Ultra-Low-Leakage and High-Performance Logic Circuit Design Using Multiparameter Asymmetric FinFETs

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Recently, multigate field-effect transistors have started replacing traditional planar MOSFETs to keep pace with Moore's Law in deep submicron technology. Among different multigate transistors, FinFETs have become the preferred choice of the semiconductor industry owing to low fabrication cost, superior performance, lower leakage, and design flexibility. The back and front gates of a FinFET can either be shorted or remain independent, leading to two modes of operation: Shorted-Gate (SG) and Independent-Gate (IG). For a given mode of operation, the physical parameters of the FinFET can either be symmetric or asymmetric in nature. In this article, for the first time, we analyze multiparameter asymmetric SG FinFETs and illustrate their potential for implementing logic gates and circuits that are both ultra-low-leakage and high-performance simultaneously. We restrict this work to SG devices because IG FinFETs (symmetric/asymmetric) suffer from severely degraded on-current, which makes them unattractive for high-performance designs. We first compare head-to-head all viable single- and multiparameter symmetric/asymmetric SG FinFETs. Among all such FinFETs, the traditional SG (which are symmetric in nature), Asymmetric Workfunction Shorted-Gate (AWSG), and Asymmetric Workfunction-Underlap Shorted-Gate (AWUSG) FinFETs show the most promise. We characterize these devices under process variations in gate length (L_G), fin thickness (T_{SI}), gate-oxide thickness (T_{OX}), gate underlap (L_{UN}), and gate-workfunction (Φ_G) as well as supply voltage (V_{DD}) variations, followed by a gate-level leakage/delay analysis at different temperatures. Although AWSG FinFETs consume very low leakage power, they do suffer from performance degradation relative to SG FinFETs. Similarly, our study reveals that no other single-parameter asymmetric FinFET provides a good combination of low-power and high-performance design. We show that gates/circuits based on AWUSG FinFETs are faster, yet consume much less leakage power and less area than gates/circuits based on traditional SG FinFETs. We observe 53.4% (30.2%) maximum (average) reduction in total power at temperature $T = 348K$ while meeting the same delay constraint, with 14.2% (13.5%) reduction in area for AWUSG circuits relative to SG circuits. At $T = 373K$, we see 68.6% (46.9%) maximum (average) reduction in total power.

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1. INTRODUCTION

FinFETs have recently been adopted as the most viable among the multigate transistor alternatives [Nowak et al. 2004] by most of the leading semiconductor companies at the 22nm technology node and beyond. FinFETs are favored at deep submicron technology nodes primarily because of their tighter control over the channel, thus resulting in low leakage, superior performance, low cost due to seamless transition from the old fabrication process, and design flexibility. FinFETs also offer a plethora of device choices with unique features. This opens up new research opportunities for novel circuit designs.

Both bulk and Silicon-on-Insulator (SOI) FinFETs are being used. In this work, we focus on SOI FinFETs (Figure 1). Such FinFETs have a metal gate that wraps around the thin silicon fin that stands on an insulating base. When a thick spacer material is used at the top, it acts like a double-gate device controlled using both the front and back gates. When the top spacer is not used, the device can be controlled from the top as well and becomes a Trigate device (favored by Intel). Since the FinFET channel is either undoped or lightly doped, the effect of random dopant fluctuations, which is a big concern in bulk CMOS, is mitigated.

In SG FinFETs, the front and back gates are connected at the top (as shown in Figure 1), whereas in IG FinFETs, the top part is etched away, leading to independent front and back gates. SG FinFETs have much higher on-current (I_{ON}), whereas IG FinFETs have much lower off-current (I_{OFF}) but very poor I_{ON} . The back gate of an IG FinFET can be forward (reverse) biased to dynamically change its I_{ON}/I_{OFF} . However, its I_{ON} is still far inferior to the I_{ON} of an SG FinFET.

FinFETs can also be classified as symmetric or asymmetric, independent of their SG or IG modes of operation. Some parameters within the same FinFET that may assume different values are L_{UN} , Φ_G , and source/drain doping (N_{SD}). These devices are called asymmetric. These parameters assume the same value within a symmetric FinFET. We may further classify asymmetric FinFETs as single- or multiparameter asymmetric. In single-parameter asymmetric devices, only one of the parameters takes different values, whereas in multiparameter asymmetric devices, more than one parameter takes nonidentical values. So far, researchers have primarily explored FinFETs with just one of the several parameters being asymmetric, such as AWSG, Asymmetric Doping SG (ADSG), and Asymmetric Underlap SG (AUSG). AWSG FinFETs and logic gates based on them, which are much better placed in the leakage-delay spectrum relative to symmetric SG devices, have shown promise in power/performance optimization of logic circuits, flip-flops, latches, and SRAMs. However, ADSG and AUSG FinFETs have only been explored in the context of SRAM cell design.

FinFETs offer a panoply of choices spanned by SG/IG modes of operation and asymmetric single- and multiparameter devices. They offer very different combinations of I_{ON}/I_{OFF} pairs. However, unless runtime threshold voltage (V_{th}) control is desired or the independent front and back gates are fed separate signals to implement an OR operation, any of the preceding combinations involving an IG FinFET would be much inferior to the corresponding combination involving an SG FinFET in terms of I_{ON} , and hence circuit performance. Thus, in this article, we only characterize various combinations that involve SG FinFETs. It is very important to the semiconductor industry to find transistors that have both high I_{ON} and very low I_{OFF} . We show that some of the preceding combinations offer this possibility.

The key contributions of this article are as follows:

- We characterize all possible symmetric and asymmetric SG FinFETs and compare them head-to-head to establish their relative standing in terms of I_{ON}/I_{OFF} . Although some single-parameter asymmetric devices have been explored in the

Fig. 1. A typical n/p-FinFET device.

context of SRAMs, for the first time, we introduce the concept and importance of multi-parameter asymmetric FinFETs.

