Dual Mode Ferroelectric Transistor based Non-Volatile Flip-Flops for Intermittently-Powered Systems

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ABSTRACT

In this work, we propose dual mode ferroelectric transistors (D-FEFETs) that exhibit dynamic tuning of operation between volatile and non-volatile modes with the help of a control signal. We utilize the unique features of D-FEFET to design two variants of non-volatile flip-flops (NVFFs). In both designs, D-FEFETs are operated in the volatile mode for normal operations and in the non-volatile mode to backup the state of the flip-flop during a power outage. The first design comprises of a truly embedded non-volatile element (D-FEFET) which enables a fully automatic backup operation. In the second design, we introduce need-based backup, which lowers energy during normal operation at the cost of area with respect to the first design. Compared to a previously proposed FEFET based NVFF, the first design achieves 19% area reduction along with 96% lower backup energy and 9% lower restore energy, but at 14%-35% larger operation energy. The second design shows 11% lower area, 21% lower backup energy, 16% decrease in backup delay and similar operation energy but with a penalty of 17% and 19% in the restore energy and delay, respectively. System-level analysis of the proposed NVFFs in context of a state-of-the-art intermittently-powered system using real benchmarks yielded 5%-33% energy savings.

CCS Concepts

Hardware → Emerging Technologies → Analysis and design of emerging devices and systems.

Keywords

Check-pointing; FEFETs; Hysteresis; Non-volatile flip-flop.

1. INTRODUCTION

Energy harvesting from ambient sources has been extensively studied as a promising candidate to enable energy autonomous systems. In the near future, it is predicted that a number of systems will be powered using harvested energy including, toxic gas sensors, portable gadgets and medical implants [1-2]. However, scavenged energy from ambient sources such as solar, thermal and vibrations exhibits an erratic nature with intermittent power supply (V_{DD}). Such power failures have a drastic impact on standard CMOS logic, suffering from inefficient reboots and

rollbacks [3]. Therefore, it becomes important to back up the state of a logic system to alleviate the loss in computation progress.

Non-volatile computing is an emerging solution to mitigate computation progress loss due to unexpected power failures [3]. Systematic consistency-aware check-pointing mechanisms have been proposed to avoid data inconsistency and computation errors due to power failures [4]. This is achieved by backing up the states of a circuit such as, on-chip memory, flip-flops (FFs) and registers into an off-chip non-volatile memory (NVM). However, this incurs significant energy/delay overheads due to long distance data transmissions and constrained parallelism. Embedded non-volatile computing is an attractive alternate method to backup the computation states into a local on-chip NVM, eliminating the transmission overheads. Several NVFF designs using memristors [5], magnetic tunnel junctions [6] and resistive RAMs [7] as local non-volatile elements have been proposed with on-demand backup/restore (B/R). However, they may incur area overheads due to the incorporation of a B/R module [6]. Also, high write current during backup increases their power consumption [7]. Ferroelectric (FE) capacitor based designs have also been proposed, utilizing their property of polarization (P) retention in the absence of electric field (E) [8]. However, low distinguishability between their non-volatile states degrades the robustness during restore operation.

The recent advent of ferroelectric transistors (FEFETs) with the possibility to integrate FE in the gate stack of a transistor has led to a new era for logic-memory synergy [9]. Lately, FEFET based NVFFs have been proposed with a potential to overcome the challenges in FE capacitor based designs [10-11]. The innovation stems from utilizing the three-terminal non-volatile transistor to improve distinguishability and simplify the restore operation. However, these designs also contain a B/R module driven by control signals, leading to higher switching energy/delay. Hence, there is a need to optimize the B/R module by exploring new device technologies that leverage the opportunities offered by FE.

To that effect, we propose a dual mode FEFET (D-FEFET) which exhibits a unique characteristic of dynamic tuning between volatile and non-volatile modes. Exploiting such distinct features, we propose 2 variants of energy-efficient NVFF designs (referred to as DNVFF-1 and DNVFF-2). The contributions of this paper are:

- We introduce D-FEFET and extensively explain its characteristics including run-time modulation of hysteresis.
- We utilize D-FEFET in the design of NVFF with fully automatic backup without any B/R module (DNVFF-1), demonstrating significantly lower area and backup/restore energy compared to previous FEFET based NVFF [10].
- We propose another NVFF (DNVFF-2) with need-based backup enabled by compact low power B/R module, showing lower area and backup energy/speed compared to [10].
- We carry out a system-level analysis of the proposed NVFFs for intermittently-powered systems.

