Soft error study on junctionless silicon nanotube FET based 6T SRAM cell

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Abstract. In this work, the response of Junctionless Silicon Nanotube FET (JL SiNT FET) to the heavy ion irradiation and the soft error performance of JL SiNT FET based SRAM circuit are investigated using 3D numerical simulations. The impact of single event transient (SET) is studied at different locations of junctionless SiNT with different incident angles to identify the sensitive location of the device. After SET analysis, JL SiNT FET based 6T SRAM cell is studied for single event upset (SEU). Heavy ion study of JL SiNT FET is compared with junction based SiNT FET. The simulation result shows that the threshold linear energy transfer (LETth) of JL SiNT FET based SRAM is approximately three times lesser than the junction based SiNT FET SRAM.

1. Introduction
In the development of advanced semiconductor devices, multi gate structures are one of the promising solutions to reduce short channel effects (SCE) [1-4]. In that, Silicon nanotubes (SiNT FETs) introduced in the year 2012 [5] provide better SCE control among other multigate devices. The reason is in SiNT, the channel is in the form of tube and hence it is controlled by both inner and outer cylindrical gates [6-7]. Junctionless devices are other interesting devices as there is no doping concentration gradient which reduces the fabrication process complexity [8-9]. The performance of Junctionless silicon nanotube (JL SiNT FET) is analysed for AC and DC simulations in [10].

In the first part of this work, single event transient (SET) simulations are done at different locations of JL SiNT FET and also for different incident angles. SET due to energetic particle strikes, is an important reliability issue in digital circuits which are designed for radiation environment [11-15]. SETs create either temporary damage (soft error) or permanent damage (hard error) to the device. Multigate nanowire FET under radiation is analysed in [16]. SET performance of junction based SiNT FET is discussed for its sensitivity in [17].

In the second part of this work, JL SiNT based 6T SRAM circuit is demonstrated for its operation and the soft error performance of single event upset (SEU) is studied on JL SiNT based 6T SRAM. Since Static Random Access Memory (SRAM) is a major component in all modern high performance digital systems and it is studied for heavy ion irradiation. SEU is a soft error raised in SRAM cell due to the radiation and this can able to flip the SRAM cell content.
SRAM and junctionless SRAM have been explored in the literatures [18-23]. SEU of junction based SiNT SRAM is discussed in [24].

This paper work has two contributions (i) SET study of JL SiNT FET, discussed in section 3 and (ii) SEU analysis of JL SiNT based 6T SRAM cell, discussed in section 4. Section 5 gives the conclusion of this work. Next section explains the structure of JL SiNT and its dimensions, simulation models and $I_D$-$V_G$ characteristics.

2. $I_D$ – $V_G$ Characteristics

In this work, Sentaurus TCAD 3D numerical device simulator is used for simulations [25]. Device structure creation, doping, contacts and meshing are done using sentaurus structure editor (SDE). Junctionless SiNT FET structure is created based on the details reported in [10]. The device dimensions and doping details are given in the Table 1. The corresponding structure is shown in Figure 1.

![Junctionless SiNT FET structure](image)

Figure 1. (a) 3D structure of Junctionless SiNT FET (b) cross section of the device showing source, drain, channel, outer and inner gates (gate oxide and spacer are not shown for better visibility).

Table 1. Device Design Parameters used in the Simulations.

| Parameter                        | Junctionless SiNT FET |
|----------------------------------|-----------------------|
| Gate length                      | 45nm                  |
| Tube wall thickness              | 5nm                   |
| Tube outer diameter              | 32nm                  |
| Tube inner diameter              | 22nm                  |
| Source/Drain length              | 15nm                  |
| Spacer length                    | 25nm                  |
| Oxide thickness (inner and outer)| 1nm                   |
| Source/Drain and Channel Doping concentration | $1 \times 10^{19}$ atoms/cm$^3$ |
| $I_{ON}$                         | 175$\mu$A/\mu m       |
| $I_{OFF}$                        | 1.18$\mu$A/\mu m      |

Figure 2 shows the $I_D$ – $V_G$ characteristic of JL SiNT FET. This $I_D$ – $V_G$ characteristic of JL SiNT FET is obtained using the device simulator SDEVICE. The corresponding ON and OFF currents are also given in the Table 1. This characteristic is calibrated using the following models [25]: SRH recombination model, doping dependent mobility model, Philips Unified Mobility, Lombardi and field dependent mobility model. Drift-diffusion transport mechanism is activated during the simulations.
Band-gap narrowing model and carrier scattering model are also included. Quantum corrections are also taken into account in device simulation through the keyword “eQuantum potential” in the simulator.

