Impact of heavy ion irradiation on GaN devices

In collaboration with Prof. Maik Lang , GSI & BNL

Prof. Rongming Chu group

Overview

Many thanks to Prof. Maik Lang, Dr. Eric Quinn & Dr. Voss, Kay-Obbe & GSI members

GSI – Ar ion on-site

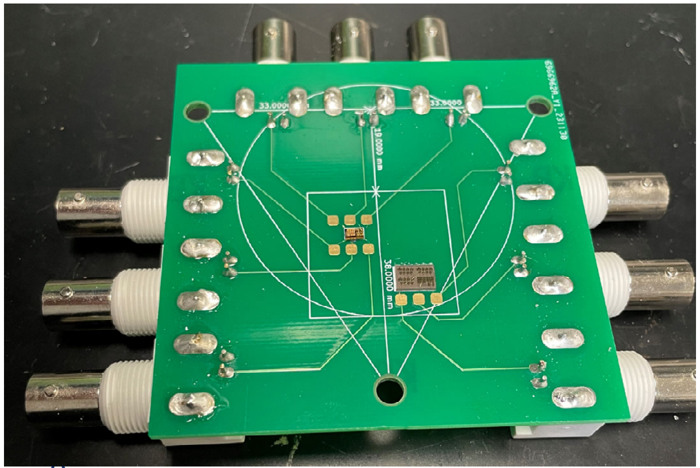
Ion	Energy	Range	LET (MeV/(mg/cm^2)
^{40}Ar	192 MeV (4.8 MeV/u)	26 μm	10.8

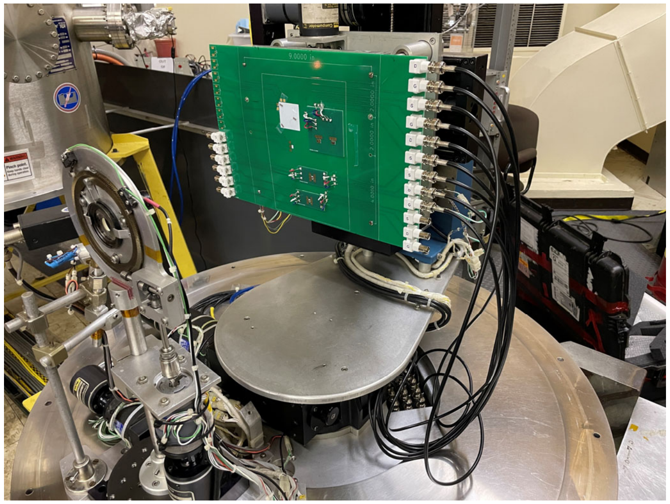
BNL – Au ion on-site

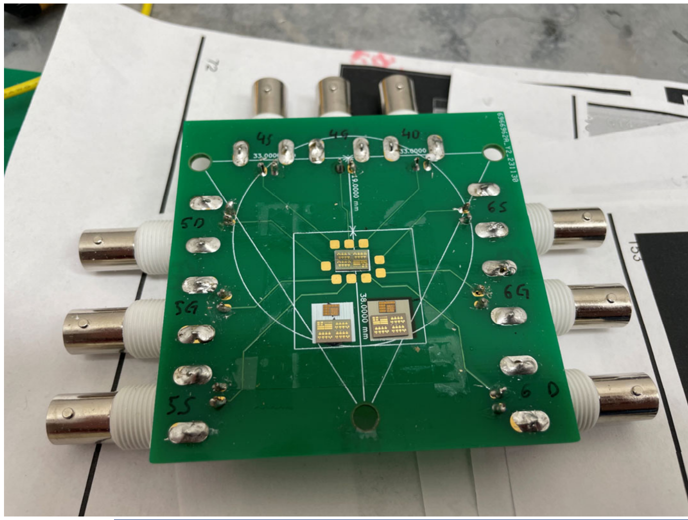
Ion	Energy	Range	LET (MeV/(mg/cm^2)
^{197}Au	333.7 MeV (1.71 MeV/u)	27.6 μm	81.47

GSI – Au ion

Ion	Energy	Range	LET (MeV/(mg/cm^2)
^{197}Au	950 MeV (4.8 MeV/u)	30 μm	72.4







Overview

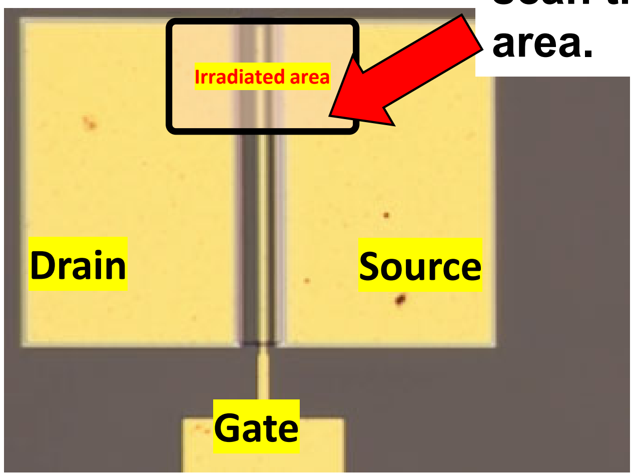
- ❑ **GSI – 192 MeV Ar – On-site test**
- ❑ **BNL – 333.7 MeV Au– On-site test**
- ❑ **GSI – 950 MeV Au – Ex-situ test**

Scanning recipe

Ion	Energy	Range	LET (MeV/(mg/cm²))
^{40}Ar	192 MeV (4.8 MeV/u)	26 µm	10.8

Fluence ramp

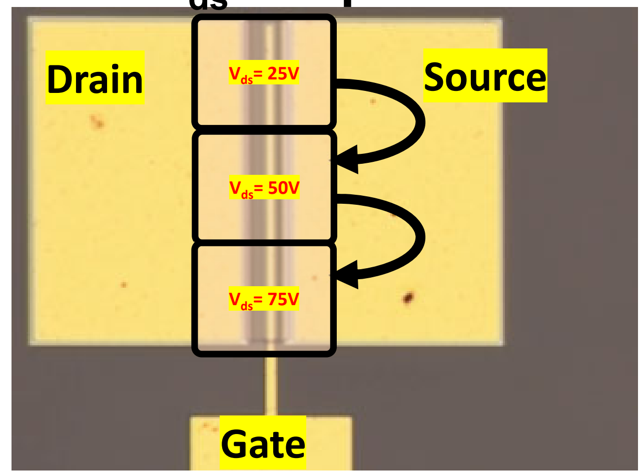
Repeatedly scan the area.

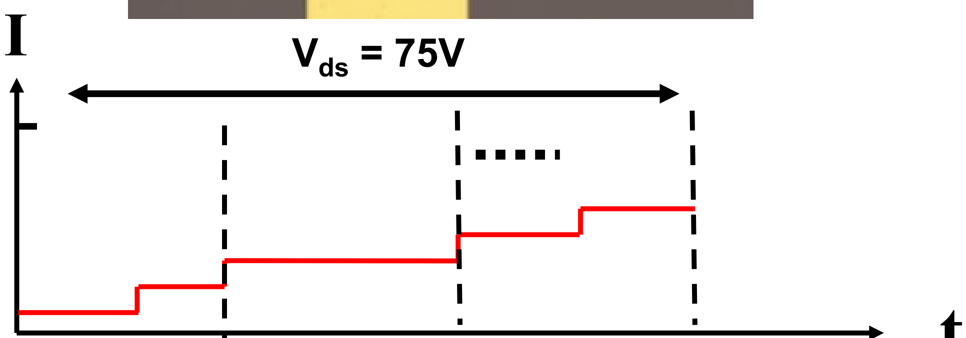


BV_{ds} = ~130V

Device bias at off-state during irradiation (V_{ds} = variable, V_{gs} = -6 V)

V_{ds} ramp

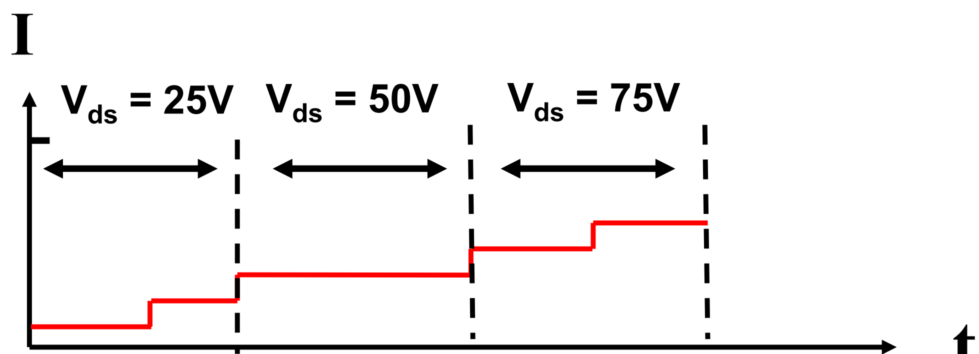




$1 \times 10^7\ \#/cm^2$ fluence

$2 \times 10^7\ \#/cm^2$ fluence

$1..1 \times 10^8\ \#/cm^2$ fluence



$1 \times 10^7\ \#/cm^2$ fluence each

Junction FET– Fluence ramp

Ion	Energy	Range	LET (MeV/(mg/cm^2))
^{40}Ar	192 MeV (4.8 MeV/u)	26 µm	10.8

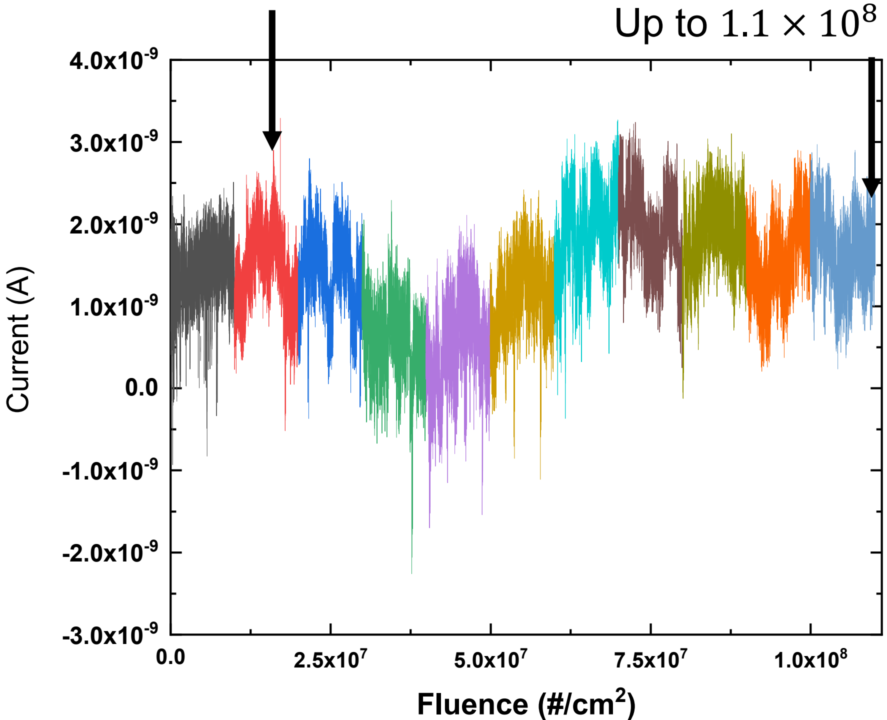
- No SEE detected up to $1.1 \times 10^8\ \#/cm^2$ fluence

