Improved Turn-on Uniformity & Failure Current Density by n- & p-Tap Engineering in Fin Based SCRs

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Abstract— **Failure threshold in Fin based SCR (FinSCR) was found to be severely limited by the non-uniform current distribution across the anode/cathode fins, attributed to non-uniform turn-on of individual fins. Unique physical insights related to FinSCR turn-on uniformity and position of hot-spot are developed as a function of the placement of n- & p- tap Fins relative to cathode and anode fins. Based on the understanding, unique tap schemes are explored in FinSCR, which offered relaxed self-heating, improved turn-on uniformity and I_{T2}. A novel Distributed Tap FinSCR (DTFSCR) device is proposed, which offers uniform conduction i.e. failure threshold scalability with the number of fins in the anode & cathode regions. Finally, the effect of placement of ESD implants in the anode and cathode regions are discussed.**

***Index Terms*—FinFETs, SCR, DTFSCR, FinFET-SCR, ESD, Electrostatic discharge.**

I. INTRODUCTION

Fin based ESD protection elements due to significantly reduced silicon volume or non-uniform ESD current conduction is prone to early ESD failure [1]-[3]. This demands engineering approaches for the ESD protection elements like SCRs and Diodes to (i) improve turn on uniformity across Fins and (ii) push the hot-spot from Fin region to bulk silicon. These aspects are missing in earlier works on Fin based SCRs [2]-[3]. This work attempts to bridge this gap using detailed 2D and 3D TCAD simulations with a goal to develop physical insights and design guidelines to improve the turn-on uniformity and I_{T2}.

In this paper device TCAD is used to develop physical insights into non-uniform current distribution in Fin based SCR. Using the developed physical insight novel tap engineering schemes are proposed to achieve uniform current distribution and thus improve the failure threshold. One of the key motivation of the work is to decrease the footprint of an SCR by creating a unit cell with as many fins as can be effectively utilized. A Conventional Fin based SCR with small number of fin per unit cell conducts uniform current, but as the number of fins per unit cell increases non-uniform current conduction takes place degrading the failure threshold of the device(Fig.2 d). Towards the end of this work a novel Distributed tap FinSCR is proposed which has the highest failure threshold and the failure threshold remains unaffected as the number of fins(Unit cells) are increased(Fig. 7c). The simulated TLP current injected has a 10ns raise time with a 100ns total time. The simulation setup (And the default parameters used) are same as the one used in [2],[3].

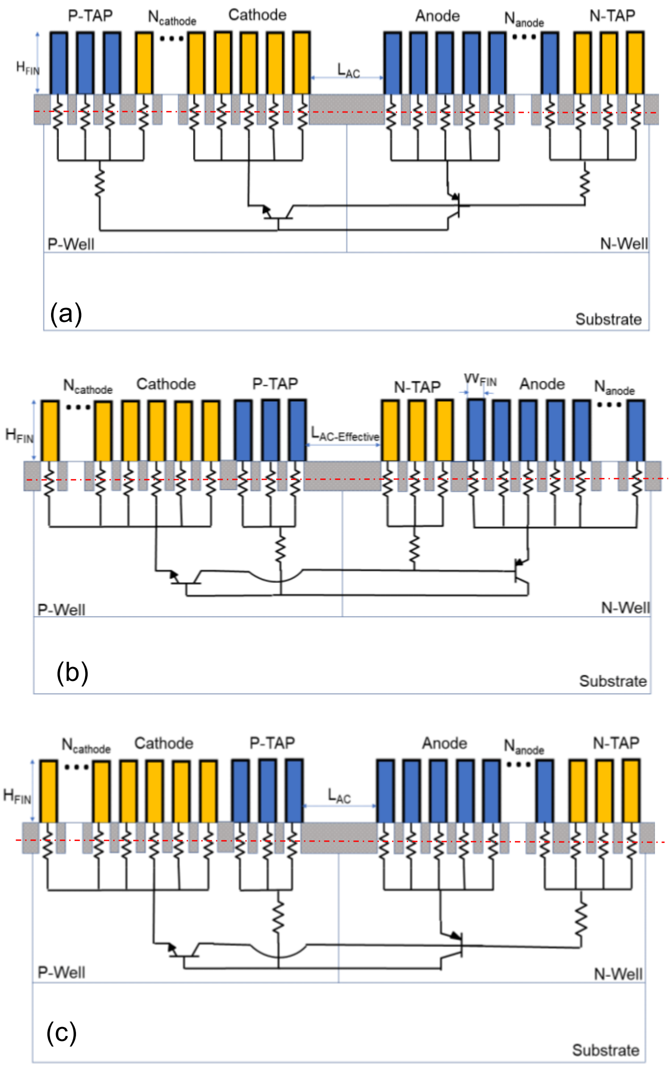

Fig. 1: Cross section view of (a) Conventional FinSCR (CFSCR) (b) Modified FinSCR-1 (MFSCR-1) (c) Modified FinSCR-2 (MFSCR-2). All the simulations are performed with a silicide blocking of 10nm unless specified otherwise.

