Recent development of finely segmented AC-LGAD sensors

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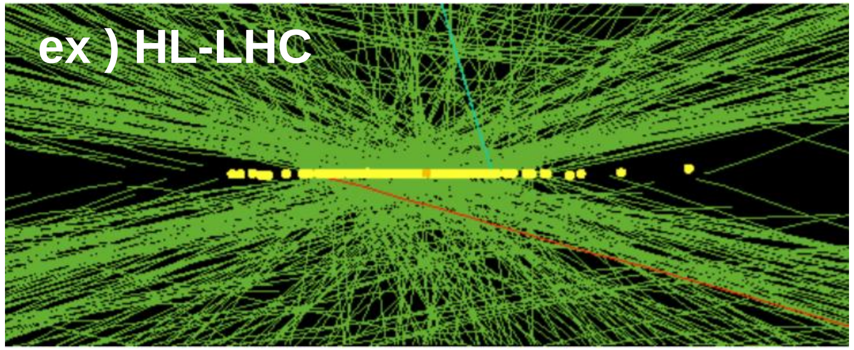
Motivation

Issues

Future hadron collider →→ High luminosity



HL-LHC : 200 interactions in an event
FCC : **1500** interactions in an event

At high luminosity collider, inner tracker has problems

1. Pile up
2. High occupancy
3. High radiation

(Pile up, High occupancy) } difficult tracking

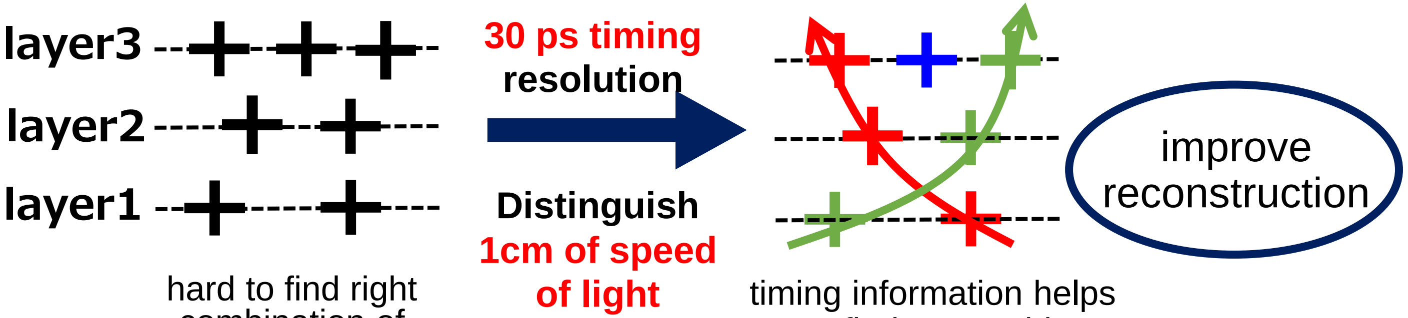
(High radiation) need radiation tolerance

solution

Tracking detector with **30ps timing resolution** is one solution.

multi-layer tracking detector

No timing resolution | with timing resolution



hard to find right combination of hits for tracks

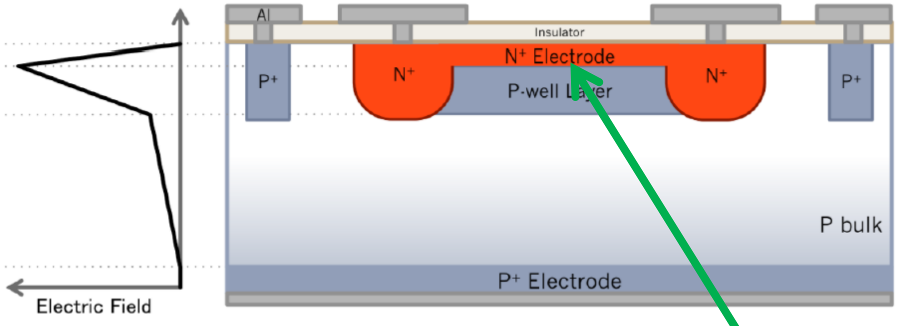
timing information helps to find correct hit combinations for tracks.

Inner tracker detector for future hadron collider must have…

1. High **spatial resolution** : ~o(10) um
2. High **timing resolution** : 30ps
3. High **radiation tolerance** : 1 x 10^{16} n_{eq}/cm^2

Low-Gain Avalanche Diode detector

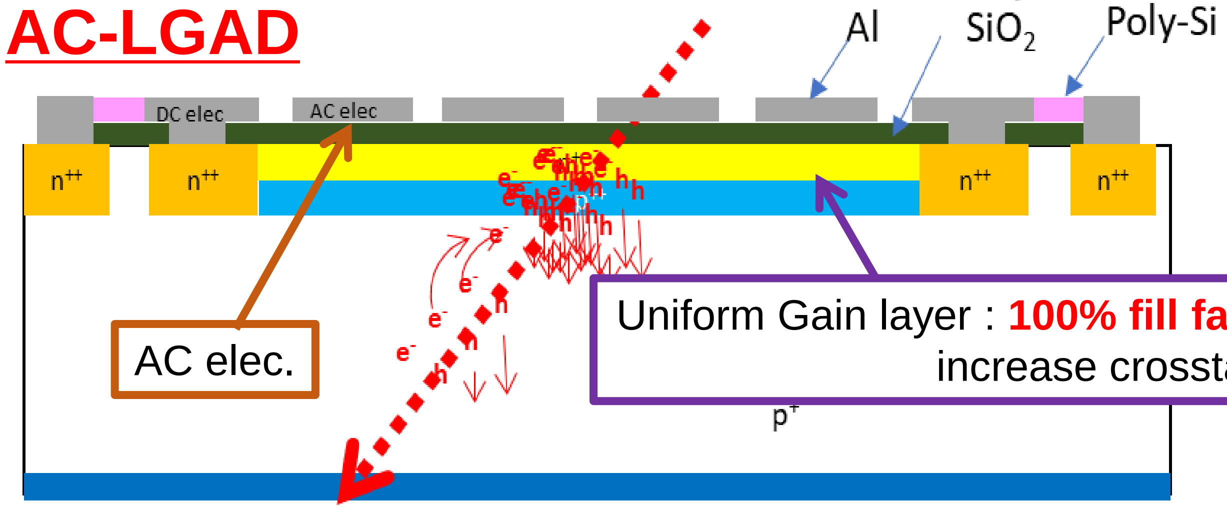
Normal LGAD detector



High electric field : **Avalanche**
→ **Precise timing resolution**

Make electrode pitch fine for **precise spatial resolution**

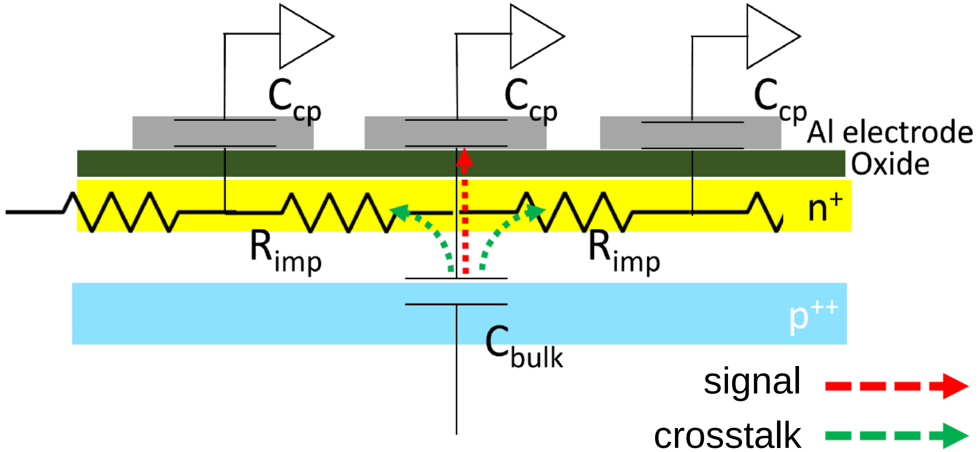
AC-LGAD



AC elec.