![Figure 2. I_D−V_G characteristic of JL SiNT FET.](image)

3. SET analysis in JLSiNT FET
In this section, the single event transient study on JL SiNT is discussed. The device simulator SDEVICE is used to perform the heavy ion irradiation at the devices. The radiation strike is modeled as Gaussian radial carrier distribution with a fixed characteristic radius of 20nm. This Gaussian time distribution is centered on 50ps, with a characteristic time of 2ps [26]. The radiation strike is happened when the device is in OFF state i.e. V_GS = 0V and V_DS = 1V. The drain current induced by the radiation is known as SET current. The radiation charge collected at the drain is estimated from the following relation

$$Q_{collected} = \int_{t_1}^{t_2} I_d(t)dt$$

Where $I_d(t)$ is the SET current, and $t_1$ and $t_2$ are the transient time instants. The radiation interaction with materials/devices is typically measured as linear energy transfer (LET). LET is defined as the energy loss per unit path length of a particle when it passes through a material. Unit of LET is MeV/(mg/cm²) or pC/μm (1 pC/μm = 100 MeV/(mg/cm²)).

![Figure 3. Five different locations in JL SiNT for heavy ion irradiation.](image)

The heavy ion may strike any location of the device. Here we considered five locations for our SET analysis namely middle of the channel (CH_M), the two end points of the channel - one is closer to drain (CH_D) and another one is closer to source (CH_S), source extension (SE) and drain extension
Figure 3 illustrates the device with above mentioned locations. The heavy ion generation profile of JL SiNT under radiation strike at CH_D and its cross section is shown in Figure 4. The charge collected from SET current is plotted in Figure 5. In Figure 5, the collected charge of JL SiNT is compared with junction based SiNT. Both Figure 4 and Figure 5 correspond to the heavy ion strike at the location of CH_D with normal incident angle and the radiation dose (Linear Energy Transfer - LET) is 10 MeV/mg/cm². Figure 5 depicts the JL SiNT has more collected charge than junction based SiNT and hence it is more vulnerable.

**Figure 4.** (a) 3D Heavy ion generation profile in CH_D of JL SiNT FET with dose of 10 MeV/mg/cm² for normal incident angle (for better view spacers, oxide material, inner & outer gates are not shown) (b) 2D cut showing a cross section parallel to XY plane.

**Figure 5.** Collected charge for LET of 10 MeV/mg/cm² at CH_D with normal incidence.
3.1. Impact of Incident Angle on SET Sensitivity

In this sub-section, SET device simulations for different angles are studied, at various locations, to extract the impact of angle of incidence on SET sensitivity. Angled ion strikes the device in parallel to XY plane and in parallel to XZ plane. Two different angles measured in parallel to XY plane ($\theta$) and in parallel to XZ plane ($\varphi$) are shown in Figure 6.

![Figure 6](image)

Heavy ion strikes the chosen five different locations of JL SiNT with different angle of incidence ($\theta$) such as 0°, ±30°, ±45° and ±60° (Clockwise and anti-clockwise directions) and the corresponding sensitivity ranking is listed in Table 2. This ranking is based on the radiation charge collected by the location. Figure 7 shows the charge collected at three different locations of JL SiNT for various $\theta$ with LET = 10 MeV/(mg/cm²). Sensitivity of a particular location depends on (i) striking locations in heavy ion entering region and striking locations in heavy ion exit region (see Figure 6 a), and (ii) the charge collection track length. For a fixed striking location in heavy ion entry side, the striking location in heavy ion exit side changes with $\theta$. For $\theta = 0^\circ$, drain is the most sensitive and source is the least one as we expected. But for increasing positive angles $\theta = 0^\circ$, 30°, 45° and 60°, if the striking location in heavy ion entry side is the source then the striking location in heavy ion exit side is varying from source, channel and drain. Thereby the sensitivity is also increasing. Around $\theta = 60^\circ$, the source region becomes more sensitive compared with other locations and hence the drain region need not be sensitive always. For negative angles $\theta$, the sensitivity trend is similar to $\theta = 0^\circ$ since the heavy ion exit is moving towards deep source side. Beyond some angle value, the radiation will not exit from the device and it will escape out of the device. This depends on the striking location, device length, tube wall thickness, and the tube inner diameter.

Similarly, heavy ion simulations with angle of incidence ($\varphi$) are performed and the results are shown in Figure 8. The results indicate the drain location is the most sensitive location for all $\varphi$. In Figure 8 (a) the decreasing trend of collected charge for $\varphi \neq 0^\circ$ is because of the characteristic radius of 20nm. The heavy ion distribution falls outside the tube, result decrement in charge generation. In Figure 8 (b) the rise in collected charge is because of characteristic radius of 5nm, which means the distribution falls within the tube.

