Single Event Effect Analysis of SiGe Low Noise Amplifier

Manel Bouhouche, Saida Latreche

***Abstract*—This paper analyzes the single event transient (SET) response of low noise amplifier (LNA) designed using SiGe heterojunction bipolar transistors (HBT). To verify the radiation tolerance of the proposed LNA, a total of four cascode configurations were designed. Comprehensive mixed-mode simulations were performed to evaluate the SET susceptibility of considered LNA cascode configurations, and we have analyzed how the strike parameters affect their output response. In this fact the strike position, linear energy transfer (LET), and track radius, were varied, and the resulting transients were compared for the different LNA configurations. Through this study, the potential capability of the inverse mode SiGe heterojunction bipolar transistor (HBT) in LNA radiation tolerance was confirmed for various strike operating conditions. It has been demonstrated that the single event sensitivity was reduced for LNA employing inverse mode SiGe HBT for strike device. The strike influence on the different LNA configurations response depends on strike LET, where a reduced SET variation is observed for high LET.**

***Index Terms*—Single event transient (SET), low noise amplifier (LNA), mixed-mode simulation, radiation, SiGe HBT inverse mode.**

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I. Introduction

THE operation of electronics in extreme environments imposes severe constraints on the comportment of the circuitry, they should be robust to ionizing radiation. As a candidate for extreme environment electronics applications, Silicon Germanium heterojunction bipolar transistor (SiGe) (HBT) continues to receive significant interest as a typical device for operation in radiation rich conditions [1]–[2]. This component is particularly well suited, not only for its competitive high-frequency capability but also due to its tolerance to radiation induced degradations [3]. SiGe HBTs are resistant to various types of ionizing radiation effects, including both total ionizing dose (TID) radiation and displacement damage (DD) [4]–[5]. Despite these advantages, SiGe HBTs are known to be sensitive to single event effects (SEE), which can produce a temporary voltage or current disturbance at the device level, resulting in false data at the output of the circuit implemented using this device [6]–[7].

Recently inverse mode SiGe heterojunction bipolar transistors (HBTs) have been proposed as a viable technique to mitigating radiation induced single event transient (SET) in analog RF applications [8]. In the inverse mode operating regime, the emitter and collector terminals of the HBT transistor are electrically swapped. This approach provides higher isolation between the electrical collector terminal and the sub-collector substrate junction, thus fewer electron-hole pairs generated during the ion strike influence the device output [9]. As a result, the SET sensitivity was reduced compared with SiGe HBT forward mode [10]. With these benefits to reduce SET sensitivity, inverse mode SiGe HBT was utilized to design various RF circuits [11].

Low noise amplifier (LNA) is one of the key blocks in RF systems, it represents the first stage in RF receivers, thereby any perturbations on the output can become amplified by succeeding gain stages. When it comes to using LNA in a radiation environment, reducing the SET sensitivity is of the utmost concern. The design of low noise amplifiers (LNAs) using inverse mode SiGe HBTs has been demonstrated to reduce significantly SET sensitivity compared with conventional forward mode [12]–[13]. However, despite their promising SET mitigation capability, inverse mode SiGe HBTs are not suitable to be utilized as active gain stages for LNA due to severe performance degradation associated with using them. Thus, inverse mode SiGe HBT is essentially utilized for non-vital transistors such as passive circuits, or buffer stages [14].

The present work focuses on modeling single event physical phenomena in LNA amplifiers. The SET response of the RF circuit was investigated via mixed-mode ion strike simulation. To study the SET robustness of LNA, different cascode configurations designed using SiGe HBTs are evaluated. We investigate the use of inverse mode SiGe HBT to approve the single event transient sensitivity of cascode core LNA. In this fact the strike parameters (LET, radius, and position) were varied, and the resulting transient was studied for considered topologies. The results indicate that the topologies using inverse mode for strike device are less sensitive to SET compared to topologies employing forward mode.

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II. Simulation Methodology

A. Simulation approach of single event effect (SEE)

To study the SET mitigation capabilities of SiGe LNA, a calibrated mixed-mode TCAD model was developed using Silvaco TCAD simulation environment. The physical behavior of studied LNA with respect to SET was obtained by mixed-mode heavy ion strike simulation. The simulation method proposes to utilize a combination of device and circuit simulation to combine external effects and transient mechanisms occurring in the device. This method provides a more accurate representation of circuit response under ion strike by considering the dynamics of the generated electron-hole at the device level [15]–[16]. For LNA SiGe simulation the circuit Netlist is built using a 2D TCAD model of the considered SiGe HBT device, where all devices in the amplifier were replaced with their TCAD model. The ion strike simulation was performed on the amplifiers by striking heavy ions in a particular device, and the resulting transient response at the output of the amplifier was then extracted.

