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Design and fabrication of an optimum peripheral region for low gain avalanche detectors

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Introduction ---- LGAD

- Moderate increase (gain ~ 10) of the collected charge
- Thus leading to a notable improvement of the signal-to-noise ratio
- Which largely extends the possible application of Silicon detectors beyond their present working field
- Requires a careful implementation of the multiplication junction
- To obtain the desired gain on the read out signal
- And a proper design of the edge termination and peripheral region
- Which prevents the LGAD detectors from premature breakdown and large leakage current

Question from Kai:

- In the recent jc papers about low gain detectors, the value of gain ~ 10 appears very frequently. Is there any special reason for this value of 10? Is it just a balanced value that neither too large nor too small to test the equipment. is the gain the lower the better?

➢ No special reason. It depends on the signal-to-noise ratio. The moderate increase can lead to a notable improvement of the signal-to-noise ratio.

Question from Ryuta:

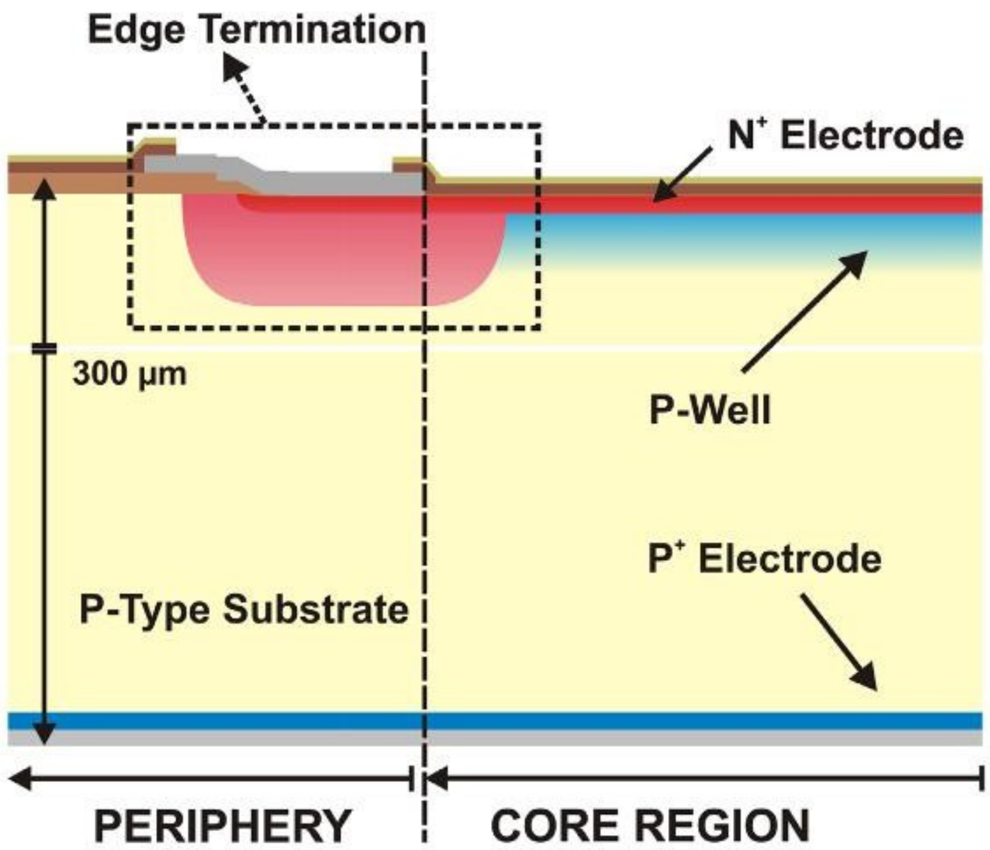
- "In the LGAD detectors the initial current is only moderately amplified in such a way that the series noise (due to the voltage) dominates over the parallel noise (due to the current), thus leading to an improvement of the signal-to-noise (S/N) ratio. In high gain detectors, parallel noise becomes important and S/N would not improve with respect to a standard diode."

- What kind of noise is expected for the high gain case by which the parallel noise becomes important, that is not the case for the "moderate" gain ?

➢ I think the conclusion coming from experimental results, but I don’t know the theory.

Introduction ---- LGAD

- Based on the standard PiN diode architecture
- Adding a moderately doped P-type diffusion(P-Well) beneath the highly doped N-type electrode
- Increase the doping concentration in the vicinity of the N+P junction with respect to the highly resistive substrate
- P-well $10^{16}cm^{-3}$



Edge termination of the multiplicationjunction

- Under reverse bias conditions, the electric field at the N+P junction rises up to a value high enough to activate the impact ionization mechanism, which leads to charge multiplication.