II. CONVENTIONAL FIN BASED SCR (CFSCR)

In CFSCR (**Fig. 1a**) the fins closer to the junction carry the highest current (**Fig. 2a**) resulting in a very severe non-uniform current distribution among the anode/cathode fins. This is because of the non-uniform distance of the fins from the

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junction resulting in the non-uniform bipolar trigger (**Fig. 3**). This severe non-uniform triggering localizes the hotspot in the inactive region of the weakest fin (Cathode fin closest to the junction) as seen in **Fig. 4a**.

The non-uniformity in current distribution (/ non-uniform bipolar trigger) can be attributed to two reasons: (1) As the distance of the fin from the junction increases, the impact ionization generated carriers required for efficient turn-on of parasitic bipolar decreases. Thereby the fins closer to the

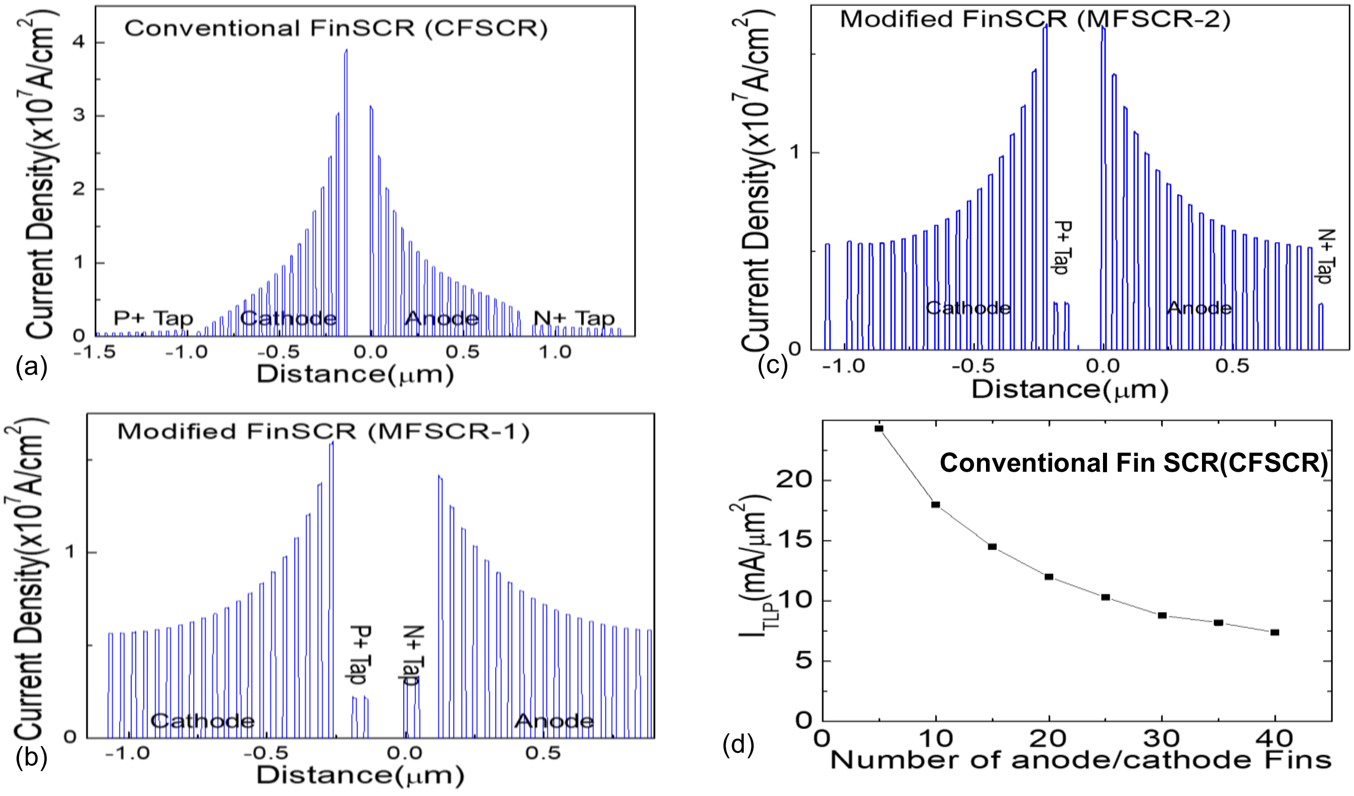