- Traditional SG FinFETs (which are symmetric in nature) are known to provide high I_{ON} but at the price of high I_{OFF} . Also, AWSG FinFETs are known to have around 30% lower I_{ON} but with the advantage of two orders of magnitude lower I_{OFF} . Ideally, we would like to work with a transistor that surpasses SG FinFETs in I_{ON} but is competitive with AWSG FinFETs in I_{OFF} . We demonstrate that AWUSG is such a FinFET.
- We thoroughly characterize the sensitivity of SG, AWSG, AUSG, and AWUSG FinFETs (among the various FinFET parameter combinations, these FinFETs stood out) to parametric variations in L_G , T_{SI} , T_{OX} , L_{UN} , Φ_G , V_{DD} , and T . Furthermore, we check the robustness of these devices under the effect of process variations in L_G , T_{SI} , T_{OX} , L_{UN} , and Φ_G , as well as variations in V_{DD} . We then perform leakage-delay analysis of logic gates made of these devices to establish their relative standing in the leakage-delay spectrum at different temperatures.
- Finally, we compare SG and AWUSG FinFET logic circuit implementations to demonstrate significant area/power reductions in the latter at the same delay constraint.

The rest of the article is organized as follows. In Section 2, we review related work. In Section 3, we give a detailed description of different types of FinFETs and characterize various symmetric/asymmetric FinFETs. In Section 4, we analyze logic gates made of single- and novel multiparameter asymmetric FinFETs. In Section 5, we establish the potential of AWUSG devices in optimizing circuit power, area, and performance. Finally, in Section 6, we conclude.

2. RELATED WORK

The promise of multigate transistors has been recognized by the research community and semiconductor industry for some time. Introduction of any new device typically demands attention in areas like fabrication, device modeling, simulation techniques, circuit design, and architectural implementation [Bhattacharya and Jha 2014]. Researchers have already fabricated various types of FinFETs, which include devices operated in both SG and IG modes. Although they have primarily focused on symmetric devices so far, the potential of AWSG FinFETs has been recognized through fabrication in the industry [Kedzierski et al. 2001] and characterization by researchers [Bhoj and Jha 2013]. Researchers have also fabricated and demonstrated the superior performance of AUSG MOSFETs [Ghani et al. 2001; Horiuchi et al. 1994].

Appropriate application of device physics and modeling techniques is very critical for FinFETs owing to their nonplanar structure. The 3D nature of FinFETs also makes

device simulation very CPU intensive. Hence, balancing the accuracy and efficiency of device simulation is a current challenge. To address this problem, in Chaudhuri and Jha [2014a], we proposed an L_{UN} adjustment-based methodology that bridges the accuracy gap between 3D and 2D device simulation even under process variations, thus making FinFET device simulations very efficient without much loss in accuracy.

L_G , T_{SI} , T_{OX} , and Φ_G are considered critical parameters for determining device behavior under process variations [Xiong and Bokor 2003; Mishra et al. 2010]. A response surface-based methodology has been developed to model leakage/delay in FinFET logic gates [Chaudhuri et al. 2012]. The interplay between process-induced and statistical variations has been studied in Wang et al. [2013] and its impact on SRAM stability has been explored further in Wang et al. [2014]. The promise of various FinFET types has motivated researchers to explore their impact at the circuit level to reap power-performance-stability benefits. Thus, leakage-delay tradeoffs based on the SG/IG modes of operation in FinFET circuits have been explored [Chiang et al. 2005; Kumar et al. 2004; Tawfik and Kursun 2007; Mishra et al. 2009]. In Mishra et al. [2009], Ouyang and Xie [2008], Swahn and Hassoun [2006], and Muttreja et al. [2007], gate sizing and multiple supply/threshold voltage methodologies have been shown to be effective at power optimization. The effect of temperature on device/gate leakage current (I_{LEAK}) has been explored in Ananthan and Roy [2006], Choi et al. [2007], and Gu et al. [2008]. The concept of multithreshold FinFETs has been explored for obtaining a better leakage/performance profile [Gaynor and Hassoun 2014] under certain restrictions. Recently, orthogonal to the concept of using multithreshold FinFETs (that use different gate workfunctions in different transistors in the IC), AWSG FinFETs (that use two different gate workfunctions in the same FinFET) have been identified as an ultra-low-leakage device. They enable extremely low power designs, but with some loss in performance. The leakage-delay spectrum of logic gates, latches, and flip-flops based on AWSG FinFETs has been investigated in Bhoj and Jha [2013]. It has been shown that AWSG FinFET-based circuits operating at a higher supply voltage compared to SG FinFET-based circuits consume less total power under the same delay constraint [Chaudhuri and Jha 2014b]. In Bhoj and Jha [2014], AWSG-based SRAM bitcells are shown to be competitive in terms of both dc metrics and dynamic writeability. ADSG and AUSG FinFETs have been proposed and analyzed in the context of robust SRAM design in Goel et al. [2011] and Moradi et al. [2011]. The impact of Gate-Induced Drain Leakage (GIDL) has been investigated for various symmetric and asymmetric FinFETs in Choi et al. [2003]. The impact is shown to be insignificant in digital circuits operating at $V_{DD} < 1.1V$. Electrical characteristics of ADSG FinFETs have been studied in Woo et al. [2002].

In this work, we propose various multiparameter asymmetric FinFETs for the first time. We further compare, analyze, and characterize these novel devices against existing FinFET device options. AWUSG FinFETs emerge from this characterization as the most attractive device from both the I_{ON} and I_{OFF} perspectives. We then show the advantage of AWUSG FinFETs at the logic gate and circuit levels from the area/delay/power perspectives.

3. SYMMETRIC AND ASYMMETRIC FinFETs

In this section, we investigate various symmetric and asymmetric FinFETs operating in the SG mode and compare them head-to-head to explore their potential in optimizing both leakage and performance. We use a Python-based integrated simulation platform from Bhoj and Jha [2013] that connects a Sentaurus TCAD Structure Editor (SE), device simulator, SVisual, and MATLAB to ease data flow among these tools [Synopsys 2011]. In our device-level characterization, we simulate a typical SG nFinFET (as shown in Figure 2) through 3D device simulations. For logic gate-level

Fig. 2. 3D nFinFET device created by SE.

Fig. 3. 2D (X-Y) cross-section of the 3D nFinFET device.

