Radiation hardness of gallium doped low gain avalanche detectors

-JC101

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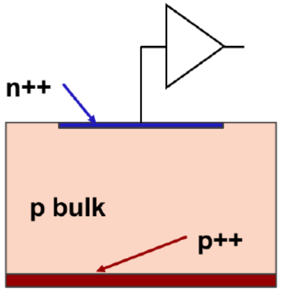
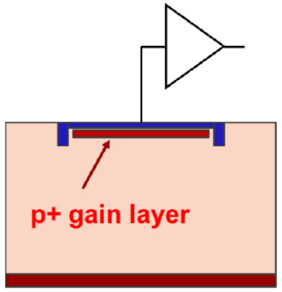
Introduction

- Low gain avalanche detectors (LGAD) exploit n++-p+-p-p++ structure to achieve high enough electric field near the junction.
- Advantage: Timing resolution can reach 26ps.
- Obstacle: Harsh radiation environments leads to decrease of gain.
  Reason: Acceptor removal in the multiplication layer.
- Improvement method: Gallium doped.
  Reason: gallium is more difficult to displace/deactivate from the lattice site than boron
- Result: The removal rate of gallium was found to be c$\approx 5 \cdot 10^{-16} cm^{-2}$, around two times smaller than for so far studied boron LGAD detectors. This feature could lead to significantly improved performance of thin Ga-LGADs at HL-LHC.



Traditional silicon diode

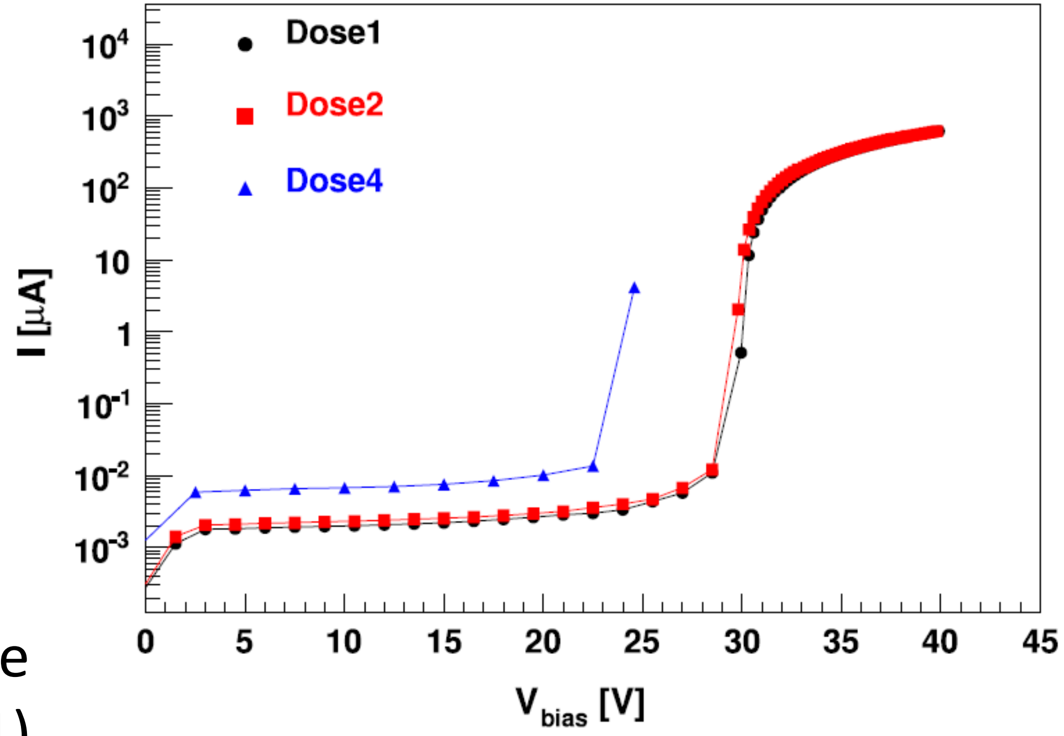


Low Gain Avalanche Diode

Performance before irradiation

- The process parameters for gallium implantation, unlike for boron, are less studied and known. As a result, the implantation profile of gallium differed from the planned one.