The simulation tool presents several radiation models, the commonly used model to perform SET simulations is the heavy-ion model [17]. When a heavy-ion passes through a semiconductor device, it deposits energy in the form of ionized charge (electron-hole pairs) along its trajectory, forming a dense track of mobile charge pairs. The collection of these electron-hole pairs could generate a large current pulse which gives rise to single event effects (SEEs) [18]. Fig.1 shows a simple model for the heavy-ion penetration process.

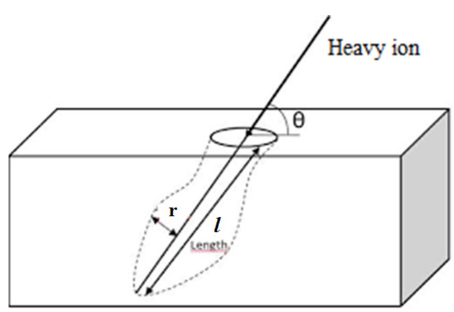


Fig. 1. Heavy ion penetration processes in the semiconductor material

The generation rate caused by the pass of the heavy ion through the device follows the equation:

$$G(l,r,t) = S\, density\, L(l)\, R(r)\, T(t) \tag{1}$$

The electron-hole pairs generated in a semiconductor device are a function of the radial distance r from the center of the track, the distance l along the track, and the time t. In this function, density present the number of generated electron-hole pairs per unit volume cm^{-3}, and S is a scaling factor given by the function:

$$S = \frac{1}{q\pi (RADIUS)^2} \tag{2}$$

Where *RADIUS* presents the track diameter.

L(l), *R(r)*, and *T(t)* describe the spatial and temporal variations of the generation rate. The factor *L(l)* defines the variation of charge or carrier generation along the path of the SEE track. The radial distribution *R(r)* is defined as a Gaussian function:

$$R(r) = \exp\left(-\left(\frac{r}{RADIUS}\right)^2\right) \tag{3}$$

The time dependency of the charge generation *T(t)* is defined by the function:

$$T(t) = \frac{2\exp\left(-\left(\frac{(t-t_0)}{T_C}\right)^2\right)}{t_C\sqrt{\pi}\, erfc\left(-\frac{t_0}{t_C}\right)} \tag{4}$$

Where t_0 specifies the time of the peak in the charge generation pulse, t_C specifies the width of the charge generation pulse and erfc is the Gauss error function complement.

B. Low noise amplifier structure

Fig. 2 depicts the circuit diagram of the cascode LNA topology used in this study. Cascode configuration is the main structure in usual LNA topologies. This configuration consists of two cascaded SiGe HBTs, denoted by common base (CB) and common emitter (CE) devices. In cascode configuration the input current applied to the base terminal of the common emitter (CE) transistor is amplified at the collector terminal and translate to the common base (CB) transistor. At the common base (CB) transistor, the amplified collector current enters the emitter and exits the collector with unity gain. The common base (CB) device with a near-unity gain acts principally as a current buffer. Considering the fact that the CE device stage determines the overall gain and noise figure of the cascode LNA, the transconductance (g_m) of this stage should be large for a high gain amplifier perspective [19]– [20].

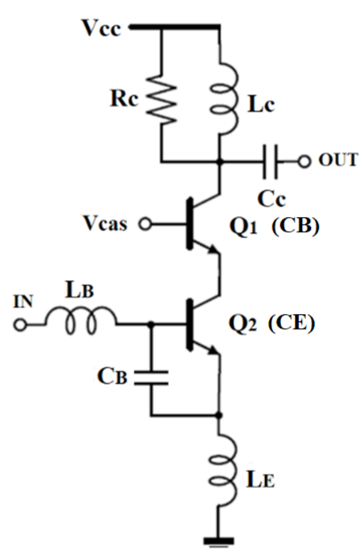


Fig. 2. Schematic of the proposed SiGe HBT cascode low noise amplifier

Conventionally, for the best LNA amplifier performances, a cascode configuration with two forward mode applied for the CB (Q1) and CE (Q2) transistors is used. However, due to the lower single event transient (SET) sensitivity of SiGe HBT inverse mode compared to SiGe HBT forward mode, different cascode configurations employing an inverse mode are proposed. In these configurations, the inverse mode SiGe HBT can be applied for CB or CE SiGe HBT transistor stages [21]. Generally, there are four possible combinations for the use of forward mode or inverse mode SiGe HBTs in cascode configurations as shown in fig. 3.

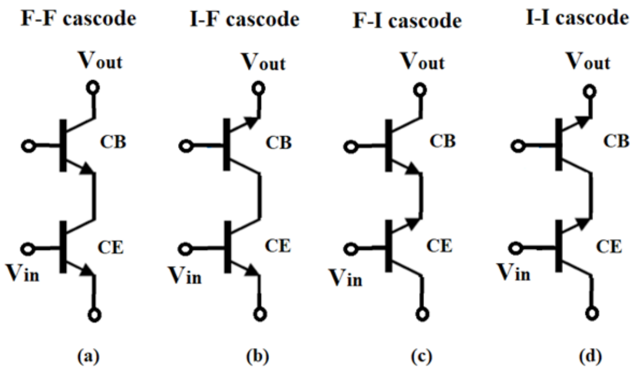


Fig. 3. Cascode configurations: (a) Forward-Forward (F-F), (b) Inverse-Forward (I-F), (c) Forward-Inverse (F-I) and (d) Inverse-Inverse (I-I).

