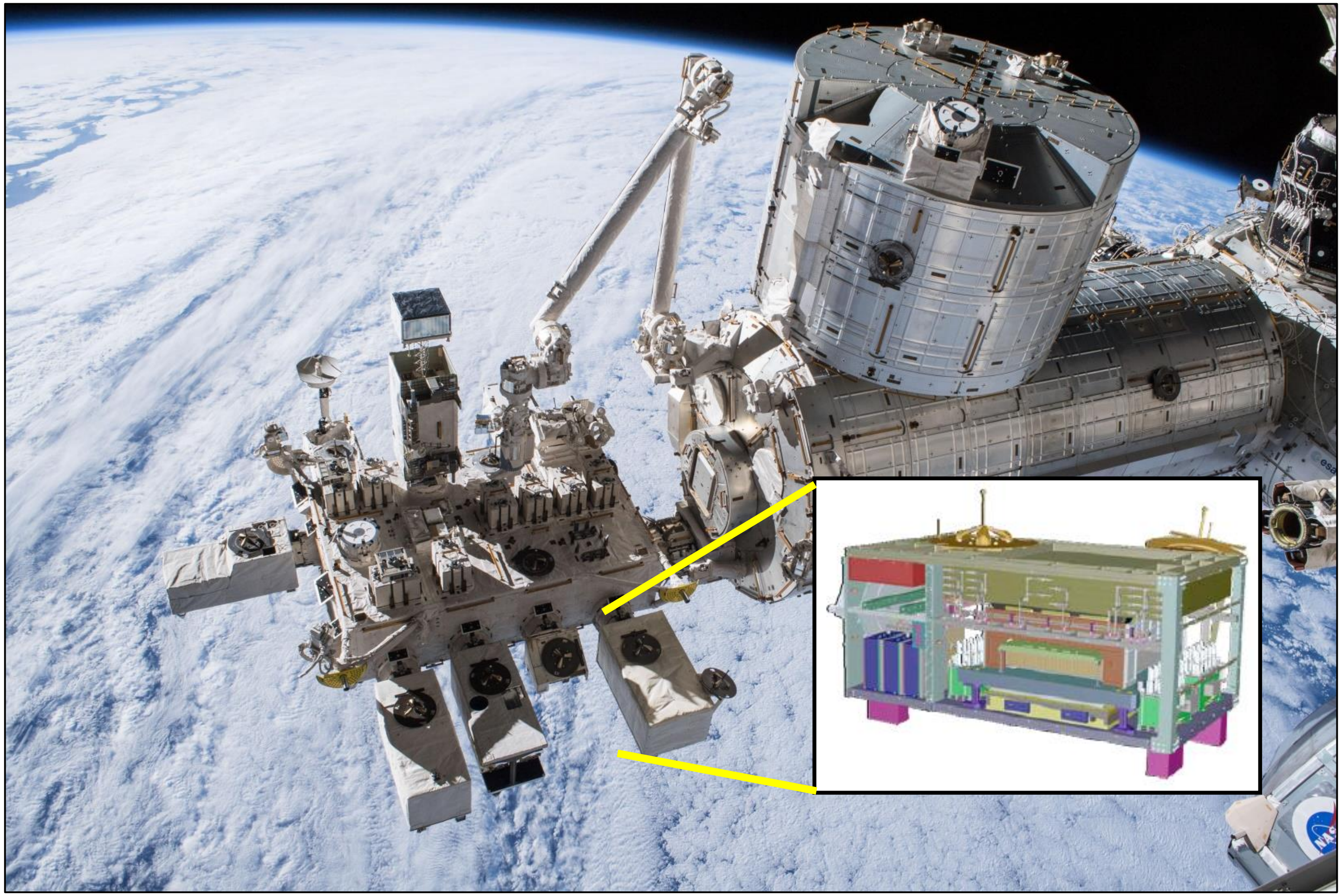


Not Shown (Located behind Power Distribution Boxes
- Housekeeping Box
- Science Flight Computers

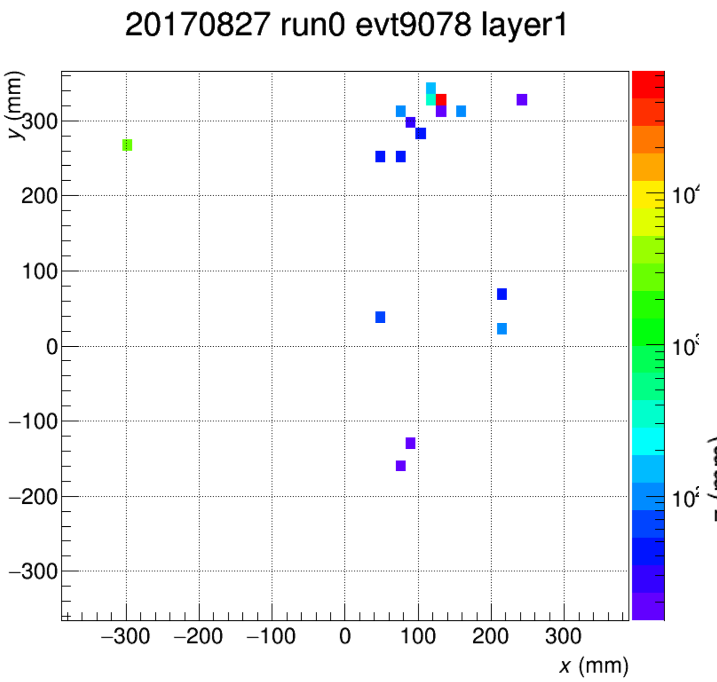
ISS-CREAM @ GSFC before TVAC test (July 22-25, 2015)



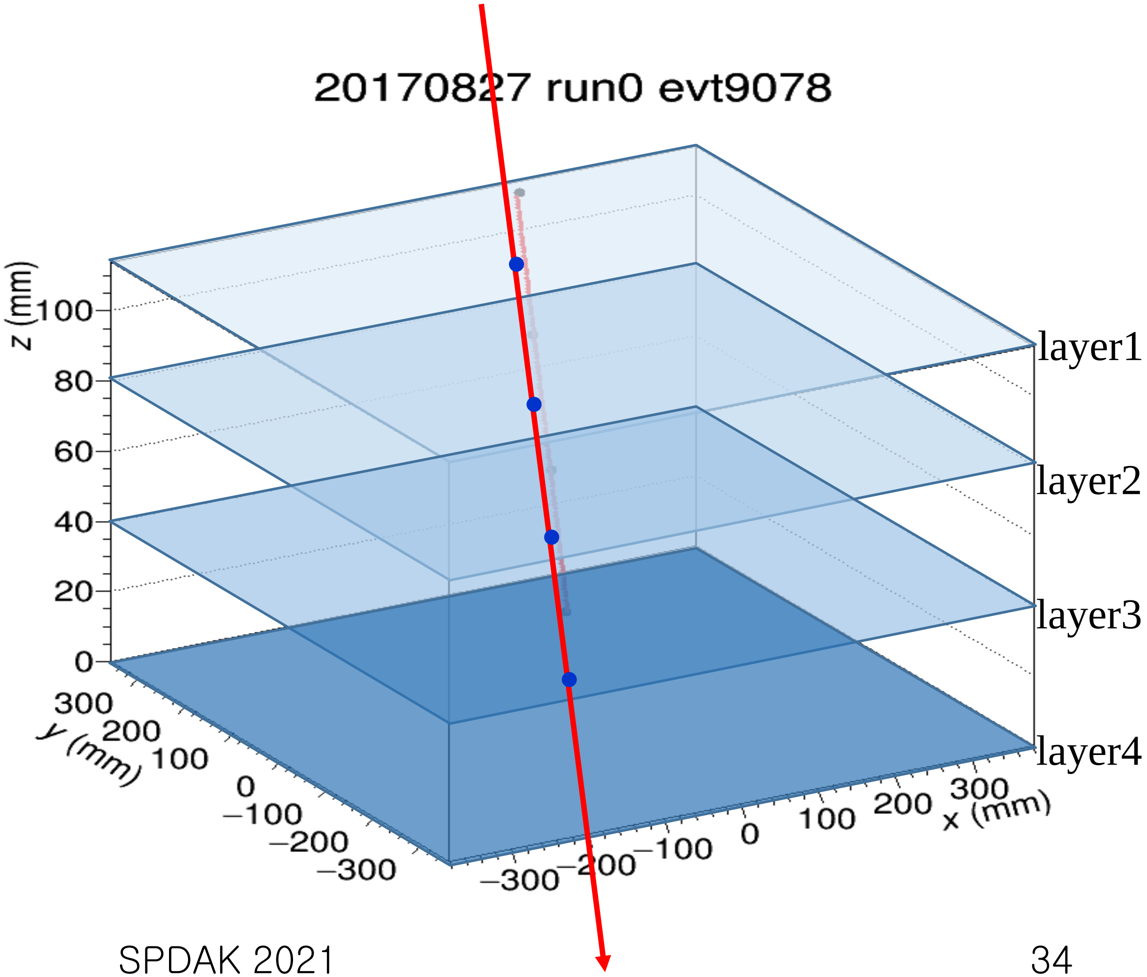
ISS-CREAM in space operation



SCD performance: standalone tracking



A 4-layer track!

