A process modification for CMOS monolithic active pixel sensors for enhanced depletion, timing performance and radiation tolerance

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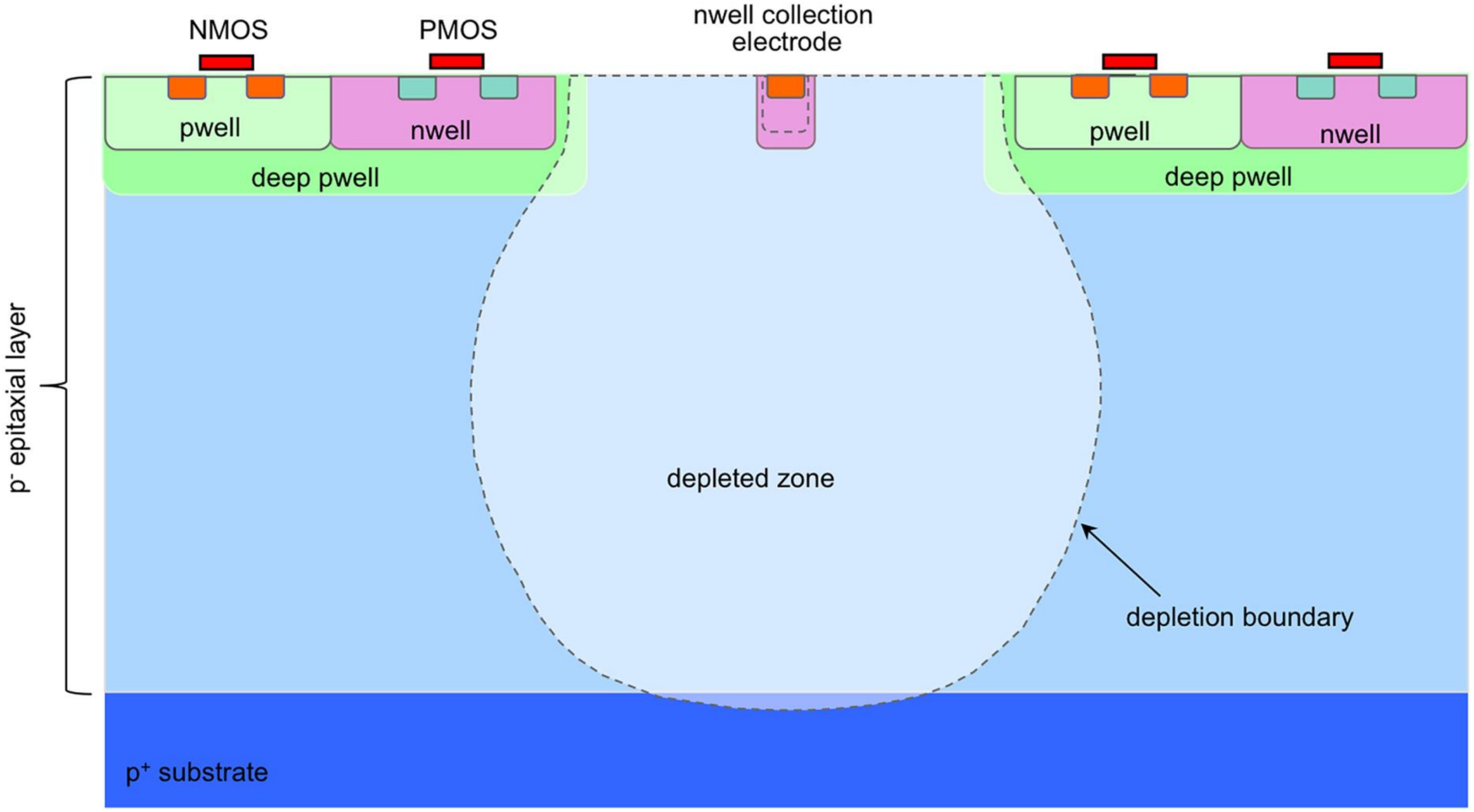
JC 57

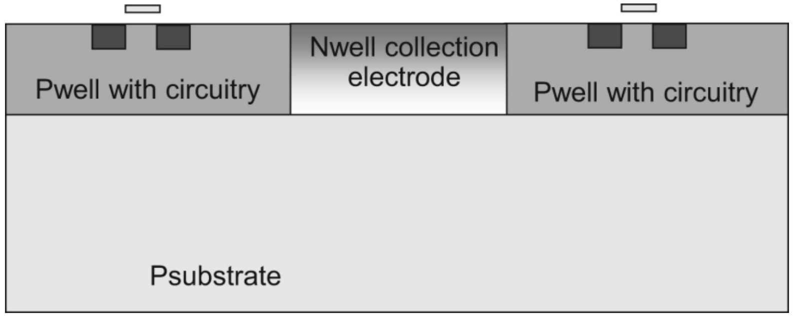
Yang Tao



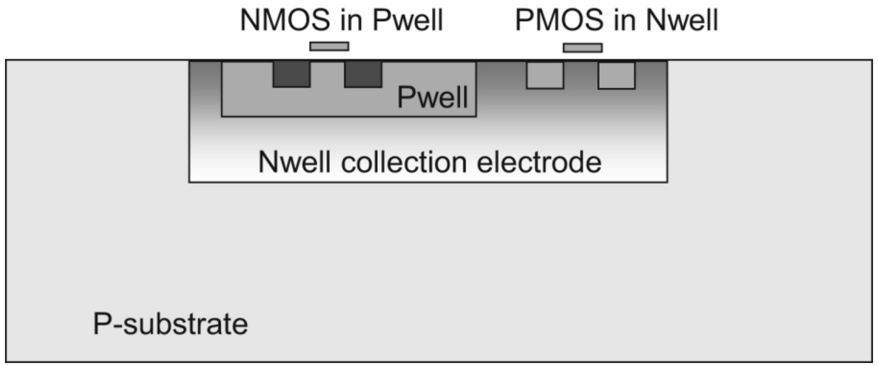
In the standard process , depletion starts at the junction of the collection electrode and expands with increasing reverse bias, but it is difficult to laterally extend the depletion region far into the epitaxial layer in between the low resistivity substrate and the deep p-well, as this requires a potential gradient or an electric field in between two equipotentials.

Towards full depletion of the sensitive layer

- Increasing the size of the collection electrode and reducing the area of the deep p-well



- place the readout circuitry in the pixel in the well implementing the collection electrode



- Silicon-on-Insulator (SOI) technology

the buried oxide is sensitive to ionizing radiation

Increase the power consumption and limit the complexity of the in-pixel circuitry

Question from Hao:

"why the power consumption increase when increasing the size of the collection electrode "?)