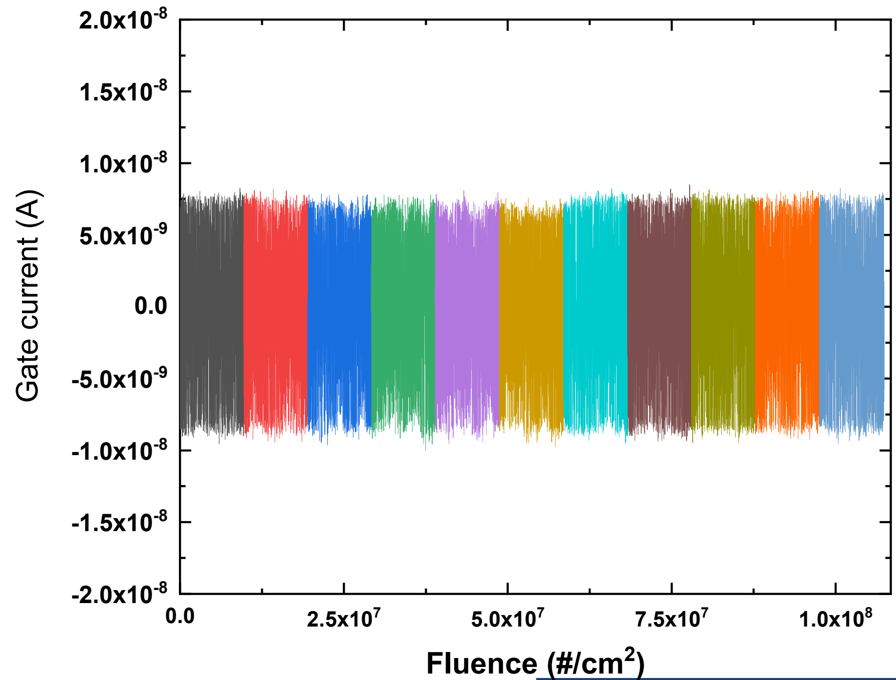
Gate current

Drain current

Each correspond to $1 \times 10^7\ \#/cm^2$ fluence

Up to $1.1 \times 10^8\ \#/cm^2$ fluence





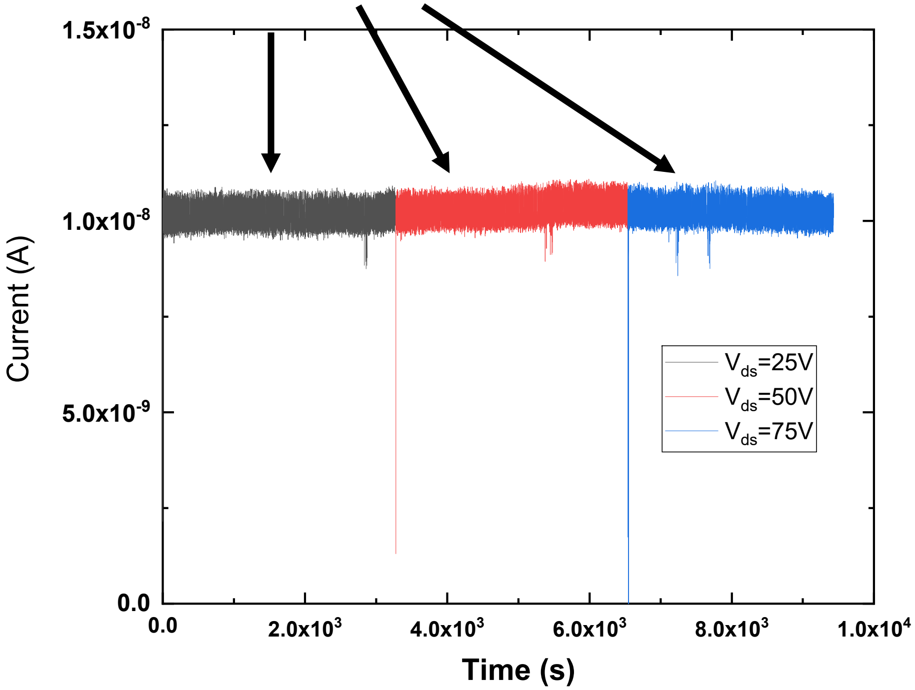
Junction FET– V_{ds} ramp

Ion	Energy	Range	LET (MeV/(mg/cm²))
^{40}Ar	192 MeV (4.8 MeV/u)	26 µm	10.8

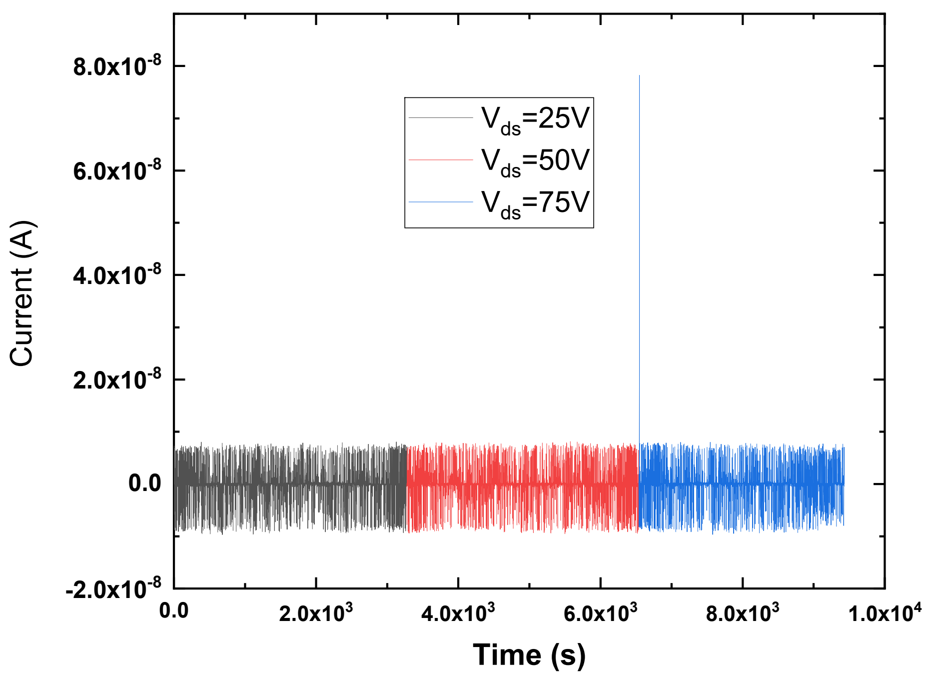
- No SEE detected up to $V_{ds} = 75\ V$

Gate current

Each correspond to $1 \times 10^7\ \#/cm^2$ fluence (non- cumulative)



Drain current



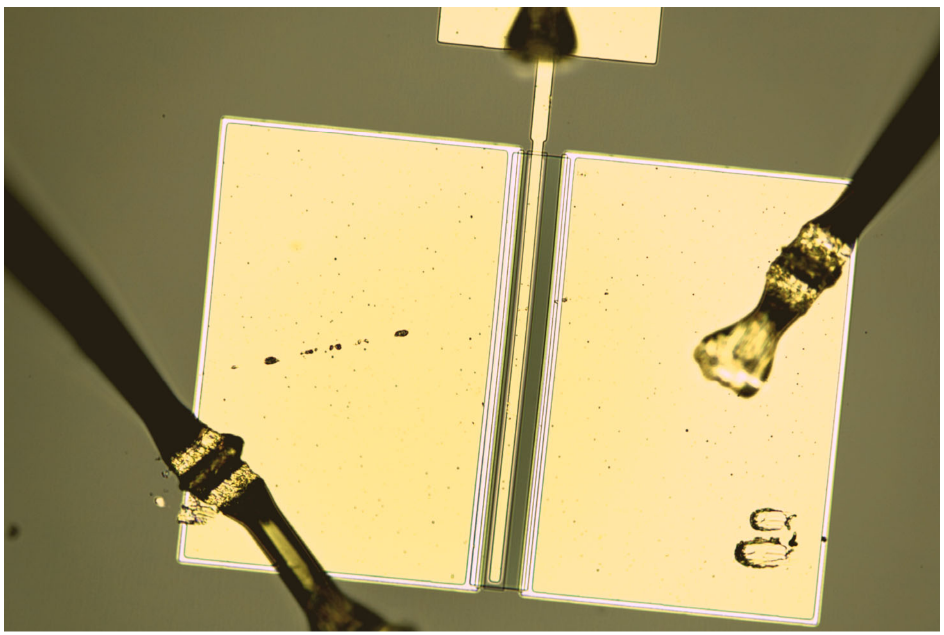
Overview

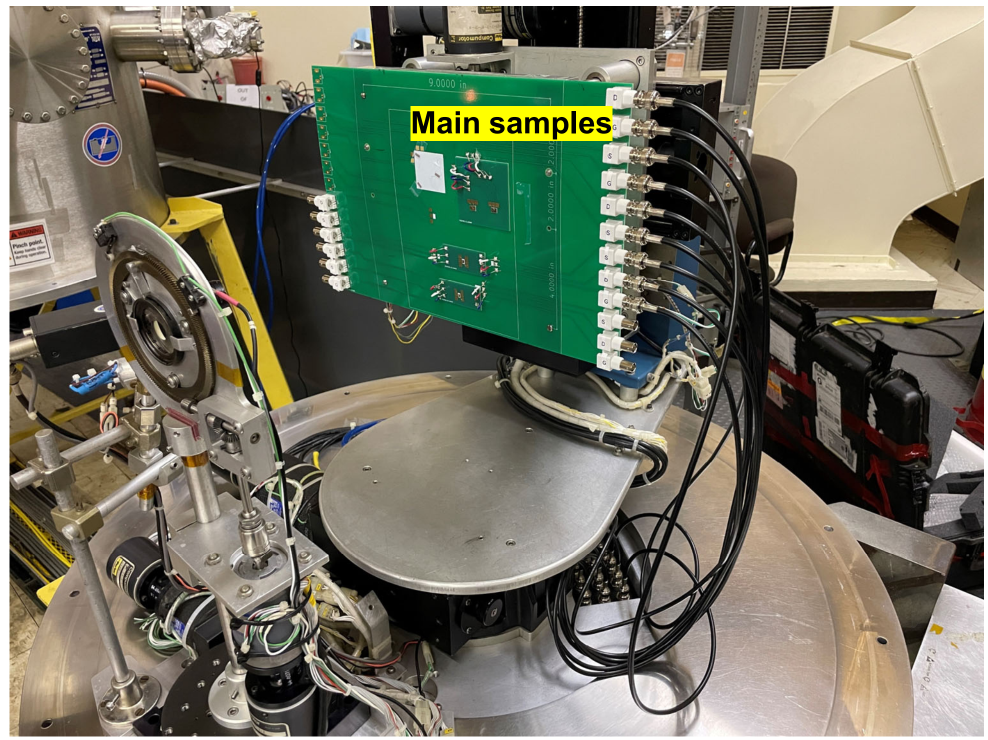
- ❑ GSI – 192 MeV Ar – On-site test
- ❑ **BNL – 333.7 MeV Au – On-site test**
- ❑ GSI – 950 MeV Au – Ex-situ test

Overview

Ion	Energy	Range	LET (MeV/(mg/cm^2))
^{197}Au	333.7 MeV (1.71 MeV/u)	27.6 µm	81.47

- PSU fabricated JFET, wire bonded
- Device bias at off-state during irradiation (V_{ds} = variable, V_{gs} = -6 V)
- Broad beam covers full sample



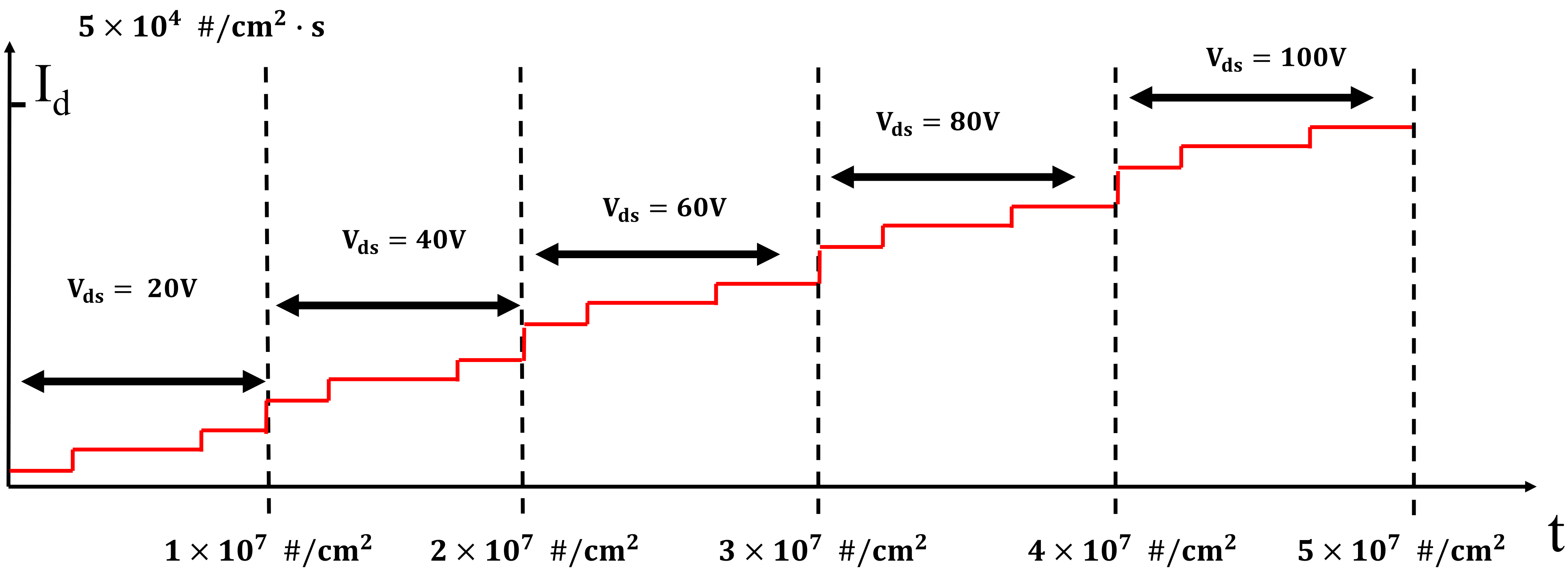


Scanning recipe

Ion	Energy	Range	LET (MeV/(mg/cm^2))
^{197}Au	333.7 MeV (1.71 MeV/u)	27.6 µm	81.47

Sampling interval : 50ms

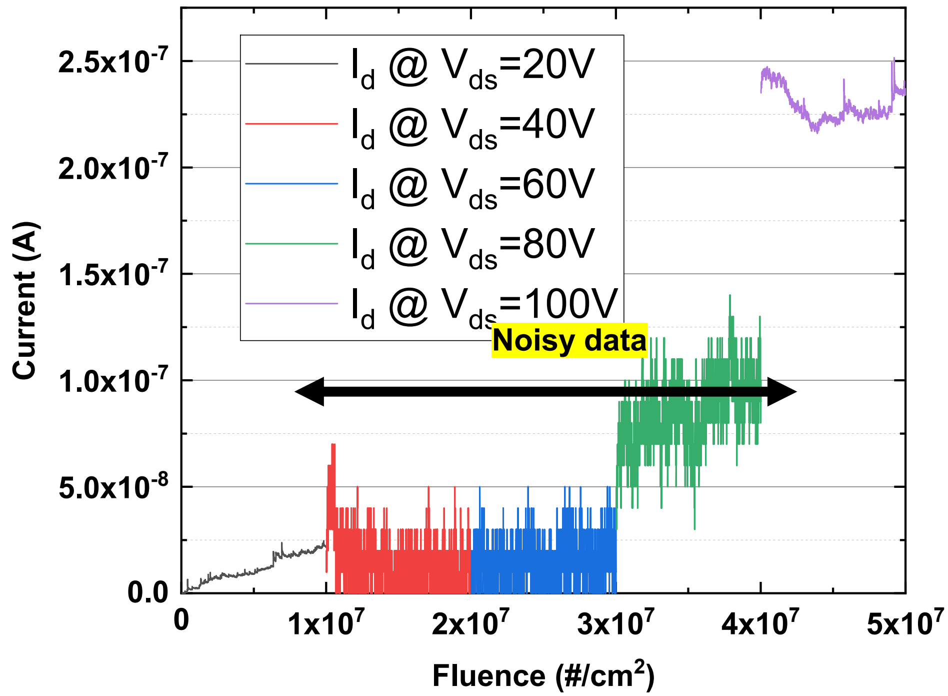
BV_{ds} = ~130V

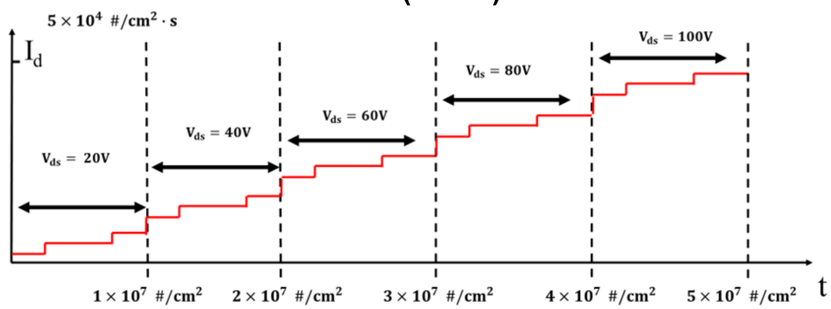


PSU JFET – Full I-t @ 5e7 #/cm² fluence

Ion	Energy	Range	LET (MeV/(mg/cm²))
^{197}Au	333.7 MeV (1.71 MeV/u)	27.6 μm	81.47