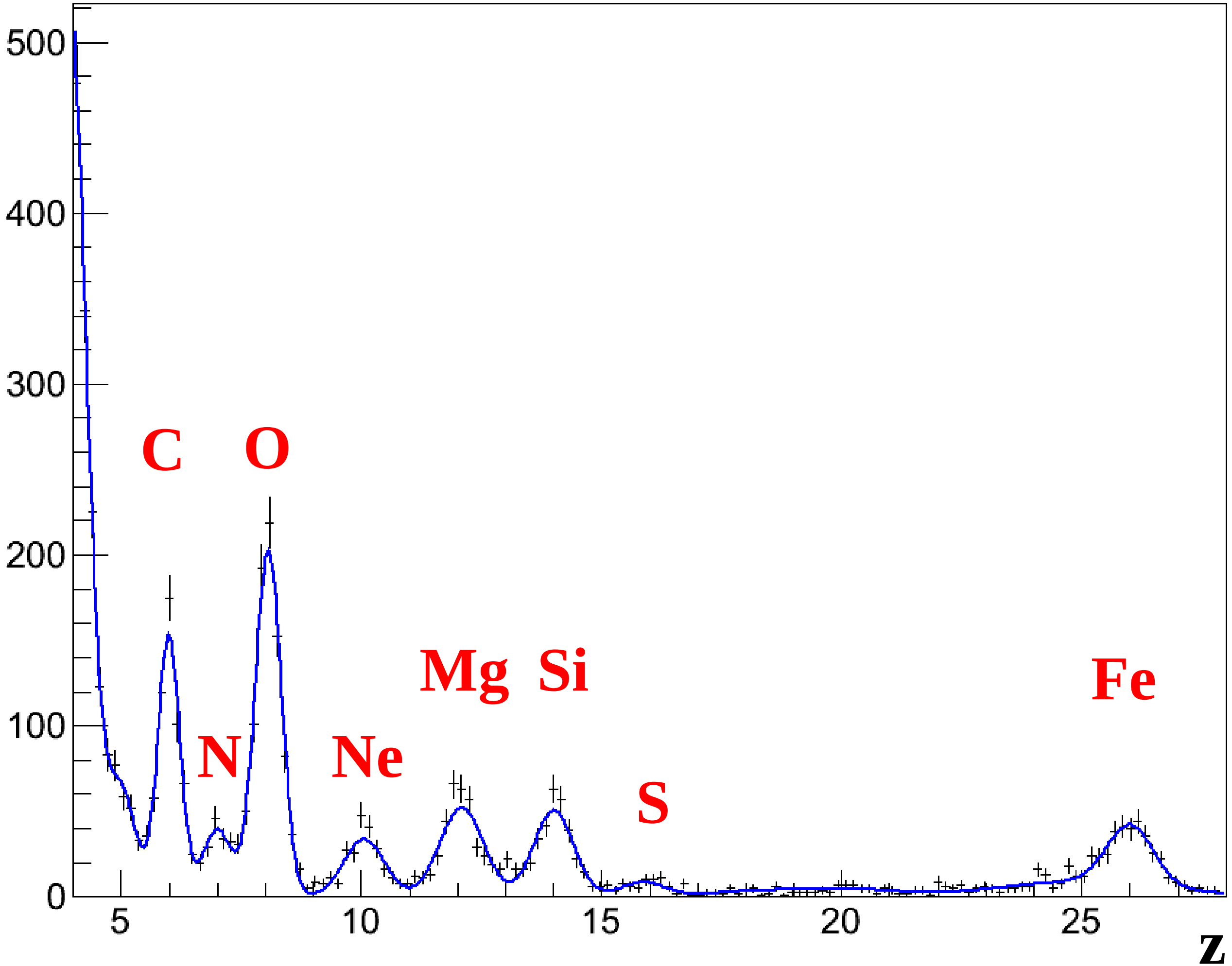


$\theta = 34.19 +1.91 -0.59°$

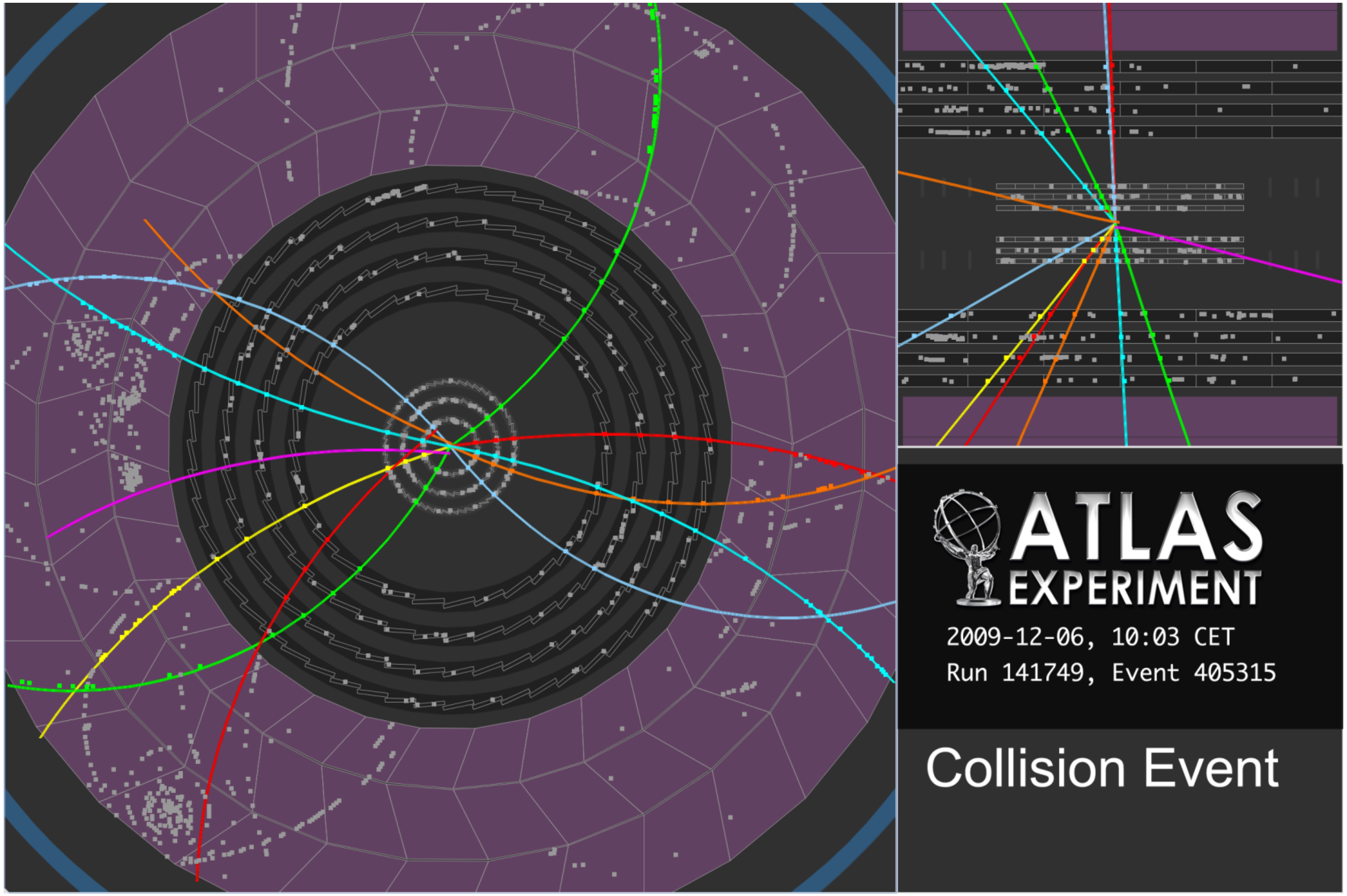
$\varphi = 105.5 +5.9 -2.9°$

SCD performance: charge measurement

Preliminary!



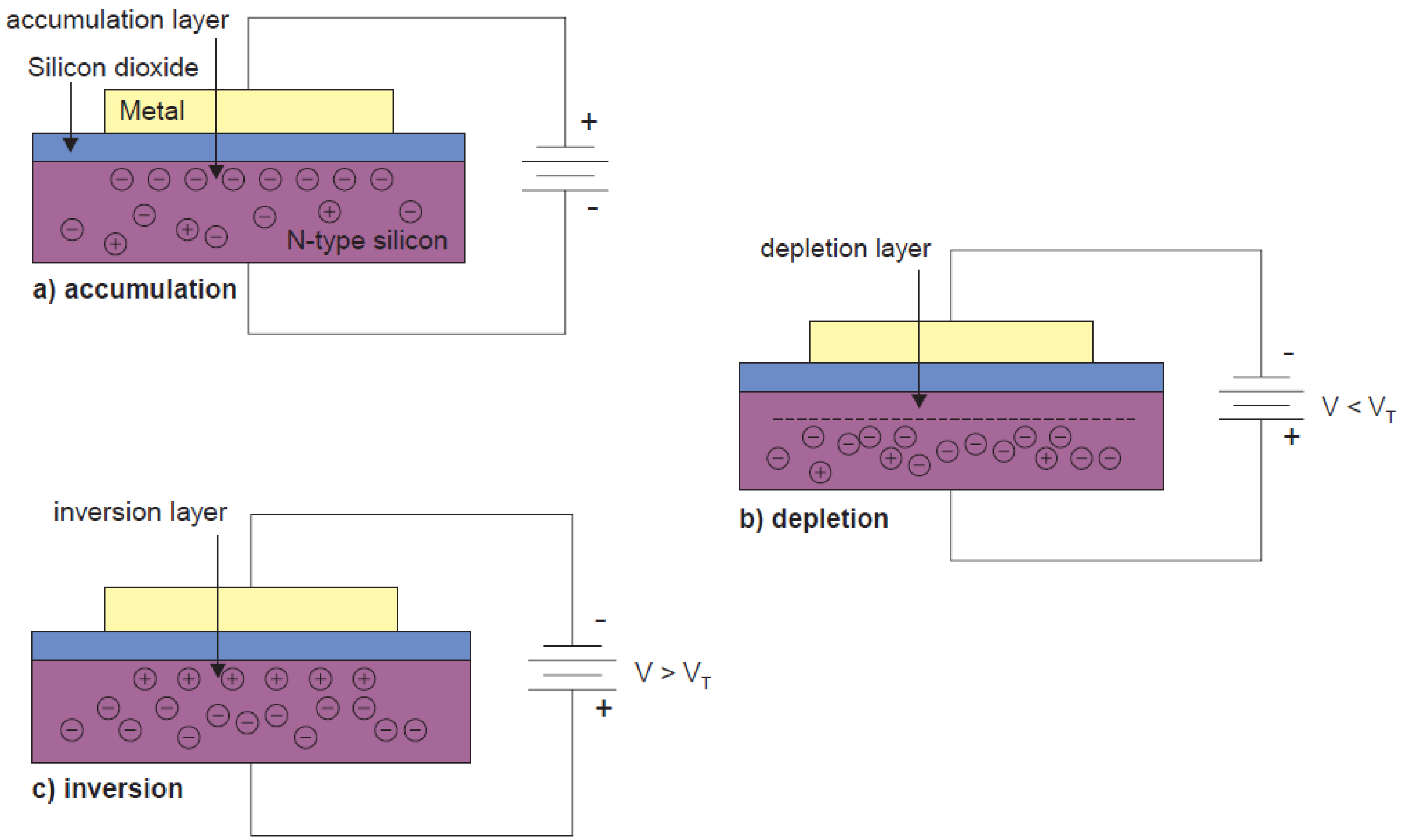
ATLAS Silicon Trackers



http://atlas.web.cern.ch/Atlas/public/EVTDISPLAY/events.html

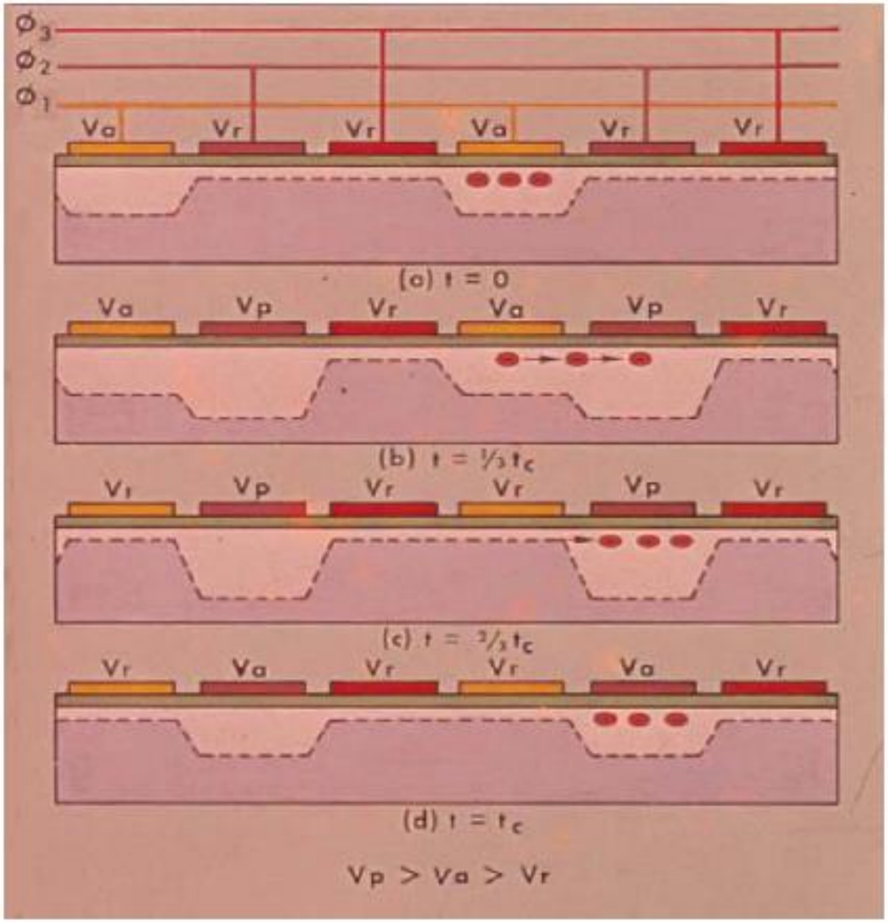
4. Silicon detectors for photon detection

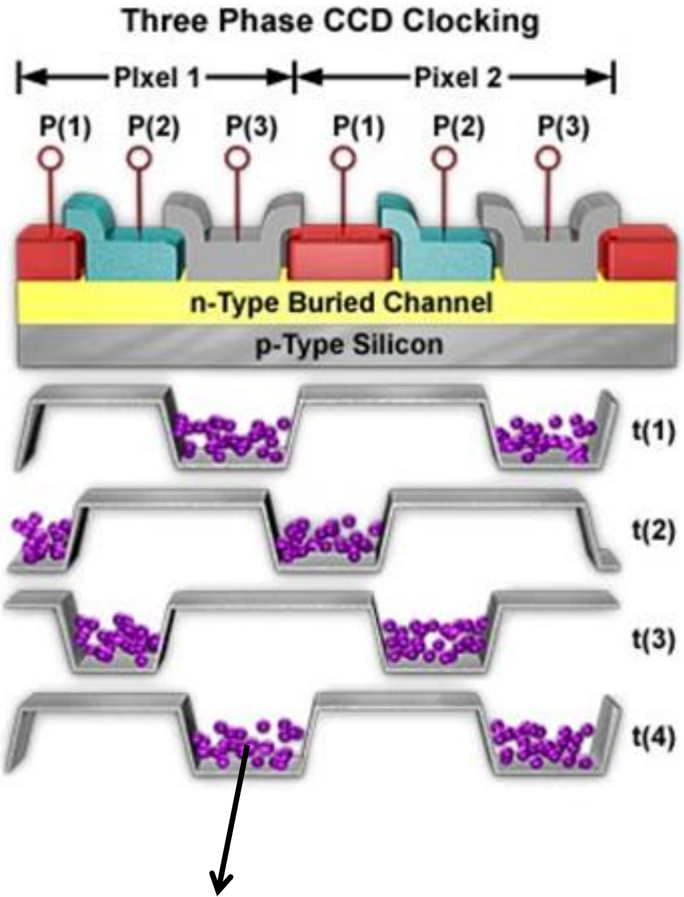
MOS structure (fundamental structure)



