

# A ReRAM-Based Nonvolatile Flip-Flop With Self-Write-Termination Scheme for Frequent-OFF Fast-Wake-Up Nonvolatile Processors

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**Abstract**—Nonvolatile flip-flops (nvFFs) enable frequent-off processors to achieve fast power-off and wake-up time while maintaining critical local computing states through parallel data movement between volatile FFs and local nonvolatile memory (NVM) devices. However, current nvFFs face challenges in large store energy ( $E_S$ ) and long voltage stress time on the device ( $T_{STRESS}$ ), due to wide distribution in the write time of NVM device as well as unnecessary writes. Moreover, heavy parasitic load on the power rail cause long wake-up time for restoring data from NVM to FFs. This paper proposes the resistive RAM (ReRAM)-based nvFF with self-write termination (SWT) and reduced loading on power rail to: 1) reduce 93+% waste of  $E_S$  from fast switching or matched cells; 2) suppress endurance and reliability degradation resulted from overprogramming and long  $T_{STRESS}$ ; and 3) achieve reliable and 26+ times faster restore operation compared with previous nvFFs. We have fabricated a nonvolatile processor and a test chip with SWT-nvFFs using logic-process ReRAM in a 65-nm CMOS process. Measured results show sub-2-ns termination response time and sub-20-ns chip-level restore time.

**Index Terms**—Flip-flop (FF), nonvolatile logic, nonvolatile processor (nv-Processor), resistive RAM (ReRAM).

## I. INTRODUCTION

**D**ESPITE the ever-increasing demand for energy efficiency, standby power continues to increase as dimensions scale. Long operational lifetime and rapid, reliable recovery are essential in ultra-low energy applications, such as smart mobile devices, wearable devices, wireless sensor networks, and the Internet of Things. Employing nonvolatile memory (NVM) to retain system states and using power-OFF is a common approach for extending the lifetime of a device through eliminating standby power. During this period, data

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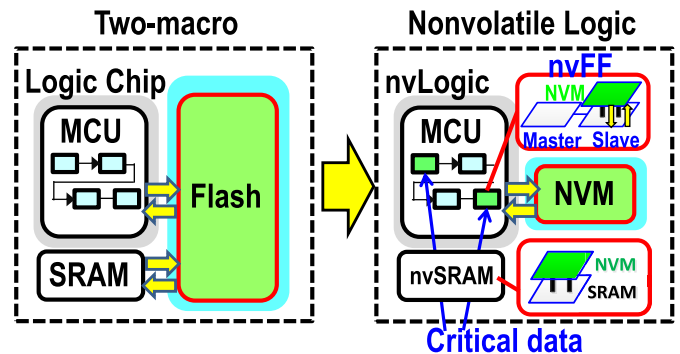


Fig. 1. Conceptual view of conventional two-macro solution versus nonvolatile logics.

in on-chip SRAM and flip-flops (FFs) are moved to the NVM macros to ensure system stability after power interruption [1]–[5]. However, this MCU + NVM two-macro approach results in great overhead in delay, energy, as well as system complexity during the store (power-OFF) and restore (wake up) operations, especially from registers distributed across the processors that do not allow random access. These overheads greatly degrade the standby-power reduction of the two-macro approach and thus result in long break-even time (BET).

Recent advances in CMOS-compatible NVM devices have led to the development of nonvolatile logics [2], [6]–[16], which merges NVM into CMOS circuitry in FFs, SRAMs, or TCAMs to enable parallel data movement between NVM devices and volatile storage elements for fast, local, and low-energy store/restore operations. Fig. 1 shows the comparison of an energy-efficient system using the two-macro approach and a system employing nonvolatile logic.

The application of each different emerging NVM has trade-offs. Ferroelectric RAM (FeRAM) [6], [7], [17], [18] has the advantage of low write energy, but suffers from small restore margins and large device area. Magnetic RAM (MRAM) [8], [19], [20] has high endurance, fast write time, but suffers from small tunneling magnetoresistance ratios (TMRs) and extremely low resistances. Phase change memory [21]–[23] has a large resistive ratio ( $R$ -ratio), yet high programming current density and heating issues limit its usage inside processors. Resistive RAM (ReRAM) [24]–[27], [37] has a

low manufacturing cost, acceptable write power, and high resistance ( $R$ )-ratio ( $R$ -ratio =  $R_{HRS}/R_{LRS}$ ) between high- $R$  (HRS,  $R_{HRS}$ ) and low- $R$  (LRS,  $R_{LRS}$ ) states. However, its physical mechanisms results in slightly worse endurance and variation.

Nonvolatile FFs (nvFFs) [6]–[8] have been proposed to store critical local computing states with faster power-OFF and wake-up time than conventional two-macro approach for frequent-OFF processors. Previous nvFFs employ the worst case programming conditions (Write Time— $T_{STORE\_MAX}$ , Voltage— $V_{STORE\_MAX}$ , and Current— $I_{STORE\_MAX}$ ) to ensure switching of the tail NVM devices. Unfortunately, many NVM devices have wide distribution in write time. Moreover, small signal ratio ( $C$ -ratio, TMR, and  $R$ -ratio) requires assist scheme for restore operations. Thus, previous nvFFs have faced the following challenges:

- 1) excessive waste of store energy in fast-switching, over-programmed, and matched cells, where a “matched cell” refers to a cell with NVM devices already in the same state as the to-be-written data;
- 2) degraded resistance ratio, endurance, and reliability as well as low  $R_{LRS}$  ( $R_{LRS\_MIN}$ )-induced write failure due to long  $T_{STRESS}$  and overwrite of fast-switch and matched cells;
- 3) long wake-up time and large wake-up power due to excessive capacitive loading [6], [7] or dc-current [8] on the power rail in order to achieve high restore yield. Details of the above-mentioned challenges will be discussed in Section II.

The remainder of this paper is organized as follows. Section II provides background information related to nvFF. Section III describes the proposed self-write-termination (SWT)-nvFF circuit and operations. Section IV analyzes the energy performance of the SWT-nvFF cell and addresses concerns regarding reliability and overhead. The full-system implementation, measured results, and comparison to previous works are also given in this section. Finally, the conclusions are drawn in Section V.

## II. BACKGROUND

### A. Operation of Employed ReRAM Device

To prevent excessive waste of energy, nonvolatile processors (nv-Processors) only execute store and power-OFF during long standby periods, whereas dynamic voltage scaling and multiple-power domains [4], [5] are more efficient for short standby periods. Most normally OFF devices are activated only a few times every few hours or one time per day. On the other hand, the restore operation must be fast and reliable for event-driven computing. The endurance requirements of the NVM device are not particularly strict; however, a sufficient ON-OFF ratio is required to overcome offset in the CMOS latches caused by process variation. ReRAM devices are promising candidates for nv-Processors, due to their high  $R$ -ratio, relatively low write current, sufficient endurance, and low manufacturing cost.

To achieve high density and reduce the cost of manufacturing, this paper employed a TiN-TiON-based contact-ReRAM sandwiched between the first metal and n+ diffusion

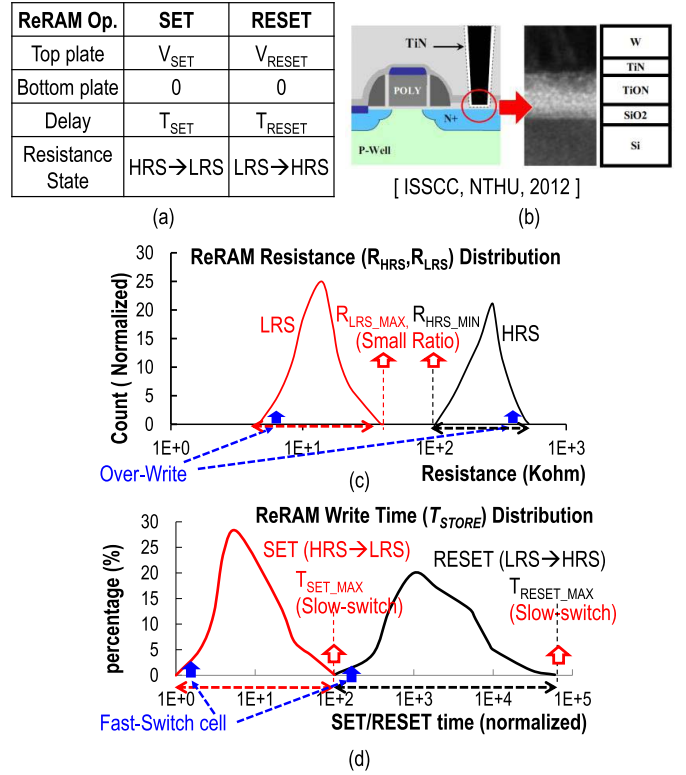


Fig. 2. Characteristics of employed ReRAM device. (a) Operation conditions. (b) Device structure. (c) Resistance distribution. (d) Programming time distribution.