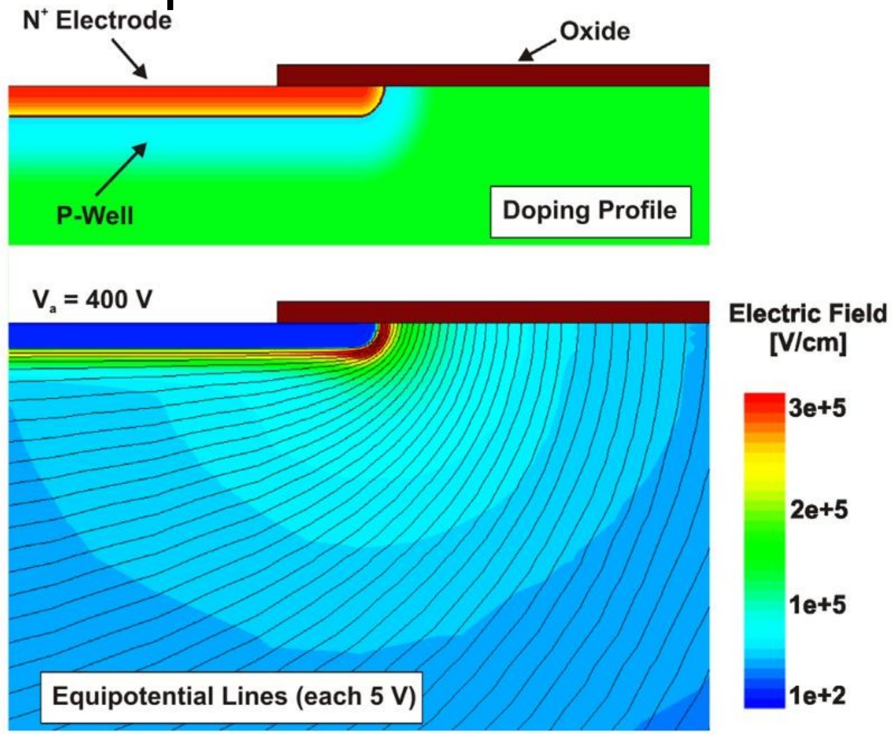


Fig. 2. Simulated doping profile (top) and electric field combined with equipotential lines distribution (bottom) at the edge termination of an unprotected LGAD multiplication junction at a reverse bias of 400 V.

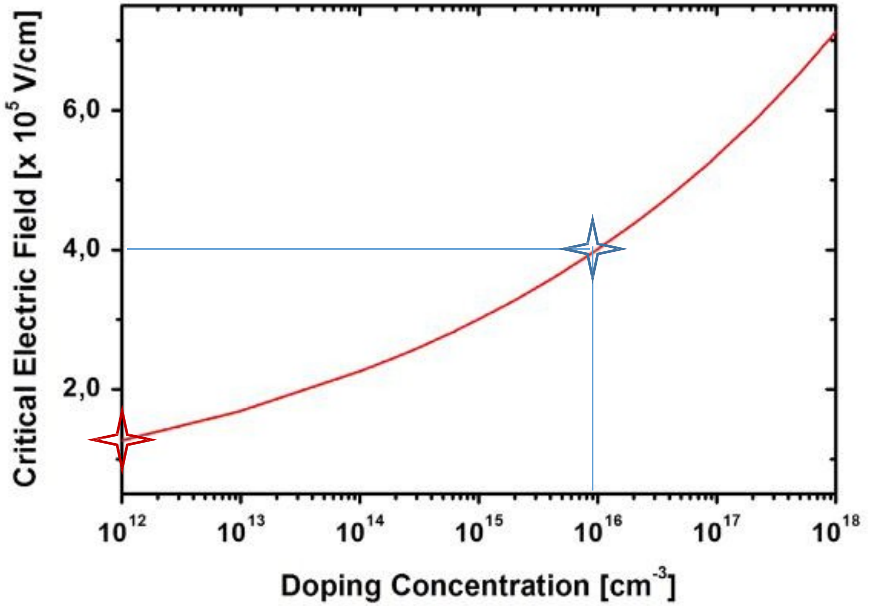


Fig. 3. Critical electric field as a function of the doping concentration, according to Baliga [7].

Edge termination of the multiplicationjunction

- Uniformity is usually the main goal when optimizing a detector design.

- $V_{BD|edge} > V_{BD|planar}$
- The electric field distribution has to be uniform -> confine the impact ionization process to the core region
- The process technology compatible with a stadard production of medium or small area(< 1 cm^2) pad detectors and segmentation of the electrodes.

1. Floating guard ring

- Width in the range of 30um
- N+ electrode shallow diffusion
- Does not remove the electric field peak at the edge of the planar junction

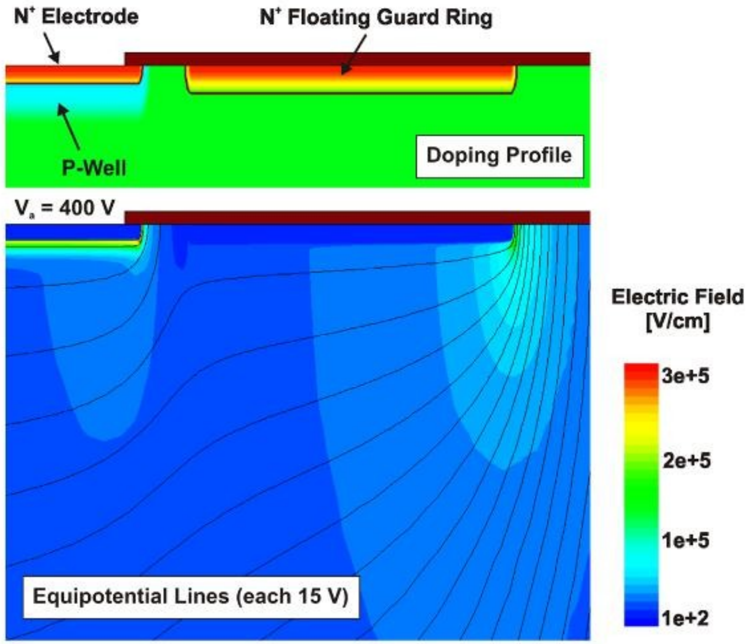


Fig. 4. Simulated doping profile (top) and electric field combined with equipotential lines distribution (bottom) at a reverse bias of 400 V when a shallow N-type floating ring is implemented.