CCD (Charge Coupled Device) sensor

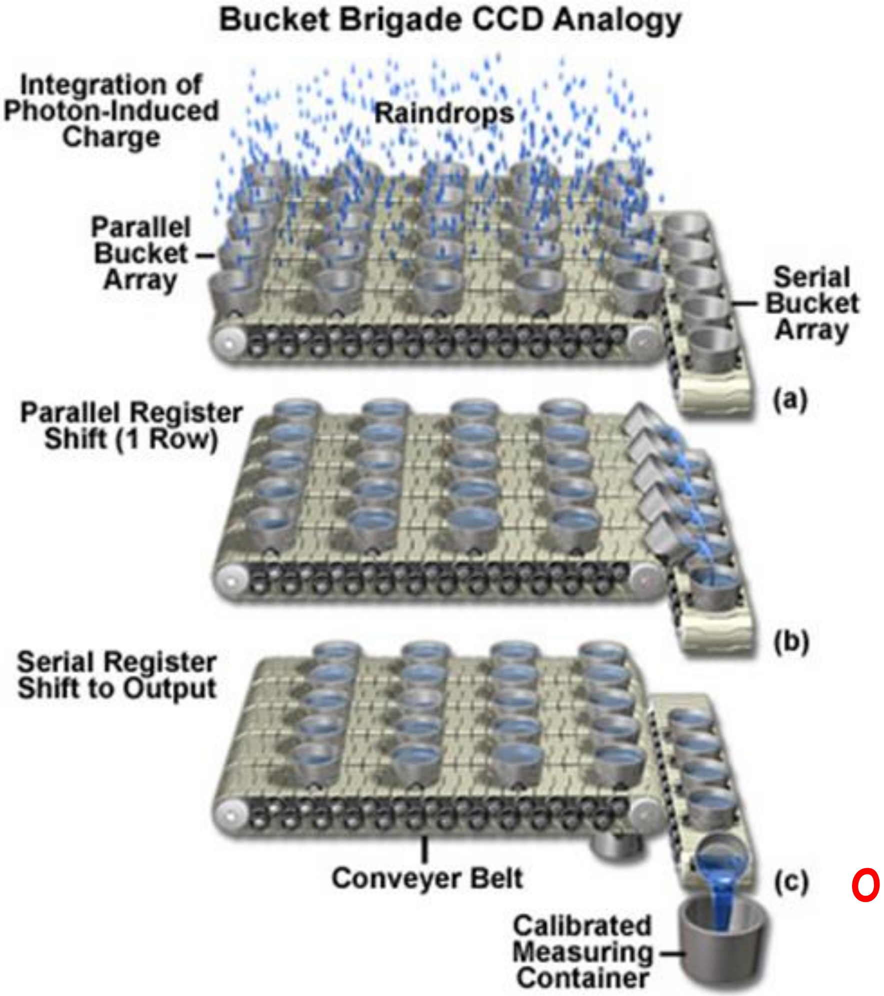
Charge Coupled Device




Three Phase CCD Clocking

Photoelectrons produced by photoelectric effect

CCD analogy



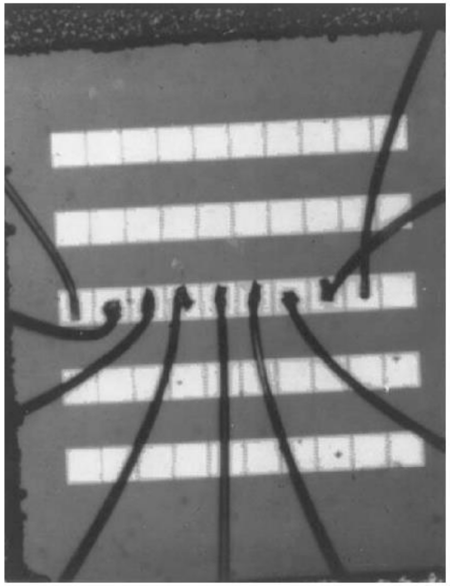
output = charge

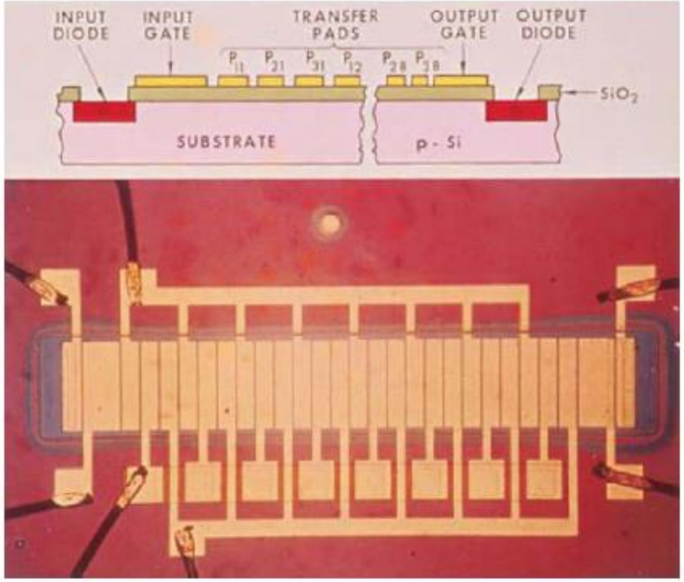
CCD inventors (winners of Nobel prize in physics in 2010)

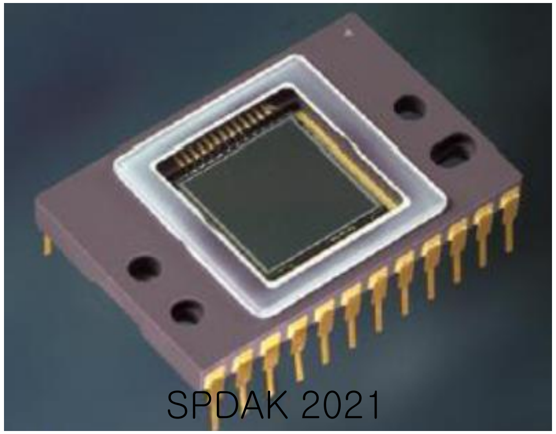
G. E. Smith & W.S. Boyle : invented CCD in 1970

Having Fun @ Bell Lab in 1974 !

How much advanced?