- This led to very high gain and consequently break down of the devices starting at around 30 V with a steep rise of the leakage current.



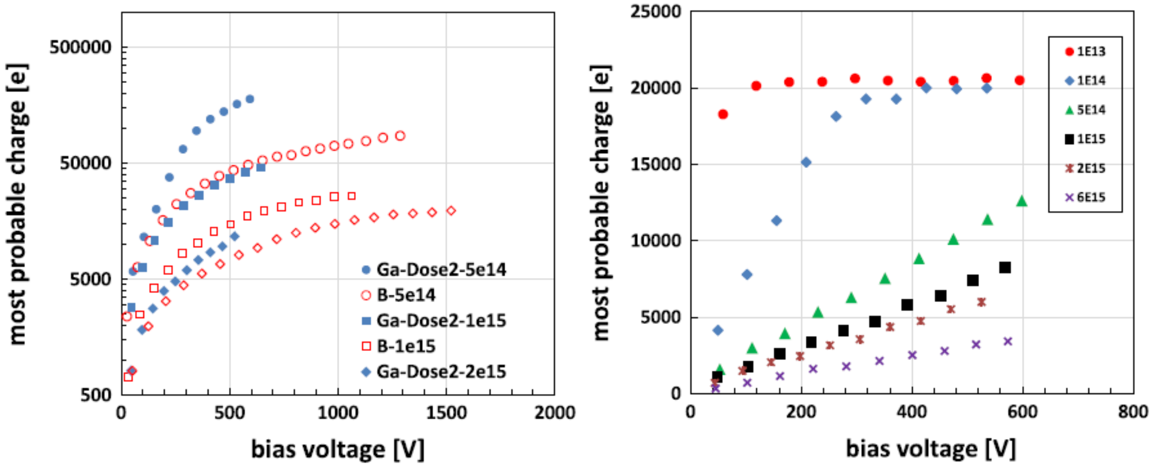
- A difference of around 25% between the highest (Dose4) and lowest dose (Dose1).

AMIT

- In point 3, **Performance Before Irradiation:** The process parameters for gallium implantation, unlike for boron, are less studied and known. As a result, the implantation profile of gallium differed from the planned one. why did they choose gallium if they didn't know the process parameter of gallium? Was this a testing for gallium?

Answer: The reason they choose gallium is that It was observed before that initial acceptor removal is smaller for gallium than for boron doped silicon after electron irradiation in solar cells. This was a test. Meanwhile, they don’t know the process parameter of implantation, but if the simulation is good, they can improve the process of implanation.