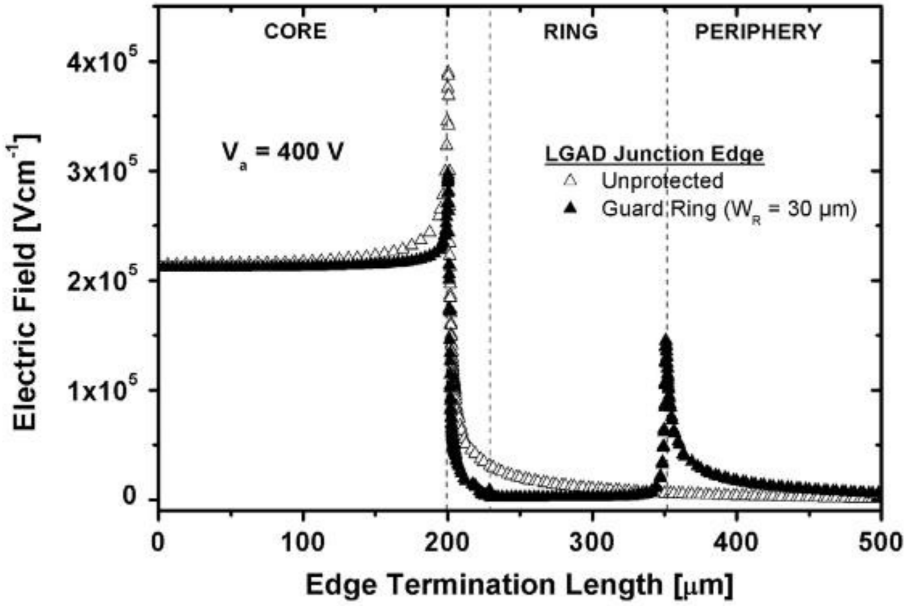


Fig. 5. Simulated electric field profile at the shallow N^+ junction depth for an unprotected multiplication junction and for the same junction protected with a floating guard ring at a reverse bias of 400 V.

2. N+ electrode extension

- Extend the shallow N+ electrode diffusion beyond the mask limits of the P-Well
- Electric field peak can be completely removed.

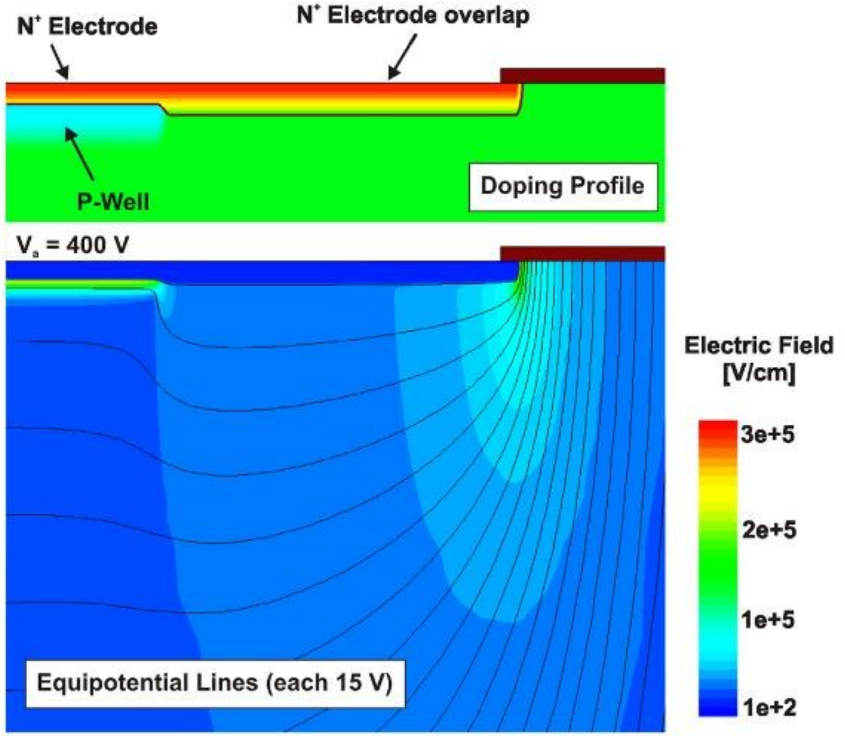


Fig. 6. Simulated doping profile (top) and electric field combined with equipotential lines distribution (bottom) at a reverse bias of 400 V when the N^+ electrode extension is implemented.

