Effect of biased field rings to improve charge removal after heavy-ion strikes in vertical geometry β-Ga_2O_3 rectifiers

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Abstract

In this study, the response to a heavy-ion strike and the resulting single effect burnout on beta-Ga_2O_3 Schottky diodes with biased field rings is investigated via TCAD. The model used to simulate the device under high-reverse bias is validated using experimental current-voltage (I-V) curves. A field ring configuration for the device demonstrates an improved charge removal after simulated heavy-ion strikes. If the time scale for charge removal is faster than single event burnout, this can be an effective mechanism for reducing the effect of single ion strikes. This study explores various configurations of the termination structure and shows the impact of different design parameters in terms of a transient response after the ion strike.

INTRODUCTION

β-Ga_2O_3 is attractive for high-temperature applications in harsh environments that cannot be tolerated by conventional electronics [1-4]. Its wide bandgap allows operation at elevated temperatures, while it is also radiation-hard [2]. The high voltage capability and higher achievable electric field strength when compared to SiC and GaN, is accompanied by low on-state resistance and the cost of production is low due to the ability to grow large diameter bulk crystals from the melt, which is absent for SiC and GaN. Some drawbacks include the low thermal conductivity and absence of p-type doping. One of the most promising devices is the vertical rectifier, with demonstrated breakdown voltages near 4 kV, forward currents > 100 A on large-area devices, and robust switching characteristics [3,4]. One of the key aspects of achieving high breakdown voltages rectifiers is the mitigation of electric field crowding at the edge of the depletion region to avoid premature breakdown. Floating metal field rings (FMRs) are a relatively simple approach for achieving this [5].

The response of these devices to single event effects is also of strong interest because of the potential applications for Ga_2O_3 in space and avionics applications where they will be subject to energetic particles. Radiation tolerance is an important factor while fabricating microelectronics and typical radiation damage suffered includes total dose effects, displacement damage, and single event effects. While there are no experimental or simulation results for single event effects in Ga_2O_3 to this point, it has become worryingly apparent that while other wide bandgap semiconductors like SiC and GaN are robust against displacement damage and total ionizing dose, they display significant vulnerability to single event effects at high Linear Energy Transfer (LET) and at much lower biases than expected [6-14]. For example, SiC power diodes exhibit single-event burnout with onsets for ion-induced leakage current and single-event burnout that saturate quickly with LET [14]. This saturation occurs before the high-flux iron knee of the Galactic Cosmic Ray (GCR) spectrum SiC Schottky diode susceptibility to single event burnout (SEB) occurs at < 50% of avalanche breakdown voltage. To date, no tested commercial SiC diodes pass above~50% of rated breakdown voltage at NASA mission LET requirement levels [13,14].

Few studies have been carried out to investigate GaN- and SiC-based rectifiers and transistors in terms of single event effects (SEE) [6-15], while there are none for Ga_2O_3 rectifiers, to the best of our knowledge. While SEE results on β-Ga_2O_3 devices are scarce, there are several publications that deal with the effects of heavy ions on β-Ga_2O_3 materials [15-18]. Heavy-ion strikes emulated in SiC-based devices have shown single-event degradation and catastrophic failure. There is some controversy as to the mechanism for SEB in SiC and this is not a settled question, but previous suggestions have included local temperature rises [6,7]. The results for SiC Schottky barrier diodes (SBDs) have identified the high field near the Schottky contact as the driving force for the thermal runaway in SiC SBDs. However, there is still some controversy as to the mechanism for SEB in SiC and this is not a settled question. TCAD does not necessarily predict the correct temperatures when the input parameters have been extrapolated some distance into unmeasured territory. Alternate explanations for SEB in WBG devices are found in [19,20]

In terms of mitigation of single event effects in wide bandgap devices, a Schottky element has been implemented in a GaN MISFET for the extraction of holes induced after irradiation. Zerarka et al.[21] studied the transient responses to heavy ions in these types of GaN transistors and used TCAD to understand the mechanism of SEEs.

This study addresses the gap in the literature on single event effects in Ga_2O_3-based devices by studying various parameters associated with SBDs with concentric rings around the Schottky contact. SBDs breakdown near the contact edge where the electric field is the highest during the voltage blocking operation and device failure is usually triggered here. Given the observation of unexpectedly low thresholds for heavy-ion induced catastrophic single event burnout in SiC and GaN power devices, we have performed simulations on the effect of floating field rings on transient single ion response of Ga_2O_3 power rectifiers. This study aims to analyze the transient response of β-Ga_2O_3 SBDs to heavy-ion strikes via TCAD simulations to understand the effect of various structural parameters. Using field metal rings has been reported to improve the breakdown voltage of these devices and biasing those rings can help control the breakdown voltage of the device [5]. The use of field rings to improve hardness of devices has been suggested for Si devices [22]

A similar study on GaN MISFETs has shown the potential of an extra Schottky element helping with SEB threshold voltage [23]. We find that such biased rings help in the removal of the charge deposited by the ion strike. The biased ring helps alleviate the electric field generated at contact corners and reduces the chances of burnout. This study focuses on the effect of the number of rings, ring spacing, and ring bias on the charge removal time, which would help prevent potential single event burnout. There is still a strong need for an understanding of the time scales for SEB occurrence and for charge removal.

EXPERIMENTAL

The experimental rectifier structure was a 10 μm thick, lightly Si-doped epitaxial layer grown by halide vapor phase epitaxy (HVPE) with a carrier concentration of 1.6×10^{16} cm^{-3} grown on a (001) surface orientation Sn-doped β-Ga_2O_3 single crystal. A full area Ti/Au backside Ohmic contact was formed by e-beam evaporation and was annealed at 550̊C for 30s under N2 ambient. 40 nm of Al_2O_3 and 400 nm of SiNx were deposited as field plate dielectric using Cambridge-Nano-Fiji ALD and PECVD tools. Dielectric windows of 40 μm ×40 μm were opened using dilute buffered oxide etchant and a 200nm Ni/Au Schottky contact was deposited with E-beam after lithography pattern followed by standard acetone lift-off. The current-voltage (I-V) characteristics were recorded at 1MHz with a Tektronix 370-A. The applied biases on the metal rings were provided by multiple voltage probes from the same voltage source Since the Schottky diode is a two terminal device, one power source is required to supply bias to the anode contact (cathode being grounded), but for biased metal rings separate probes are needed to apply biases in the different rings.