Uniform Gain layer : **100% fill factor**
increase crosstalk ?

AC-LGAD signal readout model



Signal size

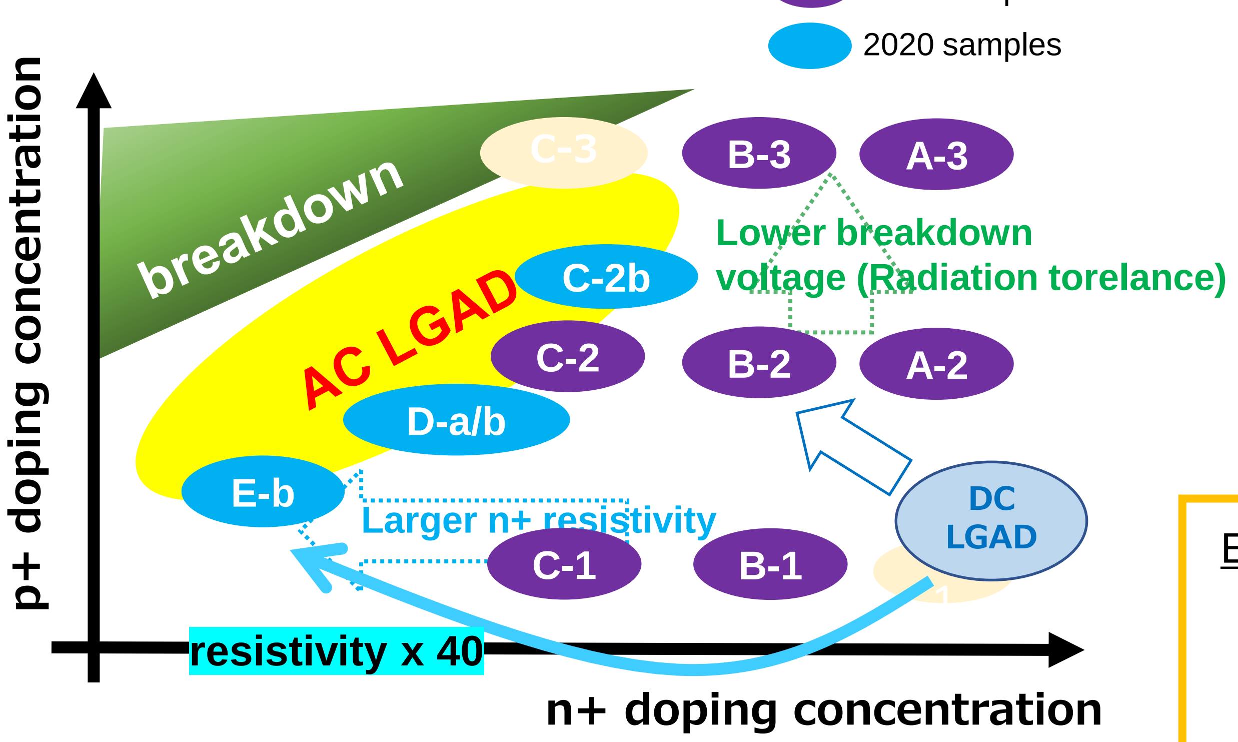
implant resistivity and coupling capacitance

charge readout as signal $Q = \frac{Z_{R_{imp}}}{Z_{R_{imp}} + Z_{C_{cp}}} Q_0$ charge created in bulk

Finer pitch electrode
: small signal and large crosstalk

Goal and samples

HPK several dose samples



Our samples

- ✓ electrode type x 3 : pad, strip, pixel
- ✓ dose type x 11 : A2~E-b

Sensor for hadron collider…

E-b type (resistivityx40, coupling capacitance x 1.5)

- SN : Signal efficiency 99.98% @ noise rate 10^{-4}
- Crosstalk : 82.68±0.06um
- Spatial resolution : 20.3±3.2um (binary readout, pitch/sqrt(12))
- Timing resolution : ~37ps (C2 pad type, FNAL testbeam)

Can use for collider experiment if low radiation condition !!
(outer tracker of hadron collider or e+e- collider)

Recent development

AC-LGAD

For inner tracker for future hadron collider

Topic1 : Timing resolution measurement at lab

Need to measure timing resolution in various condition
- HV dependency
- irradiated samples …

→ developed timing resolution measurement method at lab

Topic2 : new idea for pixel sensor

To make pixel sensor need signal size large → New type of LGAD for pixel sensor → TCAD simulation

Topic3 : Radiation tolerance

To check radiation tolerance → proton / gamma irradiation

Application for industry and medical care

Topic4 : measurement of polysilicon electrode LGAD sample

Can use LGAD sensor as photodetector ?

→ laser measurement of polysilicon electrode LGAD sample

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    - Can use LGAD sensor as photodetector ?
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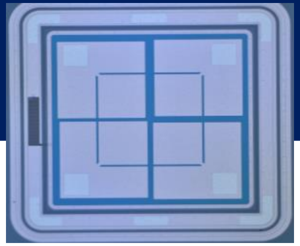
Timing resolution measurement

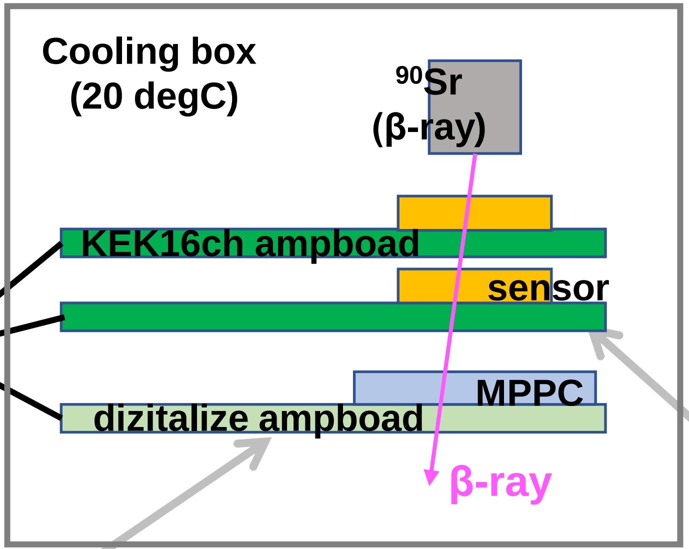
Pad sensor (500x500um)



