Threshold Defined Camouflaged Gates in 65nm Technology for Reverse Engineering Protection

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ABSTRACT

Due to the ever-increasing threat of Reverse Engineering (RE) of Intellectual Property (IP) for malicious gains, camouflaging of logic gates is becoming very important. In this paper, we present experimental demonstration of transistor threshold voltage-defined switch [2] based camouflaged logic gates that can hide six logic functionalities i.e. NAND, AND, NOR, OR, XOR and XNOR. The proposed gates can be used to design the IP, forcing an adversary to perform brute-force guess-and-verify of the underlying functionality—increasing the RE effort. We propose two flavors of camouflaging, one employing only a pass transistor (NMOS-switch) and the other utilizing a full pass transistor (CMOS-switch). The camouflaged gates are used to design Ring-Oscillators (RO) in ST 65nm technology, one for each functionality, on which we have performed temperature, voltage, and process-variation analysis. We observe that CMOS-switch based camouflaged gate offers a higher performance (~1.5 – 8X better) than NMOS-switch based gate at an added area cost of only 5%. The proposed gates show functionality till 0.65V. We are also able to reclaim lost performance by dynamically changing the switch gate voltage and show that robust operation can be achieved at lower voltage and under temperature fluctuation.

CCS CONCEPTS

• **Security and privacy** → **Tamper-proof and tamper-resistant designs**; • **Hardware** → **Combinational circuits**;

KEYWORDS

Reverse engineering, camouflage gate, threshold voltage-defined switch, ring-oscillator.

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1 INTRODUCTION

One of the biggest threats to hardware Intellectual Property (IP) is reverse engineering (RE). RE today has become a powerful tool for IP piracy and counterfeiting. Although techniques such as watermarking and fingerprinting [1] have been used to curb the spread of counterfeit products, they do not increase the complexity of RE itself. RE involves de-packaging the chip, milling down layer-by-layer, take image of each metal layer and stitch the images together to identify the logic functionality and connectivity. The objective is to unlock the IP and clone the design.

Camouflaging is a technique of hiding the circuit functionality of a few chosen gates to make RE impossible or extremely hard [2-10]. Various flavors of camouflaging have been previously proposed (Table-I). The gate camouflaging using hollow vias [4] realizes three functions with a ~5X area and power overhead. Aside from requiring a process change (e.g., hollow via), this technique fails to force the adversary to resort to exhaustive RE. Techniques to deceive the attacker using filler cells [5] and dummy transistors [6] are also proposed. Other obfuscation techniques [7,8] suffer from either extensive signal routing and/or process change. In order to increase the RE difficulty, the threshold voltage (V_T) modulation (implemented by changing channel doping concentration during manufacturing) of switches have been proposed [2,3,10]. A threshold defined switch-based multiplexer is proposed to camouflage interconnects [9]. However, it incurs routing overhead. Table-I consolidates the power delay and area overheads of the proposed methodology along with the previous discussed methods from literature. It must be noted that our proposed design is upsized and is compared to an upsized NAND-gate. We observe a ~33X and ~14X delay overhead between the NMOS-switch based and CMOS-switch based NAND-RO to the reference NAND-RO design. Due to the upsized nature, the power drawn by the two camouflage flavors are 22% and 17% lower than the reference NAND design.

We illustrate two generic gates (detailed in Section 2.2) that can exhibit 6 functionalities based on the V_T of the switches. Unlike the existing camouflaging techniques, the V_T programmable technique does not add process cost and leave no layout clues. Since proposed camouflaged gates are static logic based, they can be easily integrated with the current Electronic Design Automation (EDA) tools to provide a seamless and effective implementation.

