Signal Formation in Heavily Irradiated Silicon Particle Sensors under Charge Multiplication

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Introduction

• Aims:
  • Previous studies showed that irradiated and long annealed silicon sensors undergo charge multiplication
  • Investigation of heavy charge multiplication and the signal pulse

• Materials:
  • P-type silicon strip detectors
  • Irradiated up to a fluence of $2 \times 10^{15} \frac{n_{eq}}{cm^2}$
  • Annealed at temperatures between 60°C and 80°C

• Methods:
  • Charge collection, electric field and signal pulse measurements:
    ➢ Beta-source measurements using the ALIBAVA readout system
    ➢ Edge and top-TCT measurements
• Increase of charge and leakage current with continuous annealing
  ➢ Charge Multiplication increases
• Instable effect
• No Landau distribution recognizable any more
• Saturating the readout electronics
Signal pulse change in beta measurements

- The number of entries also decreases significantly -> Pulse exceeds the integration time
- Electronics saturate and oscillations occur
Non irradiated

- Fully depleted, signal collection also from back side
- Signal shows the sum of holes and electrons contributions
- Short pulse duration, of similar length

Unirradiated Sensor, 400 V

![Graph showing time vs. amplitude for different distances from strips]
- High field at the implants but no field at the back side, no signal
- Collection happen only on the depletion region and the only signals are therefore fast
- Charge loss in case of a MIP

Fluence: $1 \cdot 10^{15} \text{n}_{eq}/\text{cm}^2$

$60^\circ\text{C} 5000 \text{ min annealed Sensor, 800 V}$
Fluence: $1 \cdot 10^{15} \frac{n_{eq}}{cm^2}$, heavy charge multiplication

- Large hole contribution at backside:
  - Electrons reach junction and are multiplied producing a second holes cloud going back
  - Can lead to a ballistic deficit

- Is there electric field in the non depleted region?

60°C 5000 min annealed Sensor, 1100 V

70°C 2000 min annealed Sensor, 1100 V
**Fluence: $1 \cdot 10^{15} \text{n}_{eq}/\text{cm}^2$, 70\textdegree C Annealing, 1100 V**

- **Pulse length** approximately constant through entire sensor up to light charge multiplication
- **Contribution at the backside** vanishes in reverse annealing
- **Significant increase in duration** from light to heavy CM

**Edge-TCT Measurements**

- **a)** Beneficial Annealing, 70 min
- **b)** Reverse Annealing, 250 min
- **c)** Light CM, 500 min
- **d)** Heavy CM, 2000 min
• No abrupt depletion zone visible anymore for high voltages and still high charge
  ➢ Electric field also in the “neutral” bulk (ENB)[Kram] allowing electrons to reach the junction and multiply

Pulses from multiplied holes should have same steepness, as they experience the same electric field profile.

Pulse amplitude should be also the same.

- Measured a lower and much slower signal decay from the back.

- Broadening and trapping of the electron cloud created in the low field region.
  - Dispersed when reaching the multiplication point.

Question: why pulses from the back are so slower? Why are they lower?
Edge-TCT Measurements

Plasma Effect

- 400 V -> 700 V: Expected faster falling edge of the signal, cause higher voltage -> higher el. field -> higher velocity
- 700 V -> 1000 V: Unexpected slower falling edge of the signal
  - Plasma effect: Multiplied holes underly a self-screening effect and travel slower
  - Carriers drift apart due to diffusion and electrostatic repulsion -> lateral spread
  - Increases charge collection time by so-called plasma time

• Fluence: $1 \cdot 10^{15} \frac{n_{eq}}{cm^2}$, annealed 2000 min at 70°C
• Signal measured close to end of depletion zone
Top-TCT Measurements

Laser on sensor top

S: Signal Strip
N1: 1\textsuperscript{st} Neighbor
N2: 2\textsuperscript{nd} Neighbor

- Electrons immediately collected, holes travel to the backside
- Signal Strip: Longer pulse at 1100V due to slow, larger hole contribution
- 1\textsuperscript{st} Neighbor: El. and holes visible for both voltages
- 2\textsuperscript{nd} Neighbor: No hole contribution at 500V, but at 1100V \textgreater higher cluster size at 1100V
Top-TCT Measurements

- At 500V: Short signals, small hole contribution only around the signal strip
- At 1100V: Long pulses, large hole contribution, also for more neighbors
  - Plasma effect prolongs the signal
  - Electrostatic repulsion and diffusion enlargens the hole cloud
  - Increase of cluster size

Missing hole contribution at 500V also explains negative signals measured in highly irradiated sensors close to neighboring strips.
Conclusion

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• Heavy charge multiplication introduces a significant multiplied hole contribution

• Long pulses observed especially in back of the sensor, where no pulse is expected
  ➢ Charge collected throughout the entire sensor area

• Electric field present also in the non depleted area (ENB)
  ➢ Leads to long pulses due to diffusion
  ➢ Smaller amplitude due to trapping

• Plasma effect: Multiplied holes travel through the sensor and underly a self-screening effect
  ➢ Increase of signal pulse length
  ➢ Can lead to a ballistic deficit

• Due to electrostatic repulsion and diffusion: Increasing cluster size due to the hole contribution
Conclusion

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Thanks for your attention!
• Charge multiplication

  • High field close to strip implants saturates carrier speed and produces „hot“ carriers
  • Hot carriers cause impact ionization: electron-hole pair creation
  • Avalanche mechanisms: charge collection diverges

• Plasma effect

  • Free carriers are not negligible and influence the electric field distribution: screening effect -> charge „clouds“ travel slower.
  • Carriers drift apart due to diffusion and electrostatic repulsion -> lateral spread.
    • Increases charge collection time by so-called plasma time.
Experimental results and discussion

- Laser: $2 \times 10^{16} \text{n}_{eq}/\text{cm}^2$: discussion: “compensation” effect

- Very large and very negative zones

- Junction columns profile

- Larger than at lower fluence: relatively higher field distributed closer to the junction columns.

- Ohmic columns profile

- h25_py_col
  - Entries: 101
  - Mean: 34.41
  - RMS: 28.36
Bacup: Setups and Techniques

Edge-TCT Measurements

Fluence: $1 \cdot 10^{15} n_{eq}/cm^2$

- Cluster size decreases during reverse annealing.
- Keeps decreasing in light CM due to more focused charge collection near strips.
- Increase during heavy CM, hinting to a large hole contribution, spread due to diffusion and electrostatic repulsion.
Charge multiplication doesn’t depend on temperature:

Avalanche phenomena is not so strongly depending on temperature [1]:

[1] Crowell and Sze, TEMPERATURE DEPENDENCE OF AVALANCHE MULTIPLICATION IN SEMICONDUCTORS, APL (1966)
Landaus 1100V

575 min
MPV: 39.5 ± 1.3 ke

600 min
MPV: 34.5 ± 1.3 ke