Reliability and Uniformity Enhancement in 8T-SRAM based PUFs operating at NTC*

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ABSTRACT

SRAM-based PUFs (SPUFs) have emerged as promising security primitives for low-power devices. However, operating 8T-SPUFs at Near-Threshold Computing (NTC) realm is plagued by exacerbated process variation (PV) sensitivity which thwarts their reliable operation. In this paper, we demonstrate the massive degradation in the reliability and uniformity characteristics of 8T-SPUF. By exploiting the opportunities bestowed by schematic asymmetry of 8T-SPUF cells, we propose biasing and sizing based design strategies. Our techniques achieve an immense improvement of more than 55% in the percentage of unreliable cells and improves the proximity to ideal uniformity by 82%, over a baseline NTC 8T-SPUF with no enhancement.

CCS CONCEPTS

• **Security and privacy** → **Security in hardware**; *Embedded systems security*; • **Hardware** → *Integrated circuits*;

KEYWORDS

6T-SRAM, 8T-SRAM, PUF, Near Threshold, Hardware security

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1 INTRODUCTION

SRAM-based PUFs (SPUFs) have emerged as a viable security choice in resource constrained systems [3]. This can be

attributed to their obviation for dedicated circuitry and elimination of the overheads of complex encryption mechanisms [17]. SPUFs rely on inherent physical characteristics, that originate from manufacturing process variations (PV), to enable chip security [8, 9, 17]. Likewise, Near-Threshold Computing (NTC) has transpired as a promising energy-efficient design paradigm, as compared to Super Threshold Computing (STC) [6]. However, the supply voltage reduction is also accompanied by increasing effects of PV. Herein, it is important to highlight a unique property of SPUFs to reproduce the same chip signature every time it is attempted to be authenticated, often referred to as SPUF *reliability* [9]. Thus, it remains an intriguing research question whether NTC operation of SPUFs brings about any degradation in reliability, due to exacerbated PV sensitivity.

The read instability introduced by low voltage operation makes 6T-SRAMs an unfavorable design choice at NTC [6], and the addition of extra read transistors in 8T-SRAM used in NTC [4], introduces a schematic asymmetry, quite contrary to a symmetrical 6T-SRAM. We observe that, this leads to an asymmetric start-up current, which when sensitized by varying system noise and temperature, leads to a degradation in SPUF reliability. In addition to reliability concerns, we find that the shift to NTC SPUFs challenges *ideal SPUF uniformity* owing to the differences in device geometry. SPUF uniformity depicts how uniformly the 0's and 1's are distributed in the SPUF signature [7]. We observe that the schematic asymmetry exhibited by 8T-SPUFs leads to an imbalanced distribution of the start-up current within the cell, giving rise to decreased uniformity. We analyze the impact of device asymmetry on reliability and uniformity of 8T-SPUF and propose *CUBIT: Biasing based strategies* and *CUSIT: Sizing based strategies*.

Our contributions in this paper are as follows:

- We observe that there is a marked degradation in reliability and uniformity for 8T-SPUFs operating at NTC, in comparison with STC-operated 6T-SPUFs (Section 2).
- By analyzing the impact of device asymmetry on reliability and uniformity characteristics, we propose CUBIT: biasing based design strategy, and CUSIT: sizing based design strategy (Section 3).
- In comparison to state-of-the-art technique by Chang et al. [3], our proposed design strategies exhibit a comprehensive enhancement in both reliability and uniformity, with more than 55% improvement in percentage of unreliable cells, and 82% progression in the ballpark of ideal uniformity over the Baseline NTC 8T-SPUF array (Section 4).

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2 BACKGROUND AND MOTIVATION

In this section, we quantify the metrics of reliability (Section 2.1) and uniformity (Section 2.2), which are key determinants of SPUF behavior. Using the methodology discussed in Section 2.3, we demonstrate that although 8T-SPUFs exhibit an energy efficient solution [6], their naive implementation on low power platforms come with massive degradation in reliability and uniformity (Section 2.4).