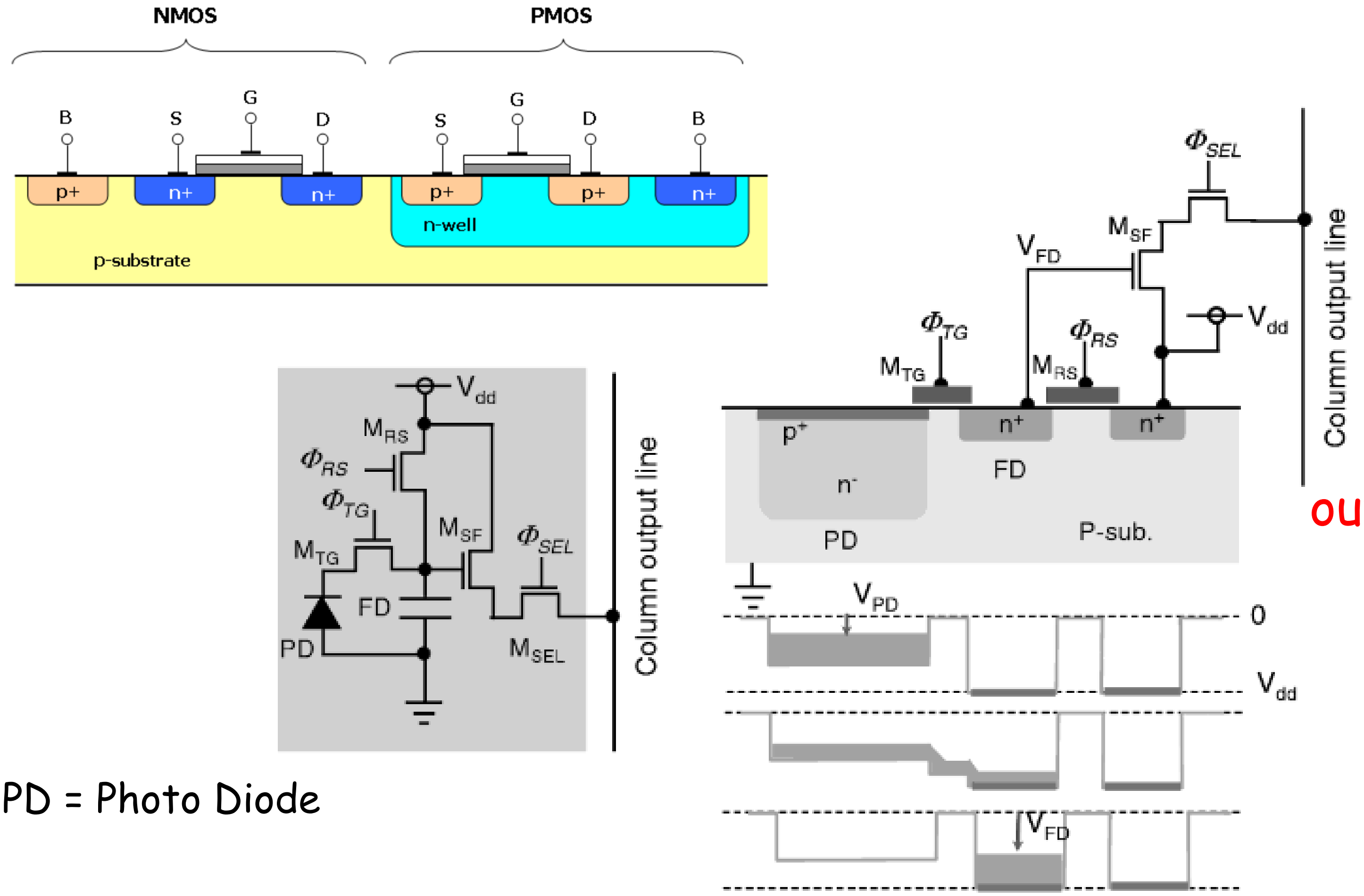
Kodak
Mega pixel CCD
~ 1cm^2

CCD application in Astronomy/Astrophysics

The galaxy cluster Abell 2218. *Image: WFPC2, Hubble Space Telescope, NASA.*

CMOS sensor

CMOS : Complementary Metal Oxide Semiconductor

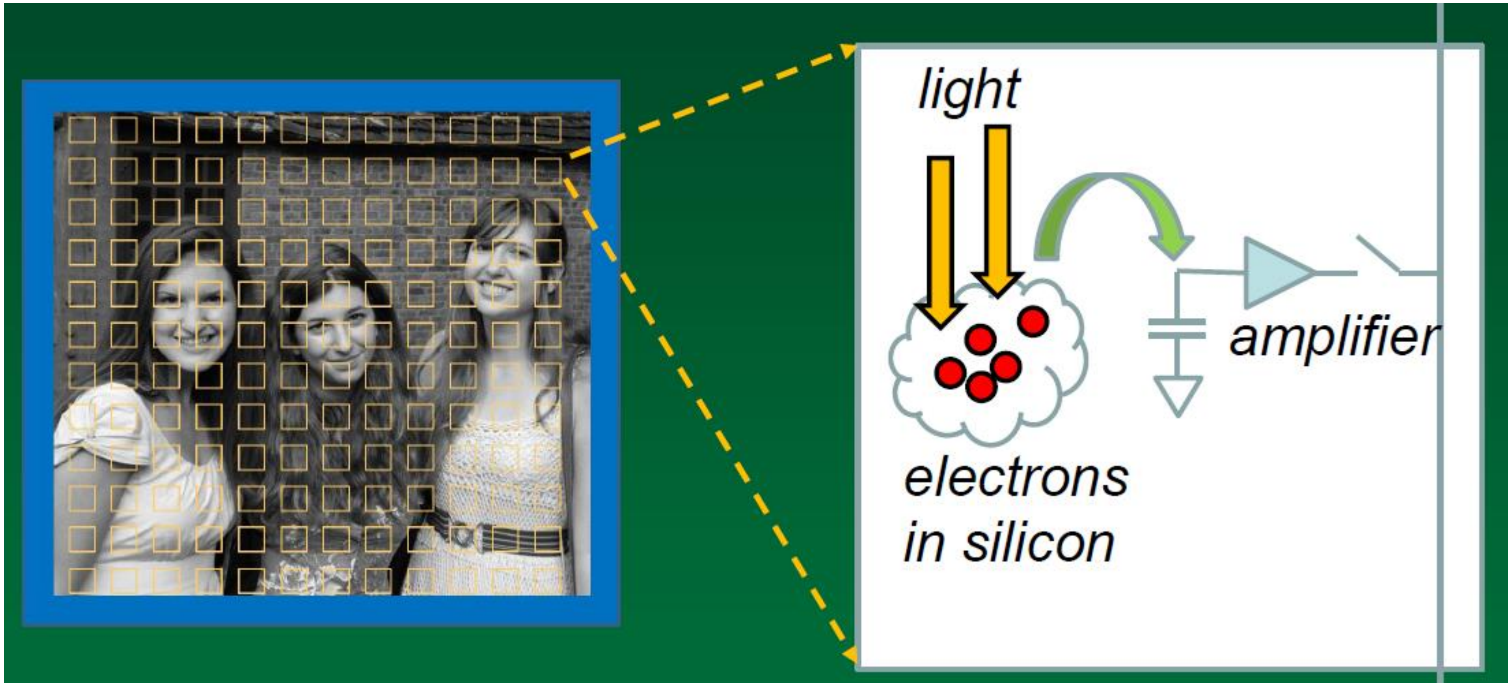


output = voltage

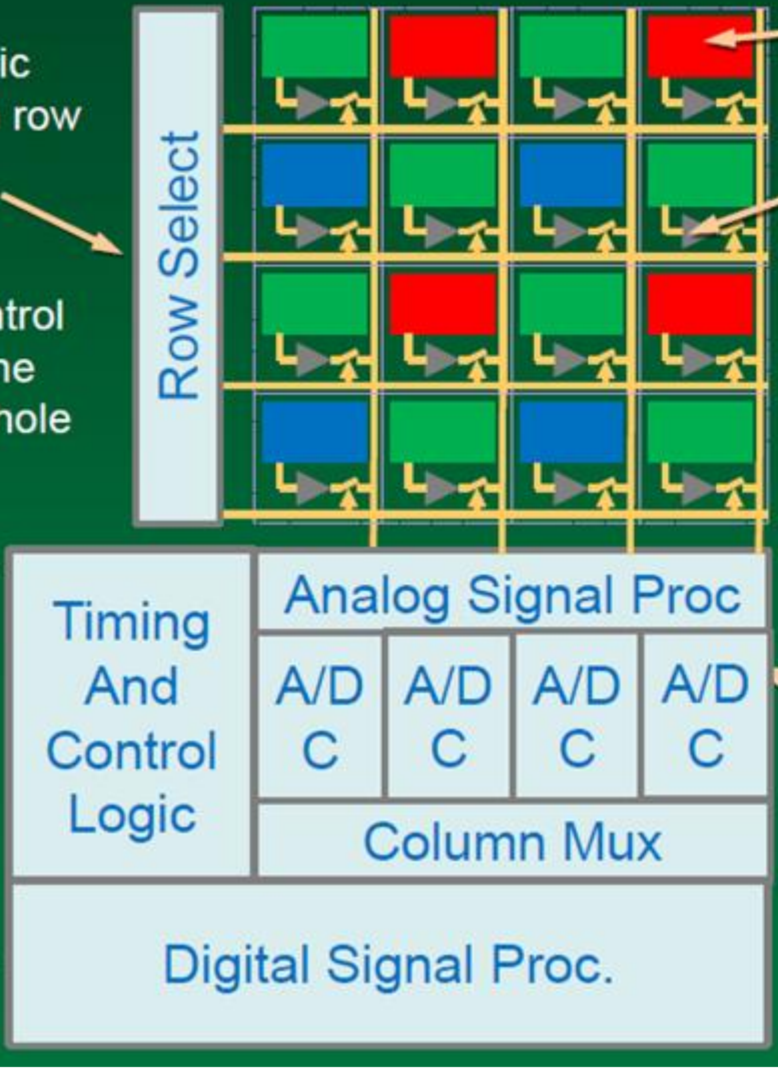
PD = Photo Diode

A pixel in CMOS sensor

Amplifier converts charge signal to voltage signal !



Layout of typical CMOS sensor



Row select logic chooses which row is selected for readout.

Timing and control logic controls the timing of the whole sensor

SoC functionality for color processing, compression, etc.

Photodetector converts photons to electrons

Amplifier converts electrons to voltage after intrapixel complete charge transfer

Analog signal processor suppresses noise and further amplifies signal

Analog-to-digital converters (ADC) convert signals from volts to bits (usually 10-12 bits resolution) in parallel

Column multiplexer used to scan ADC outputs

CCD & CMOS summary

- **원칙적으로는 동일, 즉 포토다이오드 구조로, 광의 세기가 전하량으로 변환되고, 전하를 전압으로 변환 출력**
- **변환기가 어디에 위치하는가가 두 센서의 근본적인 차이**
  - 픽셀의 정보 이동 방법의 차이, 즉 CCD는 전하로 픽셀간 이동 최종 전압으로 변환, CMOS는 픽셀 단위에서 전압으로 변환하여 이동
- **잡음이 크고, 동적폭 (dynamic range) 및 속도에서 뛰어나지 않음**
  - 동적폭 = Full Well Capacity / 잡음
  - Kodak Mega 픽셀 CCD 200,000 전자 / 20전자 = 100,000

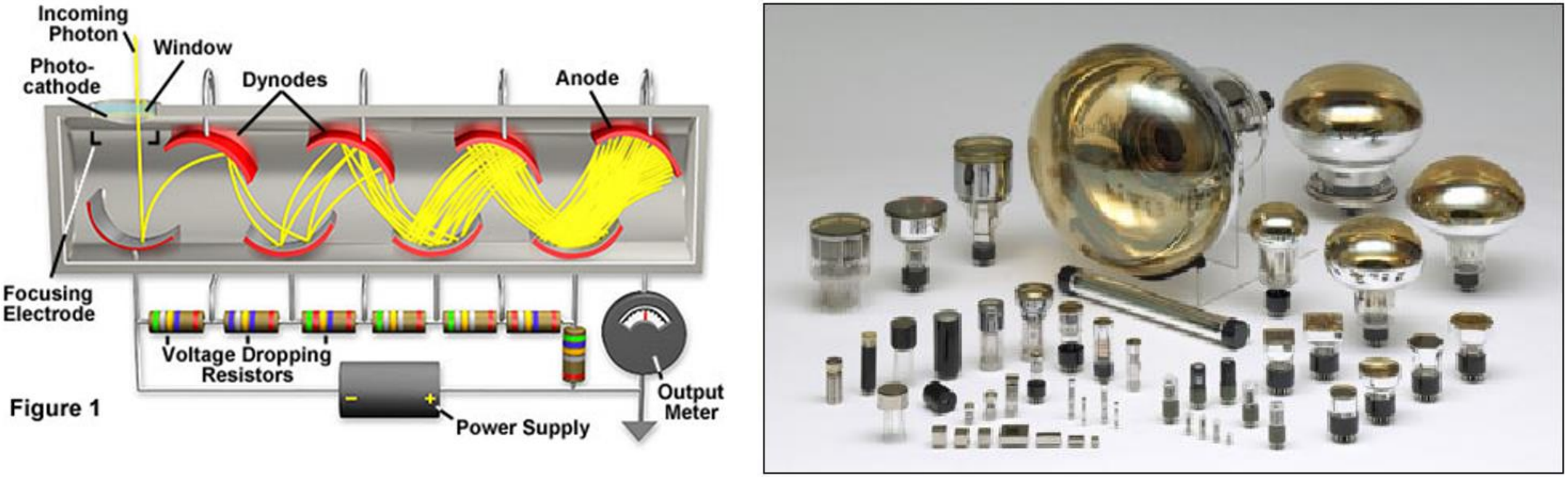
- **광량이 적은 환경에서는 고민감도의 센서가 필요하나, CCD와 CMOS는 증폭형 센서가 아니므로 야간 상황에서 그 성능에 한계**
- 우리의 눈의 민감도는 CCD 보다 우수함
  - CCD 민감도 ~ 0.03 Lux (냉각 시 0.002 Lux)

Photomultiplier

- 정확히 말하면 광전자를 다수의 전자로 증폭
- 광음극(photocathode)과 함께 사용하는 PMT(Photomultiplier Tube)와 MCP(Microchannel Plate)가 대표적으로 단일 광자 계수 가능
- 반도체 소자에서는 센서 내부에서 광전자(photoelectron)를 증폭: **ICCD(Intensified CCD), EB(Electron Bombardment)CCD, EM(Electron Multiplier)CCD, APD(Avalanche Photodiode), SiPM(Silicon Photomultiplier)**

Photomultiplier Tubes (PMTs)

- 초민감 초고속 특성을 갖는 광센서로 과거 수십년간 특수목적에 사용
- 그러나 진공관식으로 부피가 매우 크고, 충격에 취약하며 고전압을 필요로 하므로, 야전에서 내구성, 휴대성 및 실용성이 크게 떨어지며, 광량이 많아지면 소자가 파괴되는 문제



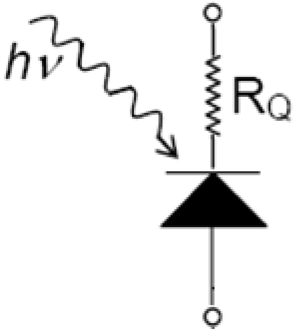
PMT의 원리와 **Hamamatsu**사 제품

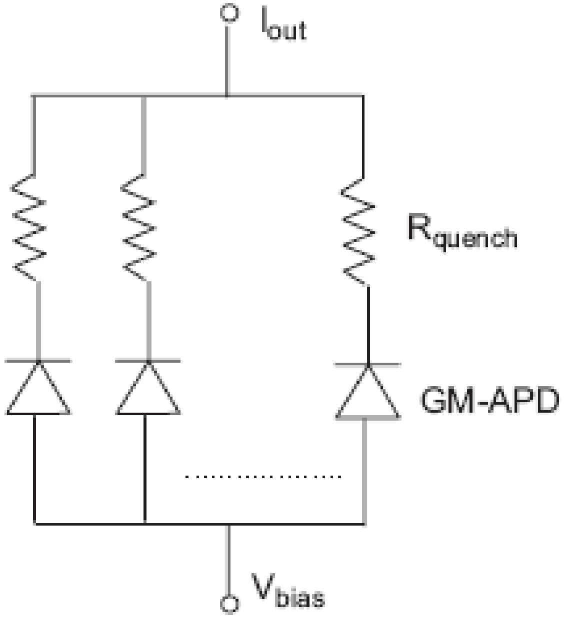
20 inch World largest PMT

For Super-K

SiPM (Silicon PhotoMultiplier)