Answer:

power consumption P is related to the signal charge over capacitance ratio as follows:

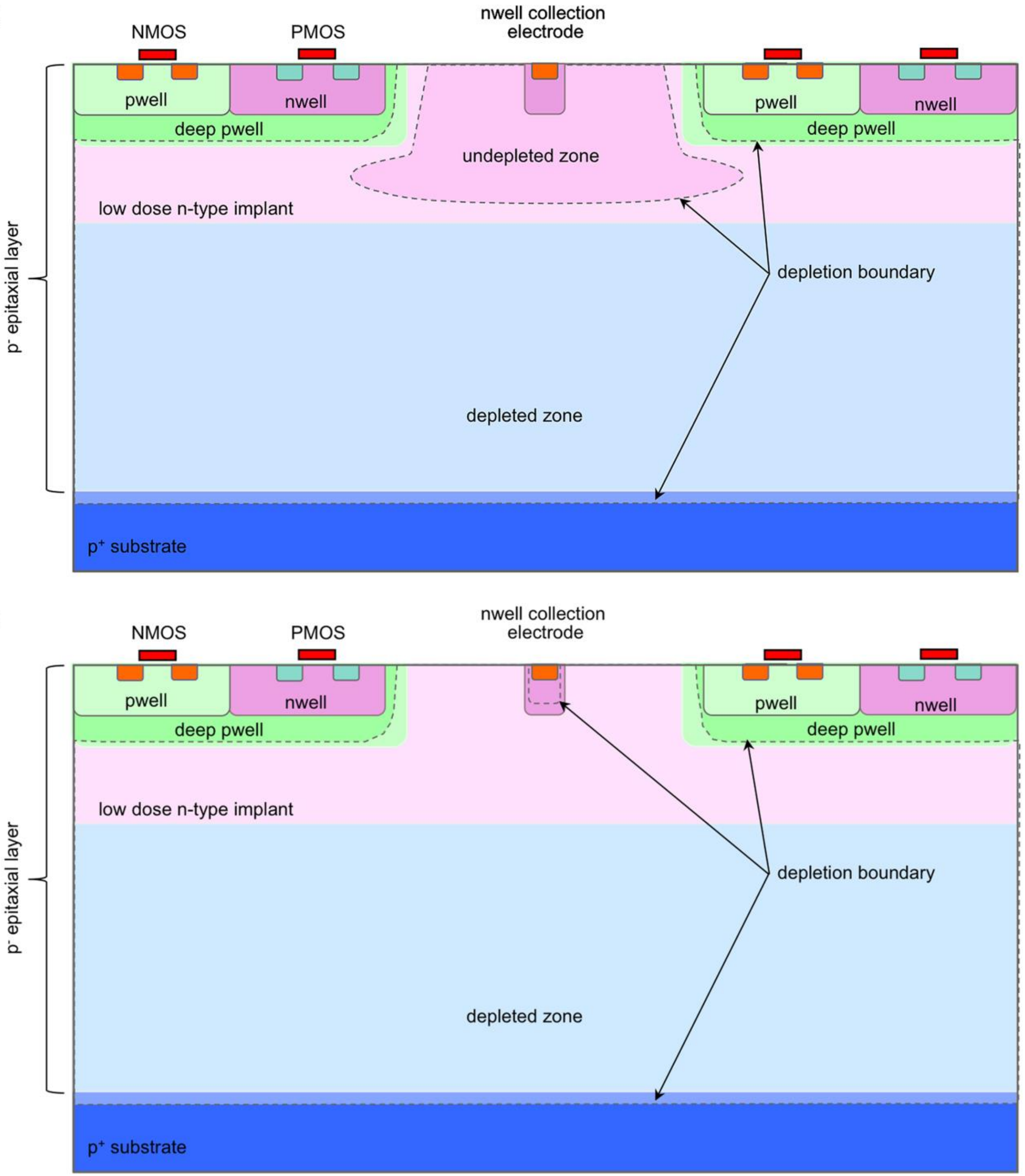
$$P \sim \left\{\frac{Q}{C}\right\}^{-m} \quad with\ 2 \le m \ll 4$$

m equals 2 if the input transistor is in weak inversion, or 4 for strong inversion.

http://dx.doi.org/10.1016/j.nima.2013.05.073

a

b



- A possible solution to achieve full depletion of the sensitive layer combined with a low capacitance collection electrode is to implement a large or even planar junction separate from the collection electrode.

A low dose deep n-type implant has been used to implement a planar junction in the epitaxial layer within the pixel matrix below the wells containing circuitry . The implant is sufficiently low dose to fully deplete it up to the n-well collection electrode implant for reverse bias voltages of a few Volts and obtain a sensor capacitance of only a few fF . Since the p-well in the pixel matrix and the substrate are now separated by a depletion layer and hence isolated , they can be biased independently, provided a sufficiently large potential barrier prevents the holes in the p-well from entering the epitaxial layer and hence avoids punchthrough .

“The critical parameter is the dose of the deep n-type implant. It should be sufficiently low to fully deplete the implant at reasonable voltages, and sufficiently high to prevent punchthrough between p-well and substrate.”

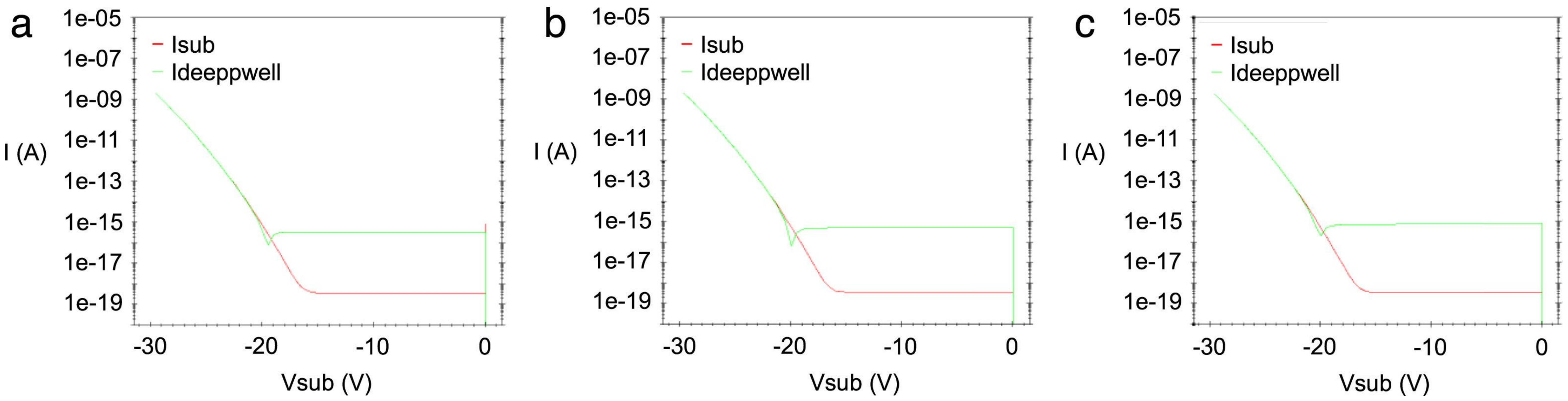


Figure shows for the 18 μm thick epitaxial layer and different nwell collection electrode biases(V_{CE} = 1 V (a), 3 V (b) and 5 V (c)) how substrate current and deep pwell current (respectively Isub and Ideep- pwell in the figure, measured in the simulation at their respective bias contacts) remain very low until they exponentially increase for reverse substrate biases beyond −20 V as punchthrough sets in. **The figure illustrates that the onset of punchthrough does practically not change with n-well collection electrode bias**.