2.1 Estimating SPUF Reliability

SPUF Reliability is a measure of repeatability of SPUF array signature. The reliability is threatened when the start-up states of cells in the unique signature of SPUF array are flipped by noise and environmental variations, leading to *unreliable cells* [9]. In Equation (1), *Bit_Flips* gives the number of times an SPUF cell c powers up to a different bit value, relative to the noiseless iteration. n is the number of power-ups of the same SPUF cell in the presence of system noise.

$$Bit_Flips(BF_c) = \sum_{i=0}^n |Bit_value_{noiseless} - Bit_value_i| \quad (1)$$

Bit_Reliable is a binary thresholder, determining whether the c -th SPUF cell is reliable. t is the threshold of number of allowed bit flips to still mark the cell as reliable.

$$Bit_Reliable(BR_c) = \begin{cases} 1 & BF_c \leq t \\ 0 & BF_c > t \end{cases} \quad (2)$$

Finally, *PUC*, gives the *Percentage of Unreliable Cells* in the SPUF with m cells, at supply voltage V and temperature T .

$$PUC(V, T) = \frac{1}{m} \sum_{c=0}^m (1 - BR_c) \times 100\% \quad (3)$$

For assessing reliability in this paper, we set $t=0, n=10, m=1000$.

2.2 Estimating SPUF Uniformity

Uniformity depicts the randomness of the SPUF array's signature. Uniform distribution of '1's and '0's in the SPUF signature ensures a strongly random key, which is difficult to be replicated by an attacker [7]. For a m -bit SPUF, Maiti et al. have defined uniformity as the percentage Hamming Weight (HW) of the m -bits [13], given by Equation (4).

$$Uniformity(\%) = \frac{1}{m} \sum_{c=0}^m Bit_value_c \times 100\% \quad (4)$$

where *Bit_value_c* is the power up state of the c th SPUF cell ('0' or '1') of SPUF with m cells. A uniformity proximal to 50% translates to more randomness in the SPUF.

2.3 Methodology

To estimate the reliability and uniformity of an SPUF array, we model 6T-SRAM and 8T-SRAM cells using Predictive Technology Model (PTM) for 32nm [1]. We instantiate 1000 unique cells to build an SPUF array by Monte Carlo simulations for Threshold voltage (V_{th}), Length (L) and Width (W), with PV of 9% for V_{th} and 4.5% for W and L . We model the noise in time-domain using all the noise sources defined in BSIM-CMG

[12]. For the frequency-domain noise modeling, the base and maximum frequency are set to $F_{min}=10^4$ and $F_{max}=10^9$ respectively [18]. We then simulate the SPUF array at supply voltage ranging from -10% V_{dd} to +10% V_{dd} and temperature from -40°C to 110°C.

2.4 Results and Significance

Figure 1a shows the comparison of *PUC* in STC 6T-SPUF and NTC 8T-SPUF array. We observe that the *PUC* variation across V_{dd} is under 5% for both the STC and NTC SPUF. However, the window of variation of *PUC* across temperatures for NTC 8T-SPUF shoots up to 30%, as opposed to 6% in STC 6T-SPUF. Fuzzy extractor and other error correcting mechanisms would have to cover a larger spread of unreliable cells across all corners of environmental variations, which leads to excessive power and area overheads [16]. The increased overheads will disrupt the entire SPUF ecosystem, which is primarily targeted for low cost security primitives. Hence, shifting from STC to NTC, SPUFs subjected to temperature variation, are plagued by decreased reliability.

Figure 1b compares the uniformity of STC 6T-SPUF and NTC 8T-SPUF at different temperatures. We see that the worst case deviation of 6T-SPUF from ideal uniformity is under 9%, as compared to the glaring deviation of 33.2% for 8T-SPUF. This anomaly can be attributed to the exorbitant skewness of the bits to a particular state for the NTC 8T-SPUF. Therefore, it is imperative to realise that the 8T-SPUFs are plagued by decrement in uniformity, making them more vulnerable to attacks. To recuperate this atrophy in reliability and uniformity characteristics, we propose our design strategies, for SPUFs operated at NTC in Section 3.