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2. MODELING AND CALIBRATION

To evaluate the proposed designs, we employ a SPICE model for FEFETs based on time-dependent Landau Khalatnikov (LK) equations coupled with predictive technology models for the transistor [12]. We perform our analysis for 10nm FinFETs showing the applications of the proposed techniques in scaled technologies. However, considering the fact that some applications may prefer older technologies to optimize leakage, we also analyze our NVFFs in 130nm technology for system-level analysis (as discussed later). For CMOS process compatibility, we use experimental data of $\text{Hf}_{0.7}\text{Zr}_{0.3}\text{O}_2$ with remnant polarization (P_R) = 20 $\mu\text{C}/\text{cm}^2$ and coercive field (E_C) = 1MV/cm [13], to calibrate our model (Fig. 1(a)). The static coefficients (α , β and γ) of the LK equation were extracted from the polarization versus voltage (P - V) loop measured from experiment [13] (Fig. 1(b)). The kinetic coefficient (ρ) was calculated for P switching time of ~100ps [14].

3. DUAL MODE FEFET (D-FEFET)

3.1 FEFET Background

FEFETs are emerging devices [9, 12], in which FE is integrated in the gate stack of a transistor above the dielectric (DE). An optional metal may also be used in between FE and DE layers. The capacitance of FE couples with that of the underlying FET leading to unique characteristics: (i) sub 60mV/decade sub-threshold swing for low power logic [12] and (ii) non-volatile transistor operation (due to P retention in the absence of E) [9]. It has been shown that, by changing the capacitance ratio between the FE and the underlying FET, for instance by varying the FE thickness (T_{FE}), one can operate the FEFETs in the non-volatile (memory) or volatile (logic) mode [15]. Although, static tuning of T_{FE} enables design-time optimization of FEFETs, run-time tuning between memory and logic modes can open new avenues for circuit design. In this work, we propose D-FEFET, which achieves dynamic reconfigurability between the volatile and non-volatile modes.

3.2 Dual Mode FEFET Design

Fig. 2(a) shows the device structure of D-FEFET. It consists of two gate stacks namely *GATE* (FE_G) and *CONTROL* (FE_C). The internal metal (IM) gate in the two stacks is common and serves as the gate of the underlying FinFET. This structure can be realized with minimal changes to the FEFET fabrication process. First, the standard process flow is used to obtain a FinFET with one/two of the fins in the middle etched and the gate stack formed up till the IM. This is followed by FE and gate metal deposition, and a selective etch (enabled by the spacing between two sets of fins) to isolate the two FE stacks. Both the FE stacks have the same T_{FE} . The ratio of capacitance of the FE_G and FE_C stack is $C_{FEG} : C_{FEC} = 2:1$. This is because FE_G is formed on two fins while FE_C is formed on a single fin. Note, D-FEFETs can also be realized using

Figure 1. (a) Calibration of model with experimental P_R and E_C values [13] (b) Extracted FE parameters for the LK model

Figure 2. (a) Proposed D-FEFET with 3 fins (b) D-FEFET realized using planar FET (c) Schematic representation

planar technologies with similar process flow (Fig. 2(b)) leveraging contact over active gate process [16]. Fig. 2(c) shows the equivalent schematic of D-FEFET with the connection of C_{FEG} and C_{FEC} with the underlying FET. Note, our simulations consider the parasitic capacitances between the FE stacks. The role of FE_C is to modulate the modes of operation as explained next.

3.3 Dual Mode FEFET Operation

The control terminal of the D-FEFET interacts with FE_G and the underlying transistor to enable reconfigurability. The internal metal potential (V_{INT}) is designed to be affected to a larger extent by the polarization (P) of the regular gate stack (P_{FEG}) compared to control stack (P_{FEC}) by ensuring $C_{FEG} > C_{FEC}$. Note that because of the presence of the common IM, P_{FEG} and P_{FEC} interact with each other, which yields unique characteristics, as discussed below.