A TCAD model of this rectifier structure is used to solve for the electric field distribution and impact ionization. Figure 1 shows the 2-D device structure schematics of the SBD used in the simulations using Synopsys Sentaurus structure and device simulator. The figure also denotes the various structural and device parameters that are analyzed in this work. The peak field was the criterion used to determine whether the diodes will survive or burnout. The ion track was assumed to be cylindrical. Table 1 shows the various design parameters and their value ranges. Even though the active epi region is 10 μm, we also simulated ion tracks that deposit their energy past the active epi - substrate interface to determine if there is any effect of charge diffusion back from this area. 1 pC/μm in β-Ga_2O_3 is equivalent to about 277 MeV-cm^2/mg leading to simulations over the LET range of 195-415 MeV-cm^2/mg. This is typical of heavy ions encountered in galactic cosmic ray fluxes. The electron-hole pair generation energy for Ga_2O_3 is 15.6 eV [24] The charge generated in the semiconductor is dependent on the original particle energy and the mass of the semiconductor, and can be calculated as

$$Q = LET(\rho)1.6\frac{x10^{-5}}{G} = LX \qquad (3)$$

where Q is the total charge deposited along the particle path length X. LET is the linear energy transfer of the ion, ρ is the density of the semiconductor material, and G is the electron-hole pair generation

The device structure is first simulated for breakdown, and experimental data is used to validate the models used in this study. To simulate the reverse leakage and the eventual breakdown, modeling done by Lingaparthi et al.[25] and Labed et al. [26] is used as the basis for this work. The top Schottky contact is given the Schottky boundary condition and barrier tunneling is turned on to simulate the thermionic field emission under high reverse bias. A nonlocal tunneling model [27] as given by the local tunneling generation rate (eq 1), using the tunneling probability calculated using the WKB approximation (eq 2) $G_{Tun}(r) = \frac{A^{*}T}{k_B}$.

$$\vec{E}.\Gamma(r)\ln\left[\frac{1+\exp\left(-q(\psi-\phi_n)/k_bT\right.}{1+\exp\left(-q(\psi-\phi_m)/k_bT\right.}\right] \qquad (1)$$

$$\Gamma(r) = exp\left[-\frac{2}{\hbar}\int_0^r \sqrt{2m\left(\frac{\phi_b}{q} + \phi_m - \psi(x)\right)dx}\right] \qquad (2)$$

Other models include an optimized Arora model for mobility, an impact ionization model based on the van Overstraeten de Man model (Chynoweth model) [28], a simple band-to-band tunneling model, and SRH recombination and generation [29]. These models maintain the concentration of charge carriers and help with convergence, and the parameters used in these models are based on values obtained from previous studies or calibrated for this work. We simulated the transient response versus strike depth (strike at edge of Schottky) as a function of the number of rings (n= 0, 1, 2) at constant d=4,10; S=0.5 and Vr/Vg=0.95, depth versus ring spacing (d=4,10; Vr/Vg=0.95; n=2) and bias ratio on the rings (d=2; S=1.0;n=1), the strike position (at fixed strike depth=4μm) versus number of rings=(0, 1, 2), bias ratio and ring spacing. The linear energy transfer (LET) of a heavy-ion strike is assumed to be similar to values measured for GaN in the absence of more precise experimental data for Ga_2O_3. The materials have similar density, but different bandgaps and carrier generation rates, the latter of which have not yet been measured.

Figure 2 illustrates the good fit between the TCAD simulation and experimental data from 40 μm diameter β-Ga_2O_3 SBDs. These results show the extremes in the range of experimental breakdowns measured on 10 devices. The agreement provides validation of our approach. The agreement and curve-fitting also shed light on the dominating mechanisms for the reverse leakage current in β-Ga_2O_3 SBDs. Adding traps to the simulation helps in improving breakdown voltage. However, this is not a good approach to design a high-performance radiation-hard device because the defects can trap mobile carriers, degrade on-resistance, and create an overall reliability issue. The overall goal for a high-performance high-power device is to have high breakdown voltage and low on-resistance with minimal unintentional defects as possible in the epitaxy to avoid reliability issues in long-term operation. Traps within the device via point defects and vacancy complexes also help with trapping extra charge generated by the heavy-ion strike. For Ga_2O_3, the understanding of the various trap-states and their origin requires more research, but particle radiation damage increases the defect concentration. The breakdown voltage has been reported to improve using biased field rings [5].

RESULTS AND DISCUSSION

The diode is biased at -500V at the time of the ion strike, using a steady-state ramp which is followed by a transient response. This is a derated value from the design values of 1400- 1600 V, but enable us to investigate the effects of ion strike in a safe operating area. Future work will establish the threshold for SEB according to the simulations. The simulation framework consists of a heavy-ion strike at the 10^{-13} s timestamp. We report on the anode current as measured at the Schottky contact, which corresponds to the cathode current measured at the bottom contact. Figure 3 shows typical transient responses as a function of ions strike depth, with charge deposition deeper in the depletion region having more effect. We interpret these results to illustrate a single event burnout when the ion penetration is >10 μm There are SiC results that show SEB does not occur if the ion strike does not penetrate the back epi- substrate interface. The 2 μm and 4 μm deep ion strikes only show leakage current.

If the strike depth is greater than the epi thickness the charge generation is accelerated. The charge removal time is unaffected but the deeper the ion strike the higher the chances of device breakdown/burnout. Since the substrate is highly conductive, the induced charge is swamped by the background carrier density, but it is still of interest to simulate ion tracks that deposit their energy past the active epi – substrate interface since they pass through the epi layer. Having the strike depth or penetration depth less than the epitaxy thickness will also cause heavily accumulated damage at the stopping range of the ions inside the epitaxy. The effects of ions that have penetration range less than epitaxy depth, hence, should also have deleterious damaging effects.

As part of the simulation framework, when rings are added to the simulation, the total anode current is measured as the sum of hCurrent at all top contacts, i.e. anode and the ring electrodes. Figure 4 shows that when using rings total anode current drops to 0, suggesting no single event burnout, whereas with no rings there is a residual charge remaining at the contact edge, as seen in Figure 5. This residual charge is explained by high electric fields at the contact edge resulting in local avalanche e-h pair generation. Adding rings improves the charge removal rate as shown in Figure 6, reducing any local avalanche generation.