region inside a contact hole [24]. Contact ReRAM eliminates the need for an additional connection from the top metal to the lower metal circuitry, as required for conventional ReRAM placed between high metal layers. Fig. 2 presents the characteristics of the unipolar ReRAM device employed in this paper. The endurance of the employed ReRAM device can exceed  $10^6$  cycles without a significant shift in resistance, and the minimum  $R$ -ratio exceeds 4. The ReRAM device stores data in two resistive states: low resistive state (LRS) and high resistive state (HRS). The SET operation switches the ReRAM resistance to  $R_{LRS}$  by applying voltage of  $V_{SET}$  for the duration of  $T_{SET}$ . The RESET operation switches the device back to  $R_{HRS}$  by applying voltage of  $V_{RESET}$  for the duration of  $T_{RESET}$ . As with most NVM devices, the  $T_{SET}/T_{RESET}$  and  $R_{HRS}/R_{LRS}$  of the ReRAM vary considerably [28]–[30] due to process variations.

### B. Challenges in Application of Nonvolatile Flip-Flop

1) *Energy and Reliability Concerns:* In NVM macros, error-correction code (ECC) blocks are used to deal with write failure caused by insufficient  $T_{STORE}$  in slow-switch cells. However, due to the data path and the area of FFs, nvFF cannot afford the overhead of using ECC and must, therefore, employ the worst case  $T_{STORE}$  ( $T_{SET\_MAX}$  and  $T_{RESET\_MAX}$ ) to ensure successful write of all NVM cells.

For fast-switching cells that switch before  $T_{STORE\_MAX}$  (shorter  $T_{STORE}$ ) or match cells that do not need switching, the SET/RESET biases are continuously applied to the cell despite the cell already being in the LRS/HRS states.

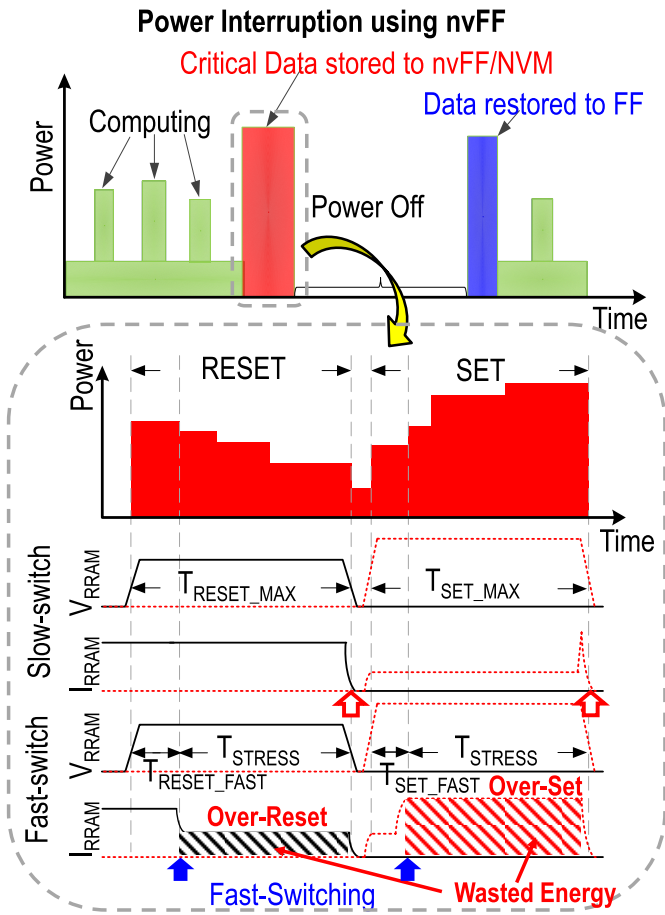


Fig. 3. Voltage and current waveforms across the RRAM device during store operations.

Applying the longest  $T_{STORE}$  to these cells wastes power and the long  $T_{STRESS}$  results in over-SET/over-RESET. The over-SET [31], [32] behavior makes HRS cells switch to LRS with ultra-low  $R_{LRS}$ , resulting in subsequent RESET failure due to insufficient bias across the ReRAM device under given RESET conditions. The over-RESET [33], [34] behavior makes an HRS cell suffer degraded reliability and subsequent SET failure. These issues, as shown in Fig. 3, have become increasingly severe as variations increase with device dimension scaling.

By terminating the NVM-write biases when an NVM cell reaches its target  $R_{HRS}/R_{LRS}$ , write termination (WT) provides an effective way to overcome challenge (1) in a memory macro [25], [26], [35]. However, the large area overhead for the conventional operational amplifier-based WT [26] scheme for memory application prevents it from being applied to nvFFs. Thus, there is a need of efficient self-WT (SWT) scheme with reduced area overhead for nvFFs.

2) *Restore Performance Concerns*: An insufficient difference (or ratio) between the ON- and OFF-states of the NVM device may lead to restore failure when this margin fails to overcome the mismatch of the latch pair due to process variations in transistors.

To achieve higher restore yield, FeRAM-capacitor-based nvFFs need to increase restore margins through assist methods.

Charge-dump-nvFF [6] dump charges from large-capacitance FeRAM cells ( $\sim 380$  fJ/cell) into small-capacitance storage nodes ( $\sim 10$  fJ) of a CMOS latch, which increases the voltage difference of  $Q$  and  $QB$ . Differential-cap-nvFF [7] uses two FeRAMs on each storage node (i.e., four FeRAM/Cell) to increasing the restore margin by  $2\times$  through capacitance division. In equalization-nvFF (EQ\_nvFF) [8], the slave latch is equalized during restore to decrease the effect of PMOS mismatch. Thus, previous nvFFs suffered from long power-rail ( $V_{DD\_FF}$ ) ramp-up times ( $T_{VDDFF\_RMP}$ ), due to a large capacitive or current load (dc-short caused by the latch-equalization) on  $V_{DD\_FF}$ . Table I shows an overview of previous silicon verified nvFFs.

### III. PROPOSED SELF-WRITE-TERMINATION NONVOLATILE FLIP-FLOP

This paper presents an SWT-nvFF using the intrinsic positive feedback of the slave latch to achieve fast and reliable termination at a compact area. To shorten the system wake-up time and restore energy when the number of nvFF in a chip is large, the NVM devices are decoupled from the power rail.

#### A. Structure of the SWT-nvFF

Fig. 4 presents the schematic and operation of the proposed SWT-nvFF, comprising a master latch (M-Latch), a dual-mode slave latch ( $M0$ - $M1$  and  $M2$ - $M3$ ), and an NVM-control unit (NVMCU). The NVMCU comprises two NVM devices (RL and RR), two isolation transistors ( $M6$  and  $M7$ ), two dual-mode switches ( $SW1$  and  $SW2$ ), store/restore polarity selectors ( $M10$  and  $M11$ ), a self-termination circuit for RESET ( $M8$ - $M9$  and  $M12$ - $M14$ ), and a self-termination bias circuit for SET ( $M4$ - $M5$ ). The SWT-nvFF has three modes: FF, store (NVM-write), and restore (wake up). In the FF mode, the dual-mode switches  $SW1$  and  $SW2$  are ON to connect  $M0$ - $M3$  to form a cross-coupled latch, as in a typical FF. Under RESET = 0, a lack of voltage stress on RL/RR enhances the reliability of NVM devices. Store operations (including RESET and SET phases) move data from the slave latch into the NVMs before power-OFF, and restore operation loads the data from the NVMs back into the slave latch at power-ON.