❖ *Tool calibration likely caused the noisy data between 40~80V*

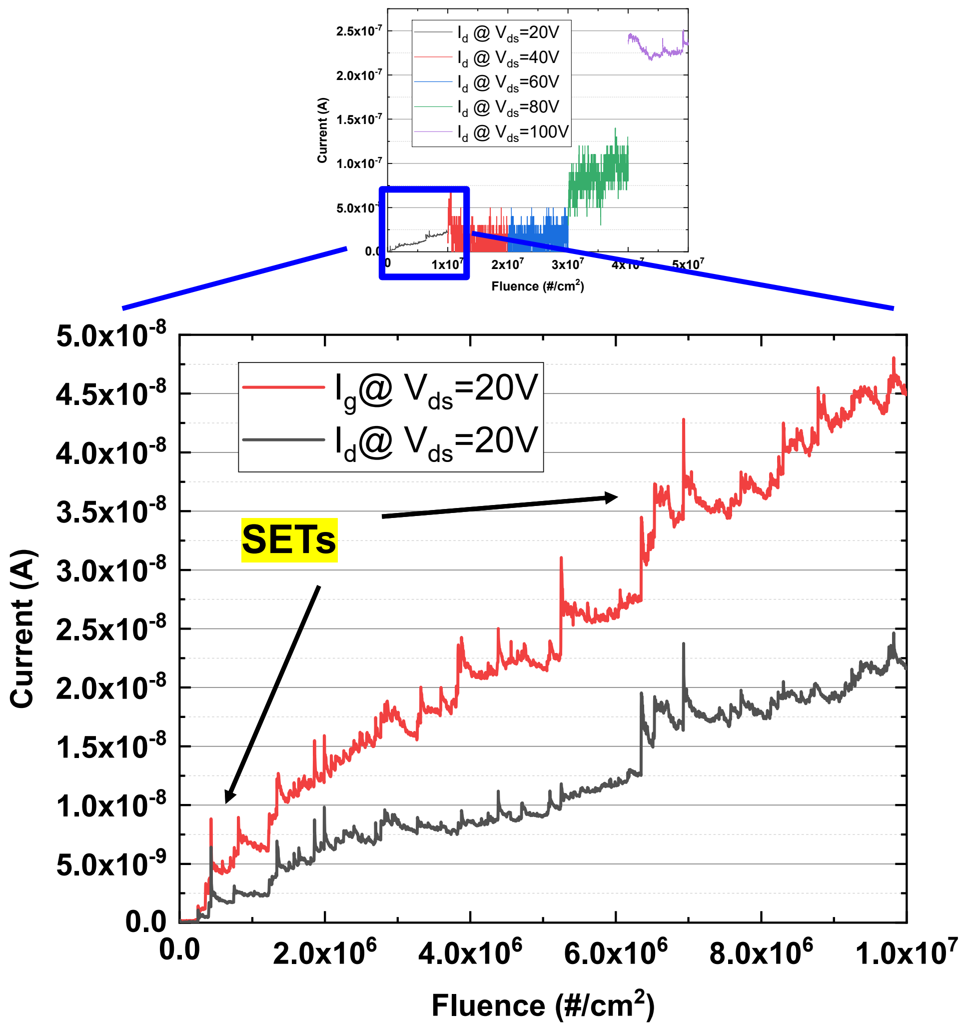




- Gradual increase of off-state leakage current over fluence and V_{ds}
- No destructive SEE observed

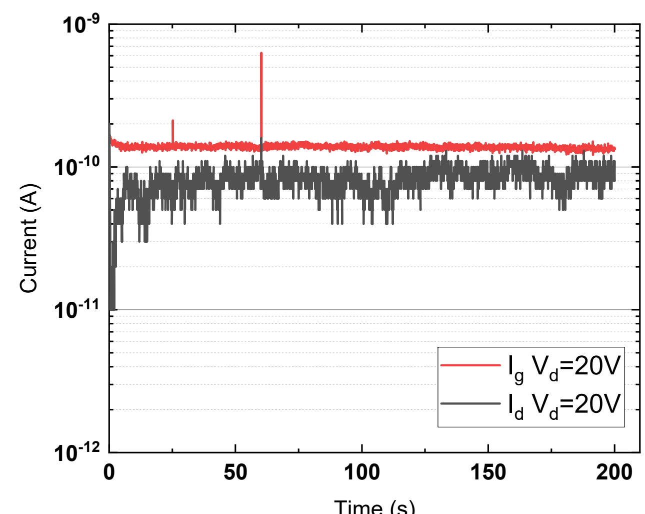
PSU JFET – V_{ds} = 20 V @ 1e7 #/cm² fluence

Ion	Energy	Range	LET (MeV/(mg/cm²))
^{197}Au	333.7 MeV (1.71 MeV/u)	27.6 µm	81.47



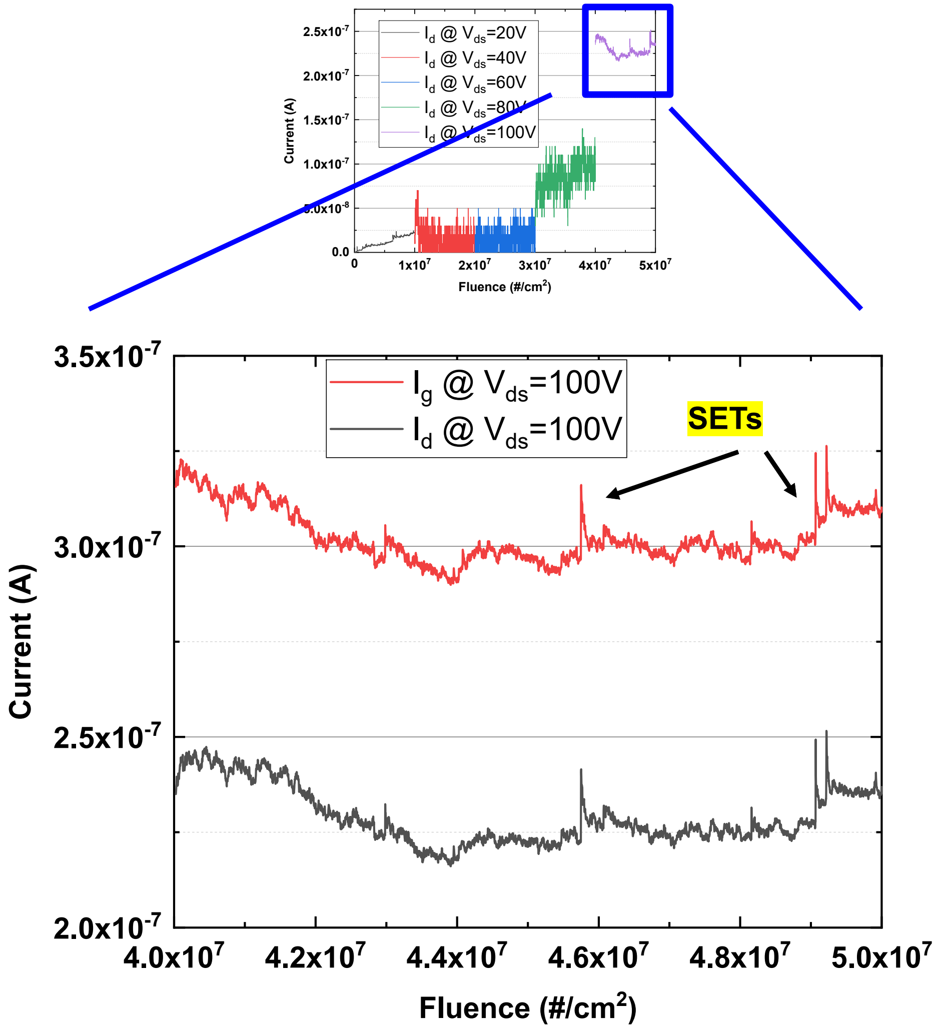
- Leakage current increasing constantly
- Each SET in I_d always correspond to one in $I_{g.}$

Device transient without any radiation



PSU JFET – V_{ds} = 100 V @ 5e7 #/cm² fluence

Ion	Energy	Range	LET (MeV/(mg/cm²))
^{197}Au	333.7 MeV (1.71 MeV/u)	27.6 µm	81.47



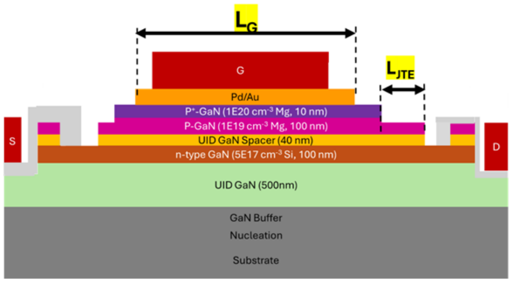
- SETs can still be observed
- Device leakage current stabilized
- No destructive SEE

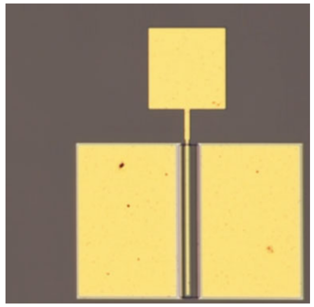
Overview

- ❑ GSI – 192 MeV Ar – On-site test
- ❑ BNL – 333.7 MeV Au – On-site test
- ❑ **GSI – 950 MeV Au – Ex-situ test**

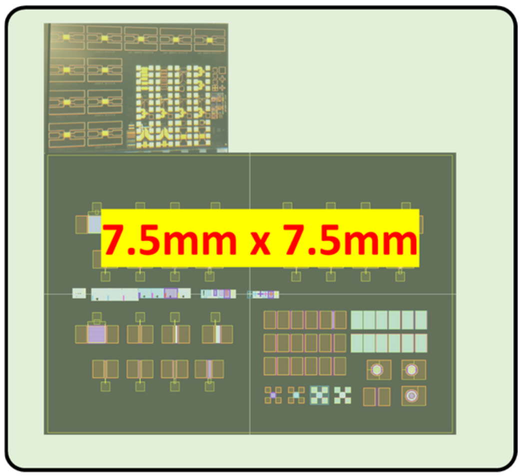
Overview

Ion	Energy	Range	LET (MeV/(mg/cm^2))
^{197}Au	950 MeV (4.8 MeV/u)	30 µm	72.4

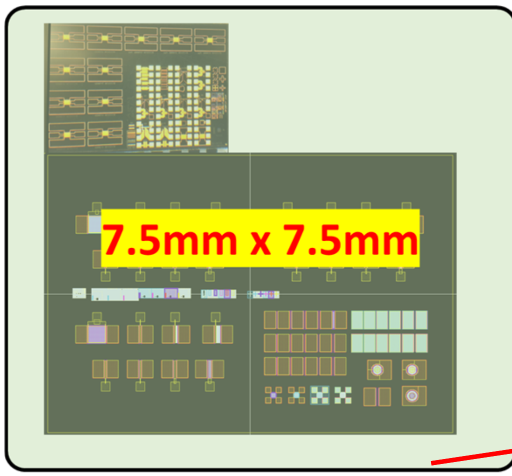




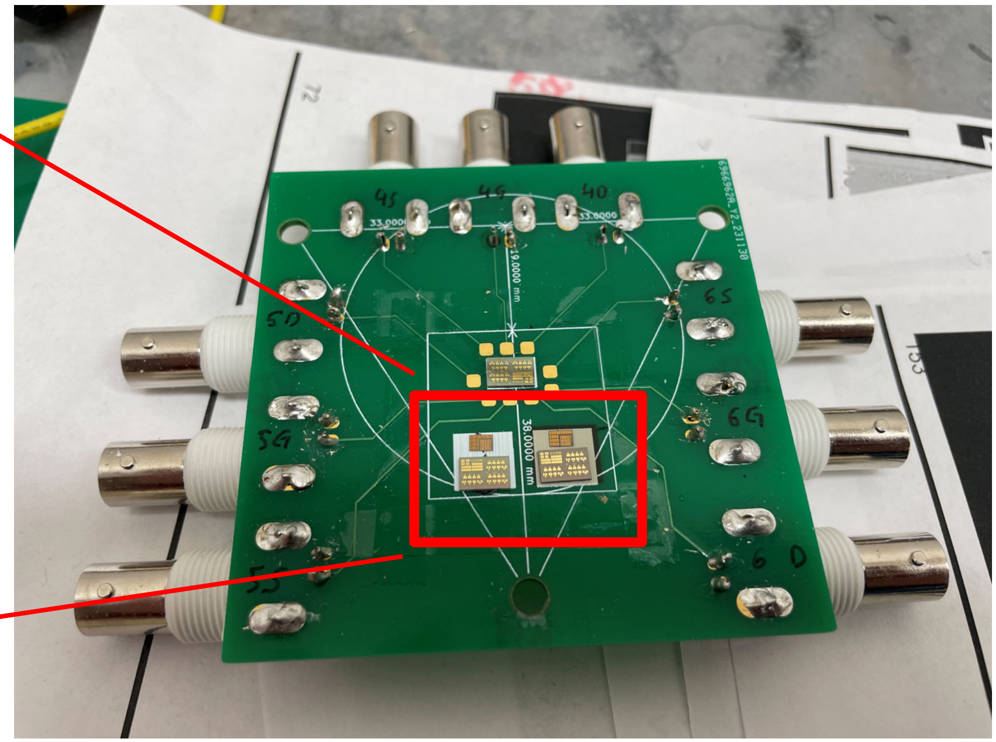
PSU made JFET samples, broad beam irradiation