In this paper, we present experimental demonstration of the static V_T defined camouflaging technique [2,3] by analyzing each of the six

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Figure 1: (a) V_T programmable NMOS switch. HVT: OFF, LVT: ON. PMOS switch works similarly; (b) The I-V plot for the HVT, NVT and LVT switches biased at $V_{SN} = (HVT+LVT)/2$.

logic functionalities as Ring Oscillators (RO). Two flavors of camouflaged gates are proposed namely, NMOS-switch based, and CMOS-switch based camouflaged gates. *To the best of our knowledge, this is the first experimental demonstration of V_T defined camouflaged gates.*

Adversarial assumptions: The proposed camouflaged gates are effective against common adversaries who have access to, (i) multiple copies of the chip to perform invasive RE, and use as the golden chip, (ii) RE tools e.g., access to high precision optical imaging and X-ray imaging equipment, (iii) partially correct netlist with some camouflaged gates with unknown functionality; (iv) knowledge that 6-functions can be assumed the camouflaged gates; (v) functional simulators and test pattern generators to generate patterns for a specific guess about the hidden gate function and validate their guess by applying the pattern to both golden chip and the netlist with the guessed gate function. We assume that adversary does not have access to expensive equipment to probe I-V characteristics of the individual transistors. Since each camouflaged gate contains 8 V_T defined switches (Fig. 2(a)) and an IP may contain 1-5% camouflaged gates the number of transistors for individual characterization can be prohibitively expensive and time intensive.

Attack Model: The attacker will try all combinations of gate functionalities one-by-one and match the netlist response to validate each guess with the golden chip. With each added camouflaged gate in the design, the brute force attack time will ramp up exponentially. While the transistor threshold voltages are not directly apparent from common RE techniques like delayering and imaging the IC, there are various methods for measuring the channel doping in literature such as, spreading resistance profiling, secondary ion mass spectrometry, scanning capacitance microscopy, kelvin force probing microscopy, and electron holography [11-15]. However, these techniques have limitations in both spatial resolution and accuracy [16-19]. Even if the available techniques could provide needed resolution and accuracy, probing V_T makes the RE process highly sophisticated and more resource intensive. Therefore, economics of RE with V_T probing by sophisticated technique may not be justified for small ad hoc attackers.

The primary contributions of the paper are as follows:

- Demonstrate the V_T defined camouflaging technique for logic obfuscation.
- Analyze the performance of the six logic functions realized as RO using both NMOS-switch and CMOS-switch based camouflaged gates.
- Perform supply voltage, temperature and process-variability analysis since V_T is sensitive to these parameters.
- Demonstrate the tuning of gate biasing of V_T defined switches (using V_{SN} and/or V_{SP}) to not only guarantee the functionality of proposed camouflaged gates, but also reclaim lost performance at low voltages and high temperatures.

The paper is organized as follows: Section II describes the basics of V_T -defined switch, camouflaged gate and relevance in hardware security. Section III and IV presents the test-chip design and experimental results. Conclusions are drawn in Section V.

2 BACKGROUND

2.1 Threshold defined switch [2, 3]

The V_T defined NMOS-switch (Fig. 1(a)) is realized by using an NMOS transistor which is biased with gate voltage V_{SN} ($V_{SN} = 0.5 \cdot (V_{LVT} + V_{HVT})$). The switch conducts when LVT is assigned on it and stops conducting when HVT is assigned. A similar process is adopted for the PMOS switch biased at V_{SP} . Fig. 1(b) highlights the variation of current for HVT, NVT and LVT under various switch gate voltage (V_{SN}). The value of V_{SN} can range from 300-650mV, while the value of V_{SP} ranges from 500-850mV for a V_{DD} of 1.2V. This provides the flexibility to choose between a low-power (high I_{ON} -to- I_{OFF} ratio of $\approx 10^4$) when V_{SN} is low and high-performance mode when V_{SN} is high. The switch is employed to compose multi-function gate whose functionality is selected through V_T assignment.

2.2 Multi-function camouflaged logic

Fig. 2(a) shows the schematic of the proposed camouflaged gate that exhibits 6-functionalities (AND, OR, NAND, NOR, XOR and XNOR) depending on the V_T of switches S1-S8. The switches (S1-S8) of selected (unselected) function are programmed to LVT (HVT) whereas the input and output buffers are programmed using NVT. This design is based on NMOS switch as pass transistor in the