#### B. Store Operation—RESET

Fig. 5 presents the Store-RESET operation. At the start of the RESET operation (STOREB = 0 and RESET = 1), RST\_FB is high to form a resistive division path between  $M10$ ,  $M14$ , and RL- $M8$ /RR- $M9$ . The selection of RL- $M8$  or RR- $M9$  path is determined by the data at  $Q/QB$ .  $M12$ - $M13$  then detects the voltage at node NX ( $V_{NX}$ ) and generates feedback bias (RST\_FB) for the write driver ( $M14$ ). RR is selected when  $Q = 0$ . If RR is LRS (mismatch), then the drop in  $V_{NX}$  turns ON  $M12$ , such that RST\_FB = 1 and  $M14$  remains ON to provide RESET current ( $I_{RESET}$ ). When the RR switches from an LRS to HRS, an increase in  $V_{NX}$  lowers RST\_FB, which further raises  $V_{NX}$ . Positive feedback

TABLE I  
PREVIOUS WORKS ON nvFFs EMBEDDED IN nv-PROCESSORS

Name	Charge-Dump nvFF [6]	Differential-cap nvFF [7]	Equalization-nvFF [8]	This work
Schematic				
NVM Device	FeRAM	FeRAM	MTJ	ReRAM
CMOS Technology	130nm	130nm	90nm	65nm
Additional Devices	22T+2C	18T+4C	18T+2MTJ	15T+2R
Write Termination	No	No	No	<b>Yes</b>
Restore Method	Charge-dump to storage node	Capacitance division	Latch-equalization + R-discharge-CVSS	R-pulldown storage node
Bottlenecks for Restore margin	Charge amount and charge difference	Capacitance Ratio	R-ratio (TMR-ratio)	R-ratio

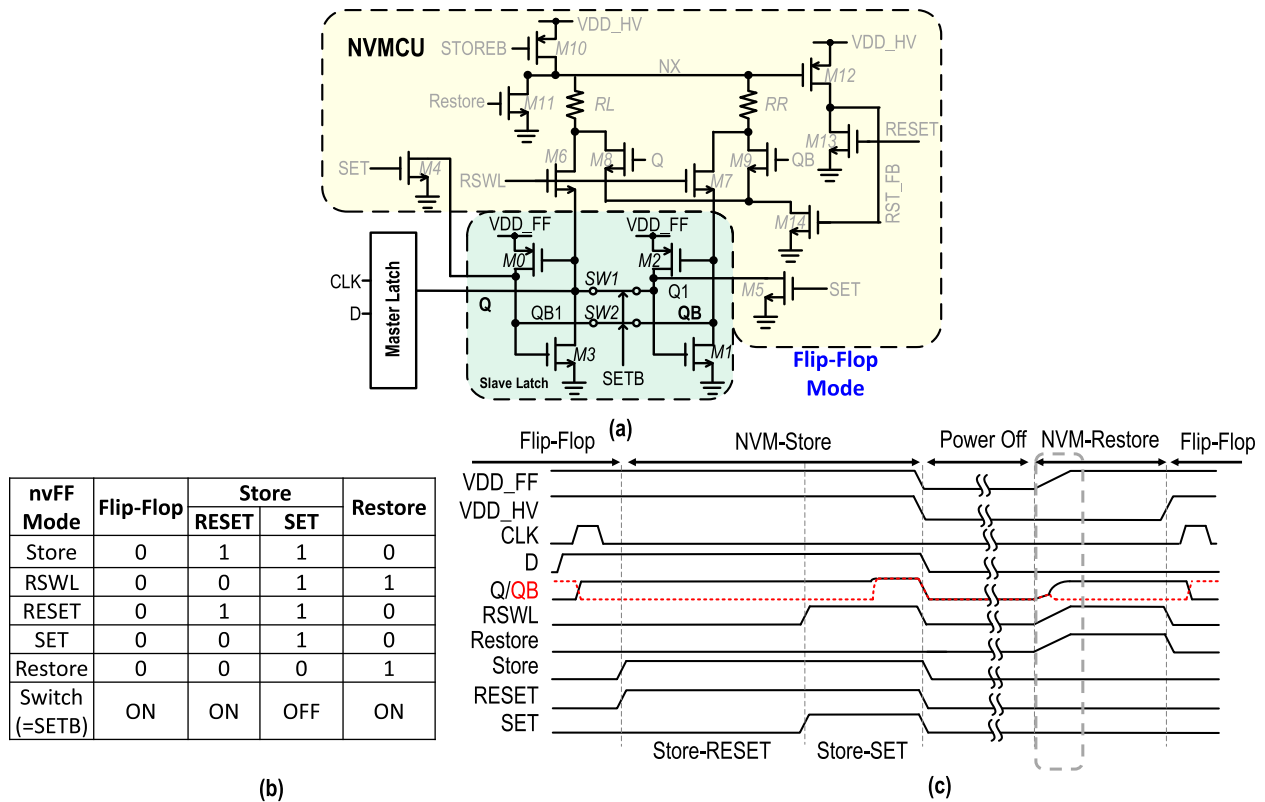


Fig. 4. (a) Full schematic of the SWT-nvFF, (b) operation control table, and (c) functional waveforms for a full power-OFF-ON cycle.

between  $M12$ ,  $M13$ , and  $M14$  leads to  $RST\_FB = 0$  and the switching OFF of  $M14$  and  $I_{RESET}$ . When the selected RL/RR is already in HRS (match), a high  $V_{NX}$  ensures that  $M12$  is

OFF and  $RST\_FB = 0$ , thereby turning OFF the  $M14/I_{RESET}$  and ensuring that the RESET operation does not occur. Note that for the RESET operation, the feedback circuit ( $M12$ - $M14$ )

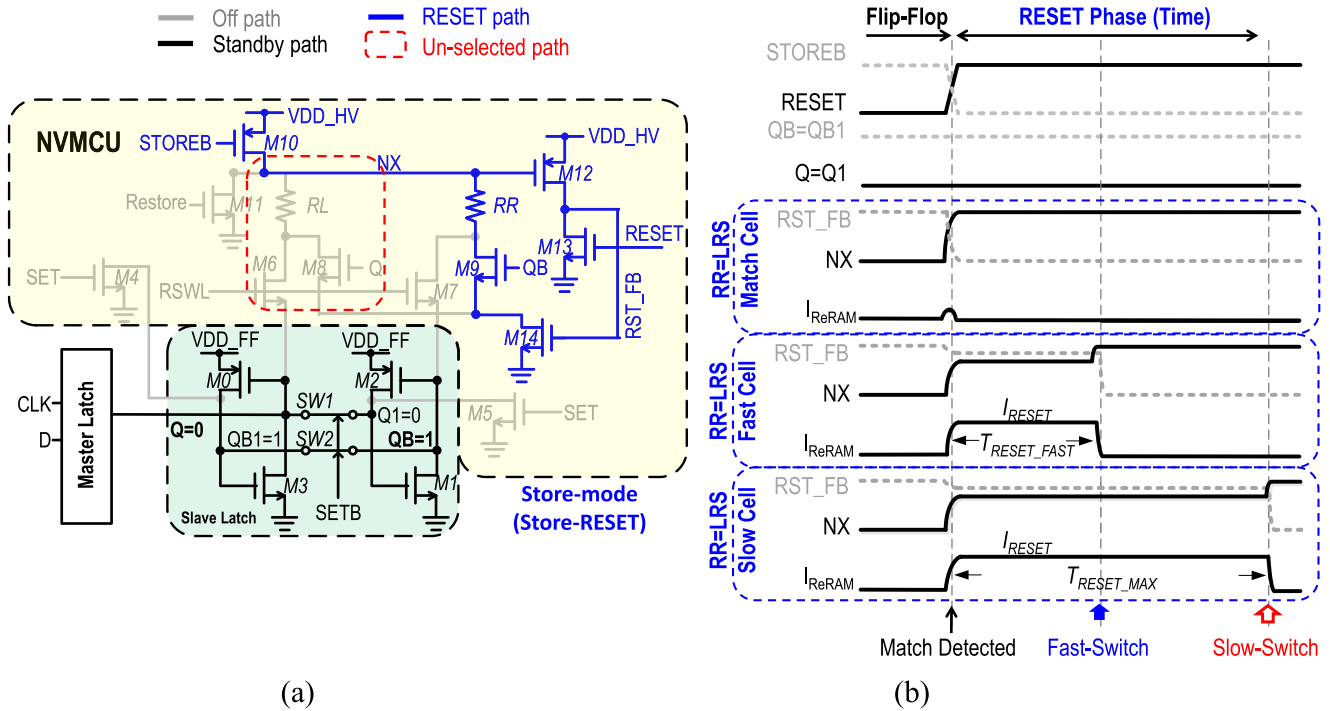


Fig. 5. (a) Active transistors and (b) operation waveform for the Store-RESET operation.