3 DESIGN

In this section, we first discuss the impact of schematic asymmetry in 8T-SPUFs amalgamated with the increased effect of PV, to justify the governing principle of our design (Section 3.1). Following which, we propose our design strategies, *CUBIT: Current Suppression with Biasing Technique* (Section 3.2) and *CUSIT: Current Suppression with Sizing Technique* (Section 3.3), to tackle the glaring degradation in reliability and uniformity characteristics of 8T-SPUFs at NTC.

3.1 Impact of Schematic Differences

The schematic difference between a 6T-SPUF and 8T-SPUF cell is the addition of the two NMOS's for read access. Schematically, as the read access transistors are only connected to one half of the cell (Fig. 2), there is an asymmetry in right half and left half supply current, I_{RH} and I_{LH} (Fig.3).

We compare the maximum of currents, I_{RH} , I_{LH} among 10 different noisy startups, until the trip point [9], from where the voltages at BL and BLB diverge to their final states. Figure 4a shows that the current I_{RH} dominates the current I_{LH} . This non-uniformity in current distribution among the SPUF cells is brought about by gate leakage current, I_g flowing from right junction JR towards the gate of transistor M7 as shown in Figure 3. I_g tries to drag down the voltage rise at junction JR .

Figure 1: Reliability and Uniformity characteristics for STC-operated 6T-SPUF versus NTC-operated 8T-SPUF

Figure 2: Schematic Representation of a SPUF cell

This phenomenon leads to more number of SPUF cells ending up to a final states '1' than '0' at J_L , i.e degraded uniformity. In addition, we observe that this current is very sensitive to temperature change and random system noise. Due to this increased sensitivity, the chances of degraded reliability increases manifold. Hence, the suppression of this current and its variation opens doors to better reliability and uniformity in NTC 8T-SPUF. In CUBIT, we demonstrate how biasing can improve the reliability by suppression of I_g . Following which, we present CUSIT, which is based on sizing to improve the uniformity by I_g suppression.

Figure 3: Current I_g is shared from only right junction J_R of the 8T-SPUF cell, rendering the current in the right half, I_{RH} asymmetric to left half current I_{LH} .

3.2 CUBIT: Biasing based Techniques

CUBIT improves the reliability and uniformity of the NTC 8T-SPUF by biasing Read Counterpart of NTC 8T-SPUF (Fig. 3) in different ways, targeting the suppression of current I_g . In Figure 4b, we show the suppression of maximum of current

I_g in SPUF cells by one of our biasing technique, which improves both reliability and uniformity. Similarly, in Figure 4c, we show the massive reduction of statistical variance of maximum of current I_g among the noisy startups for SPUF cells for the same technique. Higher magnitude and variance contributes towards decreased reliability and non uniformity respectively. Different biasing techniques are discussed in 3.2.1, as different steps of an algorithm, devised to comprehensively improve both reliability and uniformity.

3.2.1 CUBIT Algorithm. We propose an algorithm for finding the best combination among the different ways of biasing Read Counterpart (Fig. 3). At the end of the algorithm, we are presented with a stack of improved uniformity and reliability figures and the respective moves which cause it. Top of the stack is the best combination according to priority constraints given. User can also select sub optimal solutions as a trade-off with the overheads in actual implementation. We start by applying minimum possible moves first, and then move to different combinations of moves. Table 1 lists the terminologies and the objective of our algorithm 1.

T	{-40°C, 25°C, 110°C}
R	Max(% of Unreliable Cells (PUC)), across T
U	Max(Uniformity-Ideal Uniformity), across T
RLT	Reliability Loss Threshold: Maximum allowed Loss of R (in %) to gain U.
ULT	Uniformity Loss Threshold: Maximum allowed Loss of U (in %) to gain R.
Objective	Minimize U and R

Table 1: Terminologies and Objective for Algorithm 1

Different moves for the algorithm are: 1. **RE-RBL:** This is a Reliability Enhancer move, where we bias the Read Bit Line (RBL) of the 8T-SPUF cell to Biasing voltage (V_B), as shown in Fig. 6a. The SPUF array logic can be customized to provide a logic high through precharging in RBL line at the startup of the 8T-SPUF array. Simulation results in Fig. 5, show that, with $V_B=V_{dd}$, this move can decrease **R** (Fig. 5a), by 55%, but cannot decrease **U** (Fig. 5b).

