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Single Event Effect in SiGe Heterojuction Bipolar Tramsistor

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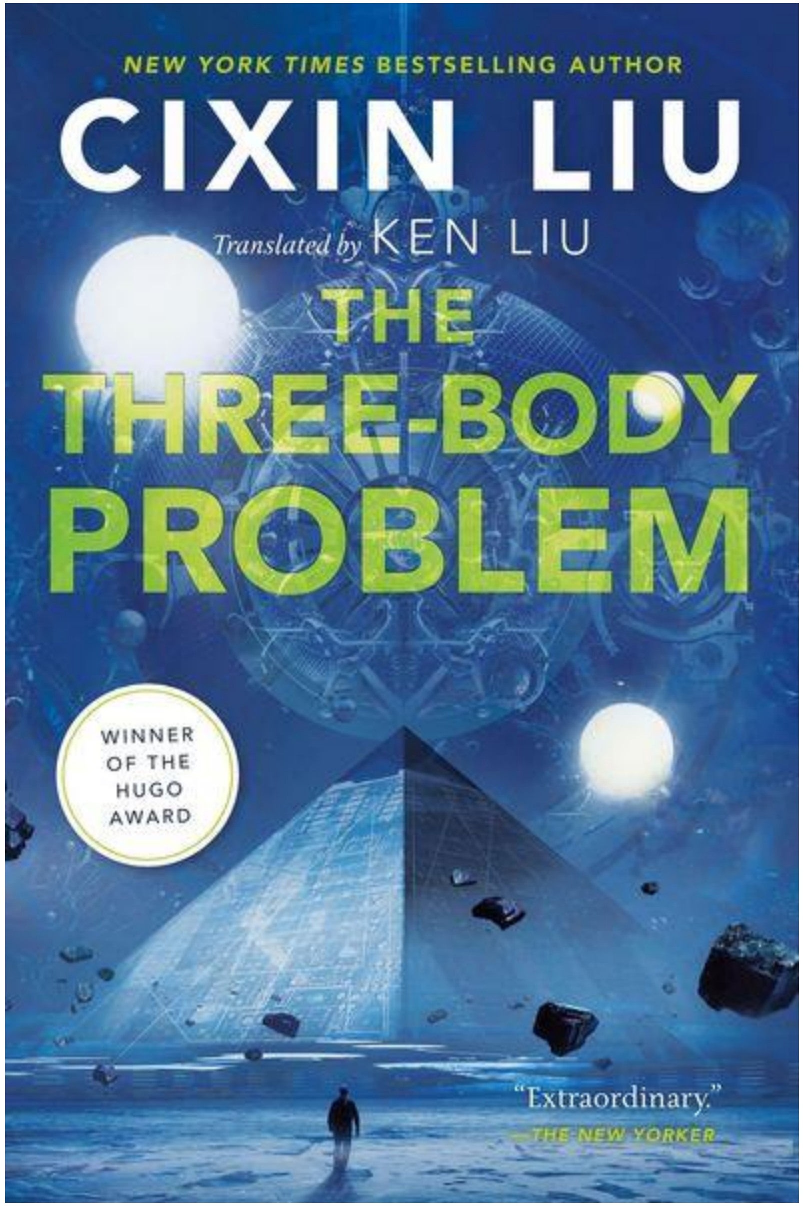
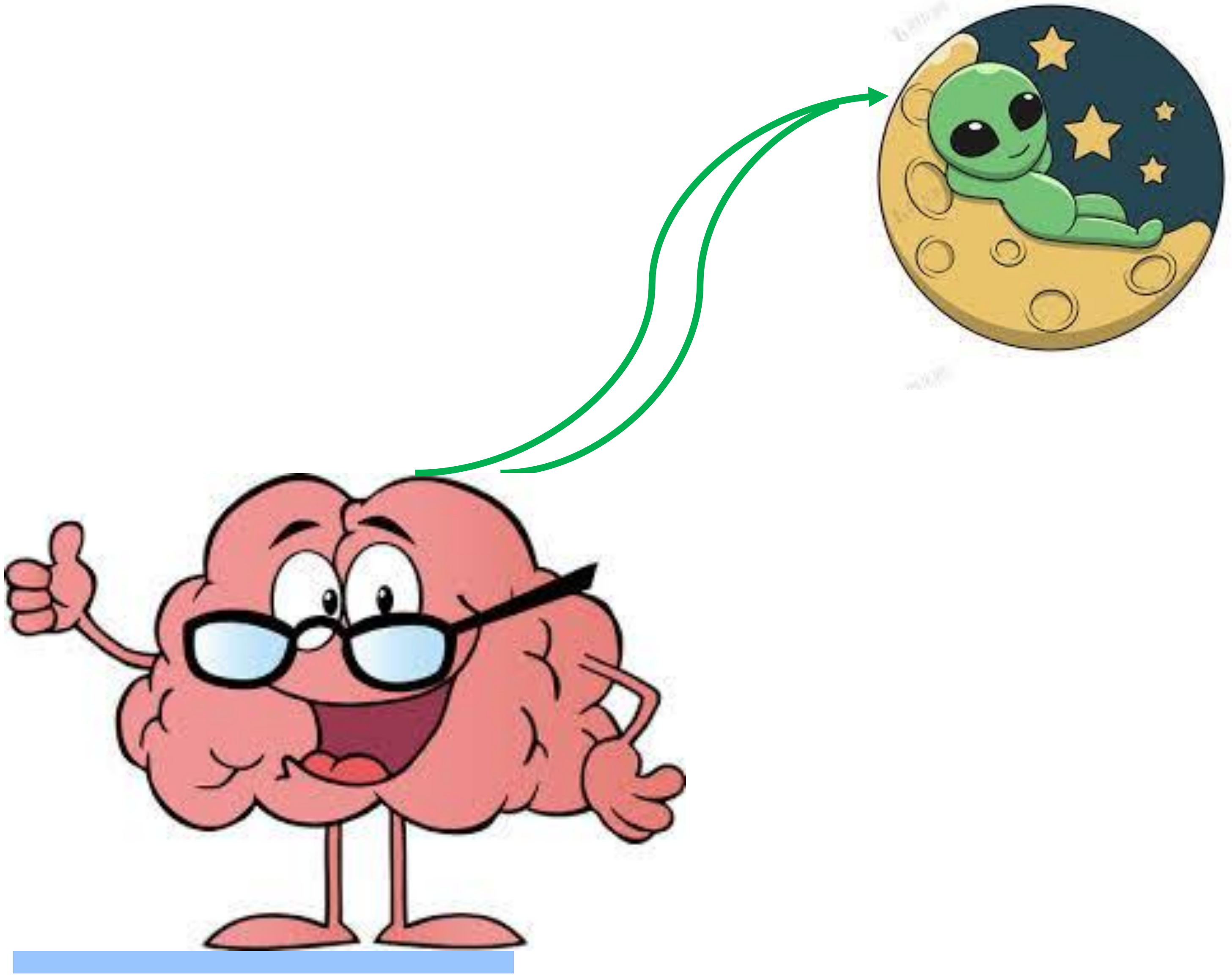
Single Event Effect in SiGe HBT

- **Outline**
  - Part 1 – Motivation
  - Part 2 – SiGe HBT and its application area
  - Part 3 – Radiation effects in modern semiconductors
  - Part 4 – SEE in SiGe HBT

0 A Small Story

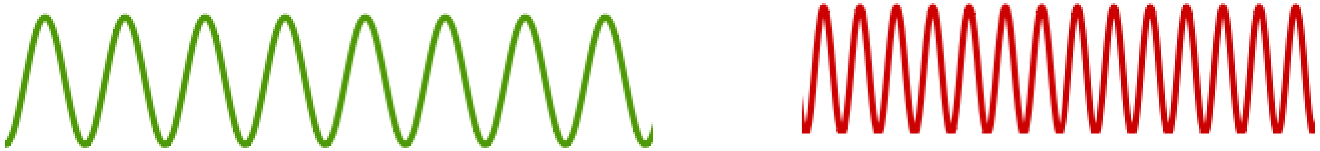




1 Motivation

PAYLOAD —— Elements of the spacecraft specifically dedicated to producing mission data and then relaying that data back to Earth.

Information → Frequency



The higher frequency, The more information

Weight

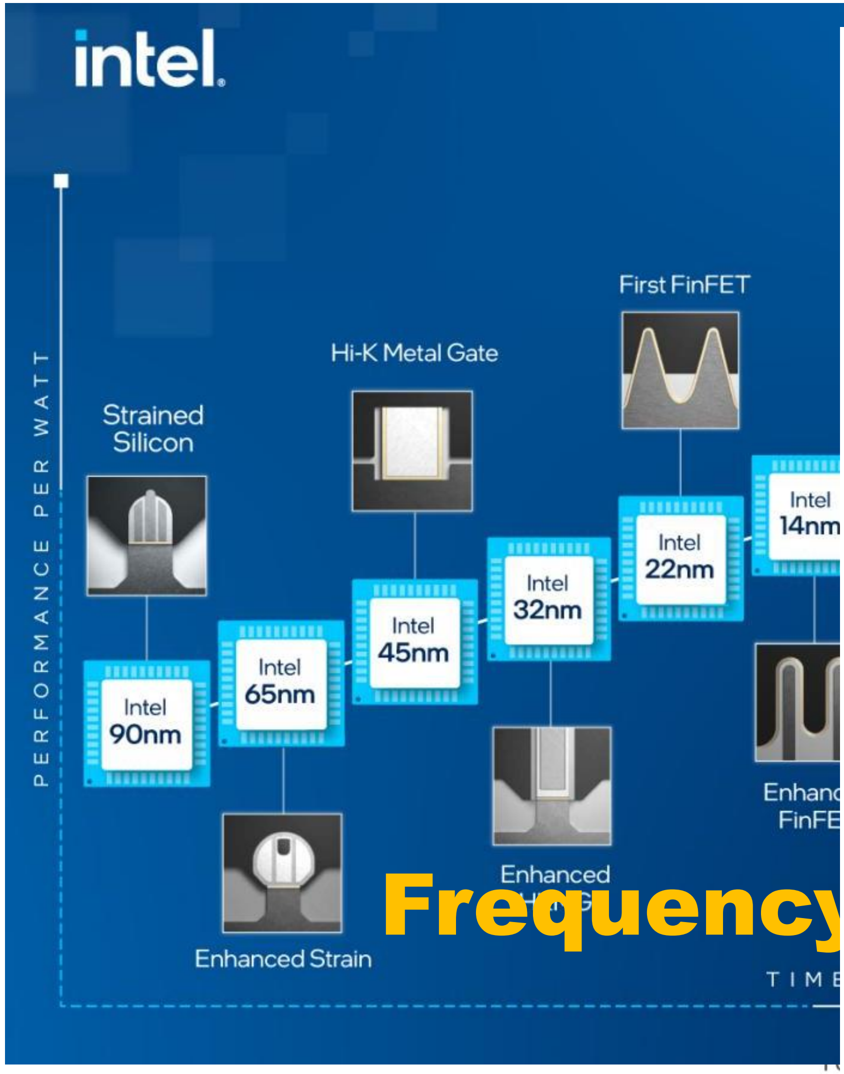
More equipment &More function under weight restriction

Transmission → Power

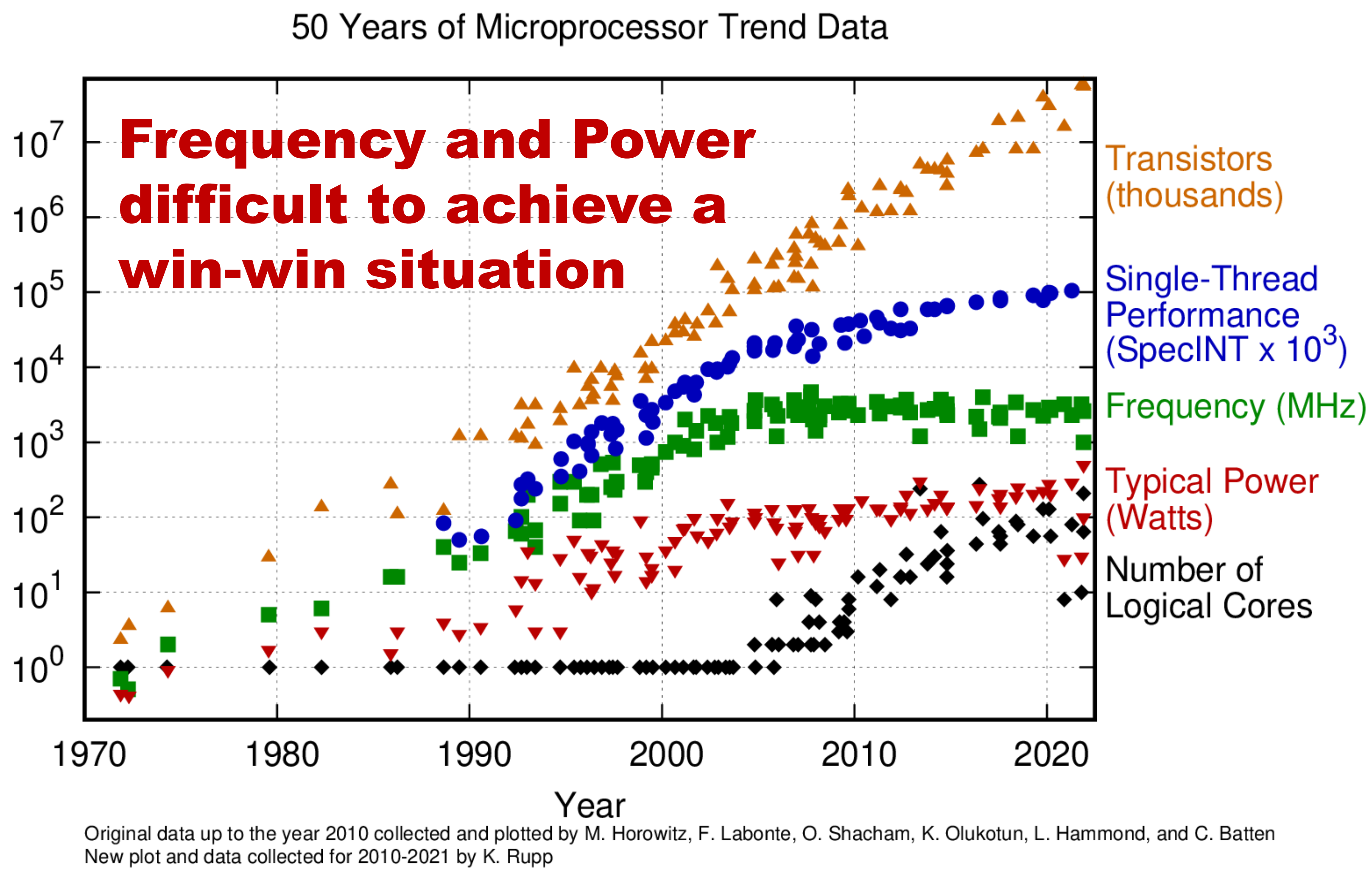
The higher power, The farther transmission