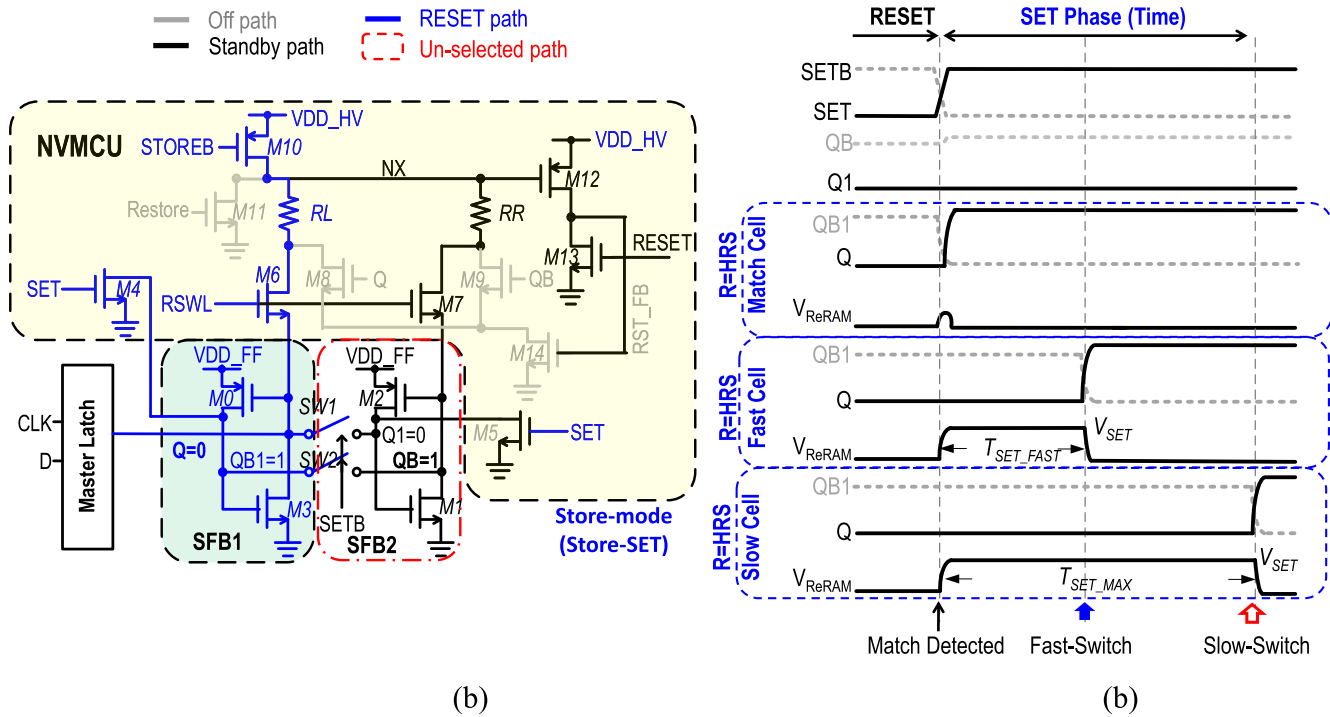


Fig. 6. (a) Active transistors and (b) operation waveform for the Store-SET operation.

uses a voltage input, since the RESET operation is a current-based operation.

C. Store Operation—SET

Fig. 6 presents the Store-SET operation. When the RESET operation ends, SET = RSWL = 1, which turns OFF the

SW1/SW2 and turns ON M4/M5 to produce two SET-feedback (SFB1) circuits (M0-M3-M4 and M1-M2-M5). When Q = 0, SFB1 (M0-M3-M4) is selected and SFB2 is disabled (QB = 1, Q1 = 0, and M1 = M2 = OFF), while the M10-RR (HRS)-M7 path weakly charges QB to prevent QB from residing in a floating state. When the RL is in

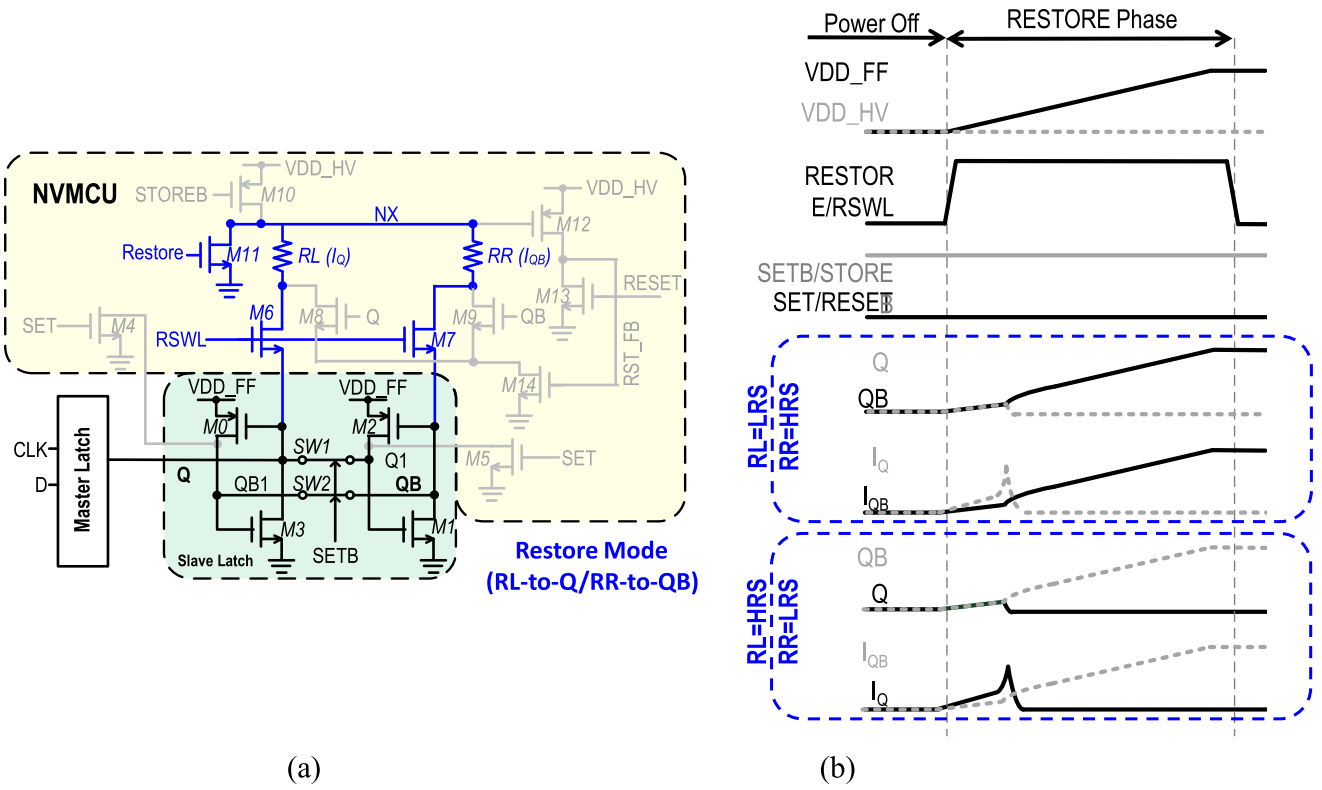


Fig. 7. (a) Active transistors and (b) operation waveform for the restore operation.