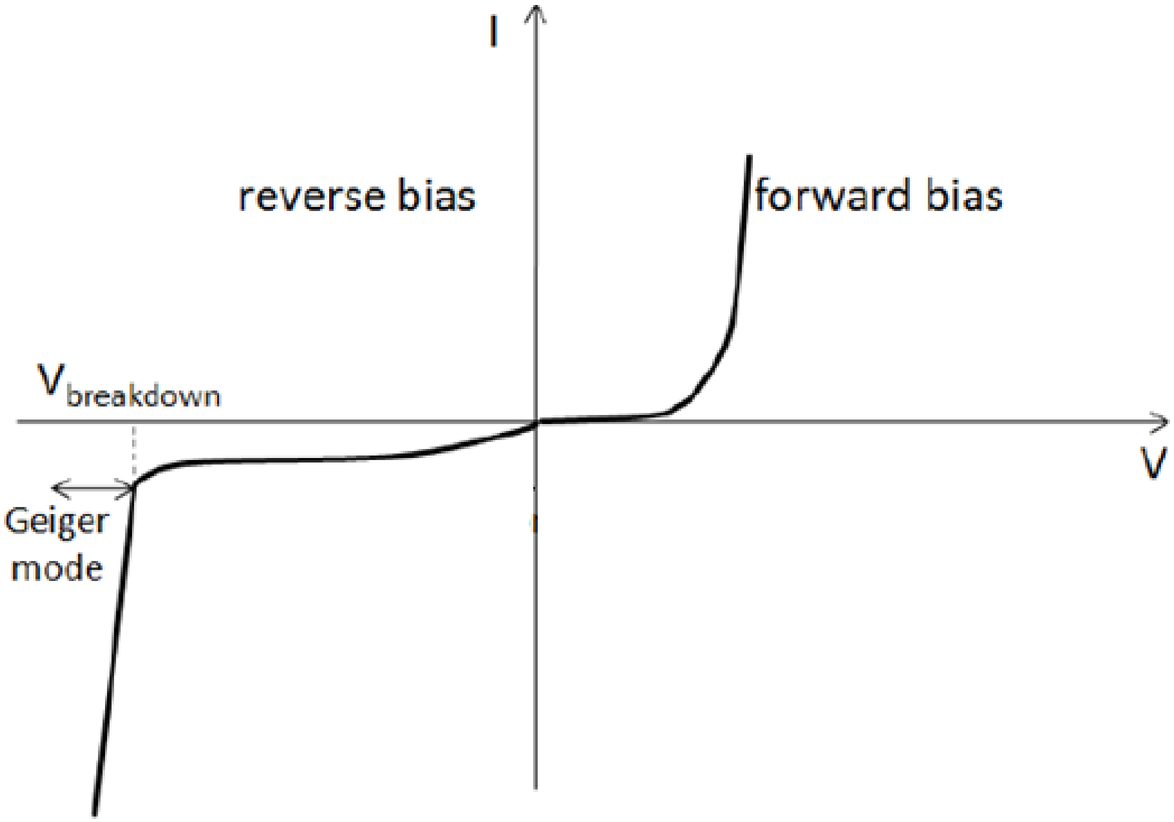
- **Micropixel (Geiger mode APD)** 어레이로 이루어진 반도체 광다이오드
- **Micropixel**의 크기는 **10~100μm**로 **1mm²**의 면적당 **100~1000**개 집적
- 각 **Micropixel** 은 공통의 인가전압과 로드 저항으로 작동, 출력신호는 모든 **Micropixel** 신호의 합**(multiplexed output)**
- 즉 **Binary**의 디지털소자로 입사광의 수를 세는 아날로그식의 광센서





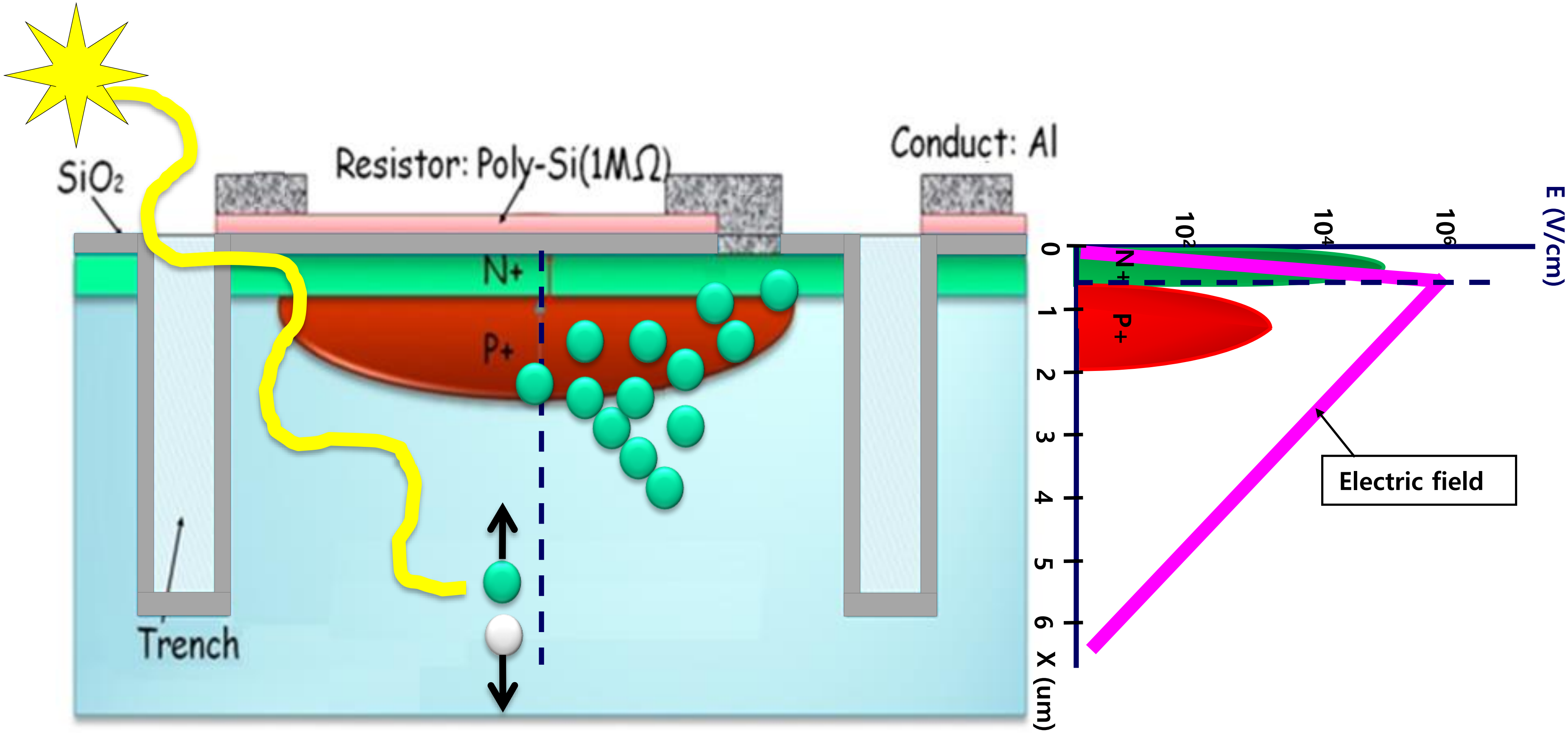
```
            V p-p(f2)       Frequency(f4+)
Current   Source off      Source off
   Mean --------------- ---------------
    Min --------------- ---------------
    Max --------------- ---------------
```

Geiger Mode



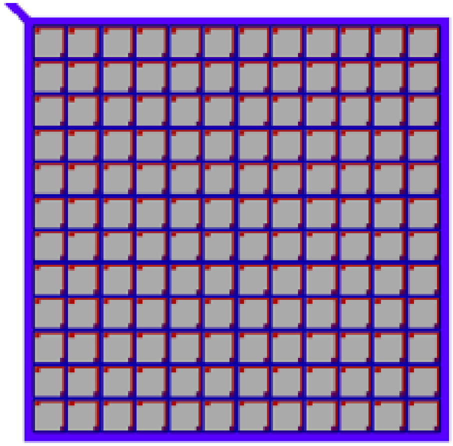
SiPM

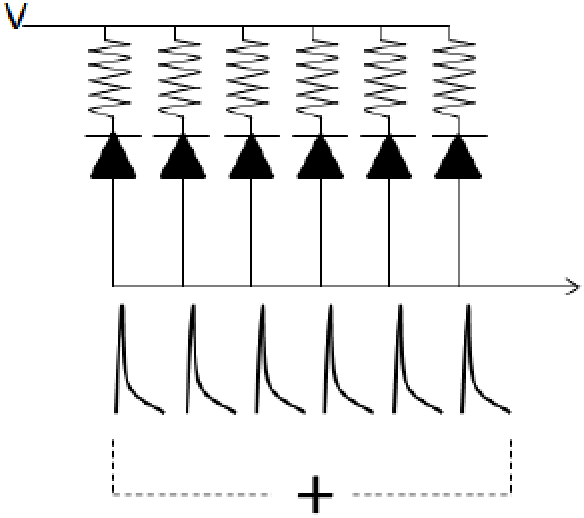
- PN 접합면에 **매우 높은 전기장 형성**
- 한 개의 광자 입사 -> **100만 배의** 전자증폭 발생 -> **초 민 감 도 !!**
- 광이 입사되었을 때 센서의 반응 속도 -> 1ns **초 고 속 도 !!**