The simulated S_{21} gain as a function of frequency for studies LNA configurations were presented in Fig. 4. The result shows that the F-F cascode LNA amplifier has the highest peak S_{21}gain of about 36 dB. For I-F cascode LNA, the peak gain S_{21} is about 30 dB which is close to the conventional F-I cascode LNA. We can observe that the F-I cascode has minimal degradation in S_{21} gain compared to the I-F cascode case (~1 dB). Compared to different cascode configurations the I-I cascode LNA has the degraded peak gain (S_{21}) of 23 dB, which is about 13dB lower than the F-F cascode LNA.

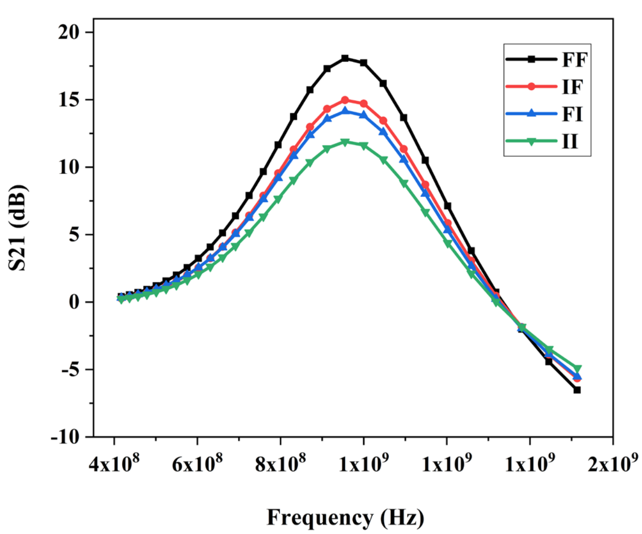


Fig. 4. S_{21} gain as a function of the frequency for F-F, F-I, I-F and I-I cascode LNAs

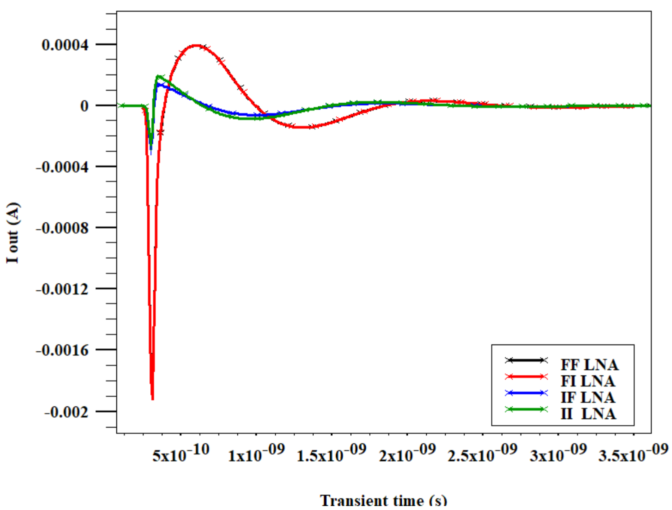
According to the results it should be noted that, when the CE device is in inverse mode operation (F-I and I-I cascode cores), the S_{21} gain was minimal since the reduced transconductance (g_m) of the inverse mode operation will lower the power gain of the cascode LNA. In cascode configurations, the transconductance (gm) of the CE transistor determines the overall LNA gain and noise figure. To obtain high LNA performances, the transconductance (gm) of the CE stage must be large [22].

III. SET Simulation Results and Discussion

A. LNA SET response

The SET ion strike simulation results under DC conditions for four different LNA cascode configurations (F-F, F-I, I-F, and I-I) are shown in Fig. 5. The transient simulation under a heavy-ion strike was performed across CB (Q1) and CE (Q2) LNA devices with a linear energy transfer (LET) of 10 MeV-cm^2/mg. To maximize electron-hole pair generation, the ion-strike direction was selected perpendicular to the base-emitter (BE) and base-collector (BC) junctions of the strike device since this part presents the most sensitive region of bipolar transistors with a vertical configuration [23].