Table 1: Comparative Analysis of Gate Camouflaging Techniques

Feature	Hollow Via [4]	Obfuscation [7,8]	MUX Gate [9]	V_T Dynamic Gates [10]	Proposed NMOS-Switch	Proposed CMOS-Switch
# of fn.	3	Varies	2^{2^m} for $2^m:1$ MUX	2	6	6
Area	3.06X	1.15X	1.15X	4.25X	2.89X **	3.05X **
Delay	1.32X	0.99X	1.48X	11.48X	~33X **	~14X **
Power	3.67X	1.16X	N/A	3.83X	0.78X **	0.83X **
Static / dynamic	Static	Static	Static	Dynamic	Static	Static
Sim/Exp	Sim	Sim	Sim	Sim	Exp **	Exp **

Note: ** experimental comparative analysis of an upsized NAND-RO (as fabricated) for the reference, NMOS and CMOS-based designs.

Note: All other comparisons are performed with respect to a standard NAND gate.

camouflaged logic. For example, a NAND logic can be realized by asserting LVT on switches S2 and S7 and HVT on all other switches. This leads to a parallel connection of PMOS transistors and a series connection of NMOS transistors. The design can be optimized to either low power or high-performance by; (i) appropriately tuning the V_T of the HVT and LVT transistors; (ii) modulating the V_{SN} and V_{SP} voltages; and, (iii) sizing the transistors accordingly. Note that the performance and area of the proposed camouflaged gate is strongly correlated to the resistance of V_T defined switches in the path. *The CMOS-based camouflage logic is achieved by replacing switches S1-S2 and S4-S8 with full-transmission gates (i.e., NMOS and PMOS switches in parallel).* The CMOS-based switch provides full conduction of V_{DD} and GND at the cost of higher design overhead.

2.3 Application in Hardware Security

Due to the overheads incurred (Table 1), the proposed camouflage gates must be used carefully. For example, swapping large gates with camouflaged gates to minimize area overhead, swapping low activity factor gates to minimize power overhead and swapping off-critical path gates to minimize delay overhead. The gates with least controllability and observability are potential candidates to be replaced with camouflaged gates to magnify the RE effort. Therefore, a trade-off exists between the overheads and security (i.e., RE effort). Note that adversary will be able to locate the camouflaged gates due to their unique appearance however, they will not know the functionality. Adversary may also be able to locate the switch gate voltage (V_{SN}/V_{SP}) however, they don't reveal the functionality. Probing of V_{SN}/V_{SP} voltage level will not provide any clue either. V_{SN}/V_{SP} are DC signals and could be routed along with power rail. Unlike power rail V_{SN}/V_{SP} do not drive load. Therefore, the routing overhead could be kept minimal by using thin tracks.

3 TEST-CHIP OVERVIEW

3.1 Design

The proposed camouflaged gates are implemented in ST-Micro 65nm technology. The die-image with the design components (annotated) is shown in Fig. 2(c). Fig. 2(b) shows the block diagram of the test-chip. The design is composed of three sets of 23 stage ring-oscillators (ROs). With one set being the reference (normal gate-based RO), the second set being the only NMOS-based (pass transistor) camouflaged gates and the third set being the full CMOS-based (transmission gate) camouflaged gates. Each set is composed of the six-logic function-based camouflaged RO. For example, the camouflaged gates are configured as NAND gates in the NAND-RO. Buffers are placed in-between each stage of RO to provide optimal swing. Additionally, the above sets (and ROs) are power-gated to ensure only the set being currently used is selected (turned ON). The output of all the sets are MUXed to a single output pin. The V_T switch voltage (V_{SN} and V_{SP}) are generated via a resistance ladder as shown in Fig. 2(b). A total of 8 voltages settings are present for both V_{SN} and V_{SP} , with V_{SN} ranging from 300mV to 650mV and V_{SP} ranging from 500mV to 850mV (for a supply voltage of 1.2V) with a 50mV step. Fig. 3 shows the layout of a standard NAND, NMOS-switch based camouflaged gate and CMOS-switch based camouflaged gate used in the test-chip. *The V_T defined switches are enlarged to reduce process variation induced V_T shift.*

3.2 Test features

We have incorporated power gating for each set along with their corresponding ROs in the design (Fig. 2(b)). This allows us to analyze the power drawn by only by the RO that is currently active. Additionally, a scan-chain implementation (Fig. 2(b)) is employed to correctly assert the necessary control signals and the select signals to

Figure 2: (a) NMOS-switch based camouflaged gate to hide 6 functionalities; (b) schematic overview of the test-chip design with a resistance ladder for generating V_{SN} and V_{SP} voltages; and, (c) die-image of the test-chip.