Timing resolution : calculated time difference of two stacked sensors

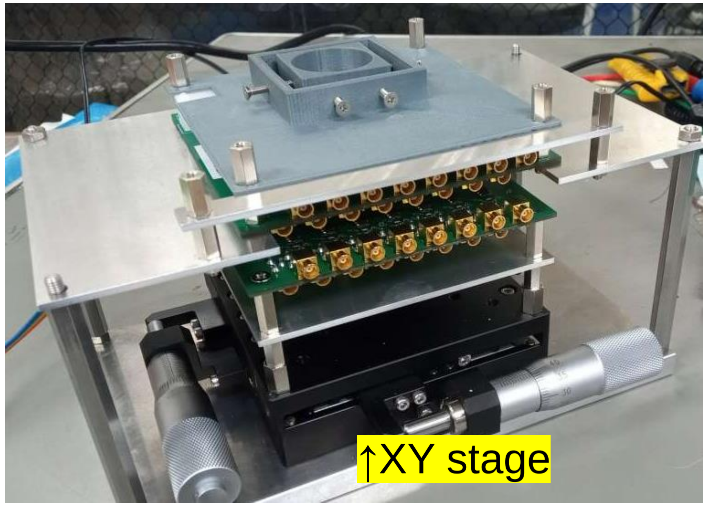
Setup

WaveRunner 8208HD
2GHz, 8ch, 10GS/s, 12bit



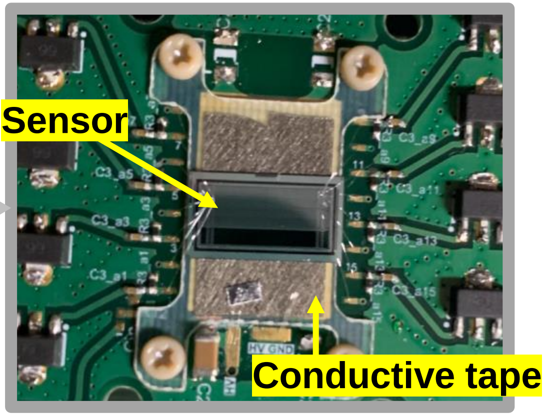
Trigger : Scintillator with MPPC

Modified ampboad
→ improve SN



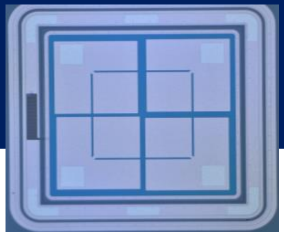
Designed and produced metal frame
→ get closer distance of two sensors
→ align position precisely

KEK 16ch ampboad



Timing resolution measurement

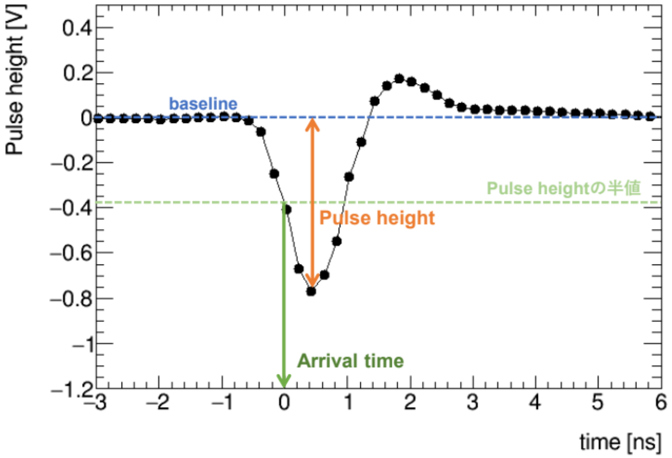
Pad sensor(500x500um)



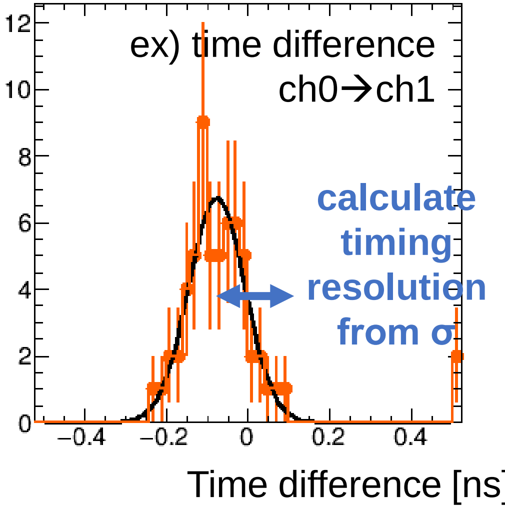
resistivity
E-b : high
C2 : low

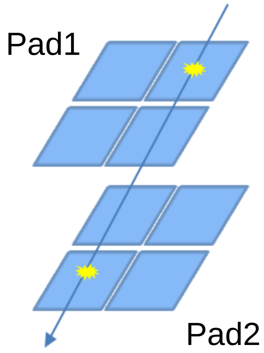
- Analysis

definition of arrival time
(pulse shape)



fit arrival time
difference by gaussian





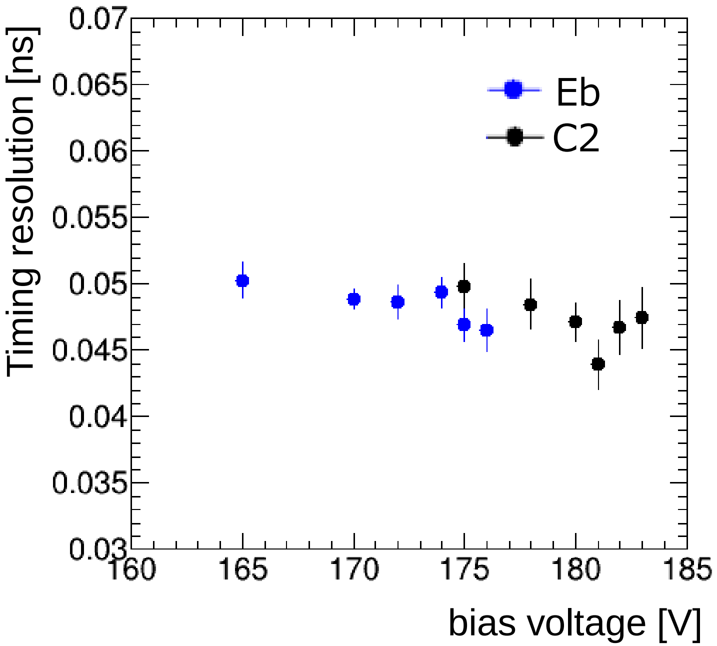
Timing resolution

$$\sigma_t = \sigma(T_1 - T_2)/\sqrt{2}$$

Evaluate time resolution for each
combination then combined
(cable route length difference considered)

- Result

Timing resolution with threshold
60mV(C2), 100mV(E-b)



Best timing resolution
(signal efficiency>99%)

C2 43.9±1.9ps (181V)

E-b 44.2±1.5ps (176V)

High timing resolution !!!

FNAL testbeam : ~37ps

✓ C2 and E-b have high timing resolution
✓ method of measurement timing resolution at lab.

Recent development

AC-LGAD

For inner tracker for future hadron collider

- Topic1 : Timing resolution measurement at lab

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  → developed timing resolution measurement method at lab

- Topic2 : new idea for pixel sensor

  To make pixel sensor need signal size large → New type of LGAD for pixel sensor → TCAD simulation

- Topic3 : Radiation tolerance

  To check radiation tolerance → proton / gamma irradiation

Application for industry and medical care

- Topic4 : measurement of polysilicon electrode LGAD sample

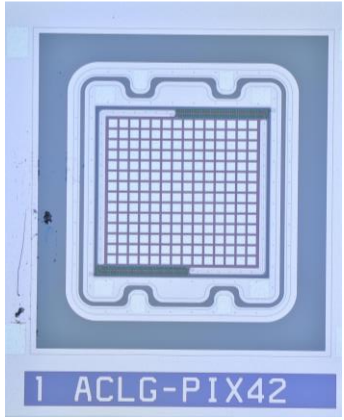
  Can use LGAD sensor as photodetector ?

  → laser measurement of polysilicon electrode LGAD sample

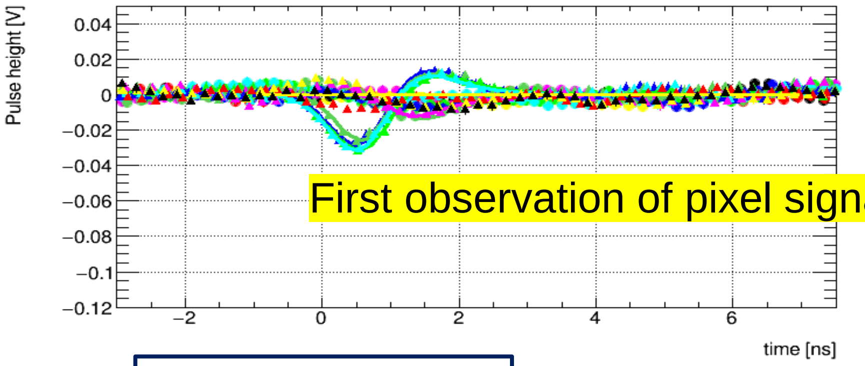
Pixel sensor challenge!