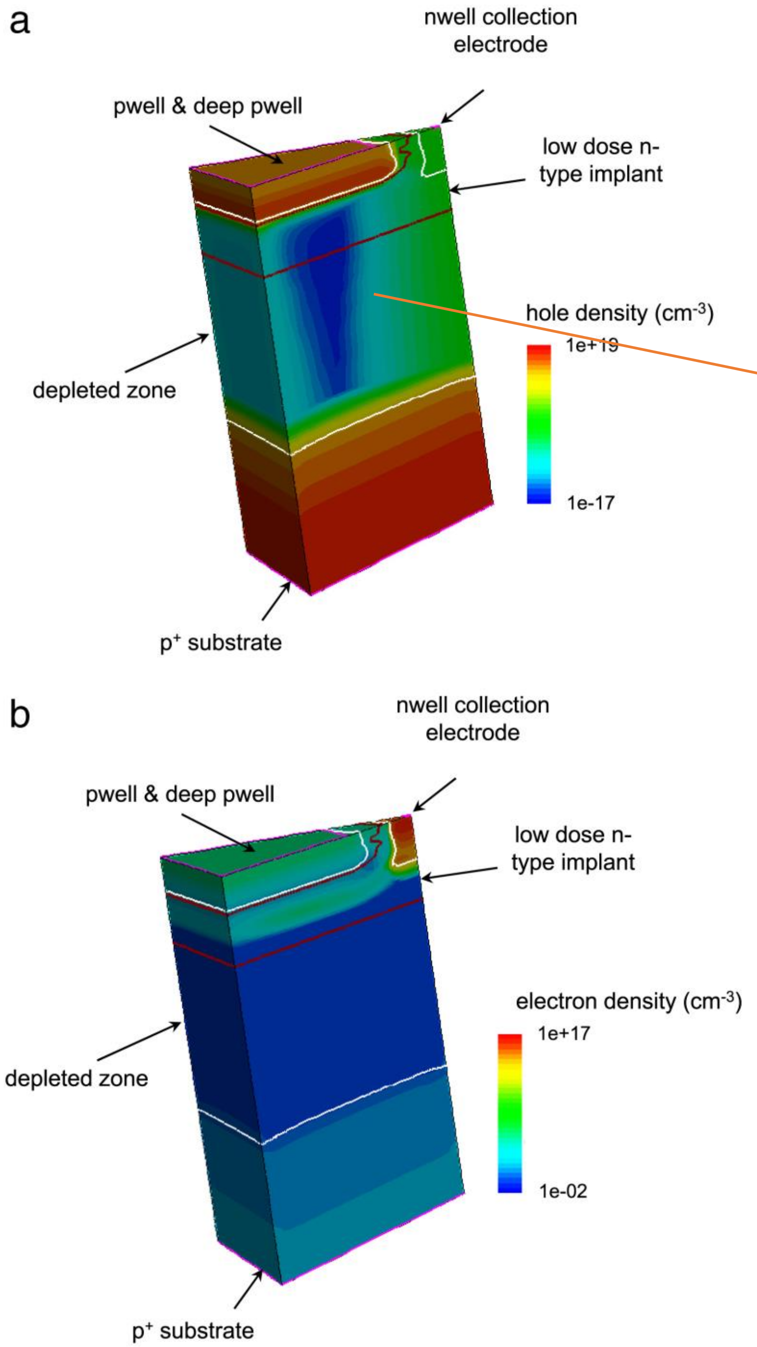


Figure on the left illustrates as an example the depletion of the sensitive layer and in particular the low dose n-type implant by plotting simulated electron and hole densities. The red lines indicate the junctions, the white lines the depletion boundary.

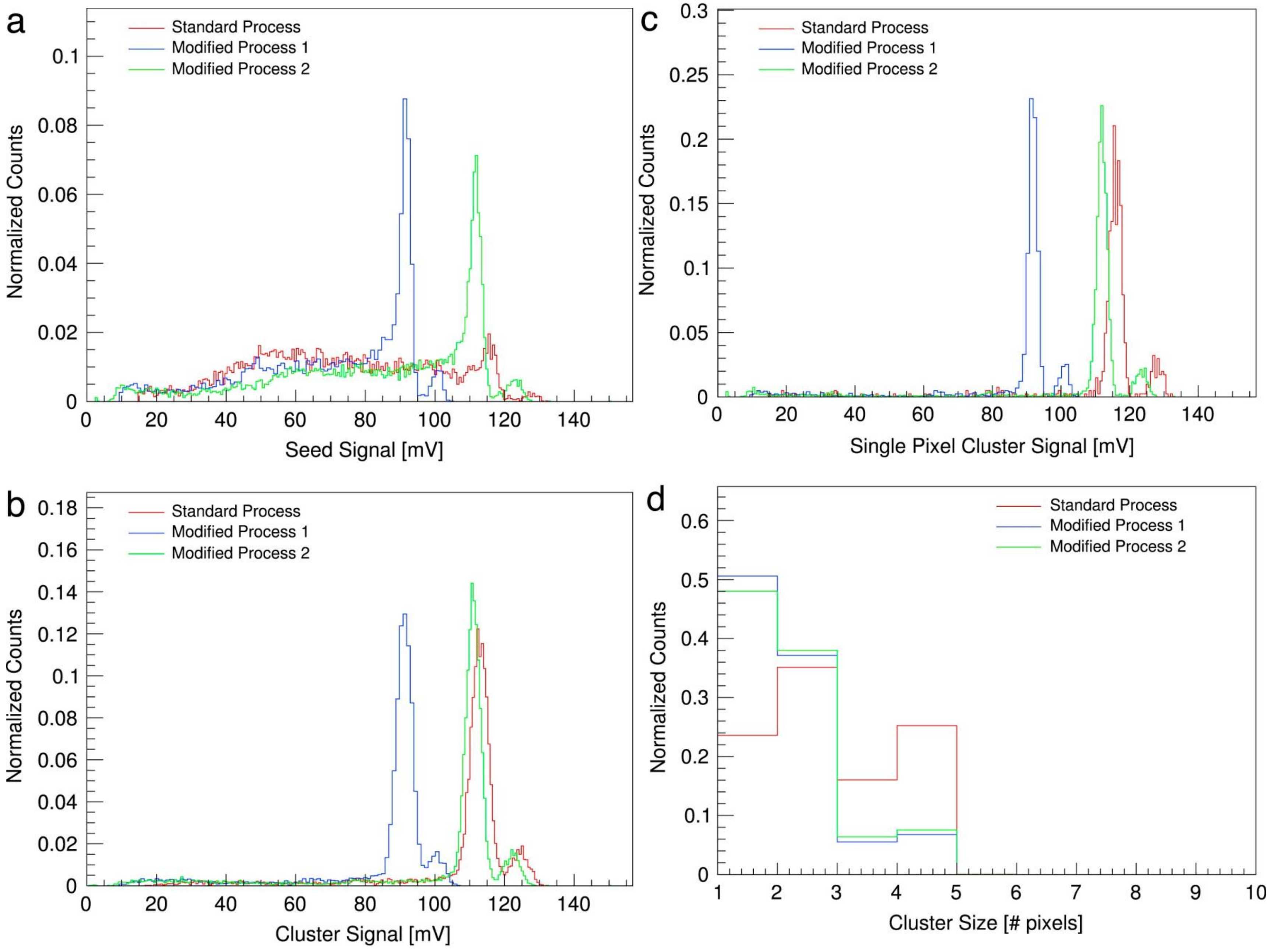
Question from Suyu:

"We can see the simulated hole and electron densities in Fig 5, but why don't they distribute on contrary in depleted zone? " (or why hole densities is not uniform?)

Answer:

In my opinion , the hole depletion with a lower level region maybe depend on p-n-p structure(pwell - n type implant – p type substrate) , but I couldn't ensure it's right. The results comes from simulation , so more details should confirm by process parameters which are not given in paper.