The charge removal can also be improved by reducing the spacing between the contacts, as seen in figure 7. However, the Vr/Vg ratio also plays an important part in efficient charge removal. If Vr/Vg is lower than 0.8, optimization can be achieved by increasing the spacing between the rings and anode. As seen in figure 8, there is avalanche generation resulting in breakdown due to the high electric fields between the anode and 1st ring. This suggests that using two rings is superior to using one larger ring.

For a vertical Schottky diode the peak field location is usually at the outermost edge of the top Schottky contact. This means any strike that is close to the edge will have higher charge collection due to avalanche generation. As seen in figure 9, the cases where the ion strike is at the edge or on the contact (cp=2, cp=4) the charge generated is the highest. This also shows the robustness of the structure in terms of charge removal.

Figure 10 shows the effect of the LET on the transient profile. As the LET value is increased the charge removal becomes slower and the peak current is also increased corresponding to a higher charge generation after the ion strike. At this early stage of radiation studies in Ga_2O_3. We do not know whether the field rings remove the charge rapidly enough to prevent single event burnout. A possibility is that the failure occurs at very short times after the ion strike, in which case the addition of the field rings would not help significantly.

The simulations conducted in this study assume that the operating voltage for the SBD is around 500V. Careful device engineering would be needed for structures with different epi-doping and optimization for design parameters would be required. Recently, there have been multiple studies [30,31] on the addition of a p-NiO layer under the Schottky contact. The p-type layer creates an additional pn junction which helps with the potential drop, opening an innovative path to further improve the device performance. The response to a heavy-ion strike and the performance of β-Ga_2O_3 diodes with the p-NiO layer will be interesting to see.

CONCLUSIONS

Given the observation of unexpectedly low thresholds for heavy-ion induced catastrophic single event burnout in SiC and GaN power devices, this study helps to identify optimized β-Ga_2O_3 diodes as a possible solution. The use of biased rings greatly improves both the breakdown voltage of the device and the charge removal after simulated heavy-ion strikes, showing a pathway to use device design to partially mitigate single event effects in β-Ga_2O_3 power rectifiers. The model described here would be greatly strengthened by the inclusion of radiation data that demonstrates the effectiveness of the field rings in mitigating SEB, which is still somewhat speculative. For example, if the device experiences SEB faster than the charge can be removed, the field rings would not be effective. Calibrating the simulations to measured pre-rad characteristics is a useful starting point but does not demonstrate that the rings will actually improve the survivability. At this stage, however, there are no published heavy ion data on burnout of Ga_2O_3 rectifiers.

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Table 1. Device parameters used to analyze the performance of the device via TCAD.

Device parameter	Details	Simulation framework/ Comments
s	Spacing between ring/s and Schottky contact	0.5 – 1.5μm
w	Width of rings	5.0 μm
p	Ion strike position/ distance from Schottky edge	-0.5 – 5.5 μm (for the device with no rings)
cp	Ion strike position defined for the device with rings	-
LET	Linear energy transfer	0.7 – 1.5 pCoulomb
d	Depth of ion-strike	2.0 – 50.0 μm
Vg	Bias applied to the Schottky contact	
Vr1	Bias applied on the first ring	
Vr2	Bias applied on the second ring	
Vr/Vg	The ratio of bias applied on outermost ring contact to the next inner contact	0.6, 0.8, 0.95

Figure Captions

Figure 1. 2-D device schematic of the β-Ga_2O_3 SBD simulated via TCAD. The dashed blue line indicates where the single-particle strikes.

Figure 2. Fit achieved between simulated and experimental reverse IV. The sample device is a 40 μm structure and Sim-1 and Sim-2 are results based on two sets of model parameters.

Figure 3. Transient responses to a heavy-ion strike at Schottky contact edge without rings as a function of strike depth.

Figure 4. Transient response to a heavy-ion strike at Schottky contact edge as a function of the number of rings. Linear time scale (inset) shows an improvement in charge removal rate when using rings.

Figure 5. Hole concentration in the device without rings as a function of time, starting from 10^{-13} (ion-strike) to 10^{-6} s.

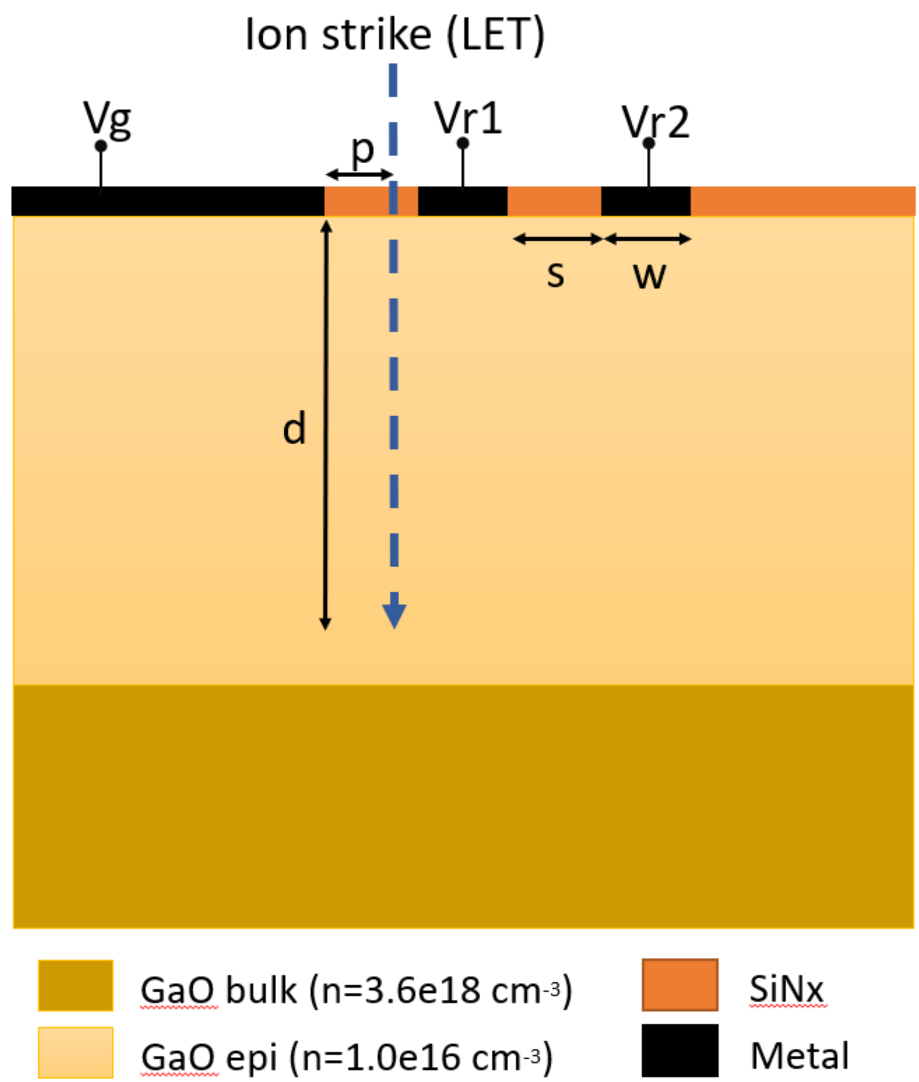
Figure 6. Hole concentrations in the device with 1 ring as a function of time starting from 10^{-13} (ion-strike) to 10^{-6} s.