All the incident angle simulations are compared with junction based SiNT [17] in the Tables 3 and 4 by means of collected charge. From the Tables 3 and 4, we can observe that the collected charge obtained from the JL SiNT is more than the junction based SiNT. It is applicable for all the angle of incidences and all the locations. It proves the poor immunity of JL SiNT to single-event in spite of a very good control of the channel potential by cylindrical gate due to heavily doped channel.
Figure 7. Collected charge at three different locations of JL SiNT for various $\theta$ with LET = 10 MeV/(mg/cm$^2$).

Table 2. Location sensitivity ranking for various $\theta$.

| $\theta$ (degrees) | SE | CH_S | CH_M | CH_D | DE |
|-------------------|----|------|------|------|----|
| -65               | 5  | 4    | 3    | 1    | 2  |
| -60               | 5  | 4    | 3    | 1    | 2  |
| -45               | 5  | 4    | 3    | 1    | 2  |
| -30               | 5  | 4    | 3    | 2    | 1  |
|  0                | 5  | 4    | 3    | 1    | 2  |
|  30               | 5  | 4    | 3    | 1    | 2  |
|  45               | 3  | 4    | 1    | 2    | 5  |
|  60               | 3  | 2    | 1    | 4    | 5  |
|  65               | 2  | 1    | 3    | 2    | 5  |

Figure 8. $Q_{collect}$ for various $\varphi$ with dose of 10 MeV/(mg/cm$^2$) in JL SiNT (a) characteristic radius of 20nm (b) characteristic radius radius of 5nm.
Table 3. Comparison of collected charge of JL SiNT with junction based SiNT for various $\theta$.

| Device type | Strike Loc. | $Q_{\text{collect}}$ (fC) | Angle of incidence (°) |
|-------------|-------------|---------------------------|------------------------|
|             | -65°        | -45°          | -30°       | 0°      | 30°       | 45°        | 65°        |
| Junction based SiNT | CH_S | 0.298 | 0.194 | 0.183 | 0.269 | 0.665 | 1.181 | 2.113 |
|             | CH_M | 0.808 | 0.648 | 0.648 | 0.789 | 1.3 | 1.511 | 1.913 |
|             | CH_D | 1.358 | 1.282 | 1.155 | 1.204 | 1.278 | 1.227 | 1.210 |
| JL SiNT [this work] | CH_S | 0.667 | 0.471 | 0.477 | 0.56 | 0.866 | 1.357 | 2.872 |
|             | CH_M | 1.308 | 0.977 | 0.906 | 0.935 | 1.366 | 2.02 | 2.715 |
|             | CH_D | 2.099 | 1.635 | 1.414 | 1.368 | 1.797 | 1.94 | 2.168 |

Table 4. Comparison of collected charge of JL SiNT with junction based SiNT for various $\phi$.

| Device type | Ion track radius | Strike Loc. | $Q_{\text{collect}}$ (fC) | Angle of incidence (°) |
|-------------|------------------|-------------|---------------------------|------------------------|
|             |                  | -60° | -30° | 0° | 30° | 60° |
| Junction based SiNT [17] | 20nm | CH_S | 0.188 | 0.244 | 0.256 | 0.231 | 0.201 |
|             | CH_M | 0.568 | 0.751 | 0.789 | 0.687 | 0.539 |
|             | CH_D | 0.848 | 1.103 | 1.204 | 1.018 | 0.830 |
|             | 5nm | CH_S | 0.289 | 0.307 | 0.262 | 0.335 | 0.201 |
|             | CH_M | 0.966 | 1.140 | 0.843 | 1.178 | 0.867 |
|             | CH_D | 1.719 | 1.783 | 1.525 | 2.065 | 1.34 |
| JL SiNT [this work] | 20nm | CH_S | 0.405 | 0.514 | 0.56 | 0.489 | 0.384 |
|             | CH_M | 0.686 | 0.861 | 0.935 | 0.821 | 0.652 |
|             | CH_D | 1.021 | 1.265 | 1.368 | 1.209 | 0.974 |
|             | 5nm | CH_S | 0.867 | 0.984 | 0.769 | 1.049 | 0.732 |
|             | CH_M | 1.100 | 1.237 | 0.983 | 1.341 | 0.939 |
|             | CH_D | 2.200 | 2.229 | 1.720 | 2.438 | 1.733 |