Toward fine pitch… → 50um pitch pixel sensor

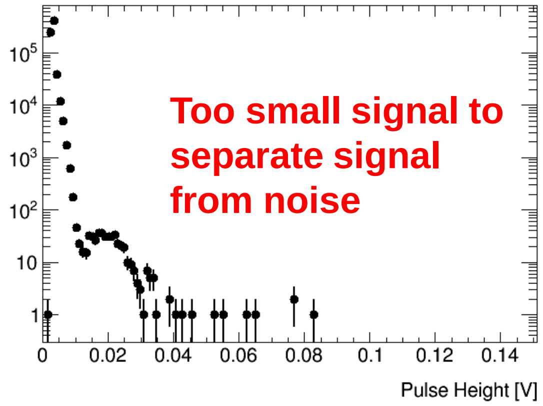
E-b type (high resistivity, high coupling capacitance)



Event display



Pulse height distribution



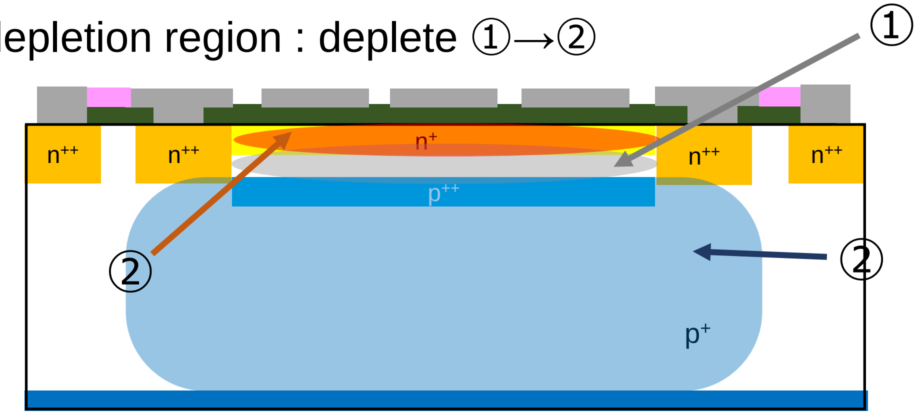
For pixelate…

need improvement to make signal larger

Idea for improvement

- ✓ To make larger Ccp
  → thinner oxide thickness (next sample)
- ✓ **To make larger n+ resistivity**
  → limitation of Foundry process

depletion region : deplete ①→②



depleted region is spread into n+ layer

$$W_n = \sqrt{\frac{2\epsilon}{eN_D}\frac{1}{1+\frac{N_D}{N_A}}V_D}$$

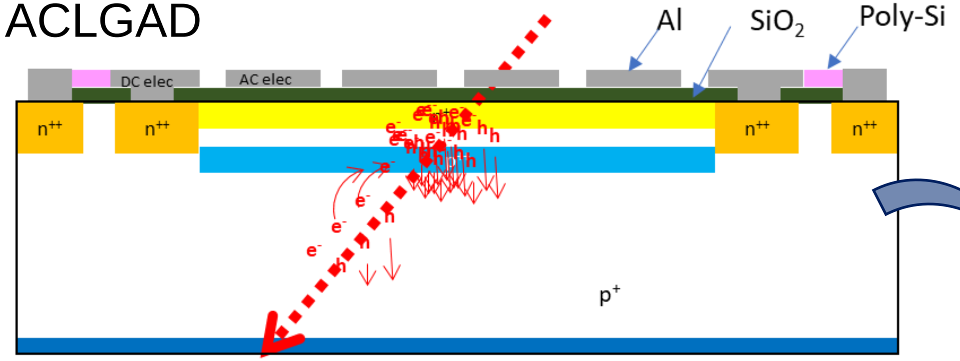
ε : permittivity
e : elementary charge
V_D : Diffusion potential
N_A : p+ doping concentration
N_D : n+ + doping concentration

reduce n+ doping concentration (=large n+ resistivity)
→ early breakdown due to reaching depletion layer to front surface.

Need some idea to make signal larger for pixel sensor…

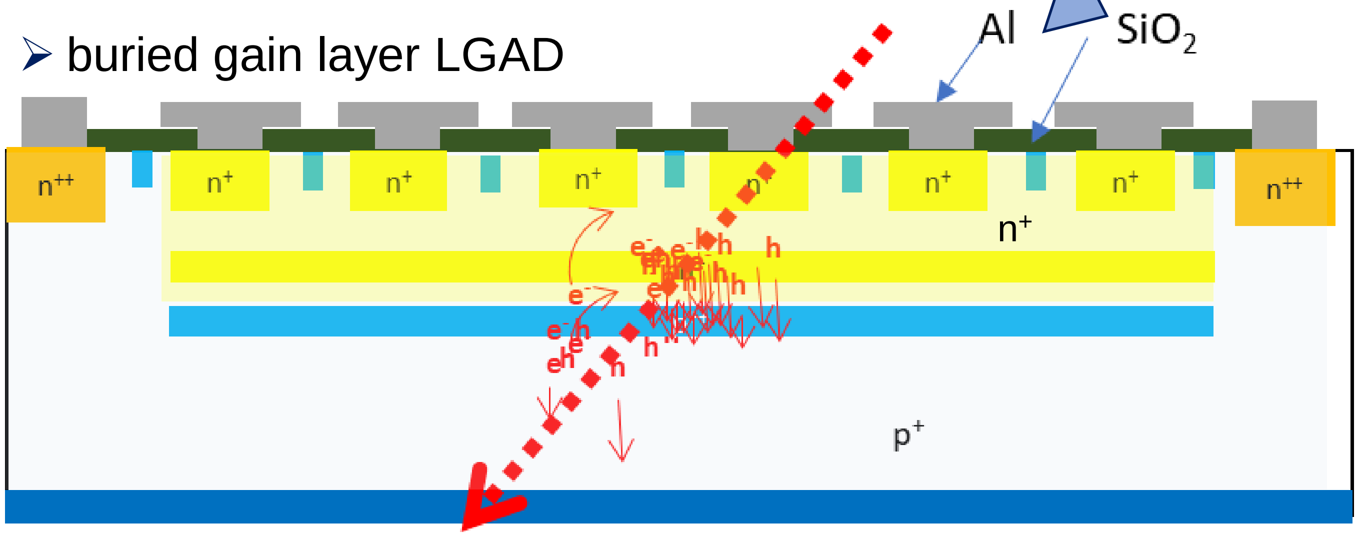
New idea and simulation model

- ACLGAD



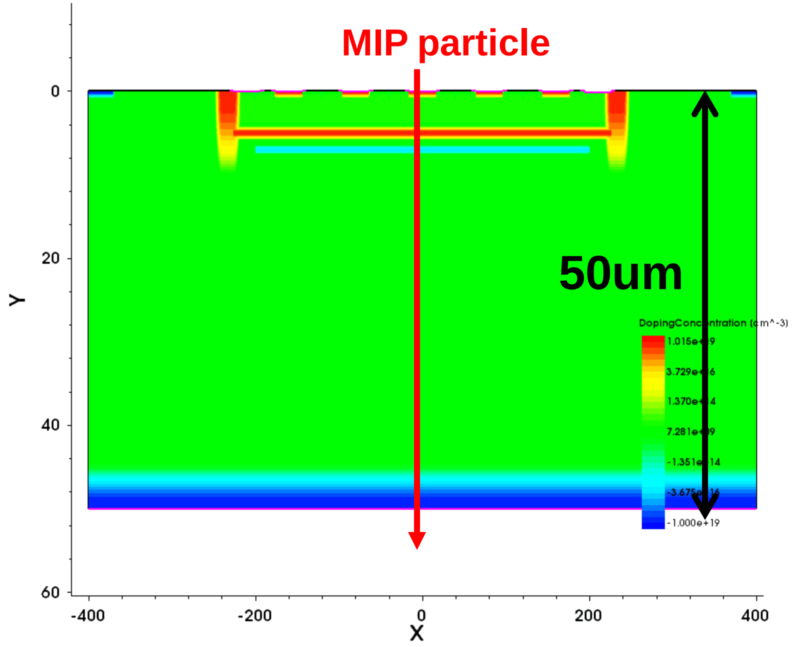
buried gain layer in bulk

- buried gain layer LGAD



buried gain layer LGAD : suppress early breakdown due to reach depletion layer to surface of the sensor ??

