Radiation effects in Low Gain Avalanche Detectors after hadron irradiations

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2019.2.22

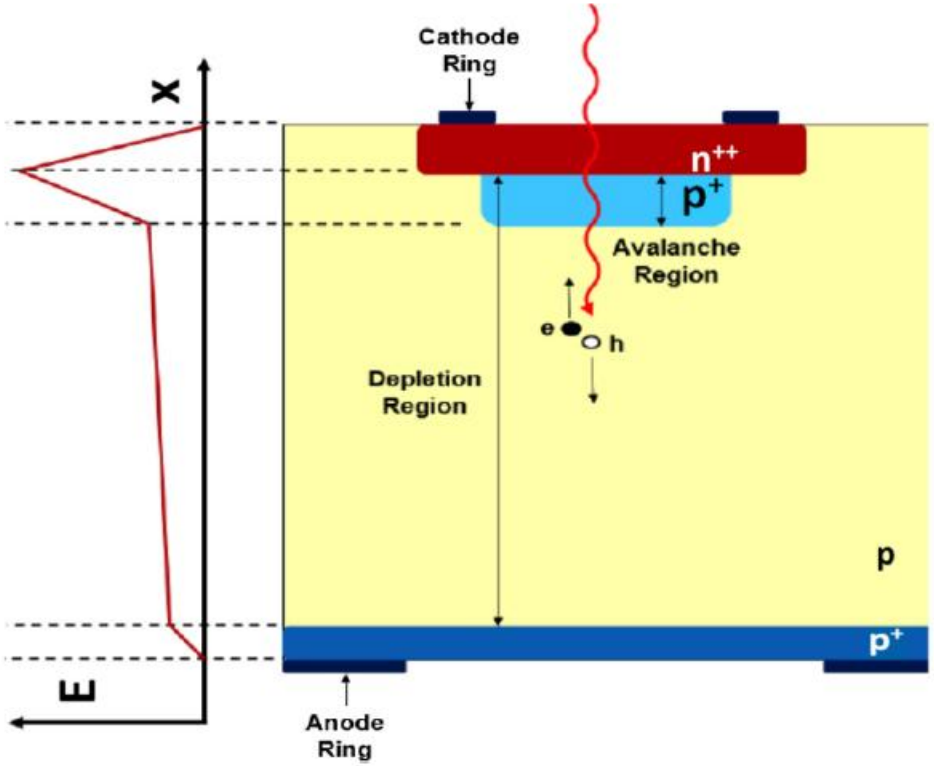
Introduction

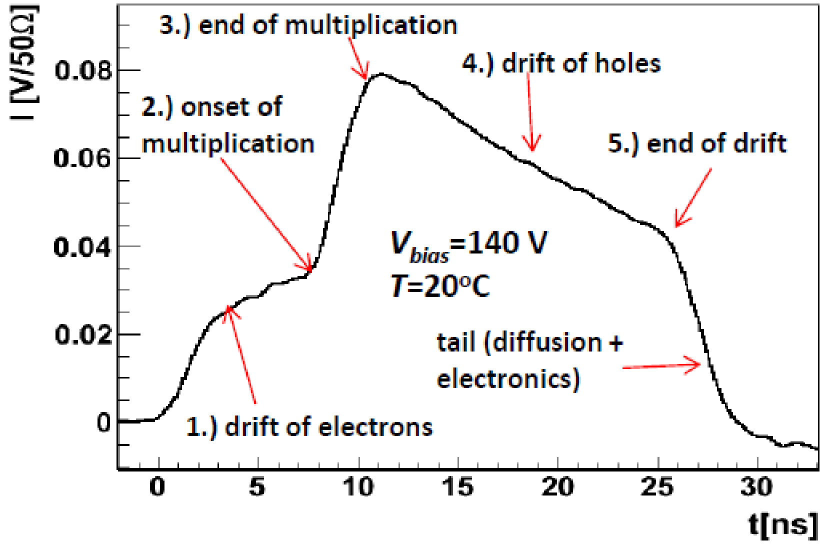
- Novel silicon detectors with charge gain were designed (Low Gain Avalanche Detectors - LGAD) to be used in particle physics experiments, medical and timing applications.