Fluence $1 \times 10^{7} \#/cm^{2}$



Fluence $5 \times 10^{11} \#/cm^{2}$



PSU FETs – Au ion fluence variance

Ion	Energy	Range	LET (MeV/(mg/cm²))
^{197}Au	950 MeV (4.8 MeV/u)	30 µm	72.4

- Extreme high fluence destroy the device

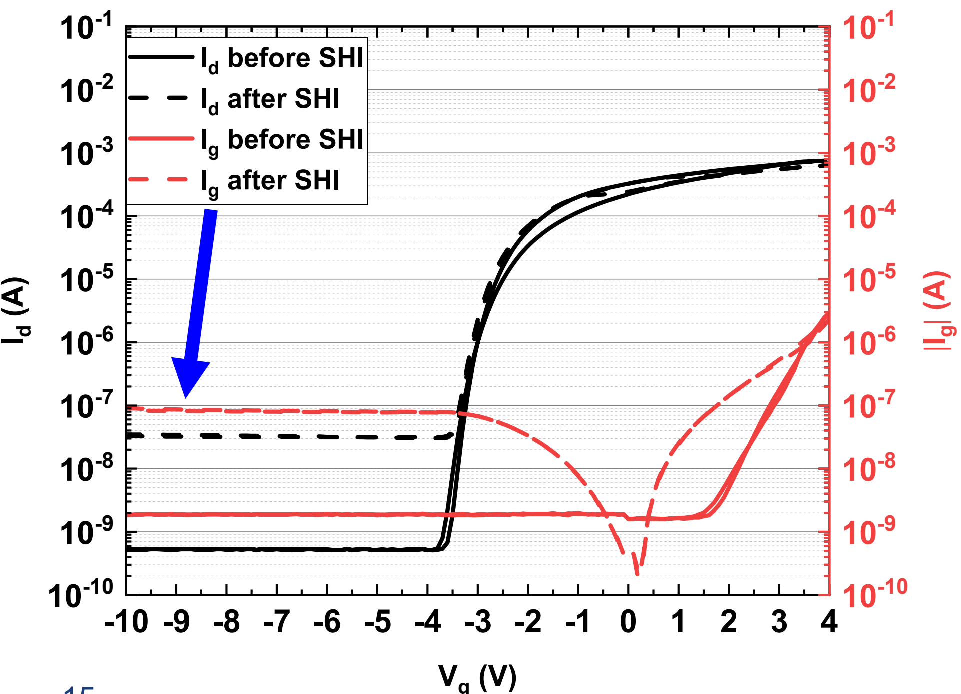
Transfer IV

Bias: V_g= -10 to 4V; V_d= 0.5V

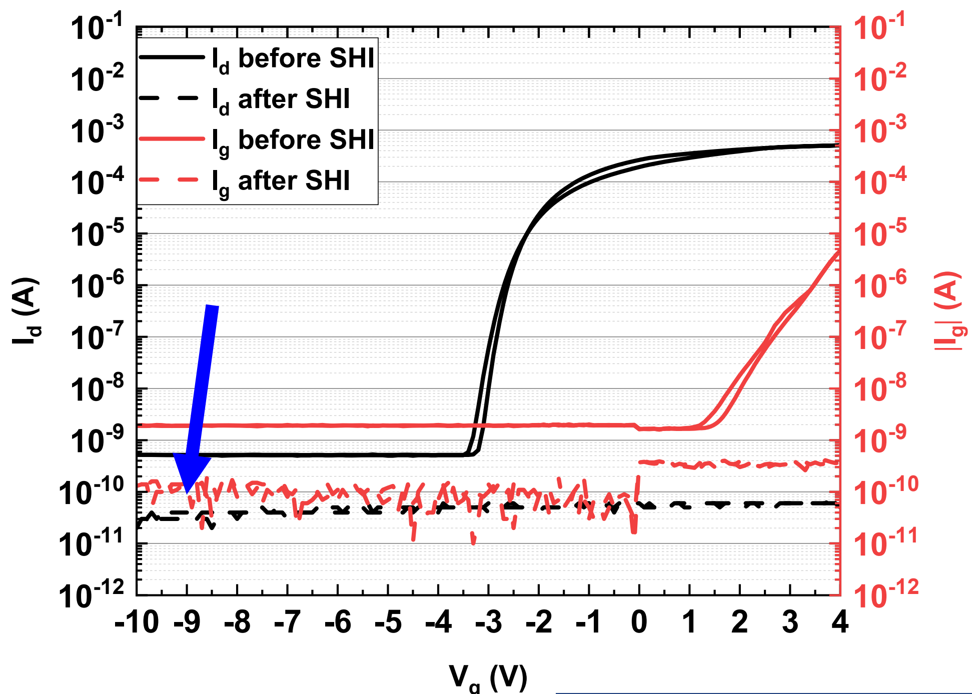
JFET

L_g=10um, L_{JTE} =10um

Au fluence = $1 \times 10^7 \#/cm^2$

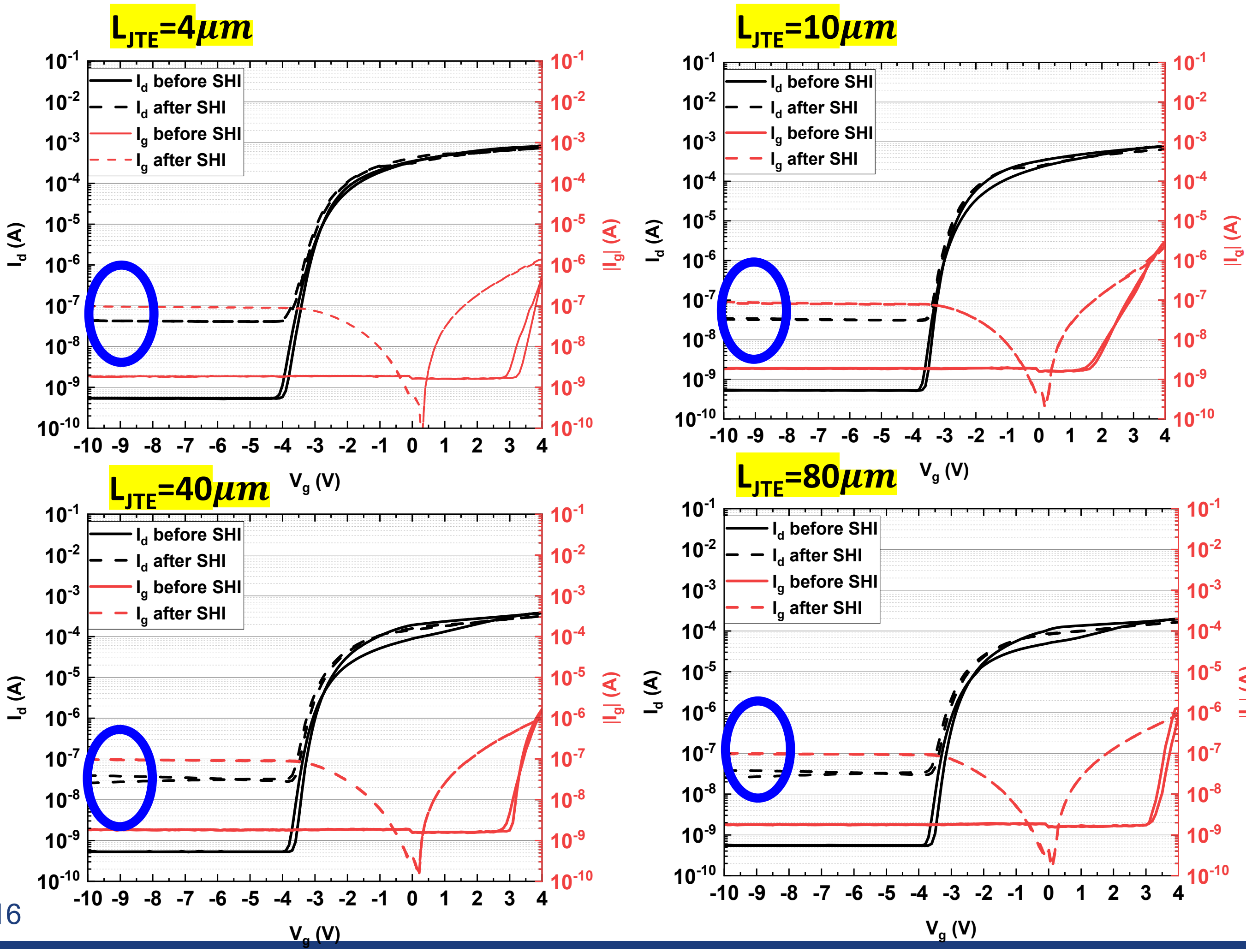


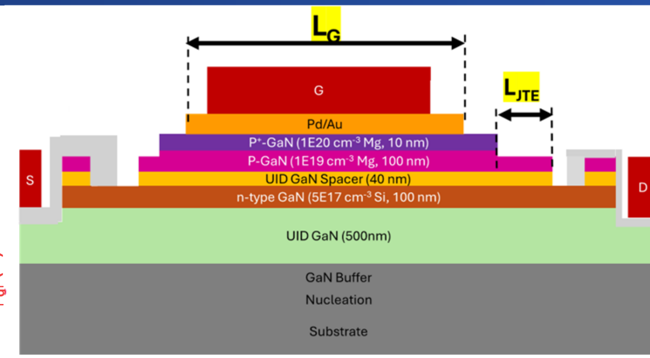
Au fluence = $5 \times 10^{11} \#/cm^2$



PSU JFETs – $1 \times 10^7 \#/cm^2$ fluence LJTE variance

Ion	Energy	Range	LET (MeV/(mg/cm²))
^{197}Au	950 MeV (4.8 MeV/u)	30 µm	72.4





Transfer IV

Bias: V_g= -10 to 4V; V_d= 0.5V

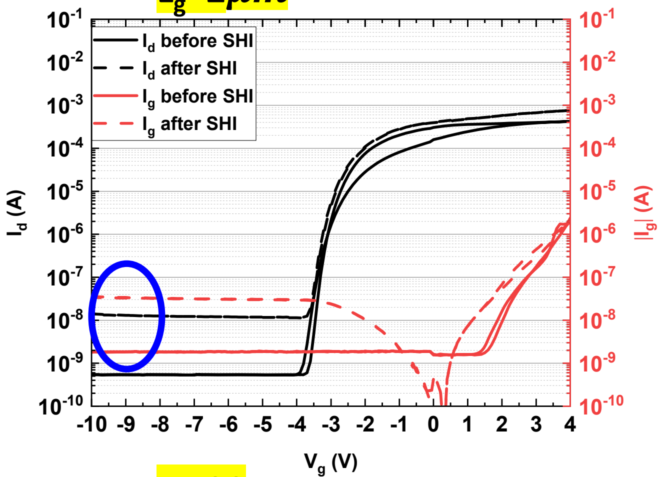
No noticeable dependence on JTE length.

PSU JFETs – $1 \times 10^7 \#/cm^2$ fluence Lg variance

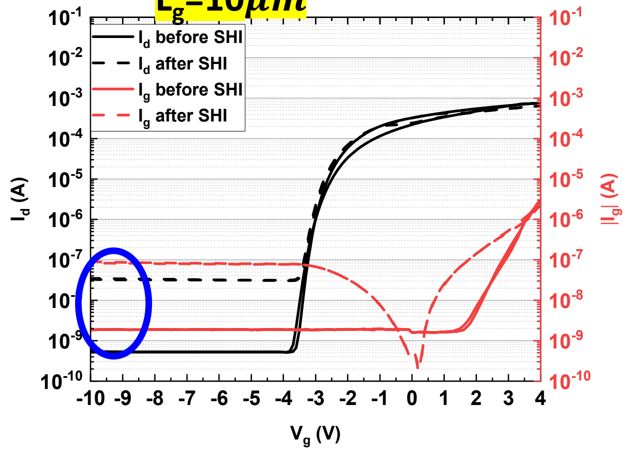
Ion	Energy	Range	LET (MeV/(mg/cm²))
^{197}Au	950 MeV (4.8 MeV/u)	30 µm	72.4

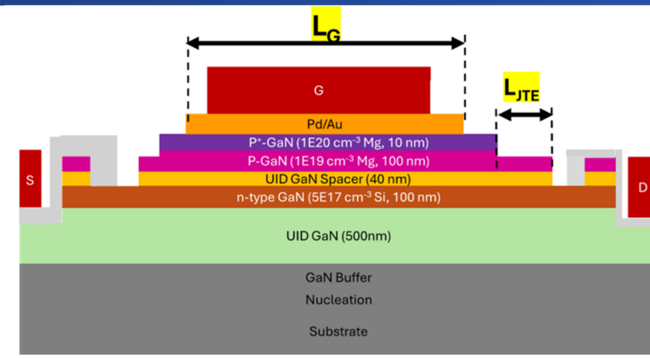
Drain / gate current increased after radiation and showed dependency on L_g.