For the CB strike condition with a linear energy transfer (LET) of 10 MeV-cm^2/mg, both the I-F and I-I exhibit a reduced peak transient compared to the F-F and F-I cascode structures. The I-F and I-I configurations have respectively 86% and 88% smaller peaks compared to the F-F core. With regard to the duration, we can observe that when the CB transistor was struck the transient durations for I-F and I-I cascode cores were shorter respectively by about 0.11ns and 0.18ns compared to the duration observed for F-F cascode configuration. For the CE strike case with the same ion-strike LET, the F-F cascode LNA shows the largest current swing, with a collector current peak of about 4.32mA. The I-I and F-I cascode configurations exhibit the smallest transient peak magnitudes due to the use of SiGe HBT inverse mode for the strike device. We can observe for the CE strike, that the I-I and F-I cascode LNAs exhibited respectively about 84% and 80% reduction in transient peaks compared to the F-F cascode LNA. Concerning the SET duration, we can also observe a slight decrease in the transient duration for the I-I and F-I cascode when the CE (Q2) was struck. The SET transient durations were respectively 2.49ns and 2.54ns for the F-I and I-I cascode, which were shorter than those observed for the F-F cascode with 2.66ns. It should be noted that for both devices strike, the CB (Q1) transistor strike shows reduced transient amplitudes compared to the CE (Q2). The CB (Q1) strike produces lower transient peaks for both the F-F, F-I, I-F, and the I-I cascode cores. We can explain the reduction in SET sensitivity for CB device strike by considering the amplifier topology. In cascode topology, the CE device presents a significantly high impedance at the emitter terminal of the CB transistor which helps to reject the charge carriers coming from this device. Consequently, the majority of the carriers cannot drift from this terminal and are left to recombine within the device, resulting in reduced output transient [20]. This can also explain the fact that when the CB transistor is struck the operating mode of the CE device has a low effect on the SET response of the CB device strike condition. We can see from fig. 5 that both the F-F and the F-I cascode structures exhibited almost a similar transient amplitude, whereas the I-I and I-F cascode structures had the smallest transient peak. On the other hand, we can observe that when the CE device is struck the operating mode of the CB device affect the SET response of LNA. In the CE strike case, most of the excess ionized charges generated in the CE device are trained to the electrical emitter of the CB device. When the CB device is in forward mode, the majority of the injected carriers can travel from the emitter to the collector, resulting in higher output peaks. However, when the CB device is in inverse mode, some of the injected carriers drift through the Collector-Substrate (CS) junction, which reduces the output collector transient peak.



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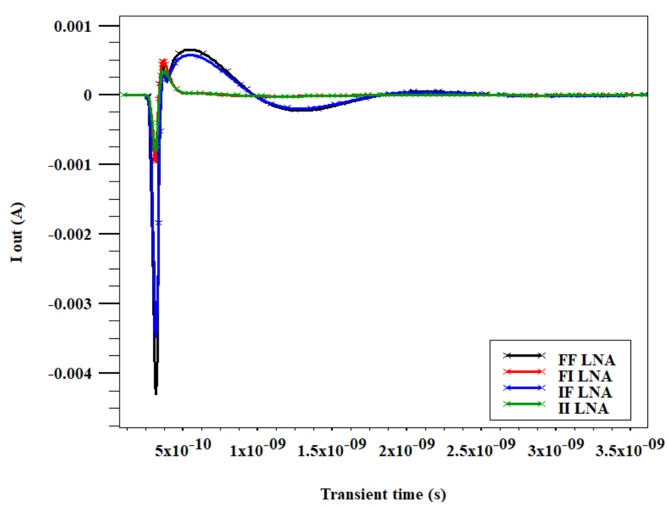


(b)

Fig. 5. Output transient current for (a) CB strike, (b) CE strike

Based on these results we can say that the inverse mode SiGe HBT can generally reduce the impact of SET. However, the use of the inverse mode as an active gain stage for a CE transistor is not the best choice since the transconductance (gm) of the CE stage determines the LNA performances like gain and noise figure. On the other hand, since the CB stage is used as the unity current gain stage, employing an inverse mode SiGe HBT for this stage can be a better option for SET mitigation [21]. In this case, the performance degradation associated with the use of the inverse mode is minimal.

B. Impact of Strike Location on LNA SET response

Previous simulation results have been obtained for an ion strike at the emitter center, although SET in SiGe HBT is closely related to the strike position. In this study, we will investigate how strike positions along the x-axis affect the SET response of the different LNA cascode configurations. According to the geometry structure of the device, nine typical strike positions are selected. From fig. 6 we can see that for positions 1 and 2 the strike pass through both the BE, BC, and CS junctions, for positions 3 and 4 the heavy-ion only passes through the CS junction. Positions 5 to 9 however, are fully contained outside the CS junction. The device is axially symmetrical, therefore we only simulated the vertical irradiation on the right side of the device.