- In order to study radiation hardness of LGAD, which is one of key requirements for future high energy experiments, several sets of diodes were irradiated with reactor neutrons, 192MeV pions and 800MeV protons to the same equivalent fluences.

- It was found that the gain decreases with irradiation, which was attributed to effective acceptor removal in the multiplication layer

The structure of LGAD

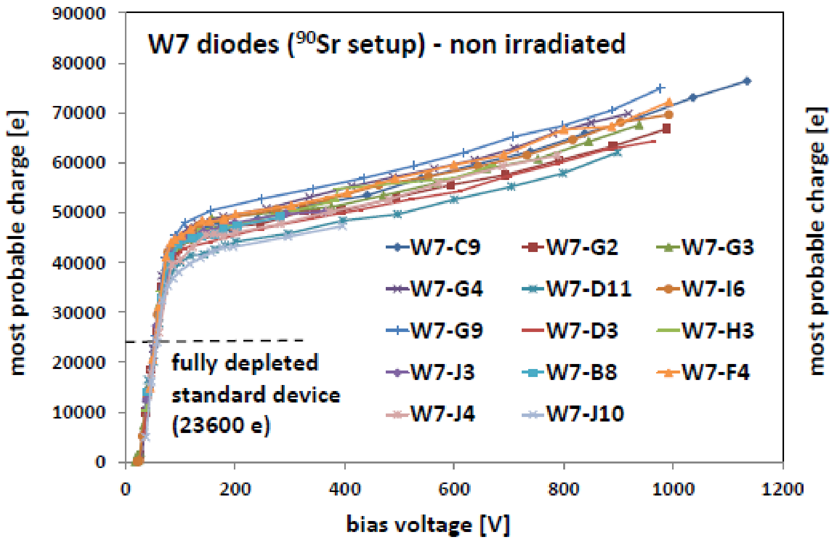




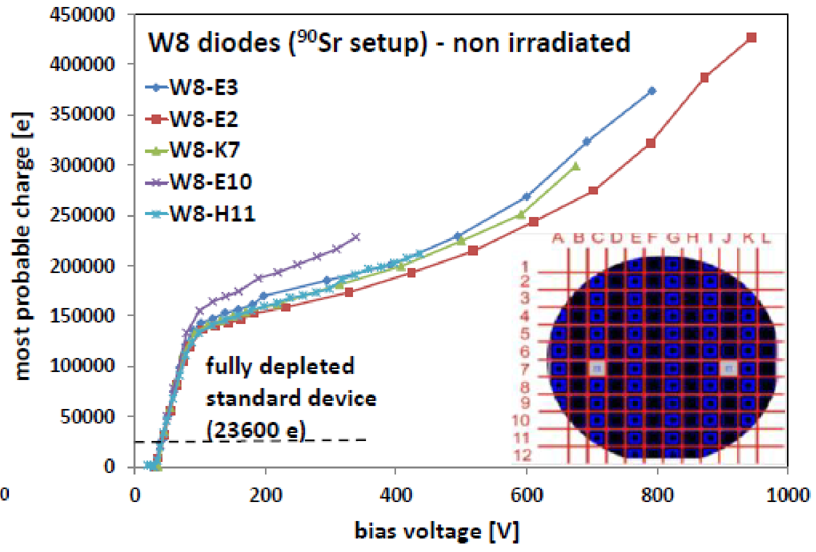
(b)

(b) Measured induced current in a W8 sample with indicated stages of signal evolution after illumination of the detector’s back side by a short pulse of red light.

Non-irradiated samples:1



(a)



(b)