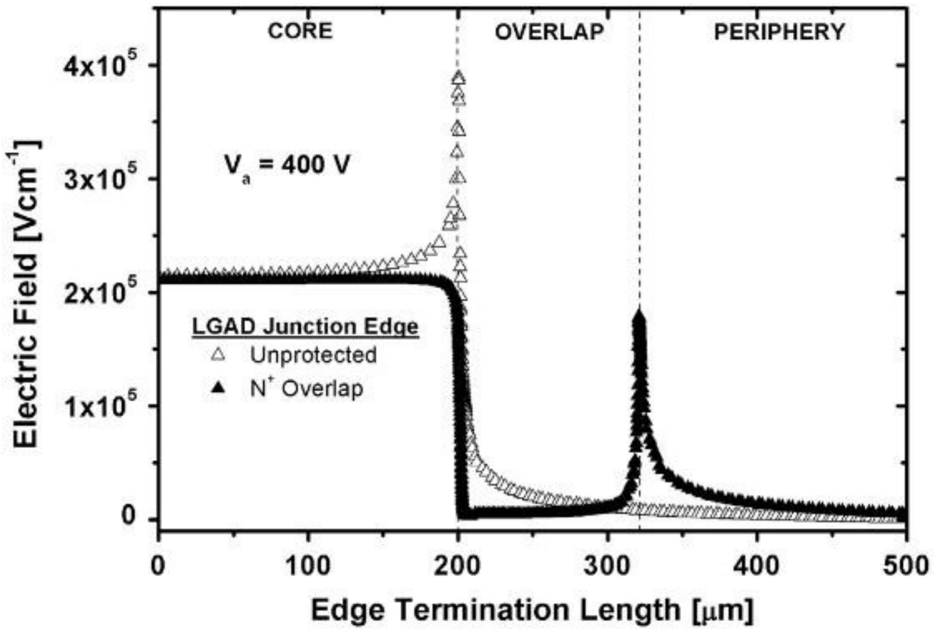


Fig. 7. Simulated electric field profile at the shallow N^+ junction depth for an edge termination consisting of an extension of the N^+ electrode diffusion beyond the junction curvature at a reverse bias of 400 V.

3. Deep N-type diffusion

- Requires an additional mask level
- Corroborate the reduction of the electric field profile at the N+ junction depth

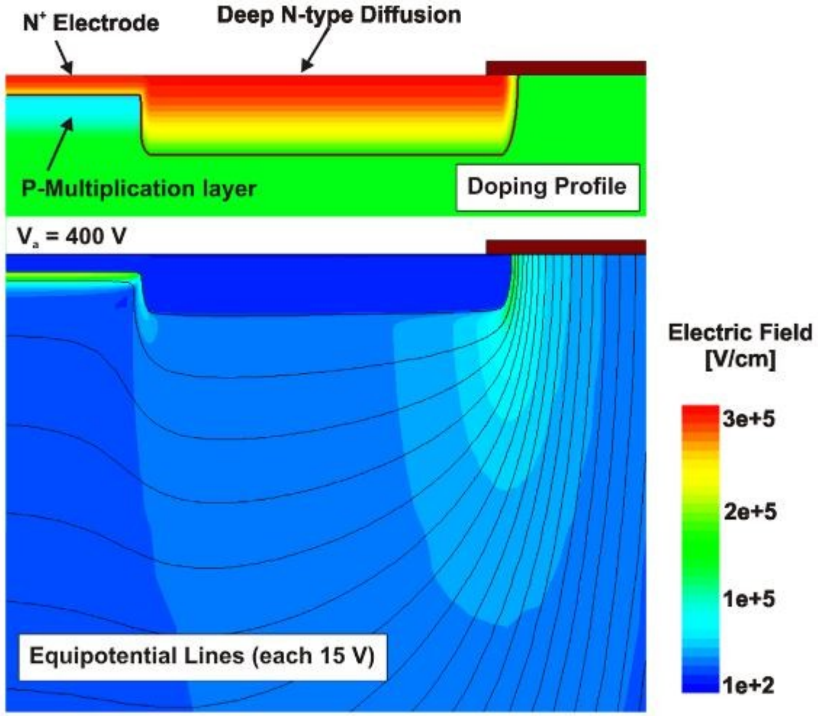


Fig. 9. Simulated doping profile (top) and electric field combined with equipotential lines distribution (bottom) at a reverse bias of 400 V when the deep N-type diffusion is implemented.

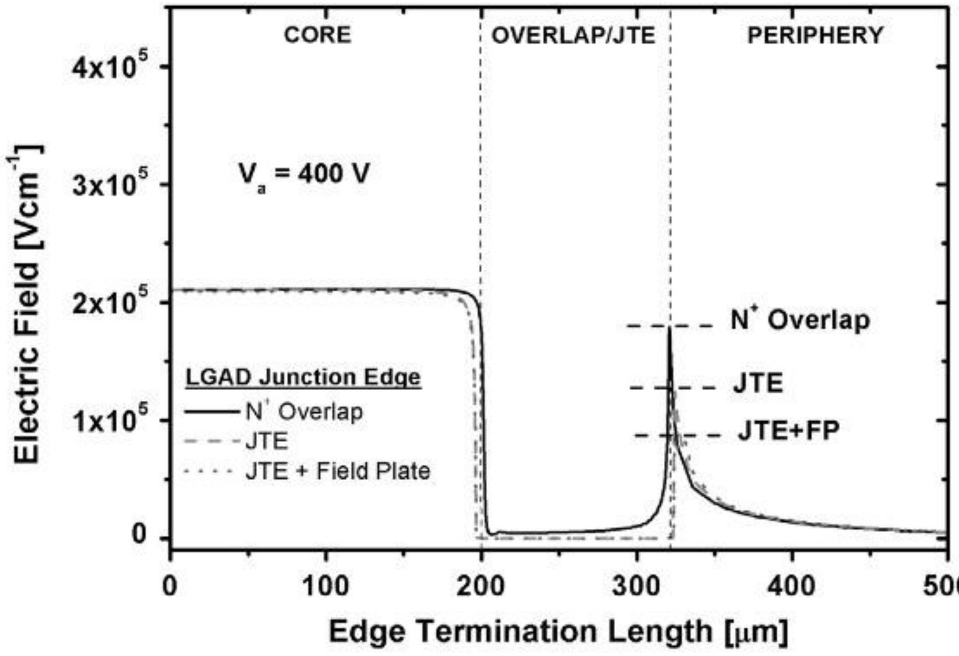


Fig. 10. Simulated electric field profile at the shallow N^+ junction depth for a multiplication junction protected by the extension of the N^+ electrode (N^+ overlap) and by a deep N-type diffusion (JTE) with and without Field Plate (FP) at a reverse bias of 400 V.