Table I. Typical Symmetric FinFET Device Parameter Values

Parameter (Unit)	Value
L_{GF}, L_{GB} (nm)	20
T_{OXF}, T_{OXB} (nm)	1
T_{SI} (nm)	11
H_{FIN} (nm)	40
H_{GF}, H_{GB} (nm)	24
L_{UN} (nm)	10
F_P (nm)	60
N_{BODY} (cm^{-3})	10^{15}
Φ_G (eV)	nFET: 4.4, pFET: 4.8
N_{SD} (cm^{-3})	10^{20}
V_{DD} (V)	0.9

mixed-mode analysis, we simulate a 2D cross-section (as shown in Figure 3) of the 3D n/p-FinFETs for drastically improved simulation efficiency. The analysis is based on hydrodynamic device simulations, which consider the bandgap narrowing model, Philips-unified model for carrier mobility, and Shockley-Read-Hall and band-to-band tunneling models to accurately capture the effect of carrier recombination [Synopsys 2011].

Table I shows typical physical parameter values of a symmetric SG n/pFinFET at the 22nm technology node, which are calibrated based on data from the foundries [Guillorn et al. 2008; Wu et al. 2010; Yamashita et al. 2011]. In our prior work [Chaudhuri and Jha 2014a], we presented drain-current I_{DS} versus gate voltage V_{GS} curves that are in agreement with the data presented in the literature. Referring to Figure 3, the process parameters are front (back) physical gate length L_{GF} (L_{GB}), fin thickness (T_{SI}), front (back) gate oxide thickness T_{OXF} (T_{OXB}), front (back) gate thickness H_{GF} (H_{GB}), and L_{UN} . W_{NEFF} and W_{PEFF} denote the effective widths of an nFinFET and pFinFET, respectively, and are defined as $2nH_{FIN}$ (where n is the number of fins in the FinFET and H_{FIN} is the fin height) for an SG FinFET (whether symmetric or asymmetric). These effective widths take into account both the front and back inversion channels

Fig. 4. 2D cross-section of an (a) AWSG nFinFET, (b) AUSG nFinFET, and (c) ADSG nFinFET.

that are formed in a typical FinFET. Other device parameters are body doping N_{BODY} , source/drain doping N_{SD} , fin pitch F_P that denotes the minimum distance required between the midpoint of two adjacent fins, and operating voltage V_{DD} .

Among the various physical parameters, Φ_G , L_{UN} , and N_{SD} can potentially assume different values within the same FinFET, giving rise to different asymmetric FinFETs. Hence, for asymmetric FinFETs, we refer to these parameters as front/back gate workfunction (Φ_{GF}/Φ_{GB}), source/drain gate underlap (L_{UNS}/L_{UND}), and source/drain doping (N_S/N_D). FinFETs in which just one physical parameter is asymmetric are classified as single-parameter asymmetric. Examples of such devices are AWSG, AUSG, and ADSG FinFETs, which are shown in Figure 4. On the other hand, FinFETs in which more than one physical parameter are asymmetric are classified as multiparameter asymmetric. Some examples are Asymmetric Gate-Workfunction/Gate-Underlap SG (AWUSG), Asymmetric Gate-Workfunction/Doping SG (AWDSG), Asymmetric Gate-Underlap/Doping SG (AUDSG), and Asymmetric Gate-Workfunction/Gate-Underlap/Doping SG (AWUDSG) FinFETs, as shown in Figure 5. It is possible to adjust the workfunction of the gate material, which determines the V_{th} of the device. For symmetric SG FinFETs (which are the traditional FinFETs), 4.4eV (4.8eV) is chosen as the workfunction for nFinFETs (pFinFETs) to implement high-performance logic. In FinFETs that incorporate asymmetric workfunctions, the front and back gates are associated with these different workfunctions, respectively. Table II shows typical values these asymmetric parameters can take, based on the optimizations performed in Bhoj and Jha [2013], Goel et al. [2011], Moradi et al. [2011], Ghani et al. [2001], Horiuchi et al. [1994], and Woo et al. [2002]. However, note that the exact choice of asymmetric parameter values is orthogonal to the study of FinFET asymmetry, which is the focus of this work. As we will see later, the advantages of

Fig. 5. 2D cross-section of an (a) AWUSG nFinFET, (b) AWDSG nFinFET, (c) AUDSG nFinFET, and (d) AWUDSG nFinFET.

Table II. Asymmetric FinFET Device Parameter Values

Parameter (Unit)	Value
Φ_{GF} (eV)	4.4
Φ_{GB} (eV)	4.8
L_{UNS} (nm)	0
L_{UND} (nm)	10
N_S (cm ⁻³)	10 ²⁰
N_D (cm ⁻³)	10 ¹⁹

asymmetric FinFETs are maintained even when the parameter values are changed within a range.

AWSG FinFETs were originally fabricated and investigated by IBM researchers [Kedzierski et al. 2001]. They fabricated both symmetric and asymmetric devices to

establish the similarity in their fabrication process. Symmetric device fabrication was carried out on a 65nm SOI wafer, topped by a 50nm oxide hard mask. Optical lithography and hard mask trimming were used to define fin layers. A high tilt angle was used to implant extended regions that include multiple wafer twists. On the other hand, asymmetric device fabrication was done on a 120nm wafer along with a 90nm oxide hard mask. The fins were defined using the same procedure that was used in the case of symmetric devices. Likewise, similar techniques were used to implant extended regions and poly gates. Because of the significant similarities in the fabrication processes of symmetric and asymmetric devices, a seamless transition to asymmetric FinFETs is feasible if desired. Researchers have also fabricated and investigated AUSG planar MOSFETs [Horiuchi et al. 1994; Ghani et al. 2001]. Such asymmetric devices can be fabricated by just following conventional planar CMOS fabrication steps.

3.1. Single-parameter Asymmetric FinFETs

In this section, we first analyze the traditional symmetric SG FinFETs in light of device physics to better understand their I_{ON}/I_{OFF} characteristics. We then investigate various single-parameter asymmetric FinFETs—AWSG, AUSG, and ADSG—to look for a FinFET with a better I_{ON} than a symmetric SG FinFET but with a drastically lower I_{OFF} . We perform hydrodynamic mixed-mode 3D device simulations to account for temperature effects using refined meshes optimized for convergence. We ignore gate tunneling effects since the channel is undoped and because gate leakage is negligible due to the use of a relatively thicker oxide made up of high- κ dielectric.