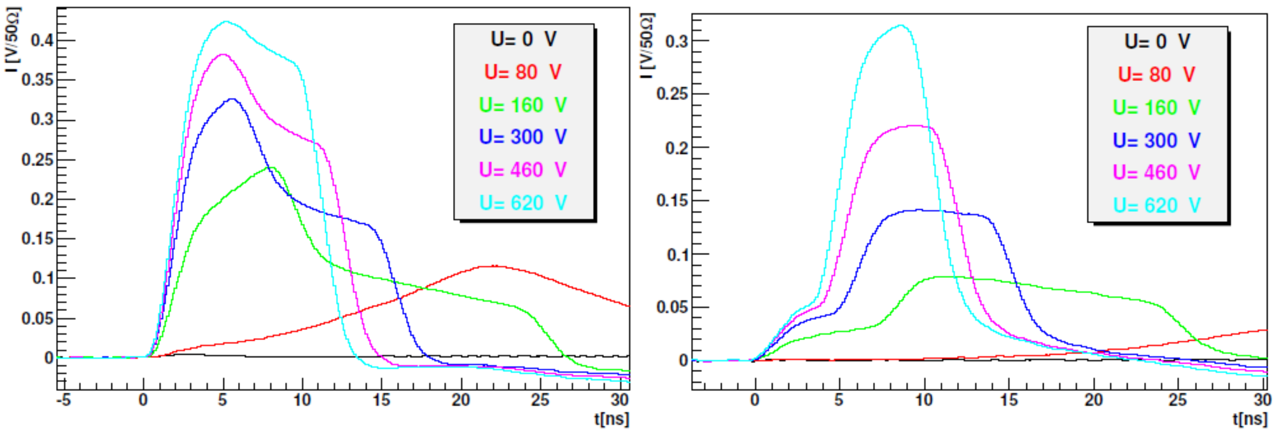
A very good gain homogeneity was observed across the wafer showing a good control of the doping profile (see figures 4a, b).

Suyu:

In Figure 4 (a) & (b), I think the turning point from steeply rising to moderately rising locates on 100V. Why do they say "300 V is required to raise the electric field"?

Answer: My thoughts: When the bias voltage is around 300V, the gain will not change much when the detector is affected by a small amount of irradiation or other factors. But if we use 100V, gain fluctuations will be very large.

Non-irradiated samples:2



(c) (d)

Figure 4. Dependence of measured charge on bias voltage at $T = -10°C$ for different non-irradiated samples across wafers (a) W7 and (b) W8. The dashed line denotes the charge in fully depleted standard detector of the same thickness. The inset in (b) shows the location of the sensors in the wafers. Induced currents (TCT) in the detectors from (c) W7 and (d) W8 after detector back illumination (electron injection).

The TCT signals after back side illumination (electron injection) are shown in figures 4c,d. A clear difference between LGAD from W7 and W8 can be observed in the gain.

Boron doping is from process simulations.

W7 → 1.6 × 10^{13}cm^{-2} gain = 3

W8 → 2.0 × 10^{13} cm^{-2} gain = 15

Yuzhen:

In Figure 4 (c) and (d), the indicated stages of signal are different between W7 and W8, especially the 1.)drift of electrons, why?

Answer: There is an upper limit to the current generated by the electron drift in the non-multiplier region when U is certain. Because of the high gain of W8, the voltage in the non-multiplier region is relatively low, and the current rises slowly, the current is easy to reach the upper limit.

Leakage current without Irradiated :