Experimental results:



Signal and cluster distribution from a ^{55}Fe radioactive source measured at room temperature for standard and modified process with higher (modified process 1) and lower (modified process 2) dose for the low dose implant :

(a) seed signal
(b) cluster signal,
(c) single pixel cluster signal
(d) cluster size distribution

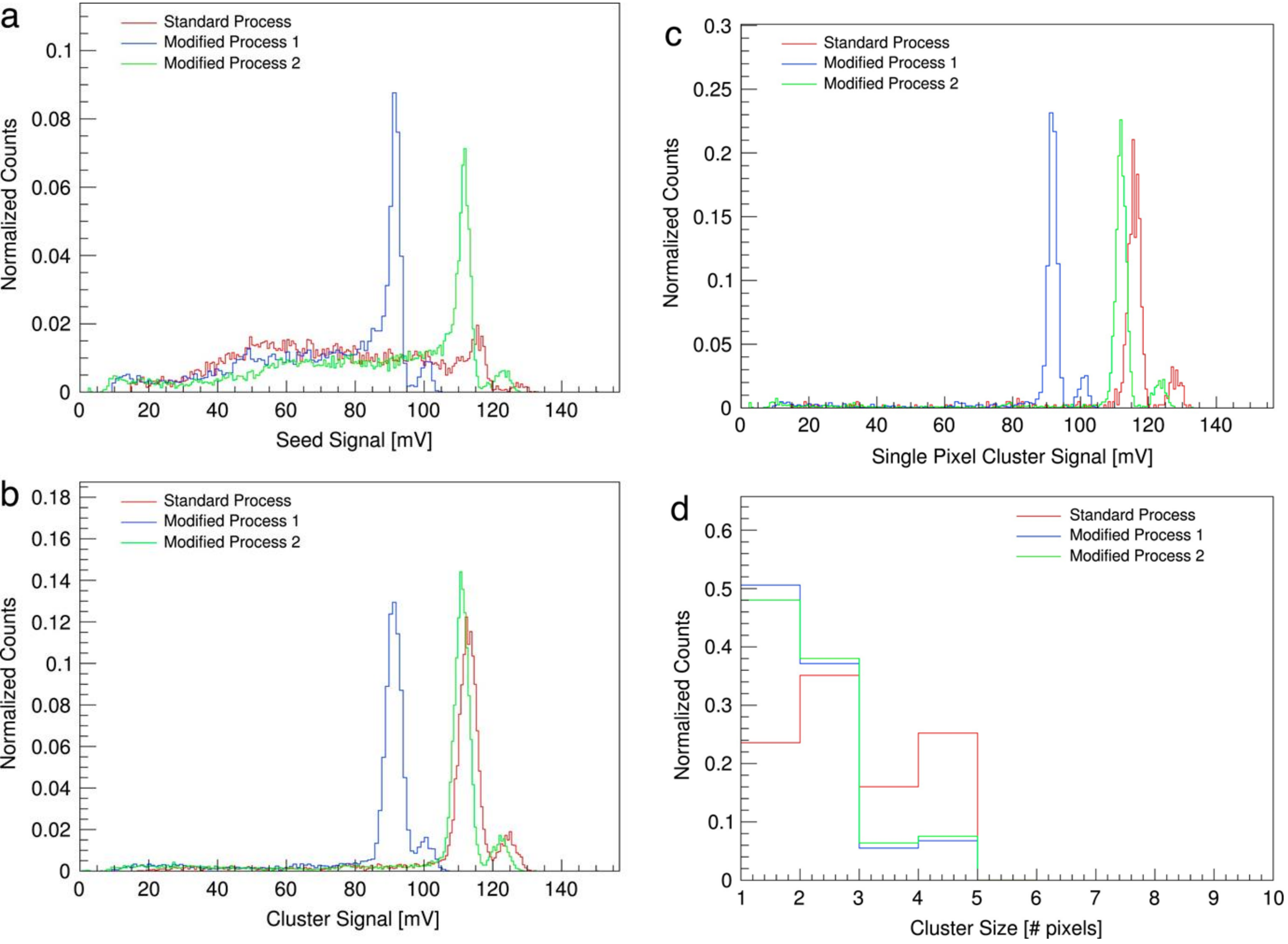
Question from Maoqiang:

"what is the difference between seed signal and cluster signal in this paper?"

Answer:

Seed signal : the pixel with signal over threshold establishing there was a hit.