HRS (mismatch),  $M3$  keeps  $Q$  low to provide SET current  $I_{SET}$  ( $< I_{SET-MAX}$ ) and SET voltage  $V_{SET}$  across RL. When RL switches from an HRS to LRS, the low  $R_{LRS}$  generates a large dc-current  $I_{SET-dc}$  ( $> I_{SET-MAX}$ ), which causes  $Q$  to rise, thereby lowering the voltage at  $QB1$  via the  $M0$ - $M4$  voltage-divider pair and further raising  $V_Q$ . When the resistance of RL is lower than the designed  $R_{LRS-TH}$ , positive feedback turns OFF  $M3$ , such that the SET operation is terminated. When the RL is already in LRS (match), the large current  $I_{SET-dc}$  ( $> I_{SET-MAX}$ ) causes  $Q$  switching from 0 to 1, thereby lowering  $QB1$  and quickly turning OFF  $M3$  to end the SET operation. When  $Q = 1/QB = 0$ ,  $V_{NX}$  is high and the SET operation switches RR to LRS. In this case, the feedback circuit ( $M0$ - $M5$ ) uses a current input, since the SET operation is a voltage-based operation.

D. Restore of the SWT-nvFF

In restore mode, the application of  $RSWL = Restore = 1$  enables nodes  $Q$  and  $QB$  to have differential discharge currents flowing through RL ( $I_Q$ ) and RR ( $I_{QB}$ ), respectively. The LRS (HRS) discharge path provides a larger (smaller)  $I_Q/I_{QB}$ , resulting in a lower (higher) voltage at node  $Q/QB$  ( $V_Q/V_{QB}$ ), whereupon the slave latch pulls the higher (lower) voltage at  $Q/QB$  to logic-1 (logic-0). The active circuits during this restore period are shown in Fig. 7.

In contrast to FeRAMs and MRAMs, the suitable resistance ranges and sufficient  $R$ -ratio of our ReRAMs eliminates the need of additional assist schemes to increase restore margin

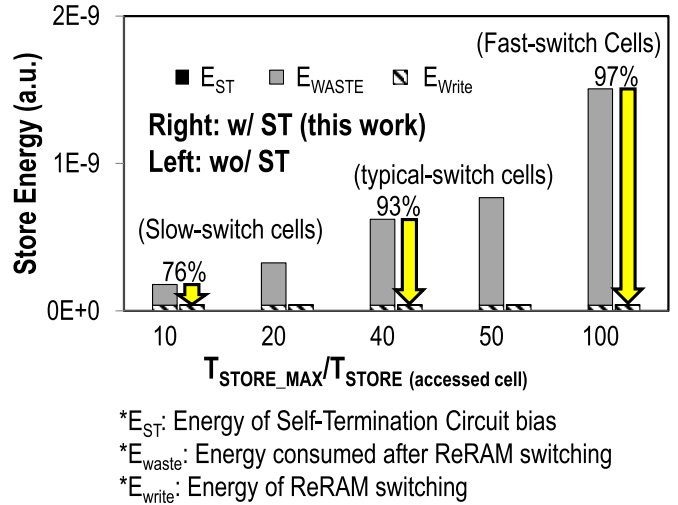


Fig. 8. Store energy of cells with different  $T_{STORE}/T_{STORE-MAX}$ .

and achieve high restore yield. This avoids the excess capacitance/dc-current loading on the power rail, which allows our ReRAM-based nvFFs to achieve fast wake up and low restore energy.

IV. ANALYSIS AND MEASUREMENT RESULTS

In this section, we perform analysis on the energy, speed, yield, and area of the SWT-nvFF. We then present the implementation in an nv-Processor and the measured results of a test chip.

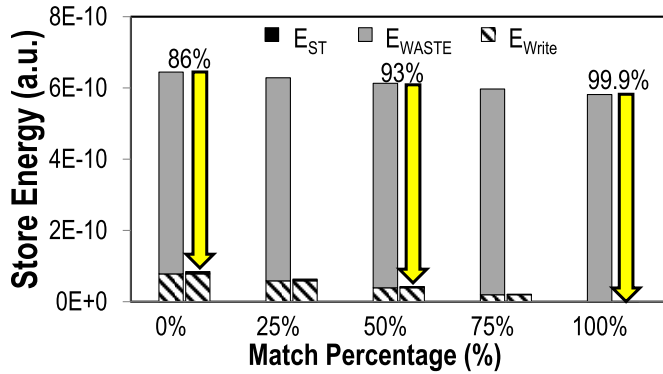


Fig. 9. Store energy for different match percentages.

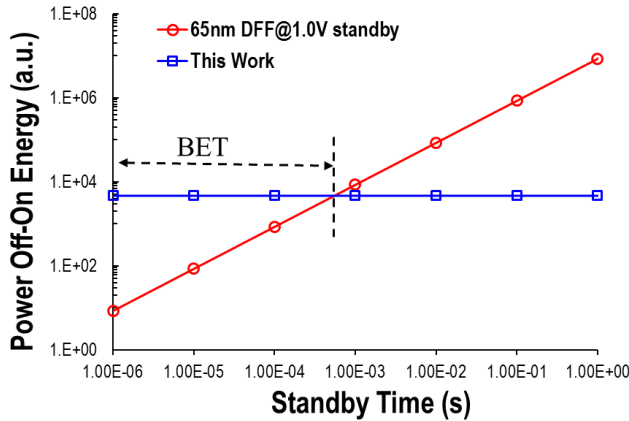


Fig. 10. Energy comparison of standby and power-OFF-ON operations.

### A. Performance

Fig. 8 presents the store energy ( $E_S$ ) when writing cells with different  $T_{STORE}$ . Without the SWT scheme, the write biases are supplied throughout  $T_{STORE-MAX}$ , and nearly 80% of  $E_S$  is wasted as dc current even for an average slow-switching cell ( $T_{STORE-MAX}/T_{STORE} = 10$ ). As the cell switches faster, an increased amount of energy is wasted during the store cycle.

With a small bias current, the SWT scheme efficiently cuts off the store conditions within picoseconds after switching, eliminating the dc current, and achieving a 76% reduction in  $E_S$  for slow-switching cells. For cells with typical switching time ( $T_{STORE-MAX}/T_{STORE} = 40$ ) and fast-switching cells ( $T_{STORE-MAX}/T_{STORE} = 100$ ), a 93% and 97% reduction in  $E_S$  can be achieved, respectively.

Fig. 9 presents the store energy consumption under different percentages of match cells. When 0% of the data is match, all cells need to be written and the SWT-nvFF saves 86% energy, mainly due to termination of fast-switching cells. On the other hand, for a 100% match, all cells keep its previous value and no write operation is required. Under this condition, the SWT saves more than 99.9% energy by terminating match cells. It is worth noting that embedded benchmarks have an average of above 78% match [36].

Fig. 10 presents a comparison of total energy consumption in standby and power-OFF-ON operations. During

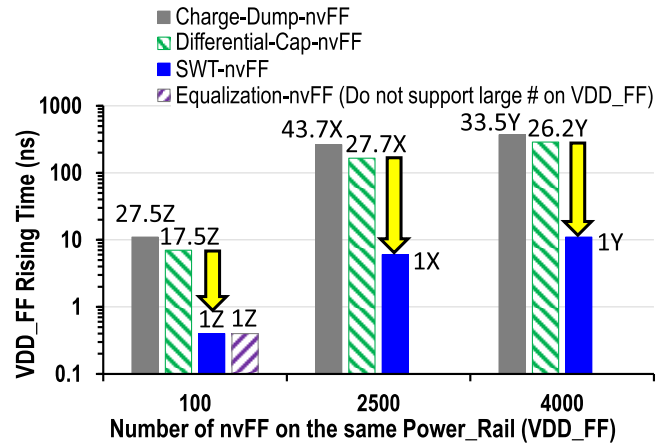


Fig. 11. Restore speed of various nvFFs for a different amount of cells on the power rail.