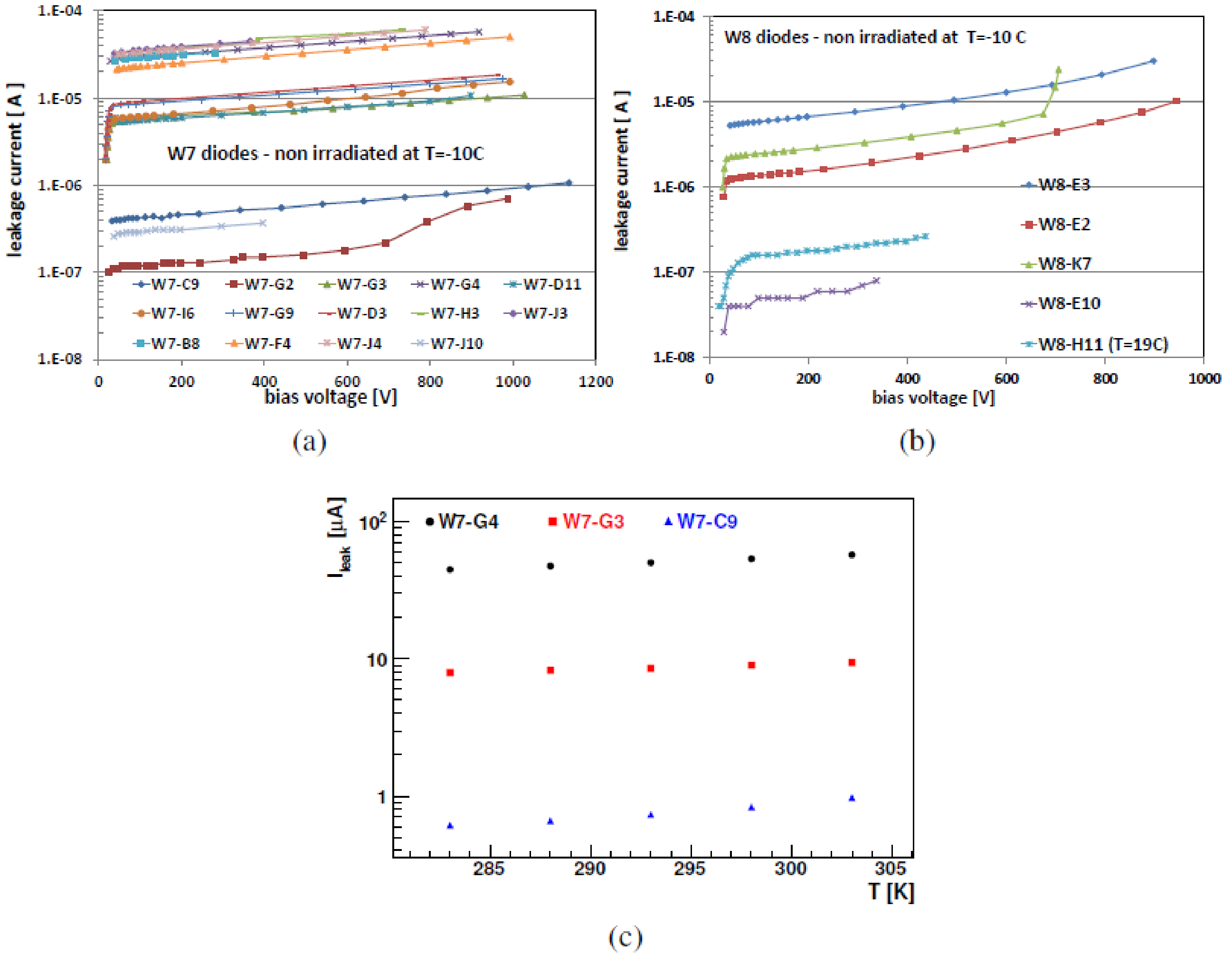
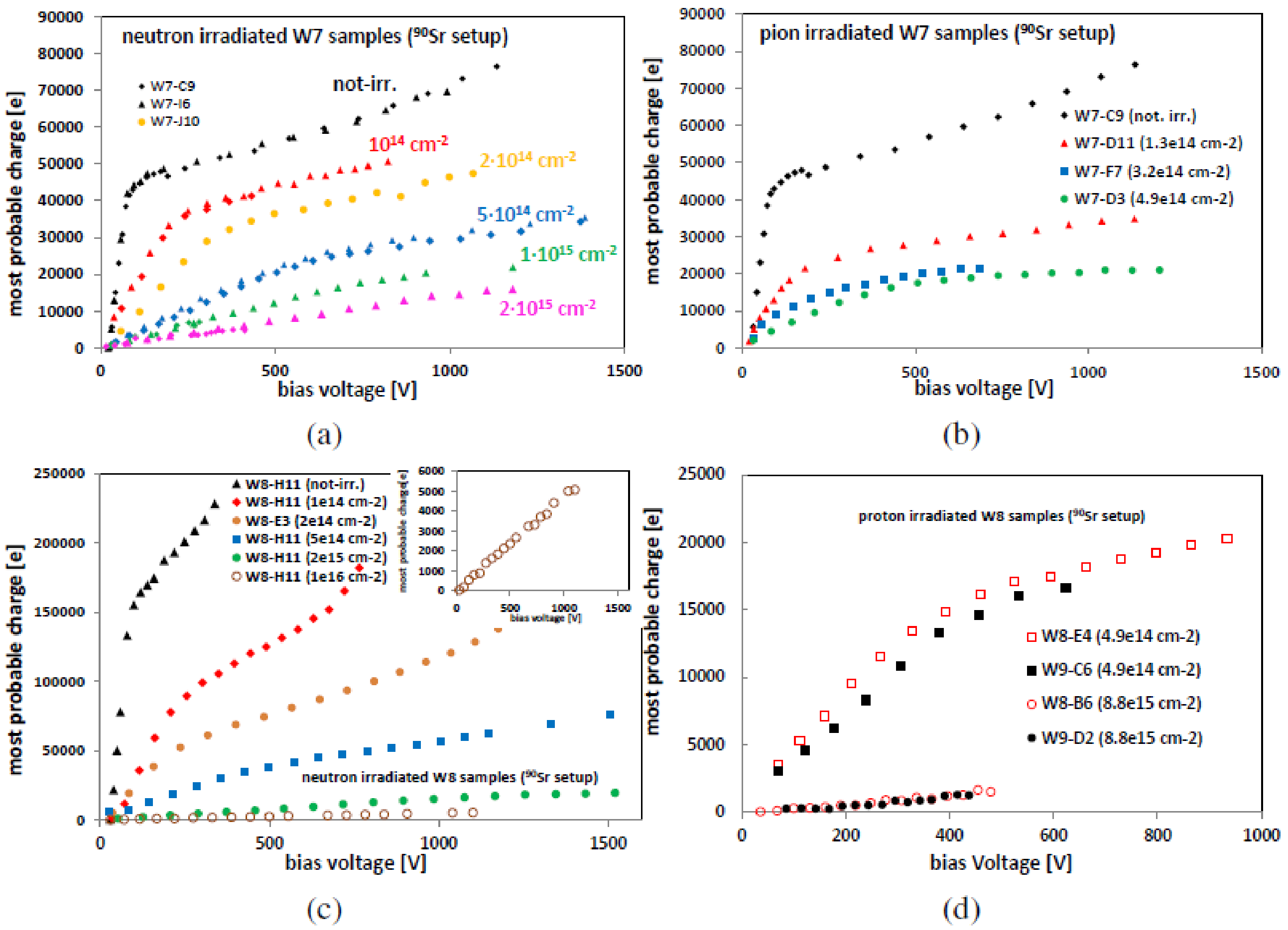