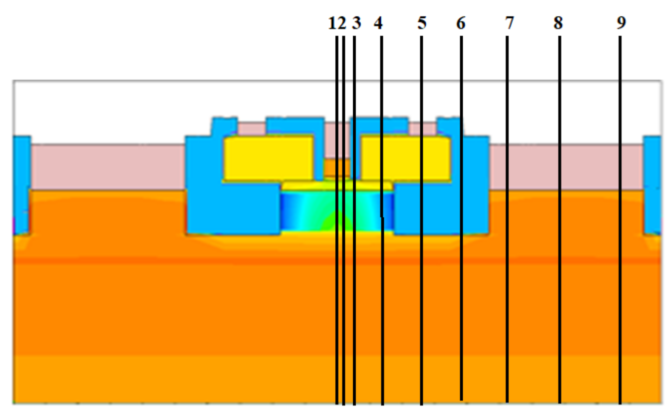


Fig. 6. Cross-sectional view of SiGe HBT device structure and ion strike locations

Fig. 7 (a) and (b), show the SET response of different LNA cascode topologies obtained for different strike locations in CB and CE devices. In all cases, the linear energy transfer (LET) has been fixed to 10 MeV-cm^2/mg. The interest of the inverse mode to mitigate SET is confirmed for all strike positions, the I-I cascode LNA shows the reduced transient amplitude for both CB and CE strike cases. Based on the simulation results of different LNAs cases configurations the worst-case transient peak has been shown to occur for an emitter-centered strike for both CB and CE transistors. We can observe that the transient peak amplitudes for CB and CE transistors are maximum at the center of devices and decrease as the strike position moves away from the emitter. The most vulnerable location to strike was observed at the center of devices when the strike occurs inside the CS junction.

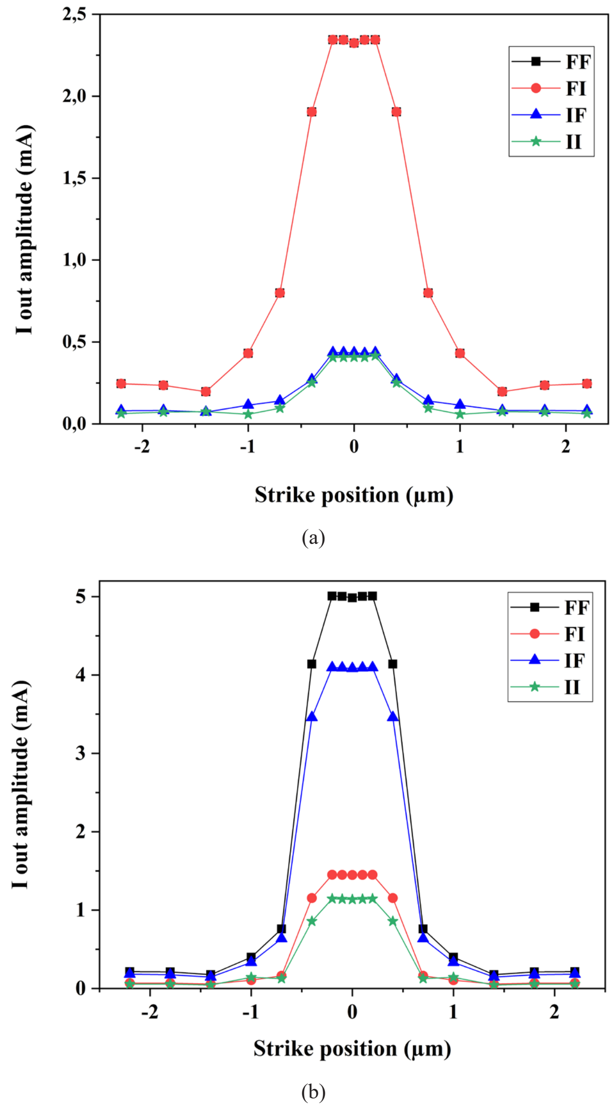


Fig. 7. The SET peak-to-peak amplitude as a function of the strike position for (a) CB strike, (b) CE strike.

C. Impact of strike linear energy transfer on LNA SET response

The linear energy transfer (LET) of the incident ion plays an important role in determining the SET response of the LNA. This energy fixes the density of excess ionized carriers generated along the particle path. To explore the effect of heavy-ion linear energy transfer (LET) on the produced SETs of CB and CE devices, the LET was swept from 1 to 100 MeV-cm^2/mg. For this simulation, the track radius characteristic was defined to be 0.05µm, and the width characteristic to be 20ps. Fig. 8 shows the peak-to-peak amplitude of simulated transients as a function of linear energy transfer (LET) for different LNA cascode configurations (F-F, F-I, I-F, and I-I) obtained when CB and CE devices are striked. The results confirm the interest of the inverse mode in reducing the SET transient current of LNA. The results indicate that the structures employing inverse mode for strike device are less vulnerable to the SET across all simulated LETs. As seen the transient peak-to-peak amplitudes produced when the strike device is in inverse mode are significantly lower than those produced when the strike device is in forward mode.

