Comparison between Laser and Heavy Ions test results from NSSC

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Outline

- **General Background –Pulsed Laser SEE**
- **Pulsed Laser Quantitative SEE Testing Technique**
  - Quantitative Calibration
  - Sensitive Region Location
- **Review and Prospect**

General Background

For device manufacture ,spacecraft electronic instrument development and the mechanism investigation, the SEE sensitivity of Devices have to be evaluated. Usually by heavy ion accelerator, BUT:

- Time and money consuming (To be booked in advance)
- Need radioprotection-Vacuum
- Not adequate to evaluate sensitivity for sensitive region mapping
- Identical LET not available for heavy ions penetration depth issue etc.

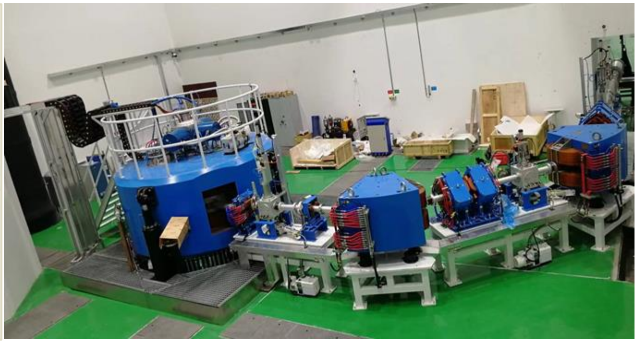
So pulsed laser could be a complementary tool to overcome the above issues. AND:

- SEE sensitive region mapping need visible and accurate location
- SEE fundamental research need the spatial, temporal and original characterization
- SEE pre-evaluation of various configurations/complex components need relatively universal calibration between laser and heavy ion

Single Event Effects Facility

Lanzhou Heavy ion accelerator（HIRFL）

NSSC 50 MeV proton accelerator



NSSC pulsed laser facility

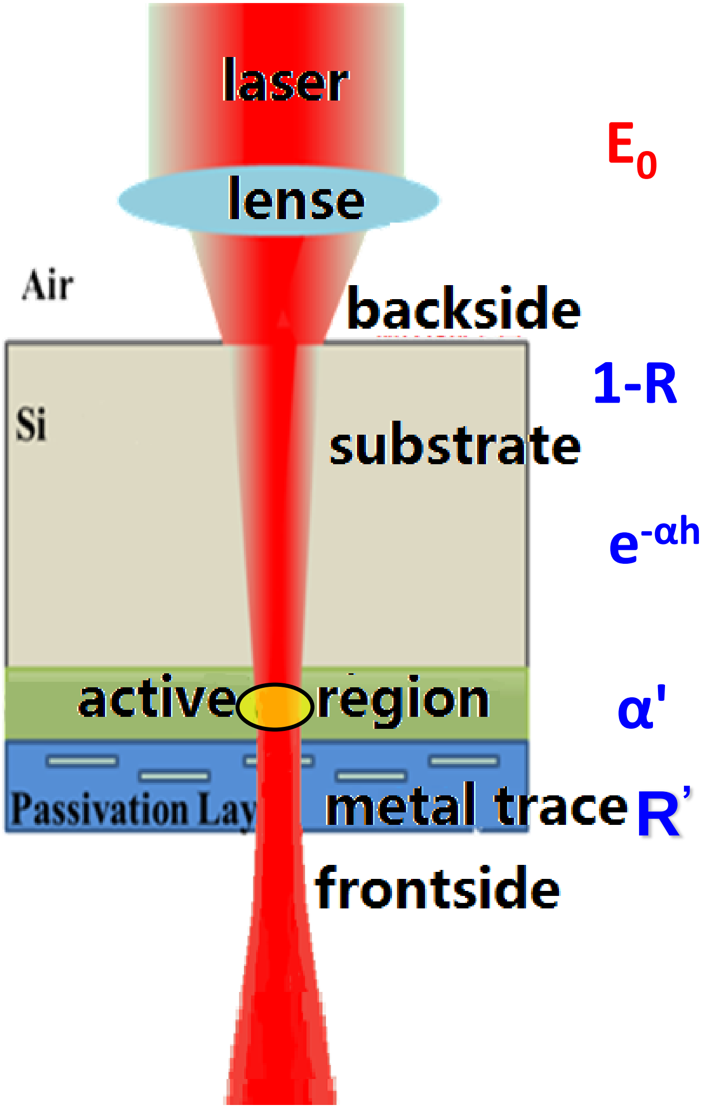
Heavy ion → Proton → Laser

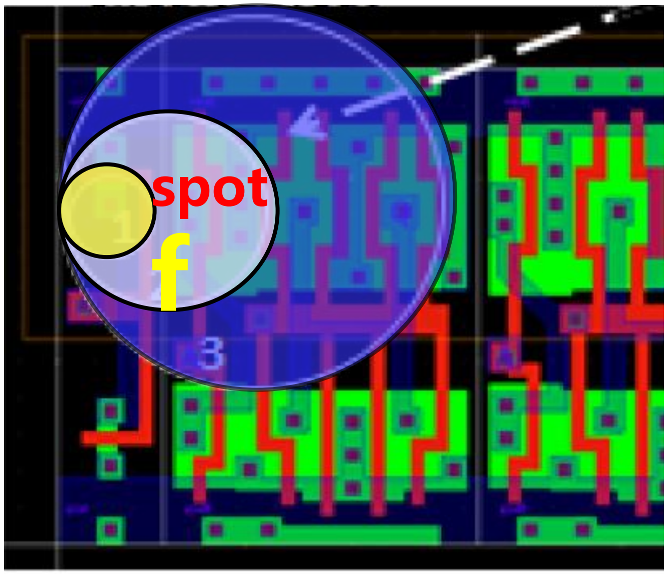
➢Pulsed Laser Test Conditions

Facility		DUT	
Wavelength	280-2600 nm	**Sample Preparation**	Chip on Board repackaging; SIP SOP plastic packages; Flip chipped device; Ceramic packages possible
Pulse Width	35 fs/15 ps	**Reflection on the substrate surface**	R=0.38~0.40
Pulsed Laser Energy E_{eff}	Measured value	**silicon substrate thickness h**	Measured value
Penetration Depth	>1000 μm	**absorption coefficient α**	Measured value
Spot size Diameter	<2 μm	**Reflection on the metal layer interface R'**	Measured value