Question from Yuhang:

- Junction Termination Extension is a technique for increasing avalanche breakdown voltage and controlling surface electric fields in P-N junctions. But the extension of the shallow N+ diffusion does not provide a high breakdown voltage, the relationship between Junction Termination Extension and Deep N-type diffusion.

➢ If you're asking the what the relationship between them is, I would say that Junction Termination Extension is just a kind of technique for us to get deep N-type diffusion.

Peripheral region

- To obtain high performing LGAD detectors able to sustain high voltage values with minimum leakage current injection into the core region

1. General aspects

- If the peripheral region is too short, the depletion region can eventually reach the chip edge, leading to a high current injection into the core region.
- A common design rule to avoid this undesirable effect lies in extending the peripheral length **at least twice the thickness** of the substrate.

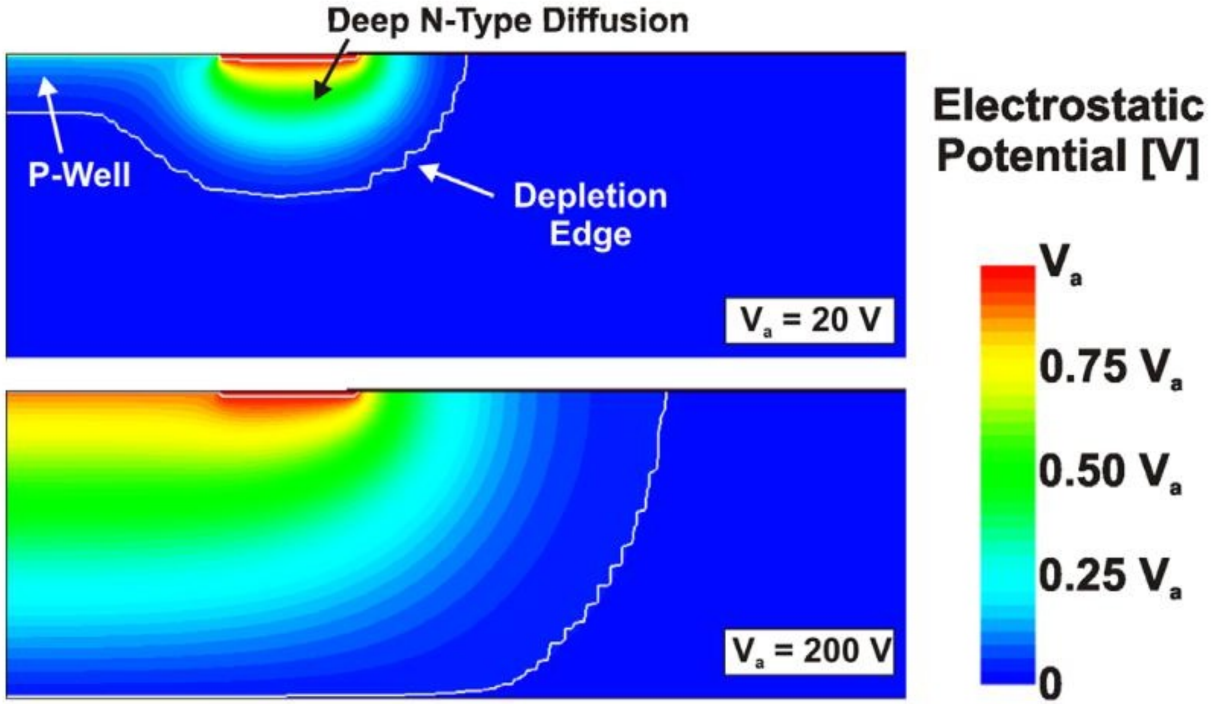


Fig. 12. Simulated depletion dynamics in the peripheral region of an LGAD detector at reverse bias of 20 V ($< V_{FD}$) and 200 V ($> V_{FD}$).

2. Positive oxide charges

- Carriers generated in the peripheral region do not undergo multiplication since they are not collected through the multiplication junction.
- Hence, the detector readout may show two superposed signals.

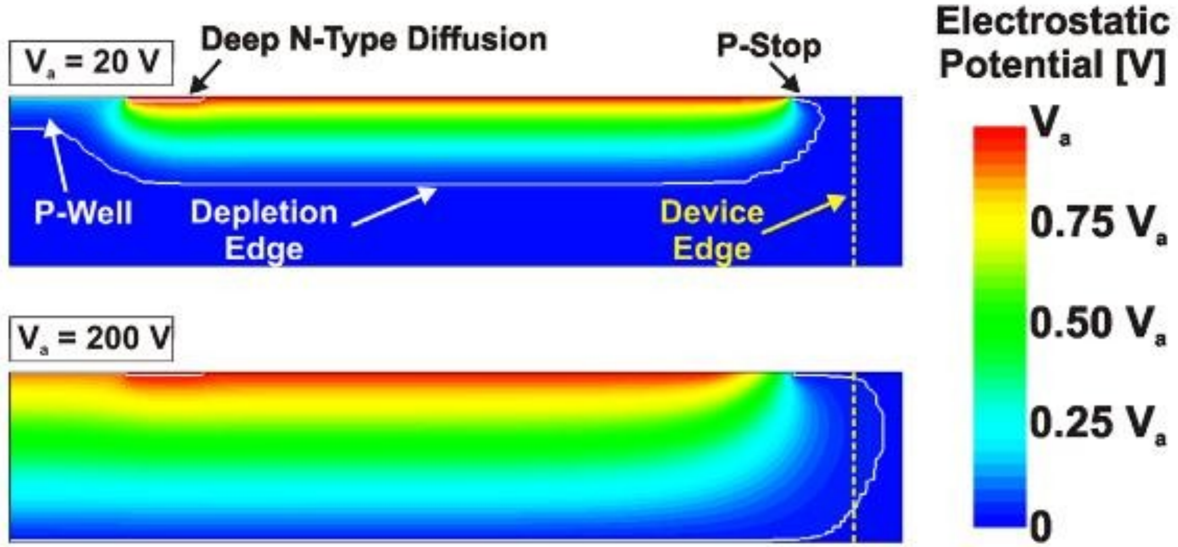


Fig. 14. Depletion dynamics with a 1e11 cm^{-2} of positive fixed charges in the field oxide.