Figure 6 shows the electrostatic potential distribution and electron density within the fin region of an SG nFinFET in the OFF-state ($V_{DS} = 0.9V$, $V_{GS} = 0V$) and in the ON-state ($V_{DS} = 0.9V$, $V_{GS} = 0.9V$). Figure 6(b) clearly shows severe band bending near both the front and back gates, which helps form prominent inversion regions, as can be seen from Figure 6(d), leading to a high I_{ON} . On the contrary, in Figure 6(a), we observe a high potential barrier in the region adjacent to both gates, leaving very little room for a leakage path. However, the potential barrier decreases significantly toward the fin center, enabling a prominent leakage path and giving rise to a high I_{OFF} . We obtained an I_{ON} of $146.16\mu A$ ($76.81\mu A$) and I_{OFF} of $1.83nA$ ($0.11nA$) for the SG nFinFET (pFinFET).

In Bhoj and Jha [2013], AWSG FinFETs and logic gates/latches/flip-flops were thoroughly investigated, demonstrating superior subthreshold behavior and ultra-low leakage. Here, we revisit characteristics and related physics of such devices to better understand their limitations in achieving both very low I_{OFF} and high enough I_{ON} . AWSG FinFETs are fabricated through an adjustment of gate workfunctions on front and back sides using selective implantation. Thus, they have two different workfunctions on the two sides of the gate [Bhoj and Jha 2013]. The same two workfunctions are used on the two sides of both AWSG nFinFETs and pFinFETs to reduce fabrication cost. Hence, in our experiments, both AWSG n/pFinFETs are assumed to have 4.4eV and 4.8eV gate workfunctions, with source/drain doping determining the majority carrier in the ON-state. Use of asymmetric workfunctions leads to a very steep subthreshold slope [Bhoj and Jha 2013]. This results in a very low I_{OFF} but at the price of a slight degradation in I_{ON} . Figure 7 shows the electrostatic potential and electron density in the fin region during the OFF- and ON-states of the AWSG FinFET. In Figure 7(b), we observe a similar band bending as in the case of the SG FinFET. This forms the inversion region adjacent to the gate, as can be seen from Figure 7(d) but is somewhat less severe. This results in a degraded I_{ON} . On the other hand, AWSG gates display superior OFF-state behavior because no prominent leakage path in the fin region (not even in the fin center) is present, as can be seen from Figure 7(c). We obtain a 28.1% (34.7%) lower I_{ON} of $105.12\mu A$ ($50.16\mu A$) and 97.8% (97.3%) lower I_{OFF} of $0.04nA$ ($0.003nA$) for

Fig. 6. Electrostatic potential within the fin region of an SG nFinFET in the (a) OFF-state and (b) ON-state. Electron density within the fin region of an SG nFinFET in the (c) OFF-state and (d) ON-state.

an AWSG nFinFET (pFinFET) relative to the SG nFinFET (pFinFET). Thus, although AWSG FinFETs are wonderfully suited to ultra-low-leakage design, they are not very well suited to high-performance design due to their degraded I_{ON} .

Next, we explore AUSG and ADSG FinFETs, which were proposed in Goel et al. [2011] and Moradi et al. [2011]. AUSG FinFETs have a gate overlap on one side and an underlap on the other side. They can be fabricated using standard FinFET fabrication process steps. However, to introduce an underlap on the drain side, an additional asymmetric spacer formation or tilt ion implantation step is required. An asymmetric spacer can be formed by depositing spacer material on the drain side with a mask on the source side. Further, spacer material can be etched using reactive ion etching [Goel et al. 2011]. Because of this asymmetry, appropriate biasing of these devices is important, yielding different operating configurations for n/p-FinFETs. Maintaining $V_{DS} > 0$ ($V_{DS} < 0$) for the nFinFET (pFinFET) with an underlap on the drain side yields a higher I_{ON} relative to SG FinFETs, with a minor increase in I_{OFF} [Goel et al.

Fig. 7. Electrostatic potential within the fin region of an AWSG nFinFET in the (a) OFF-state and (b) ON-state. Electron density within the fin region of an AWSG nFinFET in the (c) OFF-state and (d) ON-state.

2011]. An SRAM implemented with such FinFETs at the 7nm node has recently been investigated thoroughly [Goud et al. 2015]. Figure 8(b) shows massive band bending, which results in a strong inversion in the fin region, as is evident from Figure 8(d). Figure 8(a) and (c) show the electrostatic potential and electron density in the fin region in the OFF-state. They show a very prominent leakage path in the fin center. Hence, this device is not attractive for low-power design. We obtain a 24.9% (49.0%) higher I_{ON} of $182.55\mu A$ ($114.43\mu A$) and 122.4% (127.3%) higher I_{OFF} of $4.07nA$ ($0.25nA$) for an AUSG nFinFET (pFinFET) compared to an SG nFinFET (pFinFET). This observation shows its potential to be competitive with SG FinFETs if somehow its I_{OFF} could be brought down without compromising much on I_{ON} .

In Moradi et al. [2011], an ADSG FinFET was proposed that uses asymmetric doping on the two sides of the device. Table II shows typical doping values used for this type of FinFET. Maintaining $V_{DS} > 0$ ($V_{DS} < 0$) for an nFinFET (pFinFET) with higher doping

Fig. 8. Electrostatic potential within the fin region of an AUSG nFinFET in the (a) OFF-state and (b) ON-state. Electron density within the fin region of an AUSG nFinFET in the (c) OFF-state and (d) ON-state.

being on the source side yields better results and is, hence, assumed here. Figure 9(d) shows weaker inversion in the ON-state in the fin region relative to the SG FinFET and, hence, a much lower I_{ON} . However, the OFF-state electron density is somewhat identical to that of the SG FinFET. This explains comparable I_{OFF} values. We obtain a 37.1% (32.1%) lower I_{ON} of 91.98 μA (52.19 μA) and 26.8% (27.3%) lower I_{OFF} of 1.34 nA (0.08 nA) for an ADSG nFinFET (pFinFET) relative to an SG nFinFET (pFinFET). The significantly lower I_{ON} makes the ADSG FinFET less competitive for high-performance designs. In addition, although ADSG FinFETs are competitive with AWSG FinFETs in I_{ON} , they are not at all competitive in I_{OFF} .