Pulsed Laser SEE Testing Technique

➢Quantitative Calibration

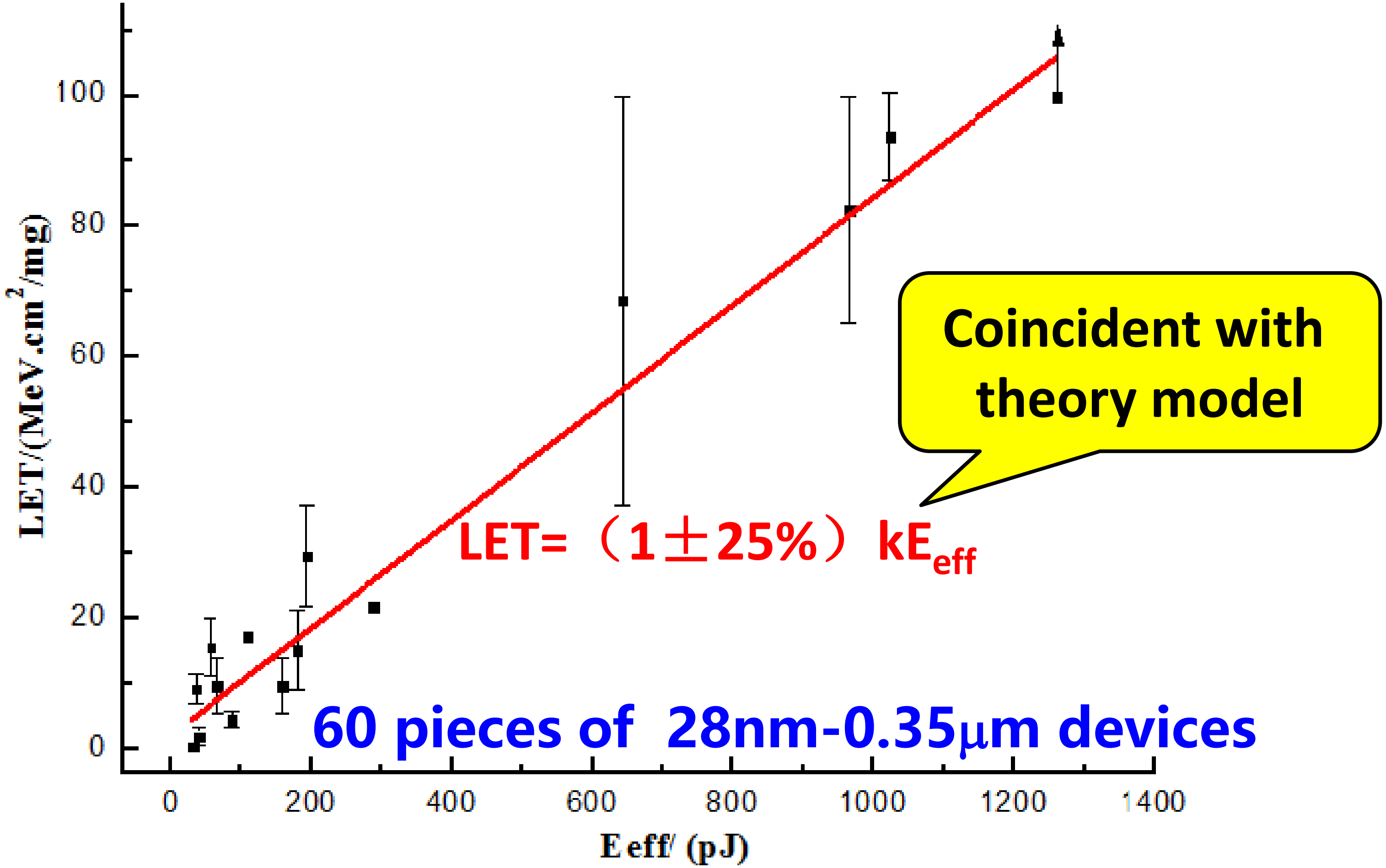




$$E_{eff} \propto (1-R)\, e^{-\alpha h} (1+ R')\, E_0$$

$$E_{eff}=(1-R)\, e^{-\alpha h}(1+R')\, f.\, E_0$$

✓SEL Laser Quantitative Calibration



LET= （1±25%） kE_{eff}

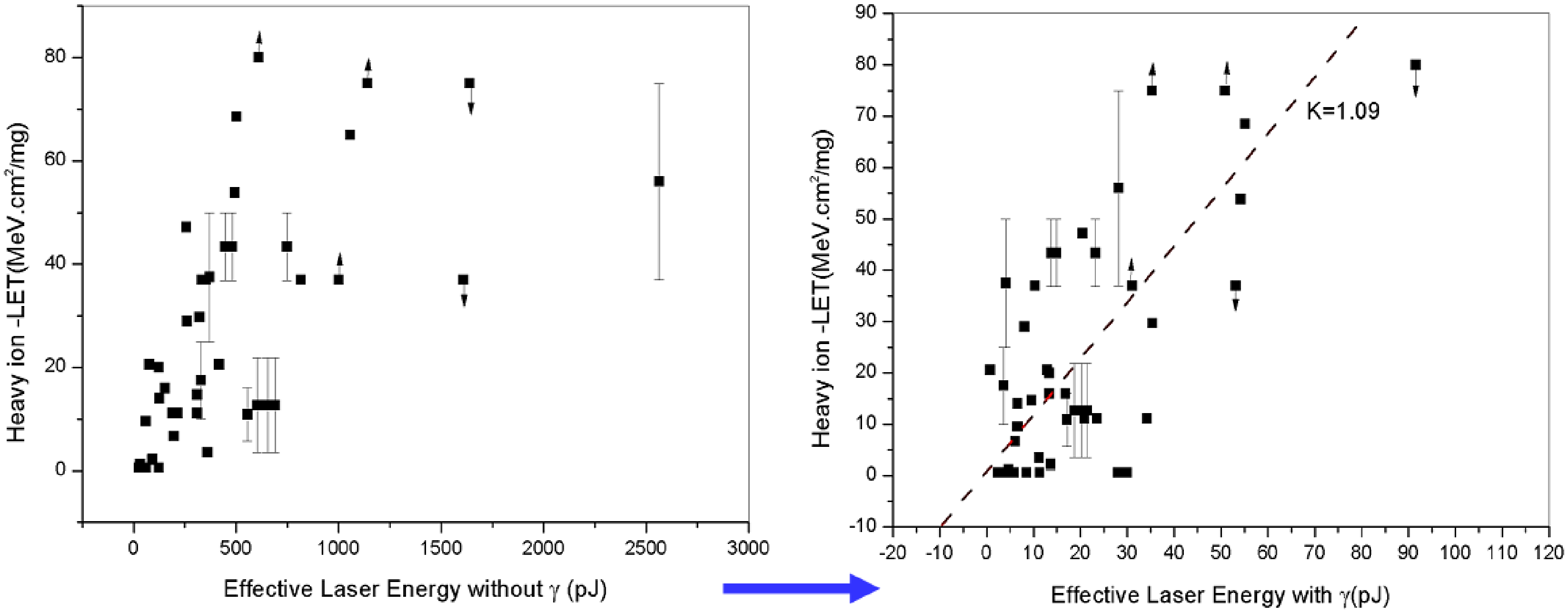
60 pieces of 28nm-0.35μm devices

SEL threshold of laser energy-HI LET

[1]Ma Yingqi et al. IEEE NSREC2018.

✓SEU Laser Quantitative Calibration

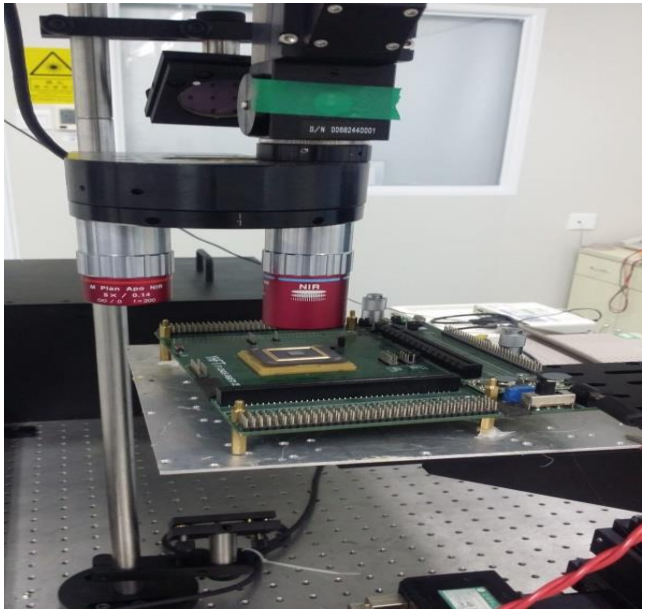
$$\mathrm{LET}\ (\mathrm{MeV.cm^2/mg}) = 1.09\ \gamma.\ E_{\mathrm{eff}\perp}\ (\mathrm{pJ})$$

