Study of Behaviour of n-in-p Silicon Sensor Structures Before and After Irradiation

n-in-p Structures and Measurements

- In case of n-in-p sensor with p-stop isolation
- Inter-strip/pixel resistance between two readout implants
- Electric potential of p-stop structures
- Onset voltages of Punch-Through Protection (PTP) structures
- Location of microdischarge (MD) at high voltages

Y. Unno, 2013/2/18
Proton Irradiations at CYRIC

- Tohoku University, Sendai, Japan
- 70 MeV protons from 930AVF Cyclotron
- Irradiation setup in the 32 course
  - CYRIC exp. no. 9214
- Fluences:
  - $5.2 \times 10^{12}, 1.1 \times 10^{13}, 1.2 \times 10^{14}, 1.2 \times 10^{15} \text{ } n_{eq}/\text{cm}^2$
Let’s first go through measurements
Inter strip resistance decreased as accumulating the fluence

– It is due to the “radiation damage”, but which damage?
Potential of P-stop Structure

- Electric potential of p-stop implant decreased first (around $1 \times 10^{13}$) and then saturated.
  - It sounds familiar...

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Punch-Through Protection (PTP) Structure

- “Full gate” induced PTP onset in lower voltages than “No gate”.
- Onset voltage went down first and then started to increase.
  - What causes the transitions?

Fluence dependence of PTP onset voltage

- BZ4D-3 (No gate)
- BZ4D-5 (Full gate)
After \( \gamma \) irradiation, onset of microdischarge occurred at the n-implant, instead of p-stop edges, and “annealed” along the accumulation of dose.

- MD at n-implant edge could be a “corner” effect, but ...
- (A warning: Be prepared for a large drop of MD onset voltage initially.)
Microdischarge After Irradiation

S. Mitsui et al.,
Nucl. Instr. Meth. A699 (203) 36-40

• Hot electron images confirm that
  – hot spots were observed first at the edge of the bias ring, and then at the inside of the edge metal.
  – the highest electric field is at the bias ring ($n^+$ implant), not at the edge ring ($p^+$ implant).

CYRIC proton irradiated
$1 \times 10^{14} \, n_{eq}/cm^2$
10 uA at 2000 V
-15 °C

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How can we explain these measurements with TCAD simulations?

(The summary of my last year’s presentation was)

• Performance before and after irradiation has been accumulated.
  – We have had a number of evidences that require a fundamental explanation.
    • The explanation must be simple if understood (my guess).
  – If you have already had the explanation, let’s have a dinner together.
  – We hope to have a quantitative explanation by the next workshop.
TCAD Simulation

• Semiconductor Technology Computer-Aided Design (TCAD) tool
  – ENEXSS 5.5, developed by SELETE in Japan
  – Device simulation part: HyDeLEOS

• N-in-p strip sensor
  – 75 µm pitch, p-stop $4 \times 10^{12} \text{ cm}^{-2}$
  – 150 µm thickness
  – p-type bulk, $N_{\text{eff}} = 4.7 \times 10^{12} \text{ cm}^{-3}$, $V_{FDV} = 80 \text{ V at } 150 \mu\text{m}$

• Radiation damage approximation:
  – Increase of acceptor-like state $\leftarrow$ Effective doping concentration
  – Increase of leakage current $\leftarrow$ SRH model
  – Increase of interface charge $\leftarrow$ Fixed oxide charge

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Simulation of the bulk current

• After irradiation, the current increases as a function of fluence as
  – $\Delta I / V \sim 4 \times 10^{-17} \text{ (A/cm)} \times \phi (n_{eq}/\text{cm}^2)$
  – E.g.,
    • Volume = 75 µm x 1 µm x 150 µm = 1.13 x 10^{-8} cm³
    • $\phi=1\times10^{15} n_{eq}/\text{cm}^2$
    • $\Delta I \sim 45$ nA

• Community has a view that
  – the leakage current increases with an introduction of levels near the middle of the forbidden band,
  – with the energy of band gap being half (of the full gap), the leakage current flows order of magnitude larger...

• Unfortunately, we have no freedom to change/add a program to the ENEXSS, but
  – we can tune the leakage current by modifying the model parameters to an unrealistic world...

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Shockley-Reed-Hall (SRH) Model

• Leakage current: SRH model
  – Generation-recombination of carriers (electrons and holes)
  – $A_n, A_p$, etc. are model parameters.

$$U_{SRH} = \frac{n^2_i - pn}{\tau_p (n + n_i) + \tau_n (p + n_i)}$$

$$\tau_{n,p} = A_{n,p} \left( \tau_{n,p}^{\min} + \frac{\tau_{n,p}^{\max} - \tau_{n,p}^{\min} \left( N / N_{n,p}^{t} \right)^{B_{n,p}}} {1 + \left( N / N_{n,p}^{t} \right)^{B_{n,p}}} \right)$$

$n_i$: intrinsic carrier density,

$n, p$: electron, hole carrier density
Increase of Leakage Current

- SRH $A_n, A_p = 1.0$ (default)
- Saturated current $\sim 3.7$ pA

- SRH $A_n, A_p = 1 \times 10^{-8}$
- Current $\sim 6.7$ nA (at 200 V)
  - 3 orders of magnitude increase
Leakage Current at 200 V

Leakage current can be increased by 3 orders of magnitude by varying the SRH modeling parameter, $A_n$ and $A_p$.