1 Motivation

Payload get more possibility in Modern Integrated Circuits (IC)



Frequency

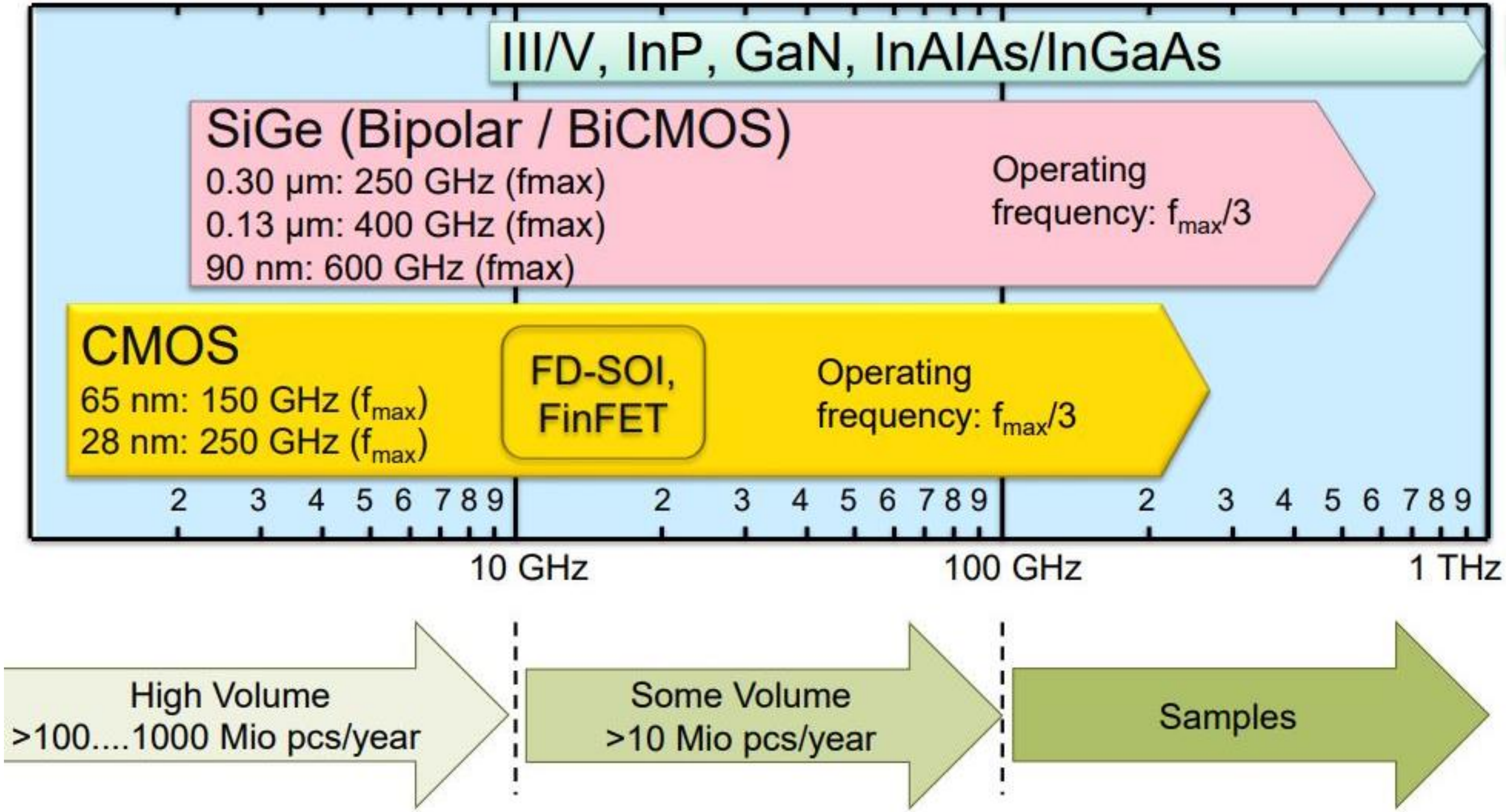


Frequency and Power difficult to achieve a win-win situation

Original data up to the year 2010 collected and plotted by M. Horowitz, F. Labonte, O. Shacham, K. Olukotun, L. Hammond, and C. Batten
New plot and data collected for 2010-2021 by K. Rupp

1 Motivation

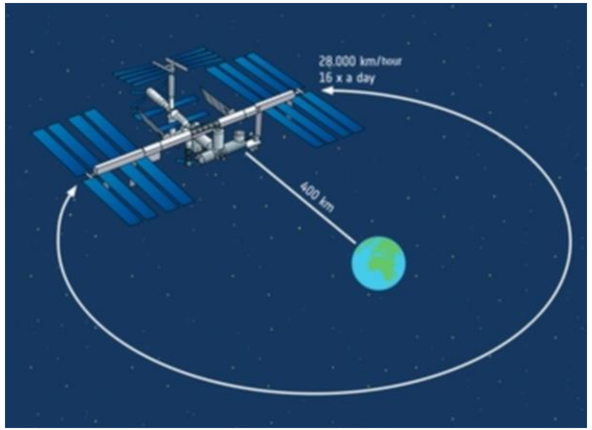
Compound semiconductors are the solution



1 Motivation

Weight introduced by “warm box” is one of the key factor for payload in space

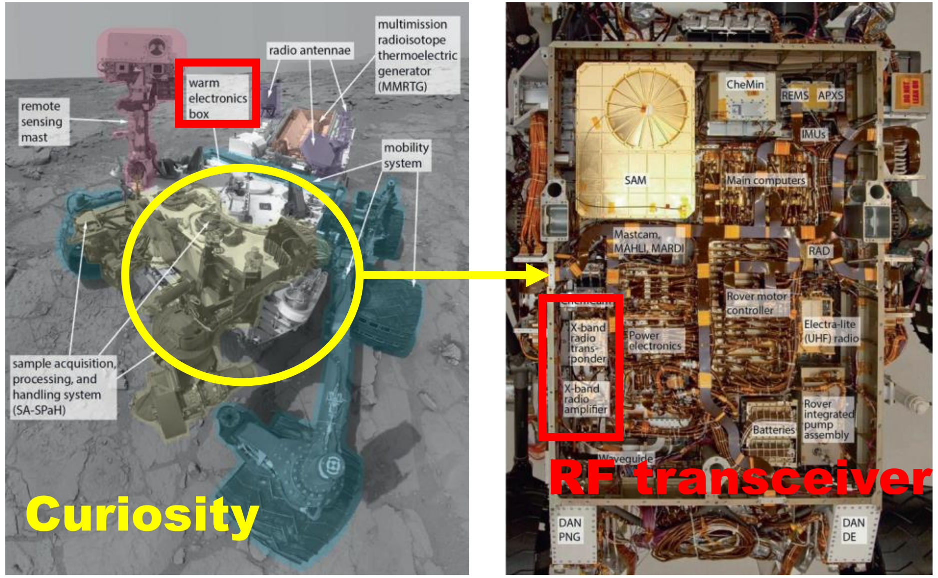
400km space station
-157℃ ~121℃

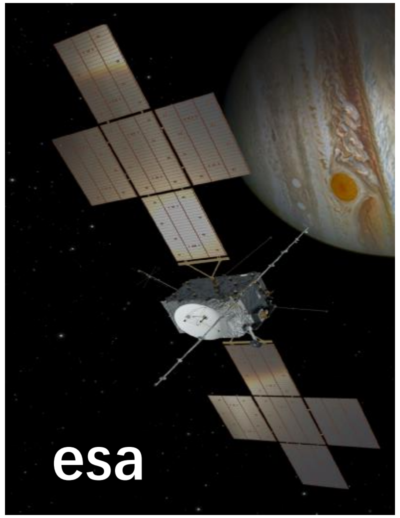


Moon
-183℃ ~ 106℃

Mars
-153℃ ~ 20℃

Jupiter -110℃



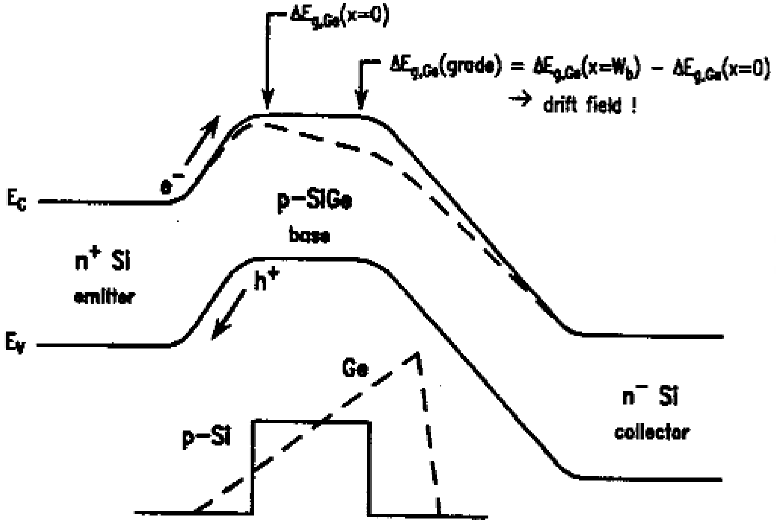


RADEM of JUICE work at -30℃

Spacecraft for deep space exploration need a huge “warm box”

2 SiGe HBT and its application area

SiGe HBT is the only device that can work well at 300mK, and it also can operate over a wide temperature range



Gain

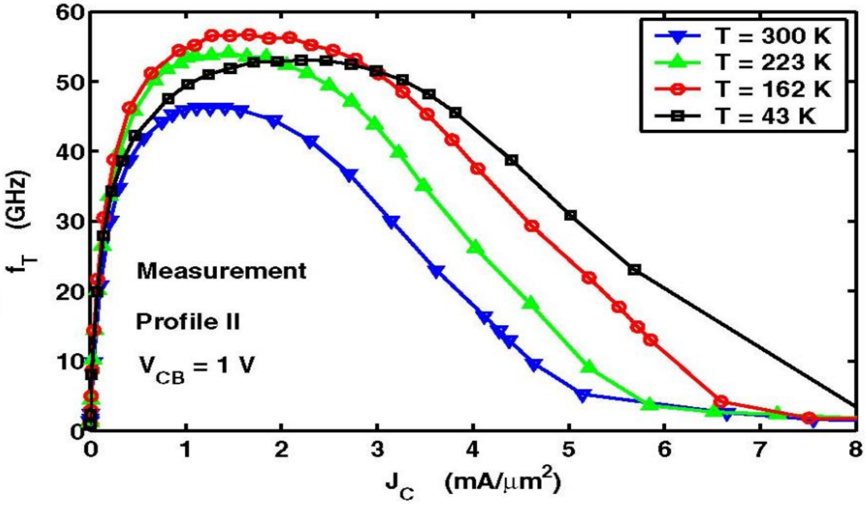
$$\left.\frac{\beta_{SiGe}}{\beta_{si}}\right|_{V_{BE}} \equiv \Xi = \left\{\frac{\tilde{\gamma}\tilde{\eta}\Delta E_{g,Ge}(grade)/kT\, e^{\Delta E_{g,Ge}(0)/kT}}{1-e^{-\Delta E_{g,Ge}(grade)/kT}}\right\}$$

Transition Time

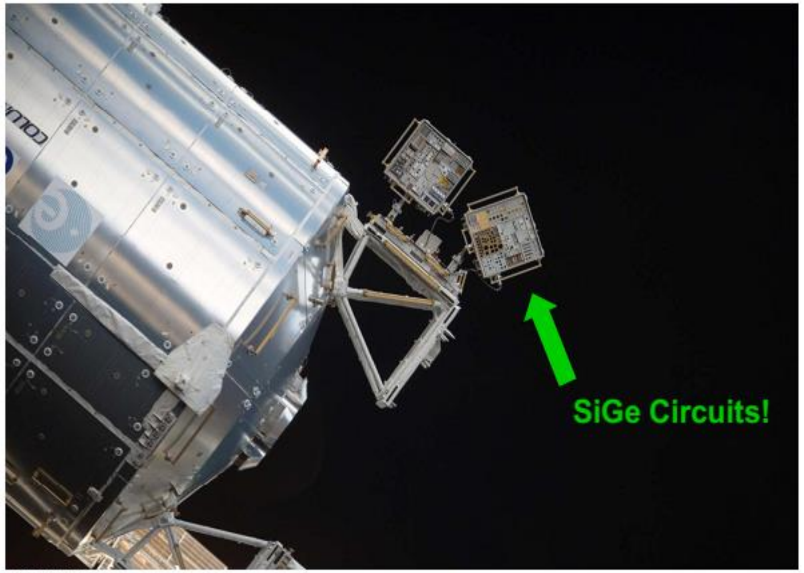
$$\frac{\tau_{b,SiGe}}{\tau_{b,Si}} = \frac{2}{\tilde{\eta}}\frac{kT}{\Delta E_{g,Ge}(grade)}\left\{1-\frac{kT}{\Delta E_{g,Ge}(grade)}\left[1-e^{-\Delta E_{g,Ge}(grade)/kT}\right]\right.$$

Early Voltage

$$\left.\frac{V_{A,SiGe}}{V_{A,Si}}\right|_{V_{BE}} \equiv \Theta \simeq e^{\Delta E_{g,Ge}(grade)/kT}\left[\frac{1-e^{-\Delta E_{g,Ge}(grade)/kT}}{\Delta E_{g,Ge}(grade)/kT}\right]$$



Technology	Temperature（℃）				
	<-150	-150~-55	-55~200	>200~500	>500
CMOS with SOI substrate	🟥	🟨	🟩	🟥	🟥
Bipolar with SOI substrate	🟥	🟨	🟩	🟥	🟥
SiGe HBT	🟩	🟩	🟩	🟥	🟥
GaN RF HEMT/HBT	🟥	🟥	🟩	🟩	🟨
SiC power transistor or diode	🟥	🟥	🟩	🟩	🟩
Vacuum Microelectronics	🟥	🟥	🟩	🟩	🟩
Diamond JFET	🟥	🟥	🟩	🟩	🟩



S123E009551

Recent NASA photograph of MISSE-6 after deployment, taken by the Space Shuttle Crew