In Figures 10 and 11, we compare I_{DS} versus V_{GS} characteristics of both n- and p-type single-parameter asymmetric FinFETs and the SG FinFET. Table III summarizes I_{OFF}/I_{ON} results for all these FinFETs (the $1\times$ suffix denotes the fact that the FinFETs have just one fin). We observe that the AUSG (AWSG) FinFET is superior to an SG

Fig. 9. Electrostatic potential within the fin region of an ADSG nFinFET in the (a) OFF-state and (b) ON-state. Electron density within the fin region of an ADSG nFinFET in the (c) OFF-state and (d) ON-state.

FinFET in I_{ON} (I_{OFF}). Thus, if we could combine the I_{ON} advantage of an AUSG FinFET with the I_{OFF} advantage of an AWSG FinFET, we could achieve high performance and low power simultaneously in circuits built with the new FinFET. This motivates us to explore multiparameter asymmetric FinFETs.

3.2. Multiparameter Asymmetric FinFETs

So far, we have considered asymmetries in L_{UN} , Φ_G , and N_{SD} . If we combine such asymmetries in a single FinFET, multiparameter asymmetric FinFETs result (e.g., AWDSG, AWUSG, AUDSG, and AWUDSG). In Table IV, we report I_{OFF}/I_{ON} results of all such n/pFinFETs and compare them to SG FinFETs. In Figures 12 and 13, we compare I_{DS} versus V_{GS} characteristics of all these FinFETs. We observe very low I_{OFF} for AWUSG, AWDSG, and AWUDSG n/pFinFETs. However, only AWUSG FinFETs

Fig. 10. I_{DS} versus V_{GS} of symmetric and single-parameter asymmetric nFinFETs.

Fig. 11. I_{DS} versus V_{GS} of symmetric and single-parameter asymmetric pFinFETs.

Table III. I_{OFF}/I_{ON} of Various Symmetric and Single-Parameter Asymmetric FinFETs

Type	Style	$I_{OFF}(nA)$	% Change	$I_{ON}(\mu A)$	% Change
nFinFET1×	SG	1.83	-	146.16	-
	AWSG	0.04	-97.8	105.12	-28.1
	AUSG	4.07	122.4	182.55	24.9
	ADSG	1.34	-26.8	91.98	-37.1
pFinFET1×	SG	0.11	-	76.81	-
	AWSG	0.003	-97.3	50.16	-34.7
	AUSG	0.25	127.3	114.43	49.0
	ADSG	0.08	-27.3	52.19	-32.1

have competitive I_{ON} with SG FinFETs. The AWSG nFinFET (pFinFET) has similar (11.6% higher) I_{ON} to an SG nFinFET (pFinFET), yet a 94.0% (90.9%) lower I_{OFF} . Thus, this suggests a FinFET that can simultaneously enable high performance and ultra-low-leakage power (and, hence, low overall power). Such an observation can also be explained by understanding the qualitative attributes of AWSG and AUSG FinFETs. We discussed earlier how an imbalance in the gate workfunction leads to a very low I_{OFF} in an AWSG FinFET. Similarly, we also saw how an unequal underlap in an AUSG FinFET effectively increases the supply of carriers in the channel region during the

Table IV. I_{OFF}/I_{ON} of Various Multiparameter Asymmetric FinFETs

Type	Style	$I_{OFF}(nA)$	% Change	$I_{ON}(\mu A)$	% Change
nFinFET1×	SG	1.83	-	146.16	-
	AWDSG	0.03	-98.4	77.88	-46.7
	AWUSG	0.11	-94.0	144.76	-0.1
	AUDSG	3.44	88.0	99.62	-31.8
	AWUDSG	0.07	-96.2	89.79	-38.6
pFinFET1×	SG	0.11	-	76.81	-
	AWDSG	0.001	-99.1	40.62	-47.1
	AWUSG	0.01	-90.9	85.72	11.6
	AUDSG	0.22	100.00	60.82	-20.8
	AWUDSG	0.004	-96.4	52.20	-32.0

Fig. 12. I_{DS} versus V_{GS} of symmetric and multiparameter asymmetric nFinFETs. Fig. 13. I_{DS} versus V_{GS} of symmetric and multiparameter asymmetric pFinFETs.

ON-state, which translates into a very high I_{ON} . Hence, when we combine these two features in an AWUSG FinFET, we get the best of both worlds.

We show the electrostatic potential and electron density distribution of an AWUSG nFinFET in the fin region in Figure 14. Figure 14(b) shows strong band bending in the ON-state, as in an SG nFinFET, which results in a strong inversion near the gate, as evident from Figure 14(d). This explains why the I_{ON} of such devices is competitive

Fig. 14. Electrostatic potential within the fin region of an AWUSG nFinFET in the (a) OFF-state and (b) ON-state. Electron density within the fin region of an AWUSG nFinFET in the (c) OFF-state and (d) ON-state.

with that of SG FinFETs. In addition, Figure 14(c) shows no prominent leakage path in the OFF-state. It possesses an electron density distribution similar to that of the AWSG FinFET. Thus, the AWUSG FinFET combines the benefits of a higher I_{ON} of the SG FinFET with a lower I_{OFF} of the AWSG FinFET.

In Table V, we report V_{th} and subthreshold slope (SS) of all single-/multiparameter asymmetric FinFETs along with those of the SG FinFET. All FinFETs have very good subthreshold characteristics. However, n/p-type AWSG and AWUSG FinFETs have relatively high V_{th} values, which explains their very low I_{OFF} values. We obtain the SS for these devices through regression analysis. We probe the characteristics curve every 10mV in the subthreshold region and then obtain a linear fit. The slope of the linear fit gives us the SS of the device.