- TCAD model



MIP simulation

MIP injected center electrode of five

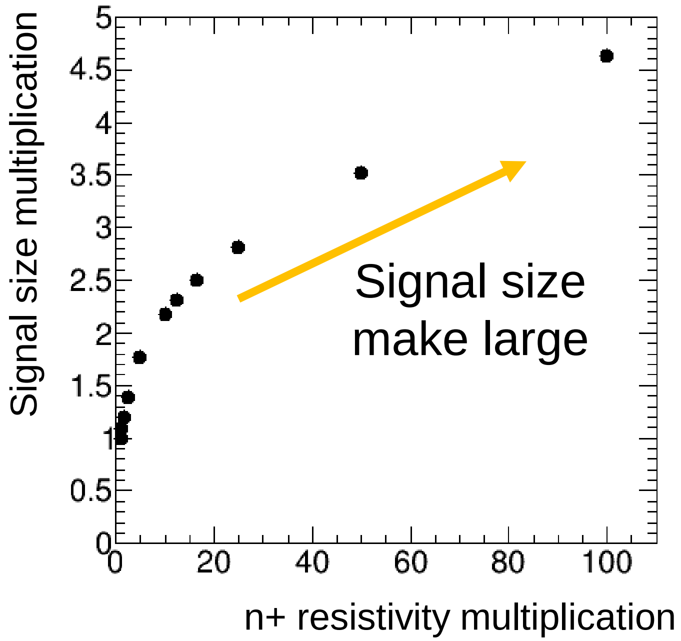
<u>Make sure</u>

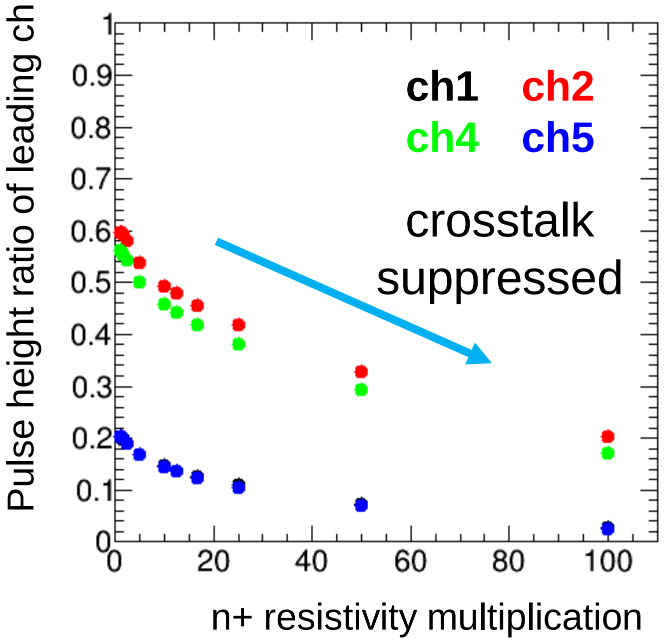
- ✓ if it works as LGAD sensor
- ✓ signal size change with n+ doping concentration ?

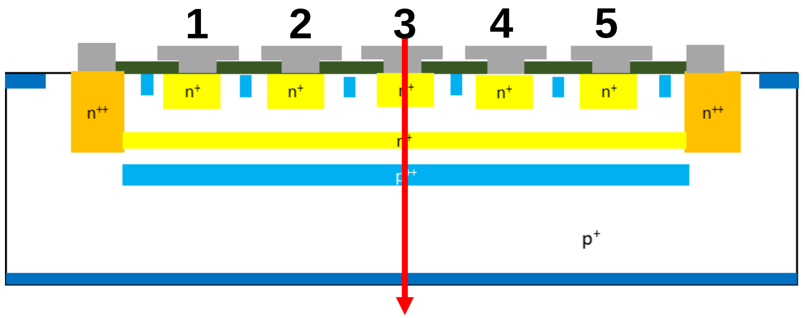
Signal size and crosstalk simulations

Signal size and crosstalk change with n+ resistivity ?

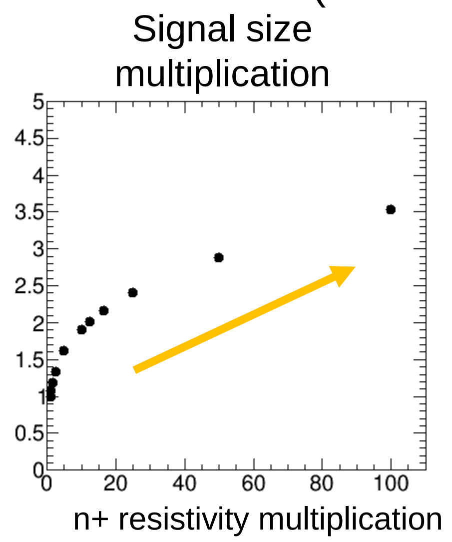
→ change n+ doping concentration (1e17 ㎝$^{-3}$～1e19 ㎝$^{-3}$)

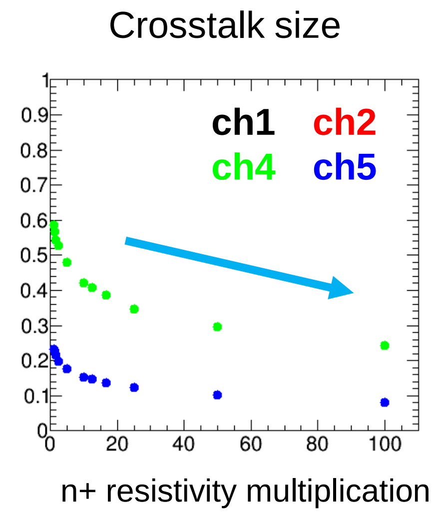






Simulated result of ACLGAD
(same condition)





n+ resistivity make large
→ signal size large, crosstalk suppressed

buried gain layer LGAD
- ✓ It works as LGAD sensor
- ✓ signal size and crosstalk feature is similar to AC-LGAD

Recent development

AC-LGAD

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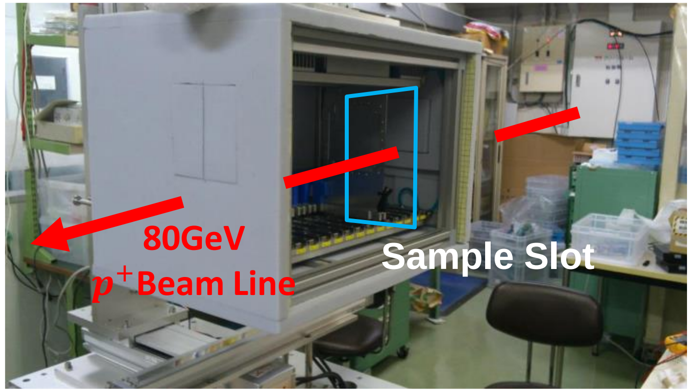
  - Can use LGAD sensor as photodetector ?
  - → laser measurement of polysilicon electrode LGAD sample