Concerning the LET influence, the output SET exhibits a close relationship with linear energy transfer (LET) for all considered LNA topologies. As seen in both CB and CE strike cases, the SET amplitudes increase monotonically with increasing LET. However, the rate of increase is not quite linear, the SET amplitude shows saturate trend for high LET, as the device and circuit non-linearities start to limit the LNA response. Indeed, increasing linear energy transfer (LET) will increase the density of excess ionized charge generated in the strike device and will increase the collected charge as well. However, when the linear energy transfer (LET) continues to increase the number of carriers that can be ionized grows slightly and the collected charges are difficult to increase sufficiently. Therefore, the uptrend of SET amplitude is gentle and end to saturate for high LET. Comparing the SET response for different cascode config-

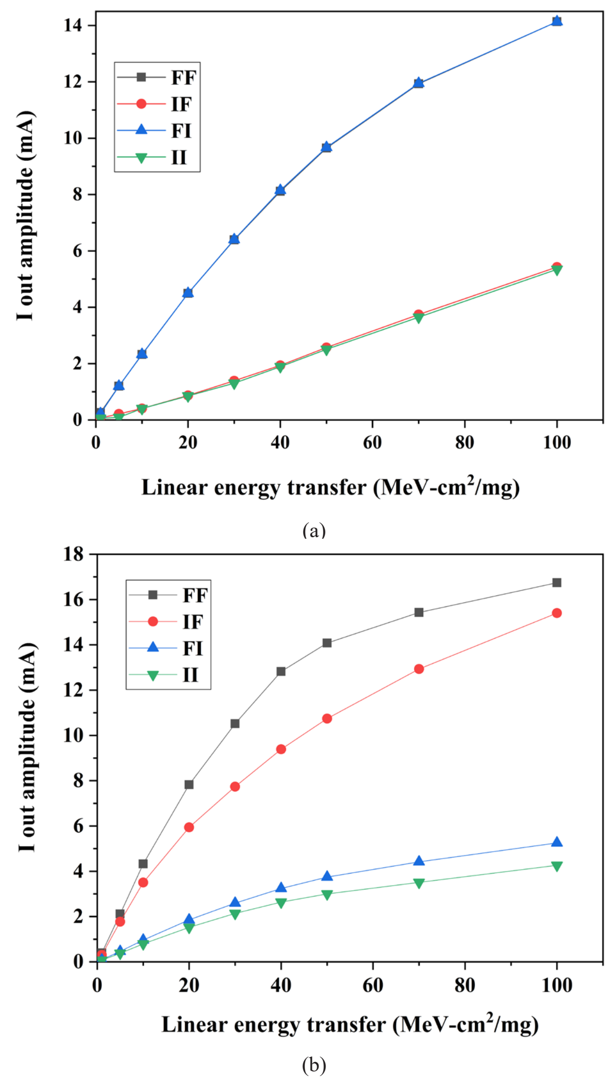
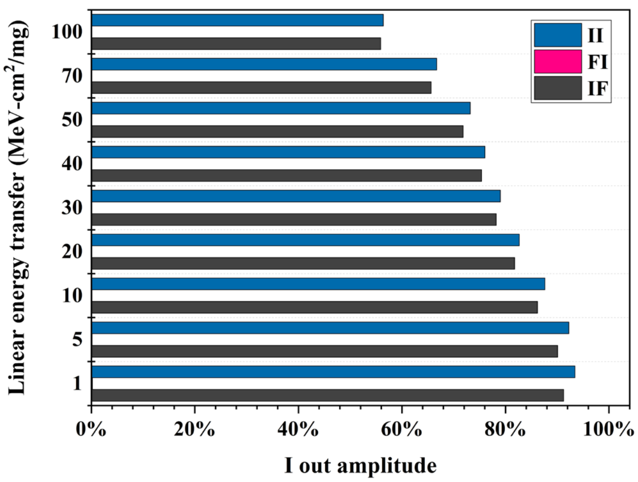


Fig. 8. The SET peak-to-peak amplitude versus the LET value for (a) CB strike, (b) CE strike.

urations, we can see that the SET amplitude saturation was more evident when the strike device is in forward mode. The reason is that the inverse mode provides greater isolation between the collector terminal and the sub-collector substrate diffusion current. Therefore, the majority of the generated carriers within the strike device cannot easily flow to the LNA output. This allows reaching the SET amplitude saturation for higher LET.

The SET reduction of the different topologies employing inverse mode compared to the conventionally F-F cascode LNA for different LET is computed and presented in fig. 9. The SET amplitude reduction for the different topologies is more important for low values of LET. We can observe that the I-I cascode LNA exhibits for CB and CE strike respectively about 93% and 85% reduction in transient amplitudes compared to the F-F cascode LNA for LET of 1 MeV-cm^2/mg. However, 56% and 79% peak reduction is observed for LET of 100 MeV-cm^2/mg.