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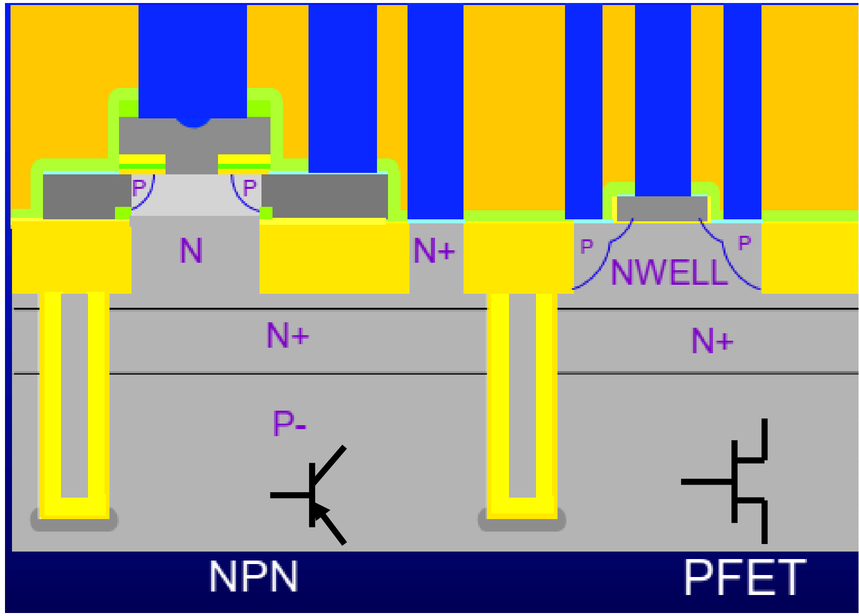
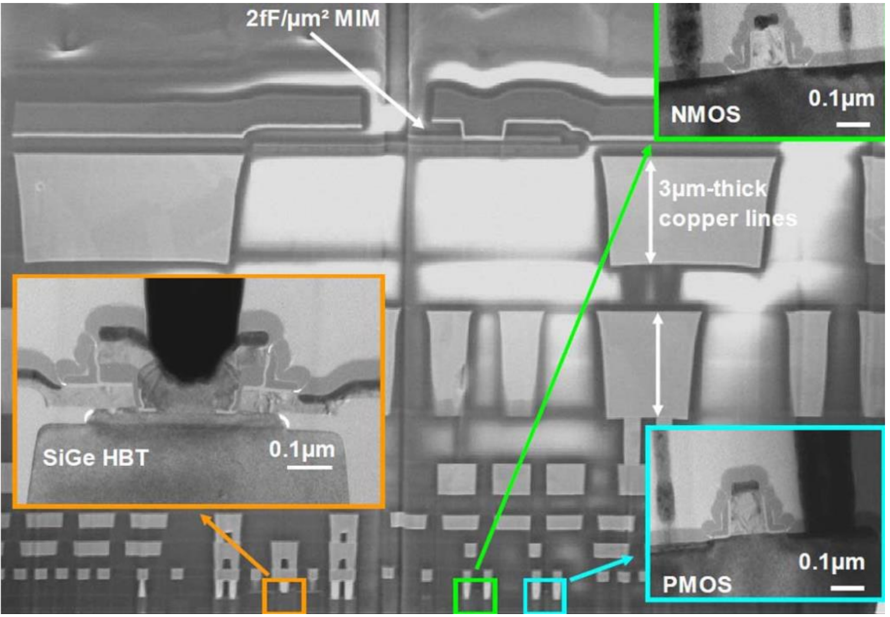
SiGe HBT and its application area

SiGe HBT well integrated with conventional high-performance Si CMOS realizing a BiCMOS technology

- **IC based on Silicon:** cost-effectively realize system-on-a-chip (**SoC**) and system-in-a-package (**SiP**) solutions
- **BiCMOS application:** analog blocks, digital blocks, and AD Conversion
- **Higher electronic performance:** RF communications





Application Area

- Wireless Communications
- Radio Access Networks
- Radar, Radar Imaging
- Navigation
- Actuation and control
- Sensors/ Sensors Interface

3

Radiation effects in modern semiconductors

45% failure of spacecraft on-orbit is caused by radiation effects

Space Radiation Environment
(solar system)

Trapped Particles (Rad.belts)
(only applicable to planets with magnetic field)

Transient Particles

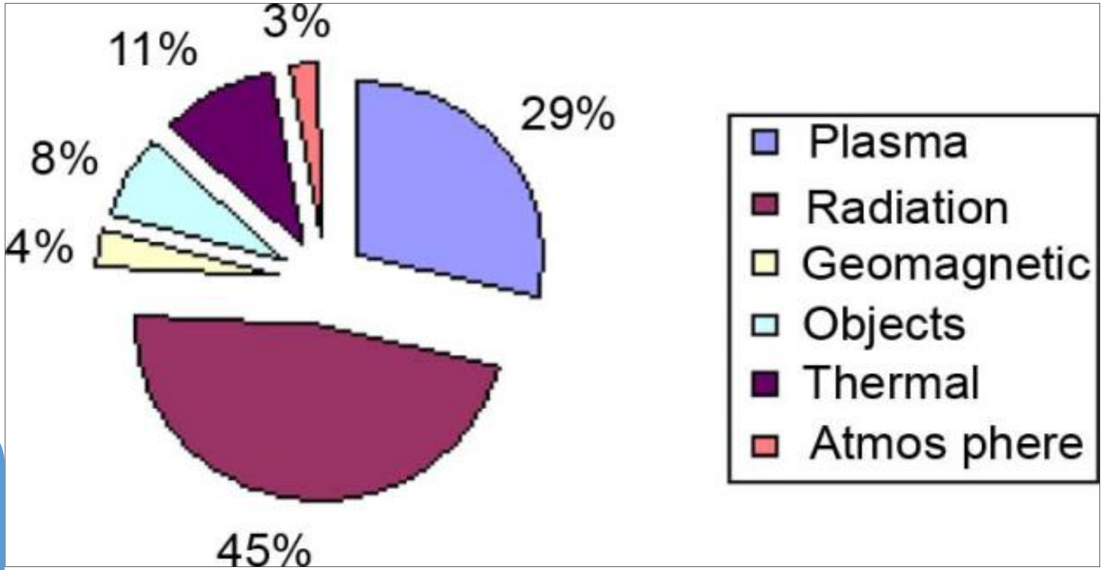
protons
<100× MeV

electrons
<10× MeV

Heavy Ions
<100× MeV

Galactic Cosmic Rays (GCR)
<1TeV
Z=1~92

Solar Energetic Particle Events
<1GeV



3 Radiation effects in modern semiconductors

Radiation Environment

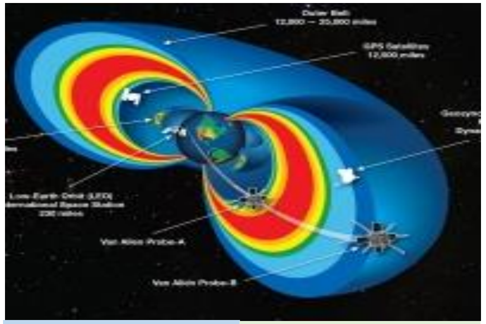
Galactic Cosmic Rays

Heavy ions

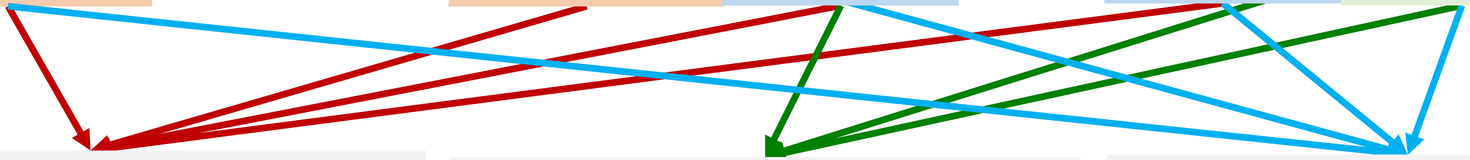
Solar events

Heavy ions | Protons

Van Allen Belts



Protons | Electron

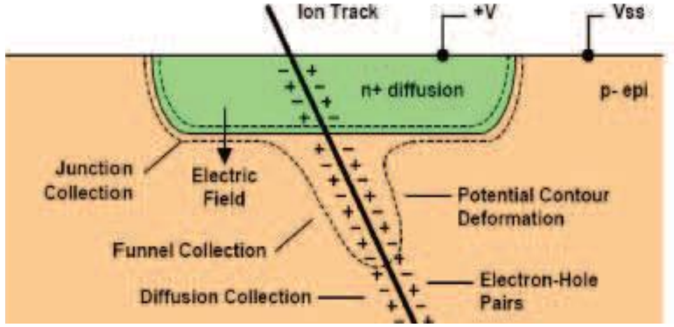


Radiation Effects

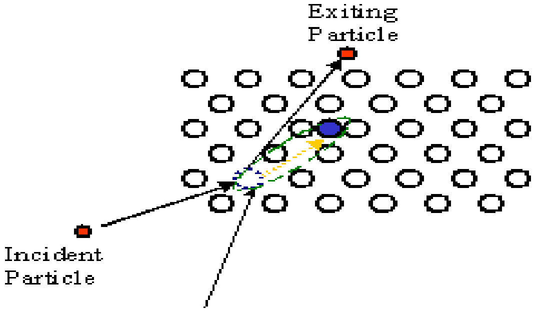
Single Event Effects(SEEs)

Displacement Damage(DD)

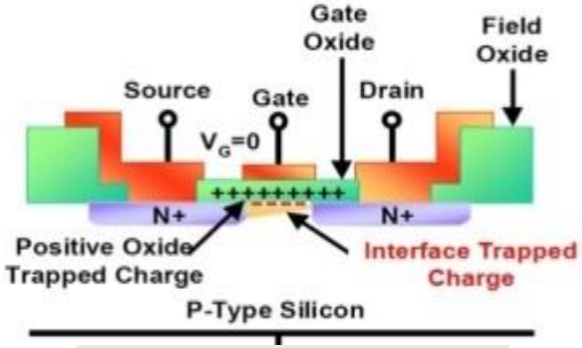
Total Ionizing Dose (TID)



Ionized carriers induced by single particles



Lattice defects

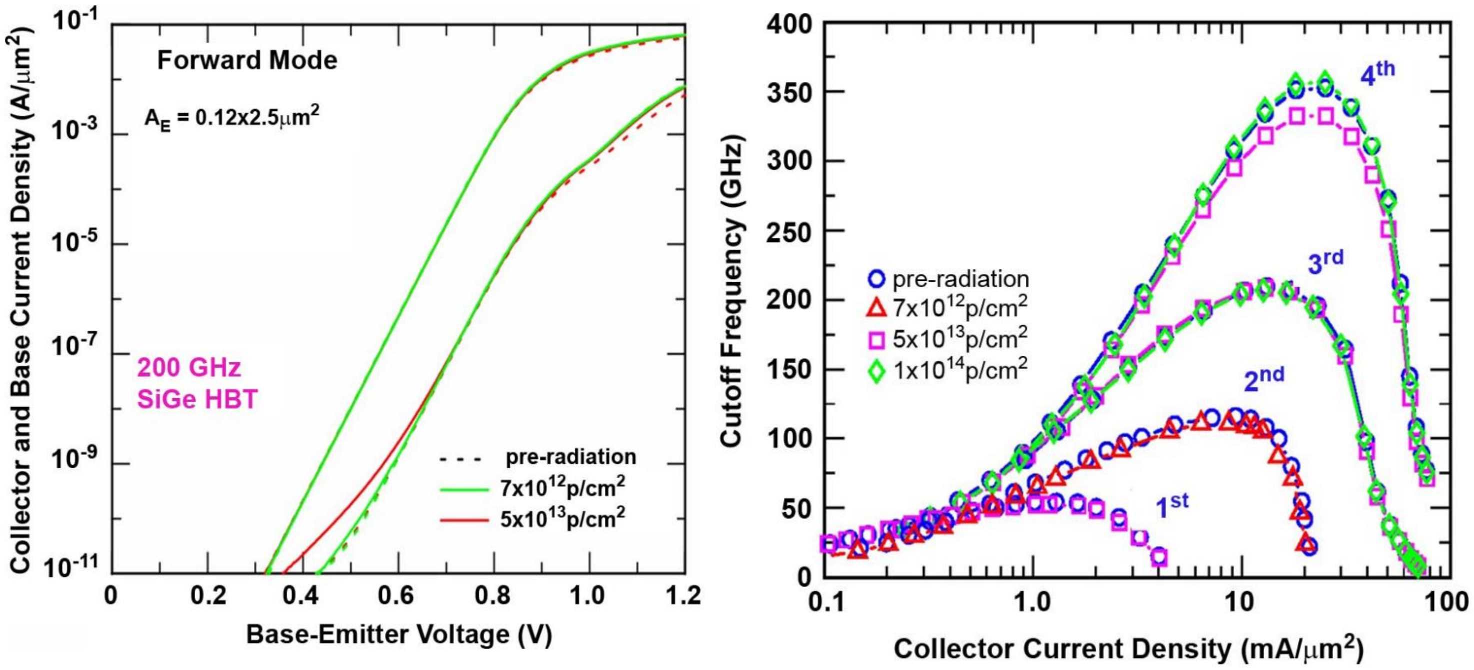


Trapped charges

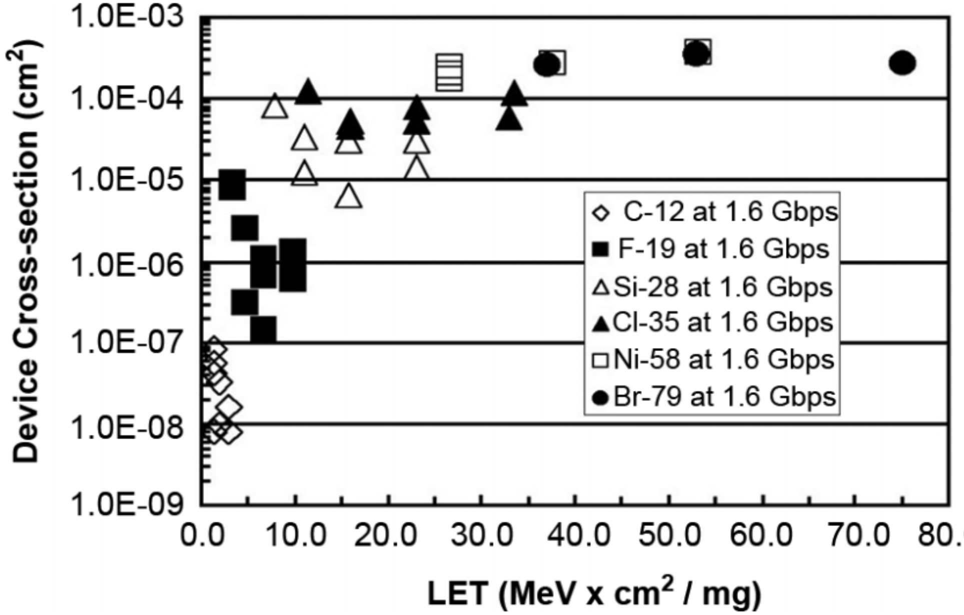
3 Radiation effects in modern semiconductors