(i) *Non-volatile ('NV') mode*: For the 'NV' mode, we apply control voltage (V_{CL}) = 0. Hence, voltage across FE_C (V_{FEC}) = $-V_{INT}$ and voltage across FE_G (V_{FEG}) = $V_{GS} - V_{INT}$ (where V_{GS} is the gate voltage). Note, since $C_{FEG} > C_{FEC}$, V_{INT} is affected to a larger extent by capacitive coupling of FE_G than FE_C . The coercive voltages (V_C) of the FE are designed (with $T_{FE} < 11\text{nm}$) such that P switching occurs in both the gate stacks, as described below. Let us consider V_{GS} sweep from a negative to positive value and back (with drain voltage $V_{DS} = 0\text{V}$). To start with, application of negative V_{GS} ($= -0.8\text{V}$) yields negative P_{FEG} ($-P$) and negative V_{INT} (Fig. 3(a, c)). In turn, negative V_{INT} yields a positive V_{FEC} (since $V_{FEC} = -V_{INT}$), leading to positive P_{FEC} (Fig. 3(b)). As V_{GS} is increased, P_{FEG} switches to a positive polarization ($+P$) when V_{FEG} exceeds V_C . P_{FEG} switching results in an increase in V_{INT} to a positive value (Fig. 3(c)) due to the capacitive coupling of C_{FEG} . Hence, V_{FEC} ($= -V_{INT}$) becomes negative which yields negative P_{FEC} (Fig. 3(b)). Similarly, during the reverse sweep of V_{GS} , P_{FEG} switches from $+P$ to $-P$, yielding $V_{INT} < 0$, $V_{FEC} > 0$ and $P_{FEC} > 0$ ($+P$). Thus, in the 'NV' mode ($V_{CL} = 0$), FE_G and FE_C always exhibit opposite polarizations. Due to this opposing effect of FE_C , the effect of FE_G on V_{INT} is reduced compared to that in a standard FEFET. Hence, lower $|V_{INT}|$ is obtained in D-FEFETs (Fig. 3(c)). This increases the critical $|V_{GS}|$ for P_{FEG} switching (since V_C of $\text{FE}_G = |V_{GS}| - |V_{INT}|$). As a result, a larger hysteresis is observed in D-FEFETs compared to standard

Figure 3. Polarization of (a) Gate stack, (b) Control stack and (c) Internal metal voltage versus gate voltage. $T_{FE} = 8\text{nm}$; $V_{DS} = 0\text{V}$

FEFETs with two fins (Fig. 3(a)). Note, P_{FEG} (with bi-stability at $V_{GS}=0$ in the 'NV' mode) define the low and high resistance states (LRS/+P and HRS/-P) of the D-FEFET since it influences the channel electrostatics to a larger extent than P_{FEC} .

ii) Volatile ('V') mode: To operate D-FEFETs in the 'V' mode, we apply $V_{CL}=V_{DD}$ (0.8V). Due to positive V_{CL} , P_{FEC} remains at +P for the entire range of V_{GS} ($V_{FEC} > +V_C$ always; Fig. 3(b)). For $V_{GS} < 0$ (-0.8V), $P_{FEG}=-P$ is obtained. This yields negative V_{INT} (despite positive P_{FEC} because $C_{FEG} > C_{FEC}$). As shown in Fig. 3(c), V_{INT} is slightly less negative than the 'NV' mode ($V_{CL}=0V$) due to the effect of the positive P_{FEC} (since $V_{CL}=V_{DD}$). This results in a slightly larger V_{GS} required for P_{FEG} switching from -P to +P (since V_C of $FEG = V_{GS}-V_{INT}$). During the reverse V_{GS} sweep (from positive to negative values), both P_{FEG} and P_{FEC} are +P initially. Hence, V_{INT} is much larger compared to 'NV' mode. In fact, V_{INT} is even larger than FEFETs (inset; Fig. 3(c)) due to $V_{CL}=V_{DD}$ ($P_{FEC}=+P$). A large V_{INT} enables FEG switching from +P to -P at $V_{GS} > 0$ ($V_{GS}-V_{INT} = -V_C$), resulting in the 'V' mode (one stable state at $V_{GS}=0$, Fig. 3(a)).