2. **RE-RWL:** This is also a RE move, where we bias the Read Word Line (RWL) of the 8T-SPUF cell to V_B as shown in Fig. 6b. The SPUF array logic can be customized to enable RWL, also at the startup. Simulation results in Fig. 5, show that, with $V_{SB}=V_{dd}$, this move can decrease **R** (Fig. 5a), by 53%, but cannot decrease **U** (Fig. 5b).

Figure 4: Fig. 4a : Plot of the maximum supply currents distributed to right and left half of 8T-SPUF cell. Fig. 4b : Effective suppression of I_g by biasing techniques. Fig. 4c : Effective suppression of Variance of I_g by biasing techniques. Maximum and variance are calculated among the maximum currents until trip point, of 10 different noisy startups

3. **RUE-SGT and UE-SGTf:** Biasing the Source Ground Terminal (SGT) of M7 with voltage $V_B = V_{dd}$, as shown in Fig. 6c, at the startup of the 8T-SPUF cell, gives us Reliability and Uniformity Enhancer (RUE) move. As the sink of the current I_g is SGT, rising its potential from ground suppresses the I_g very effectively. Simulation results in Fig. 5 show that bias of $V_B = V_{dd}$ at SGT is able to reduce R and U by 55.8% and 56% respectively. RUE-SGT improves the uniformity by aggressively turning around the population of '1' skewed cells to from 83% (67% above ideal) to 35% (30% below ideal). Hence, by reducing the degree of suppression with lowering V_B from V_{dd} , the uniformity can be brought closer to ideal uniformity. This give us Uniformity Enhancer (UE) moves, UE-SGTf, where f is V_B as fraction of cell V_{dd} (V_B / V_{dd}). Simulation results in Fig. 5b shows improvement of U with decrease of V_B . However, as the V_B goes on decreasing, reliability decreases severely as shown in Fig. 5a. Hence, true benefit of UE-SGTfs can be extracted only by coupling with RES.

3.3 CUSIT: Sizing based Techniques

CUSIT is a sizing based technique to suppress the effects of current I_g , for better reliability and uniformity. CUSIT scales the sizes of the transistors of I_g source (Write counterpart) and sink (Read counterpart) in such a way that I_g , relative to supply current, $I(V_{dd})$ is decreased. This scaling ensures that the impact of I_g on reliability and uniformity is curtailed. Figure 7 shows the variation in I_g for upscaling write transistors relative to read transistors, with six different scaling factors. I_g is normalized to $I(V_{dd})$ and observed till the time a 8T-SPUF reaches its trip point. It is evident from the figure that I_g decreases with an increase in the upscaling factor. To establish the adaptive nature of CUSIT in the light of varying currents in the transistor, we present two different approaches to transistor resizing. First, scaling down the size of read transistors (relative to write transistors), and second, scaling up the size of write transistors (relative to read transistors). In light of implementation feasibility, the Read and Write Counterparts of 8T-SPUF cells (Fig. 3) can be sized independent of each other, unlike the meticulous sizing constraints of conventional 6T-SPUF cells [2].