Fig. 2: Conduction current density plotted for an injected current of 10mA/μm^2 along the dotted red line in (a) Fig.1(a) (b) Fig.1(b) (c) Fig.1(a). Highly non-uniform current distribution is evident in CFSCR. This severely limits the failure threshold of a CFSCR device. To address this MFSCR-1 device was proposed. It is evident from Fig.2(b) that MFSCR-1 has much better current distribution than CFSCR. All the engineering has been done to change the amount of current influenced by the taps. (d) Failure current of CFSCR vs No of anode/Cathode Fins : Result of non-uniformity in current conduction

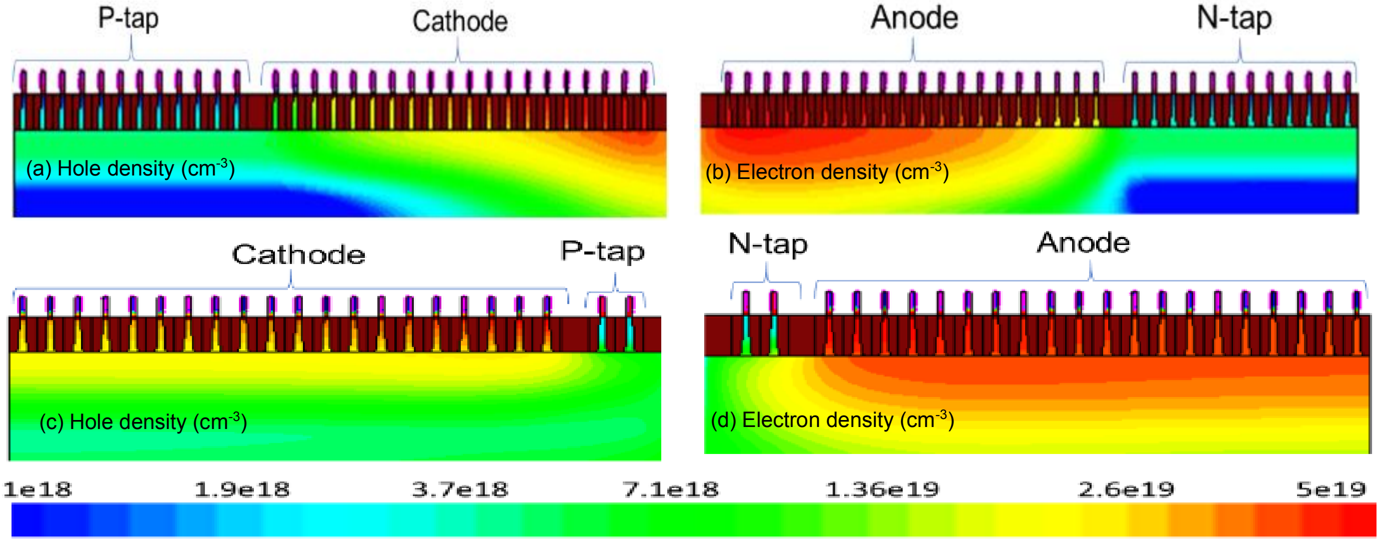

Fig. 3: Electron density contour of (b) CFSCR & (d) MFSCR-1. Hole density contour of (a) CFSCR & (c) MFSCR-1 Plotted for an injected current of 10mA/μm^2. The hole(/electron) density distribution in the cathode(/anode) side of MFSCR-1 is much more uniform than that of CFSCR, implying that the bipolar turn on among the fins is uniform in MFSCR-1's cathode(/anode) side.