Cluster signal : combine the signals from all pixels in the cluster

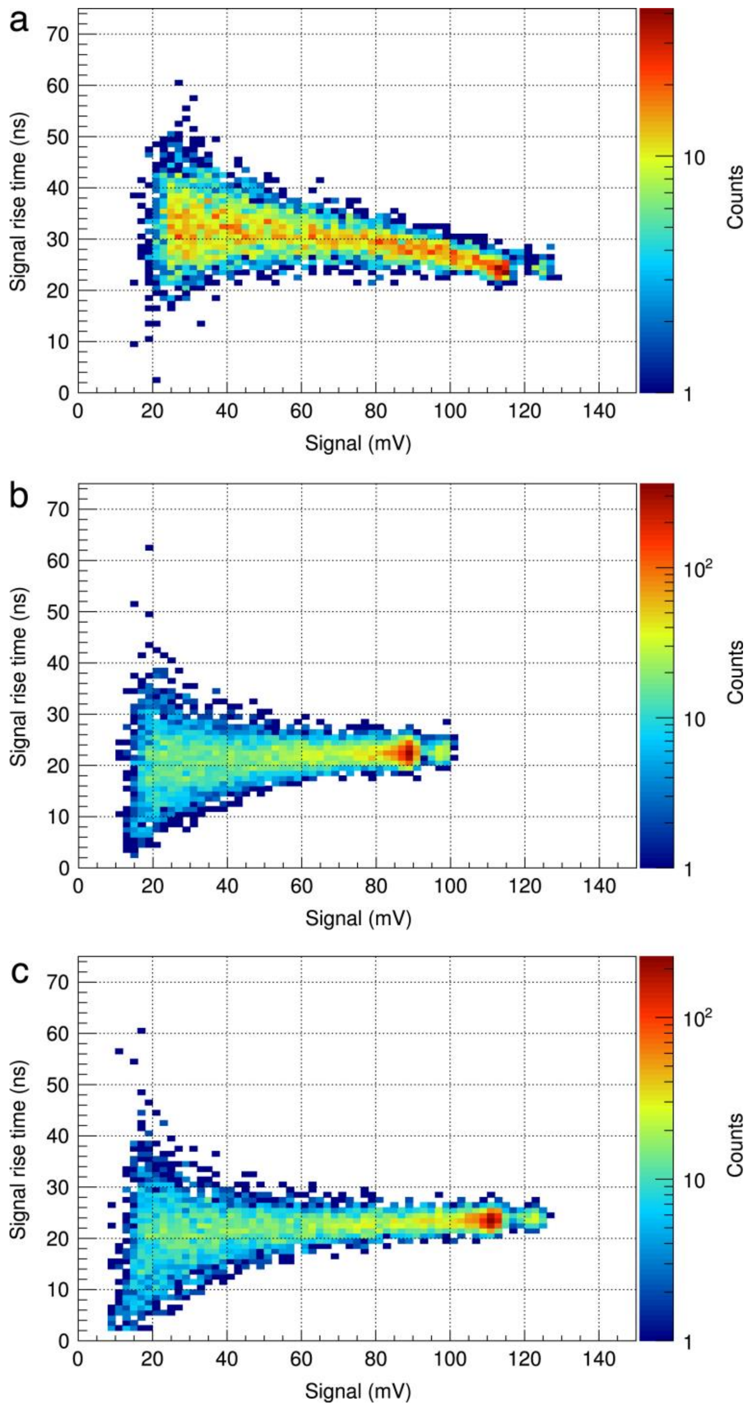


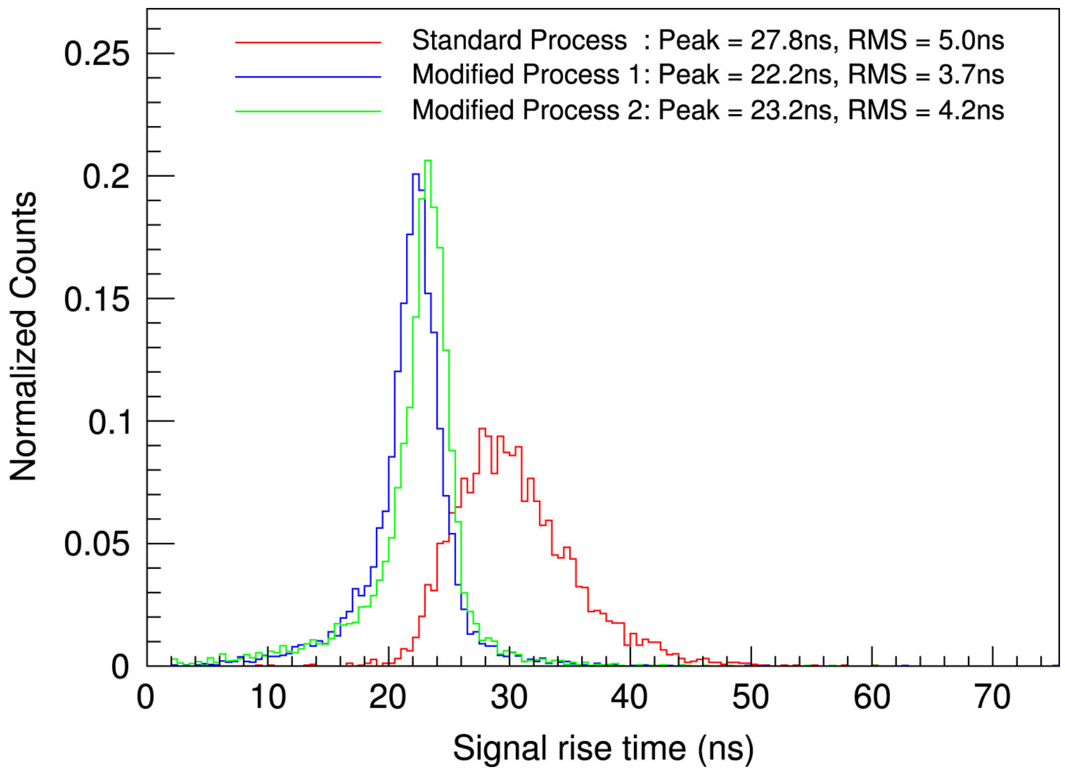
Question from Xin:

"How to understand the signal shift in Fig.7?"

Answer:

1. For X-ray seed signal peaks .The higher dose of the deep implant in the modified process is higher than the lower one by several tens of percent, it depends on cluster size distribution.
2. For the peak positions , the higher implant dose yields a slightly higher sensor capacitance, for a lower dose there is no sensor capacitance penalty , so peak signal for process-1 is small than peak for process-2.
3. For cluster signal peak, the peak is somewhat wider as the noise of the different pixels is added.
4. …





Measured charge collection time **at room temperature** versus signal from a 55Fe radioactive source ;

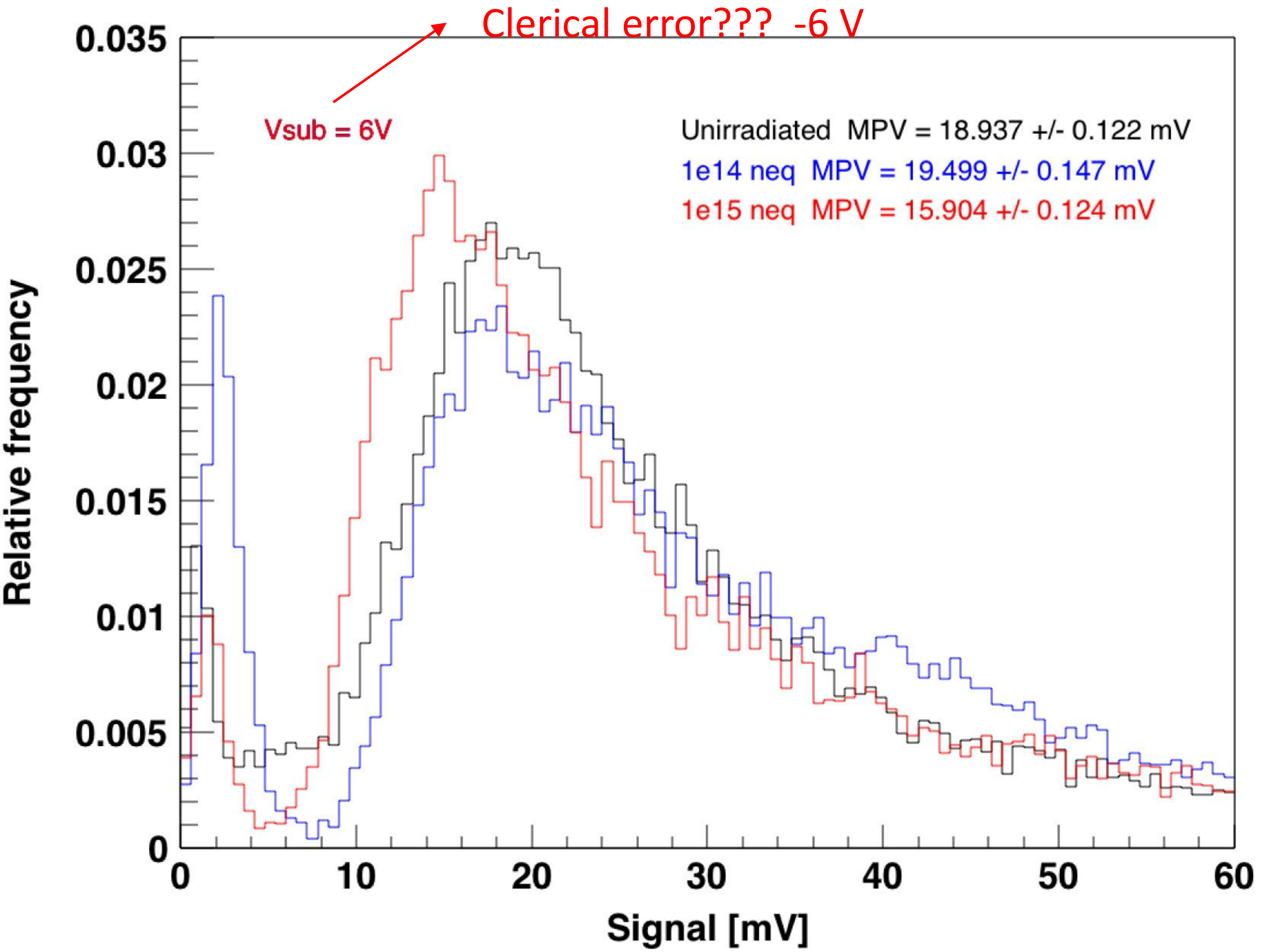
(a) standard process

(b) modified process with higher

(c) modified process with lower

Since the epitaxial layer is not depleted there, and charge has to be collected by diffusion, this explains the increase of the average charge collection time with decreasing pixel signal. For the modified process charge sharing is much less frequent but also signal rise time is not dependent on the size of the signal or whether the signal is shared between pixels or not.