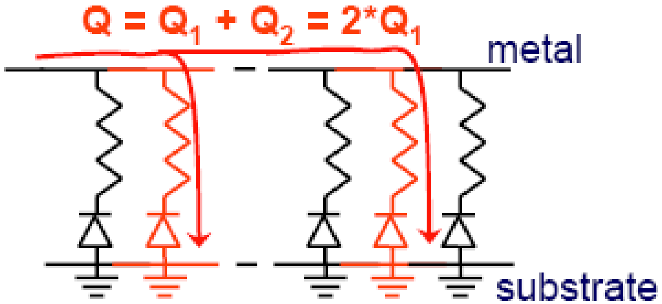


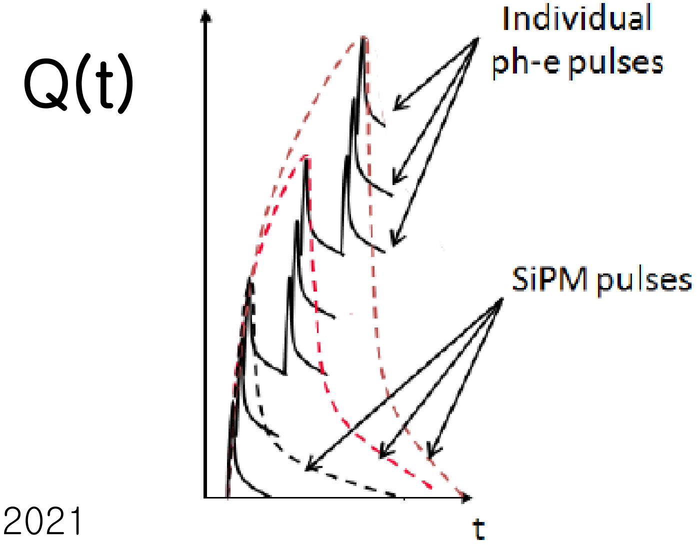
SiPM의 **Micropixel**

Analog Signal

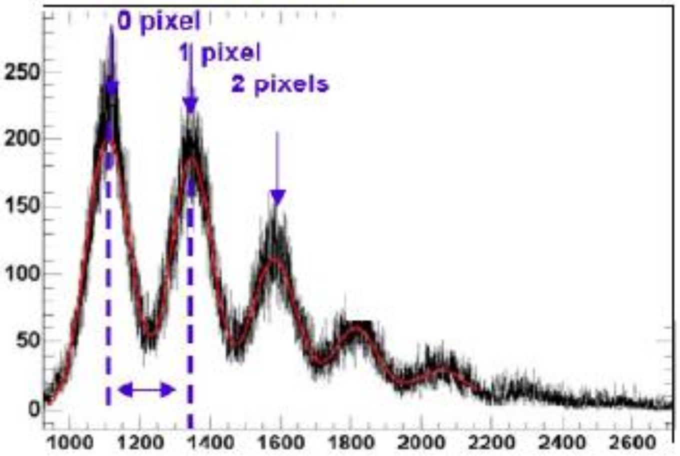






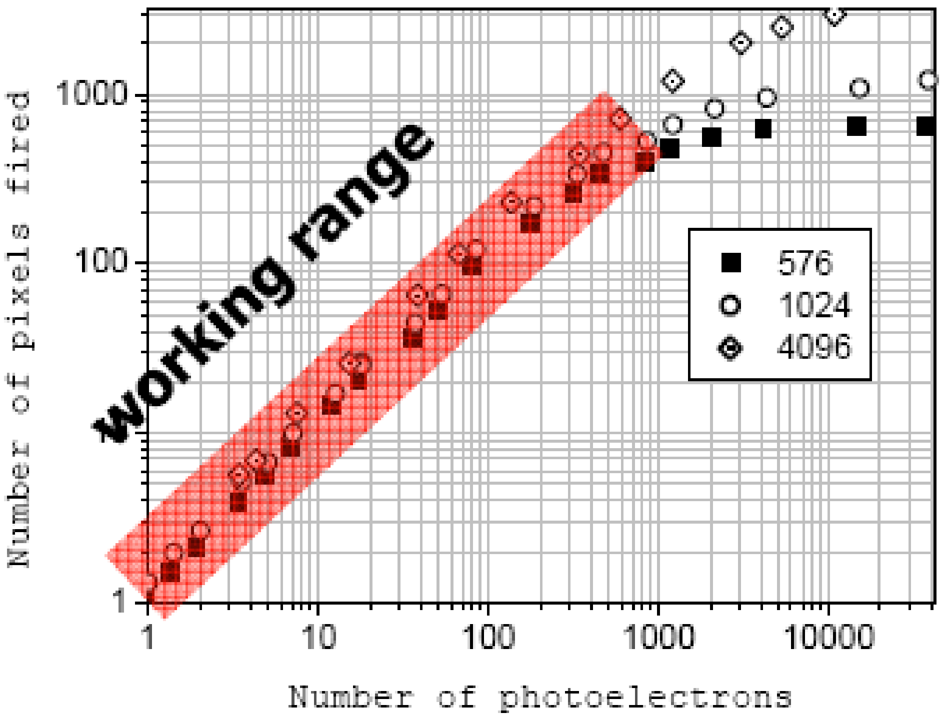


Analog Signal & Dynamic/Working Range



Gain calibration

IRST of INFN Pisa

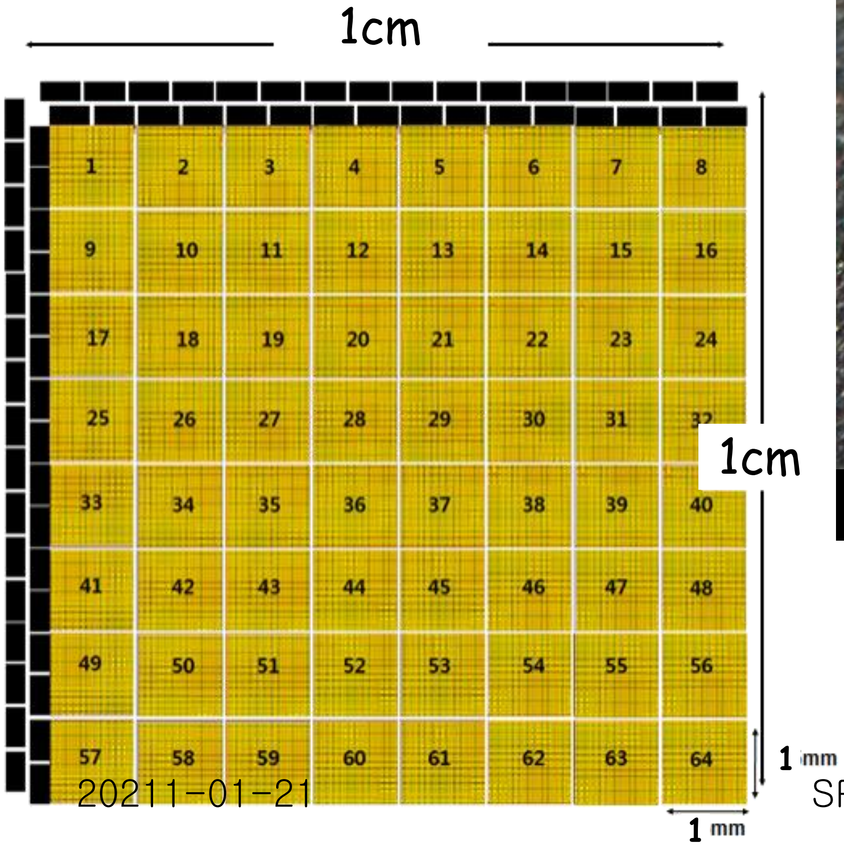


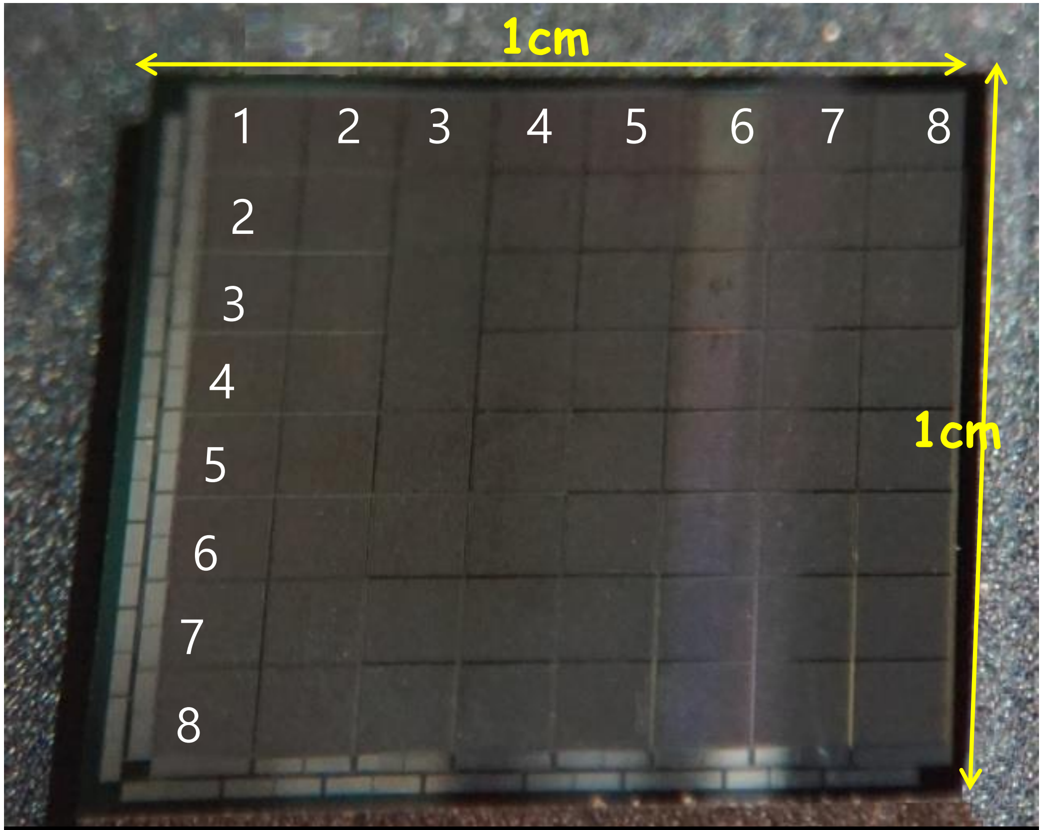
다화소용 8 × 8 픽셀 어레이 소자

- ◆ **SiPM 픽셀**
  : 1 x 1 mm² 크기
  (30x30μm²크기, 10³개의 마이크로 픽셀)

- ◆ **64ch SiPM 소자 : 1 x 1 cm²**

64ch 설계도

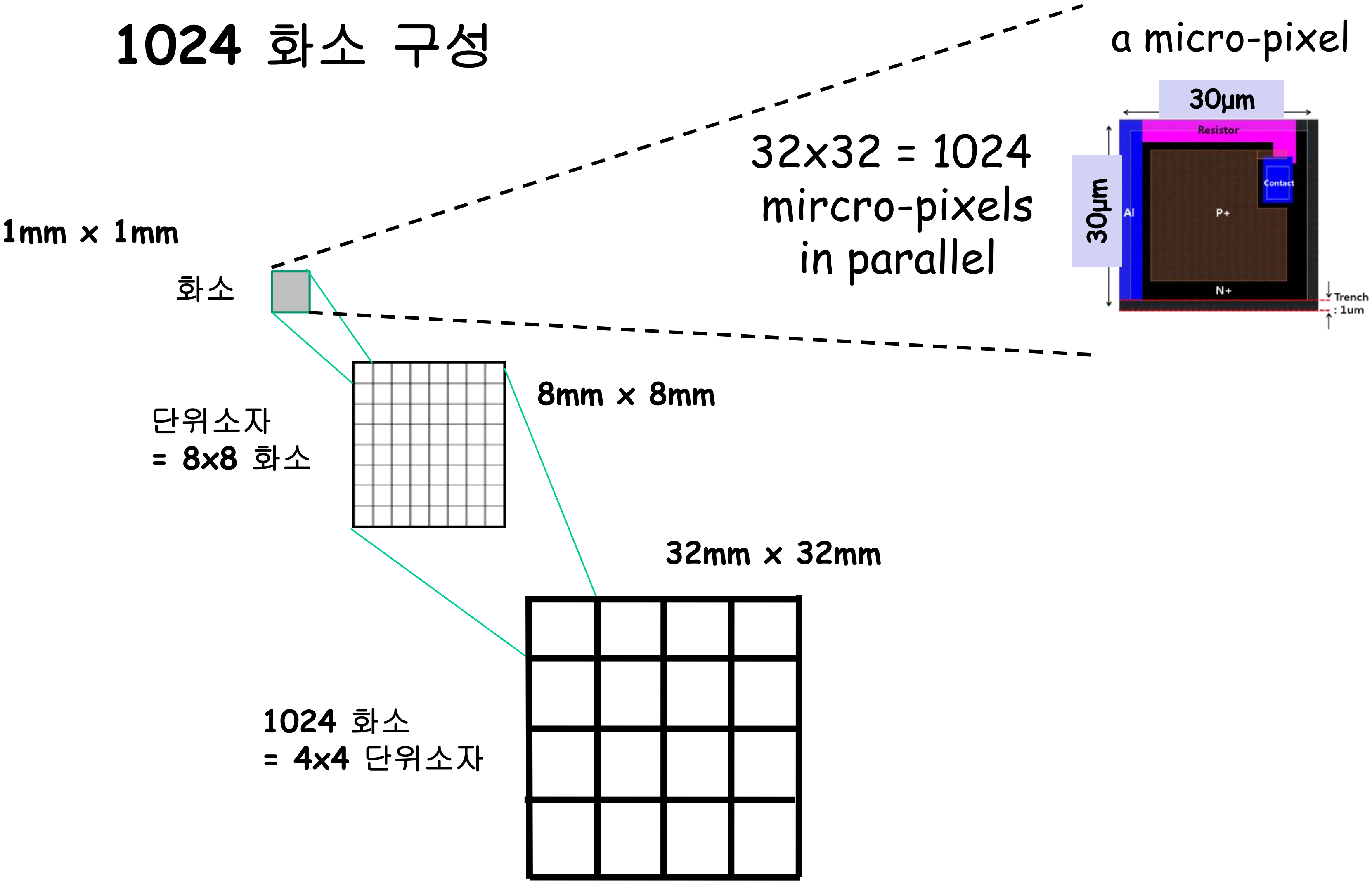




64ch SiPM 센서(1cm²)의 현미경 사진

1024 화소 배열

1024 화소 구성



a micro-pixel

32x32 = 1024
mircro-pixels
in parallel

1mm x 1mm

화소

8mm x 8mm

단위소자
= 8x8 화소

32mm x 32mm

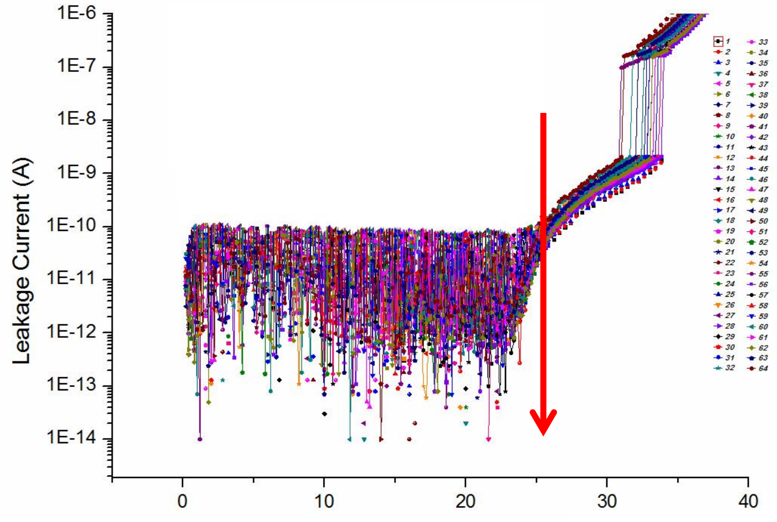
1024 화소
= 4x4 단위소자

16개의 8 x 8 SiPM 픽셀 어레이로 구성된 다화소 (1024-ch)