Charge collection

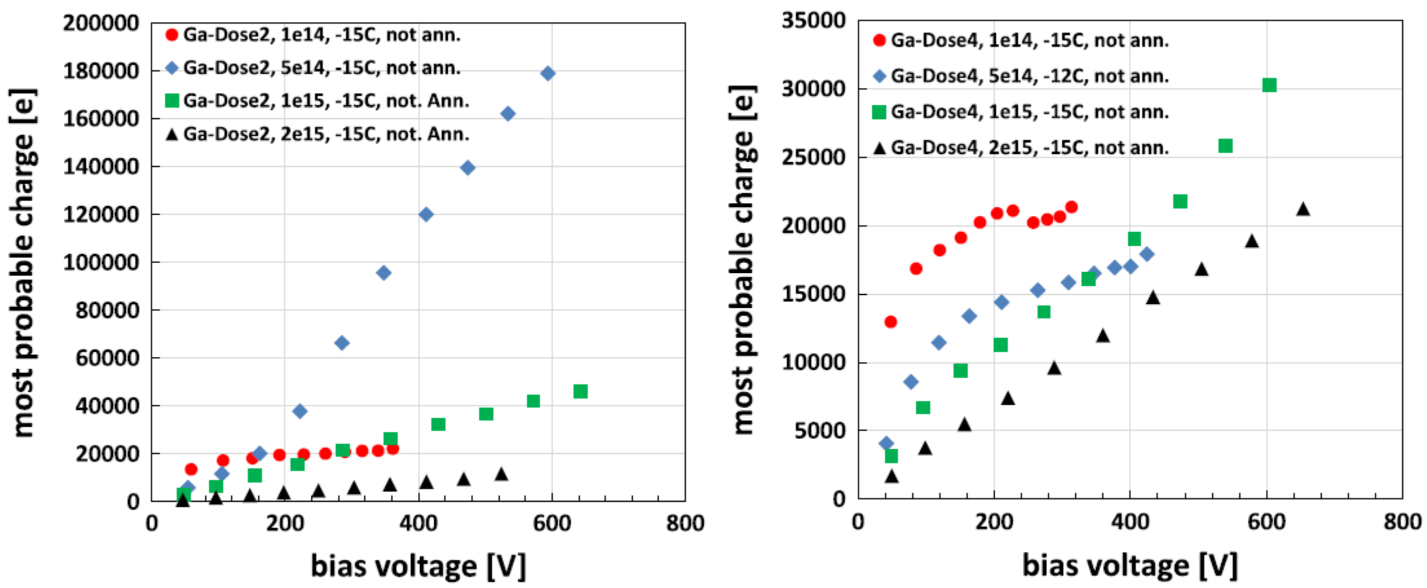


(a) (b)

a).Most probable charge for 90Sr electrons in Ga-LGADs (Dose2) irradiated to different fluences and comparison with similar B-LGADs.
b). The charge collection of control/no-gain samples at the investigated fluences.

Conclusion: It is clear that Ga-LGADs perform better in terms of charge collection when compared not only control/no-gain devices, but also better than similar B-LGADs.

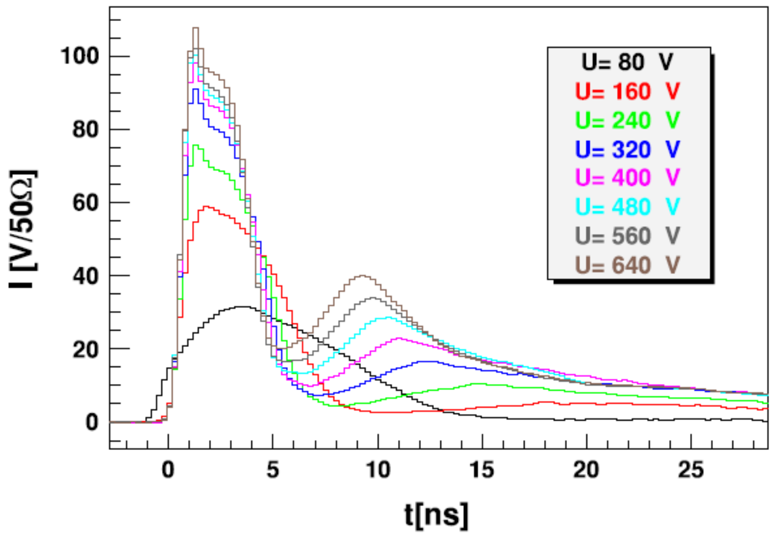
The gain of LGAD



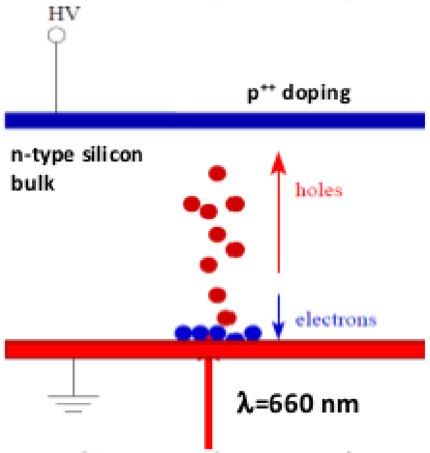
- Dependence of most probable charge for 90Sr electrons for (a) Dose2 devices and (b) Dose4 devices.
- The Dose4 becomes more efficient at the fluence of $2 \times 10^{15} cm^{-2}$.
- At intermediate fluences the gain for the medium gallium dose device (Dose2) is higher than for the highest gallium dose device (Dose4).
- The stronger the irradiation intensity, the lower the gain is not necessarily.