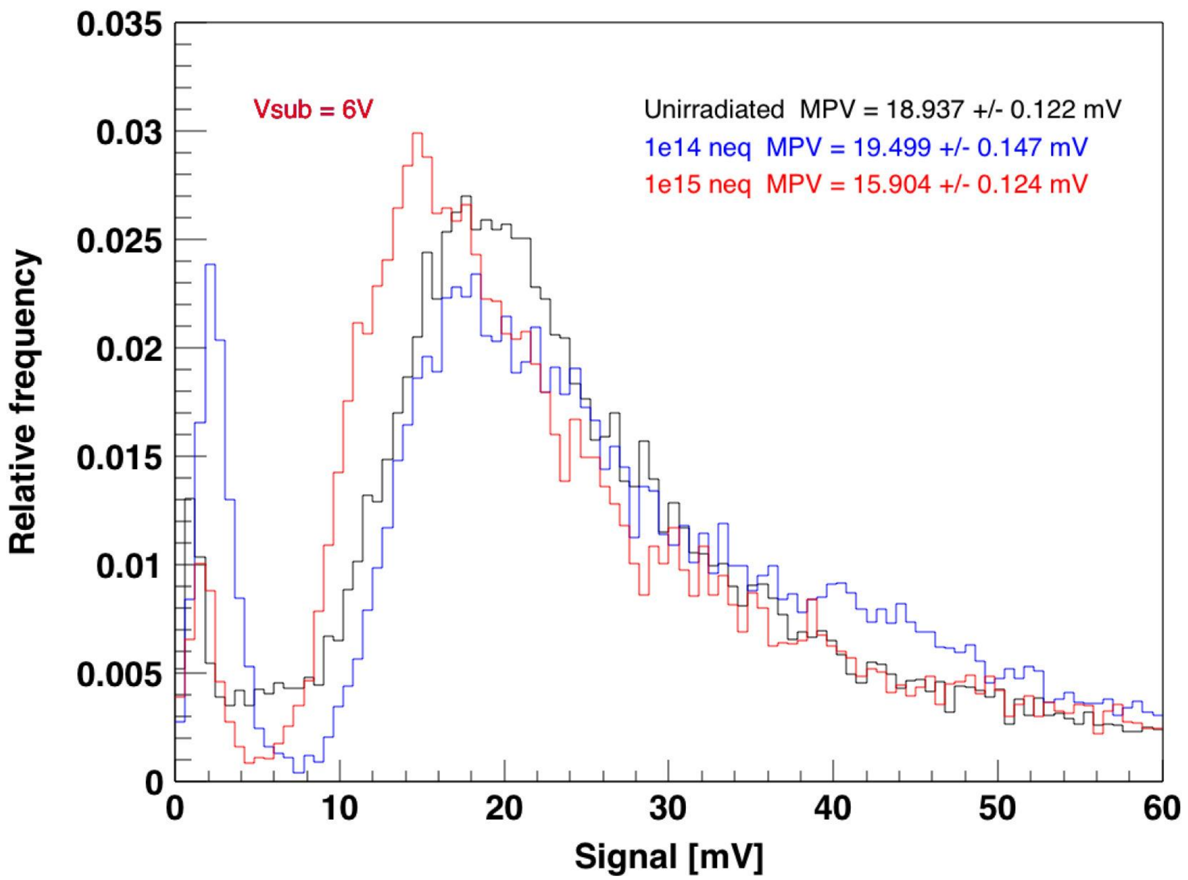
The much larger fraction of single pixel hits and the lower and more uniform collection time all indicate a drastically increased depletion volume in the sensor for the modified process, confirming the device simulations.

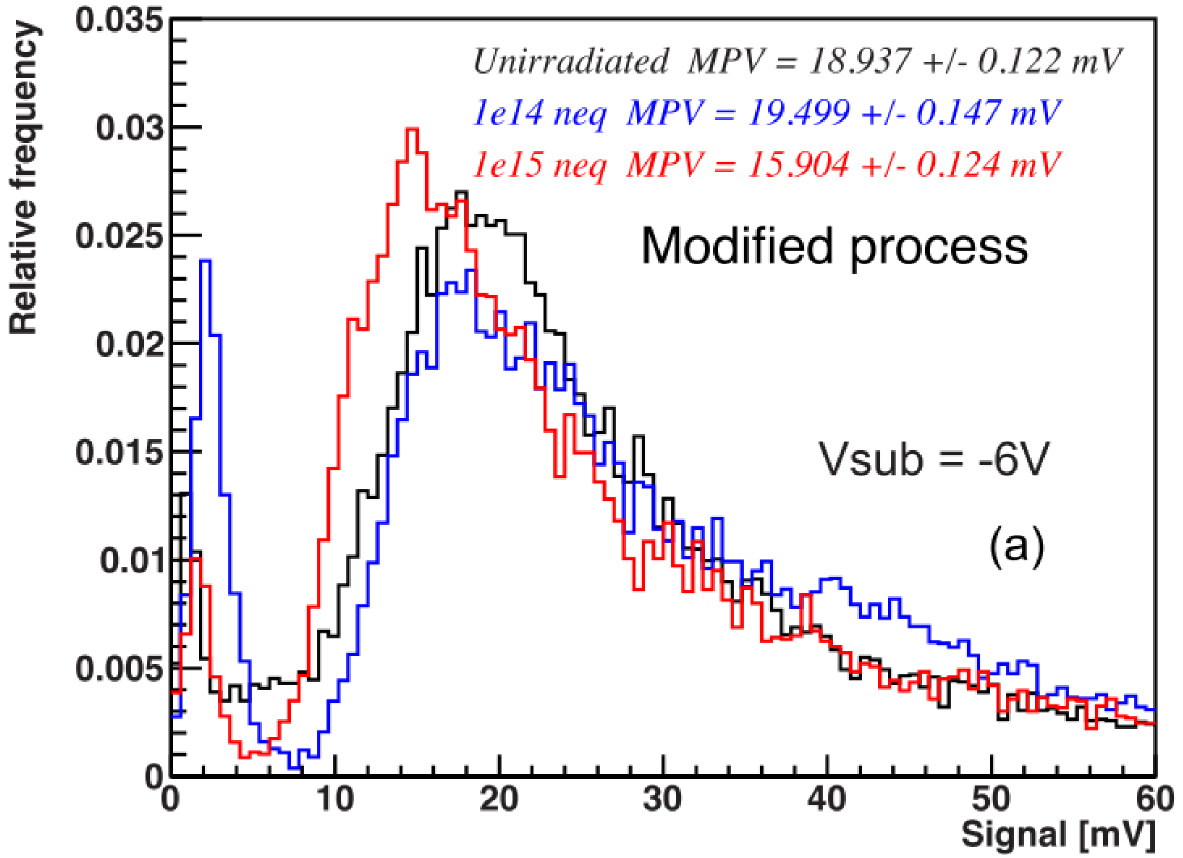


To verify tolerance to non-ionizing energy loss, chips were irradiated up to various neutron fluences, and performance before and after irradiation was compared using a ^{90}Sr radioactive source. The irradiated devices were cooled to −30 °C, the unirradiated device was measured at room temperature.

Figure shows the spectrum for the modified process with the higher implant dose before and after neutron irradiation, and illustrates the only minor degradation after 1015 1 MeV $n_{eq}/cm^2$with a mean probable signal value reducing from about 19 to about 16 mV .

Test need be under Reverse-Bias , so substrate bias should be negative.