Table V. V_{th}/SS of Various Asymmetric n/pFinFETs

Style	$V_{thn}(V)$	$SS_n(mV/dec)$	$V_{thp}(V)$	$SS_p(mV/dec)$
SG	0.27	68	-0.34	69
AWSG	0.42	69	-0.52	70
AUSG	0.27	71	-0.34	72
ADSG	0.27	68	-0.32	66
AWUSG	0.34	66	-0.42	68
AWDSG	0.39	63	-0.42	64
AUDSG	0.26	70	-0.31	68
AWUDSG	0.33	61	-0.40	63

3.3. Sensitivity to Various Parameter Variations

In the previous section, we identified a few winning devices: AWSG (best I_{OFF}), AUSG (best I_{ON}), and AWUSG (best of both worlds). In this section, we investigate the I_{OFF}/I_{ON} sensitivity of these nFinFETs with respect to variations in various parameters: L_G , T_{SI} , T_{OX} , L_{UN} , Φ_G , and V_{DD} (pFinFETs exhibit similar sensitivities). We include SG nFinFETs for the sake of comparisons. Figure 15 shows the sensitivity of I_{OFF} to variations in L_G , T_{SI} , T_{OX} , L_{UN} , Φ_G , and V_{DD} . We observe that I_{OFF} decreases significantly with increasing L_G , L_{UN} , and Φ_G ; increases significantly with increasing T_{SI} ; and is relatively indifferent to variations in T_{OX} and V_{DD} . It is also evident that I_{OFF} is most sensitive to variations in Φ_G and T_{SI} . In Figures 15(e), the x -axis represents different sets of Φ_G values depending on transistor type. For an SG FinFET, values 1 through 5 on the x -axis denote 4.38eV, 4.39eV, 4.40eV, 4.41eV, and 4.42eV, respectively, whereas for other asymmetric FinFETs, they represent a pair of Φ_G values: 4.38/4.78eV, 4.39/4.79eV, 4.40/4.80eV, 4.41/4.81eV, and 4.42/4.82eV, respectively. We assume that both front- and back-gate workfunctions vary in the same direction based on the assumption that they are realized using a similar process recipe.

In Figure 16, we show the sensitivity of I_{ON} with respect to changes in the various parameters. We see that I_{ON} decreases linearly with increasing L_G and L_{UN} , but increases roughly linearly with T_{SI} and V_{DD} . I_{ON} is not very sensitive to variations in T_{OX} and Φ_G .

We also observe that, in the case of I_{OFF} variations, SG and AUSG cluster together, as do AWSG and AWUSG. However, in the case of I_{ON} variations, SG and AWUSG tend to be closer. This is very desirable since it shows that AWUSG FinFETs share the I_{OFF} characteristics of AWSG FinFETs and the I_{ON} characteristics of SG FinFETs under a wide range of parameter values.

3.4. Sensitivity to Temperature Variation

I_{OFF} of FinFETs increases exponentially with an increase in temperature T . Figure 17 shows this trend. However, AWSG and AWUSG FinFETs maintain their relative advantage over SG and AUSG FinFETs even at higher temperatures. I_{ON} does not change much with T . For example, within a wide variation range in T (300–373K), I_{ON} only varies within 10% for all device types considered here.

3.5. Effect of Process Variations

L_G , T_{SI} , T_{OX} , L_{UN} , Φ_G , and V_{DD} have been shown to be the most susceptible to process variations [Xiong and Bokor 2003; Mishra et al. 2010]. In this section, we analyze the robustness of SG/AWSG/AUSG/AWUSG nFinFET1 $\times$ under combined variations in these parameters. We use Sobol sequence-based quasi-Monte Carlo (QMC) simulation [Singhee and Rutenbar 2007], which is known to need several orders of magnitude fewer samples than Monte Carlo simulation to achieve a similar accuracy, for this

Fig. 15. Sensitivity of I_{OFF} to variations in (a) L_G , (b) T_{SI} , (c) T_{OX} , (d) L_{UN} , (e) Φ_G , and (f) V_{DD} .

analysis. Thus, we use QMC simulation to generate 100 sample variation cases with each parameter having a $3 * \sigma / \mu = 10\%$ variation, and we perform 3D hydrodynamic device simulations with these values. We show I_{OFF} and I_{ON} distributions under such variations in Figure 18. We can see that the AWUSG FinFET has reasonable I_{ON}/I_{OFF} spreads relative to the other FinFETs.

4. FinFET LOGIC GATES

In this section, we study leakage-delay characteristics of logic gates built atop the FinFETs characterized in the previous section. We focus on size $1/2 \times$ logic gates. Tables VI and VII show average leakage current (across all input vectors), I_{LEAK} , for the $1 \times$ and $2 \times$ logic gates at 300K temperature. As expected, AWSG and AWUSG FinFET-based $1/2 \times$ logic gates maintain their advantage in this respect, even across temperatures, as seen from Tables VIII, IX, X, and XI. In Tables XII and XIII, we compare the delays of the $1/2 \times$ logic gates. We observe a delay reduction of 15.0% (14.5%), 4.2% (4.8%), and 12.4% (12.5%) for the AWUSG inverter $1 \times$ ($2 \times$), NAND $1 \times$ ($2 \times$), and NOR $1 \times$ ($2 \times$)

Fig. 16. Sensitivity of I_{ON} to variations in (a) L_G , (b) T_{SI} , (c) T_{OX} , (d) L_{UN} , (e) Φ_G , and (f) V_{DD} .

gates, respectively, relative to the corresponding SG FinFET-based logic gates. Thus, AWUSG FinFETs enable both lower delay and a drastic reduction in leakage current. The $1 \times (2 \times)$ inverter, NAND, and NOR gates, respectively, have 1 (2), 1 (2), and 1 (2) fins in all nFinFETs and 2 (4), 1 (2), and 4 (8) fins in all pFinFETs. These configurations were chosen to account for the difference in hole and electron mobility and yield comparable rise/fall delays. This explains why the NAND gate delay is higher than the NOR gate delay. Note that a $2 \times$ NAND gate has only 8 fins (as opposed to 10 fins in a $1 \times$ NOR gate). Thus, a $2 \times$ NAND gate both occupies less area and is faster than a $1 \times$ NOR gate.

5. FinFET LOGIC CIRCUITS

In this section, we evaluate the circuit-level impact of AWUSG FinFETs relative to SG FinFETs. Since AWUSG FinFET-based logic gates are faster, we first obtain the fastest possible circuit implementations based on $1 \times$ logic gates (inverter/NAND/NOR)

Fig. 17. I_{OFF} versus T of the SG/AWSG/AUSG/AWUSG nFinFET.

Fig. 18. (a) I_{OFF} distributions of the SG/AWSG/AUSG/AWUSG nFinFET under process variations, (b) I_{ON} distributions of the SG/AWSG/AUSG/AWUSG nFinFET under process variations.