Proton irradiation sample

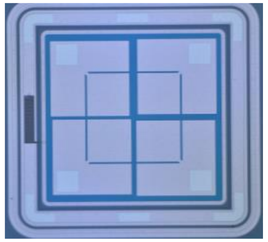
Radiation damage

- ✓ NIEL : Bulk damage
- ✓ TID : Surface damage
- ✓ acceptor removal (decrease p+ doping conc)

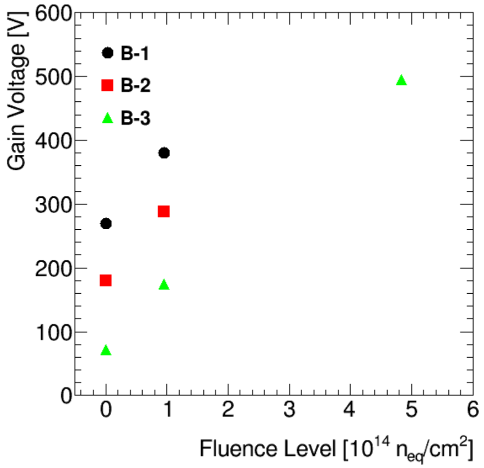
Irradiation at CYRIC (Tohoku University)



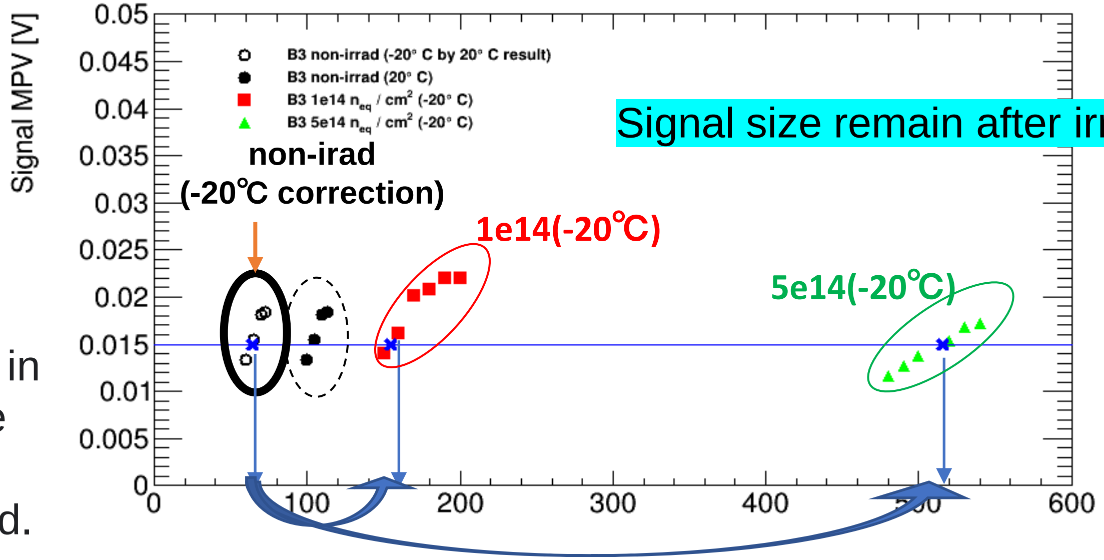
Pad sensor
(B-1, B-2, B-3)
less ↔ much
p+ doping concentration

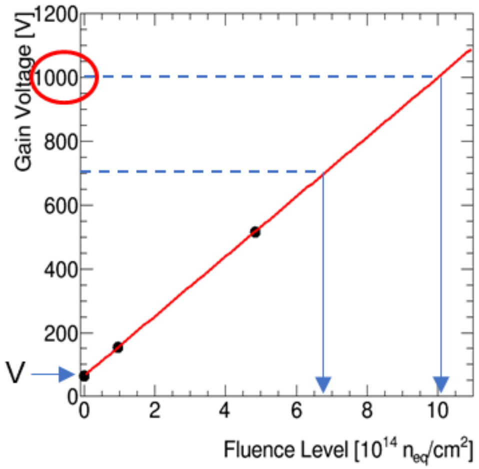


The amount of increase in gain voltage is the same even if the p+ doping concentration is changed.



Signal size vs bias voltage (B-3 type)





$$\frac{dV_G}{d\phi} = 93.57 \pm 0.03\ \mathrm{V}/\ 10^{14}\ \mathrm{n_{eq}/cm^2}$$

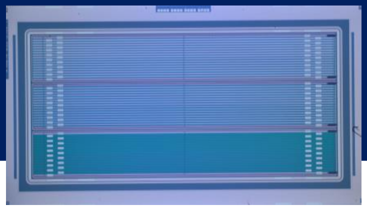
700 V → $0.67 \times 10^{15}\ \mathrm{n_{eq}/cm^2}$

$1e15\ \mathrm{n_{eq}/cm^2}$: need >1000V

need to find a way to reduce gain voltage increase by radiation damage (acceptor removal)

Gamma irradiation sample

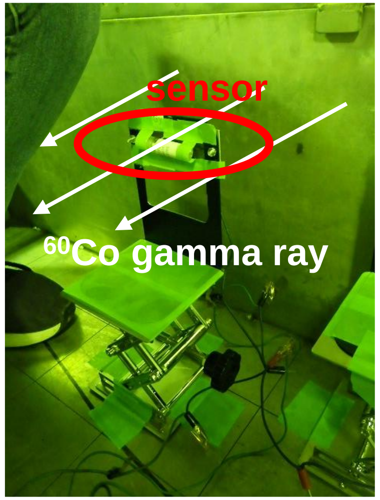
Strip sensor (E-b)



Radiation damage

- ✓ NIEL : Bulk damage
- ✓ TID : Surface damage
- ✓ acceptor removal (decrease p+ doping conc)