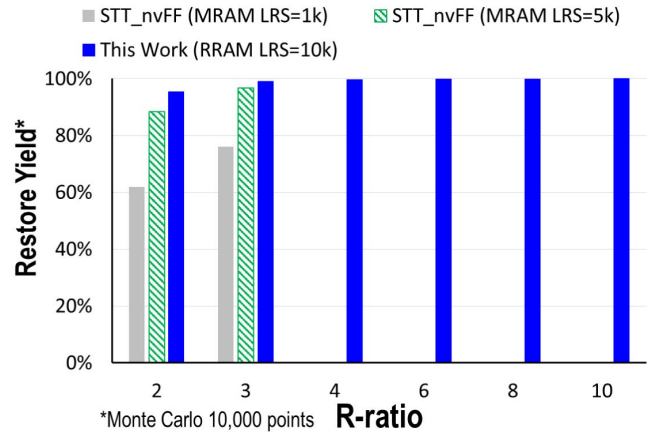
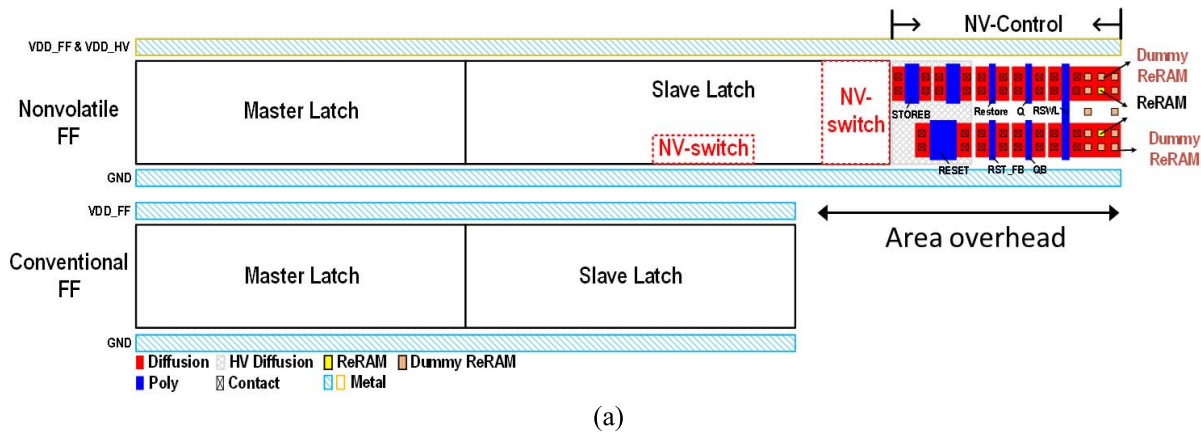


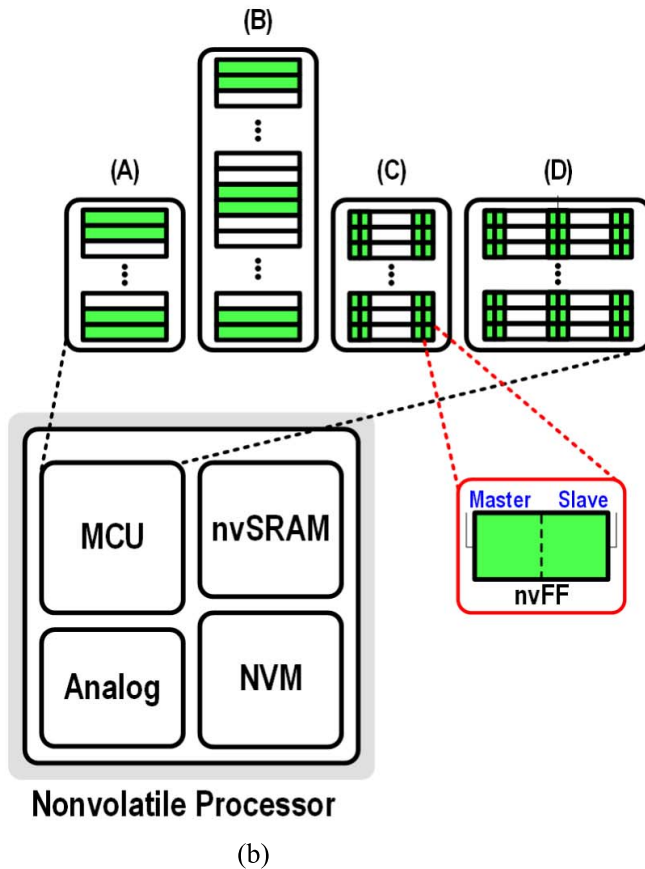
Fig. 12. Restore yield for different structures,  $R_{LRS}$ , and  $R$ -Ratio.

standby, the FFs consume constant leakage current, which increases the total energy consumption over time. Current leakage can largely be eliminated using power-OFF-ON operations, albeit at the cost of additional energy to store data in NVM during power-OFF operations and restore data back to the FF during power-ON operations. The BET is defined as the standby time in which the total leakage energy is equal to the store and restore energy. In this paper, the BET was 700  $\mu$ s. For standby periods exceeding BET, the use of power-OFF-ON operations is more energy efficient.

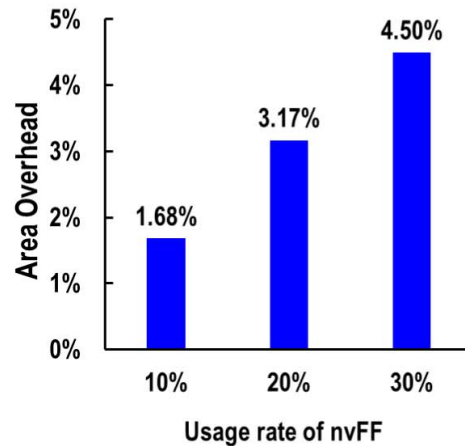
Fig. 11 shows the restore delay of this paper compared with the previous nvFFs. Due to the need to charge excess capacitive loading during power-up, FeRAM-based nvFFs require a 17+ times larger  $T_{VDD_{RMP}}$  compared with resistive-type nvFFs with 100 nvFFs on the power rail. EQ\_nvFF has fast rise time, but fails at large FF-count (i.e., 2500 or 4000) as a result of large dc current drawn from the supply, which causes  $V_{DD\_FF}$  unable to reach  $V_{DD}$ . As a result of our higher  $R$ -ratio, a decoupling of NVM devices from  $V_{DD\_FF}$ , and the elimination of the latch equalization, the SWT-nvFF achieves 27+ times faster  $T_{VDD_{RMP}}$  for nvFF count sufficient to ensure system stability (i.e., 2500 nvFF).



(a)



(b)



(c)

Fig. 13. (a) Layout of a single nvFF cell, (b) placement approaches of the nvFFs in the MCU, and (c) area overhead for different application rates of nvFF.

Along with the  $R$ -ratio, the absolute resistance of the NVM devices also plays a critical role in the restore performance. When both  $R_{HRS}$  and  $R_{LRS}$  are low ( $<5k$ ), both states are equivalently “fully turned-ON transistors,” which makes it difficult for a transistor-comprised latch to distinguish the two states. Likewise, if both  $R_{HRS}$  and  $R_{LRS}$  are high, the latch sees two “OFF transistors,” which also leads to reduced yield. Therefore, nonvolatile logics have the best performance when the employed NVM devices have resistances comparable to that of the latch, in which the latch will see  $R_{HRS}$  as an “OFF transistor” and  $R_{LRS}$  as an “ON transistor.” Fig. 12 presents the restore yield obtained from a 10 000 point Monte Carlo simulation. Current state-of-the-art MRAM has an

$R$ -ratio of 2–3, and still require restore assist techniques to overcome variation. Variations in the resistance of our ReRAM device are based on measurement results obtained from previous work using the same devices [37]. As a result of larger  $R$ -ratio ( $>5$ ) and suitable device resistance, the RRAM-based nvFF achieves a 22+% improvement in restore-yield compared with MRAM-based nvFFs.