L_g=2μm



L_g=10μm

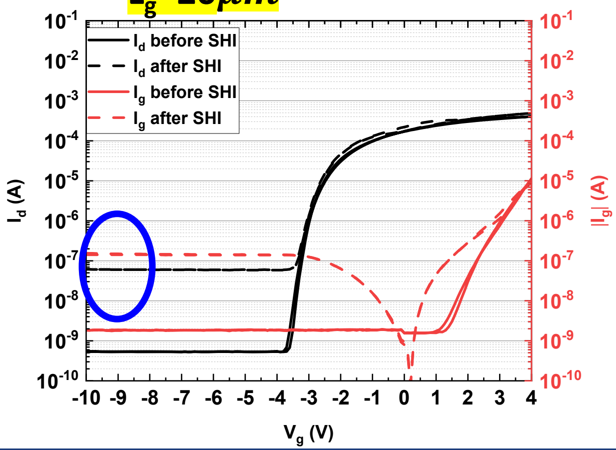




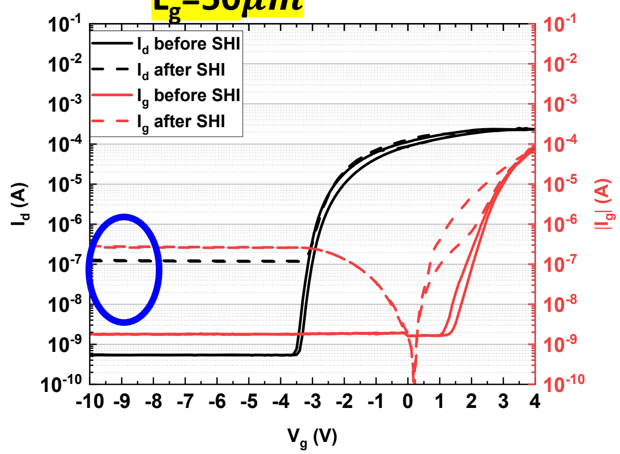
Transfer IV

Bias: V_g= -10 to 4V; V_d= 0.5V

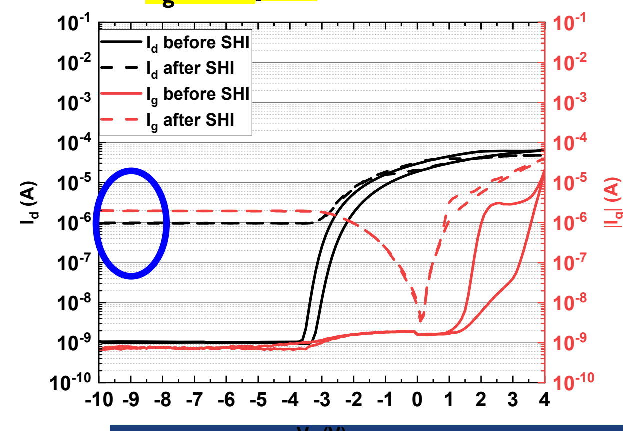
L_g=20μm



L_g=50μm



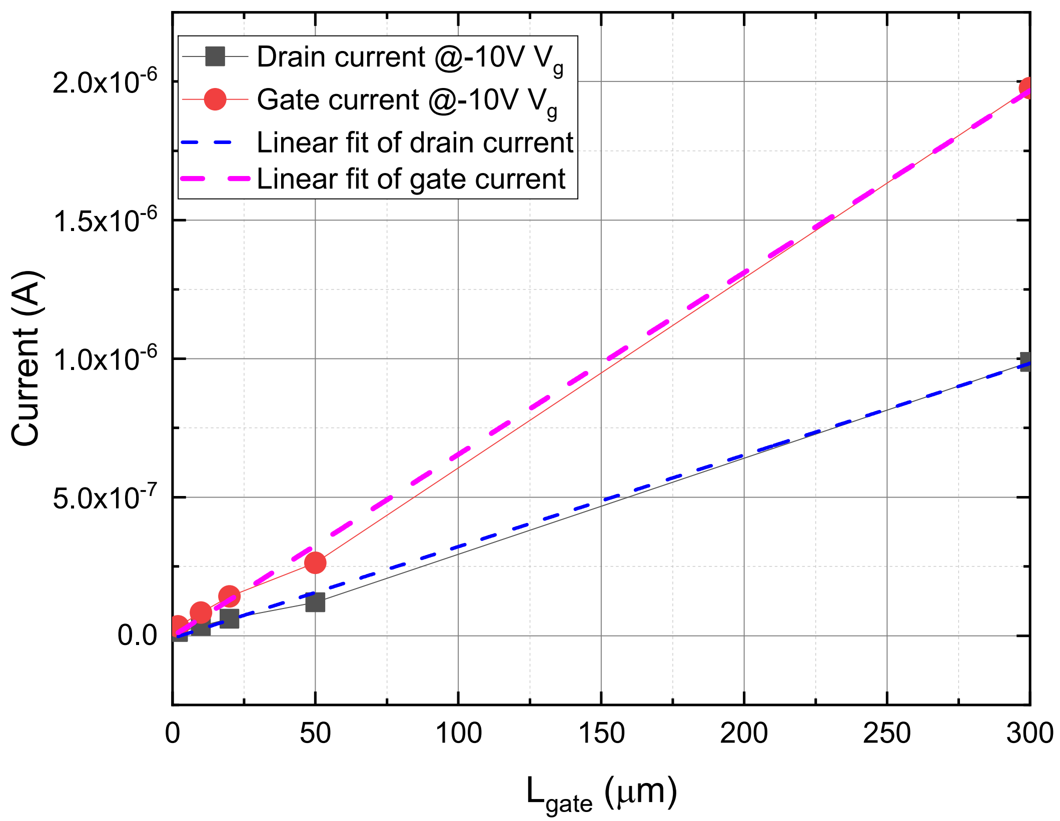
L_g=300μm

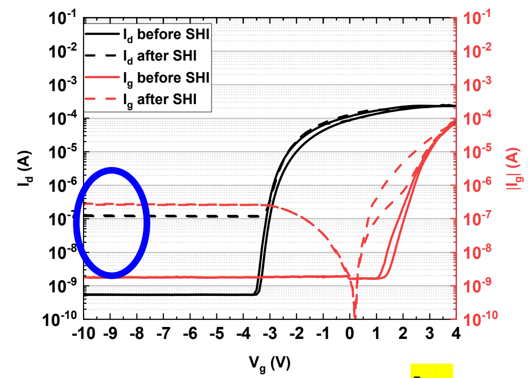


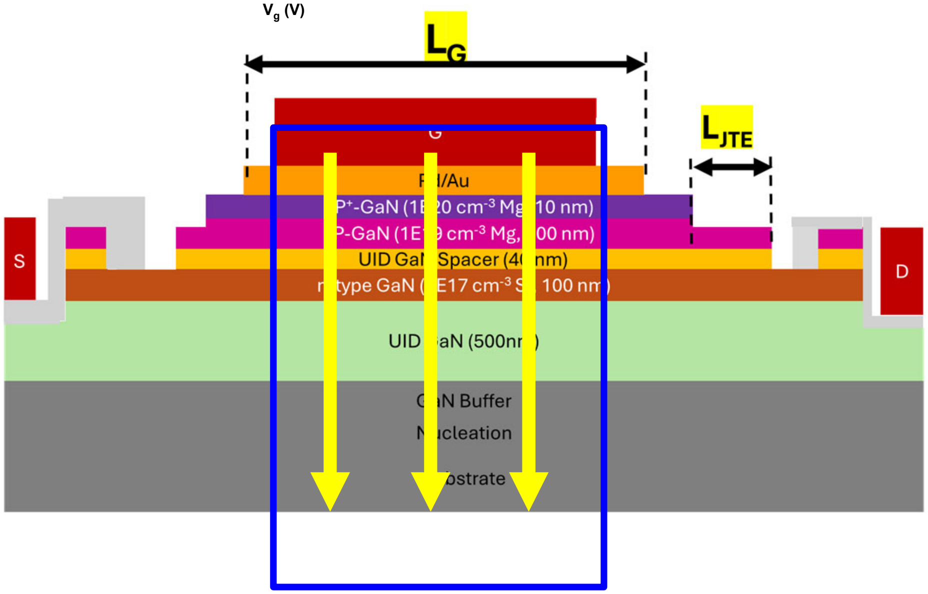
PSU JFETs – $1 \times 10^7 \#/cm^2$ fluence Lg variance

Ion	Energy	Range	LET (MeV/(mg/cm²))
^{197}Au	950 MeV (4.8 MeV/u)	30 µm	72.4

- The leakage current is proportional to gate length (gate junction area) - > indicating junction leakage







PSU JFETs – $1 \times 10^7 \#/cm^2$ *fluence temperature I-V*

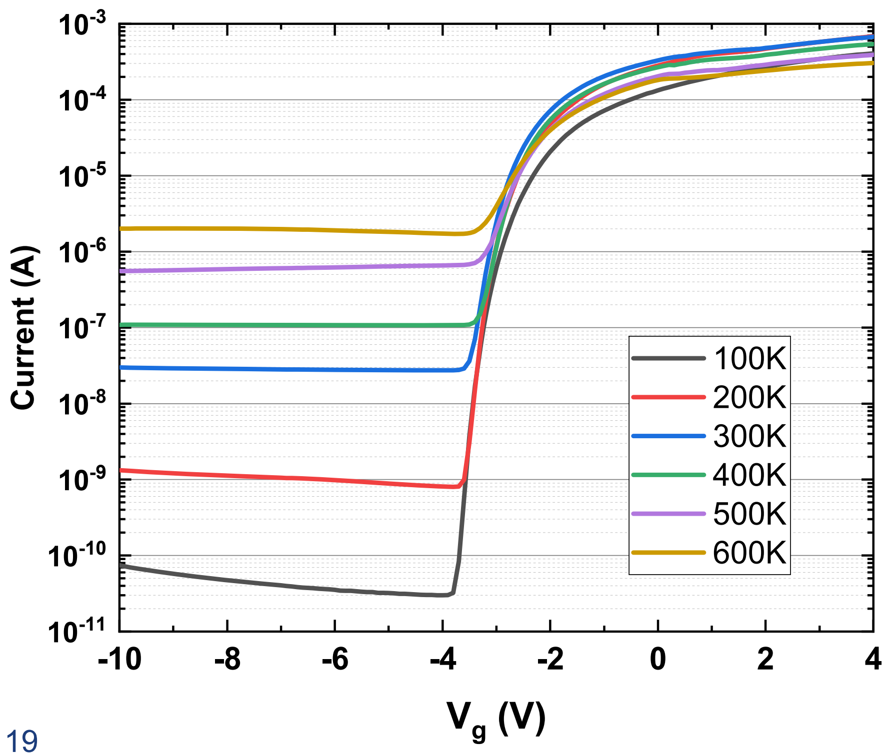
Ion	Energy	Range	LET (MeV/(mg/cm²))
^{197}Au	950 MeV (4.8 MeV/u)	30 µm	72.4

- The leakage current is strong function of temperature

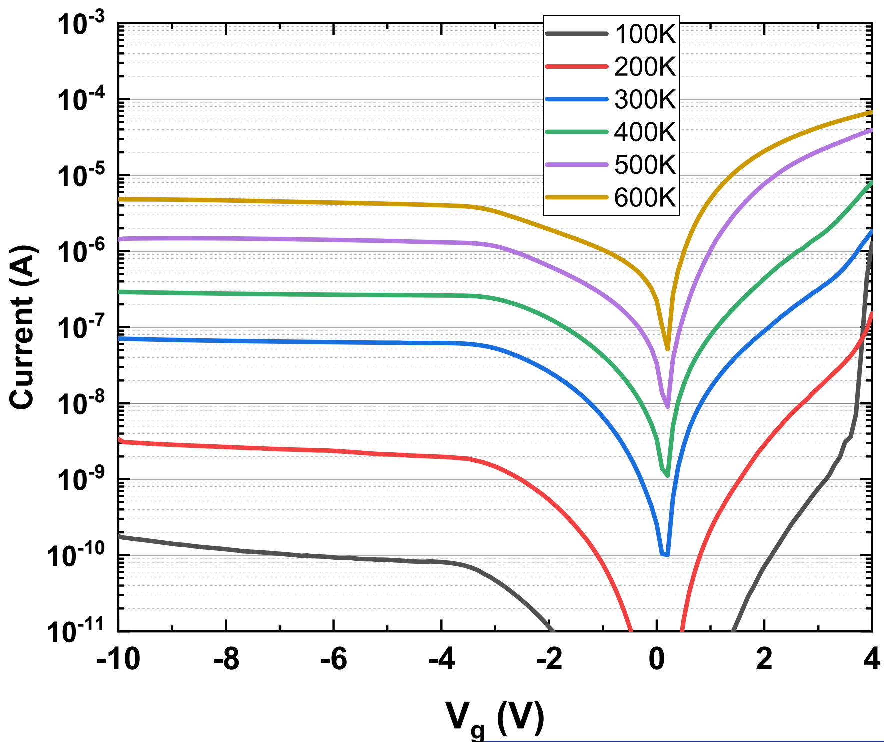
JFET

L_g=10um, L_{JTE} =10um

Drain current



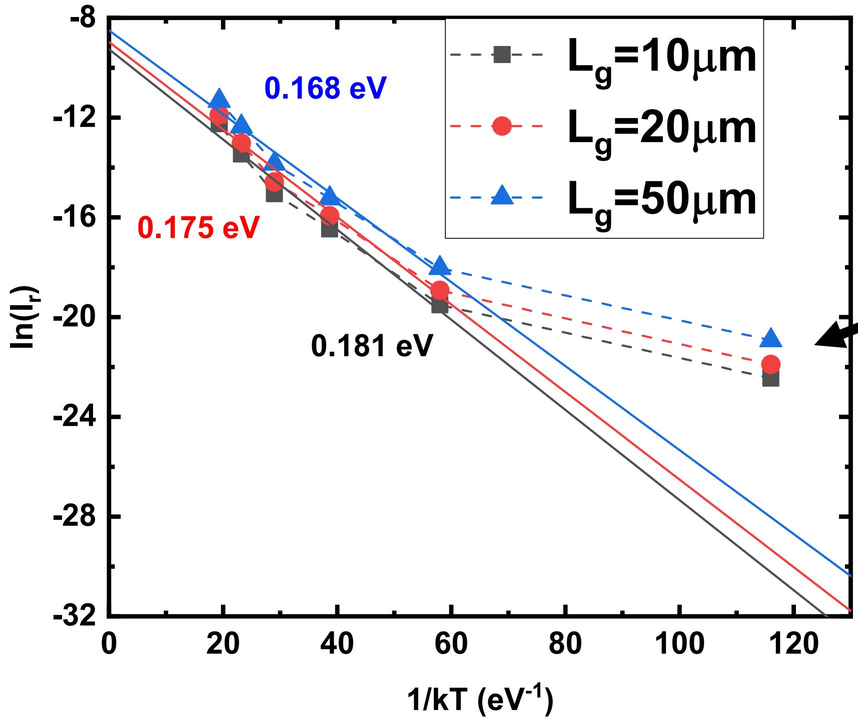
Gate current



PSU JFETs – $1 \times 10^7 \#/cm^2$ fluence temperature I-V

Ion	Energy	Range	LET (MeV/(mg/cm²))
^{197}Au	950 MeV (4.8 MeV/u)	30 µm	72.4

Arrhenius plot E_a extraction



Activation energy = 0.168 ~ 0.181 eV

100 K data point deviated from thermal current – further study required for investigating the mechanism

Summary

❑ GSI – 192 MeV Ar – On-site test

- No SEE observed

❑ BNL – 333.7 MeV Au – On-site test

- Constantly increased leakage over fluence
- Can identify SET current peaks but did not lead to any destructive SEE

❑ GSI – 950 MeV Au – Ex-situ test

- Leakage current increased after irradiation
- Is linearly dependent to junction area indicating junction leakage
- Temperature dependent leakage –

Activation energy E_a = 0.16~0.18 eV

Next

- Beam irradiation with improved PSU devices, and further components modified based on the JFET
- Additional electrical characterization for leakage mechanism study

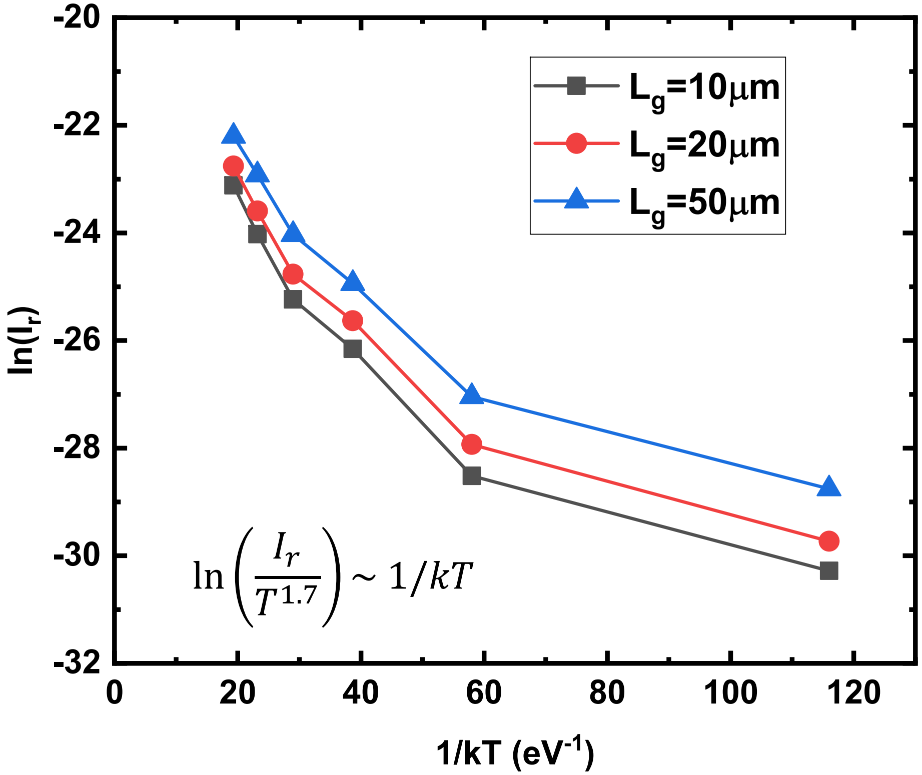
Thank you!