I-T: Front and Backside illumination

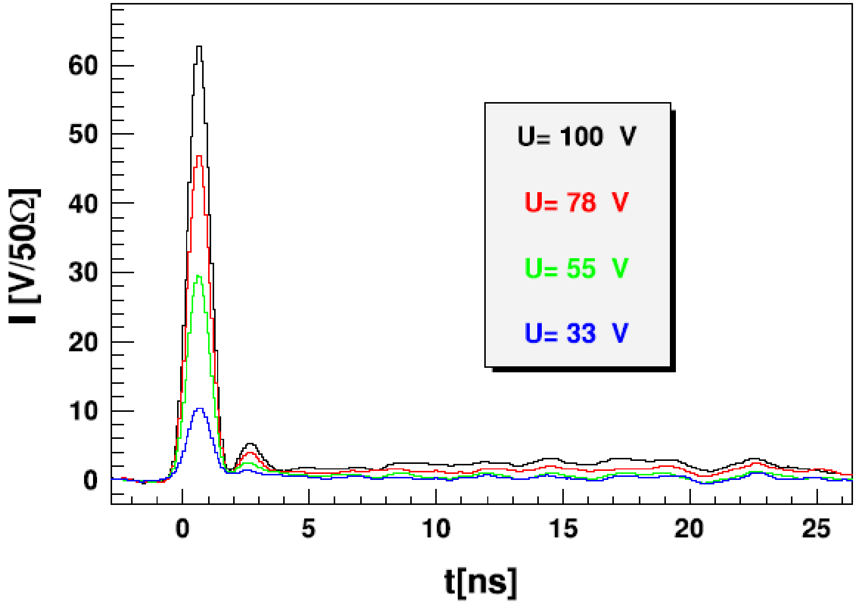
Backside

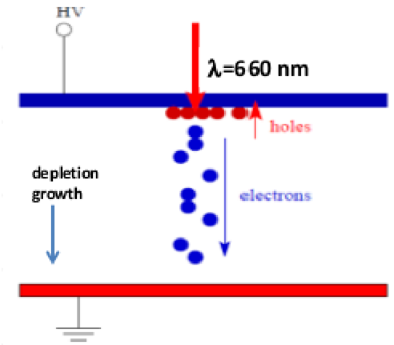


(a)