The application of V_{DS} decreases P [17] and increases V_{INT} , due to the capacitive coupling of drain and IM. This results in shifting of the P - V characteristics towards the right. Fig. 4(a) shows the drain current vs V_{GS} characteristics. Note that for logic design, it is critical to optimize T_{FE} to ensure switching of P_{FEG} from -P to +P occurs within the 0 to V_{DD} window.

The ON current (I_{ON}) of D-FEFET (with $T_{FE}=8nm$) in the 'V' mode shows about 36% increase compared to FinFET (Fig. 4(a)). This is because FEG operates in the negative P - V region [12] in the ON state ($V_{FEG} < 0$, $P > 0$), yielding a voltage step-up action [12] ($V_{INT} > V_{GS}$ since $V_{INT} = V_{GS} - V_{FEG} = 0.84V$; Fig. 3(c)). In the 'NV' mode, the currents at $V_{GS}=0V$ (defining HRS and LRS), exhibit a large ratio ($> 10^5$; Fig. 4(b)), yielding excellent distinguishability.

By utilizing the dynamic reconfigurability between 'V' and 'NV' modes of D-FEFETs, we propose two NVFF designs next.

4. NVFF with AUTO BACKUP: DNVFF-1

4.1 Circuit Design

Our first design (DNVFF-1) features a fully automatic backup operation by virtue of a truly embedded NV element (D-FEFET) in the FF (Fig. 5(a)). This is unlike previous designs [5-8] where the NV element is in a separate B/R module, interfacing the FF via external control signals. (Note, embedding of FEFET in FF is challenging because of the requirement of $V_{GS} < 0$ for P switching). The slave latch is re-designed utilizing two D-FEFETs. The rest of the other devices are standard transistors. One of the D-FEFET is used in the pull-down network (M4) of the feedback path while the other as nMOS (M6) of inverter INV1. The control gates of D-FEFETs are tied together, which can dynamically reconfigure their operation between the 'V' and 'NV' modes as discussed before. The D-FEFETs are used in the 'V' mode for the normal and restore operations, while in the 'NV' mode during backup operation. The

Figure 4. (a) Transfer characteristics of the D-FEFET and 3-fin FinFET. (b) LRS-HRS currents for various T_{FE} in the 'NV' mode.

Figure 5. (a) Schematic of the proposed DNVFF-1 (b) VTC of INV1 (c) Layout of DNVFF-1. #fins for std. nMOS=1; pMOS=2 embedding of D-FEFET affects the Clock-to-Q (C-to-Q) delay and energy consumption of the FF during normal operation since, P switching may not be as fast as standard FETs. To alleviate the effect on C-to-Q, inverter INV2 is employed to bypass INV1 and obtain output Q. Standard FETs are sized considering optimized area and similar C-to-Q delay for rising/falling outputs. All simulations are carried out with FO4 load at Q with input slew rate = 100ps at $V_{DD}=0.8V$ (Transient waveforms in Fig. 6).

4.2 Circuit Operation

(i) Normal Operation: During the normal operation, V_{CL} of the D-FEFETs is driven to V_{DD} to operate them in the 'V' mode, in order to function as a switch (OFF/ON when $V_{GS} = 0/V_{DD}$). Thus, the normal operation of DNVFF-1 is similar to the conventional FF (Fig. 6(b)). Note, the voltage transfer characteristics (VTC) of INV1 shows hysteretic behavior (Fig. 5(b)), exhibiting improved hold stability. P_{FEG} of D-FEFETs switches as per its V_{GS} . Thus, when Q is at V_{DD} , X and XN are at V_{DD} and 0 respectively and FEG of M4 and M6 store +P and -P respectively (Fig. 7(a)). Similarly, when Q is at 0, FEG of M4 and M6 store -P and +P, respectively. Note, using INV2 to bypass INV1 in the C-to-Q path has minimal impact on the delay. However, the energy consumption increases due to P switching. These aspects are discussed later.