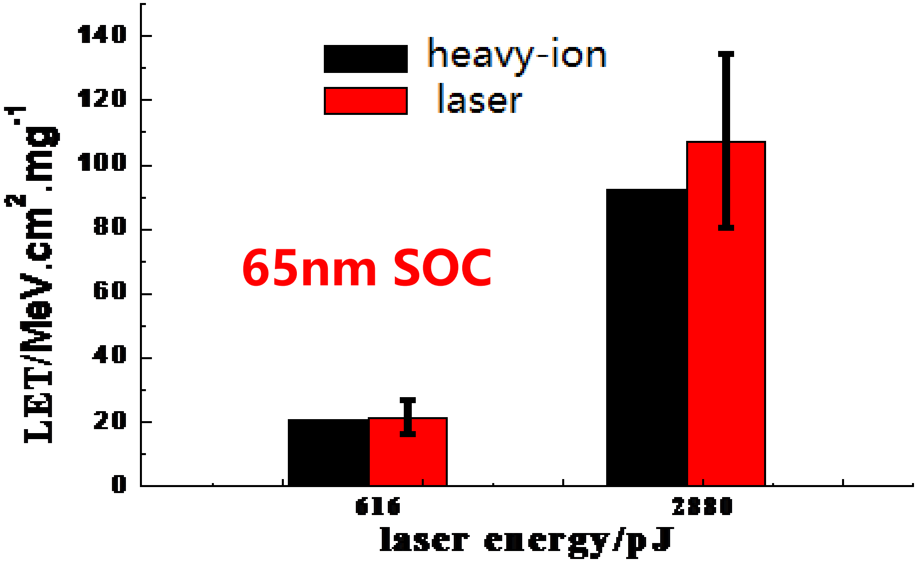


effctive spot factor (γ)

SEU threshold of laser energy-HI LET

✓SEL Verifacation of Laser Quantitative Calibration



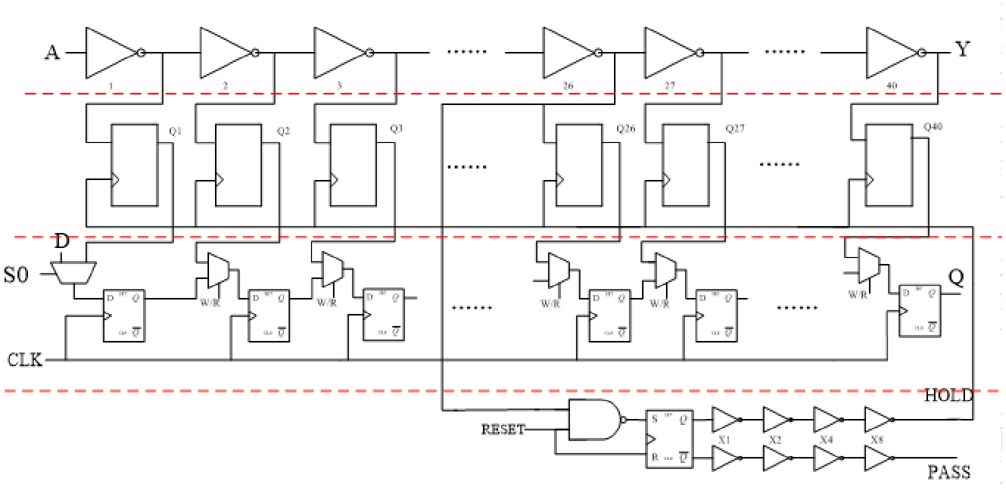


Device	Part Type	Equivalent LET thresholds/ MeV·cm^2/mg	Heavy ion LET thresholds/ MeV·cm^2/mg
CAN BUS	A	12.5±2.7	5.7-17.3
DDS	B	13.7±2.9	5.7-17.3

✓DSET Verifacation of Laser Quantitative Calibration

- **DUT**

bulk silicon CMOS 200-stage inverter chain with SET pulse width for on-chip test is designed.