3. Collector ring

- The surface leakage current in high resistive substrates significantly degrades the signal-to-noise ratio in radiation detectors.
- Implemented with the same deep N-type diffusion used in the edge termination structure and placed close to the core region edge to avoid the sustaining voltage capability degradation, the collector ring collects the bulk and the surface leakage currents generated within the detector periphery.

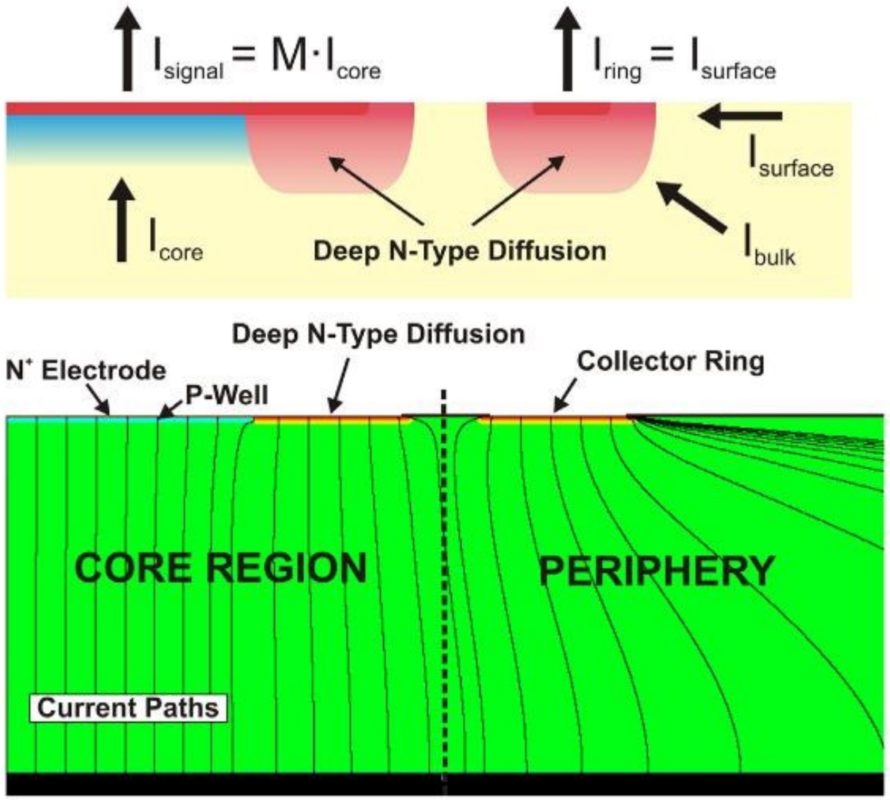


Fig. 13. Schematic operation of an LGAD detector provided with a collector ring (top) and simulated current paths (bottom).

4. P-Spray and P-Stop

- To avoid an electrical connection between the detection electrode and the added ring.

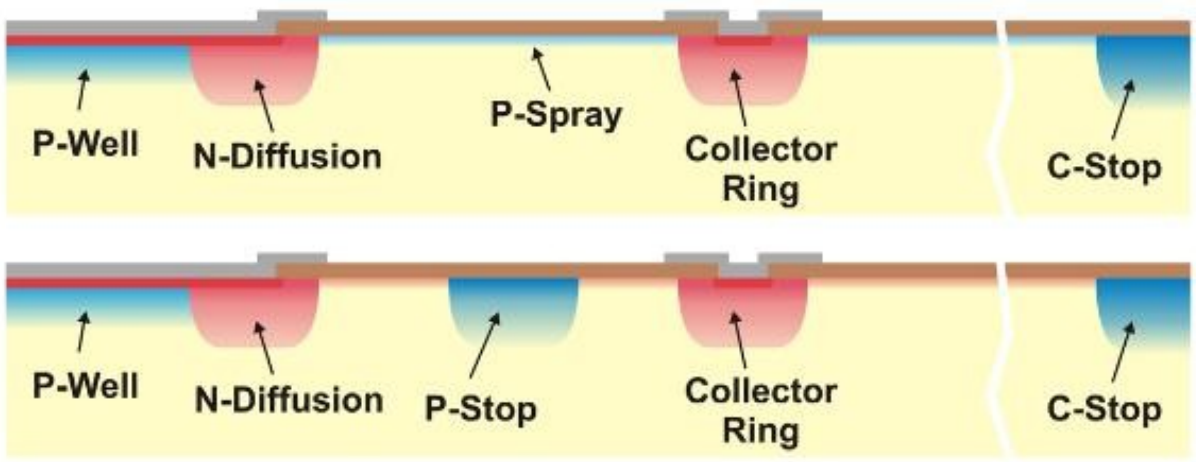


Fig. 15. Technical solutions to avoid the surface inversion effect in very low doped P-type substrates due to the positive fixed charges in the field oxide.

requires a precise control of implantation process and the total thermal budget

created by using the channel stopper implantation, the most effective way to eliminate the surface current path at the cost of added peripheral area

Experimental results

- The LGAD detector exhibits a 5 times higher leakage current than that of the corresponding PiN diode counterpart at a reverse bias of 400V due to the inherent multiplication effect.