Fig. 13(a) shows the layout of a single nvFF. IO devices are included as a part of the transistors to ensure device reliability, to account the fact that current ReRAM devices require more than 2 V for store operations. We made the height of the nvFF the same as that of the conventional FF in order to fit the track height of standard cells for auto place and route



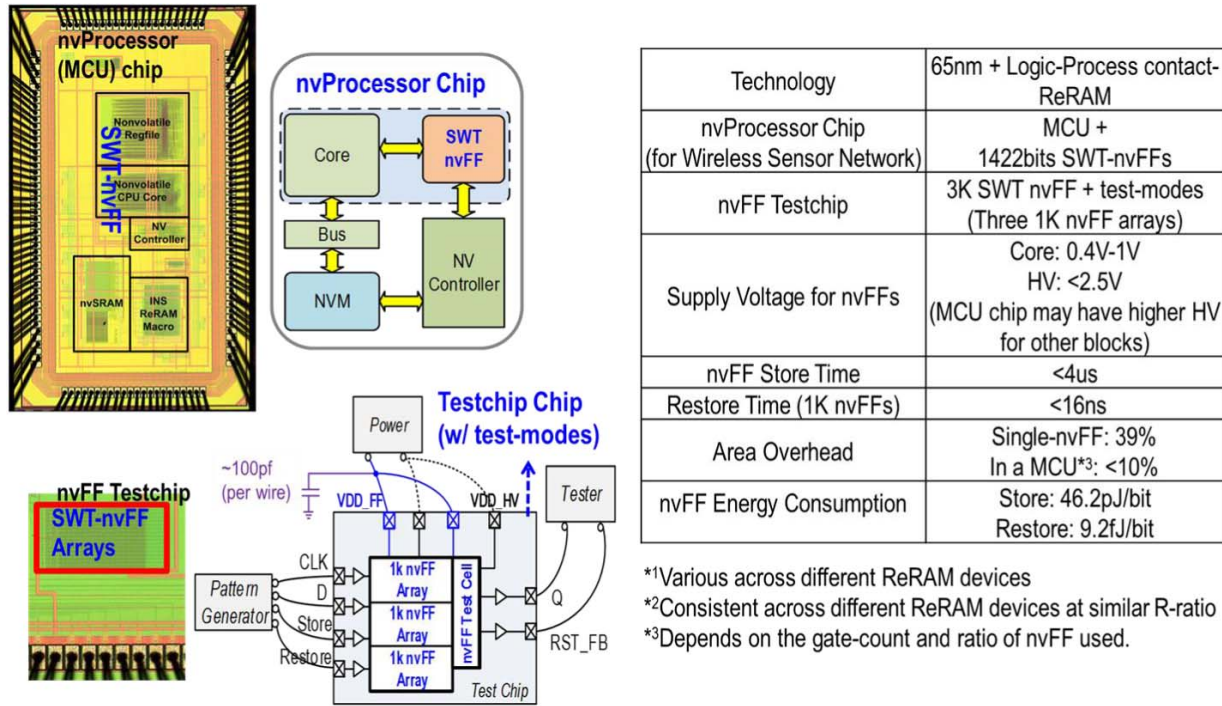


Fig. 14. Structure, die photo, and performance of the nv-Processor and the test chip.

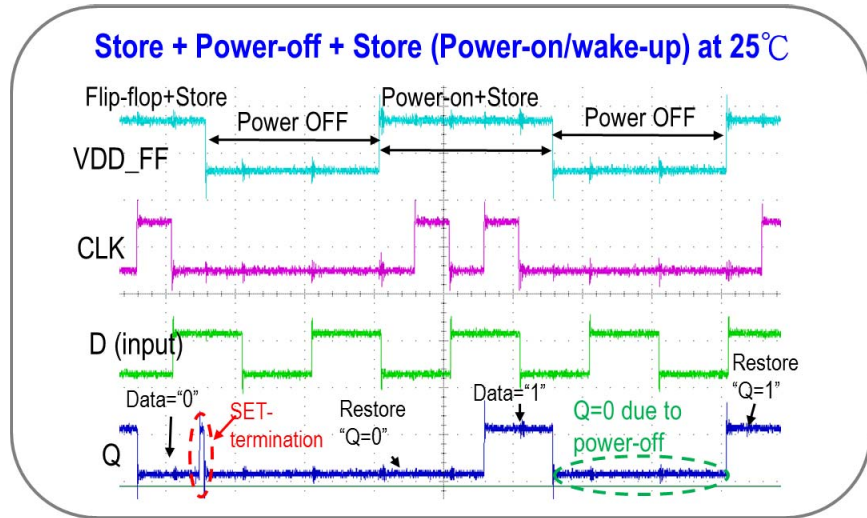


Fig. 15. Measured power-OFF-ON cycle waveform of the SWT-nvFF.

operations. The layout of the master latch is the same as that of conventional FF. The additional switches and nv-control circuit make the slave stage of our nvFF wider than that of conventional FF, resulting in area overhead 39% greater than that of conventional FF. Dummy ReRAM devices are placed around regular ReRAM devices to increase the yield against proximity effects.

For the sake of uniformity in the placement of nvFFs, the devices were clustered into groups. This also reduced the proximity effect of the ReRAM devices, decreased the area overhead of the high-voltage transistors, and enabled a more relaxed routing path for the high-voltage supply and

nonvolatile control signals. The various blocks differed with regard to the grouping of nvFFs clusters. Fig. 13(b) presents four possible approaches to the placement of each nvFF group in a sub-block. In case-A, nvFFs are placed along top or bottom tracks. These tracks are not the same as those used for input/output logic cells of nvFFs. In case-B, a central group of nvFFs is added to blocks with high volumes of tracks for standard cells. In case-C, each nvFF group is placed at the left or right edge of the tracks used for the input/output logic cells of nvFFs. In case-D, for blocks with a long track, additional groups are added at the center of each track.

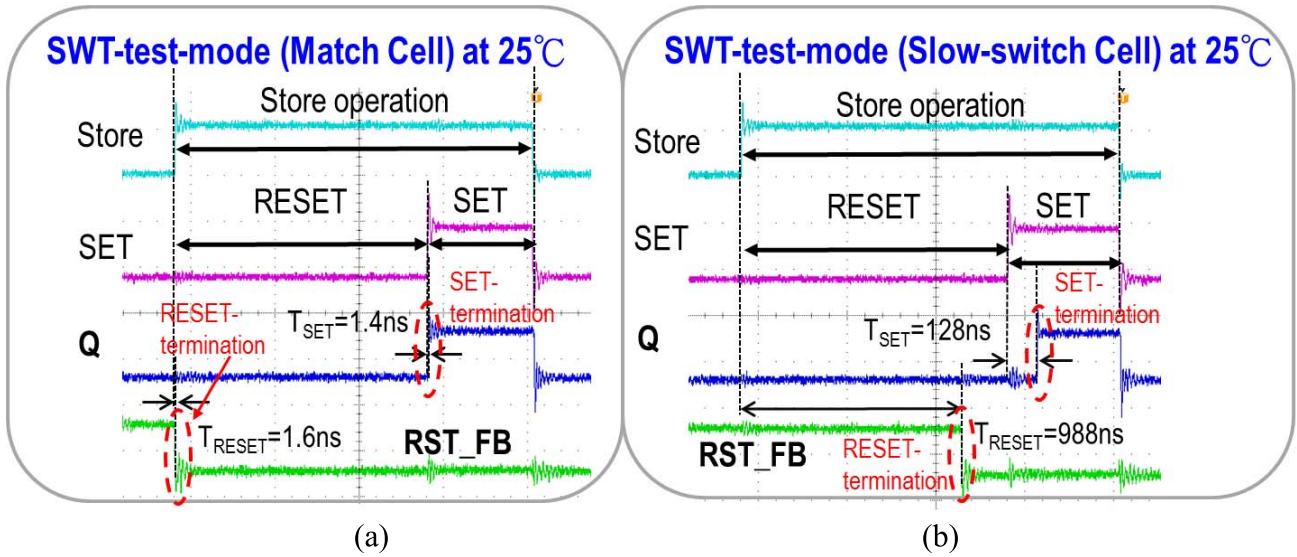


Fig. 16. Measured self-termination waveforms for (a) match cell and (b) slow-switching cell.