SET impulse testing

SET latch circuit

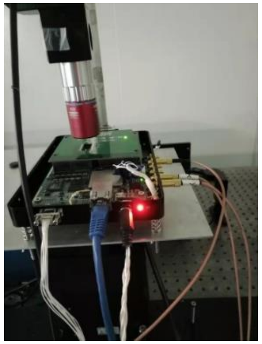
Flip-flop test circuit

trigger circuit

- **Facility**

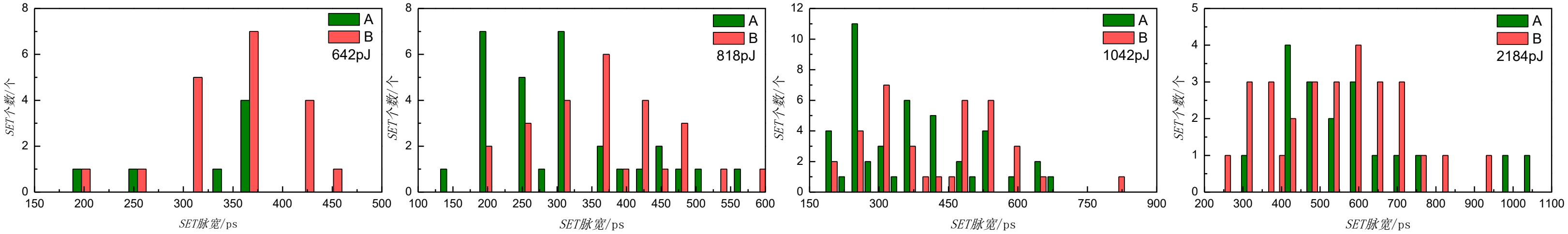
Heavy ion	energy /MeV	LET / (MeV·cm²/mg)	Ion range / μm
Fe	6.3	29.2	20
Xe	1994.1	49.65	150.44
Xe	1209.5	66	87.88
Bi	1283.3	97.8	69.8

Laser wavelength /nm0	1064
Frequency/Hz	1000
Pulsed width/ps	25
Spot diameter /μm	≈2
fluence	4E6

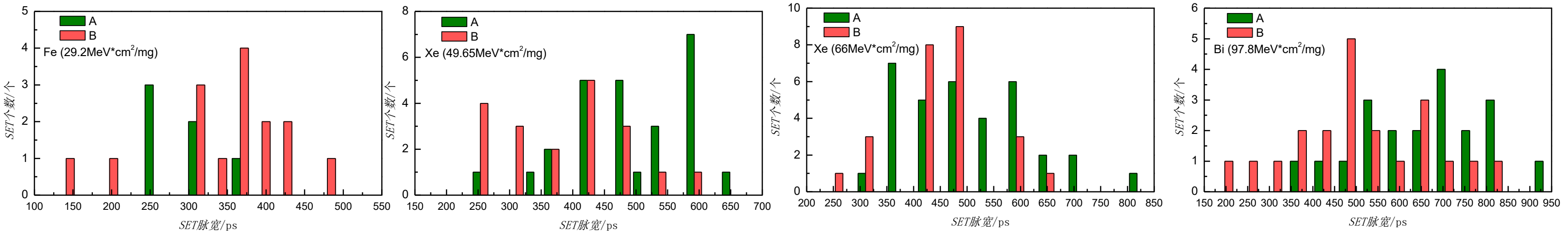


✓DSET Verification of Laser Quantitative Calibration

SET pulse width distribution results of different laser energy, heavy ion LET value and PMOS gate length for the combined logic device inverter chain



Relationship between SET pulse width distribution and laser energy

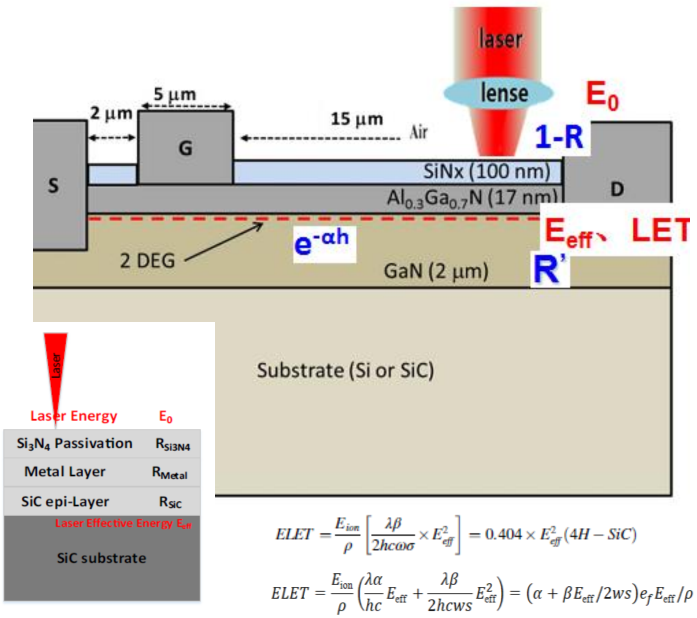


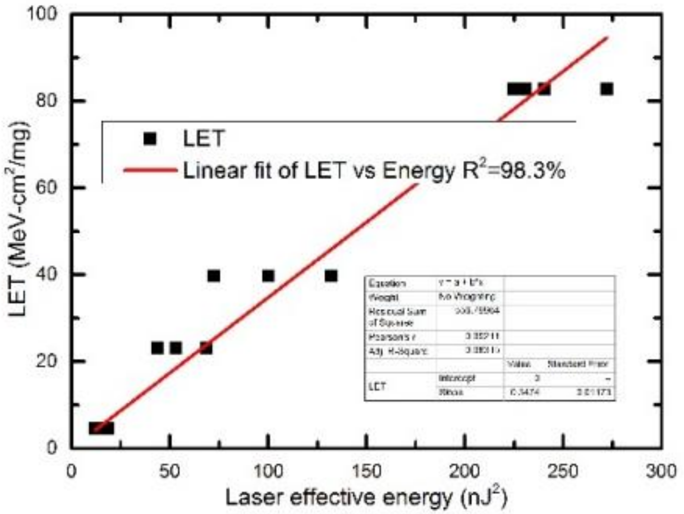
Relationship between SET pulse width distribution and LET

☐ In double-well CMOS technology, the parasitic bipolar effect and charge sharing effect of PMOS are the main reasons for the double (multiple) peak distribution of SET pulse width at high laser energy and high LET value.