Figure 7. Transient response to a heavy-ion strike at Schottky contact edge, where n=2 rings and d=4μm, as a function of the spacing between rings (s). Linear time scale (inset) shows smaller spacing between rings faster charge removal rate.

Figure 8. Transient response to a heavy-ion strike at the Schottky contact edge, where n=1, s=0.5μm, and d=4μm, as a function of Vr/Vg.

Figure 9. Transient response to a heavy-ion strike at various positions, where n=2 rings and d=4μm and Vr/Vg=0.95.

Figure 10. Transient response to a heavy-ion strike at the Schottky contact edge as a function of the LET value, where n=0 rings and d=4μm.


Ion strike (LET)
Vg
p
Vr1
Vr2
s
w
d
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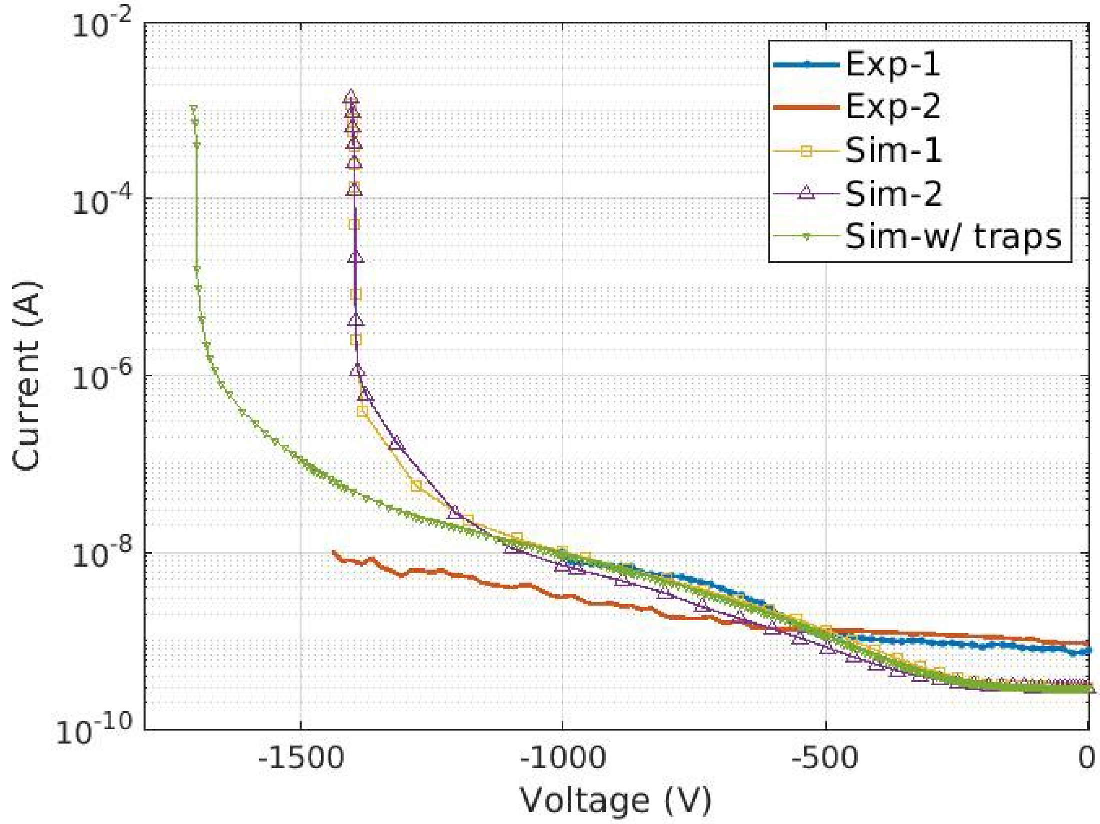
GaO epi (n=1.0e16 cm-3)
SiNx
Metal



Exp-1
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10^-2
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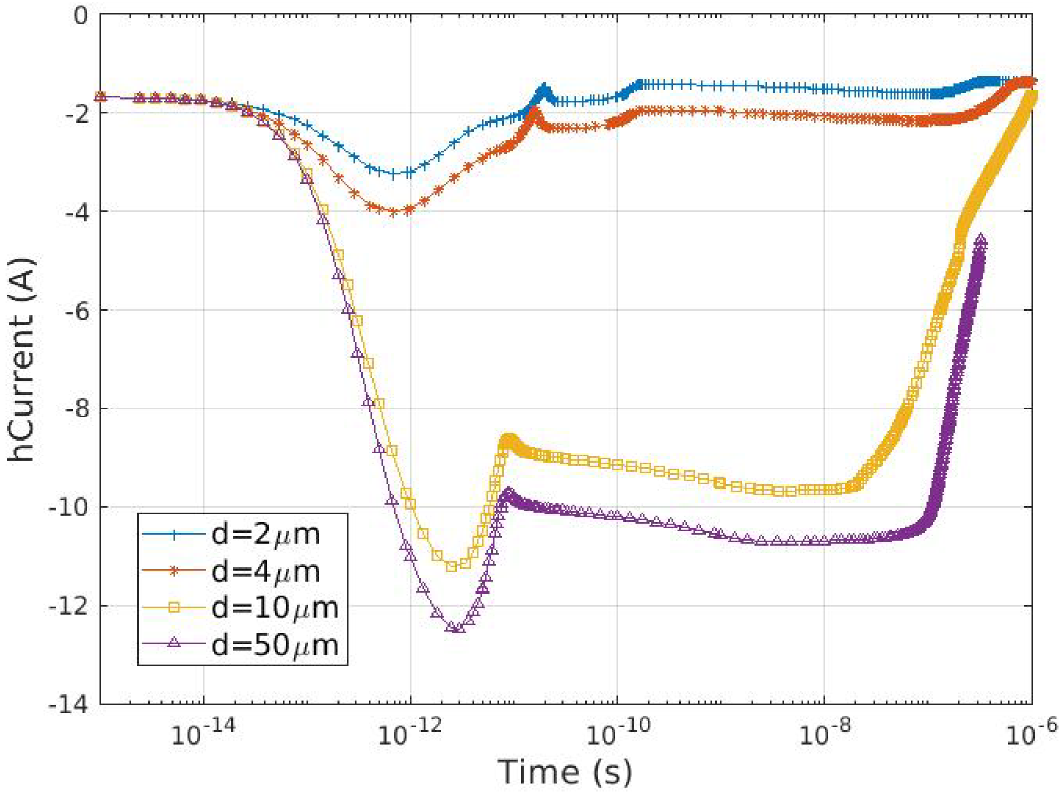