(ii) Auto Backup Operation: One of the most appealing features of DNVFF-1 is its automatic backup operation, without the use of external circuitry or signals. This makes it very useful for systems requiring frequent check-pointing. P_{FEG} of D-FEFETs correspond to the storage nodes X and XN, as discussed before. During power

Figure 6. (a) Transient waveforms of DNVFF-1. (b) Normal and Auto-backup operation showing polarization switching (c) 2 step restore operation. The polarizations are normalized with $P_C = 14\mu C/cm^2$ (see Fig. 1(a)). $T_{FE}=6nm$

Figure 7. Slave latch schematic showing (a) Normal Operation (b) Step-1 and (c) Step-2 of restore operation of the state $Q=1$

outage, V_{CL} becomes 0 and the D-FEETs dynamically and automatically change operation from the 'V' to 'NV' mode. This leads to retention of P_{FEG} in M4/M6 corresponding to X/XN. Note, FEG of only one of the D-FEETs undergoes $+P$ to $-P$ switching when power shuts down (to maintain opposite P in FEG and FEC in 'NV' mode; Fig. 3(a, b)). This results in minimal backup energy.

(iii) Restore Operation: Like backup, the restore operation does not require any additional circuitry. Note that the IM gate potential, which stores the information of the resistance state of the D-FEETs (corresponding to X and XN) during the 'NV' mode, is floating. Therefore, over time, gate leakage can lead to discharging of V_{INT} to 0V (HRS). However, it is important to note that P_{FEG} , containing the information of the storage nodes of FF, is still retained [18]. In our analysis, we have considered the worst-case scenario, where V_{INT} discharges to 0V during the 'NV' mode, and propose a two-step restore process. (a) *Step-1:* CLK and V_{CL} are asserted when power supply is restored. V_{DD} of the FF is raised till V_B (0.35V) to bias the gates of the D-FEETs (X and XN) at an intermediate voltage within the hysteresis of the 'V' mode (see Fig. 7(b); Fig. 3(a)). This ensures that P_{FEG} of the two D-FEETs are undisturbed when $V_{CL}=V_{DD}$. However, this step leads to P switching in FEC of the D-FEET whose initial P_{FEC} was $-P$ (because in the 'V' mode $P_{FEC}=+P$ always; Fig. 3(b)). This switching of P_{FEC} to $+P$ leads to charging of V_{INT} to V_R (0.7V) in the D-FEET (Fig. 8(a); Fig. 3(c)). Thus, the D-FEET with initial $P_{FEC}=-P$ ($P_{FEG}=+P$) undergoes V_{INT} restoration (LRS). The D-FEET storing $+P$ in its FEC does not undergo any switching and V_{INT} remains at 0V (HRS; Fig. 8(b)). (b) *Step-2:* After V_{INT} restoration in Step-1, V_{DD} is raised to 0.8V (full V_{DD}) and FF state is restored depending on the resistance states of the D-FEETs. Note, to enhance the robustness to variations, the 'V' mode hysteresis width can be increased by optimizing T_{FE} (Fig. 4(a)). Also note, restore biasing using slow V_{DD} ramp-up has also been employed in [19].

Let us explain the restore operation further considering that Q was at V_{DD} before the power outage. As discussed before, FEG of M4 and M6 store $+P$ and $-P$ respectively during auto-backup. Step-1 includes the assertion of CLK, V_{CL} ('V' mode) and powering V_{DD} to V_B . M1 and M5 turn ON as V_{DD} is powered up (Fig. 7(b)). This switches P_{FEC} of M4 from $-P$ to $+P$ leading to V_{INT} restoration (to $V_R=0.7V$; LRS). V_{INT} of M6 remains at 0V (HRS). During Step-2 (V_{DD} raised till 0.8V), stronger pull-down by virtue of LRS of M4 and M3 keeps the node XN at '0' overcoming the effect of M1, while M5 pulls X to V_{DD} . The large LRS-HRS ratio in D-FEETs along with the cross-coupled action of the slave latch, leads to restoration of

Figure 8. Step-1 of restore operation for V_{INT} restoration when (a) initial $P_{FEC} = -P$ and (b) $P_{FEC} = +P$. $V_B=0.35V$; $V_{DD}=0.8V$

the state $X=V_{DD}$ and $XN=0$ as illustrated in Fig. 7(c). The transient waveforms of the restore operation are shown in Fig. 6(c).