☐ The parasitic bipolar transistor effect of PMOS transistor is significant at higher laser energy and LET value, and the parasitic bipolar effect of inverter chain circuit with smaller PMOS gate length is more serious.

✓SEB of Wide Bandgap Semiconductor Devices for Laser Quantitative Calibration





SiC

$\mathrm{ELET}_{720nm}=0.347E_{eff}^{2}$

GaN

$$\mathrm{ELET}_{620nm} = 2.24 \times E_{\mathrm{eff}}^{2}$$

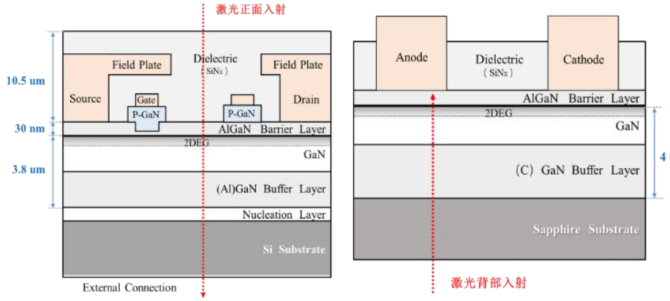
$$\mathrm{ELET}_{720nm} = 0.66 \times E_{\mathrm{eff}}^{2}$$

$$ELET = \frac{E_{ion}}{\rho}\left[\frac{\lambda\beta}{2hc\omega\sigma} \times E_{eff}^{2}\right] = 0.404 \times E_{eff}^{2}(4H-SiC)$$

$$ELET = \frac{E_{\text{ion}}}{\rho}\left(\frac{\lambda\alpha}{hc}E_{\text{eff}} + \frac{\lambda\beta}{2hcws}E_{\text{eff}}^{2}\right) = \left(\alpha + \beta E_{\text{eff}}/2ws\right)e_{f}E_{\text{eff}}/\rho$$

4H-SiC laser Eeff vs heavy ion LET induced SEB.

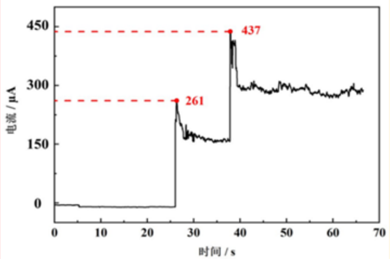
Device	Laser Energy (nJ)	Laser E_{eff} (nJ)	Laser ELET (MeV. cm^2/mg)	Heavy ion LET (MeV.cm^2/mg)
C4D40120D	18.0 (250 V)	9.3	33.3	39.0 (250 V)
	16.0 (350 V)	8.2	25.9	22.5 (350 V)



[1] Shangguan shipeng et al. MR 2021.
[2] Cui YX, Ma YQ et al.Photonics.2022

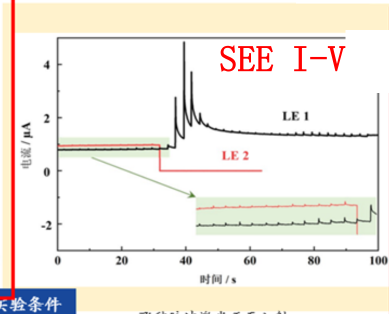
✓SEB Location of Wide Bandgap Semiconductor Devices