Algorithm 1 CUBIT

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1: REcombinations = {RE-RWL, RE-RBL, {RE-RWL, RE-RBL}}
2: RUEmove = {RUE-SGT}
3: UEmoves = {UE-SGTf1, UE-SGTf2, ..., UE-SGTfn}
4: procedure MAIN
5:   Apply RUE_move
6:   Push move and (R, U) to stack
7:   for (r in REcombinations) do:
8:     Apply r
9:     if (RU-IMPROVED(R, U) == 1) then
10:      Push r and (R, U) to stack
11:   end if
12:   ENHANCE UNIFORMITY
13: end for
14: end procedure
15: procedure ENHANCE UNIFORMITY
16:   for u in UEmoves do:
17:     Apply u
18:     if (RU-IMPROVED(R, U) == 1) then
19:       Push u and (R, U) to stack
20:     end if
21:   end for
22: end procedure
23: procedure RU-IMPROVED( $R_i, U_i$ )
24:   ( $R_{i-1}, U_{i-1}$ ) ← Top value of stack
25:    $RG \leftarrow \frac{(R_i - R_{i-1})}{R_{i-1}} \times 100\%$ 
26:    $UG \leftarrow \frac{(U_i - U_{i-1})}{U_{i-1}} \times 100\%$ 
27:   if ( $RG > 0$  and  $UG > 0$ ) then
28:     return 1
29:   else if ( $RG > 0$  and  $-ULT \leq UG \leq 0$ ) then
30:     return 1
31:   else if ( $UG > 0$  and  $-RLT \leq RG \leq 0$ ) then
32:     return 1
33:   else
34:     return 0
35: end if
36: end procedure

```

4 RESULTS

Section 4.1 presents the results obtained by applying CUBIT and Section 4.2 presents results obtained by applying CUSIT, comparing it with a comparative sizing scheme in literature.

4.1 CUBIT Results

In this section, we present and analyze the results of applying CUBIT algorithm. Table 2 shows the final combination of RE/RUE/UE moves which minimize the (R, U) with different priority constraints. We are able to obtain an excellent enhancement of more than (51%, 76%) in (R, U) across the Baseline NTC 8T-SPUF across all priority constraints. We observe that the optimal combination of biasing techniques for best Reliability and Uniformity is a trade-off. If we favor Reliability (Uniformity), we get 55.8% (82.86%) enhancement in

Figure 5: Improvement in Reliability (Fig. 5a) and Uniformity (Fig. 5b) obtained by different biasing schemes. Individual biasing schemes cannot always address comprehensive improvement in both reliability and uniformity.

Figure 6: Moves to effectively suppress the magnitude and/or variation of the current I_g , which bias a voltage V_B at different terminals of Read Section of 8T-SPUF cell in CUBIT Algorithm.

Figure 7: Suppression of normalized current I_g with different size upscaling factors of CUSIT

R(U). Also, even by only using a single voltage source which eliminates the need of additional low voltage source, we get (54.9%, 76.8%) enhancement in (R, U) as compared to Baseline 8T-SPUF.

4.2 CUSIT Results

In this section, we present the improvement in reliability obtained with CUSIT. As we do not have a sizing technique for 8T-SPUF's quality improvement in literature, we compare CUSIT with a sizing technique [3] demonstrated for 6T-SPUFs which holistically upscales the size of all transistors of SPUF cell targeting V_{th} variation (VCTS- V_{th} Centric Transistor Sizing). For CUSIT, we upscale the size of transistors in write

counterpart relative to the size of transistors in read counterpart, targeting suppression of current I_g . Table 3 shows that reliability improvement with size upscaling is similar in both techniques, achieving improvement in PUC by more than 50% when upscaling factor reaches 5. However, CUSIT vastly outperforms VCTS in terms of comprehensive enhancement of both reliability and uniformity as CUSIT achieves more than 72% enhancement in proximity to ideal uniformity, compared to an insignificant 3% improvement by VCTS. VCTS cannot achieve uniformity improvement because, holistic scaling of all the transistors with a common factor can't reduce the effect of asymmetric current I_g . Hence, it is imperative to deduce that CUSIT is a superior comprehensive technique than VCTS for NTC 8T-SPUFs.

4.3 Overhead Analysis

The techniques in CUBIT can be realized in SPUF array at the granularity of array logic and column. Like most of other circuit level techniques [3], area and power overheads of CUBIT relative to the entire SPUF array is insignificant because the area and power consumed by the SPUF cells hugely dominates the resources consumed by SPUF's array logic [15][3].