5. NVFF with GATED BACKUP: DNVFF-2

5.1 Circuit Design

We propose another NVFF design, which features need-based backup, and therefore requires an external B/R module to trigger the B/R operations (Fig. 9(a)). Since, backup occurs only when the power is about to go OFF, DNVFF-2 mitigates the large operational energy (E_{OP}) cost incurred in DNVFF-1. DNVFF-2 employs a B/R module with 5 transistors including 2 D-FEETs unlike [10] which uses 8. Transistors M1 and M2 connect the B/R module to the slave latch. M4 and M5 are the D-FEETs which store the states of the FF. Transistor M3 connects the drains of M4 and M5 to ensure P_{FEG} of M4/M5 = $-P$ during the normal operation as explained next.

5.2 Circuit Operation

(i) Normal Operation: During the normal operation (transient waveforms in Fig. 9(b)), M1 and M2 are turned OFF isolating the FF from the B/R module. Thus, D-FEETs have minimal impact on the normal operation of the FF. In the B/R module, M3 is turned ON and V_{CL} is asserted to operate D-FEETs M4 and M5 in 'V' mode. Just before the normal operation (i.e. after the restore operation finishes), one of the D-FEETs is in LRS. By turning ON M3 we ensure that the drains/gates of both the D-FEETs are driven to 0V. With V_{GS} of D-FEETs = 0 and $V_{CL} = V_{DD}$, FEG of M4 and M5 store $-P$ (HRS) (Fig. 3 (a)). Operating D-FEETs in HRS is critical during the initial stages of backup, as discussed next.

(ii) Backup Operation: For backup, M1 and M2 are turned ON with M3 OFF and $V_{CL}=0$ ('NV' mode). At the beginning of backup, both the D-FEETs are in the HRS (as discussed above). Now, depending on the voltages of nodes X and XN, one of the D-FEETs receives $V_{GS}=0$ and the other receives $V_{GS}=V_{DD}$. For

Figure 9. (a) Schematic of the proposed DNVFF-2 (b) Transient waveforms showing normal, backup and restore operations. (c) Layout of DNVFF-2. (d) Normal (e) Backup and (f) Restore (step-2) operations in the B/R module of DNVFF-2. $T_{FE}=6nm$

Figure 10. (a) Backup Delay (b) Restore Delay (c) Backup Energy (d) Restore Energy and (e) Clock-to-Q delay versus V_{DD} . (f) Normalized Operation Energy (w.r.t standard volatile FF) vs Kinetic coefficient (ρ) for DNVFF-1, DNVFF-2 and previously proposed NVFF [10]. Note, we optimize T_{FE} in FEFET (11nm) and D-FEFET (6nm) to equalize the hysteresis width.

example, consider the case where $X=V_{DD}$ and $XN=0$, which brings V_{GS} of M4 to V_{DD} and M5 to 0. This results in M4 switching its state to LRS (+P); while M5 remains in HRS (-P) (Fig. 9(e)). In this manner, the state of the FF is stored as P_{FEG} of D-FEFETs.

To understand why D-FEFETs must be in HRS before backup, let us consider a case when this condition is not met. Let $Q=0$ (i.e., $XN=V_{DD}$ and $X=0$) before backup. If M4 and M5 store LRS (+P) and HRS (-P) respectively at the onset of backup, then this would result in M1 and M4 pulling down XN to a value $< V_{DD}$ (determined by the resistance ratio of M6-M7 and M1-M4). This voltage at XN might not be enough for -P to +P switching in M5, leading to incorrect backup. Therefore, by design, we ensure M4 and M5 are in HRS at the beginning of backup, as described in Section 5.2.i.

(iii) Restore Operation: When power supply is restored, M1 and M2 are turned ON. The restore operation employs the 2-step process similar to DNVFF-1 (see Section 4.2.iii) and exploits large distinguishability in D-FEFETs along with the cross-coupled action of the slave latch to restore the states of the FF (Fig. 9(f)).

6. CIRCUIT ANALYSIS AND RESULTS

In this section, we analyze the proposed DNVFFs and compare them to the NVFF in [10]. Since the design in [11] employs a different mechanism for B/R (independent of FF topology), we focus on comparison with [10] (which uses FEFETs in conjunction with cross-coupled inverter action similar to our DNVFFs).