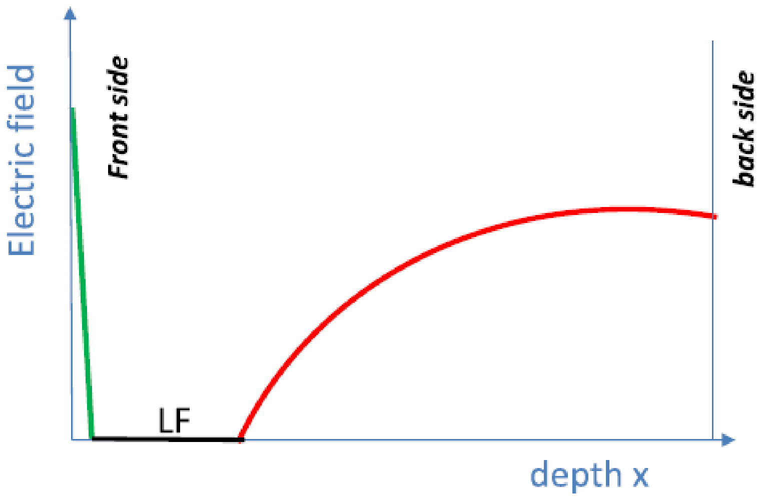


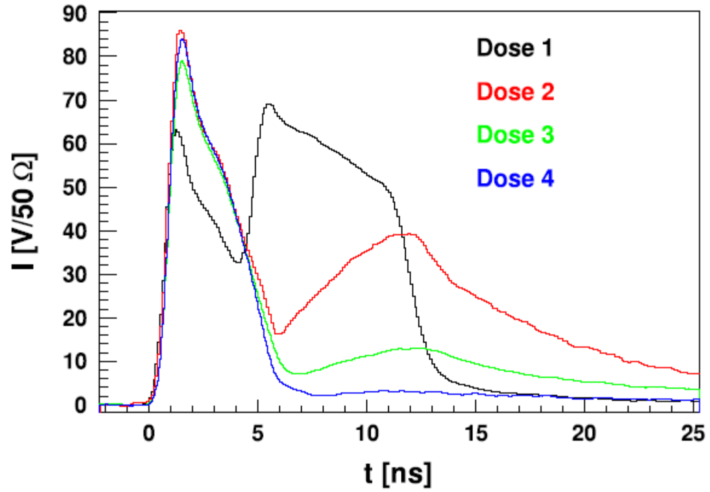
Front





Electric field model





- (left) Schematic shape of electric field model.(right) Comparison of induced currents for different devices irradiated.
- Conclusion: Electric field is almost identical (similar positive space charge) in the detector bulk for the devices with $LF \neq 0$ (Dose2,Dose3,Dose4).
- For Dose1, the electrons multiply immediately after the drift ends.
- For Dose2, LF has a wider width, so the second peak will delay about 10ns.

Yuzhen

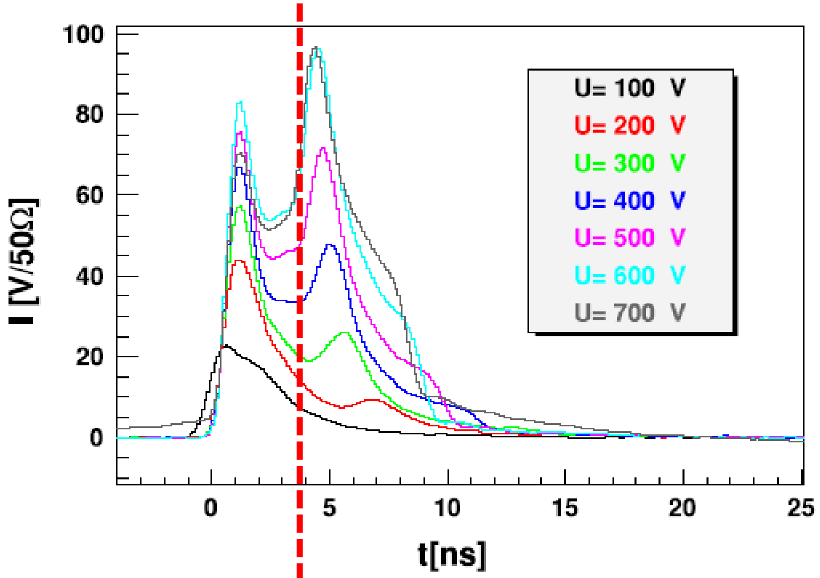
In Section 4 "4. Charge collection and gain of LGAD devices ", can you tell us about how to test the LGAD gain?