SiGe HBT has an outstanding hardness to both TID and DD

SEE could be a potential threat to space applications in SiGe HBT



63MeV proton irradiation for TID and DD evaluation

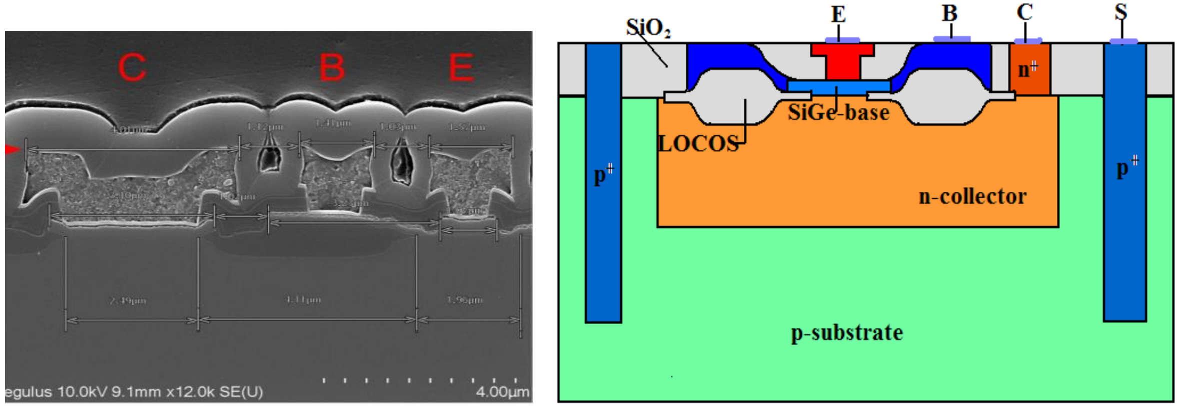


Heavy ions irradiation for SEE in 1st-generation SiGe HBT shift-register

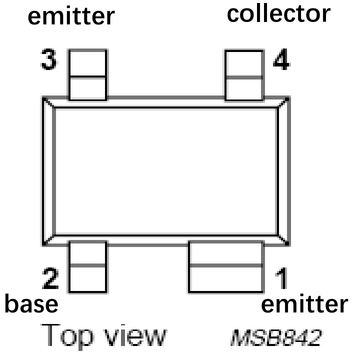
4 SEE in SiGe HBTs

➢ Sample

HBT device KT9041--commercial product



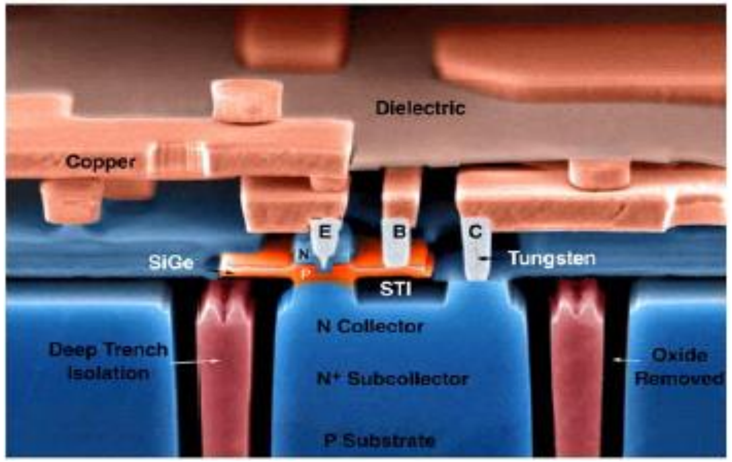
2nd generation SiGe HBTs



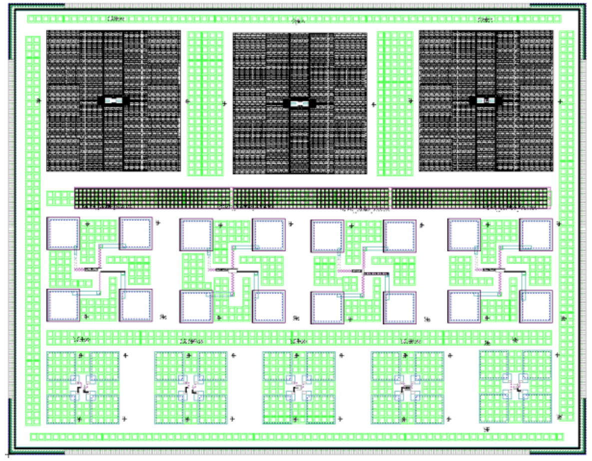
Package-SOT343

- The feature size about 0.45um
- Local Oxidation of Silicon (LOCOS) thus some different representation of TID

HBT device -- from laboratory



3rd generation SiGe HBTs

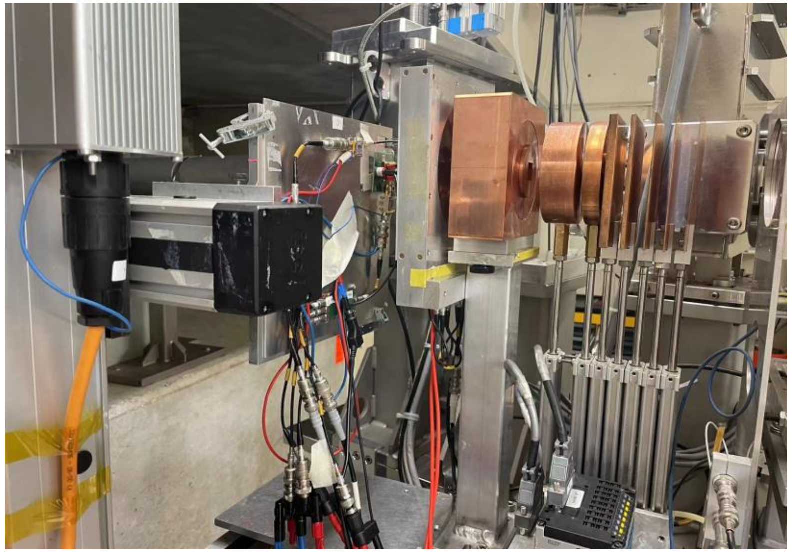


Layout of the wafer

- The feature size about 0.13um
- Shallow trench isolation (STI)
  Deep trench isolation (DTI)

4 SEE in SiGe HBTs

Experiment



Proton irradiation in PIF

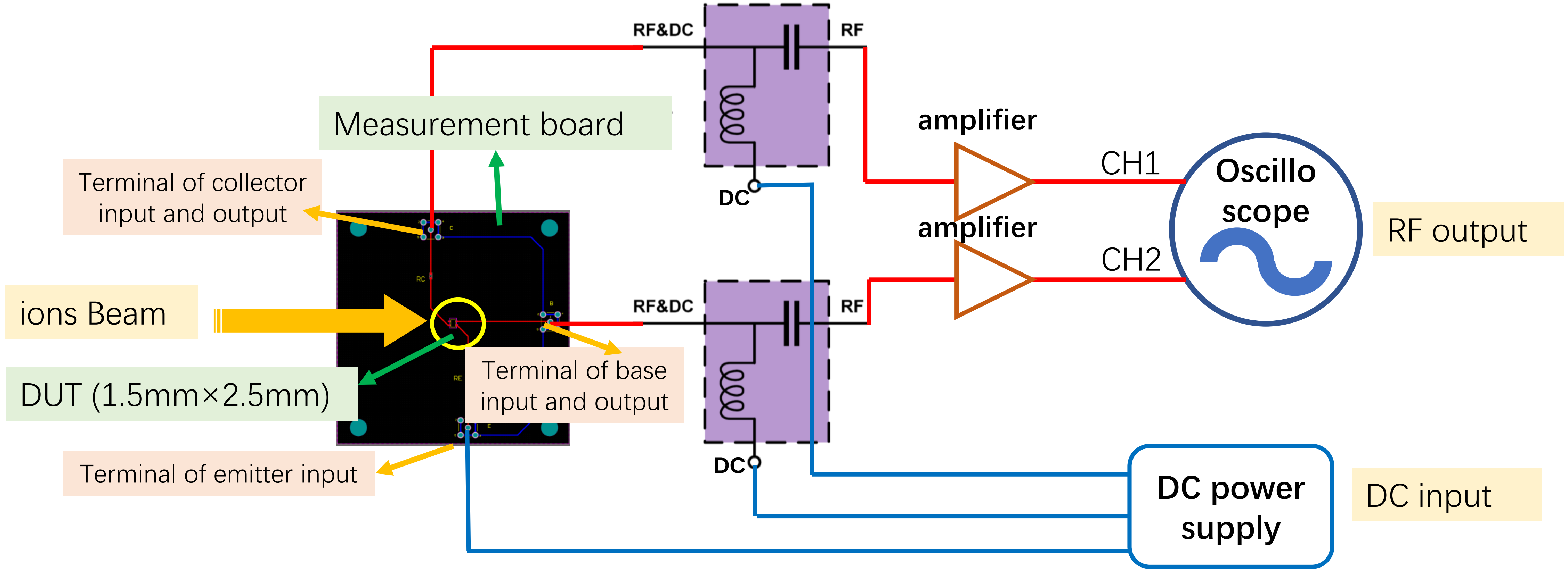
- Striking angle：0°, 90°, 180°
- Biases: ①V_{be}=0.7V & V_{bc}=-1.2V, ② V_{bc}=-5V
- Energy: 200MeV, 100MeV, 50MeV, 16MeV
- Temperature: room temperature, ≥ LN2

Heavy ions irradiation in CIAE

- wide-beam 3cm × 3cm; micro-beam 2.7μm×4.1μm
- Biases: ①V_{bc}=-1V, ②V_{bc}=-2V, ③V_{bc}=-3V
- Ions: 283MeV I+, 110MeV Cl+
- Temperature: room temperature

4 SEE in SiGe HBTs

➢ Measurement



Measurement board

Terminal of collector input and output

ions Beam

DUT (1.5mm×2.5mm)