Figure 5. Leakage current dependence on voltage at $T = -10°C$ for LGAD: (a) from W7 and (b) W8. (c) Dependence of leakage current on temperature at 400 V for different samples.

1. Unlike gain, the leakage current of devices varied for almost three orders of magnitude between the samples across the wafer with no obvious systematic trend (see. figures 5a,b).
2. It does not scale with temperature as expected for the generation current, but exhibits rather weak temperature dependence as shown in figure 5c.

Irradiated samples:



Dependence of most probable charge on voltage at different equivalent fluences for

(a) neutron irradiated LGAD from W7
(b) 192MeV pion irradiated LGAD from W7
(c) neutron irradiated LGAD from W8 (irradiated in steps)
(d) 800MeV proton irradiated LGAD from W8 and a standard control diode from W9.

The measurements were done at T=-10C for (a, b, c) and at T=-20C for (d).

a,b).It can clearly be seen that at already moderate fluences the measured charge rapidly decreases. The decrease is larger for charged hadrons irradiated samples than for reactor neutrons.
d). W8 is compared to a control pad detector without p+ layer (denoted by W9) irradiated together.

AMIT PATHAK

In the section: 3.2 Irradiated Samples, The dependence of charge collection on fluence is shown in figure 6.
Samples from both wafers were irradiated with neutrons. Selected samples from W8 were irradiated with 800 MeV protons and those from W7 with 192 MeV pions.
In the Picture Description: 6, They have irradiated W7 wafer with neutron(Picture 6a) and pions(Picture 6b)(Energy 192 MeV) but in the case of W8 wafer with neutron(Picture 6c) and protons(Picture 6d)(Energy 800 Mev).
Why are there two different energy scale to compare the dependence of charge collection on fluence?