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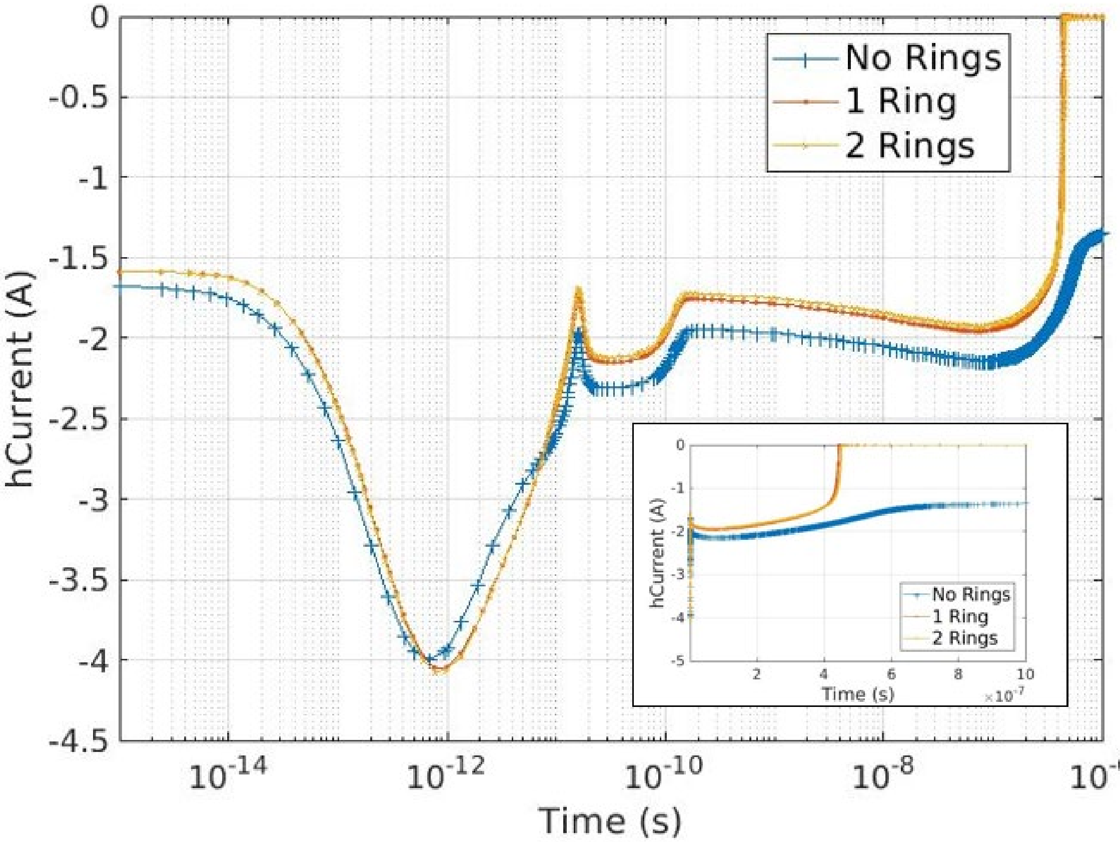
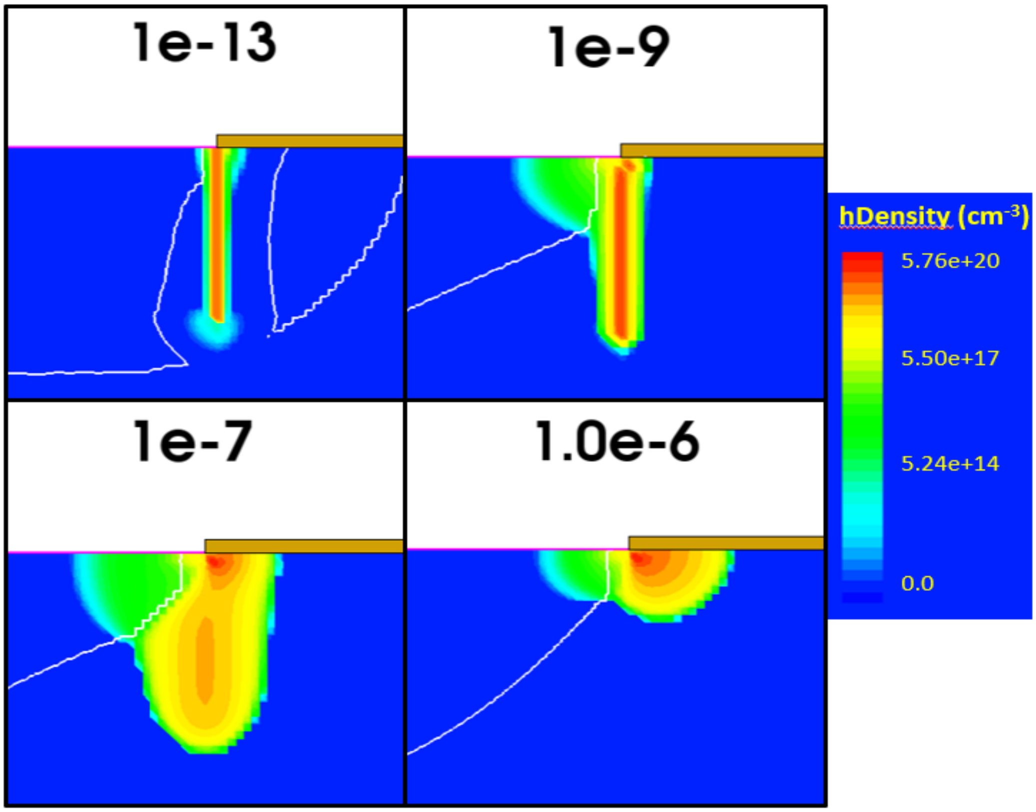