Heavy ion



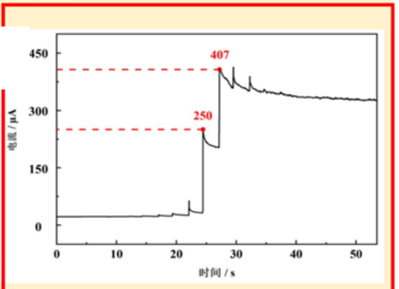
实验条件

中国原子能科学院的串列加速器（HI-13），
重离子为Ge离子，在GaN中的LET为28.5 MeV·cm²/mg

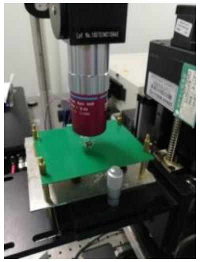


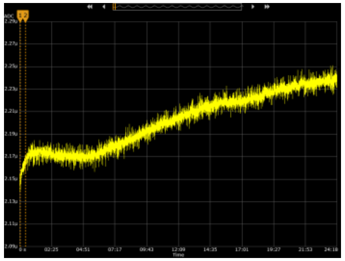
飞秒脉冲激光正面入射

Laser

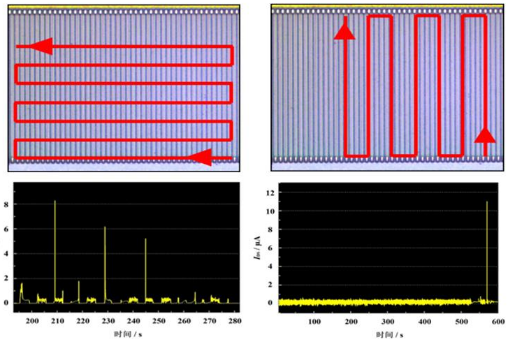


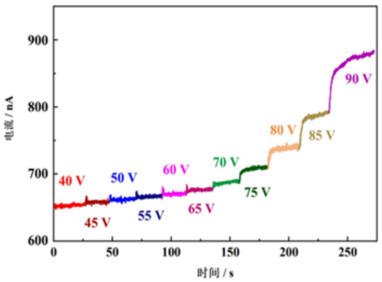
飞秒脉冲激光背部入射

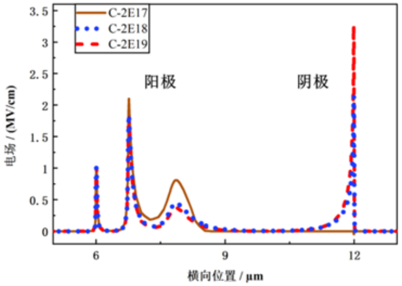


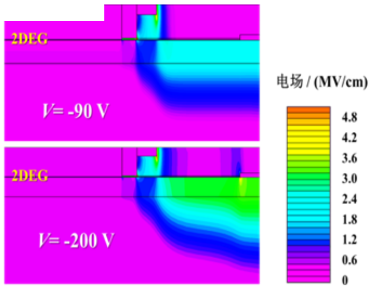


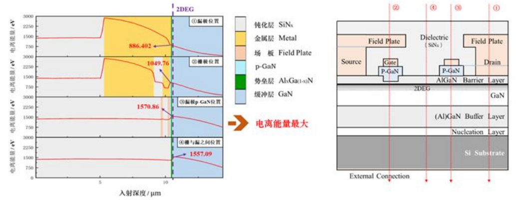
GaN HEMT







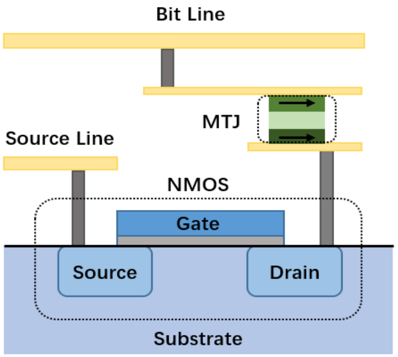


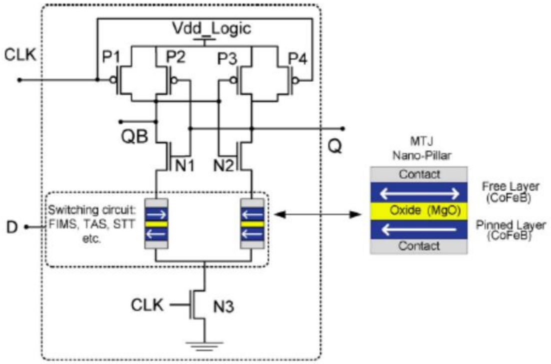


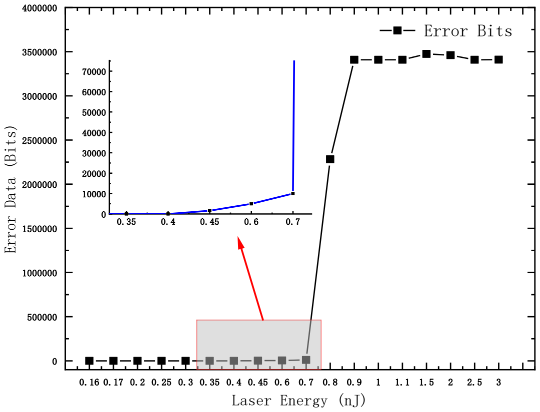
SEB Sensitive Area

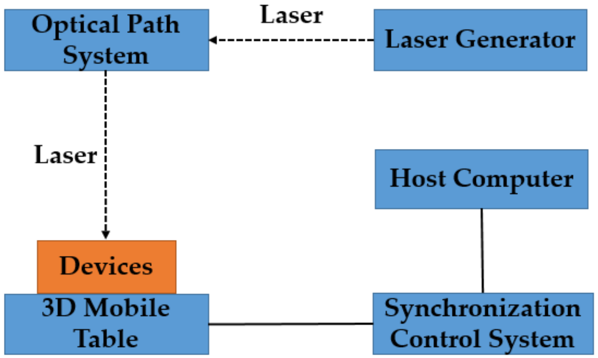
[1] Cui YX, Ma YQ et al.Photonics.2022

✓SEFI for MRAM Verification of laser test









Optical Path System

Laser

Laser Generator

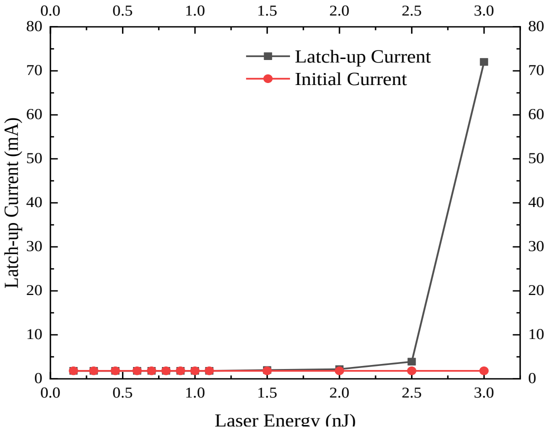
Laser

Host Computer

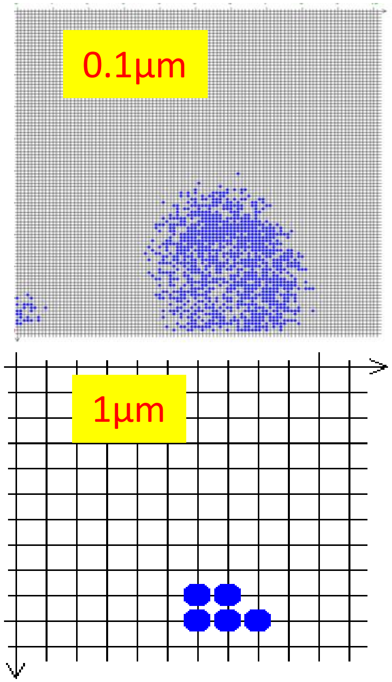
Devices

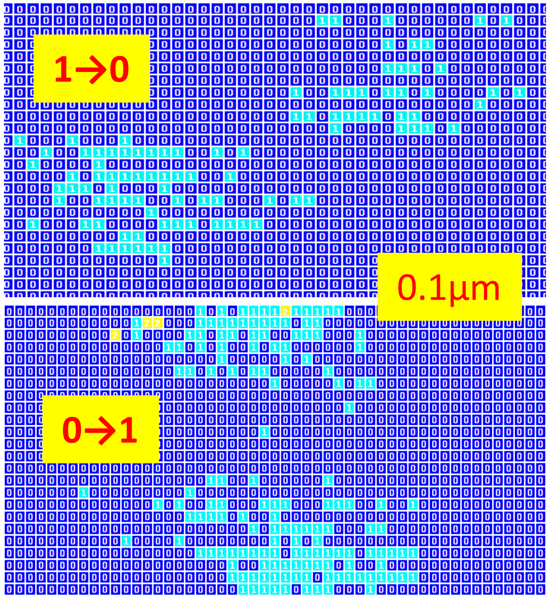
