Effects of neutron irradiation on HV-JFETs

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• HV silicon JFET  
  → for multiplexing in ATLAS ITk  
  ▪ concept  
  ▪ Measurements after irradiation  
    (TRIGA, JSI, Ljubljana, Slovenia)  
  ▪ TCAD simulation to get insight of the physics  

Review other known irradiation effects:  
- Double peak in electric field  
- Stability of scribeline  

All silicon process done in BNL Instrumentation Division Class-100 Clean Room

- Furnaces for dry oxidations and annealings  
- Double-sided mask aligner  
- Wet bench (HF, RCA I & II, piranha, polyetch, …)  
- Sputtering (Al, Al1%Si, Ti)  
- RTA for sintering  
- Laser dicing  

+ dry etching and thin films deposition, but we need to outsource:  
• Ion implantation  
• Polysilicon deposition
A novel HV silicon JFET for ATLAS, and other silicon R&D activities at BNL

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Irradiated at the TRIGA reactor at JSI (Ljubljana, Slovenia) with 4e14, 8e14, 1.5 e15 \( n_{eq}/cm^2 \)
The vertical HV Silicon JFET

Originally, conceived as a rad-hard switch to be used in the ATLAS I'Tk HV-Mux. GaN JFETs are very rad-hard, so HV-Mux will go with GaN.

We can modify the structure of the standard JFET by making a gap in the bottom-gate. Over the gap, the top-gate. The channel and the source as in the standard JFET. The drain is the back contact. The current flows (= drifts) from source to drain through the gap in the bottom-gate. The high voltage applied to the drain falls in the thick substrate, being the bottom-gate almost a planar implant.

The highest electric field develops at the junction top-gate/channel, so special care in the choice of the parameters (hole width, channel doping concentration). GR termination also needed at the border of the bottom-gate.
Interdigitated design to increase the gate width and thus the ON current (especially after irradiation). The active area is 1x1 mm², which sets the gate width to 20 cm. Triode configuration, top-gate connected to the bottom-gate. 6 photolithographic masks, 4 implants. Both n-type and p-type JFET, on 4” epitaxial wafers (TOPSIL): 50µm thick, $N_C \sim 1e14 cm^{-3}$.
I-V characteristics before irradiation

Splittings on the channel dose. At the lower doses, the channel was pinched-off already at $V_{\text{gate}}=0\text{V}$. The higher the dose, the lower $V_{\text{BD}}$.

We irradiated the devices with higher current capability (but lower $V_{\text{bd}}$).
Irradiation results

Neutrons at TRIGA, JSI

**Not IRRADIATED**

\[ V_{\text{gate}} \text{ Step}=50\text{mV} \]

1- effect of acceptor removal: lower \( V_{\text{gate}} \) needed to pinch-off the channel
2- dramatic change of \( V_{\text{drain}, \text{Saturation}} \) with fluence
3- \( V_{\text{breakdown}} \) unchanged

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**IRR=4e14 n/cm\(^2\)**

\[ V_{\text{gate}} \text{ Step}=50\text{mV} \]

\[ V_{\text{gate}}=1.9\text{V} \]

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**IRR=8e14 n/cm\(^2\)**

\[ V_{\text{gate}} \text{ Step}=100\text{mV} \]

\[ V_{\text{gate}}=1.6\text{V} \]

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**IRR=1.5e15 n/cm\(^2\)**

\[ V_{\text{gate}} \text{ Step}=50\text{mV} \]

\[ V_{\text{gate}}=1.5\text{V} \]
Suitability as a switch for HV-Mux

**ON state:**
- ideally, $V_{\text{drain}} \sim 0$, $I_{\text{drain}} \sim \infty$
- $I_{\text{drain}}$, saturation limited by the channel dose (which needs to be small to have high VBD)
- $V_{\text{Drain}}$, saturation very high: high power dissipation within the JFET

**OFF state:**
- $V_{\text{breakdown}}$ low (600V needed)
- Gate leakage current $\sim$ OK

IRR=$1.5e15$ n/cm$^2$
Perugia model:

$\text{fluence} = \Phi \, n_{eq} / \text{cm}^2$

- Trap acceptor: $e_{level}=0.42$, $\text{density}=1.6 \times \Phi$, $\text{degen}=1$, $\text{sign}=2 \times 10^{-15}$, $\text{sigp}=2 \times 10^{-14}$
- Trap acceptor: $e_{level}=0.46$, $\text{density}=0.9 \times \Phi$, $\text{degen}=1$, $\text{sign}=5 \times 10^{-15}$, $\text{sigp}=5 \times 10^{-14}$
- Trap donor: $e_{level}=0.36$, $\text{density}=0.9 \times \Phi$, $\text{degen}=1$, $\text{sign}=2.5 \times 10^{-14}$, $\text{sigp}=2.5 \times 10^{-15}$
TCAD simulation of ideal irradiated HV-JFETs

1- Perugia model does not simulate acceptor removal:
saturation currents are the same for every fluence
2- still dramatic change of $V_{\text{drain}}$ vs fluence
The height of the potential barrier that the holes need to cross before injection to the substrate (drain) increases with fluence.

- The potential barrier is lowered by $V_{\text{drain}}$, so larger $V_{\text{drain}}$ must be applied at higher $\Phi$.

- The potential barrier is due to the build-up of positive charge, from the ionized donor traps (no electrons to fill-up the traps!!)
Other effects in irradiated Silicon that can be explained with trap charging – 1

Double peak of the electric field

- Plenty of electrons towards the n+
- So “all” traps are filled with electrons:
  - donor traps are neutral,
  - acceptor traps are negative
- net negative charge close to the n+ → regular junction n+/p-

- Plenty of holes towards the p+
- So “all” traps are empty
  - donor traps are positive
  - acceptor traps are neutral
- net positive charge close to the p+ → regular junction p+/n-

- Can be simulated using the Hamburg Penta Trap model (HPTM)
- In the explored parameter range (substrate thickness, fluence, bias voltage), Perugia model doesn’t show the double peak.
Simulation of the double peak of the electric field

HPTM with $\Phi=1\times10^{15}$ $n_{eq}/cm^2$

Dominated by donor traps (empty=ionized)

Dominated by acceptor trap (filled=ionized)
Other effects in irradiated Silicon that can be explained with trap charging – 2

Stability of scribeline

Known effect that, in pin diodes, after type inversion, the scribeline doesn’t inject much current

- From the damaged region, plenty of electrons and holes
- From the simulations: close to the scribeline,
  - 10% of any trap is ionized
  - 90% of Donor traps are filled (with electrons), and neutral
  - 90% of Acceptor traps are empty ($s_p = 10s_n$), and neutral
- Low potential!
Conclusions

A new silicon structure: vertical HV-JFET successfully fabricated at BNL

• Irradiated up to the fluence level of ITk ATLAS, and characterized
• Not really the best switch for the HV-Mux ...

• Curves explained with TCAD simulations
  \[ \rightarrow \text{high } V_{\text{drain, saturation}} \text{ due to positive charges,} \]
  \[ \text{introduced by ionized donor traps} \]

• Charged (ionized) traps explain other effects, for example:
  - stability of scribeline
  - double peak effect
  - ....
BACK-UP