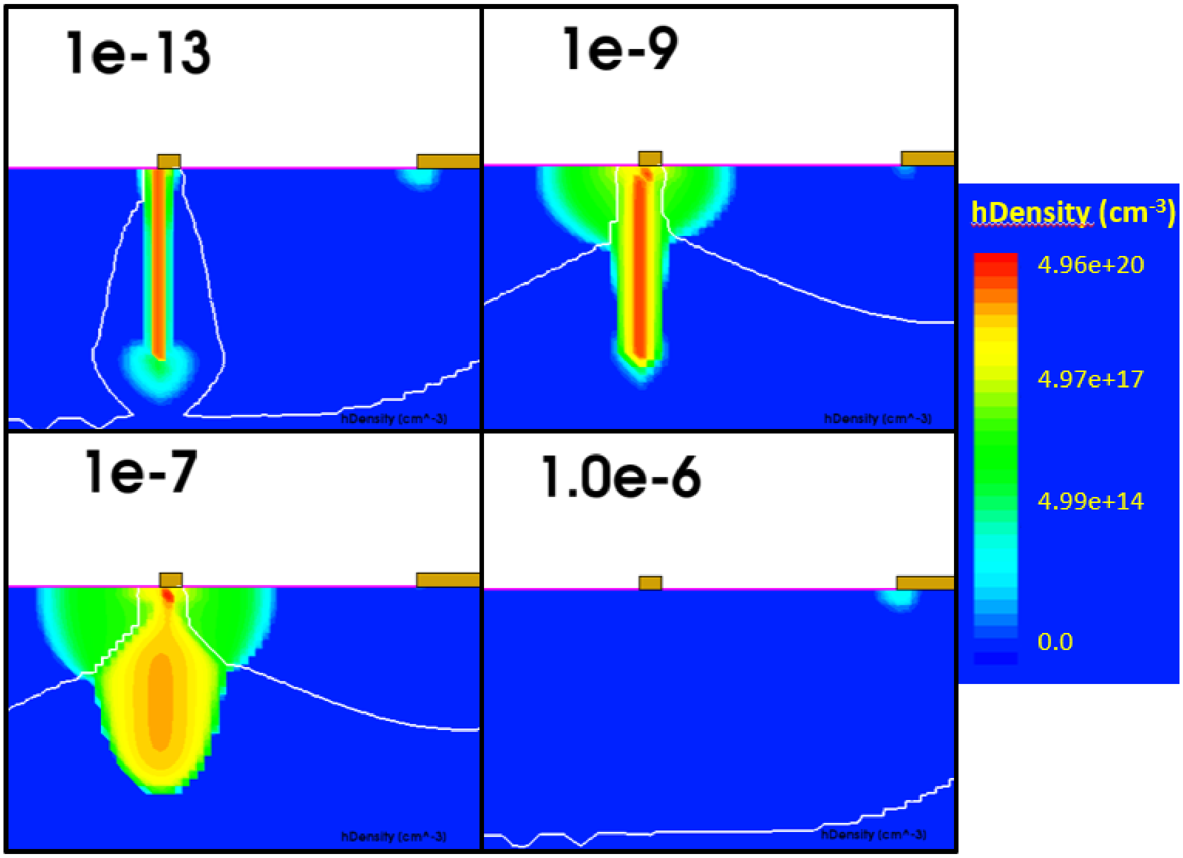
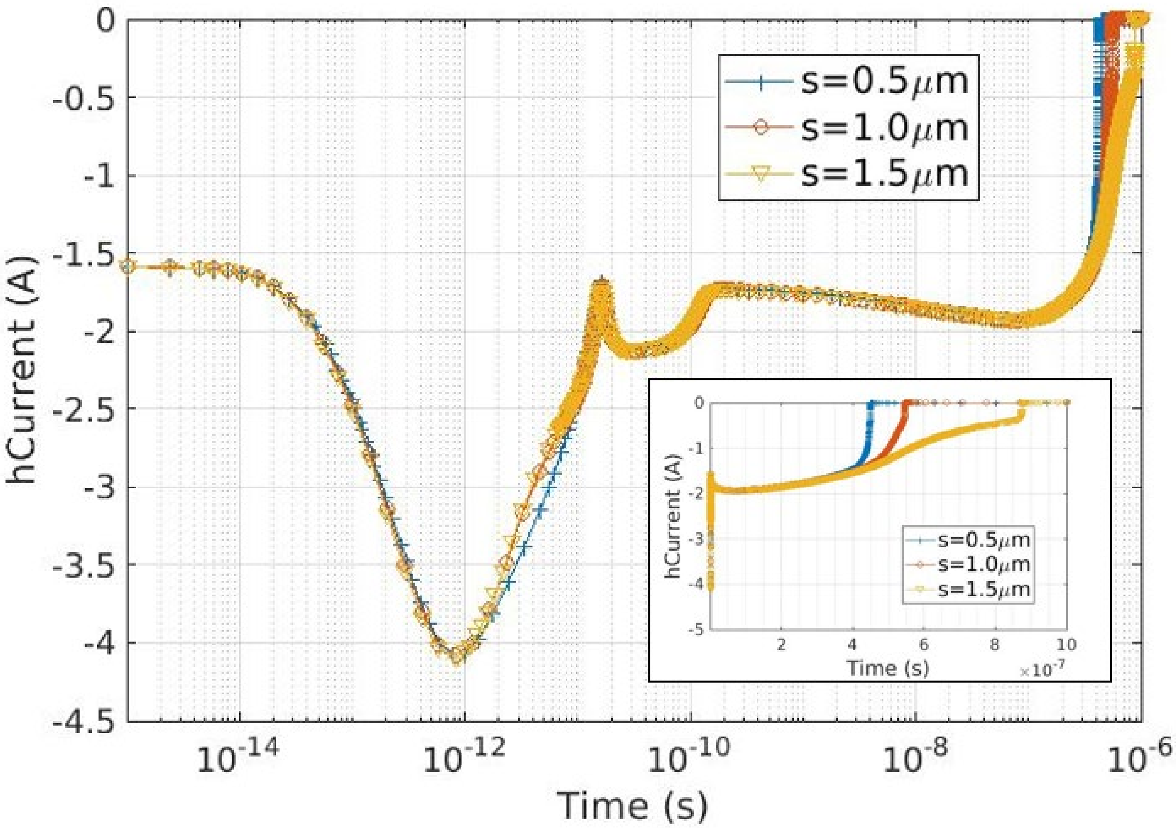
-8
-10
-12
-14
10^-14
10^-12
10^-10
10^-8
10^-6
d=2μm
d=4μm
d=10μm
d=50μm