Terminal of base input and output

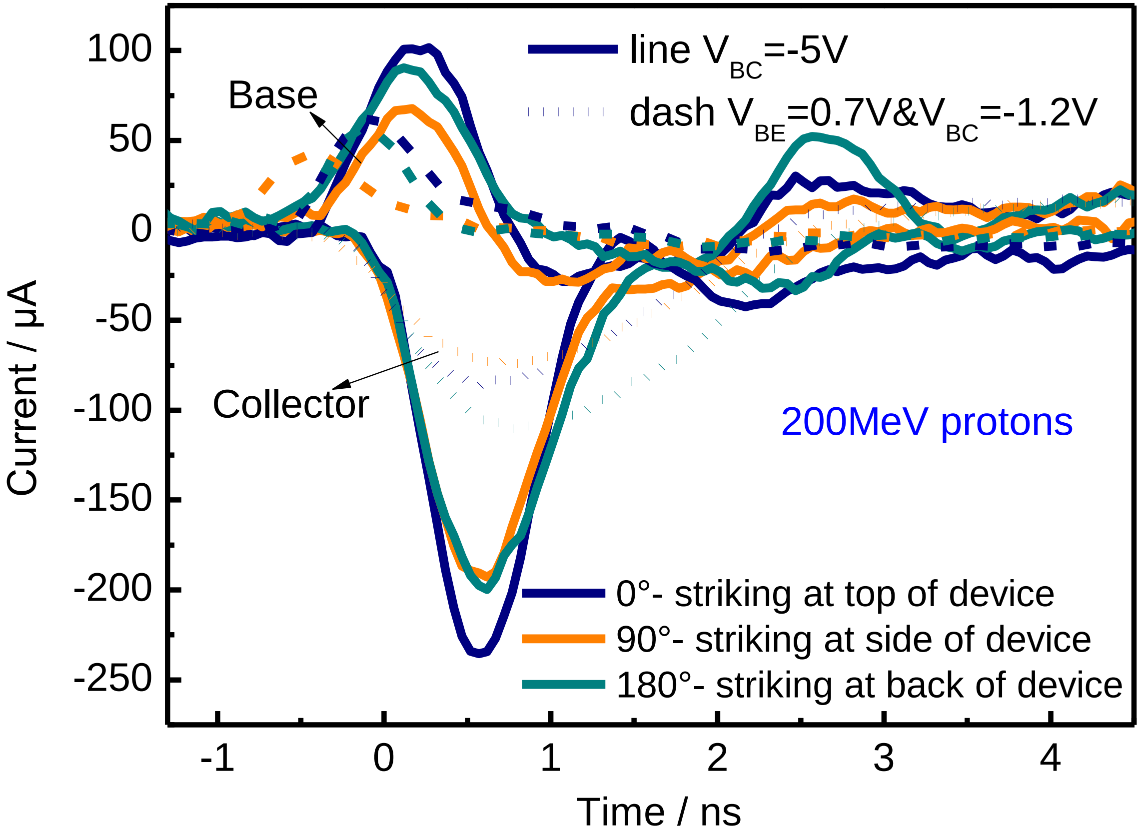
Terminal of emitter input

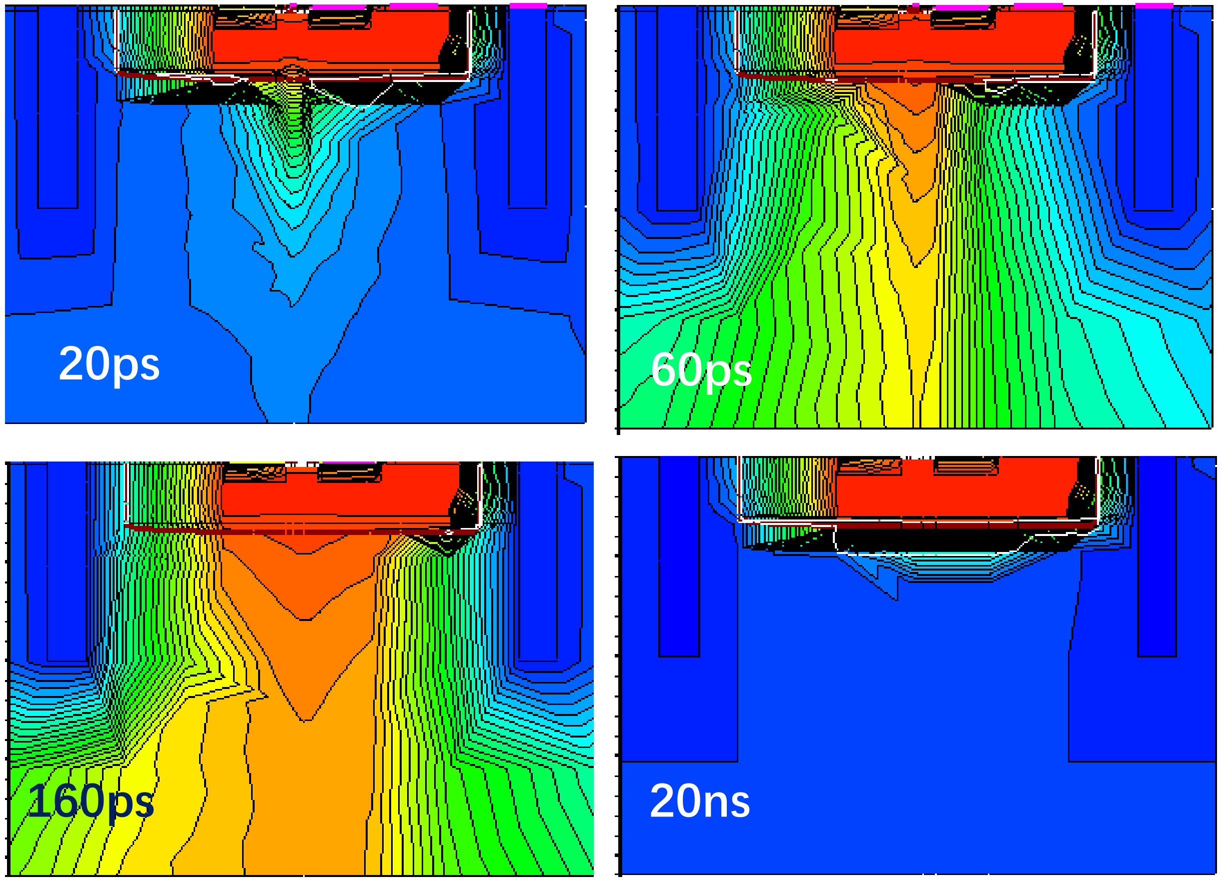
RF output

DC input

4 SEE in SiGe HBTs (PSI)

➢ Results of 0.45μm SiGe HBT



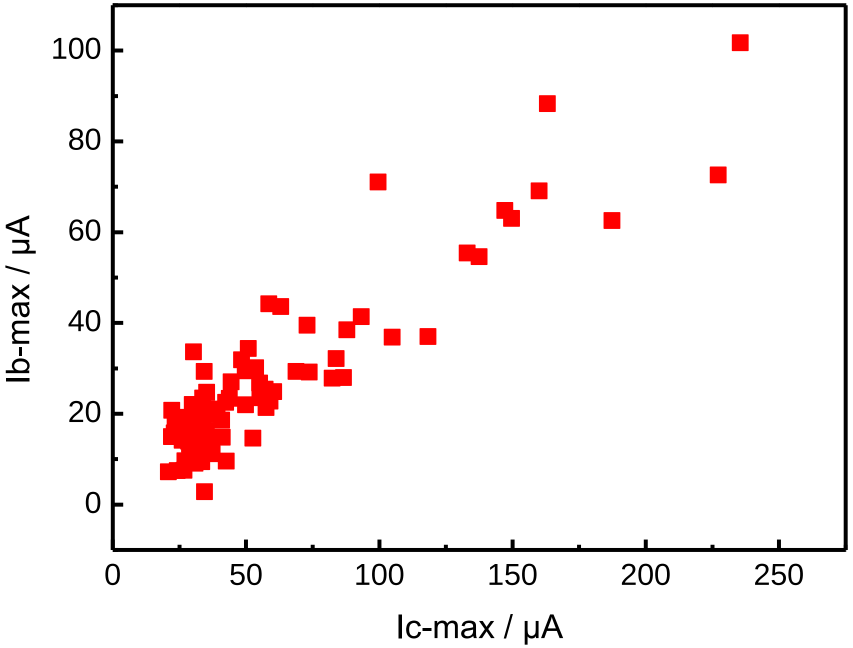


When particles strike the pn junctions of SiGe HBT, carriers will be created along their tracks disturbing the electrostatic potential. Electrons and holes will be collected through both drift and diffusion forming transient currents

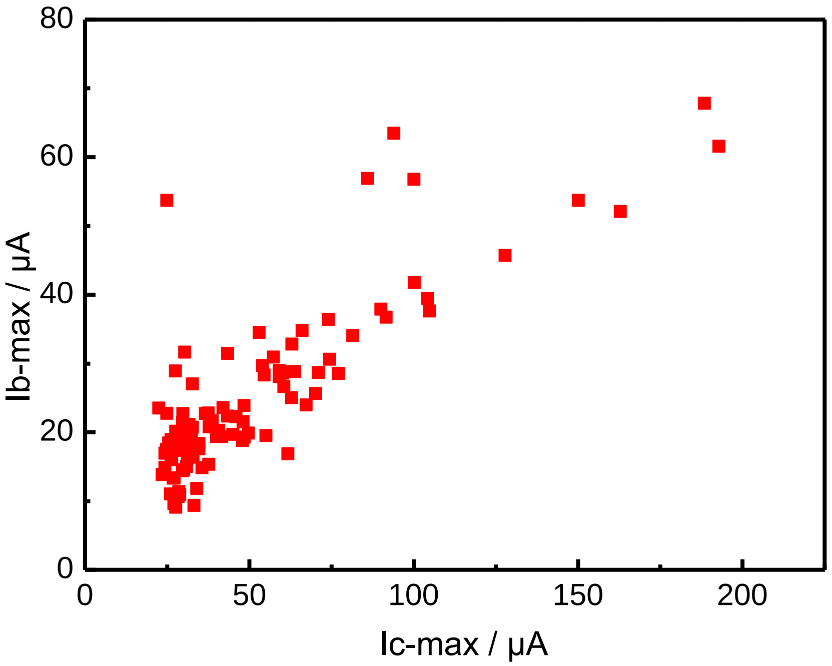
4 SEE in SiGe HBTs (PSI)

➢ Different striking angle

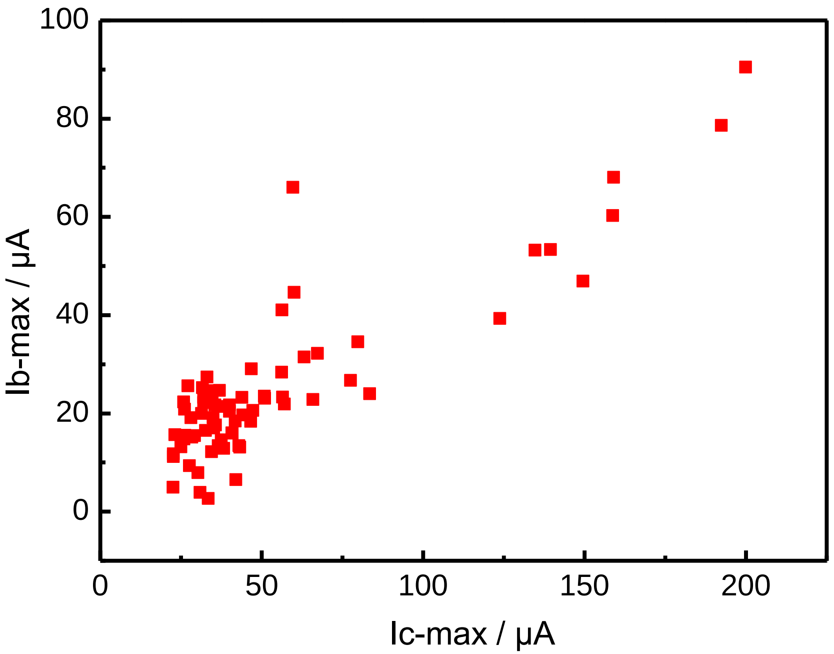
200MeV Vbc=-5V Flux=3.9E8 $cm^{-2}s^{-1}$ Fluence=5E11 p/cm^2



0° -top of device



90° -side of device



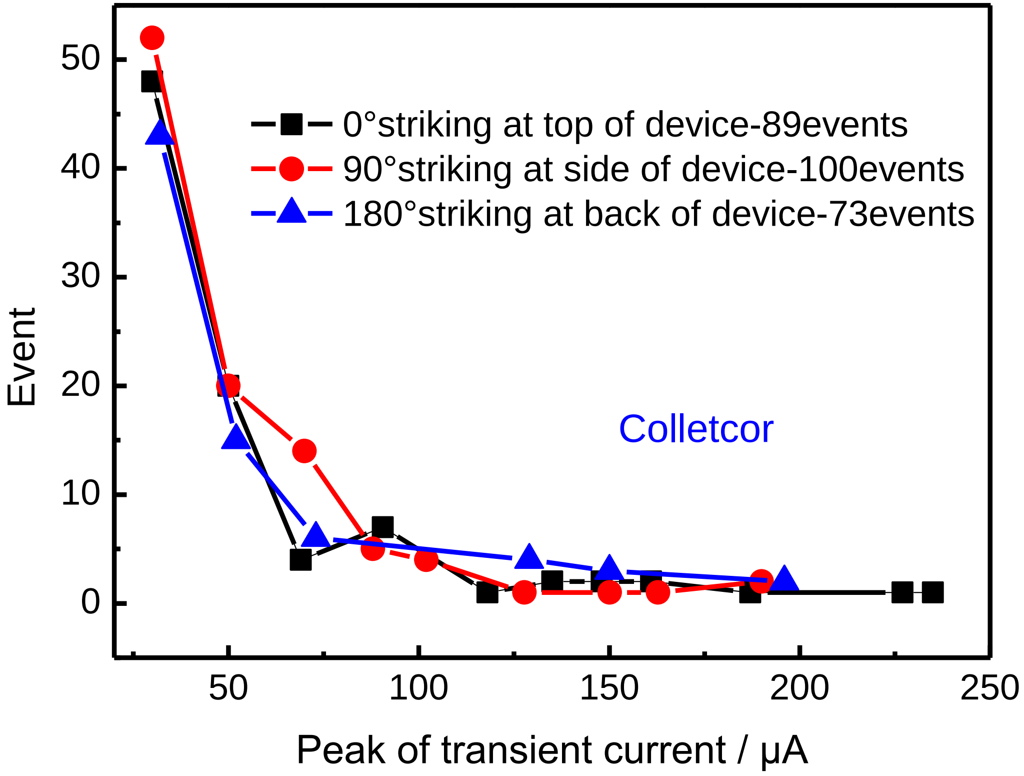
180° -back of device

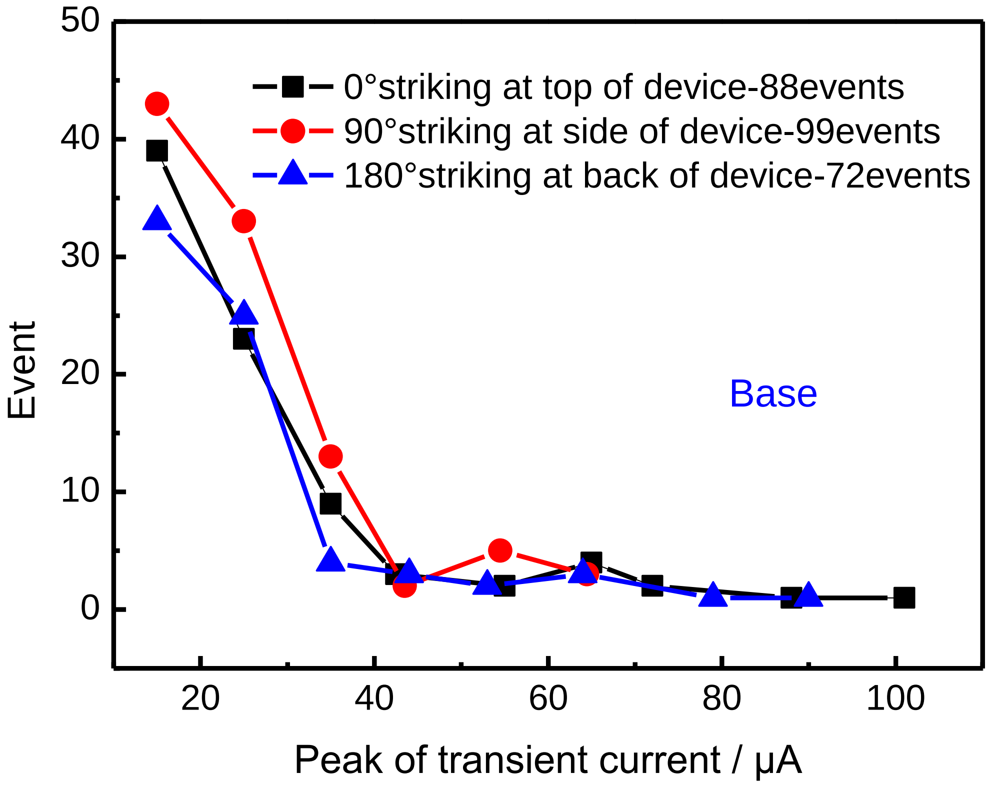
- Device structure and nuclear cross sections favor transient events distributions where both the collector and the base currents are small.
- For larger LET, one observes more roughly linear relation between collector and base current peaks