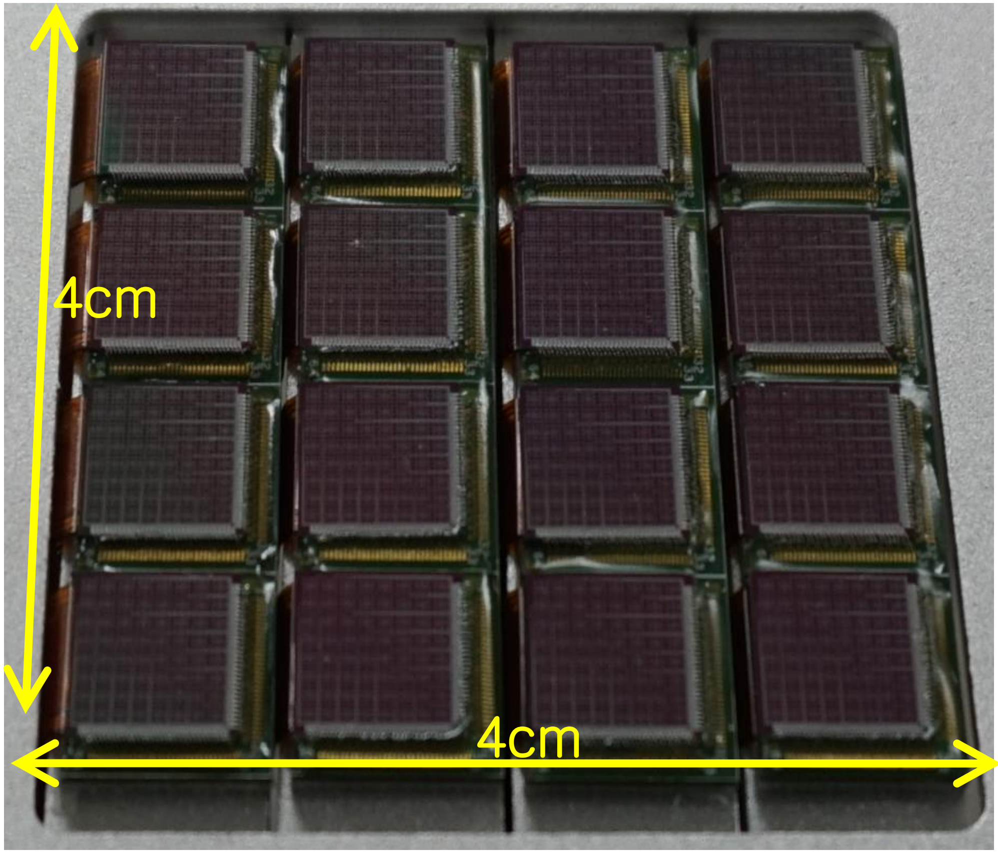
- **1단계 SiPM 픽셀 1024ch 제작**
  : 1 x 1 mm² 크기
  (30x30μm²크기, 10³개의 마이크로 픽셀)

- **64ch SiPM 소자 : 1 x 1 cm²**

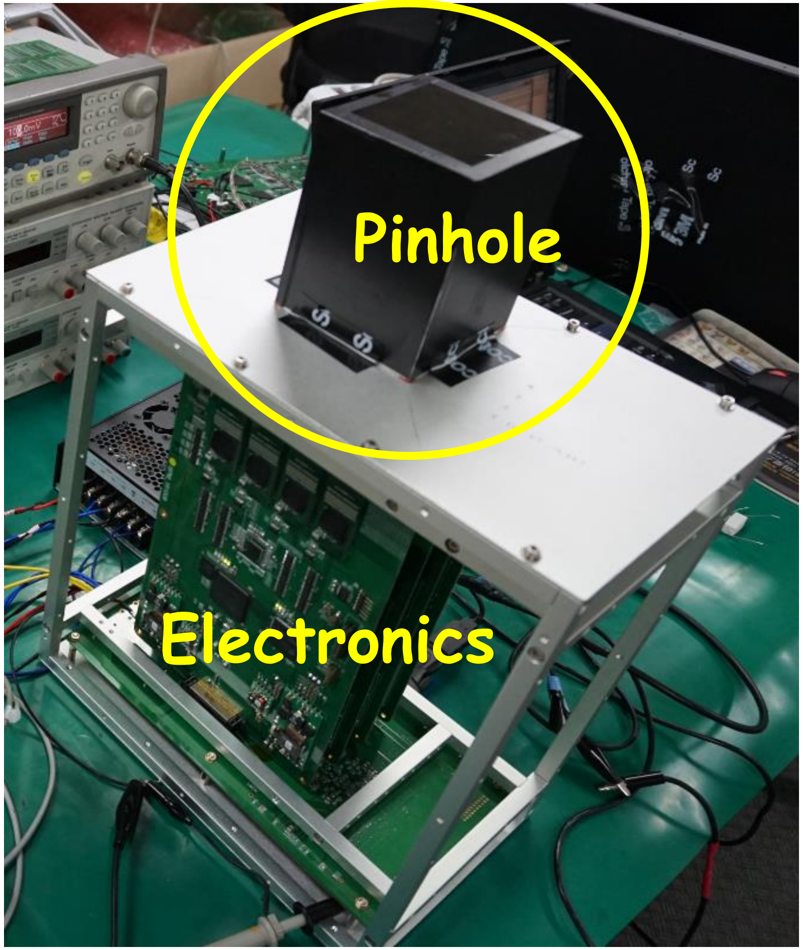
항복전압 균일
->
Multi channel test



1024-ch



1024-ch SiPM + 신호처리장치 + Pinhole



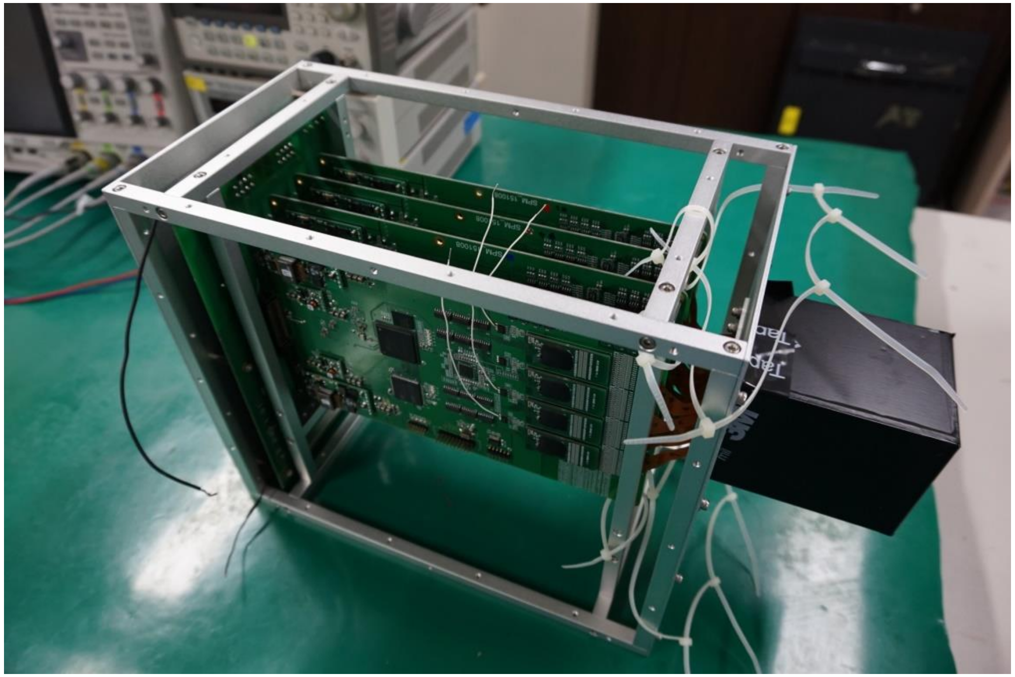
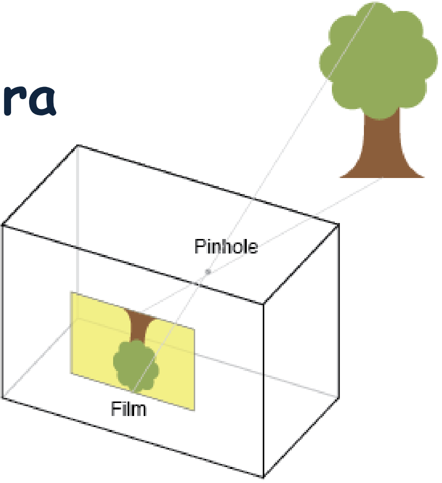
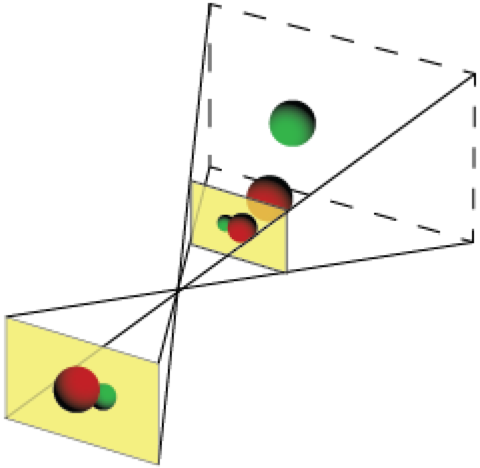
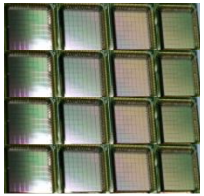