1.e.g. Blue line(U=400V):

$$\text{Gain} \approx \frac{\int_0^{20\,ns} I(t)dt}{\int_0^{3.9\,ns} I(t)dt}$$

2.Edge-TCT:

$$\text{Gain} = \frac{N_{charge-highest}}{N_{JTE}}$$



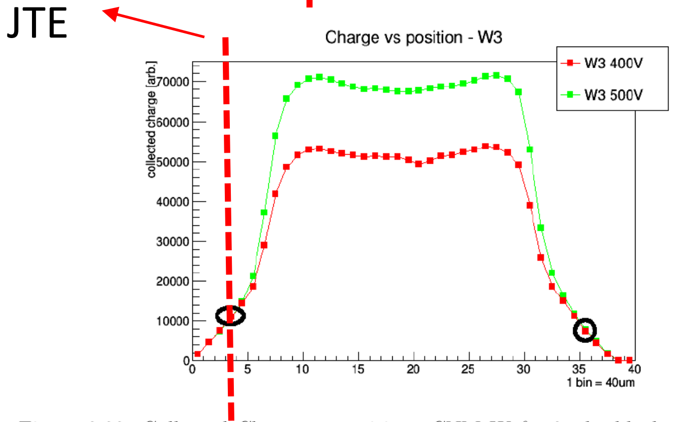
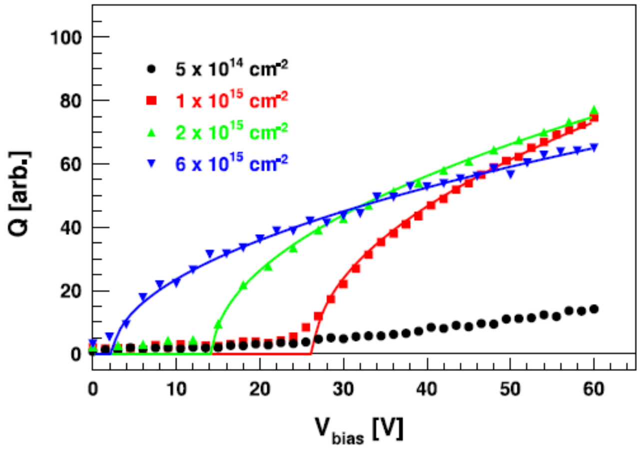
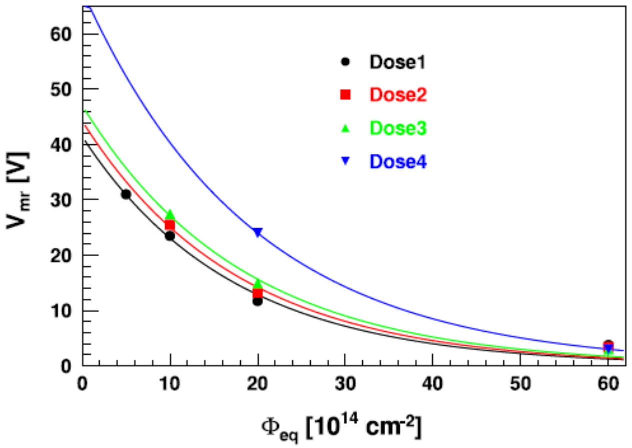


Figure 3.33: Collected Charge vs position. CNM Wafer 3, the black circles indicat the n-deep/JTE areas

Gallium removal





- (left)Dependence of induced charge on bias voltage for Dose2 devices at different fluences. The fit of $\sqrt{V_{bias} - V_m}$ to the data is also shown. (right) Dependence of Vmr on equivalent fluence for different devices.
- (left) As irradiation increases, depletion voltage V_{mr} decreases.