(i) Layout Analysis: A significant advantage of DNVFF-1 is that the B/R is achieved without any external module. DNVFF-1 (Fig. 5(c)) shows 19% lower area with respect to (w.r.t) [10]. DNVFF-2 employs a B/R module but uses lower number of transistors w.r.t [10] yielding 11% lower area (Fig. 9(a, c)). DNVFF-1 and DNVFF-2 show 16% and 31% increase in area respectively, w.r.t volatile FF. All layouts are drawn considering scalable CMOS rules [20].

(ii) Backup Delay (T_B) and Energy (E_B): Fig. 10(a, c) shows the T_B and E_B of DNVFF-1, DNVFF-2 compared to [10]. Due to automatic backup in DNVFF-1, $T_B \sim 0$ ps. Switching of FE_C during power outage (as explained before) consumes a very little amount of energy leading to 96% lower E_B w.r.t [10]. This is because: (i) only one of the FE_C of D-FEFETs undergoes P switching, (ii) lower capacitance of FE_C compared to FE_G and (iii) no external signal switching. DNVFF-2 also has an average of 16% and 21% lower T_B and E_B respectively, over a range of V_{DD} . This is attributed to only one FE switching unlike two in [10] (Section 5.2.ii).

(iii) Restore Delay (T_R) and Energy (E_R): The energy and delay comparison in the restore operation is shown in Fig. 10(b, d). The average decrease in E_R over a range of V_{DD} for DNVFF-1 is around 9%. This is because of the lower number of switching control signals required in DNVFF-1 due to the absence of an external B/R module. E_R of DNVFF-2 is 17% higher because of P switching in the FE_C , which is absent in [10]. T_R of DNVFF-1 and DNVFF-2

increases by 19%, which is attributed to the two-step restore operation. Higher T_R incurred might not be much of a concern for intermittently-powered systems, which operates at $\sim$ MHz

(iv) Clock-to-Q delay (T_{CLK-Q}) and Operation Energy (E_{OP}): T_{CLK-Q} of DNVFF-1 is 20% lower w.r.t [10], because of the higher capacitance at XN of [10] due to the B/R module. T_{CLK-Q} of DNVFF-2 is lower by 11% w.r.t [10] due to lower B/R module capacitance (Fig. 10(e)). Compared to volatile FF, T_{CLK-Q} of DNVFF-2 is similar but that of DNVFF-1 is lower. This is because, transition at XN and Q of DNVFF-1 occurs before P_{FEG} switching in M6. Before P switching, D-FEFETs exhibit lower capacitance (slope of P -V) than standard FETs, which reduces the delay. E_{OP} of DNVFF-1 includes P switching energy of D-FEFETs, resulting in a 35% E_{OP} increase (for kinetic coefficient $\rho=2.5ohm\text{-}cm$) w.r.t [10]. The E_{OP} overhead can be mitigated by employing FE with lower ρ (Fig. 10(f)). Recent experiments [14] show promising trends in this regard. For $\rho=0.25ohm\text{-}cm$, E_{OP} penalty reduces to 14%. DNVFF-2 overcomes the E_{OP} overheads of DNVFF-1 with no P switching during normal operation, achieving E_{OP} similar to [10] and volatile FF (Fig. 10(f)).

7. SYSTEM-LEVEL EVALUATION

7.1 Simulation Methodology

To evaluate the system-level energy benefits of the proposed DNVFFs in the context of an intermittently-powered system, we use a modified version of the simulation framework presented in [4, 19]. Our system-level analyses are based on the TI MSP430FR5739 MCU that runs at 24MHz [21], and uses a unified FEFET based 8KB 4T NVM [22]. NVFFs are used for designing the core registers (Fig. 11(a)). The system is powered using an energy-harvesting source that charges a supply capacitor, C_s (10nF or 100nF). Note that, circuit results for the NVFFs shown earlier were for scaled technology (FinFETs). However, for compatibility with the TI MSP430 MCU, we re-design the D-FEFETs at 130nm node (planar). The circuit-level energy/delay metrics of 130nm node (Fig. 11(b)) show trends similar to FinFETs explained in Section 6.