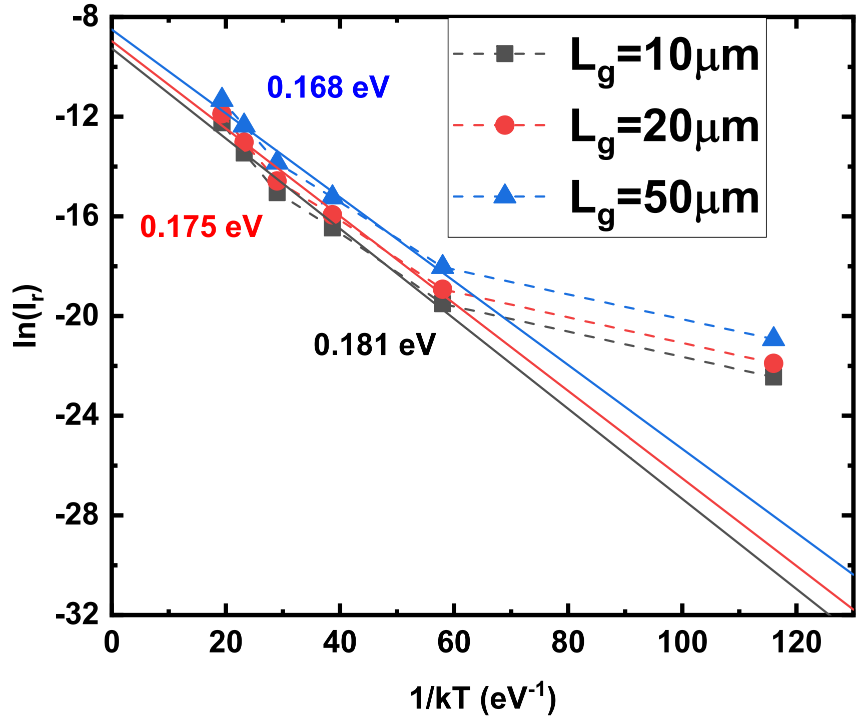
Back ups

PSU JFETs – $1 \times 10^7 \#/cm^2$ fluence temperature I-V

Ion	Energy	Range	LET (MeV/(mg/cm²))
^{197}Au	950 MeV (4.8 MeV/u)	30 μm	72.4

Uses PN junction reverse leakage – GR center level extraction





Testing Overview

Facility	Ion	Energy	Range	LET (keV/nm)	LET (MeV/(mg/cm^2)	Beamtime
GSI Germany	^{197}Au	950 MeV (4.8 MeV/u)	30 µm	44.5	72.4	Mar 4-24, 2024 (M-branch) * On Mar 18

Ex-situ data

Facility	Ion	Energy	Range	LET (keV/nm)	LET (MeV/(mg/cm^2)	Beamtime
GSI Germany	^{40}Ar	192 MeV (4.8 MeV/u)	26 µm	6.6	10.8	April 15-18, 2024 (M-branch)

On-site data

Facility	Ion	Energy	Range	LET (keV/nm)	LET (MeV/(mg/cm^2)	Beamtime
Brookhaven National Lab	^{197}Au	337 MeV (1.71 MeV/amu)	16 µm	40.3	64.5	Sept 23 2024

On-site data

Overview

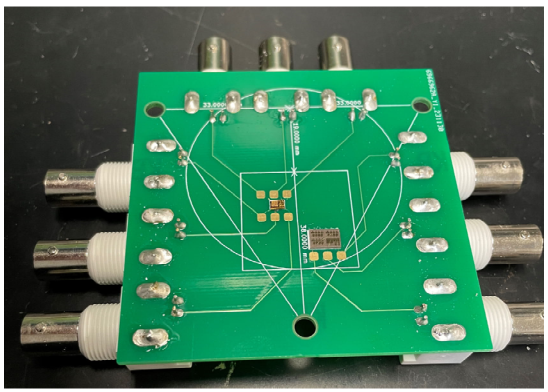
Beam condition

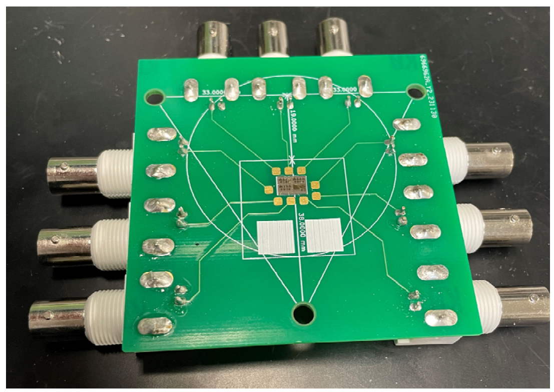
❖ *Estimated from SRIM*

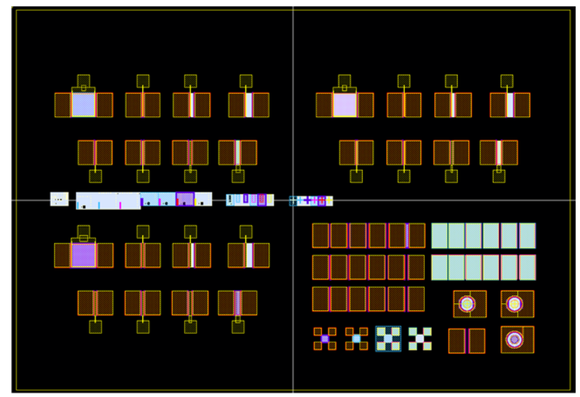
Facility	Ion	Energy	Range	LET (keV/nm)	LET (MeV/(mg/cm^2))	Beamtime
GSI Germany	^{40}Ar	192 MeV (4.8 MeV/u)	26 µm	6.6	10.8	April 15-18, 2024 (M-branch)

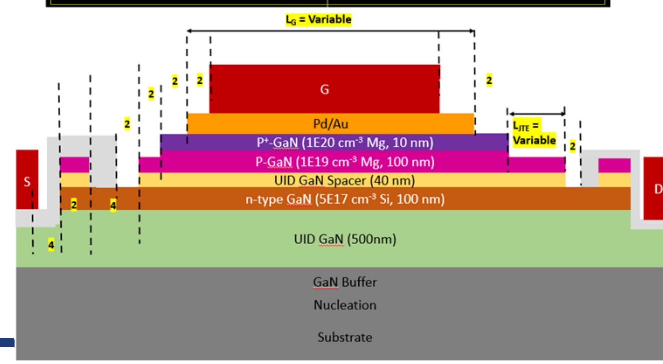
Samples

2PCBs, 5 devices.



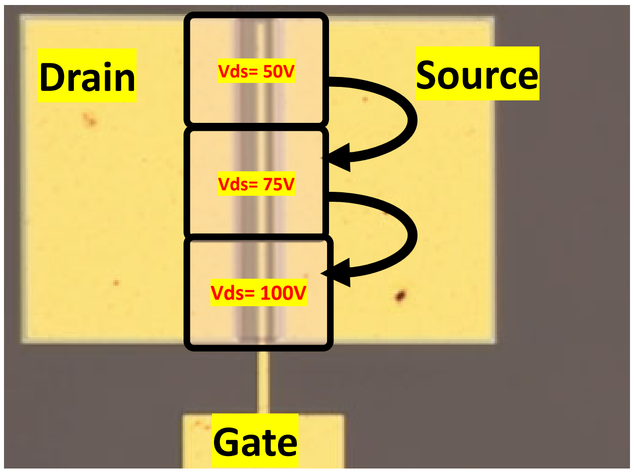


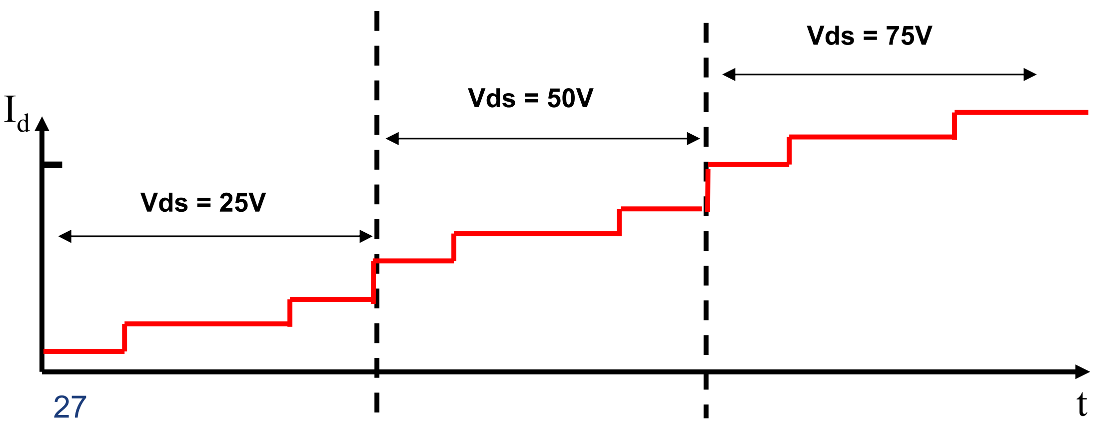




Main scan – Junction FET with Schottky contact gate – V_{ds} ramp

Increase V_{ds} and scan different locations of the device

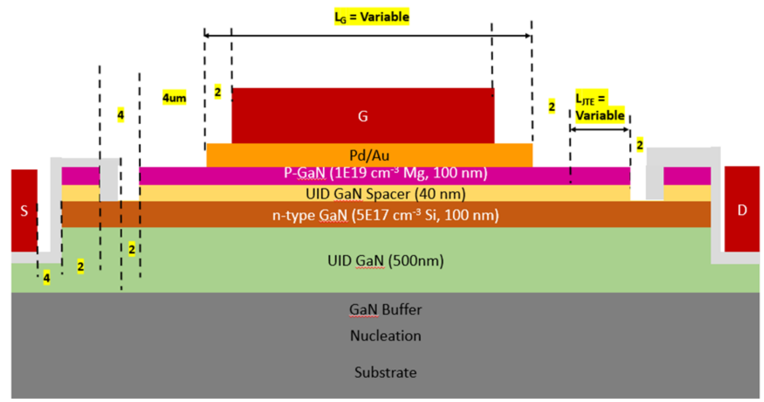




Device cross-section

L_{JTE} = 10um, L_g =10um

Index: device D9 in old summaries



Bias / beam condition during test:

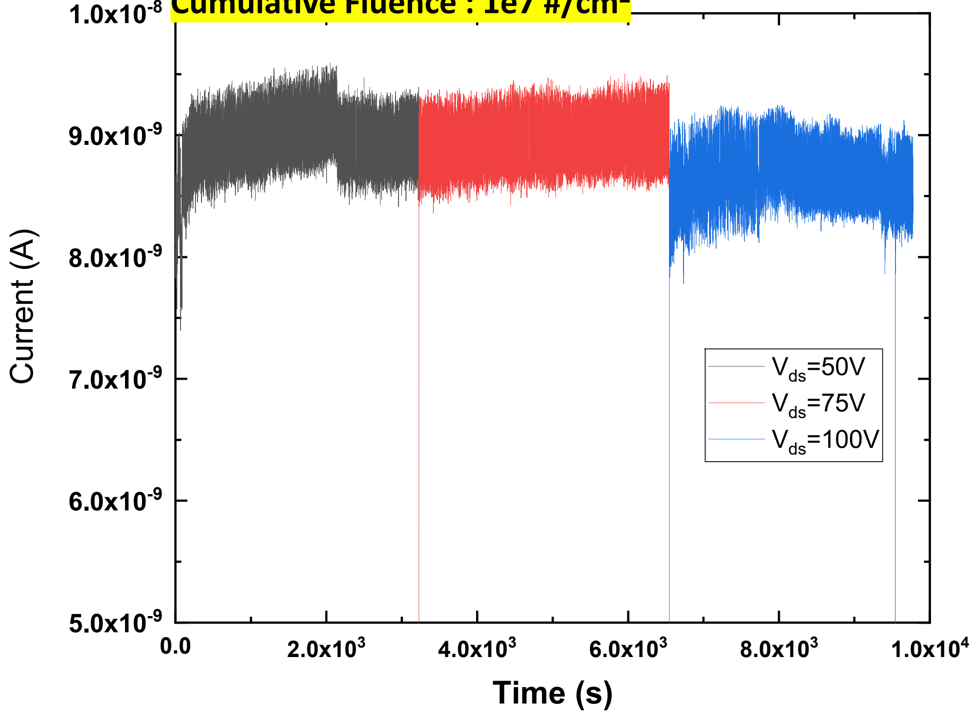
V_{ds} = 50/75/100V
V_{gs} = -6V

Ion	Energy	Range	LET (keV/nm)	LET (MeV/(mg/cm^2))
^{40}Ar	192 MeV (4.8 MeV/u)	26 µm	6.6	10.8

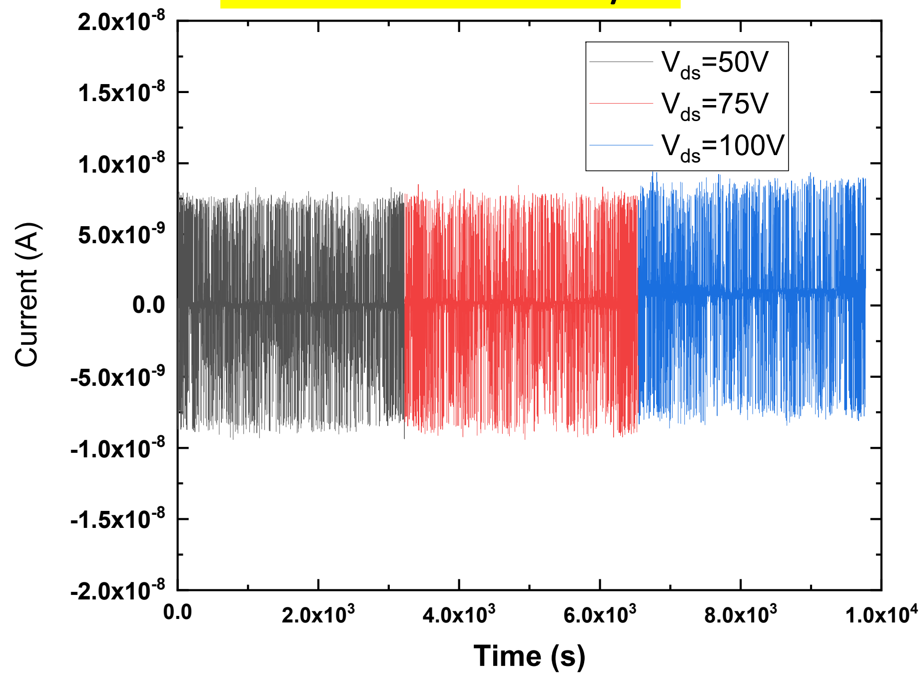
Main scan – Junction FET with Schottky contact gate – V_{ds} ramp