(CERN scenario [13]). The fluences of particles were scaled to 1 MeV neutron equivalent fluences by using hardness factors: 0.92 for reactor neutrons ($>$ 100 keV) [14], 1.14 for 192 MeV pions [13] and 0.71 for 800 MeV protons [15]. The uncertainty of delivered fluences is 10% for neutrons and

Leakage current and Irradiated :

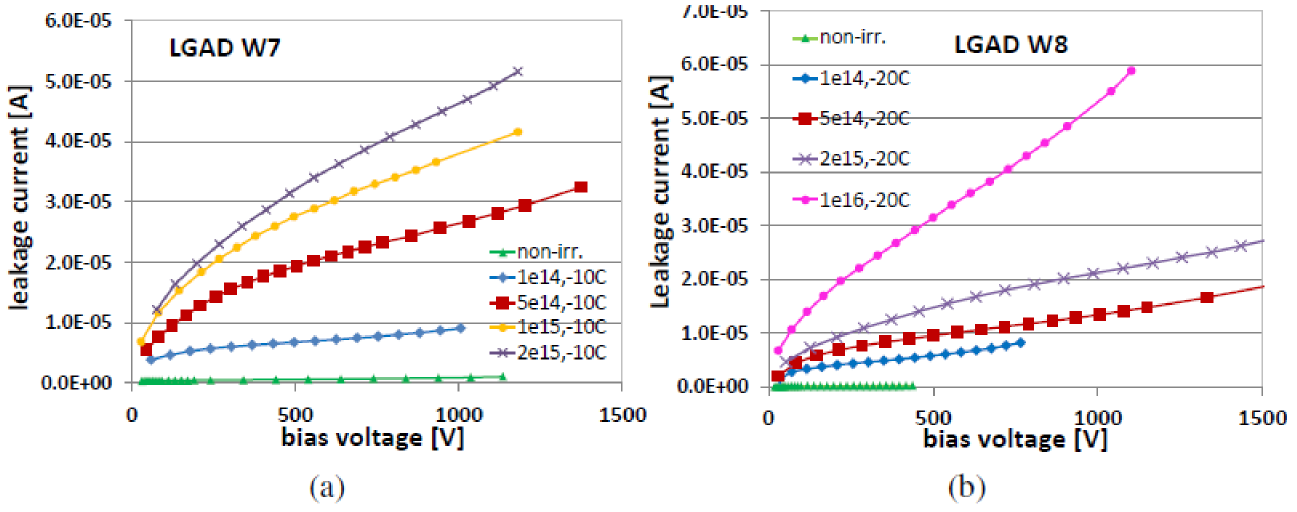


Figure 8. Leakage current dependence on fluence for low excess current samples from (a) W7 and (b) W8.

1. Under the same bias voltage, the stronger the radiation, the larger the leakage current.
2. The leakage current increased due to linear increase of generation current with fluence, but was moderated by the decrease of multiplication.

Shi xin:

On page 7, it says about the reason for gain degradation: “The reason must therefore be related to the decrease of the multiplication gain rather than trapping of the drifting charge”. How to draw this. Conclusion?

Answer: The relative decrease of measured charge is much more pronounced for LGAD than for standard devices (see figure 7). The difference between LGAD and Fz-p is the multiplication gain.