Figure 3: Layout design of: (a) reference NAND gate, (b) NMOS-switch based camouflaged gate and, (c) CMOS-switch based camouflaged gate (the gates are upsized to counter the ill-effects of process variations).

appropriately choose the required RO with the necessary settings (i.e. V_{SN} , V_{SP}). We have added flexibility to dynamically select V_{SN} and V_{SP} (to tune camouflaged RO frequency) during-test. Thus, allowing us to control the behavior of our ROs, to achieve the best performance.

4 EXPERIMENTAL RESULTS

4.1 Basic setup

The experimental setup is composed of a logic analyzer to feed in the input stream to be scanned in; a high-sampling oscilloscope to accurately analyze the oscillations observed; a dc-power supply and the test-chip (as shown in Fig. 4). The oscilloscope capture of NMOS-switch based NAND camouflaged gate oscillation is also depicted.

4.2 Optimal V_{SN} and/or V_{SP}

The camouflaged switches are controlled by V_{SN} (NMOS) and V_{SP} (PMOS). Fig. 5(a) shows the impact of V_{SN} on the frequency of the NMOS-based camouflaged switch. We note that 500mV is the optimal V_{SN} for the NMOS based switch at 1.2V. This is because 500mV provides the most overdrive for the LVT transistor without turning ON the HVT transistors. Similarly, the oscillation frequency of the CMOS-based switch for different V_{SN} and V_{SP} is shown in Fig. 5(b). From this plot, we observe that 450mV for V_{SN} and 600mV for V_{SP} are the optimal biasing points. In this case, the driving strength of the NMOS and PMOS vary, therefore, the V_{SN} and V_{SP} are not necessarily between their respective HVT and LVT settings.

4.3 Vdd scaling

Fig. 6 (a,b) illustrate the impact of V_{DD} scaling on the NMOS-switch and CMOS-switch based RO. Optimal V_{SN} and V_{SP} are used for obtaining this data. Supply voltage scaling impacts the V_{SN} and V_{SP} of the V_T switches due to the shift in the node voltages of the resistance ladder. Therefore, the oscillations die out at ~650mV V_{DD} . We sweep V_{SN} to 325mV at V_{DD} = 650mV (seen in Fig. 6(c)) and observe that the oscillation frequency increases with the increase in

V_{SN} (bringing it closer to original optimal value). It must be noted that at 325mV both the HVT and LVT NMOS'es are OFF. However, the LVT is 'less' OFF than the HVT, thus resulting in the increase of frequency with the increase in V_{SN} .

Next, we perform a similar analysis for the CMOS-based RO at V_{DD} = 650mV. Fig. 7 illustrates the variation of oscillating frequency with respect to V_{SN} and V_{SP} . The best-case frequency is observed for maximum V_{SN} and minimum V_{SP} i.e. V_{SN} of 325mV and V_{SP} of 250mV. This is due to the fact that at max V_{SN} and min V_{SP} , the LVT NMOS and PMOS are 'less' OFF than their HVT counterparts. We also note that for minimum V_{SN} and maximum V_{SP} , the oscillations fail. The above-mentioned tuning method can be extended to different V_{DD} , providing the necessary flexibility (performance to power) in selecting the bias voltage for a given V_{DD} .

Figure 4: Test setup consisting of (i) the test chip, (ii) a logic analyzer, (iii) an oscilloscope and (iv) a power supply. The oscilloscope capture of RO oscillations of camouflaged NAND gate is also shown.

Figure 5: Frequency variation with respect to (a) V_{SN} – for NMOS-switch (optimal V_{SN} = 500mV) and, (b) V_{SN} + V_{SP} for CMOS-switch (optimal V_{SN} = 450mV and V_{SP} = 600mV).