- **Drain current was at noise level**
- **Apart from a few points, gate current was around 9nA and no significant SEE**

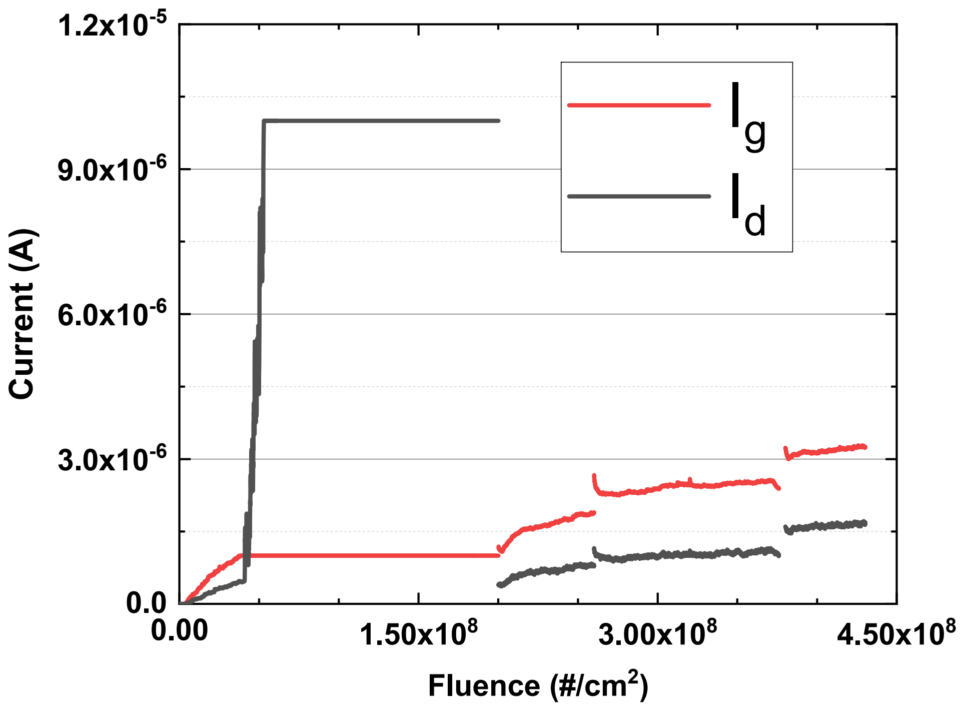
Gate current
Cumulative Fluence : 1e7 #/cm²

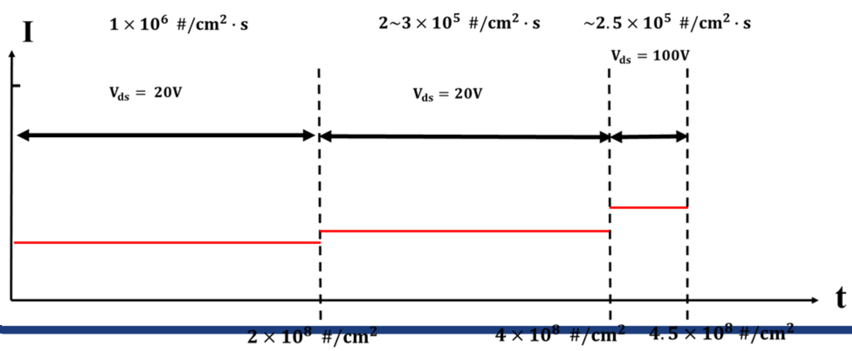


Drain current
Cumulative Fluence : 1e7 #/cm²



ND6 – PSU JFET Full I-t @ Full 4.5e8#/cm² fluence

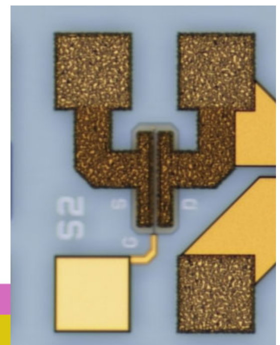




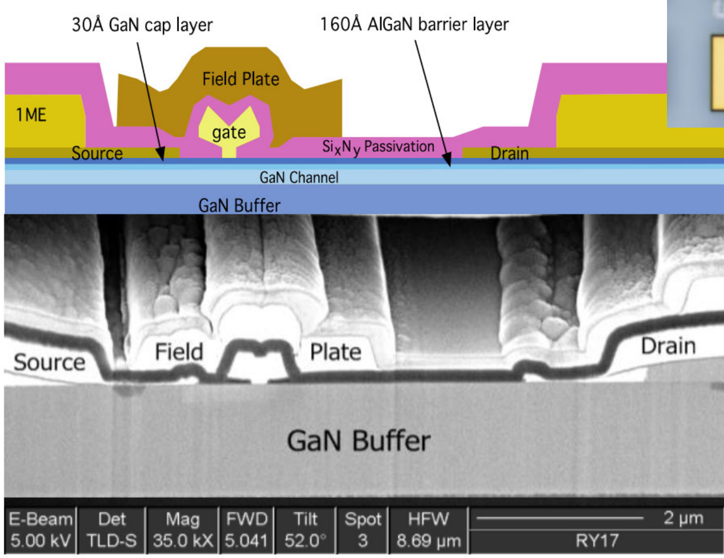
Overview

Ion	Energy	Range	LET (MeV/(mg/cm^2))
^{197}Au	950 MeV (4.8 MeV/u)	30 µm	72.4

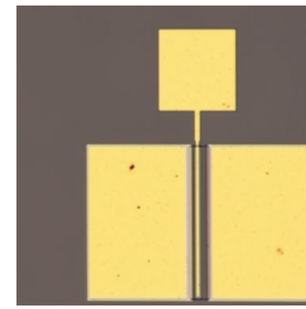
HEMTs from company M

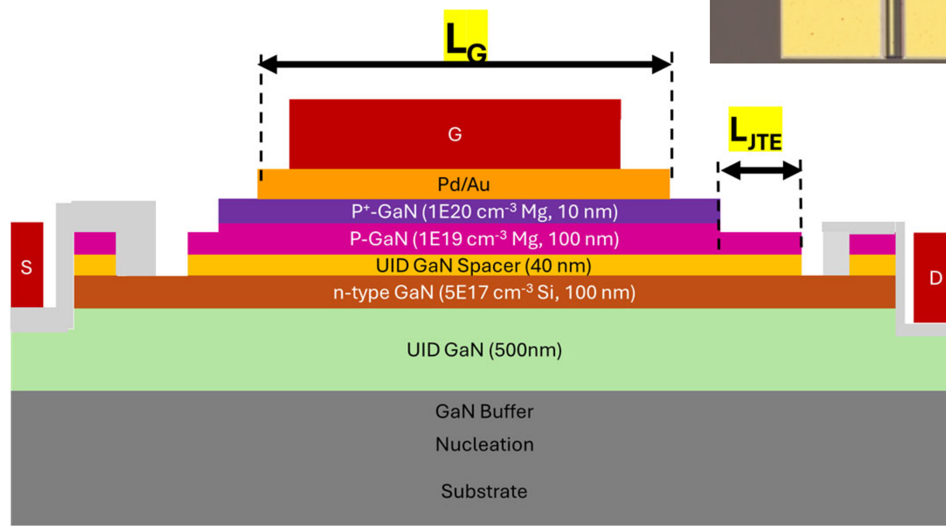


Details can be found in: Robert C. Fitch, "Implementation of High-Power-Density X-Band AlGaN/GaN High Electron Mobility Transistors in a Millimeter-Wave Monolithic Microwave Integrated Circuit Process"



FETs from PSU





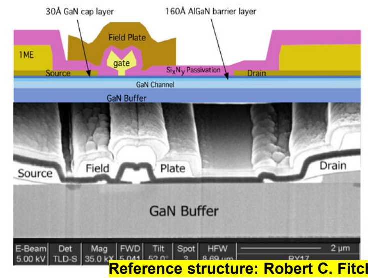
Company M FETs – $1 \times 10^7 \#/cm^2$ *fluence*

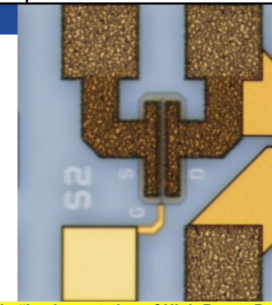
Ion	Energy	Range	LET (MeV/(mg/cm²)
^{197}Au	950 MeV (4.8 MeV/u)	30 µm	72.4

- Slight(~0.1V) threshold voltage negative shift
- -5V off leakage current increased, both drain and gate

(drain: 2×10^{-8} to 1×10^{-7} A , gate: 6×10^{-8} to 9.85×10^{-8} A)

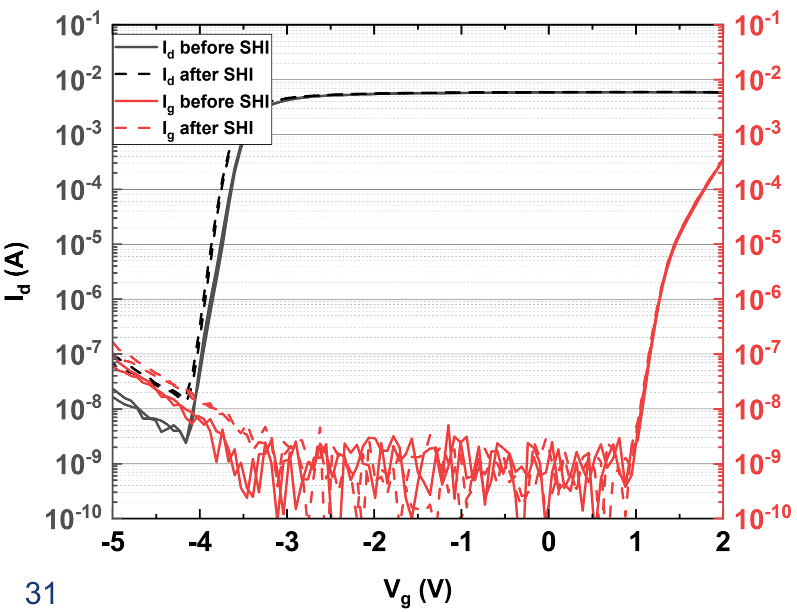
- Slightly Increased output current:



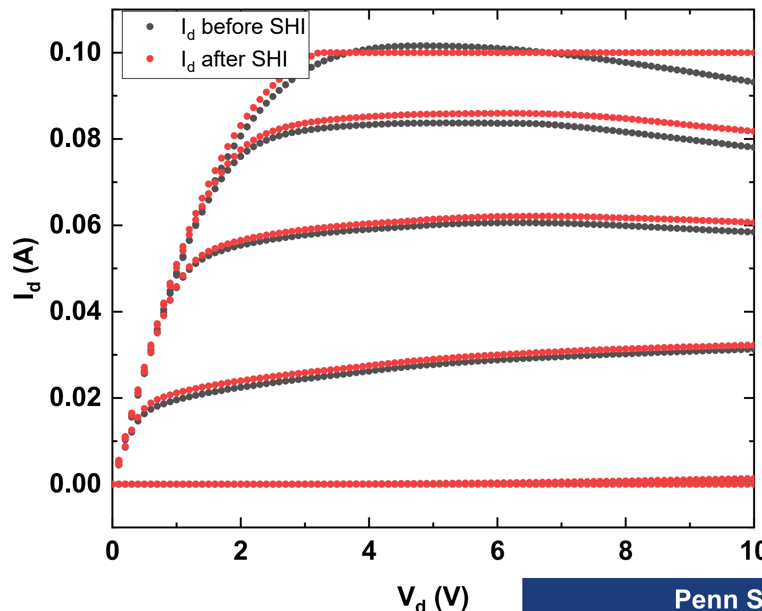


Reference structure: Robert C. Fitch, "Implementation of High-Power-Density X-Band AlGaN/GaN High Electron Mobility Transistors in a Millimeter-Wave M onolithic Microwave Integrated Circuit Process"

Transfer IV ***Bias: V_g= -5 to 2V; V_d= 0.1V***



Output IV ***Bias: V_g= -5 to 0V; V_d= 0~10V***

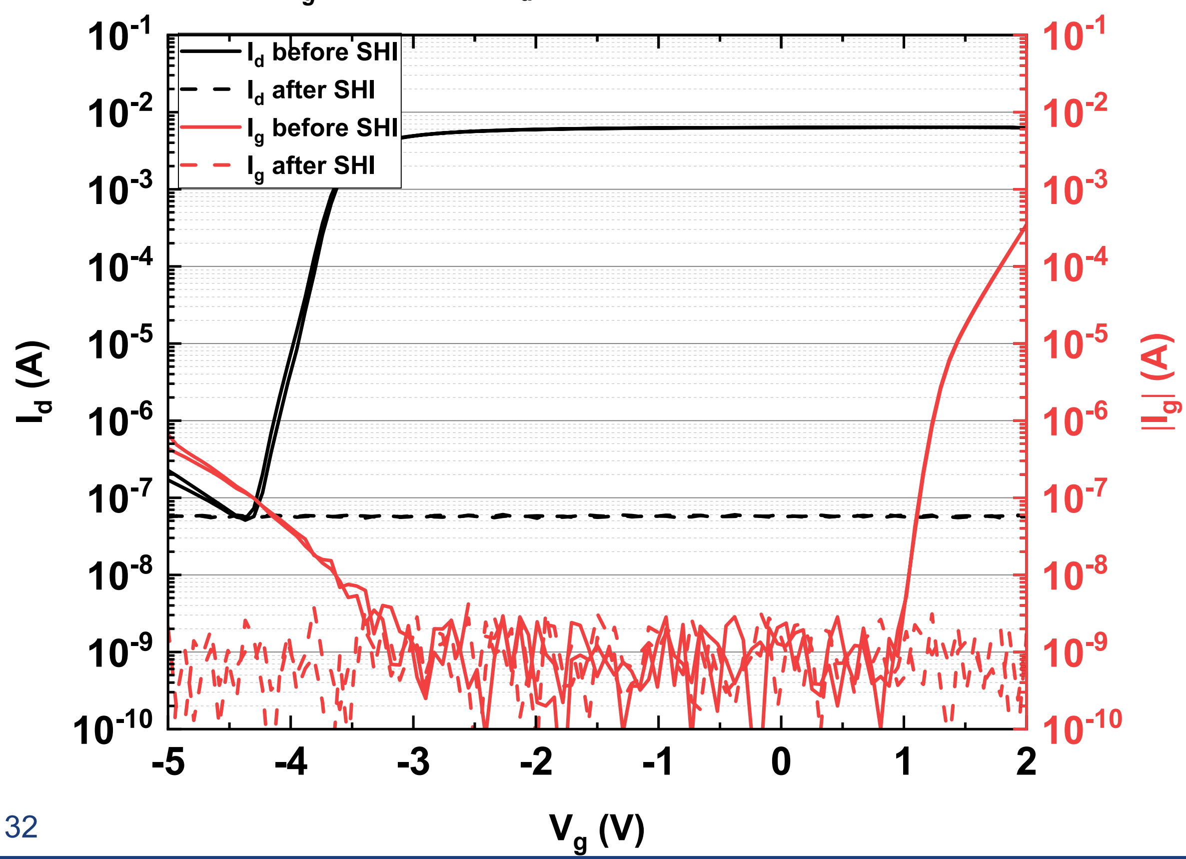


Company M FETs – $5 \times 10^{11} \#/cm^2$ *fluence*

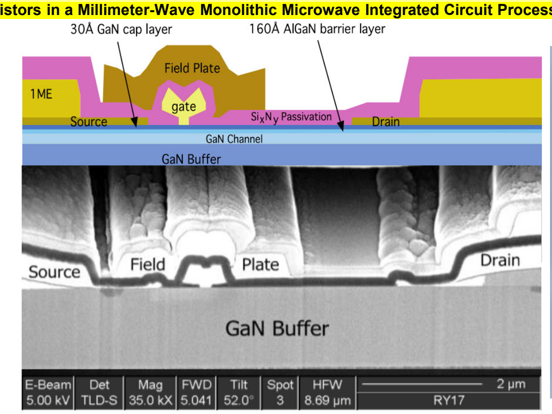
Ion	Energy	Range	LET (MeV/(mg/cm²))
^{197}Au	950 MeV (4.8 MeV/u)	30 µm	72.4