3D Mobile Table

Synchronization Control System

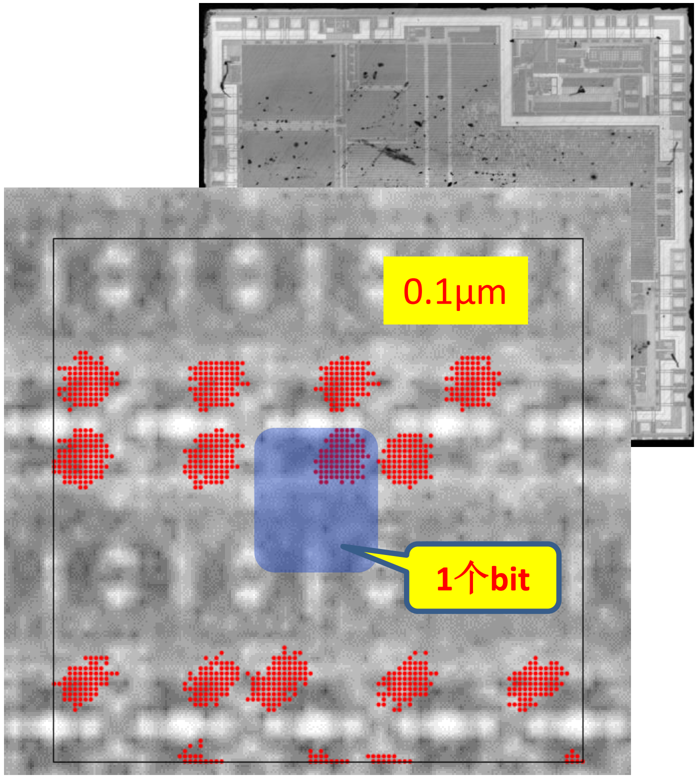


✓SEU Sensitive area location by Laser



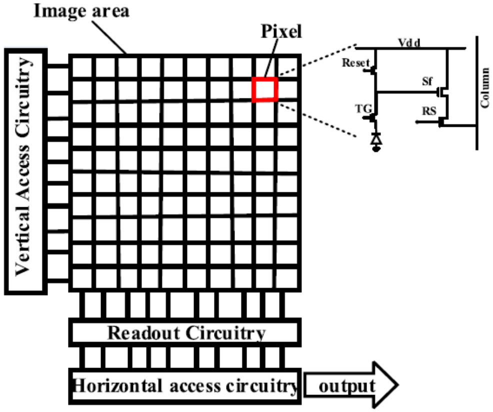


65nm SRAM SEU

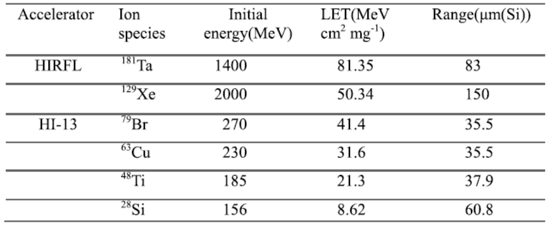


MCU SRAM

✓SET of CMOS Image Sensors(2048(H) × 2048(V))

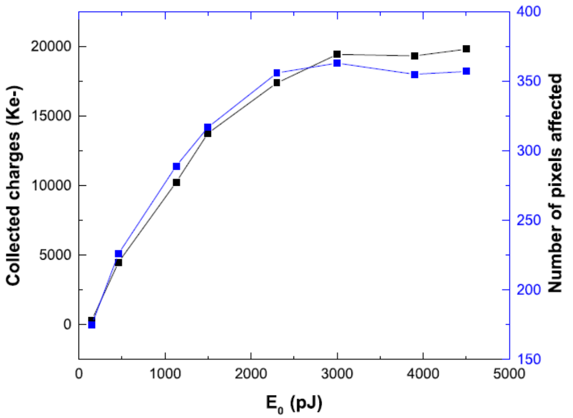


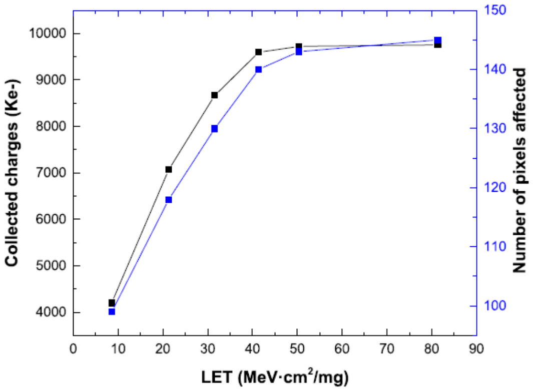
EXPERIMENTAL HEAVY-ION TYPES AND ENERGIES



Accelerator	Ion species	Initial energy(MeV)	LET(MeV cm^2 mg^{-1})	Range(μm(Si))
HIRFL	^{181}Ta	1400	81.35	83
	^{129}Xe	2000	50.34	150
HI-13	^{79}Br	270	41.4	35.5
	^{63}Cu	230	31.6	35.5
	^{48}Ti	185	21.3	37.9
	^{28}Si	156	8.62	60.8

[1]Cai et al. IEEE TNS2020.





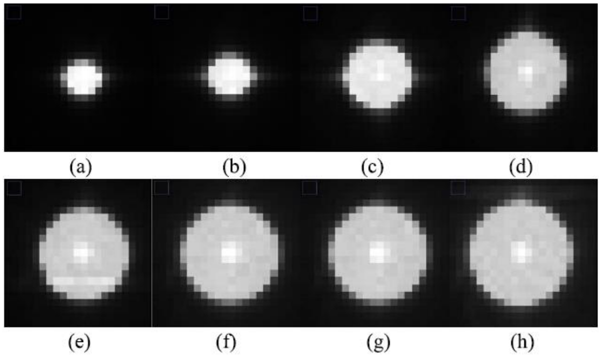


Fig. 3. Pixel clusters captured during pulsed laser irradiation with energies of (a) 150 pJ, (b) 460 pJ, (c) 1130 pJ, (d) 1500 pJ, (e) 2300 pJ, (f) 3000 pJ, (g) 3900 pJ, and (h) 4500 pJ.