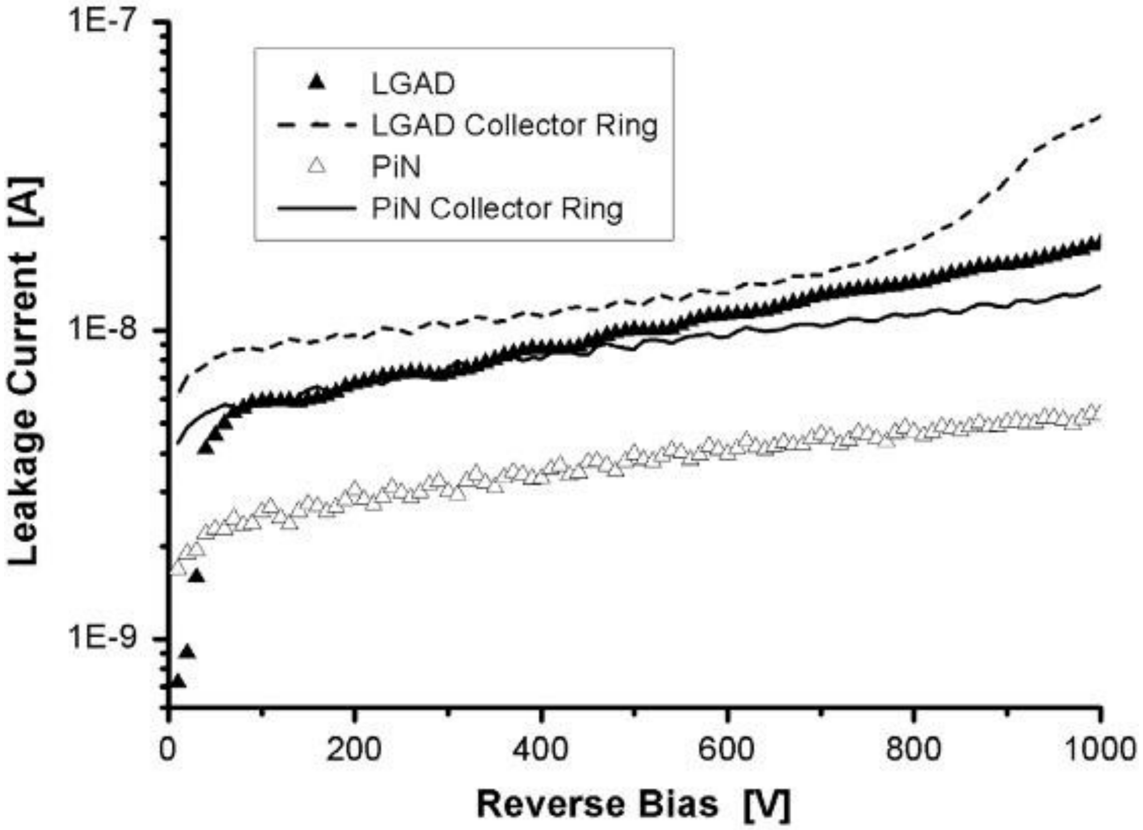


Fig. 16. Experimental I(V) characteristics of equivalent LGAD and PiN detectors.

Experimental results

20 °C, amplitude of 500 mV, frequency of 10 kHz

- An initial high capacitance value is found until the P-type multiplication layer is completely depleted. Then, the capacitance decreases with the applied reverse bias until the full depletion of the substrate. From VFD on, the capacitance is almost constant with a littile contribution of the lateral spread of te depletion region.