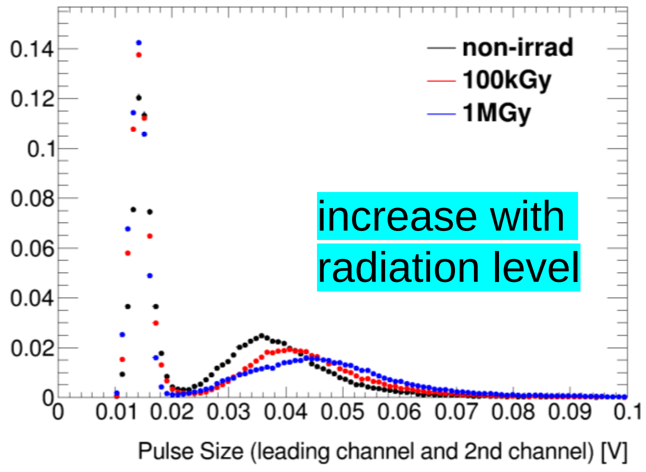
Irradiation at facility in Takasaki



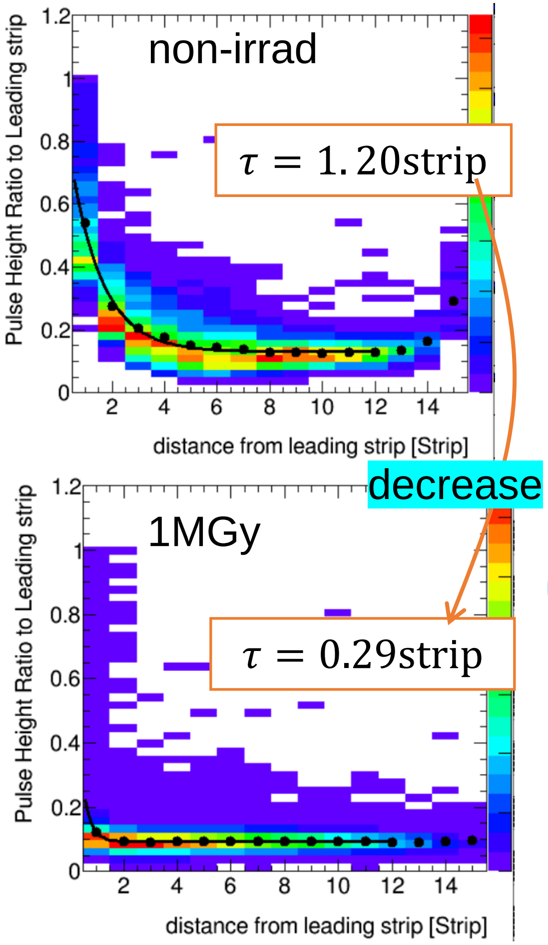
irradiated level

- ✓ 1MGy
- ✓ 100kGy

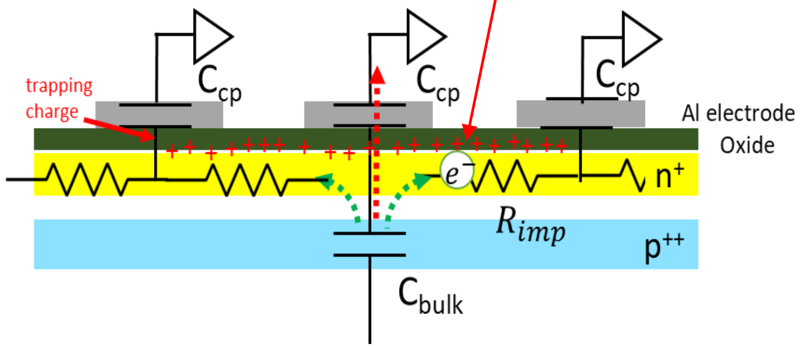
Signal size



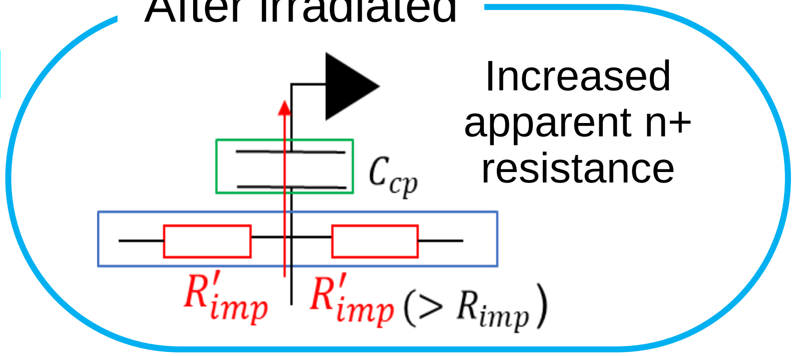
Crosstalk



TID damage
(positive trapping charge)



After irradiated



TID sample	Signal size : large Crosstalk : small

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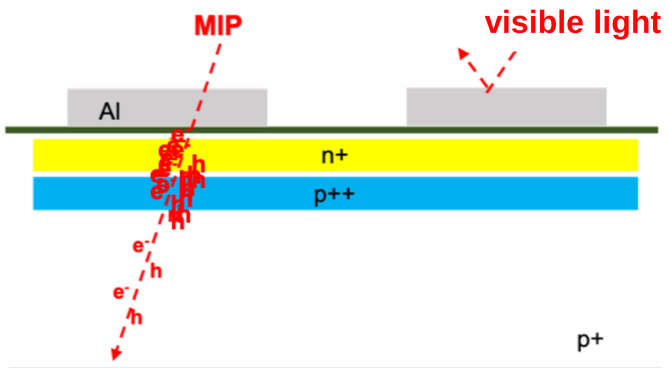
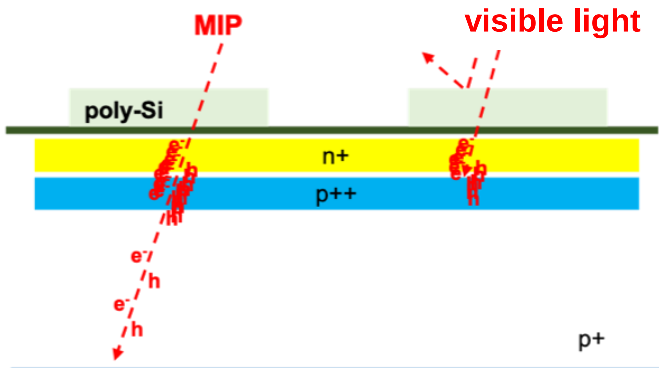
Can use LGAD sensor as photodetector ?

→ laser measurement of polysilicon electrode LGAD sample

Application to LGAD photodetector

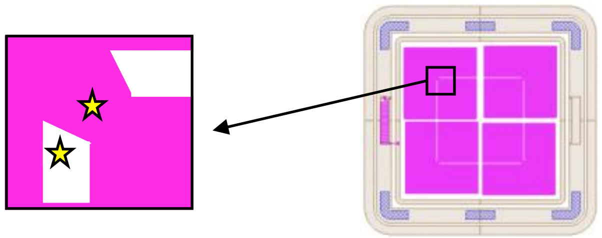
LGAD photodetector : Al electrode → polysilicon electrode

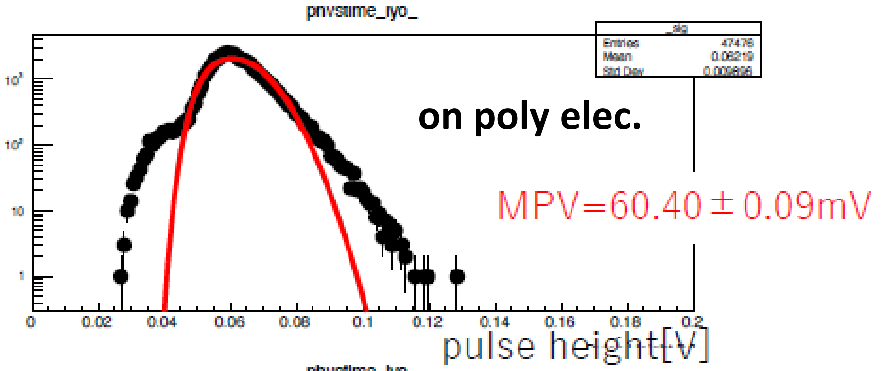


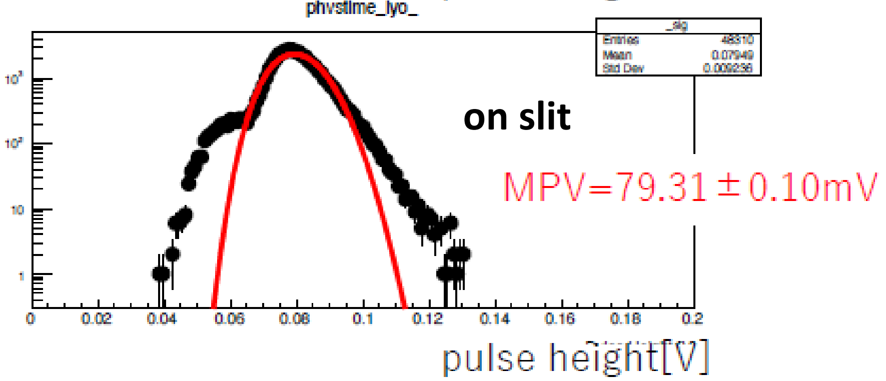


Transmittance measurement @ red laser

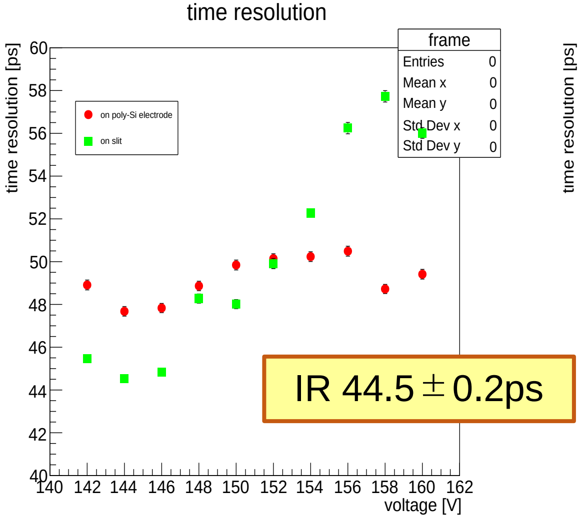
Transmittance
(red laser)
76.16 ± 0.15 %