4 SEE in SiGe HBTs (PSI)

➢ Different striking angle

200MeV Vbc=-5V Flux=3.9E8 cm^{-2}s^{-1} Fluence=5E11 p/cm^2

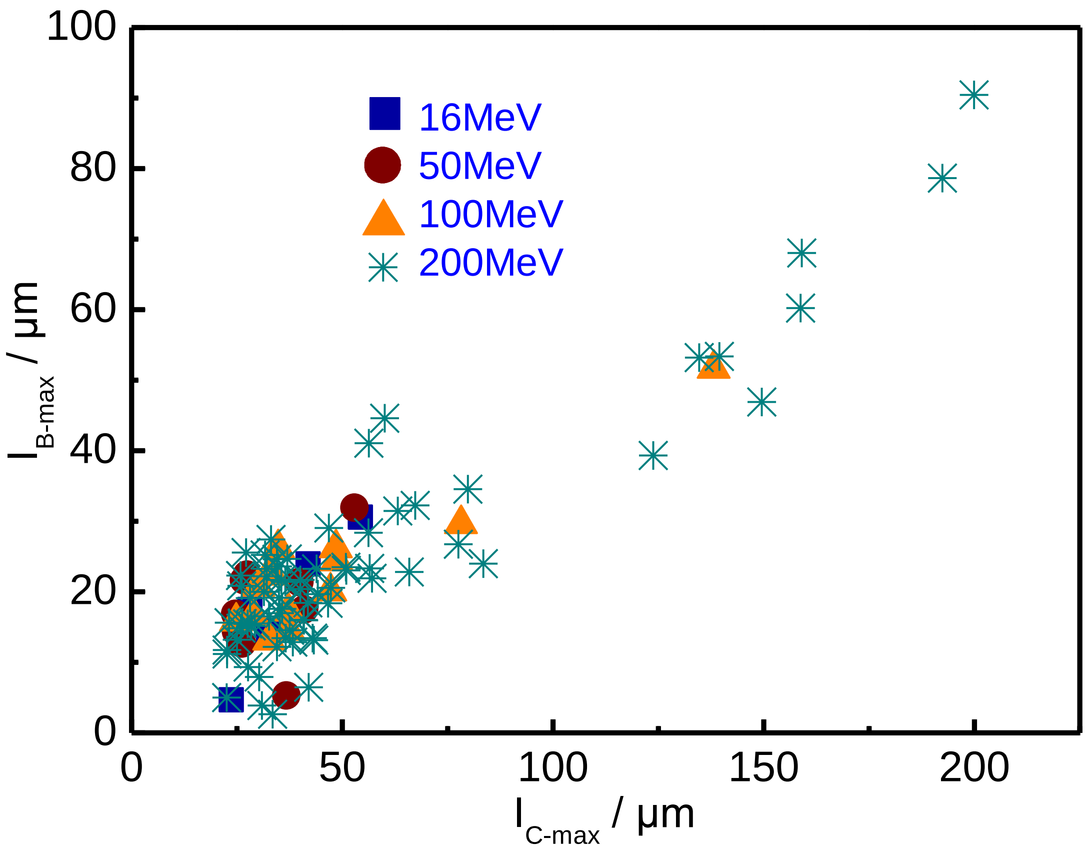


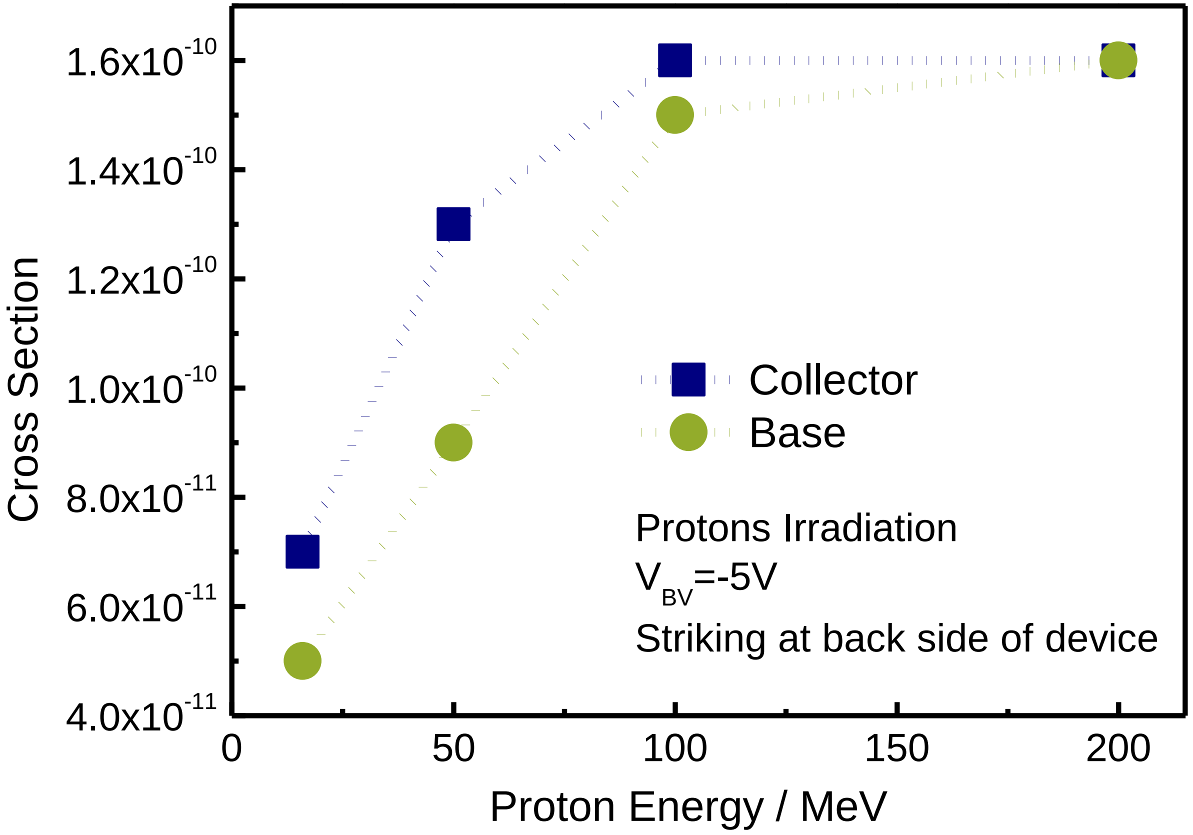


For proton case, the e-h pairs are created by secondary particles. These are produced in nuclear reactions with lattice atoms in the sensitive area. Direction of secondaries depends on nuclear reaction mechanisms.

4 SEE in SiGe HBTs (PSI)

➢ Different energy

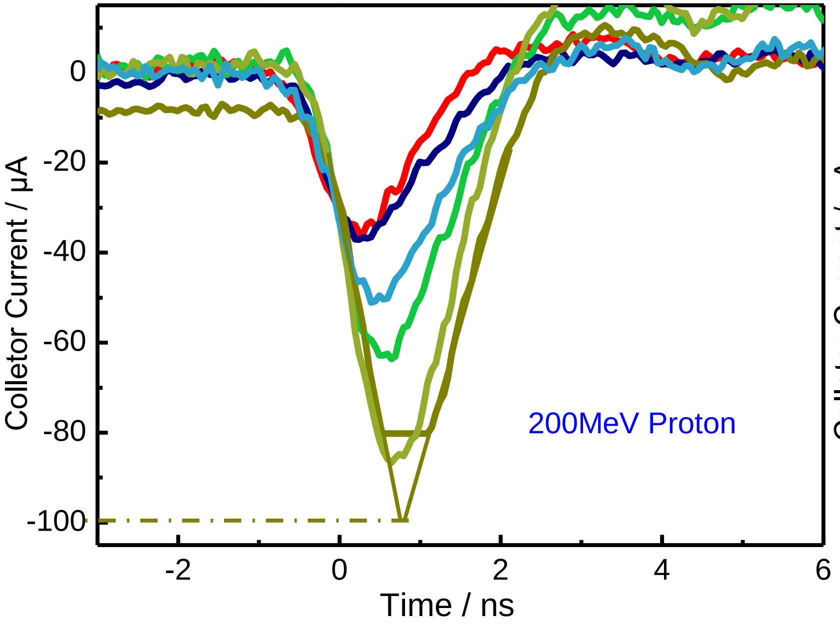




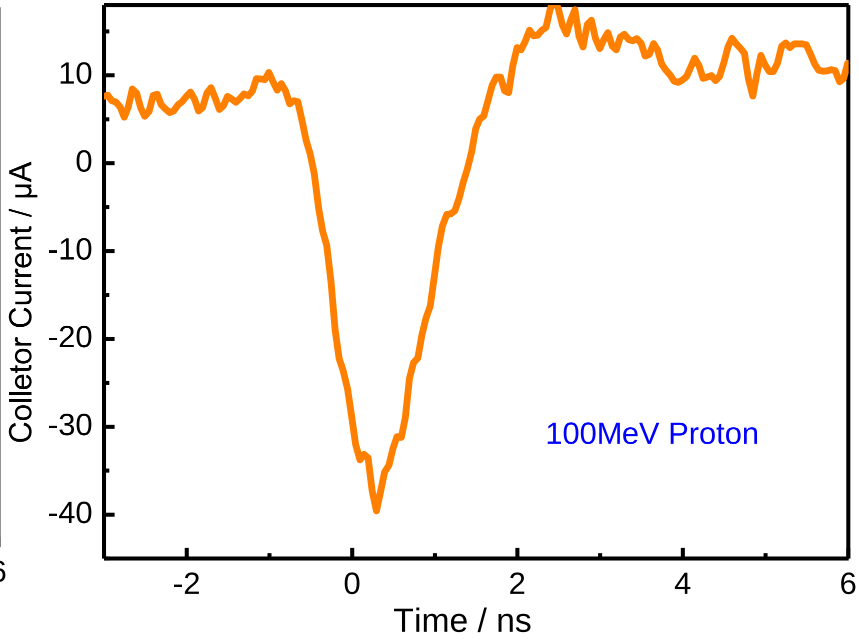
SEE cross section increases with proton energy reaching saturation around 100MeV.

4 SEE in SiGe HBTs (PSI)

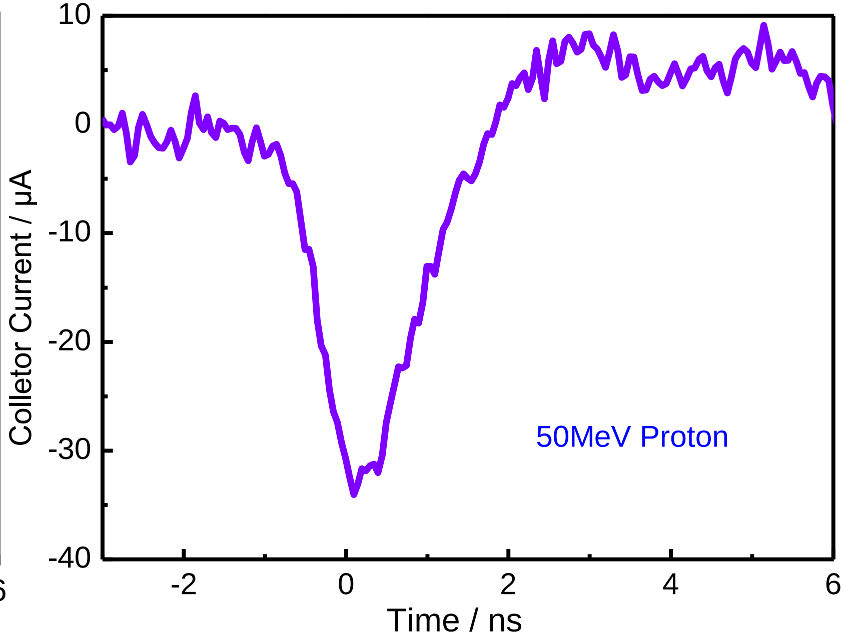
➢ Results of 0.12μm SiGe HBT



200MeV
σ≈10^{-11} cm^2



100MeV
σ≈10^{-11} cm^2



50MeV
σ≈10^{-11} cm^2

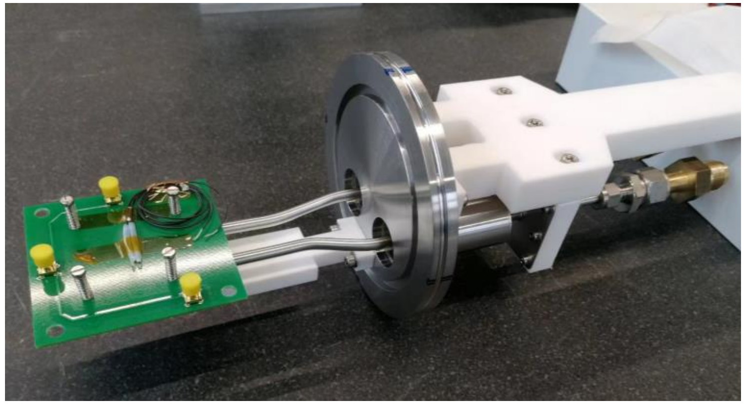
Smaller active area : →

- Smaller σ; less SEE events
- Smaller transient currents
- No transients in base

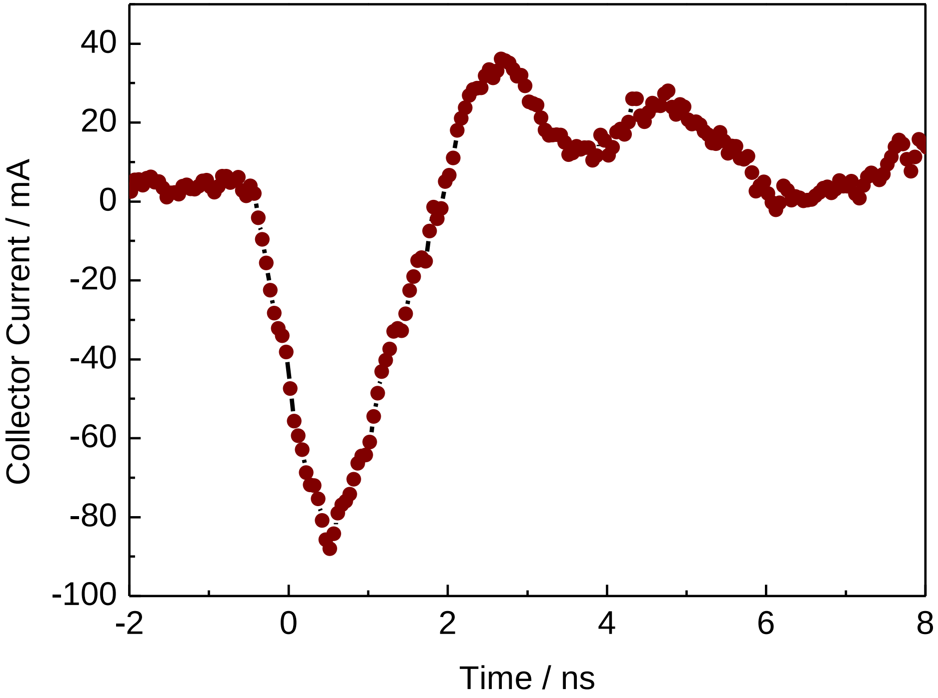
4

SEE in SiGe HBTs (PSI)