Table VI. I_{LEAK} Comparisons of $1 \times$ Logic Gates at $T = 300K$

Style	Inverter (nA)	% Change	NAND (nA)	% Change	NOR (nA)	% Change
SG	1.03	—	1.15	—	1.18	—
AWSG	0.02	−98.1	0.03	−97.4	0.03	−97.5
AUSG	2.84	175.7	3.10	169.6	2.53	114.4
AWUSG	0.06	−94.2	0.06	−94.8	0.06	−94.9

Table VII. I_{LEAK} Comparisons of $2 \times$ Logic Gates at $T = 300K$

Style	Inverter (nA)	% Change	NAND (nA)	% Change	NOR (nA)	% Change
SG	2.05	—	2.30	—	2.35	—
AWSG	0.04	−98.1	0.06	−97.4	0.06	−97.5
AUSG	5.67	176.6	6.20	169.6	5.06	115.3
AWUSG	0.12	−94.2	0.12	−94.8	0.12	−94.9

Table VIII. I_{LEAK} Comparisons of $1 \times$ Logic Gates at $T = 348K$

Style	Inverter (nA)	% Change	NAND (nA)	% Change	NOR (nA)	% Change
SG	7.02	—	7.75	—	8.40	—
AWSG	0.21	−97.0	0.23	−97.0	0.28	−96.7
AUSG	16.51	135.2	17.93	131.4	17.93	113.5
AWUSG	0.51	−92.7	0.56	−92.8	0.62	−92.6

Table IX. I_{LEAK} Comparisons of $2 \times$ Logic Gates at $T = 348K$

Style	Inverter (nA)	% Change	NAND (nA)	% Change	NOR (nA)	% Change
SG	14.04	—	15.49	—	16.80	—
AWSG	0.42	−97.0	0.46	−97.0	0.56	−96.7
AUSG	33.03	135.3	35.85	131.4	35.85	113.4
AWUSG	1.01	−92.8	1.12	−92.8	1.24	−92.6

Table X. I_{LEAK} Comparisons of $1 \times$ Logic Gates at $T = 373K$

Style	Inverter (nA)	% Change	NAND (nA)	% Change	NOR (nA)	% Change
SG	15.81	—	17.29	—	19.32	—
AWSG	0.56	−96.5	0.61	−96.5	0.74	−96.2
AUSG	34.69	119.4	37.50	116.9	38.29	98.2
AWUSG	1.31	−91.7	1.42	−91.8	1.58	−91.8

Table XI. I_{LEAK} Comparisons of $2 \times$ Logic Gates at $T = 373K$

Style	Inverter (nA)	% Change	NAND (nA)	% Change	NOR (nA)	% Change
SG	31.62	—	34.57	—	38.64	—
AWSG	1.12	−96.5	1.22	−96.5	1.47	−96.2
AUSG	69.37	119.4	75.00	117.0	76.58	98.2
AWUSG	2.62	−91.7	2.83	−91.8	3.15	−91.8

Table XII. Delay (t_D) Comparisons of $1 \times$ Logic Gates

Style	Inverter (ps)	% Change	NAND (ps)	% Change	NOR (ps)	% Change
SG	5.54	—	9.57	—	6.36	—
AWSG	7.09	28.0	12.88	34.6	8.27	30.0
AUSG	3.71	−33.0	7.22	−24.6	4.63	−27.2
AWUSG	4.71	−15.0	9.17	−4.2	5.57	−12.4

Table XIII. Delay (t_D) Comparisons of $2 \times$ Logic Gates

Style	Inverter (ps)	% Change	NAND (ps)	% Change	NOR (ps)	% Change
SG	2.76	—	4.79	—	3.19	—
AWSG	3.53	27.9	6.43	34.2	4.14	29.8
AUSG	1.86	−32.6	3.60	−24.8	2.30	−27.9
AWUSG	2.36	−14.5	4.56	−4.8	2.79	−12.5

Table XIV. Critical Path Delay for the Fastest Implementation of ISCAS'85 Benchmarks with AWUSG FinFETs

Benchmarks	Critical Path Delay (ps)
c432	660
c499	773
c880	608
c1355	764
c2670	648
c3540	1161
c5315	782
c7552	809

Table XV. Critical Path Delay for the Fastest Implementation of ISCAS'89 Benchmarks with AWUSG FinFETs

Benchmarks	Critical Path Delay (ps)
s510	116
s641	284
s713	300
s820	134
s832	163
s1238	480
s1423	315
s1488	213
s5378	444
s15850	980
s35932	222
s38584	869

built using AWUSG FinFETs (these implementations thus also consume least area). Tables XIV and XV show the critical path delay for implementations of ISCAS'85 and ISCAS'89 benchmark circuits, respectively. Next, we set these critical path delays as timing constraints for synthesis using Synopsys Design Compiler [Synopsys 2011] based on an SG library consisting of $1\times$ and $2\times$ SG FinFET-based logic gates (inverter/NAND/NOR). Note that since SG FinFET-based logic gates are slower, just using $1\times$ logic gates would not be enough to meet the timing constraint.

Table XVI shows results for ISCAS'85 benchmarks. P_D denotes dynamic power. P_{L348} , P_{T348} , P_{L373} , and P_{T373} denote leakage power at 348K, total power at 348K, leakage power at 373K, and total power at 373K, respectively. Although SG implementations meet the timing constraint in all the cases, AWUSG implementations consume 12.0% less area, on average. More importantly, AWUSG implementations also consume 25.6% (41.8%) lower total power at 348K (373K), on average. We report results for ISCAS'89 benchmarks in Table XVII. AWUSG implementations consume 14.5% less area while also consuming 38.2% (50.4%) lower total power at 348K (373K), on average. Since delay is not that sensitive to temperature in FinFET circuits, we ignore this effect. In any case, since an increasing temperature would lead to a similar minor increase in delay for both SG and AWUSG circuits, it is not important to take this phenomenon into account for a comparative analysis.