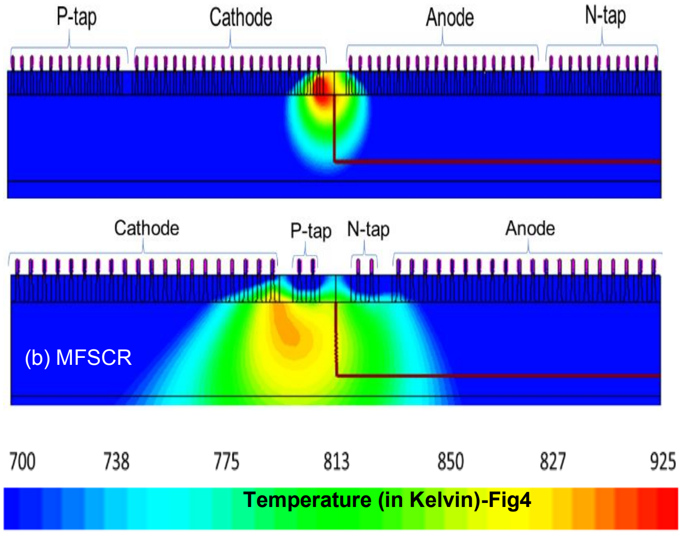

Fig. 4: Temperature contour extracted for an injected current at 90% of I_{T2} in (a) CFSCR (b) MFSCR-1. MFSCR-1 device has a relaxed hot spot which is pushed into the bulk since the anode and cathode fin closest to the junction conducts similar amount of current. Hot-spot in CFSCR can be seen to be highly localized in the inactive region of the fin which is surrounded by STI resulting in slower heat dissipation. In MFSCR the hot-spot is spread across multiple fins and is pushed into the bulk improving I_{T2}.

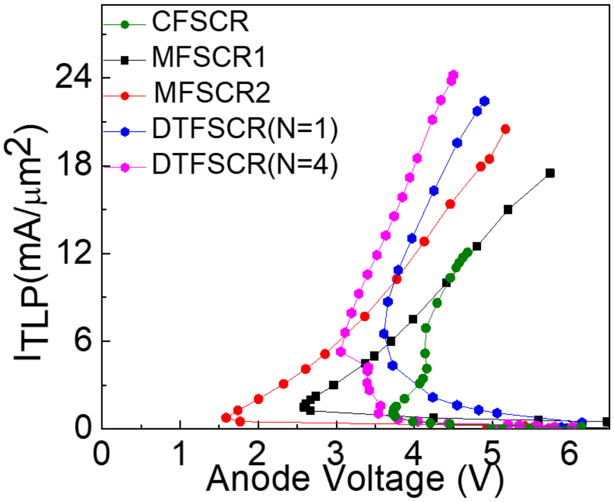

Fig. 5: Simulated TLP IV of CFSCR, MFSCR1, MFSCR2, DTFSCR with N=1 and with N=4. CFSCR devices has the lowest failure current due to non-uniform current distribution. MFSCR-2 device has a lower holding voltage than MFSCR1 device which increases their failure current despite having worse current distribution current distribution among the fins. All TLP's have been terminated at I_{T2}.