➢ Proton irradiation at cryogenic temperature



- Liquid nitrogen cooling
- Copper cold finger
- Vacuum
- T ~ -150℃

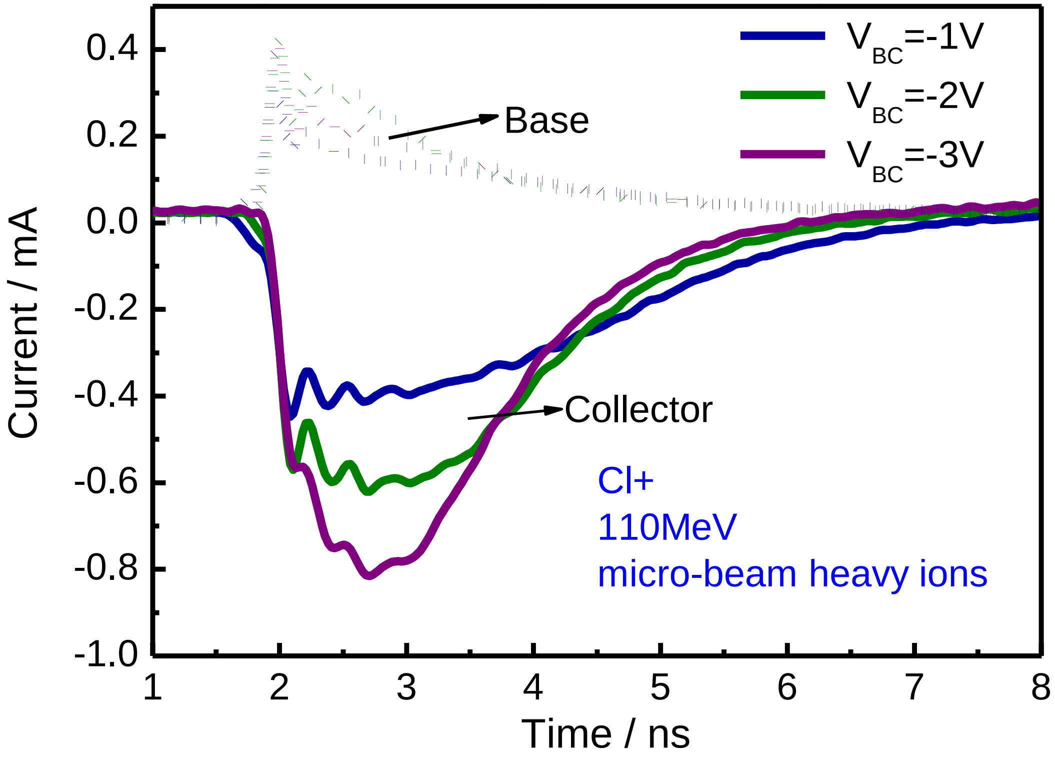


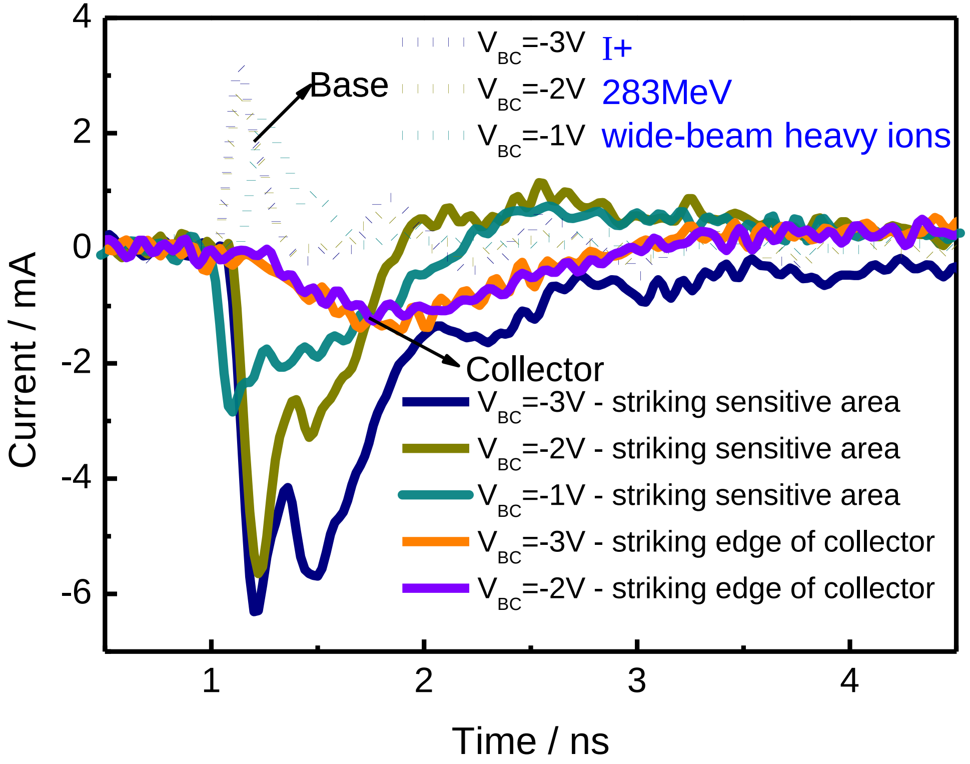
Preliminary conclusions:

- Transient currents similar as for room temperature
- Less events; lower SEE cross section

4 SEE in SiGe HBTs (CIAE)

➢ Results of heavy ions on 0.45μm SiGe HBT





Large direct ionization induced by heavy ions; excess carriers promptly collected at the electrodes

Two kinds of transients:

- Transient peaks of about 1mA. Ions strike the area near collector edge. Collection process - diffusion
- Fast rise and slow fall transients. Ions strike near the sensitive region. Collection process – drift, later diffusion.

4

SEE in SiGe HBTs

➢ Comparison proton and heavy ions

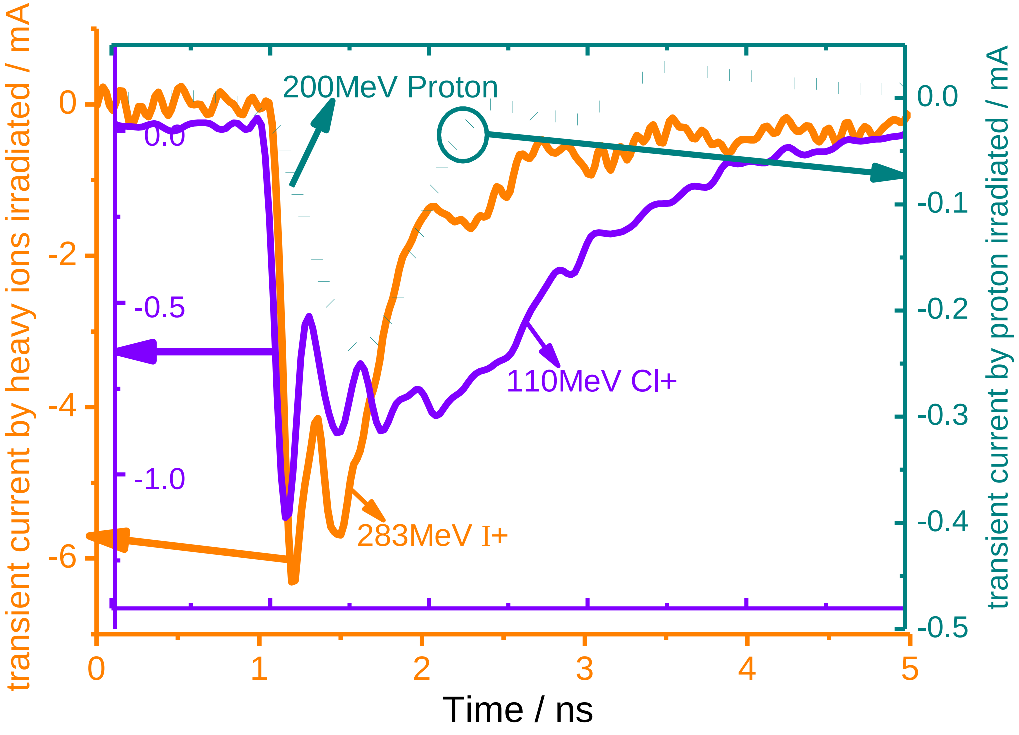


Table SEE events and cross section in protons and heavy ions irradiation

terminal	Protons (200MeV) Events	Protons (200MeV) Cross section (cm^{-2})	Heavy ions (283MeV I+) Events	Heavy ions (283MeV I+) Cross section (cm^{-2})
Collector	89	1.6×10^{-10}	60	6×10^{-6}
Base	88	1.6×10^{-10}	11	1.1×10^{-6}

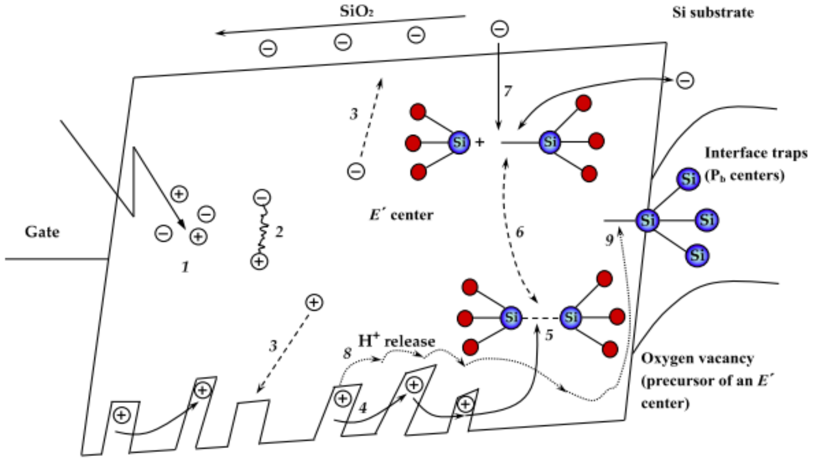
1. Transient currents induced by heavy ions much bigger (some mA) than induced by protons (few hundred μA).
2. Proton cross sections for base and collector transients similar; not the case for heavy ions.
3. Proton cross section few orders of magnitude smaller
4. Proton induced pulses shorter and with slower risetime

Thank You

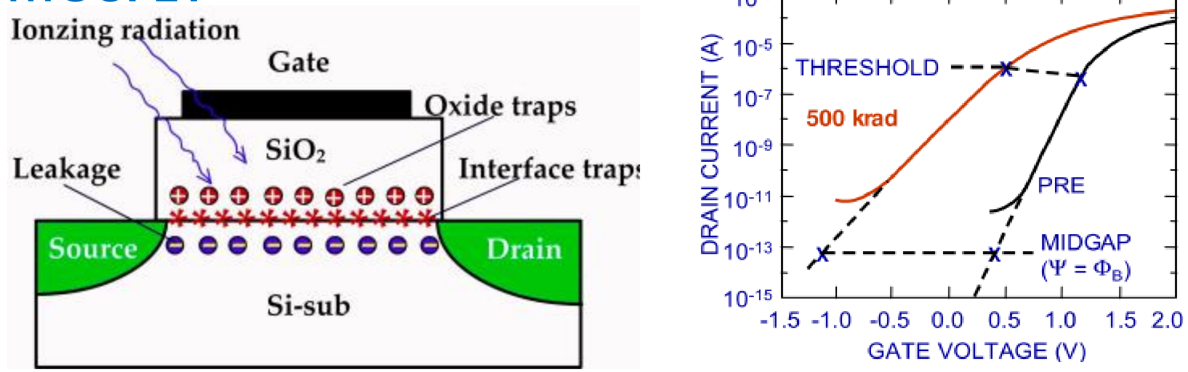
3 Radiation effects in modern semiconductors

Ionizing Radiation Damage: Total Ionizing Dose (TID)

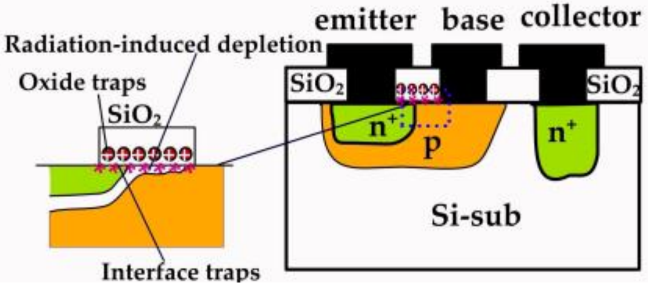
TID is a long-term cumulative effect of radiation damage

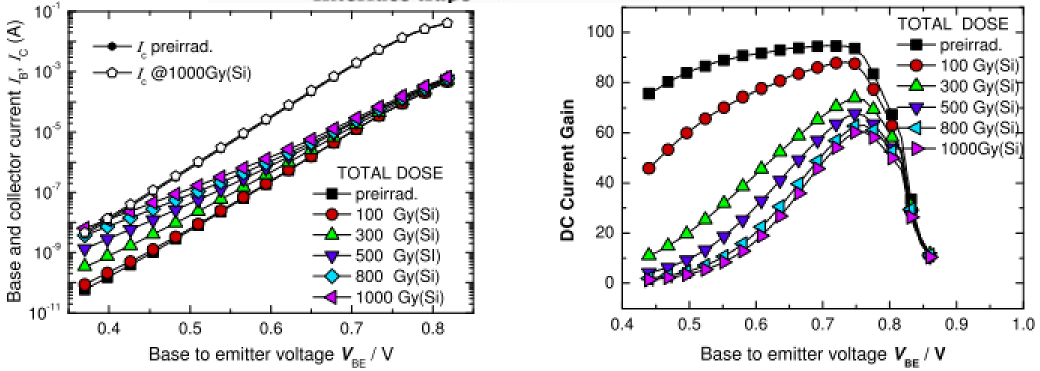


MOSFET

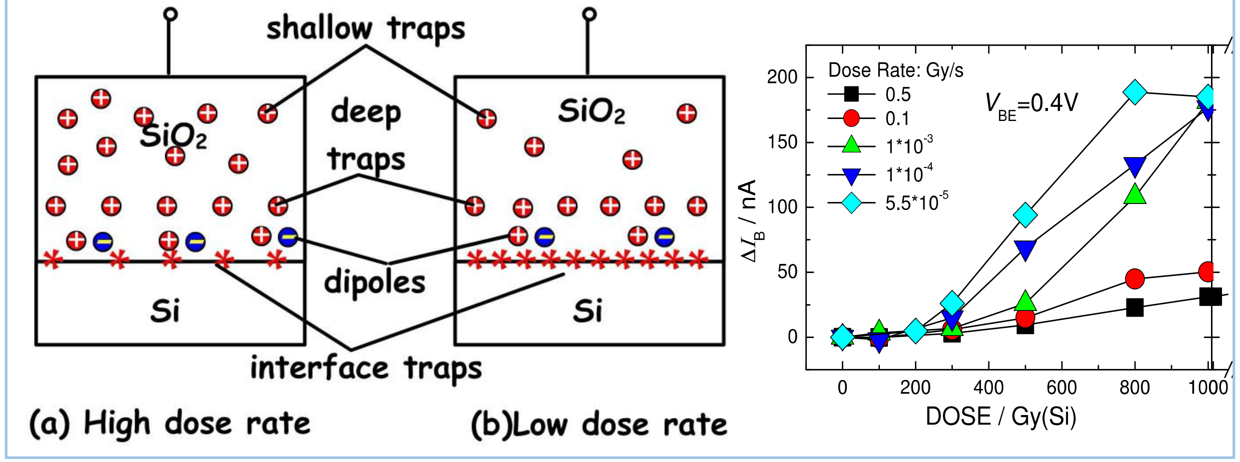


Bipolar (BJT HBT)





Enhanced Low Dose Rate Sensitive (ELDRS)in Bipolar

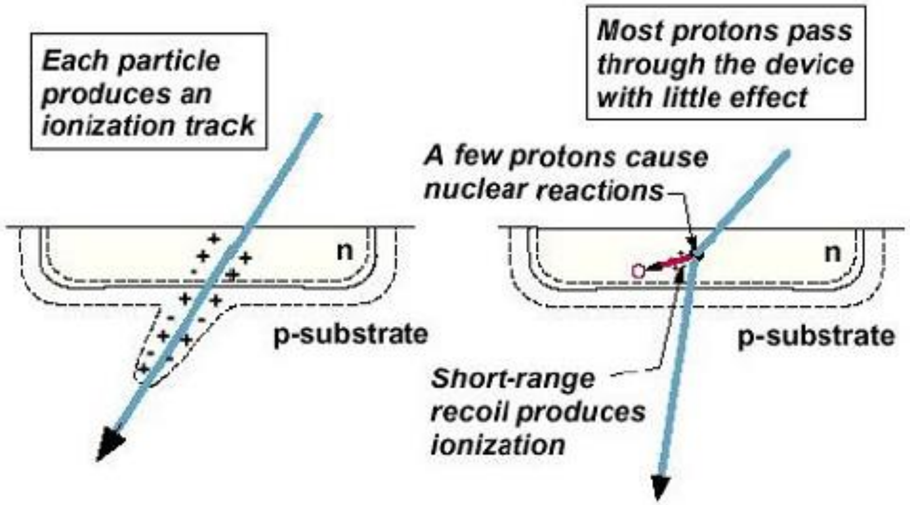


(a) High dose rate (b)Low dose rate

3

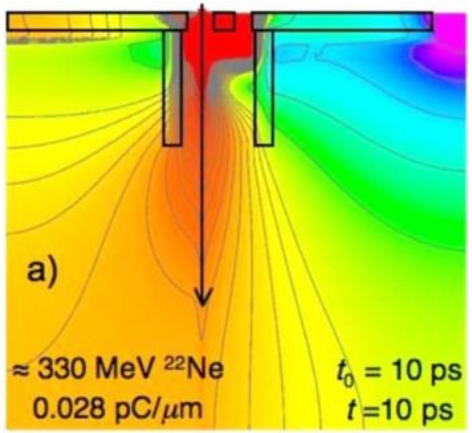
Radiation effects in modern semiconductors