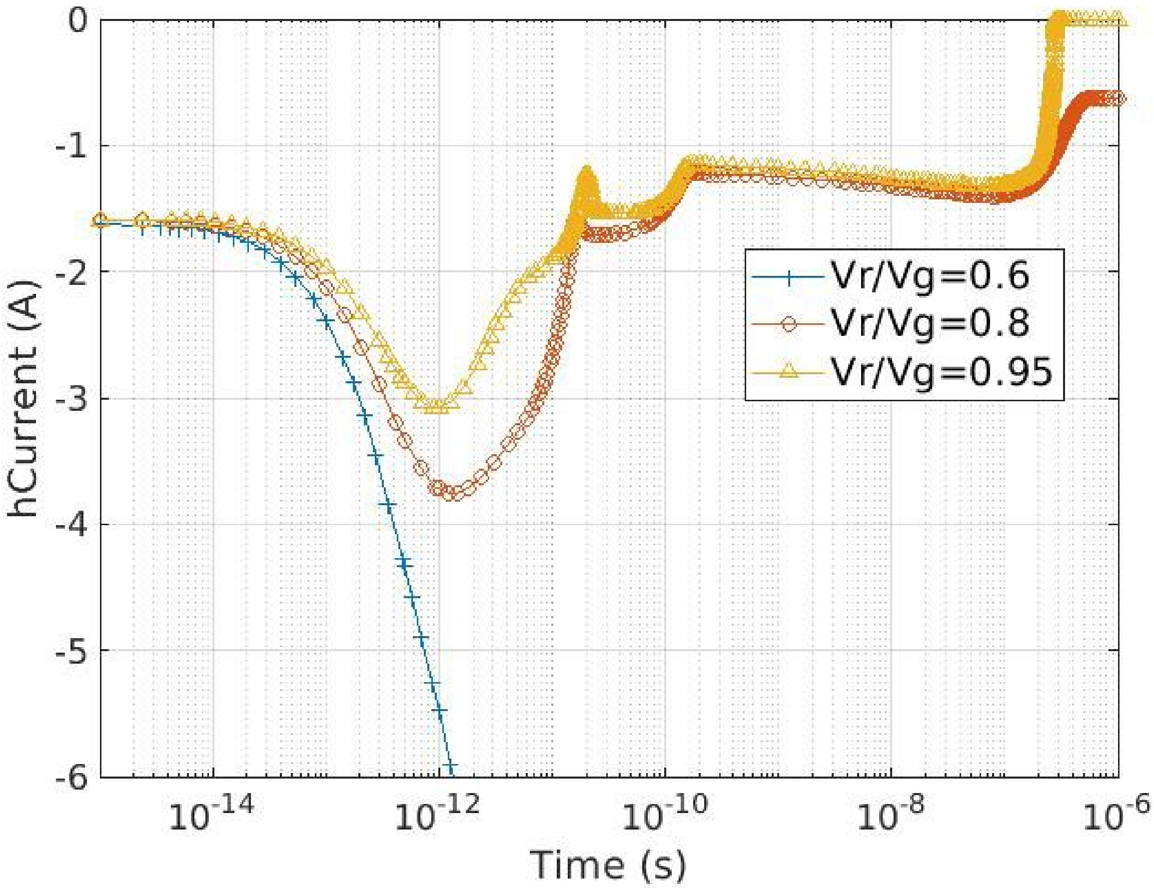

No Rings
1 Ring
2 Rings
hCurrent (A)
Time (s)
0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
-4
-4.5
10^{-14}
10^{-12}
10^{-10}
10^{-8}
10^{-6}
No Rings
1 Ring
2 Rings
hCurrent (A)
Time (s)
$\times 10^{-7}$