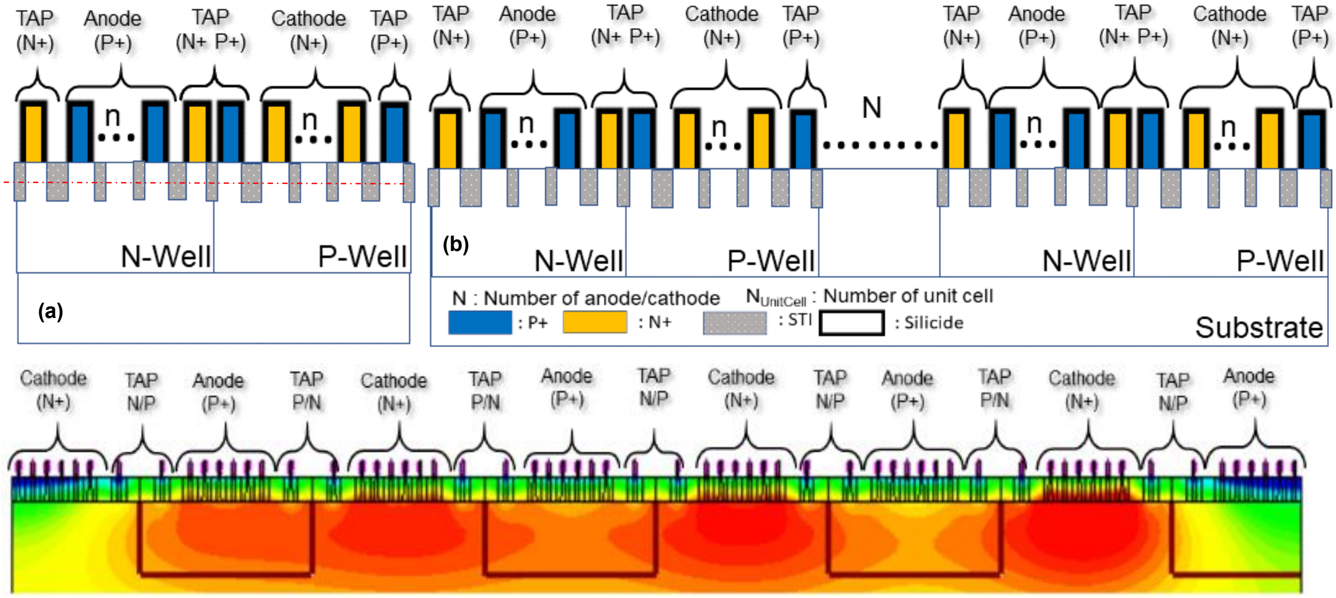

Fig. 6: (a) Cross sectional view of Distributed Tap FinSCR (DTFSCR)-With N=1 (b) Cross sectional view of a generalized DTFSCR N number of unit cells. (c) Temperature contour of DTFSCR with N=4 showing distributed hot spot for an injected current at 90% of I_{T2}. The hot-spot is distributed equally among all the unit-cell thus improving I_{T2}.

junction are the most efficient ones, carrying most of the current. (2) Taps increase the trigger voltage of the parasitic bipolar associated with the fins closer to them. Therefore, the fins closer to the taps tend to be less efficient and hence carry a lesser current load than the ones that are farther from the taps. To address these two problems leading to non-uniformity stated above, a modified device is proposed in the next section.

III. MODIFIED FIN BASED SCR (MFSCR)

To improve current distribution among the fins in an SCR, we must (1) Degrade the bipolar efficiency of fins closer to the junction. This will result in the fins closer to the junction taking a lower current load. Besides, (2) improve the bipolar efficiency of fins farther from the junction. This will result in those fins to carry higher current. Therefore, in MFSCR-1 (**Fig. 1b**) device the taps are removed from the edges and placed near the well-junction. This degrades the bipolar efficiency of the fins closer to the junction and enhances the bipolar efficiency of the fins farther from the junction.

From **Fig. 3a** and **Fig. 3c** the bipolar trigger of the cathode fins in MFSCR is more uniform than that of CFSCR device. Similarly, **Fig. 3b** and **Fig. 3d** show uniform turn-on across anode in MFSCR-1 device. This has further resulted in a relaxed hot-spot across the MFSCR devices (**Fig 4**). MFSCR has a failure threshold 60% higher than that of CFSCR device. However, in CFSCR the initial failure current was limited by the cathode fin alone, and thus it is not necessary to make changes on the anode side, which would result in an increased holding voltage, leading to early failure. Therefore, in MFSCR-2 (**Fig. 1c**) changes are made only at the anode side resulting in a reduced holding voltage (**Fig 5**). Despite having worse current distribution in MFSCR-2 than MFSCR-1, MFSCR-2 has better failure current due to reduced holding voltage. As the number of fins is increased further the failure current per unit area starts degrading because the non-uniformity becomes more severe. To address this issue a novel tap placement scheme is proposed in the next section.

IV. DISTRIBUTED TAP FINSCR (DTFSCR)

In the proposed DTFSCR (**Fig. 6a-b**) device, each well has two junctions at both the extremes increasing the impact ionization generated carriers available for bipolar turn-on. Taps are placed at both the corners of the well to reduce the bipolar efficiency of the fins on the corner and thus improve the overall current distribution (**Fig. 7a-b**). In this case the hot spot is pushed to the bulk and gets uniformly distributed across individual anode/cathode regions (**Fig. 6c**), which improves the failure threshold further. The failure threshold was found to be scalable with the number of unit-cells (**Fig. 7c**), which validates the uniform conduction in a multi-cell configuration (**Fig. 6b**).