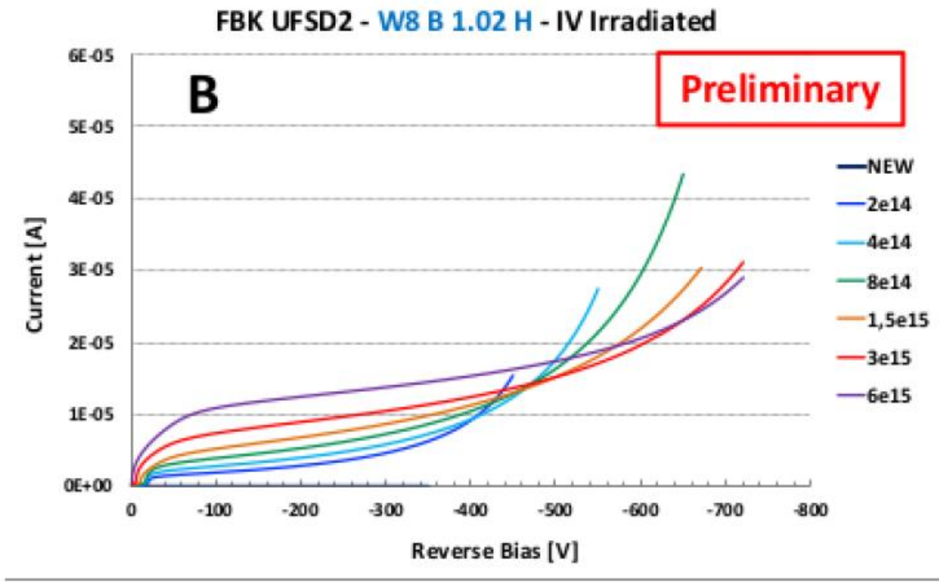
$$N_{Ga} = N_{Ga,0}\ \exp(-c\ \Phi_{eq}) \quad \Rightarrow \quad V_{mr} \approx V_{mr,0}\ \exp(-c\ \Phi_{eq}) \quad , \qquad (1)$$

- The obtained values of c=5.8, 5.6, 5.5 and 5.1 for Dose1,2,3,4 devices, which are around 1.5–2 times smaller than obtained for boron doped devices.

Xin

- At the end of the paper, it says: “the concentration of gallium in the multiplication layer was too high causing an early break down of devices before irradiations.”, could you explain more?

Answer: The break is when the bias voltage is greater than 30V, the leakage current is multiplied. Under normal circumstances, this value will be greater than 400V.

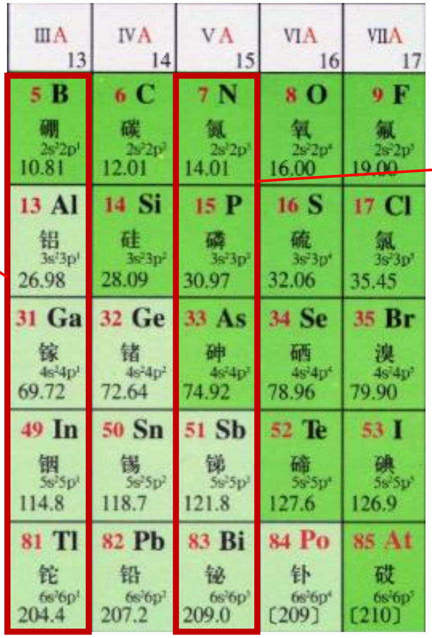


Gushan

- What is the basis for the the multiplication layer to select dopants?

Acceptor: get electronics

Multiplication layer: ⅢA



ⅢA 13	ⅣA 14	ⅤA 15	ⅥA 16	ⅦA 17
5 B 硼 $2s^22p^1$ 10.81	6 C 碳 $2s^22p^2$ 12.01	7 N 氮 $2s^22p^3$ 14.01	8 O 氧 $2s^22p^4$ 16.00	9 F 氟 $2s^22p^5$ 19.00
13 Al 铝 $3s^23p^1$ 26.98	14 Si 硅 $3s^23p^2$ 28.09	15 P 磷 $3s^23p^3$ 30.97	16 S 硫 $3s^23p^4$ 32.06	17 Cl 氯 $3s^23p^5$ 35.45
31 Ga 镓 $4s^24p^1$ 69.72	32 Ge 锗 $4s^24p^2$ 72.64	33 As 砷 $4s^24p^3$ 74.92	34 Se 硒 $4s^24p^4$ 78.96	35 Br 溴 $4s^24p^5$ 79.90
49 In 铟 $5s^25p^1$ 114.8	50 Sn 锡 $5s^25p^2$ 118.7	51 Sb 锑 $5s^25p^3$ 121.8	52 Te 碲 $5s^25p^4$ 127.6	53 I 碘 $5s^25p^5$ 126.9
81 Tl 铊 $6s^26p^1$ 204.4	82 Pb 铅 $6s^26p^2$ 207.2	83 Bi 铋 $6s^26p^3$ 209.0	84 Po 钋 $6s^26p^4$ 〔209〕	85 At 砹 $6s^26p^5$ 〔210〕