- Current saturates when $A_n, A_p < 1 \times 10^{-8}$
- Current can be tuned by a factor between 1 and $10^3$
Radiation Damage Approximation

- **Green**: Irrad.
  - Increase of full depletion voltage, $N_{\text{eff}}=1.5 \times 10^{13} \text{ cm}^{-3}$
  - Increase of leakage current, $A_n, A_p = 1 \times 10^{-8}$
- **Black**: non-irrad.
  - $N_{\text{eff}}=4.7 \times 10^{12} \text{ cm}^{-3}$, $A_n, A_p = 1.0$
- **Potential in bulk, Leakage currents**
  - Backplane at 200 V

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Decrease of interstrip resistance is qualitatively explained by the increase of leakage current (after irradiation).

- Other factors, the effective doping concentration nor the oxide interface charge, do not change the interstrip resistance.
- In retrospect, it is natural that the current is the other face of the resistance.
PTP Simulations

• TCAD
  – no bias resistor in parallel
  – NPTP: “No gate”
  – Others: “Full gate”

• Parameters:
  – NB/DB: non/damaged bulk
  – LT/HT: lo/hi interface charge
  – LC/HC: lo/hi current
  – Non irrad: NB*LT*LC
  – Irrad: DB*HT*HC

Irrad. simulation
  – Damaged bulk,
  – hi interface charge,
  – hi leakage current

TCAD simulation of
“Full gate” PTP, irradiated
Electric field at onset
when the backplane bias voltage at -200 V
$V_{test}$ (left implant) at -50 V

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PTP Simulations

- The fluence dependence can be understood as the effect of
  - Build-up of the Interface charge and
  - Increase of acceptor-like levels.
- The systematic “offset”
  - difference between the 2D simulation and the 3D real.

- Onset voltage decreased as
  - No gate (black) → Full gate (colored)
  - Interface charge increased
- Increased as
  - accepter-like state increased
Electric potential of p-stop
- Introduction of Si-SiO₂ interface charge -

- Non-irrad:
  - \( N_{\text{eff}} = 4.7 \times 10^{12} \text{ cm}^{-3} \),
  - SRH \( A_n, A_p = 1.0 \),
  - Fixed Oxide Charge = \( 1 \times 10^{10} \text{ cm}^{-2} \)

- Irrad:
  - \( N_{\text{eff}} = 1.5 \times 10^{13} \text{ cm}^{-3} \),
  - SRH \( A_n, A_p = 1 \times 10^{-8} \),
  - Fixed Oxide Charge = \( 1 \times 10^{12} \text{ cm}^{-2} \)
**Electric Potential between Strips**

- **Electric potential of p-stop**
  - decreases as the interface charge increases positively,
  - increases as the interface charge increases negatively.
  - Measurement confirms that the built-up interface charge is positive.

- **Location of the largest electric field is**
  - at n-implant side with the positive interface charge of \(+1 \times 10^{10} \text{ cm}^{-2}\),
  - moves at the p-stop side with \(+1 \times 10^{12}\).
  - The field is enhanced if the interface charge is negative, e.g., \(-1 \times 10^{12}\).
• Under the “Irradiated” condition, increasing the bias voltage to the limit.
• Breakdown occurs at high voltage at the $n^+$ edge, although the $p$-stop edge was the highest electric field at lower bias voltages.
• The rate to increase of the electric field at the $p$-stop edge is saturating at higher voltage.
• The $p$-$n$ junction eventually overtakes the highest electric field by the time of breakdown.

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Insight into what is happening

- Electron inversion layer is diminishing
  - as the bias voltage is being increased.
  - This also explains that in p-bulk the bias voltage helps to isolate the n+ implants.
- A triumph of TCAD 😊/~
Summary

• Performance of various structures in the n-in-p silicon sensors, before and after irradiation, has been measured and understood.

• Fluence dependence is understood as:
  – Decrease of the interstrip resistance is the effect of radiation damage that leads to the increase of leakage current.
  – Decrease of electric potential of the p-stop structure is the build-up of the Si-SiO₂ interface charges that is positive.
  – Decrease and increase of PTP onset voltage is the build-up of the interface charges AND the increase of effective doping concentration by radiation damage.

• Location of microdischarge at high voltages is
  – at the n⁺ edge, and not the p⁺ edge, and
  – understood as the effect of diminishing electron inversion layer from the interstrip region and the faster increase of electric field at the p-n junction at the n⁺ edge.