DTFSCR exhibits a unique non-uniform turn-on characteristic (**Fig. 8a-c**). For moderate injected current (0.35-2.11 $mA/\mu m^2$) the current conduction is limited to the fins closer to the corner with p-well termination (**Fig. 8a**). This might be because NPN transistor turns-on faster than the PNP transistor. However, as the injected current is further increased (2.11-5 $mA/\mu m^2$) the current conduction gets limited to the fins closer to the corner with n-well termination (**Fig. 8b**). Before all the unit-cells turn-on uniformly the conduction is limited to the unit-cells near the termination because at termination the N/P well has only one well-junction (Unlike the unit-cells in middle, all of which has two junctions) thereby increasing the electric field. This can result in low-current failure of DTFSCR, which would have otherwise survived high current stress. The current at which all the unit-cell turn-on uniformly was found to increase with total number of unit cell. It was found that the current at which all fins conduct can be tuned with the SCR strength (**Fig. 8d**). Anode to cathode distance (L_{AC}) was found to change the trigger voltage without changing the breakdown voltage (W/o changing the well doping). This is because as L_{AC} is increased, a non-uniformity in the current distribution among the fins in

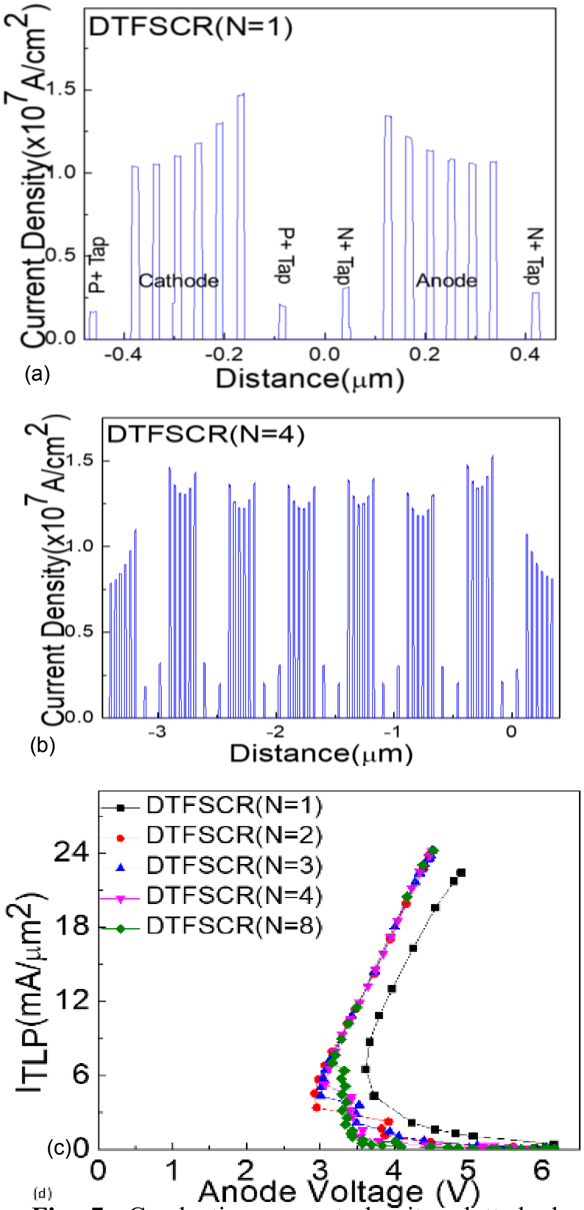

Fig. 7: Conduction current density plotted along the dotted red line in Fig4(b) with (a) N=1 (a) N=4 for an injected current of $10mA/\mu m^2$ (b) Simulated TLP IV for the device in Fig.4(b) with N= {1,2,3,4&8}. The failure current injected scales with the number of fins. I_{T2} per unit area can be seen to be a constant as the number of unit-cells is increased. This implies that I_{T2} per unit length scales linearly with the number of unit-cell. This scalability is missing in any device proposed so far.