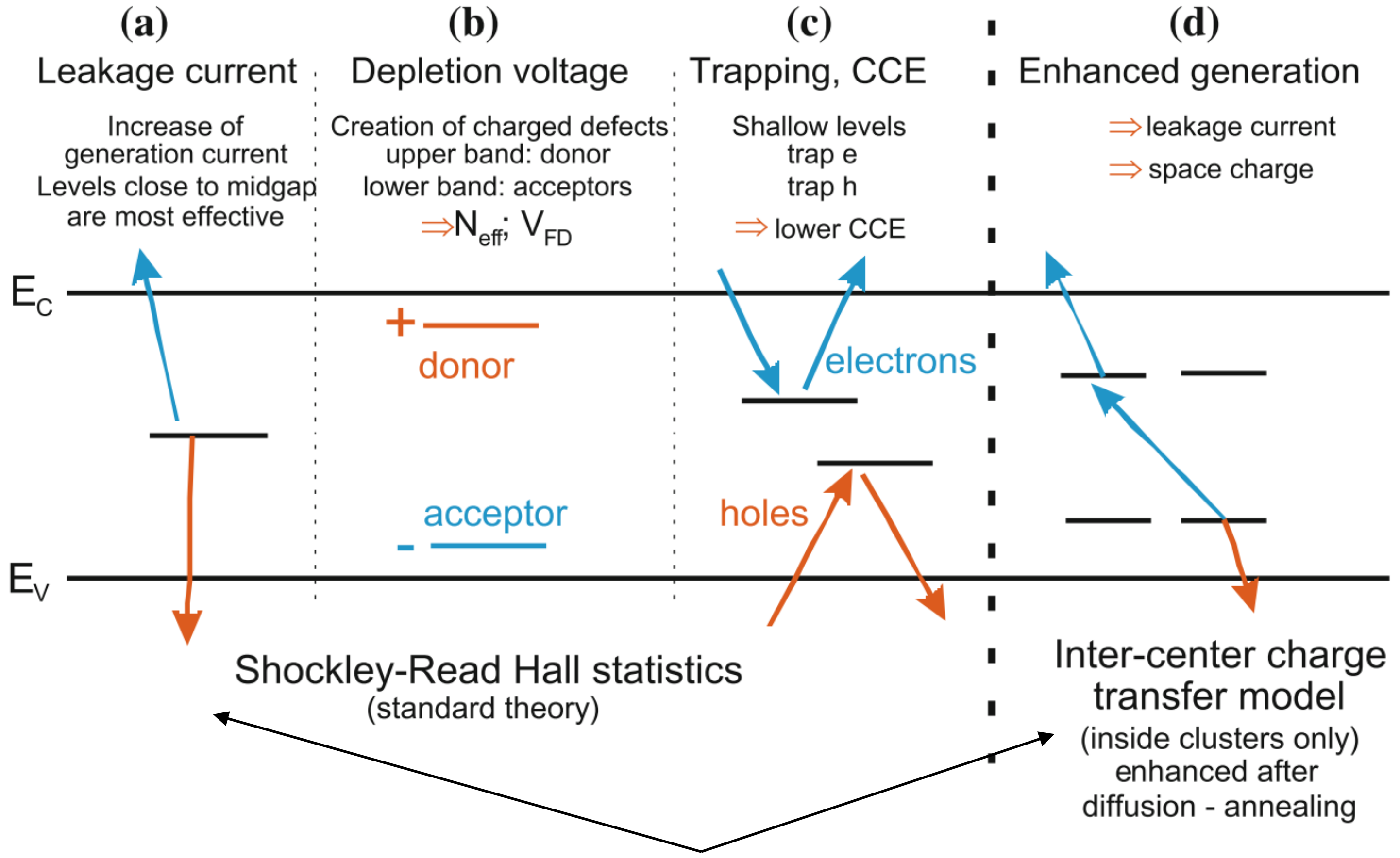


Paper for JC:

https://doi.org/10.1016/j.nima.2017.07.046

Another paper for this test

https://doi.org/10.1088/1748- 0221/12/06/P06008



Leakage current will disturb the charge signal

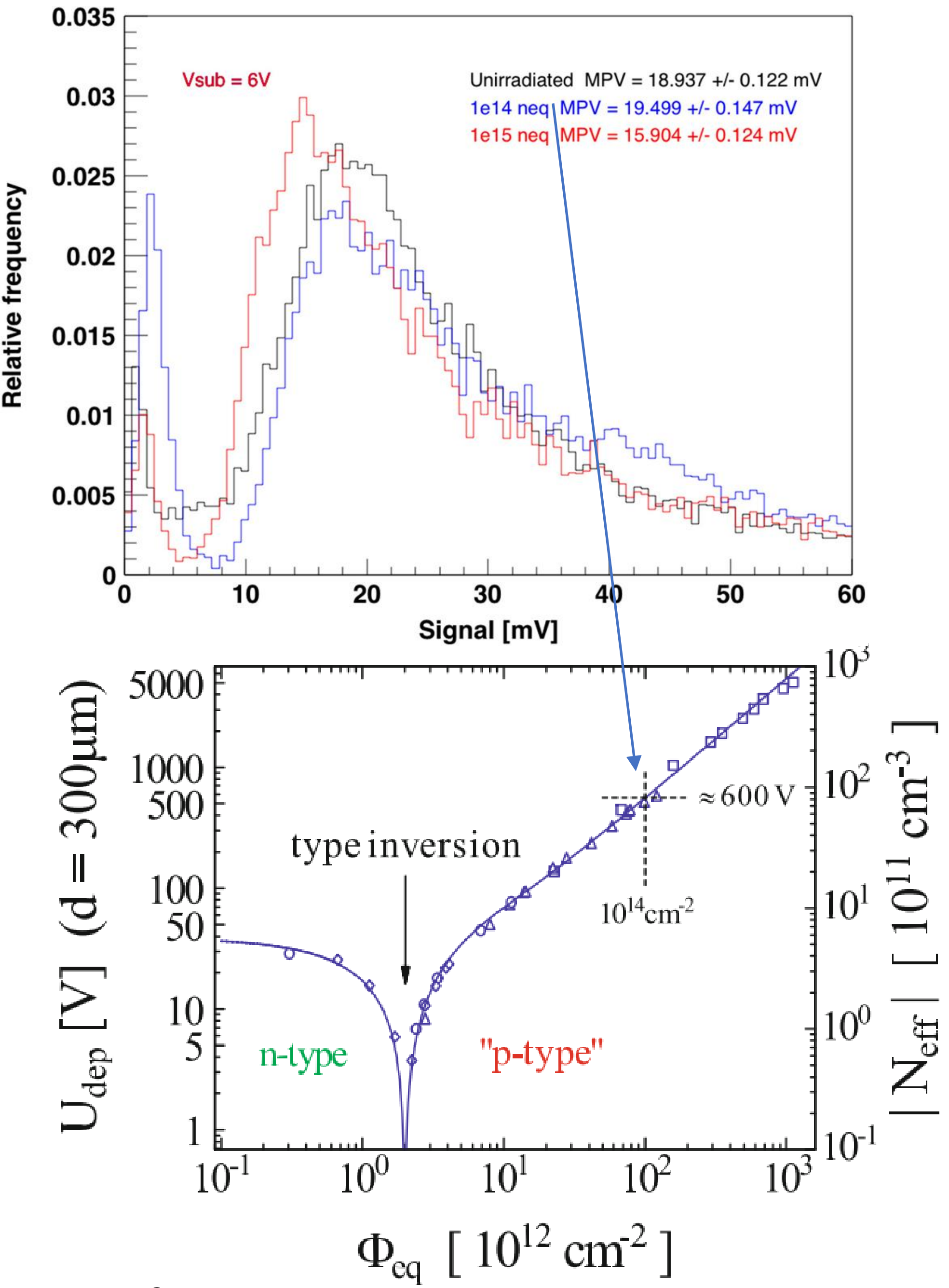
https://doi.org/10.1007/978-3-319-64436-3 chapter-2

Question from Kai:

“For Fe55 test, the signal rise time is measured at room temperature, but for Sr90 source, they tested the signal rise time at different temperatures, room temperature for unirradiated one, and others at -30 degree. In this way, the difference will not only stem from irradiation, but also could from the temperature difference. Any special reason for doing this at different temperatures?”