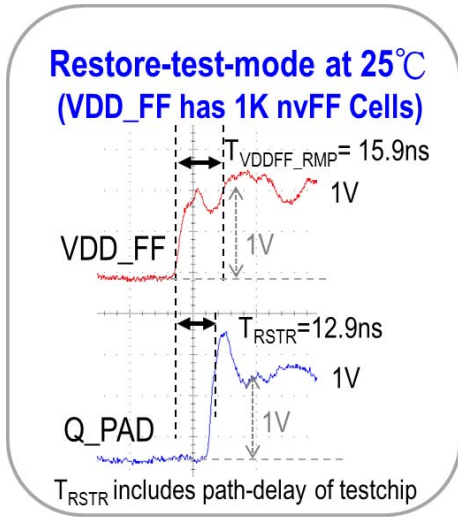


Fig. 17. Measured restore performance SWT-nvFF.

Fig. 13(c) presents the area overhead for different usage rates of nvFF (number of nvFFs/total FFs) in an nv-Processor. To avoid excessive overhead in area, only FFs storing critical data require the nonvolatile function. The overall area overhead of applying the SWT-nvFF to 10% and 30% of the total FFs in the MCU is 1.68% and 4.50%, respectively.

**B. Implementation and Measurement Results**

An nv-Processor and a test chip were fabricated using 65-nm CMOS process and logic-compatible ReRAM. Fig. 14 presents the die photo, structure, and performance of the 8-bit nv-Processor, which consists of an adaptive nonvolatile controller, 8-kB code ReRAM, 1422 adaptive nvFFs, and a configurable 4-kB nvSRAM. The test chip includes three nvFF arrays, each 1 kb in size.

Captured waveforms confirm the functionality of the FF, store, power-OFF, and restore modes of the nv-Processor. All measured delays include the path delay due to I/O drivers, pad

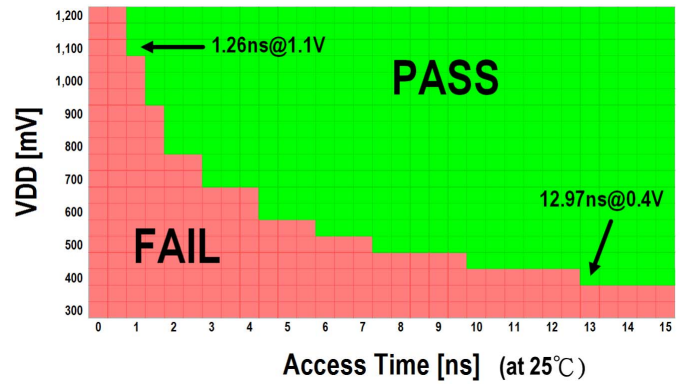


Fig. 18. Measured Shmoo plot of the SWT-nvFF.

delays, as well as test-board parasitic load. Fig. 15 presents the power-ON-OFF cycle for the two possible data conditions. Note that when SET termination occurs, both  $Q$  and  $QB$  rise to 1, which can be observed in a switching of  $Q$  when  $Q = 0$ . Fig. 16 presents the detailed waveforms of the SET/RESET termination for matched cells and slow-switching cells. We can observe that a matched nvFF clearly undergoes early switching on RST\_FB (falling edge) with sub-2-ns response time, while slow-switching cells show late switching in RST\_FB. The measured  $E_S$  of a matched-nvFF is 99+% smaller than that of a slow-switch nvFF. In Fig. 17, the measured  $T_{RSTR}$  and  $T_{VDDFF\_RMP}$  for a 1-K nvFF array are shown. The measured restore time is less than 20 ns with additional  $\sim 100$ -pF test-board parasitic load. Fig. 18 presents the measured Shmoo plot. All measured delays include the test-path-delay due to I/O drivers, pad delays of test chip, and test-board parasitic load. The nvFF access time (including test-path-delay) was 1.26 ns at  $V_{DD} = 1.1$  V and 12.97 ns at  $V_{DD} = 0.4$  V. In simulations, the nvFF presented a 20-ps penalty in CLK- $Q$  delay; however, this was difficult to measure the access time overhead due to the minimum resolution of the measurement system and test-mode implementation.

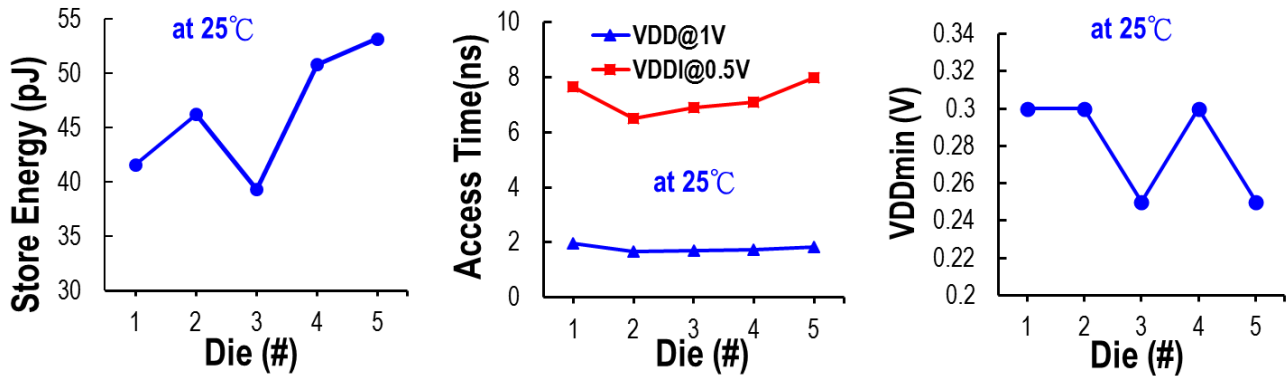


Fig. 19. Measured performance distribution across different dies. (a) Store energy. (b) Access time at  $V_{DD} = 1$  V and  $V_{DD} = 0.5$  V. (c) Minimum operating voltage.

Fig. 19 presents the performance results averaged across five dies. The store energy (SET + RESET) averaged 46.2 pJ/bit with distribution ranging from 39.3 to 53.2 pJ/bit. The worst case access times in FF mode at nominal  $V_{DD} = 1$  V and low  $V_{DD} = 0.5$  V were 1.97 and 8 ns, respectively. The minimum operating voltage ( $V_{min}$ ) ranged from 0.24 to 0.3 V.

## V. CONCLUSION

Non-volatile logic combining emerging NVMs with CMOS is a promising candidate to enable processors with high performance and ultra-low power. In this paper, an SWT-nvFF using logic-compatible ReRAM process has been proposed to address the challenges of previous nvFFs in terms of area, store energy, restore time/energy, as well as reliability. The SWT-nvFF achieves a 93+-% reduction in store energy ( $E_S$ ) and 27+ times in restore time ( $T_{RSTR}$ ) compared with the previous nvFFs. The fabricated nv-Processor and test chips confirmed the nonvolatile functions, energy savings, and sub-20-ns restore times.

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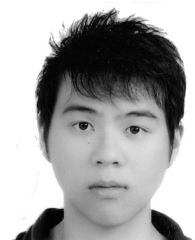
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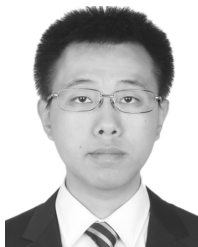
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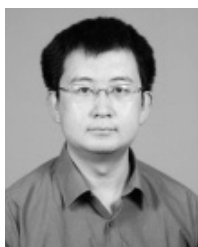
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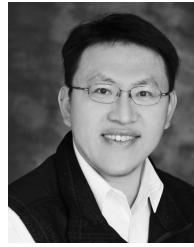
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