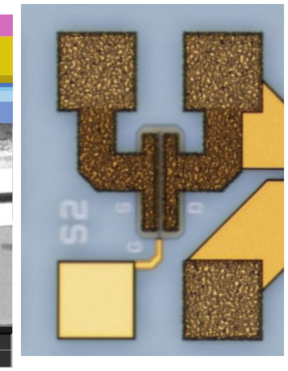
- Device destroyed after high fluence radiation (no current response)

Transfer IV ***Bias: V_g= -5 to 2V; V_d= 0.1V***



Reference structure: Robert C. Fitch, "Implementation of High-Power-Density X-Band AlGaN/GaN High Electron Mobility Transistors in a Millimeter-Wave Monolithic Microwave Integrated Circuit Process"



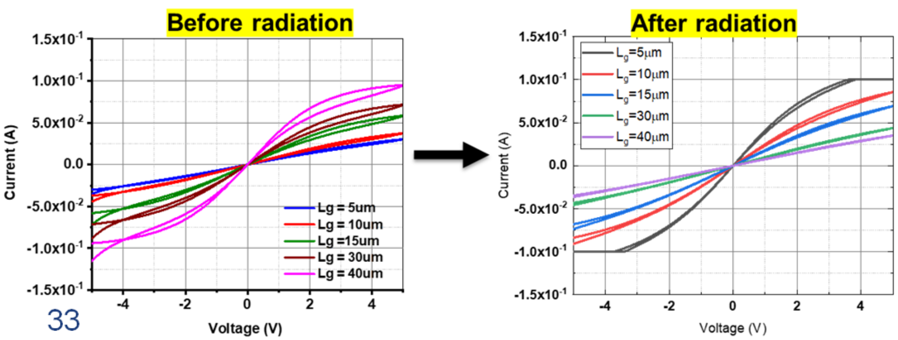


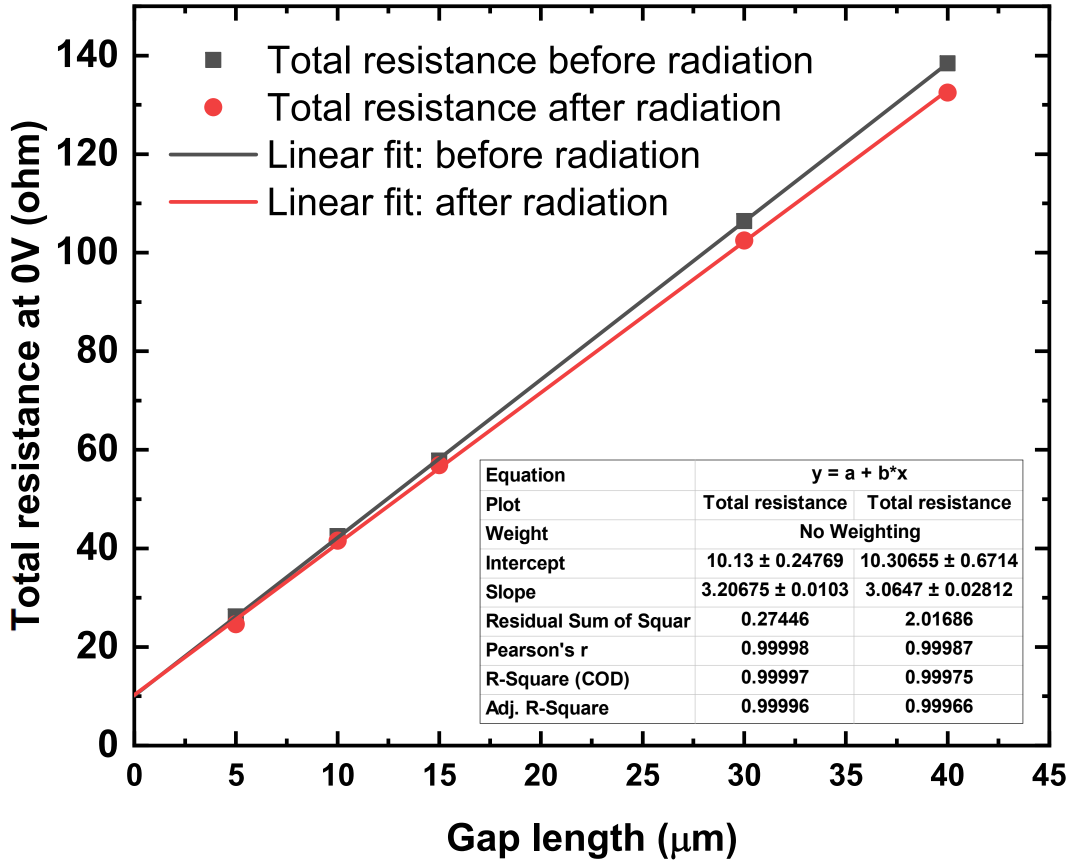
Linear scale

Company M TLM

Ion	Energy	Range	LET (MeV/(mg/cm^2))
^{197}Au	950 MeV (4.8 MeV/u)	30 µm	72.4

- No noticeable change in sheet resistance and contact resistance from TLM measurements



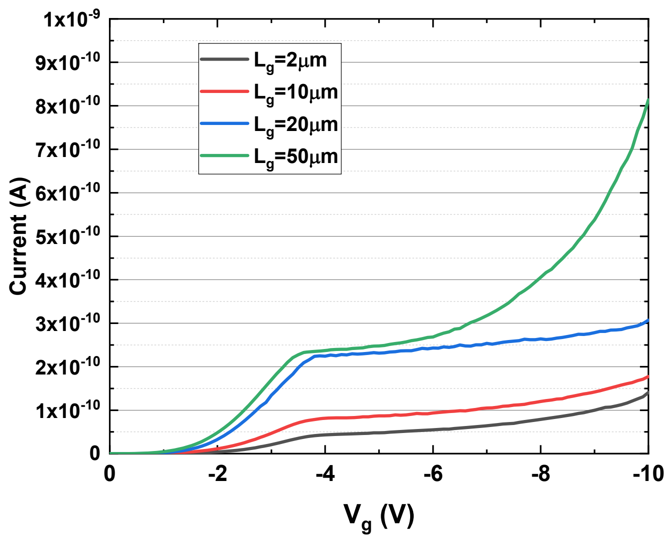


PSU JFETs – $1 \times 10^7 \#/cm^2$ fluence temperature I-V

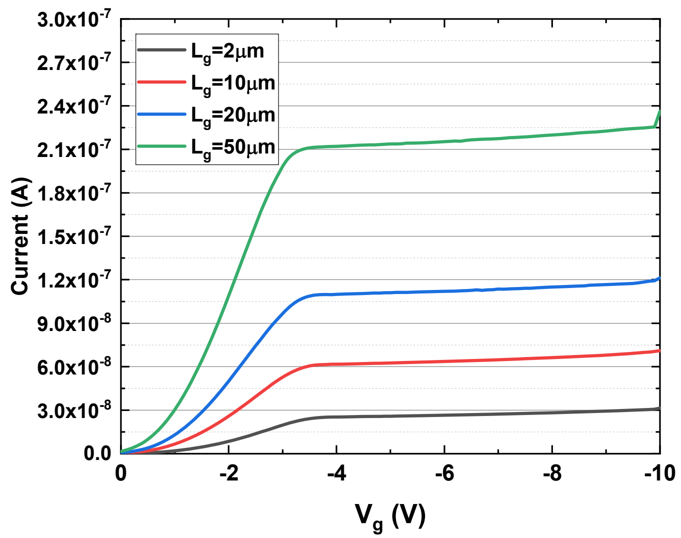
Ion	Energy	Range	LET (MeV/(mg/cm²))
^{197}Au	950 MeV (4.8 MeV/u)	30 µm	72.4

- The leakage current is still gate length dependent – junction current

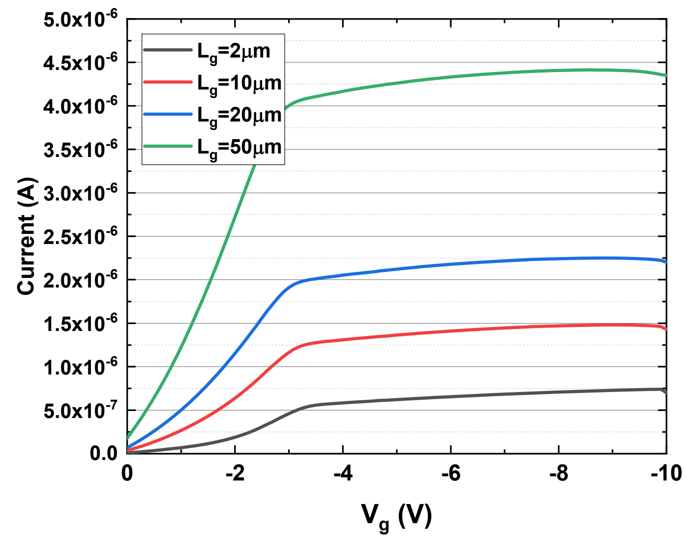
T=100K



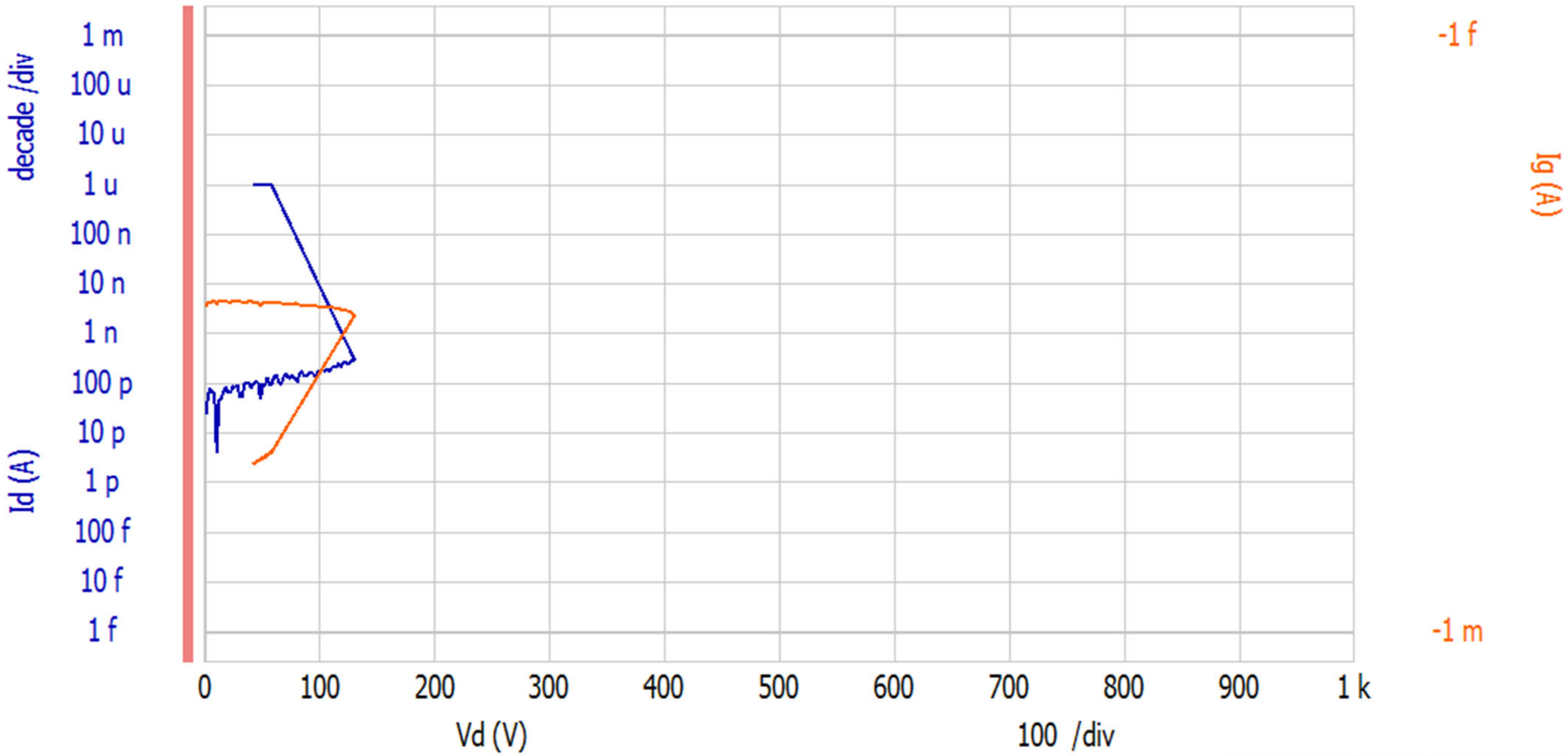
T=300K



T=500K



–FET Breakdown tests; V_{GS} = -6 V



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