For CUSIT, we observe that CUSIT's relative sizing over VCTS's holistic sizing achieves linear savings in transistor's active area and power consumption with size upscaling factors (Table 3). Although overheads in CUBIT increase linearly with upscaling factors (Table 3), we can amortize them with respect to conventional 6T-SPUFs by adopting future technology nodes in design. This is because the size of 8T-SPUFs can be smaller than 6T-SPUFs along the future technology nodes, as 6T-SPUF's further shrinkability with future technology nodes is already limited by their cell stability issues [10, 14].

5 RELATED WORKS

The improvement of SPUFs has been explored in previous works with primary focus on STC operated 6T-SRAM cells. Garg et al. addresses uniformity and reliability improvement by utilizing aging effects, like application of NBTI stress [7]. This technique cannot control the gate leakage current which is primarily responsible for degraded uniformity, in an 8T-SPUF.

Priority	RLT	ULT	Bias Set	PUC(%)			Uniformity(%)			Enhancement (R, U) (in %)
				-40°C	25°C	110°C	-40°C	25°C	110°C	
Reliability Favoring	5%	10%	{RE-RBL, RE-RWL, UE-SGT0.17}	17.4	16.7	17.5	49.09	47.16	43.77	(55.8%, 81.35%)
Uniformity Favoring	10%	5%	{RE-RBL, UE-SGT0.33}	18.8	18.9	18.4	56.50	51.21	44.27	(52.27%, 82.86%)
Single Voltage Source	10%	10%	{RE-RWL, RUE-SGT}	17.8	16.2	17.9	42.29	42.84	44.17	(54.79%, 76.8%)

Table 2: Different (R, U) enhancements over base line NTC 8TSPUF, by application of different priority constraints in the CUBIT algorithm.

Comparative Schemes	Size Upscaling	(Area,Power)	PUC(%)			Uniformity(%)			Enhancement (R, U) (in %)
			-40°C	25°C	110°C	-40°C	25°C	110°C	
CUSIT	Baseline	(1x,1x)	14.8	22.6	39.6	83.27	80.10	73.32	(-, -)
	Relative X2	(2x, 2.15x)	13.3	19.0	30.0	71.02	67.67	63.50	(24.24, 36.79)
	Relative X3	(3x, 3.26x)	13.0	17.7	24.4	65.11	63.04	60.24	(38.38, 54.56)
	Relative X4	(4x, 4.38x)	12.0	15.6	21.1	61.70	60.52	57.89	(46.71, 64.80)
	Relative X5	(5x, 5.51x)	10.7	14.4	19.5	59.09	58.56	56.09	(50.75, 72.67)
VCTS	Baseline	(1x,1x)	14.8	22.6	39.6	83.27	80.10	73.32	(-, -)
	Holistic X2	(1.75x, 2.12x)	9.9	15.0	27.1	82.76	79.31	72.00	(31.57, 1.51)
	Holistic X3	(2.5x, 3.23)	8.4	12.7	21.8	82.88	79.09	71.50	(44.95, 1.16)
	Holistic X4	(3.25x, 4.31x)	6.7	11.2	17.3	82.76	79.29	71.14	(56.31, 1.50)
	Holistic X5	(4x, 5.45x)	6.5	10.4	16.3	82.53	78.67	70.79	(58.83, 2.21)

Table 3: Comparative analysis of Enhancement of Reliability and Uniformity

Chellappa et al. proposes an alternative SRAM cell power-up strategy, by raising the wordline and decoder voltage higher than array voltage [5]. The voltage raise defeats the key purpose of NTC operation. Chang et al. implements sizing strategies to enhance SPUF reliability, but this methodology is flawed at NTC regime [3]. A sub-threshold PUF based on the 10T-SRAM cell, introduced by Kaseem et al., is a suitable low-power solution for secure devices [11]. This parameters of reliability and uniformity have not been addressed at sub-threshold operation for the 10T-SRAM PUF.

To the best of our knowledge, this is the first work which has explored reliability and uniformity characteristics for SPUFs operated at NTC and adopt efficient design strategies to overcome their adverse effects.

6 CONCLUSION

We analyze the various threats to reliability and uniformity characteristics of NTC-operated SPUF. Leveraging the impact of device asymmetry on these characteristics, we improvise current suppression techniques. The principles governing CUBIT and CUSIT schemes are based on biasing and sizing respectively. CUBIT and CUSIT adaptively mitigate the accentuated effects of PV on reliability and uniformity, by giving a comprehensive improvement of more than 82%(55%) in our reliability and uniformity metrics with negligible overheads. Thus, our work embraces on making the SPUF not only more energy-efficient but also, highly robust.

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