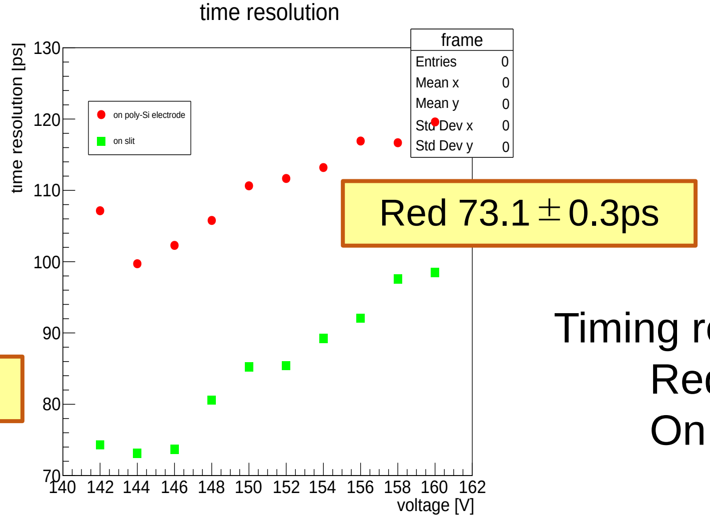






Timing resolution measurement



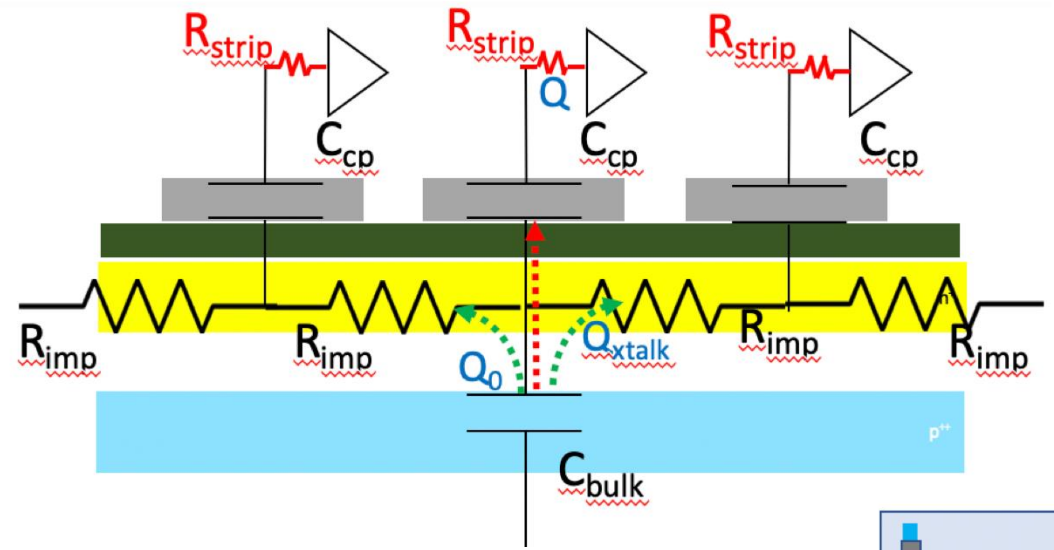


Timing resolution
Red > IR
On elec. > slit

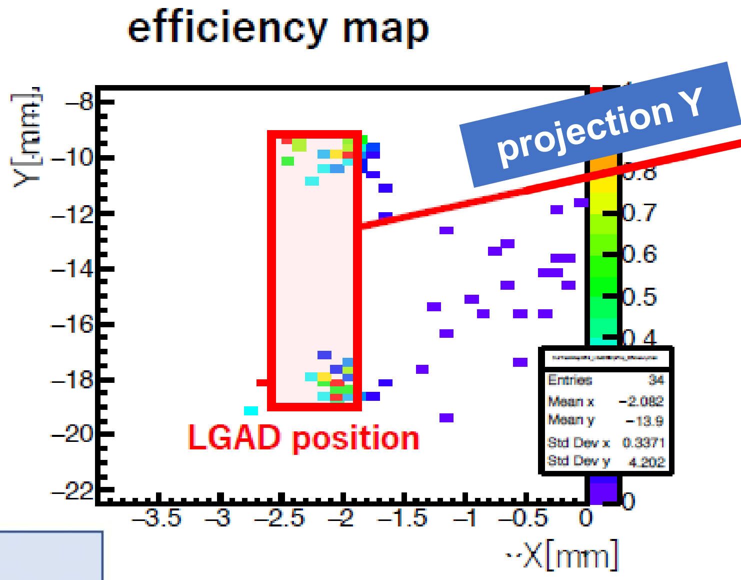
Signal attenuation by electrodes

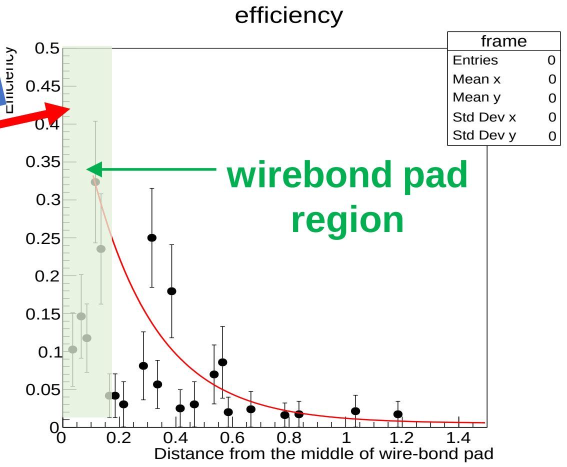
Strip sensor
(80um pitch)

Signal readout model (polysilicon elec. version)



Testbeam @ ELPH





$$y = Aexp\left(-\frac{x}{\tau}\right) + B$$

$$\mathbf{0.23 \pm 0.05\ mm}$$

Signal size : poly-Si elec. < Al elec.

- ✓ Signal cannot separate from noise.
- ✓ Reason : Large resistance of poly-Si ??

$$Q = \frac{Z_{R_{imp}}}{Z_{R_{imp}} + Z_{C_{cp}} + Z_{R_{strip}}} Q_0$$

Z_{Rstrip} increases in proportion to the distance from the wirebond pad

Signal was attenuated due to the resistance of poly-Si elec. itself
→ make sample with reduced polysilicon resistance

Conclusion

LGAD detector : precise timing and position resolution

Topic1 : Method of timing resolution measurement at lab

Timing resolution measurement
C2 43.9±1.9ps (181V)
E-b 44.2±1.5ps (176V)

Established method of timing resolution measurement at lab

Important step for developing

Topic2 : new idea for pixel sensor

buried gain layer LGAD

TCAD simulation → confirm to work as a sensor

produce prototype sample

Topic3 : Radiation tolerance

Proton irradiation

Signal size : not reduced
Gain voltage : large

→ **need improvement for hadron collider**

Gamma irradiate

Signal size : larger
crosstalk : smaller

Topic4 : measurement of polysilicon electrode LGAD sample

Measurement poly-Si elec. sample

Transmittance : 76.16±0.15 % (red laser)
Timing resolution : 44.5±0.2ps (IR laser)

Serious study for the application is performed