Answer:

To reduce the radiation- induced leakage current, the irradiated devices were cooled to −30 ◦C, the unirradiated device was measured at room temperature. After radiation, mid-gap levels are mainly responsible for dark current generation, according to the Shockley–Read–Hall statistics and decreasing the charge carrier lifetime of the material



Question from Ryuta:

"It is already known that the type inversion from n-type to p-type happens after a beam irradiation. we can expect that the newly inserted "implant" becomes "p-type" after the radiation. If it is the situation, I am not sure we can apply different voltages for p-well and substrate each, but are there any explanations or hints in the paper ?"

Answer:

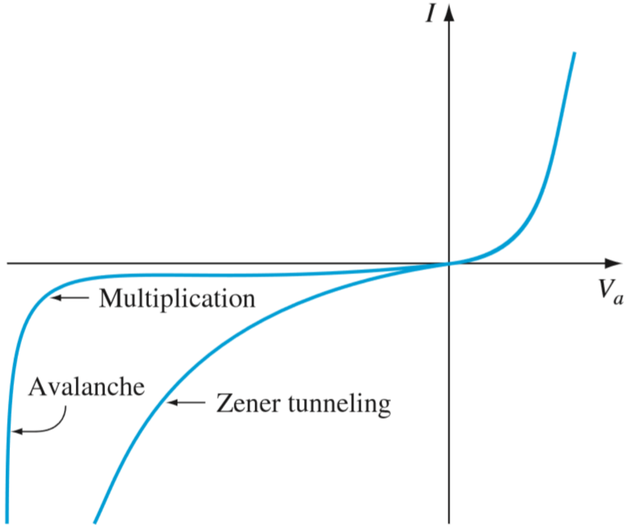
If type inversion really occurs after radiation ,we do not have to care about the punchthrough since p-well and 'implant' are the same . But it seems they only set the substrate bias to -6V but not mention the p-well bias.

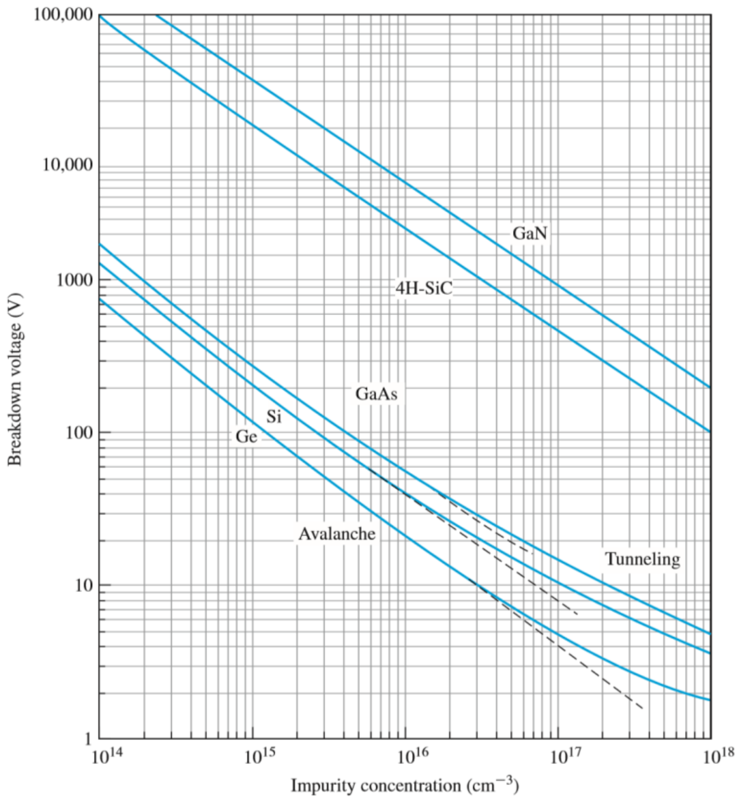
I find another paper which does detailed description about this test : https://doi.org/10.1088/1748- 0221/12/06/P06008 and it also just only mention substrate bias but p-well. And it doesn't talk about if n-type is inversed after radiation(or leakage current between p-well and implant layer after radiation).

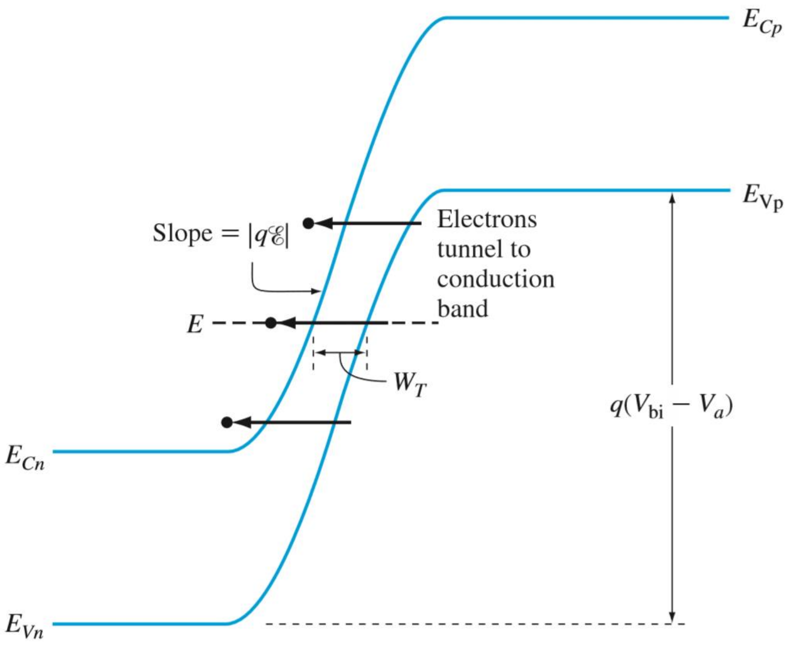
by the way, they say this special process could enhance the radiation tolerance and just only provide experimental results but detailed reasons. Maybe it's secret technology about "implant"…

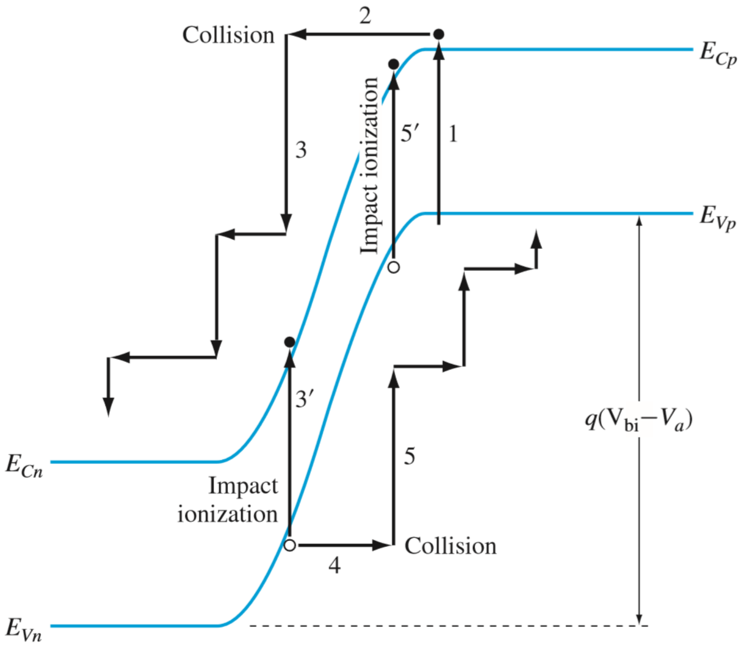
Figure from DESYTHESIS-1999-040, ISSN-1435-8085, http://mmoll.web.cern.ch/mmoll/thesis/

Backup









While Zener tunneling results in a soft breakdown and predominates in heavily doped junctions (small tunneling distance), avalanche gives a sharp breakdown and predominates for more lightly doped junctions.