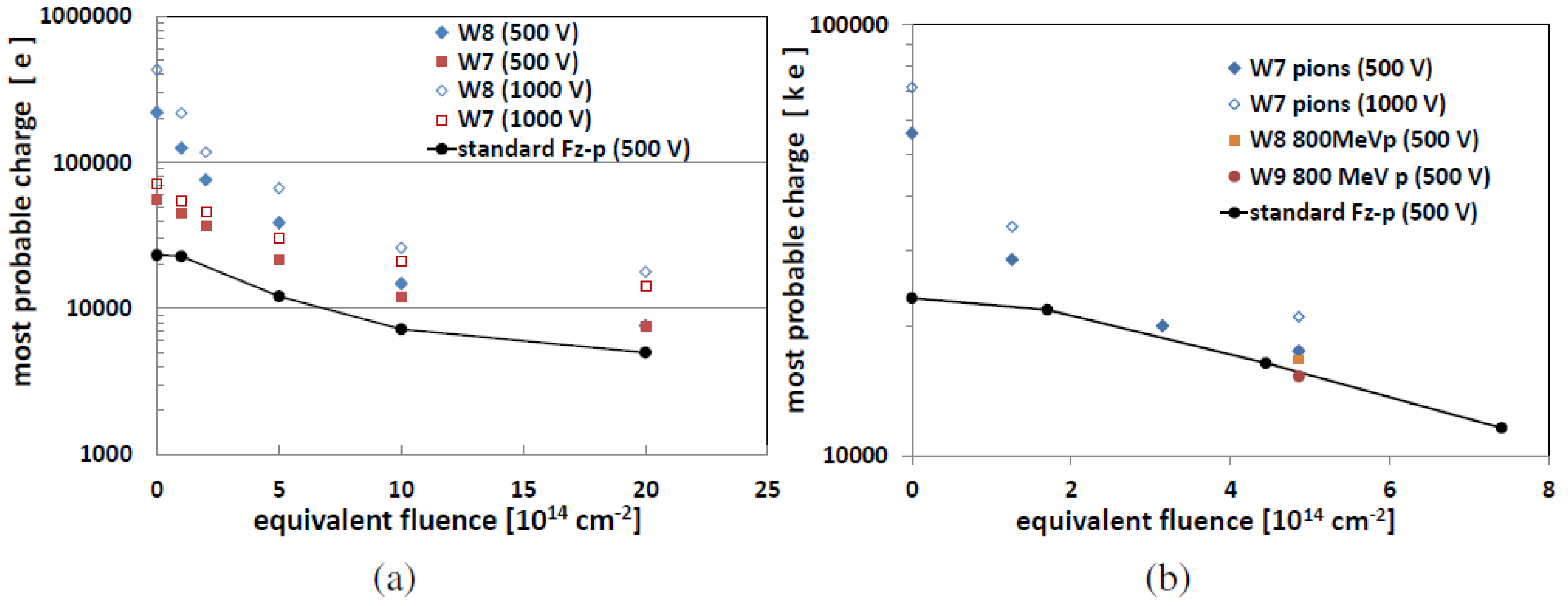


Figure 7. Dependence of measured charge on equivalent fluence at 500 V and 1000 V for (a) neutron irradiated LGAD and (b) charged hadrons irradiated LGAD. Measured charge in a standard diode at 500 V is also shown for the reference [17].

Ryuta:

Q: About Fig.11, what is the meaning of Vmr ? Especially, why the curves start to rise up from certain values (=Vmr) ? and the degreasing of Vmr toward 0V might indicate what ?

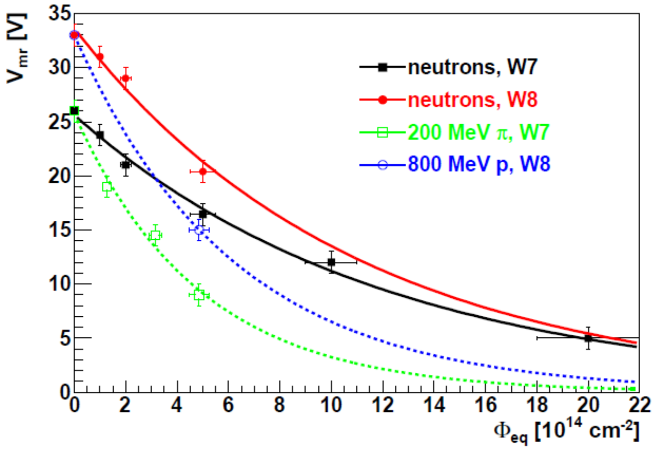


Figure 12. Dependence of V_{mr} on the equivalent fluence. The fit of eq. (4.1) to the measured points is also shown.

Vmr:

ures 4a,b). The dependence of collected charge on voltage has a very distinct shape. Almost no charge is measured up to around 30 V which is the voltage required to deplete the multiplication p^+ layer (V_{mr}). Electric field in the multiplication layer becomes high enough for charge multipli-

is in agreement with gain degradation after charged hadron and neutron irradiations. If it is assumed that the removal of effective acceptors (N_A) occurs with the same rate everywhere in the p^+ layer, then the V_{mr} is proportional to an average N_A in the p^+ layer. Decrease of N_A can be a consequence

Answer: Vmr is depletion voltage of p+ layer. The value of Vmr is is determined by doping concentration in p+ layer. When Vmr toward 0V, the gain is 0, and there is no multiplier layer.