Ionizing Radiation Damage: Single Event Effects (SEEs)

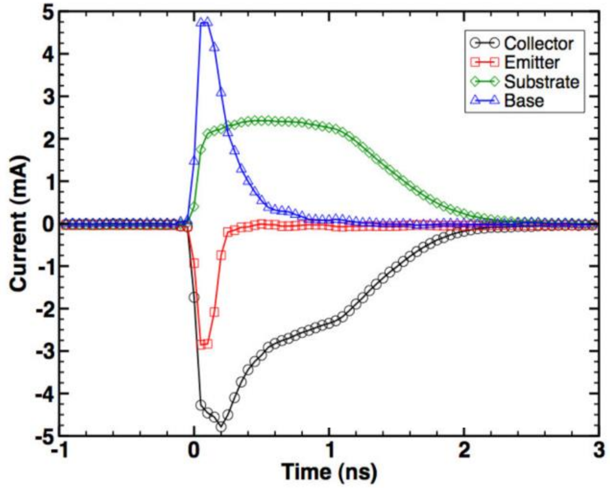


Single particle strikes sensitive area of microelectronic device. The excess carriers cause some changes of electrical properties. As the reduced of feature size, there are much more accounted of SEEs.

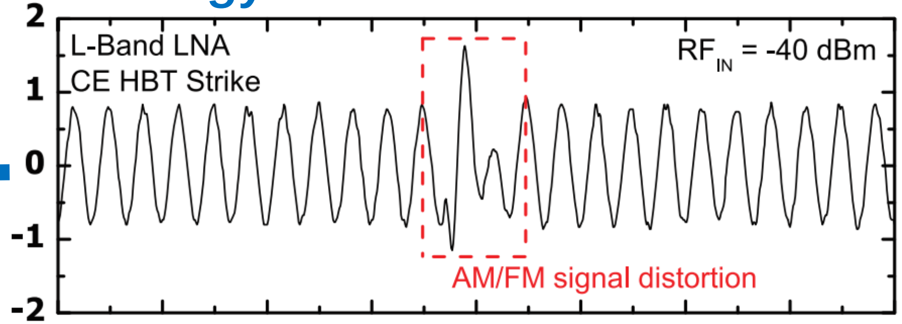
SEE on SiGe HBT



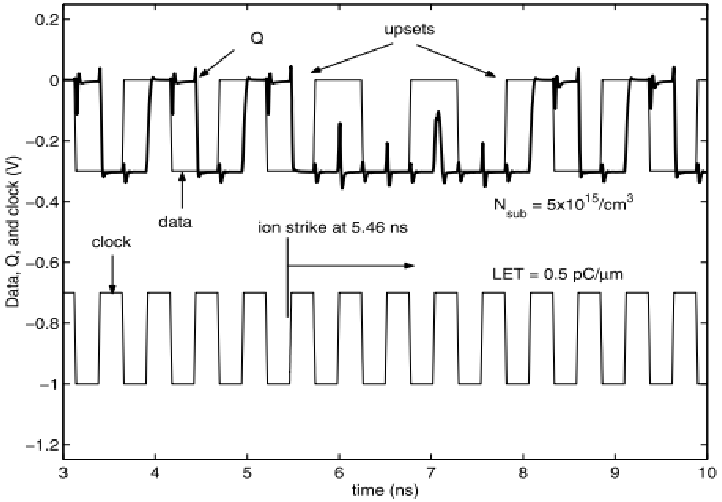
0° strike through emitter



SET on SiGe HBT analogy circuit



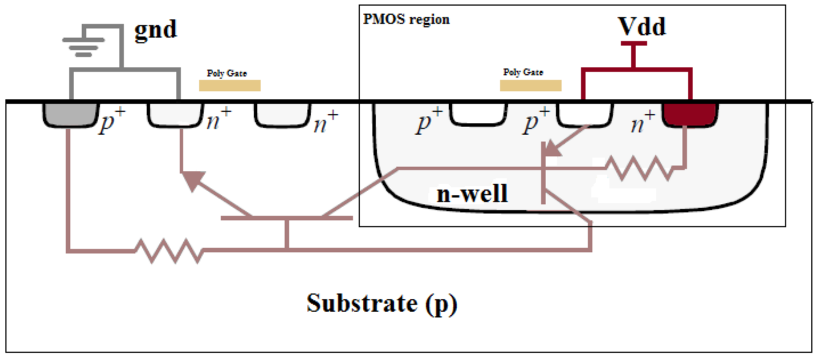
SEU on SiGe HBT digital circuit



3 Radiation effects in modern semiconductors

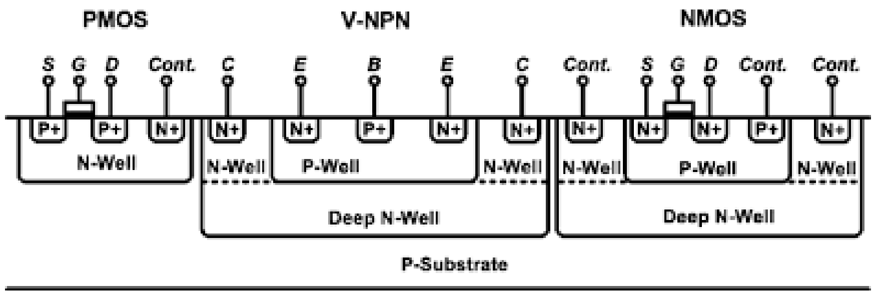
Ionizing Radiation Damage: Single Event Effects (SEEs)

Single Event Latchup (SEL)

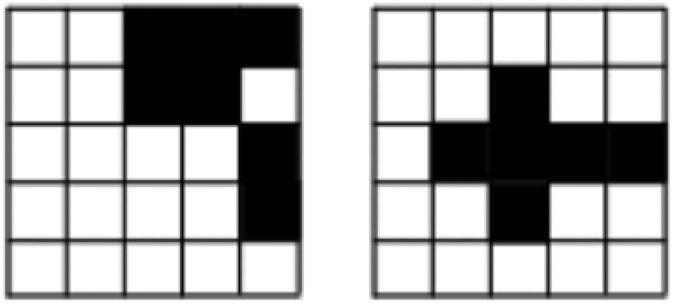


parasitic bipolar junction transistors in the CMOS technology

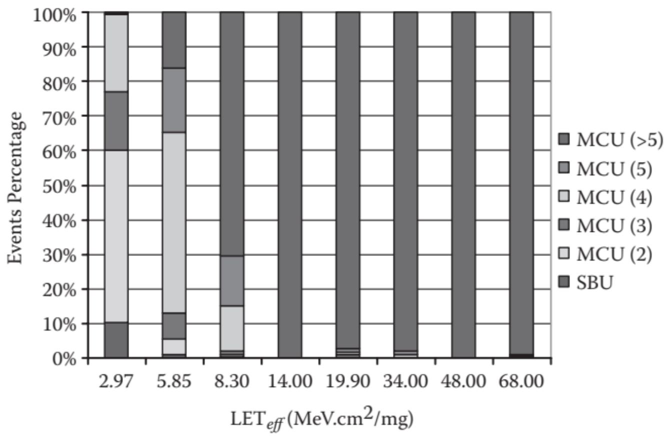
Multiple Cell Upset (MCU)



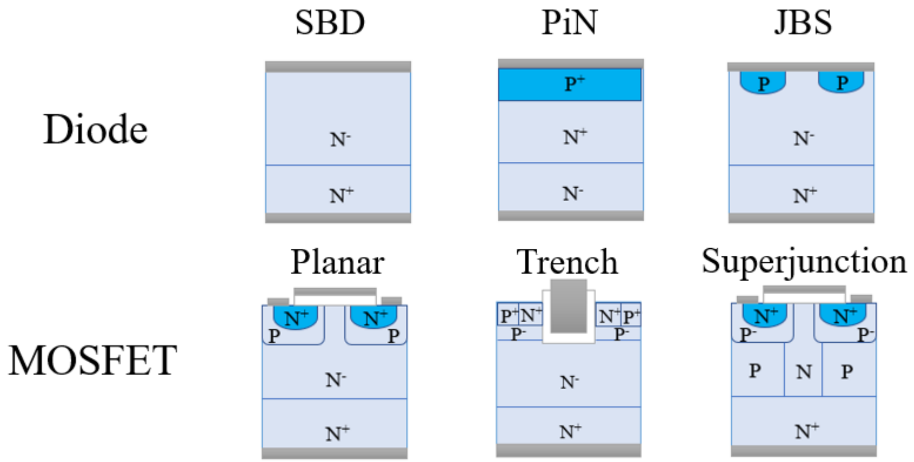
Cross-sectional of triple-well CMOS technology



Multiple Cell Upset (MCU)



Single Event Burned (SEB) on SiC



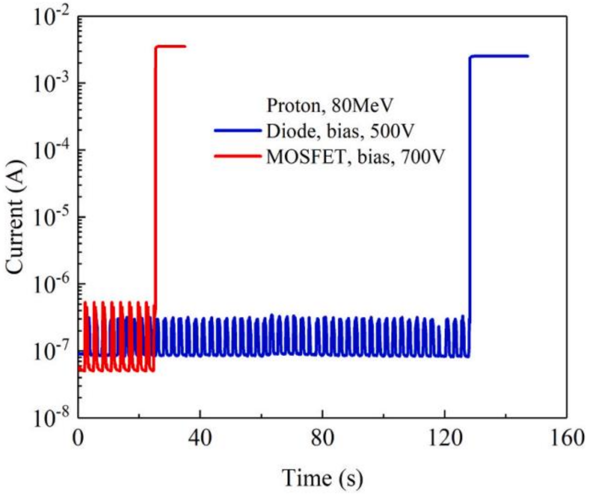


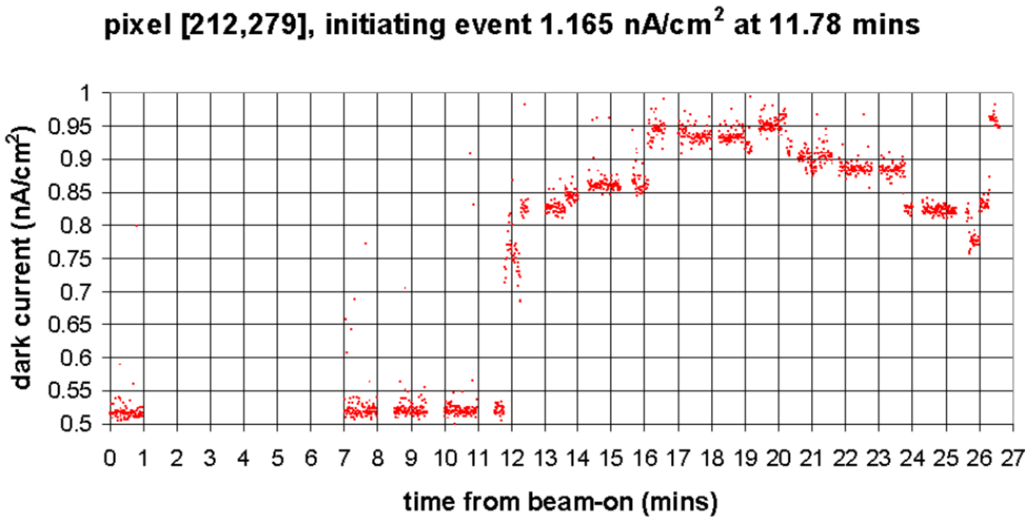
Fig. 2. The SEB events of SiC diode and MOSFET.

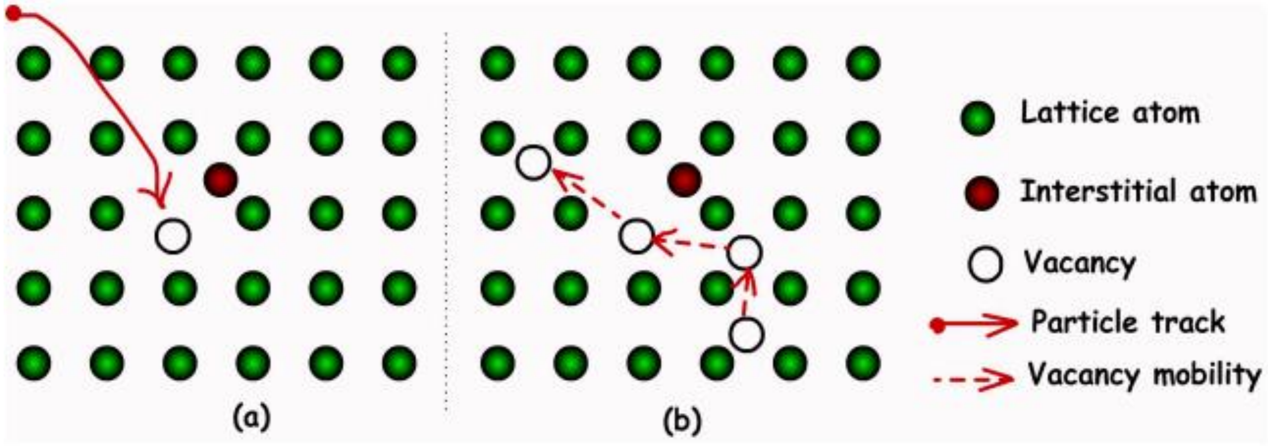
3 Radiation effects in modern semiconductors

non-Ionizing Radiation Damage: Displacement Damage (DD)

The collision between an incoming particle and a lattice atom subsequently displaces the atom from its original lattice position.

These vacancy become recombination centers, leading to charge loss in the devices, and damaging the electrical characteristics





DD degrades the charge transfer efficiency in a CCD, resulting in a loss of signal charge, it induces defects in silicon which degrade key photodiode parameters such as Quantum Efficiency, charge to voltage conversion gain (CVF), FWC, and increases the dark current