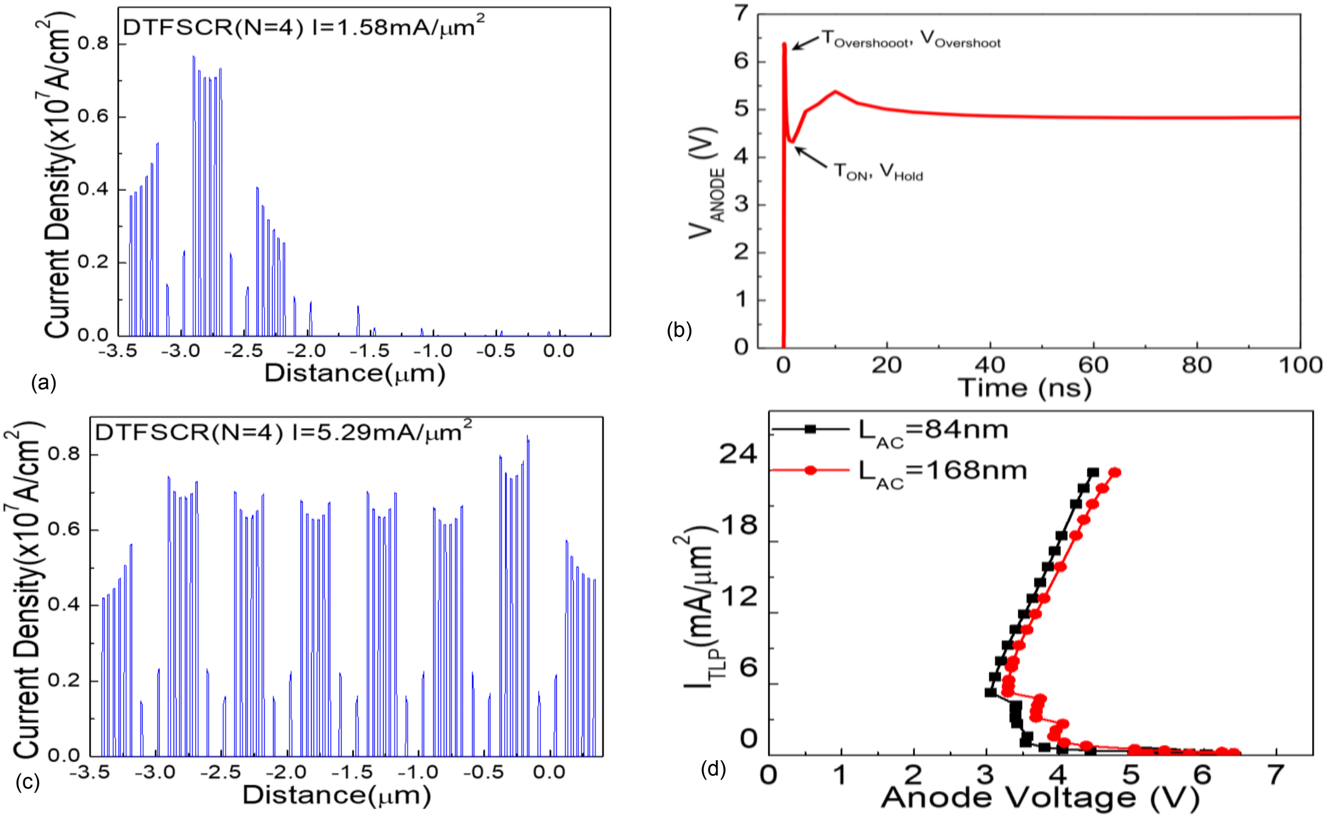

Fig. 8: Conduction current density plotted along the red line in Fig.5(b) for an injected current of (a)1.58mA/μm^2, (b)Methodology to extract turn-on time and overshoot voltage. (d)Simulated TLP IV of DTFSCR with N=4 anode to cathode distance (L_{AC}) varied. Fig.8d shows that as anode-cathode distance is changed the holding voltage and holding current changes. This effectively changes the current at which uniform-conduction occur. Thus, by tuning the SCR strength (Anode/cathode distance, well doping, number of taps in each well, number of anode/cathode fins) the latch-up immunity can be engineered.