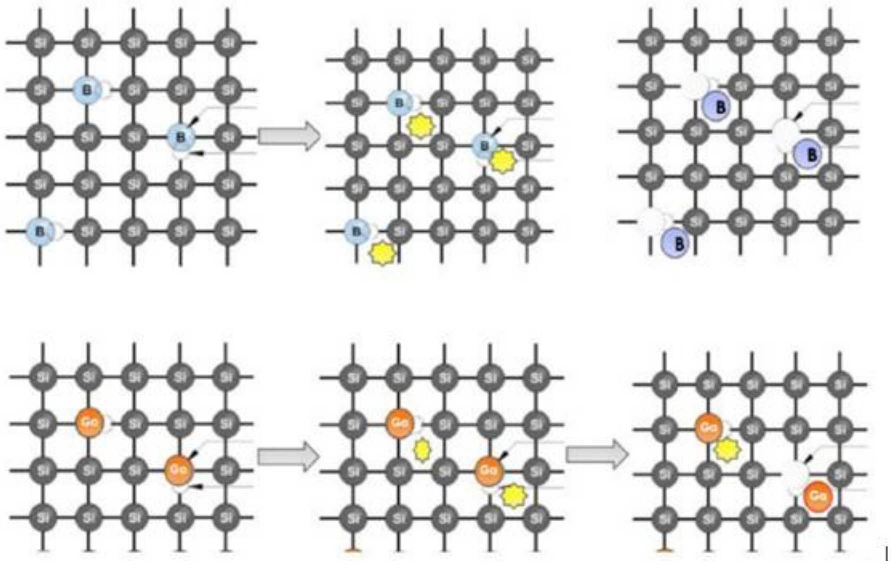
Donor: provide electronics

Doping: 1.Choose ⅢA as acceptor and form P-N junction with donor
2.ⅣA change the performance of semiconductors

Suyu

- Why could gallium mitigate the acceptor removal? Is there theoretical explanation?

Answer: Gallium is heavier than boron and thus more difficult to displace from the lattice site and could be less susceptible to reactions with vacancies in the Si lattice (V) and interstitial silicon atoms (I).



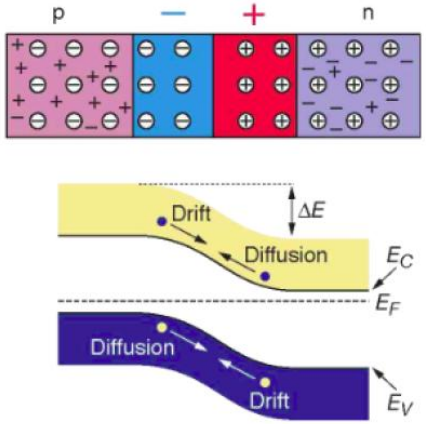
Ryuta

- Q. In page 1, the sentence,

"Gallium is heavier than boron and thus more difficult to displace from the lattice site ..."
explains the motivation of the introduction of Gallium, as well as one of possible interpretation of the obtained results.

Similarly, can we think about the indium (In) as the acceptor at the multiplication layer or not ?
What would be different between Gallium/Boron and Indium ?

Answer: Si-In was used as infrared detectors. I think the ΔE(Ec-Ev) is different between Si-Ga, Si-B, and Si-In. Others are not clear.



Thank you