4. JL SiNT 6T SRAM Cell

JL SiNT FET, discussed in section 3, being a recent device, the feasibility of JL SiNT-based circuits/applications and their behavior are of current interest to us. We have demonstrated JL SiNT FET-based SRAM operation and studied its Read, Write and Hold SNMs. Regular 6T-SRAM topology is taken for the study. The dynamic stability of SRAM is affected by dynamic disturbance which includes heavy ion particles, cross talk, power supply variations etc [28]. Heavy ion strike/Single event effect (SEE) can lead to single event upset (SEU) also known as soft error which flips the cell content. Hence SEU is an important reliability concern in SRAMs.
4.1. JL SiNT FET based 6T SRAM cell

The JL SiNT device replaces CMOS devices in conventional 6T-SRAM topology and makes the JL SiNT SRAM cell. The resultant JL SiNT SRAM circuit is shown in Figure 9. All the devices in the SiNT SRAM cell have equal dimensions with a Vdd of 1 V. The rise time/fall time, pulse width and period are of 10ps, 20ps and 70ps for access pulse and 10ps, 50ps and 100ps for data pulse. Figure 10 depicts the JL SiNT SRAM operation by showing the various node voltages (WL, BL, V1 and V2) of Figure 9.

![Figure 9.6T JL SiNT SRAM cell with gate length of 45nm (spacers, inner & outer gates are not shown for better clarity).](image)

![Figure 10. JL SiNT SRAM cell waveforms.](image)

Static Noise Margin (SNM) measurements are done during Hold, Write and Read modes of the cell. The measured SNM of JL SiNT SRAM cell having minimum size JL SiNT transistors during Hold, Write and Read modes are 0.41V, 0.42V and 0.16V respectively.

4.2. SEU analysis in 6T JL SiNT SRAM cell

After verifying the SRAM functionality, Single Event Upset (SEU) simulation is performed in the circuit and the corresponding circuit setup is shown in Figure 11. For SEU simulation, the appropriate heavy ion model is activated. Heavy ion strike is initiated at the sensitive node (the node which stores logic value ‘1’) during the non-access period (i.e when WL = 0V) of the simulation. The threshold LET (LETth) is our interest to measure its radiation performance in the circuit and it is the minimum LET required to flip the SRAM cell content.
A location in the given device could become sensitive to radiation depending upon the incident angle. Since the sensitive angle for various locations are already given in Table 2, they are used directly to find out the SEU performance at various locations of the chosen device (i.e. N type device in OFF state). For example, Figure 12 indicates the heavy ion strike at the location CH_D of N1 device (OFF state device) for normal incidence and its SEU results are shown in Figure 13. Figure 13 (a) corresponds to a dose of 21 MeV/(mg/cm²), and this amount of dose does not flip the cell content. But Figure 13 (b) corresponds to a dose value of 22 MeV/(mg/cm²) which can able to flip the cell. Since the cell content has been flipped, the device N1 gets into ON state. Three locations (CH_S, CH_M and CH_D) are struck with their respective sensitive angles (60°- CH_S, 45°- CH_M, 0°- CH_D) and their LET_th values are given in Table 5.

Table 5 compares the SEU simulation results of JL SiNT SRAM with junction based one with respect to LET_th. The Table 5 indicates that the junctionless SiNT based SRAM has lesser LET_th than junction based which confirms that they are less immune to irradiation. For JL SiNT SRAM, the worst case LET_th is found to be 11 MeV/(mg/cm²) and it is highlighted in the Table 5.
Figure 13. SEU simulation results of JL SiNT based 6T SRAM cell (V1 and V2). Heavy ion strikes the location CH_D of N1 transistor at 120ps with normal incidence (a) No flipping for the dose of 21MeV/mg/cm² (b) cell content flipping for the dose of 22MeV/mg/cm².

Table 5. LET_{th} (MeV/mg/cm²).

| Circuit                      | Strike Location of OFF state N1 | 0°  | 45°  | 60°  |
|------------------------------|---------------------------------|-----|------|------|
| Junction based SiNT SRAM [24]| CH_S                            | 130 | 57   | 36   |
|                              | CH_M                            | 60  | 42   | 40   |
|                              | CH_D                            | 52  | 59   | 55   |
| JL SiNT SRAM [this work]    | CH_S                            | 43  | 18   | 11   |
|                              | CH_M                            | 25  | 15   | 12   |
|                              | CH_D                            | 22  | 19   | 17   |

5. Conclusion
This work discussed about the impact of single event transient in JL SiNT FET and its SRAM circuit. In the first part of this work, SET analysis is done in JL SiNT at different locations for different angles. It was observed that the sensitivity of a location to radiation depending upon the incident angle. In the second part of the work, SEU simulations are performed in JL SiNT SRAM. The simulation results are compared with Junction based SiNT and they confirmed that the JL SiNT FET is more prone to heavy ion irradiation than junction based SiNT FET because of its heavily doped channel. All the simulations are done using 3D TCAD simulator.

6. References
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