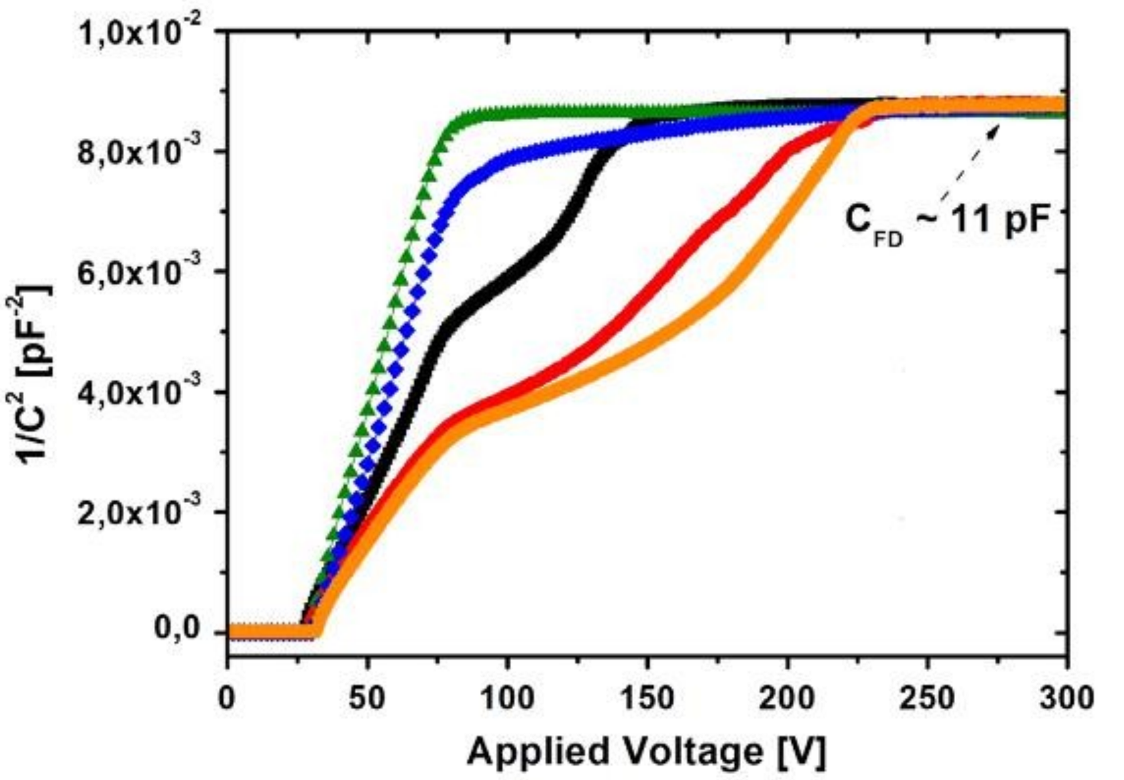


Fig. 17. Experimental capacitance performance ($1/C^2$ versus V) of fabricated LGAD detectors with P-Spray to avoid surface inversion.

Question from Xin:

- In the end, why “The use of a different dielectric on top of the peripheral region with reduced or even negative charge density could enhance the detector performance without using any additional P- type diffusion at the peripheral region.” ?

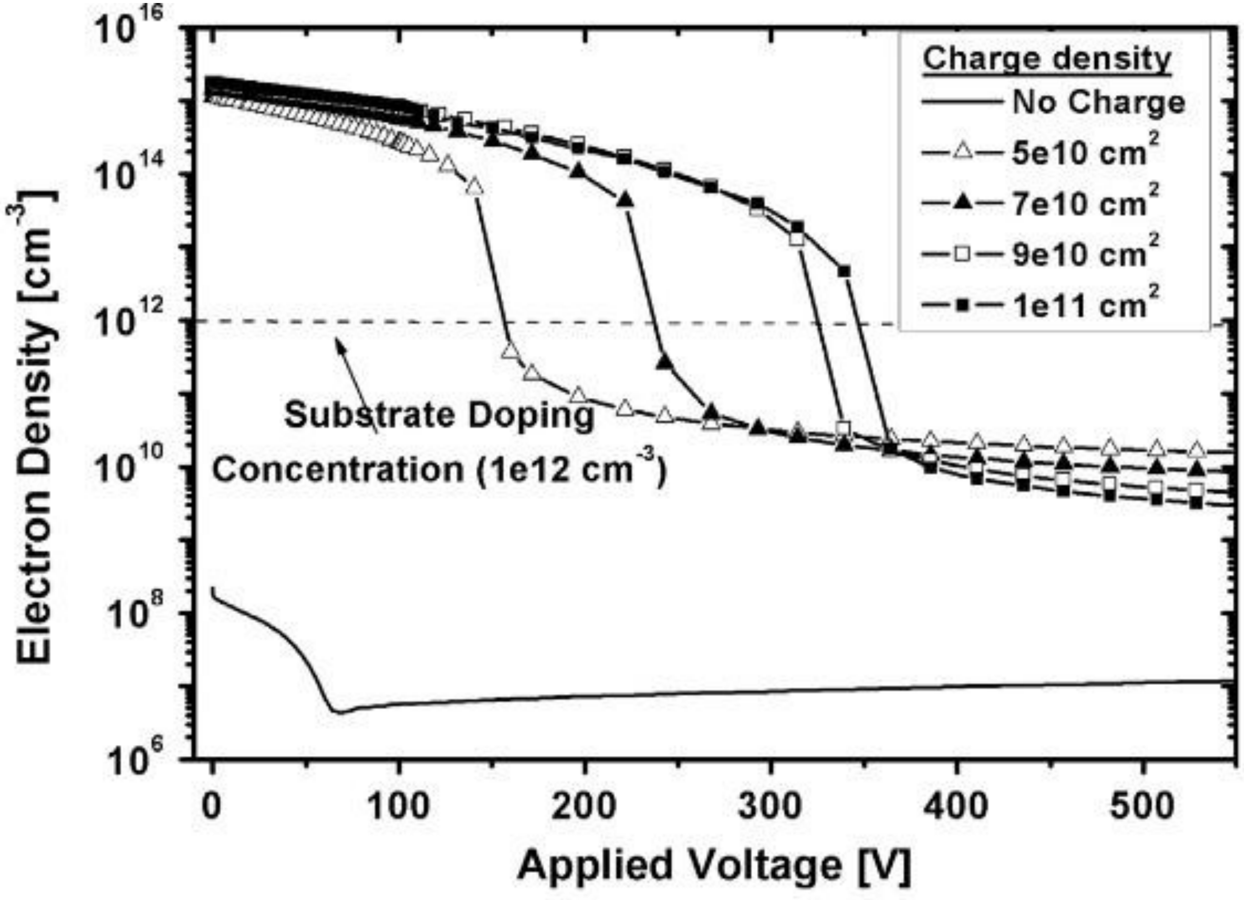


Fig. 18. Simulated electron density at the Silicon surface of the peripheral region.

Conclusions

- The deep N-type diffusion is the best performing solution in terms of electric field profile at the Silicon surface.
- The P-Stop diffusion is also included to eliminate the electrical connection between N-type diffusions due to the surface inversion layer.