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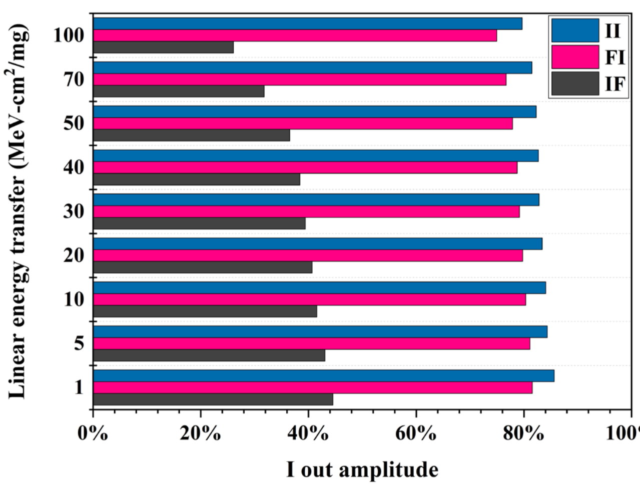
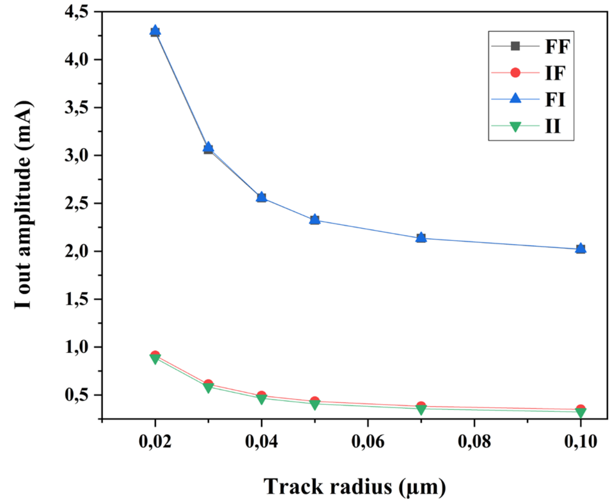


(b)

Fig. 9. The SET amplitude reduction of I-F, F-I and I-I cascode LNAs compared to F-F cascode LNA for different LET (a) CB strike, (b) CE strike.

D. Impact of track radius on LNA SET response

Fig. 10 shows the changes in the SET response of different LNA cascode topologies (F-F, F-I, I-F, and I-I) across multiple track radius, obtained when CB and CE devices are striked. The simulation results were performed for a given LET of 10 MeV-cm²⁄mg and various ion track diameters of 0.01 µm to 0.1 µm. For all considered cascode configurations the SET amplitude variation, shown in fig. 10 is found to decrease with increasing track diameter. These results are expected, since the relationship between the amount of generated charge and the track radius is inverse quadratic, as shown in (1). Even though, the strike with the smaller track radius generates higher charge density, which in turn pushes the CS junction of the strike device deeper into the substrate. As the junction extends, the collected charge increases and the SET amplitude will be higher.



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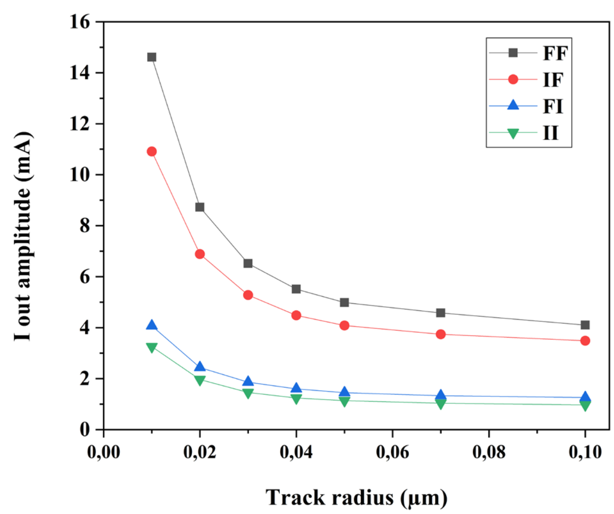
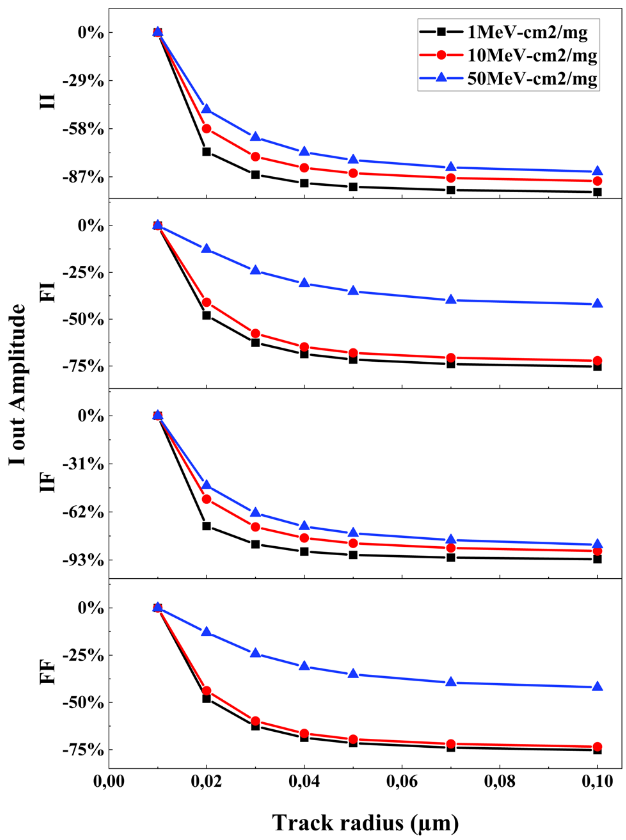