We can deploy such libraries to higher level architectural simulation tools like FinCANON [Lee and Jha 2014] and McPAT-PVT [Tang et al. 2015] for a complete

Table XVI. SG vs. AWUSG Implementations at Different Temperatures for ISCAS'85 Benchmarks

Benchmarks	Type	V_{DD} (V)	P_D (μW)	P_{L348} (μW)	P_{L373} (μW)	P_{T348} (μW)	% Reduction	P_{T373} (μW)	% Reduction	t_D (ps)	Area	% Reduction
c432	SG	0.9	10.04	6.04	12.82	16.08	-	22.86	-	659.1	3445	-
	AWUSG	0.9	11.29	0.34	0.80	11.63	27.7	12.09	47.1	660	3509	-1.9
c499	SG	0.9	67.13	14.73	31.29	81.86	-	98.42	-	769.8	8710	-
	AWUSG	0.9	71.65	0.77	1.83	72.42	11.5	73.48	25.3	773	8183	6.1
c880	SG	0.9	21.49	13.29	28.24	34.78	-	49.73	-	606.5	7960	-
	AWUSG	0.9	22.83	0.65	1.54	23.48	32.5	24.37	51.0	608	6782	14.8
c1355	SG	0.9	80.40	16.67	35.42	97.07	-	115.82	-	763.6	9826	-
	AWUSG	0.9	72.92	0.75	1.78	73.67	24.1	74.70	35.5	764	8016	18.4
c2670	SG	0.9	46.35	19.94	42.38	66.29	-	88.73	-	646.8	11988	-
	AWUSG	0.9	48.98	1.12	2.65	50.10	24.4	51.63	41.8	648	11384	5.0
c3540	SG	0.9	82.42	38.34	81.54	120.76	-	163.96	-	1161.0	22678	-
	AWUSG	0.9	78.94	1.78	4.23	80.72	33.2	83.17	49.3	1161	18346	19.1
c5315	SG	0.9	129.07	52.17	110.90	181.24	-	239.97	-	781.8	31105	-
	AWUSG	0.9	122.17	2.49	5.89	124.66	31.2	128.06	46.6	782	25552	17.9
c7552	SG	0.9	193.31	75.53	160.51	268.84	-	353.82	-	808.9	43309	-
	AWUSG	0.9	212.13	3.58	8.50	215.71	19.8	220.63	37.6	809	35970	17.0

Table XVII. SG vs. AWUSG Implementations at Different Temperatures for ISCAS'89 Benchmarks

Benchmarks	Type	V_{DD} (V)	P_D (μW)	P_{L348} (μW)	P_{L373} (μW)	P_{T348} (μW)	% Reduction	P_{T373} (μW)	% Reduction	t_D (ps)	Area	% Reduction
s510	SG	0.9	18.85	6.27	13.37	25.12	-	32.22	-	115.5	4273	-
	AWUSG	0.9	25.22	0.32	0.76	25.54	-1.7	25.98	19.4	116	3700	13.4
s641	SG	0.9	6.29	6.96	14.78	13.25	-	21.07	-	283.0	4109	-
	AWUSG	0.9	5.85	0.32	0.76	6.17	53.4	6.61	68.6	284	3525	14.2
s713	SG	0.9	6.09	6.36	13.53	12.45	-	19.62	-	299.8	3838	-
	AWUSG	0.9	5.74	0.30	0.72	6.04	51.5	6.46	67.1	300	3355	12.6
s820	SG	0.9	12.42	8.25	17.58	20.67	-	30.00	-	133.6	5454	-
	AWUSG	0.9	15.08	0.36	0.86	15.44	25.3	15.94	46.9	134	4177	23.4
s832	SG	0.9	10.81	7.79	16.59	18.60	-	27.40	-	162.4	5072	-
	AWUSG	0.9	12.15	0.37	0.88	12.52	32.7	13.03	52.5	163	4184	17.5
s1238	SG	0.9	18.95	16.45	35.03	35.40	-	53.98	-	479.7	10502	-
	AWUSG	0.9	20.78	0.87	2.05	21.65	38.8	22.83	57.7	480	9416	10.3
s1423	SG	0.9	23.60	16.42	34.93	40.02	-	58.53	-	314.8	10284	-
	AWUSG	0.9	22.64	0.76	1.79	23.40	41.6	24.43	58.3	315	8688	15.5
s1488	SG	0.9	90.79	22.54	47.98	113.33	-	138.77	-	212.9	14325	-
	AWUSG	0.9	97.31	1.03	2.44	98.34	13.2	99.75	28.1	213	11271	21.3
s5378	SG	0.9	40.86	31.89	67.85	72.75	-	108.71	-	442.3	19749	-
	AWUSG	0.9	40.99	1.52	3.59	42.51	41.6	44.58	59.0	444	23884	-20.9
s15850	SG	0.9	109.90	85.64	182.23	195.54	-	292.13	-	979.2	53124	-
	AWUSG	0.9	96.11	3.38	7.98	99.49	49.1	104.09	64.4	980	37432	29.5
s35932	SG	0.9	625.24	184.34	393.43	809.58	-	1018.67	-	221.7	125776	-
	AWUSG	0.9	612.60	9.11	21.52	621.71	23.2	634.12	37.8	222	101405	19.4
s38584	SG	0.9	663.29	236.33	502.29	899.62	-	1165.58	-	865.1	146984	-
	AWUSG	0.9	619.25	11.04	26.12	630.29	29.9	645.37	44.6	869	120149	18.3

Process-Voltage-Temperature (PVT) analysis. FinCANON is a comprehensive tool for the power/delay simulation of caches and on-chip networks under PVT variations. Likewise, McPAT-PVT is an integrated framework for power/delay simulations of FinFET processors under PVT variations.

6. CONCLUSION

Although single-parameter asymmetric FinFETs were previously explored in the context of SRAMs, only the AWSG FinFETs were explored in the context of logic circuits. Also, the universe of multiparameter asymmetric FinFETs had not been explored. In this article, for the first time, we performed a thorough analysis of various multiparameter asymmetric FinFETs and discovered AWUSG to be the most valuable for optimizing both performance and leakage. We found that AWUSG FinFETs offer both higher I_{ON} and drastically lower I_{OFF} compared to traditional SG FinFETs. Looking for such transistors has been an important goal of researchers and the semiconductor industry. We analyzed AWUSG FinFETs under process variations and showed they have I_{ON} and I_{OFF} spreads similar to other FinFETs. We then analyzed logic gates based on various promising FinFETs and again found AWUSG logic gates to have the best combined leakage-delay characteristics. We showed that AWUSG circuit implementations consume both less area and significantly less total power relative to SG circuit implementations. The power advantage grows at higher temperatures.

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