Image Test

Pinhole Camera







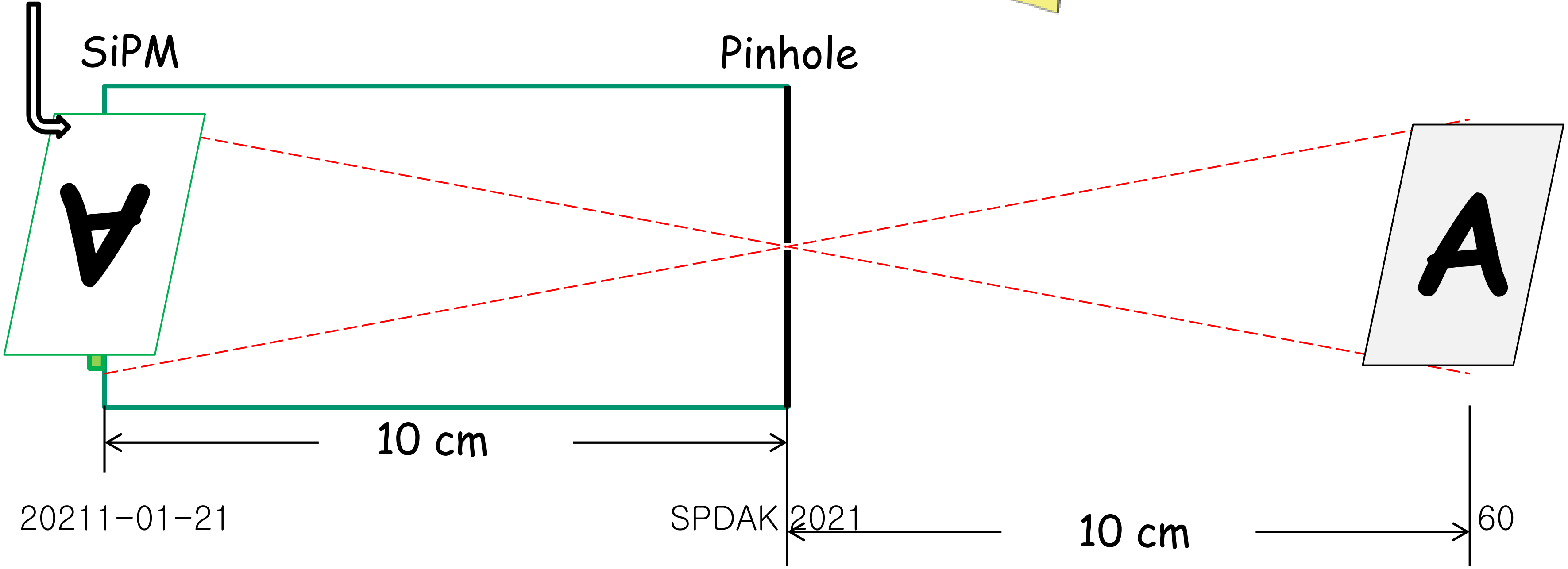
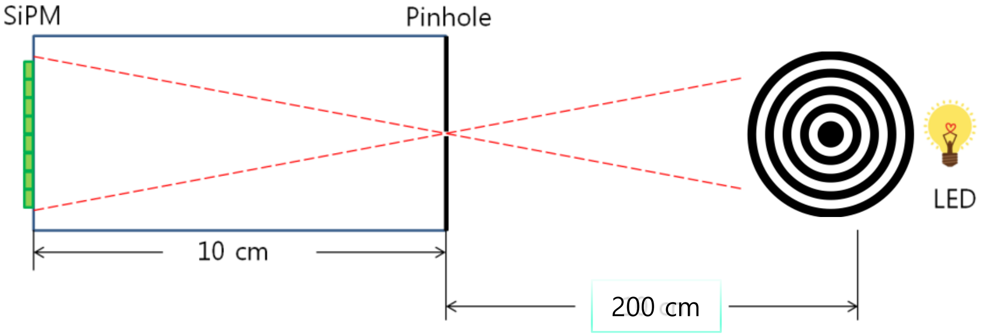
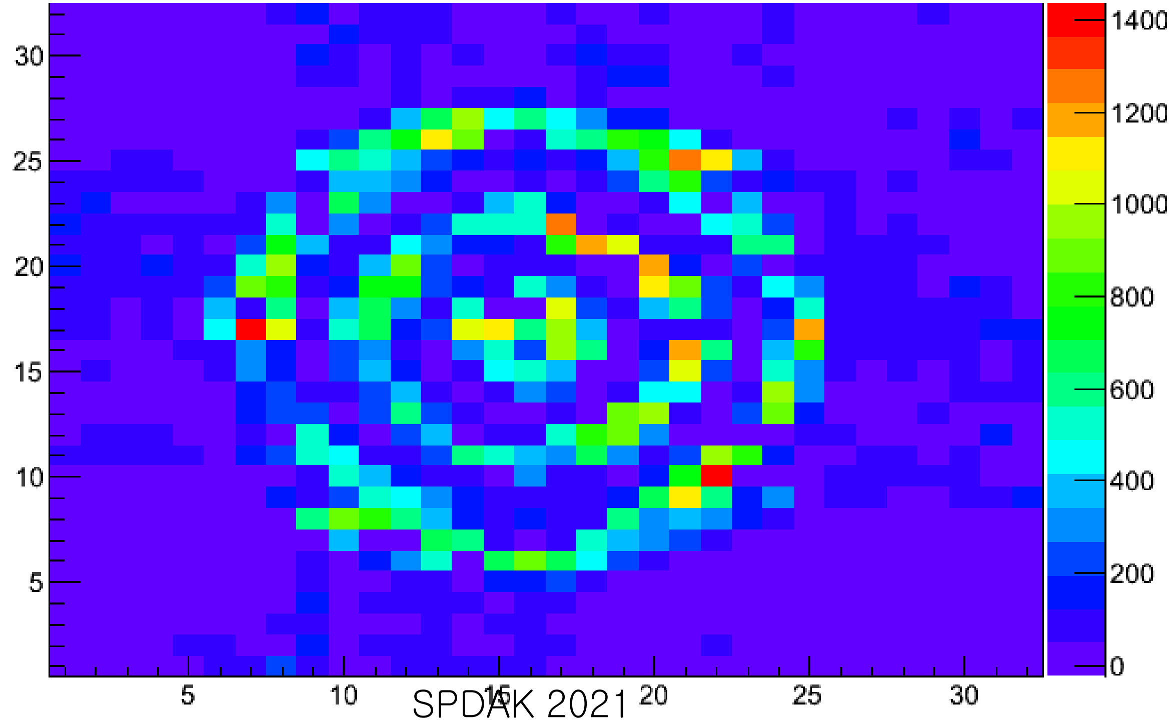


Image Test

Pinhole Camera



Absolutely Dark!
CCD or CMOS cameras can NOT get this image!



5. Summary

Summary

- Silicon is one of most popular material for radiation detection in the fields of Particle physics/Astro-particle physics
  - Charged particle detection
  - Photon detection

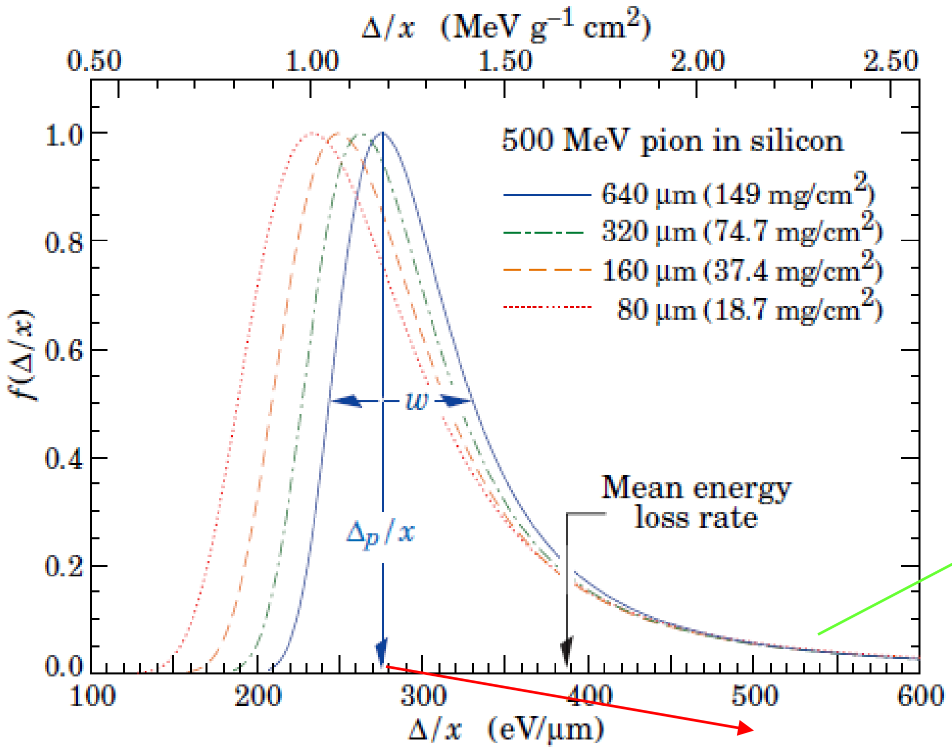
- During Lab, try to understand
  - C-V & I-V characteristics of silicon detectors
  - Responses (signals) of silicon detector to radiation sources or cosmic muons
    - Signal as a function of V_{bias} ?

Back-up slides

dE/dx is of random nature

From Review of Particle Physics

Probability density Function ~ Landau Function

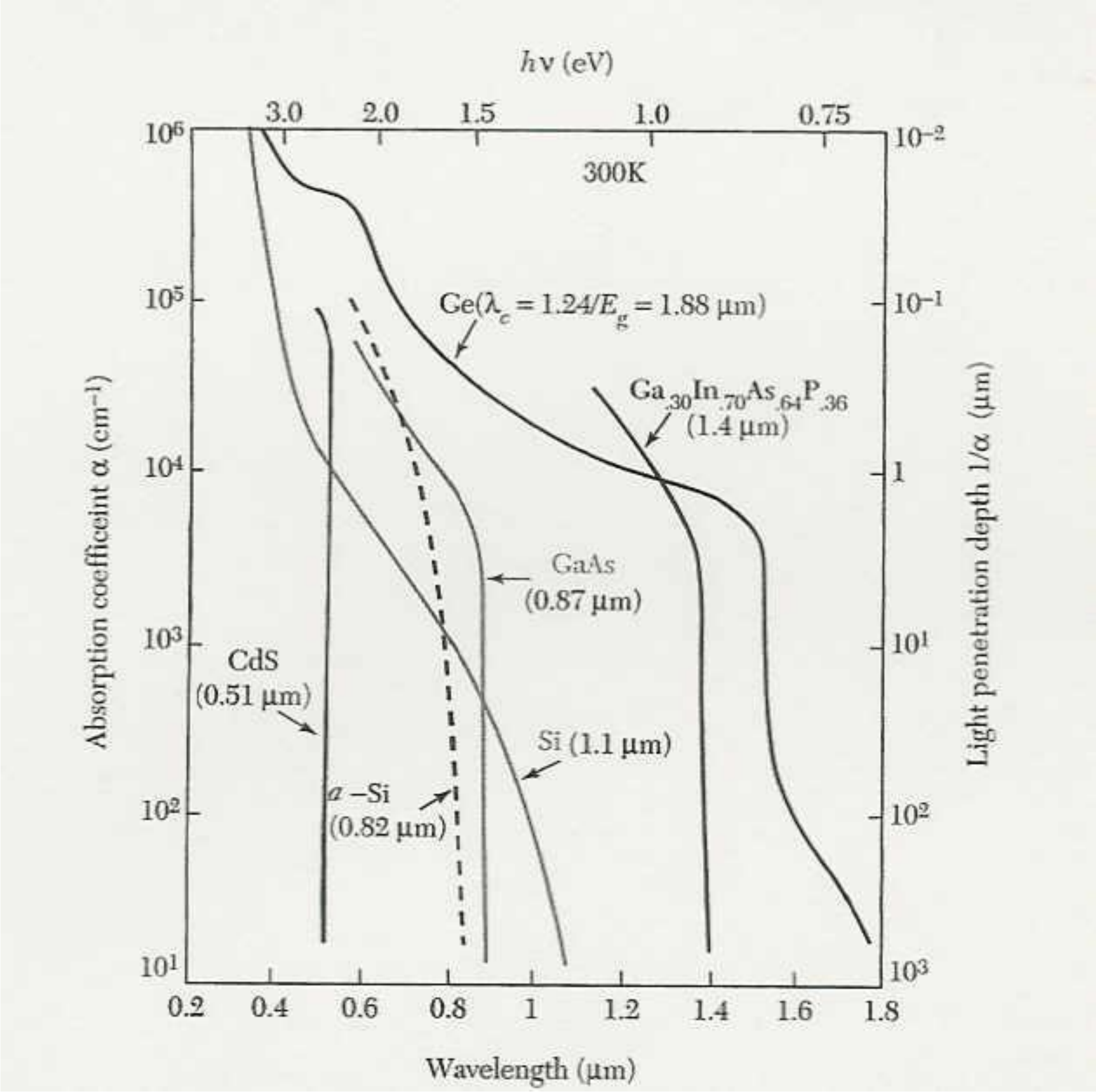


Due to δ rays: Knock-on electrons

Most probable dE/dx

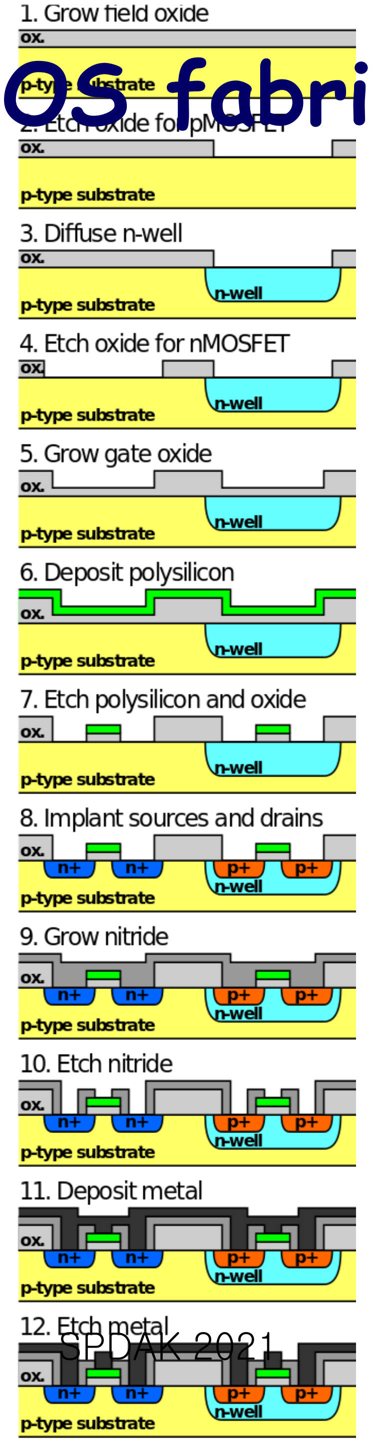
Landau function $$f_L(\lambda) = 1/\pi \int_0^\infty du \quad \exp[-u(\ln u + \lambda)] \sin \pi u$$

Absorption Coefficient



From 'Semiconductor Devices Physics and Technology Second Edition' by S.M. Sze

Example of CMOS fabrication process



From
https://en.wikipedia.org/wiki/CMOS