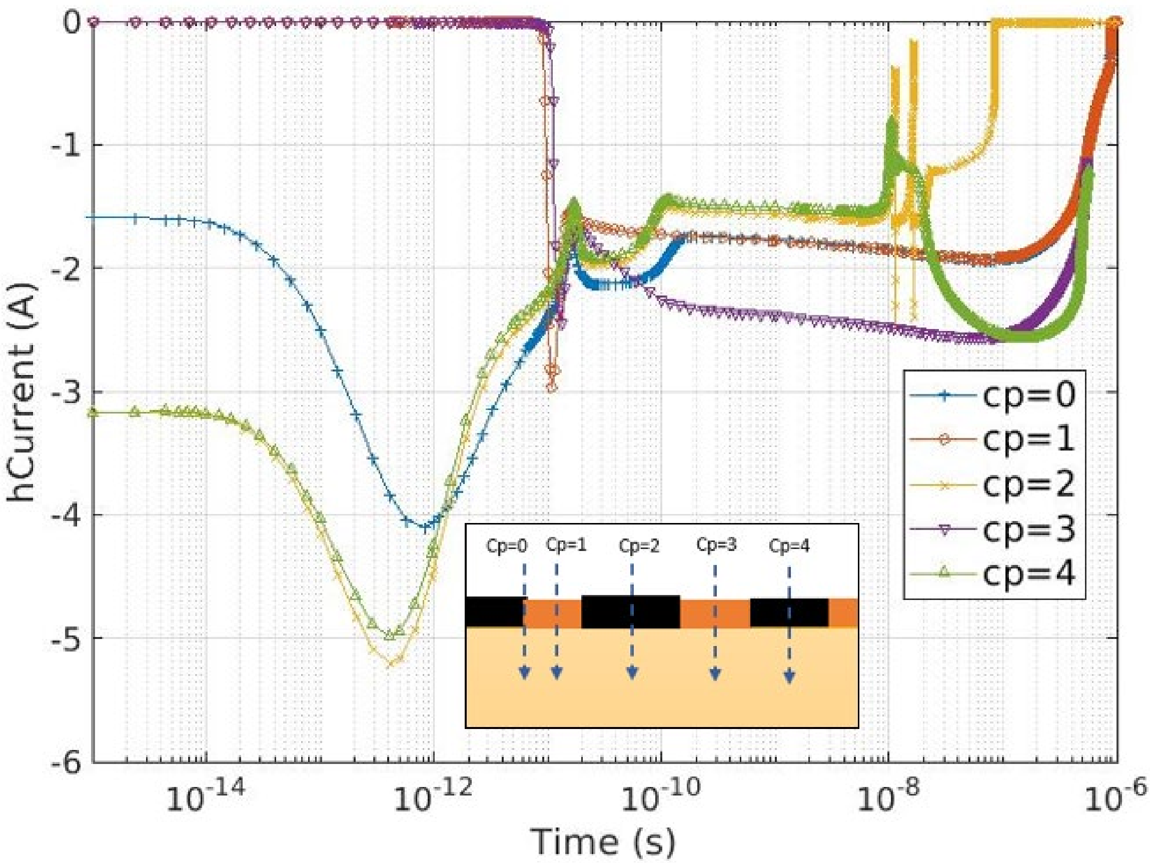

1e-13
1e-9
1e-7
1.0e-6
hDensity (cm-3)
5.76e+20
5.50e+17
5.24e+14
0.0


1e-13
1e-9
1e-7
1.0e-6
hDensity (cm^-3)
hDensity (cm^-3)
hDensity (cm^-3)
hDensity (cm^-3)
hDensity (cm-3)
4.96e+20
4.97e+17
4.99e+14
0.0

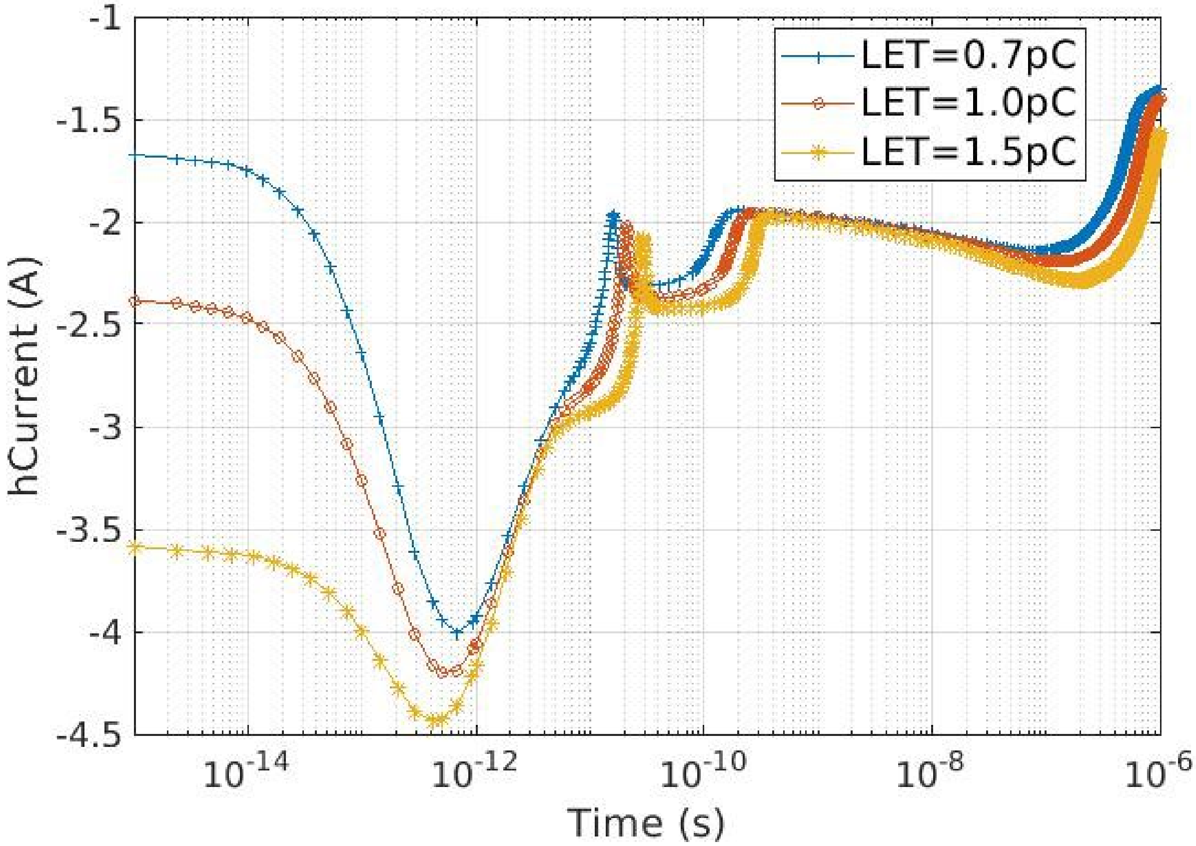


hCurrent (A)
Time (s)
s=0.5μm
s=1.0μm
s=1.5μm
0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
-4
-4.5
10^-14
10^-12
10^-10
10^-8
10^-6


0
-1
-2
-3
-4
-5
-6
hCurrent (A)
10^{-14}
10^{-12}
10^{-10}
10^{-8}
10^{-6}
Time (s)
Vr/Vg=0.6
Vr/Vg=0.8
Vr/Vg=0.95



hCurrent (A)
Time (s)
cp=0
cp=1
cp=2
cp=3
cp=4
Cp=0
Cp=1
Cp=2
Cp=3
Cp=4


-1
-1.5
-2
-2.5
-3
-3.5
-4
-4.5
hCurrent (A)
10^-14
10^-12
10^-10
10^-8
10^-6
Time (s)
LET=0.7pC
LET=1.0pC
LET=1.5pC