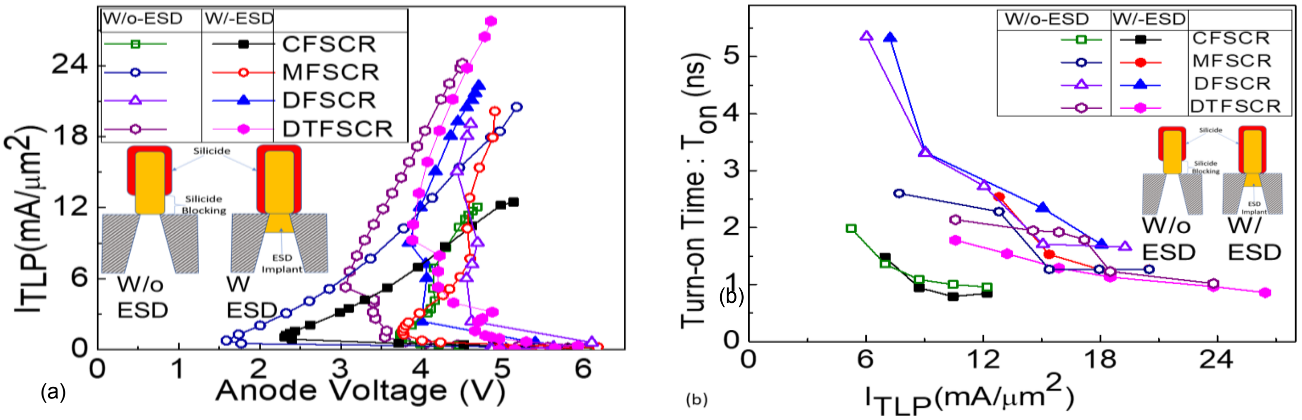

Fig. 9: (a) Simulated TLP IV of CFSCR, MFSCR-2, DFSCR and DTFSCR devices with and without ESD implant. (b)Turn-on characteristics of CFSCR, MFSCR-2, DFSCR and DTFSCR (4-unit cells) with and without ESD implant. In CFSCR with ESD implant placement turn-on time decreases since the taps are placed close to the fin taking negligible amount of current and thus the ESD implant improves the overall current distribution. In DTFSCR the turn-on decreases with ESD implant placement since the effect of taps on the middle fin is screened by impact ionization generated carriers from both the side of the well

each unit cell is introduced. Thus, the amount of current that flows through the fins closer the taps raises, increasing the effect of taps.

V. EFFECT OF ESD IMPLANT

ESD implant was found to improve IT2 in DFSCR [3] and DTFSCR whereas no significant improvement was found in CFSCR and MFSCR devices (**Fig.9a**). An ESD implant decreases the effective STI height, thus improves the bipolar efficiency of the cathode/anode fin and increases the effects of taps. As the number of fins increases in CFSCR/ or MFSCR, the effect of the non-uniform distance from the junction dominates reducing any effect ESD implant has. Since there are only two fins in DFSCR the effect of non-uniform distance from the junction is suppressed, thus they are sensitive to ESD implant.

The failure current in the DTFSCR is sensitive to ESD implant since the effect of non-uniform distance from the well-junction is suppressed by having two well-junctions in each well. Turn-on time was extracted as shown in **Fig.8b**.DTFSCR and CFSCR devices were found to have lower turn-on time followed by MFSCR and DFSCR respectively (**Fig.9b**). In CFSCR devices since the taps are placed close to the fins that conduct a negligible amount of current, they have lower turn-on time. In DTFSCR devices despite the taps being closer to the fins taking the highest amount of current, they have lower turn-on time. This is because the cathode/anode fins in the middle of the well also carry a significant amount of current and are not being influenced by the taps. However, in MFSCR and DFSCR the turn-on time is higher since the taps present near the junction severely degrades the bipolar efficiency of fins carrying the highest current load.

Overshoot voltage at 90% of I_{t2}

Device	Without ESD implant	With ESD implant
CFSCR	6.5V	6.5V
MFSCR	7.1V	6.4V
DFSCR	6.2V	6.2V
DTFSCR	6.6V	6.5V

The overshoot voltage in the table above have been extracted as shown in **Fig. 8b.** From this table we can conclude that the overshoot voltage of DFSCR proposed in [3] is the least whereas the overshoot voltage of MFSCR without ESD implant turns out to be the worst of all. However, ESD implant was found to improve MFSCR device's overshoot voltage. DTFSCR and CFSCR have similar overshoot voltages.

VI. CONCLUSIONS

Failure current in conventional Fin-SCR is limited by the non-uniform current distribution among anode and cathode fins. This is due to the non-uniform distance of each fin from the well-junction resulting in non-uniform turn-on of individual fins. Furthermore, the n- & p-taps placed close to the anode & cathode fins, respectively, however farthest from the well-junction degrade their bipolar efficiency. N- & P-Tap placement close to the well-junction results in an improved current distribution across anode & cathode fins. Using the insights developed from CFSCR and MFSCR, a distributed tap scheme (DTFSCR) is proposed, which further improves the current uniformity and I_{T2} scalability. Besides, it also shifts the hot spot to bulk silicon region, away from narrow fins, which significantly boosts I_{T2}.

VI. REFERENCES

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