Figure 6: Frequency variation with respect to (a) VDD for NMOS-switch @ $V_{SN} = 500\text{mV}$, (b) VDD for CMOS-switch @ $V_{SN} = 450\text{mV}$ and $V_{SP} = 600\text{mV}$, and, (c) V_{SN} at 650mV VDD. It must be noted that resistance ladder voltage changes with VDD, thus leading to a smaller V_{SN} step size.

Figure 7: Optimal V_{SN} and V_{SP} for CMOS-switch at 650mV VDD (optimal $V_{SN} = 325\text{mV}$ and $V_{SP} = 275\text{mV}$).

4.4 Process variations

We have analyzed the frequency response of the NMOS-switch and CMOS-switch based camouflaged gates for 10 test-chips (Fig. 8(a)). We observe $\sim 5\%$ variation in the frequency distribution for each function. A 5X to 7X improvement in the speed is observed between the CMOS-switch to the NMOS-switch based camouflaged gates. The designs exhibit less sensitivity to process variation due to the enlarged switch sizes. The experimental results indicate that the proposed gates are robust with respect to process variations.

4.5 Temperature variation

Temperature has a direct impact on the performance of the camouflage gates since V_T is a function of temperature. Fig. 8(b) illustrates the impact of temperature on the oscillation frequency of the NMOS switch-based RO. With the increase in temperature, the transistor's V_T reduces, which correspondingly shifts the HVT and LVT values. If left unchecked, the OFF switches with HVT will turn ON. This in turn will start contending with internal signals and corrupts the functionality. Therefore, V_{SN} and V_{SP} need to be adjusted appropriately to restore the optimal functionality. This is illustrated in Fig. 9, where the device is heated to a temperature of $\sim 65^\circ\text{C}$ and the

V_{SN} bias is swept from 300mV to 650mV to find the optimal bias point for a NMOS-based RO. It must be noted that the V_T of the device reduces by $\sim 2\text{mV}$ for each degree rise in temperature, which would therefore shift the V_T of the device by $\sim 80\text{mV}$ at 65°C . From the experiment, we observe that the optimal V_{SN} bias point has shifted from 500mV at 25°C to 450mV at 65°C . This result indicates that bias voltage can be optimized to counter the effects of temperature. All modern processors include temperature sensors. The temperature and supply voltage combinations can be used to select appropriate V_{SN} and V_{SP} settings for the robust operation of the camouflaged gates.

5 DISCUSSION

5.1 Security Analysis

Although the proposed camouflaging is obtained free of cost due to multi- V_T feature offered in advanced nodes, they are sensitive to temperature which is a vulnerability. The adversary can use temperature to gain insights about the camouflaged gate functionality since each individual gate flavor provide different delay signature with temperature. However, modulation of V_{SN}/V_{SP} of switches under temperature variation can eliminate the side channel signature.

5.2 Integration with EDA tools

The proposed technique adds minimal changes to the EDA flow. First, the standard cell library is modified to include the NMOS-switch based and CMOS-switch based camouflaged gates. This is achieved by creating a liberty file of the above two flavors of camouflage gates. The values used in the liberty file are populated by characterizing the gates in terms of area, delay and power. Then, tools such as, Synopsys dc shell [20] can be employed to perform in-depth design, analysis and synthesis of any combinational logic design that utilized the two flavors of camouflage gates. Finally, appropriate layout files (LEF/GDS) are developed and made available to the physical designers for implementation.

6 CONCLUSION

We demonstrate V_T switches to hide six logic functionalities and proposed two camouflaged gates i.e. NMOS-switch and CMOS-switch based design experimentally. The CMOS-switch offered higher performance with only a minimal increase in area. Biasing knobs i.e. V_{SN} and V_{SP} are used to study the impact on performance with supply voltage scaling and temperature variation and can be tuned dynamically to combat ill effects of temperature, voltage and

Figure 8: (a) Frequency distribution of 10 die for both the NMOS-switch and CMOS-switch based RO; (b) variation of oscillating frequency under change in temperature for an NMOS-switch based RO.

Figure 9: Optimal VSN bias shift under the effect of temperature (65°C).

process variations. The proposed design does not leave any logic or physical level clues, and when used judiciously, improves the overall RE effort.

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