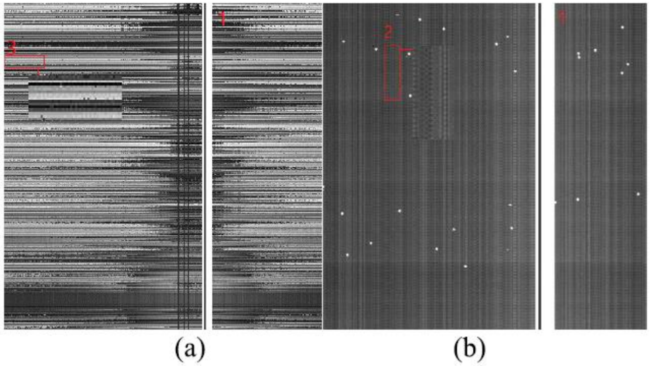
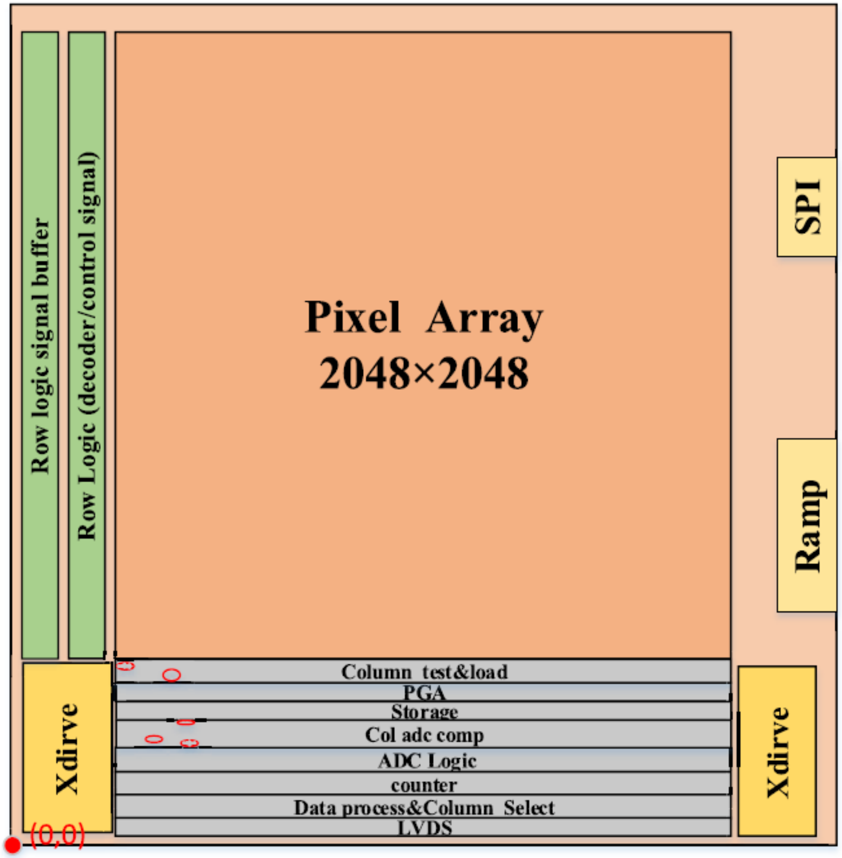


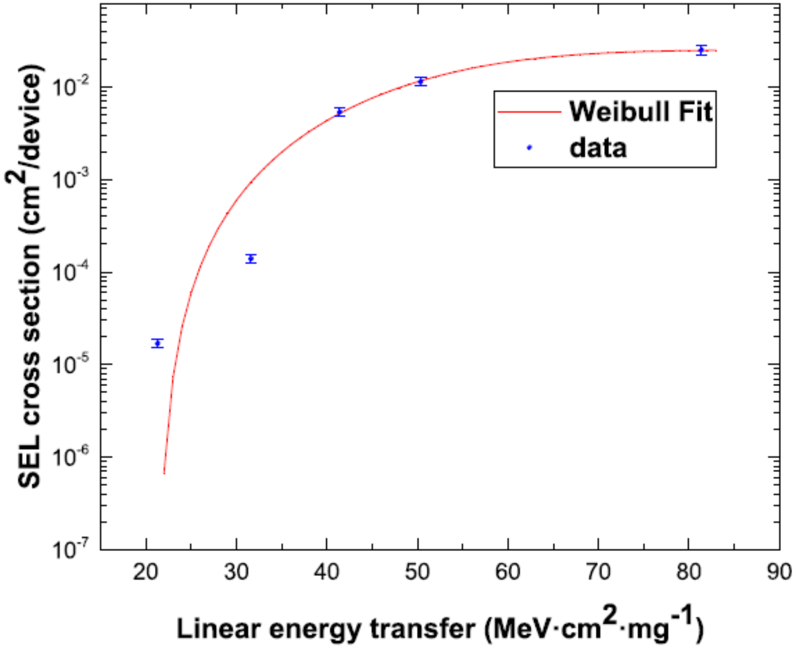
Fig. 5. Image corruption caused by (a) Xe and (b) Br.

✓SEL of CMOS Image Sensors(2048(H) × 2048(V))



Mapping results by picosecond pulsed laser

[1]Cai et al. IEEE TNS2020.

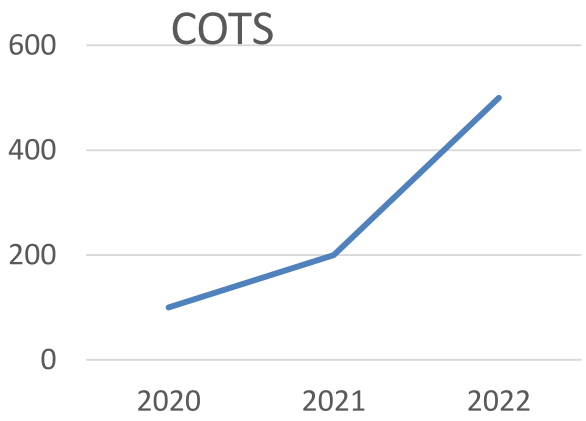


SEL cross section versus LET

- For CIS, using pulsed laser mapping tests to measure the number of sensitive volumes is an effective method for calculating space SEL rates.

2020-2022 COTS Devices for Laser test in NSSC

2020-2022



Devices Type

- Power Devices：DCDC、LDO、MOSEFET；
- Controllers： CPU、SOC、DSP
- Memory： E^{2}prom，Flash，DDR4
- ……

Review and Prospect

Now

By theoretical modeling and determination of the key parameters, the laser heavy ion equivalent relationship models for bulk silicon process and wide bandgap semiconductor process devices were obtained, and the above relationship and uncertainty were verified through a series of experiments with single photon and two-photon absorption.

- laser could be an suitable choice with applicable depth of penetration and easier sample preparation.
- Quantitative laser testing is what engineers need.

Next

- Standardization: reliable calibration, repeatability

How to be equivalent with ground-based accelerator ions and outer-space particles is still an challenging job, especially for the COTS devices.

Thanks for Your Attention