7.2 Results and Observations

Here, we compare application-level energy consumption for DNVFF-1, DNVFF-2, NVFF [10] and a standard volatile FF (STD), by running various synthetic and real benchmarks.

Figure 11. (a) MCU Core Registers mapped to NVFF (b) energy/delay metrics of NVFFs at 130nm. LP: Leakage Power

Figure 12. Normalized core register energy consumption of different NVFFs for synthetic benchmarks. The energies are normalized with (a) STD and (b) NVFF [10] energies.

(i) *Synthetic Benchmarks:* Since, the energy benefits of using DNVFF-1, DNVFF-2 and NVFF [10] depend significantly on the number of system checkpoints (assumed to be hardware triggered) during application execution, we construct a synthetic benchmark with 25% of all instructions to be register reads, 25% to be register writes, and 50% to be memory bound instructions. In addition, we also vary the number of checkpoints (#Ckpts) while keeping the checkpoint size (256 bytes) and total number of instructions (100K) constant (results in Fig. 12). Note that, in Fig. 12(a) and (b), the energies are normalized w.r.t the energy consumed by STD and NVFF [10], respectively. In Fig. 12(a), we observe that as #Ckpts increase, the energy savings with NVFFs increase rapidly compared to the STD. This is because, the cost of check-pointing the core registers to the unified NVM (includes writing into NVM and serial transfer of checkpoint data) is orders of magnitude higher than the energy required to locally checkpoint in NVFFs. As a result, DNVFF-1, DNVFF-2 and NVFF [10] outperform STD FF (59%–99% better in energy consumption). From Fig. 12(b), we observe that for a small #Ckpts, DNVFF-1 performs worse than either DNVFF-2 or NVFF [10] due to its relatively larger E_{OP} . However, as #Ckpts increase, the overall energy consumption of DNVFF-1 starts to decrease w.r.t DNVFF-2 and NVFF [10], because check-pointing energy of DNVFF-1 is substantially lower than that of DNVFF-2 and NVFF [10]. W.r.t NVFF [10], DNVFF-1 energy savings range from 23% worse (#Ckpts=4) to 34% better (#Ckpts=2048). On the other hand, the energy savings for DNVFF-2 are always better than NVFF [10] by 9%–25%. At lower #Ckpts (<512), DNVFF-2 performs better than DNVFF-1 due to the former’s lower E_{OP} . However, at high #Ckpts (>512), DNVFF-1 begins to outperform DNVFF-2.

(ii) *Real Benchmarks:* For real application benchmarks [18], we observe that DNVFF-1, DNVFF-2 and NVFF [10] showcase 99% and 98% energy improvements compared to STD on average for $C_s = 10\text{nF}$ and 100nF respectively, which is consistent with our observation earlier. Fig. 13 shows the core register energy savings (normalized to NVFF [10]) achieved by DNVFF-1 and DNVFF-2 using real benchmarks. Fig. 13(a) demonstrates energy savings for DNVFF-1 and DNVFF-2 of 33% and 25% on average respectively, w.r.t NVFF [10] for $C_s = 10\text{nF}$. Fig. 13(b) shows that DNVFF-1 and DNVFF-2 obtain 5% and 16% average energy savings respectively,

Figure 13. Normalized core register energy of different NVFFs for real benchmarks using (a) $C_s = 10\text{nF}$ and (b) $C_s = 100\text{nF}$

w.r.t NVFF [10] for $C_s = 100\text{nF}$ (the savings are lower because, a larger capacitor leads to fewer checkpoints).

8. CONCLUSION

We propose D-FEFET, a specially designed FEFET, with a unique property of dynamic tuning between the volatile and non-volatile modes of operations. Based on their intriguing properties, we propose two variants of NVFF designs. DNVFF-1 shows a complete automatic backup feature without the need of any external module, leading to lower backup/restore energy compared to NVFF in [10]. DNVFF-2 mitigates the operational energy costs of DNVFF-1 with improved backup energy/delay metrics compared to NVFF in [10]. Finally, we analyzed the system level implications of the DNVFFs showing a large promise for intermittently-powered systems.

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