Irradiated VS Non-Irradiated:

Non-Irradiated

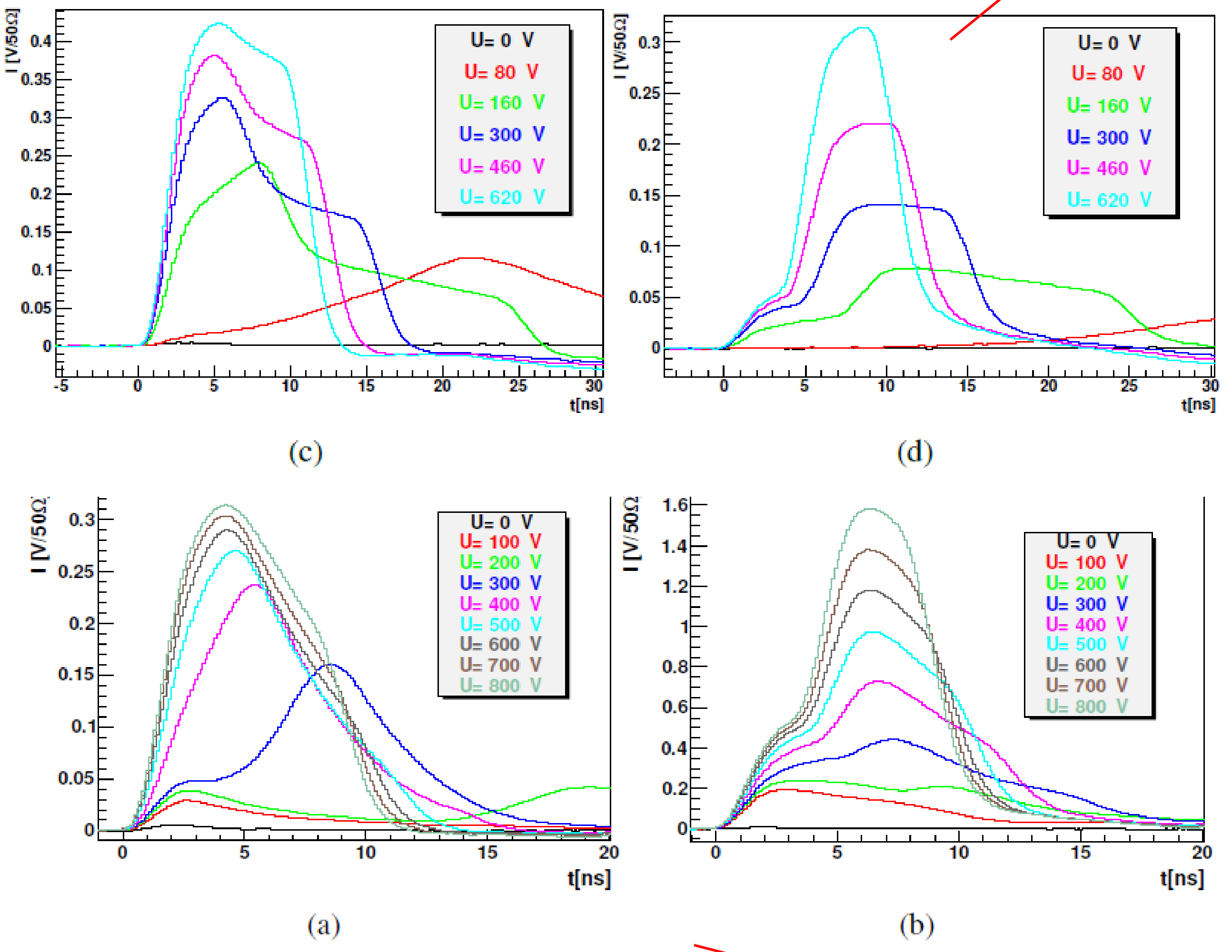


Figure 10. Measured induced currents after back illumination in the LGAD irradiated to $\Phi_{eq} = 2 \cdot 10^{14}$ cm^{-2} from (a) W7 and (b) W8.

Irradiated

In U=620V: Non-Irradiated: W7
I=0.45A (c)
In U=600V: Irradiated:W7
I=0.29A (a)

In U=620V: Non-Irradiated: W8
I=0.31A (d)
In U=600V: Irradiated:W8
I=1.2A (b)

Why does the current get bigger?

Summary

- The gain of the devices decreased fast and almost vanished at irradiation fluences of $10^{15}cm^{-2}$.
- The decrease of the gain after irradiation was attributed to removal of acceptors in the p+ layer. The removal was faster for charged hadrons.
- The leakage current increased due to linear increase of generation current with fluence, but was moderated by the decrease of multiplication.

Thank you