(b)

Fig.10. The SET peak-to-peak amplitude versus the track radius for (a) CB strike, (b) CE strike.

Fig. 11 shows the SET amplitude reduction versus track radius observed for three strike LETs of 1 MeV-cm²⁄mg, 10 MeV-cm²⁄mg, and 50 MeV-cm²⁄mg obtained for different cascode structures. The TCAD simulation results indicate that the impact of the track radius is most evident at low LET. We can observe that the variation of the SET amplitude with increasing



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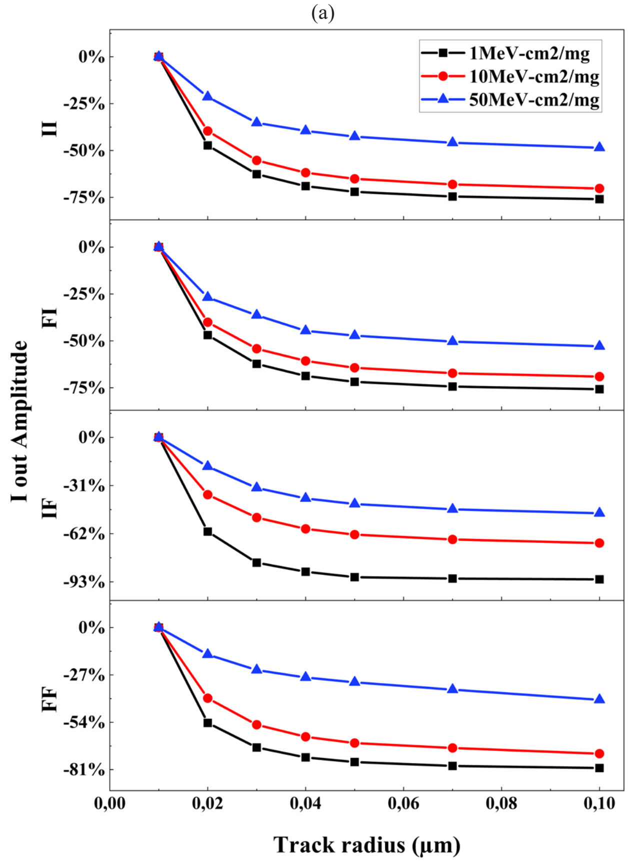

(b)

Fig. 11. The SET peak-to-peak amplitude versus the track radius obtained for strike LET of 1 MeV-cm²⁄mg, 10 MeV-cm2⁄mg, and 50 MeV-cm²⁄mg for (a) CB strike, (b) CE strike.

diameter is more pronounced at low LETs. However, with increasing LET the effect of the track diameter on SET response becomes much weaker. For the CB strike case, the F-F and I-I cascode LNA exhibited about 75% and 95% reduction in transient amplitude for LET of 1 MeV-cm²⁄mg. However, for LET of 50 MeV-cm²⁄mg the SET amplitude reduction is about 42% for F-F cascode LNA and 82% for I-I cascode LNA. For the CE strike case, the F-F and I-I cascode LNAs exhibited respectively 80% and 76% reduction in transient peak amplitude for LET of 1 MeV-cm²/mg. However, with increasing LET the SET reduction becomes much weaker. For LET of 50 MeV-cm²⁄mg, less than 41% change in transient peak amplitude is observed for F-F cascode LNA and 48% for I-I cascode LNA.

IV. Conclusion

In this paper, the SET behavior of LNA amplifiers implemented in SiGe HBT is investigated. To verify the potential of SiGe HBT for reducing SET sensitivities in the proposed LNA, four different cascode configurations were considered. The results show that the use of inverse mode SiGe HBT for strike device can effectively improve the SET tolerance of studied LNA. The LNA cascode configuration employing inverse mode for strike device shows the reduced susceptibility to single event transients, which is verified and analyzed for various strike operating conditions. In this fact, the resulting transient responses confirm a significant reduction in the output current peak magnitudes when strike position occurs outside CS junction. With regard to strike LET the results show that the strike impact on LNA SET responses decreases for high LET.

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