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Khaja Ahmad Shaik, Kiyoo Itoh, Amara Amara. 0.5-V 350-ps 28-nm FD-SOI SRAM Array with Dynamic Power-Supply 5T Cell. S3S, Jan 2016, Wine Country, SanFrancisco, United States. hal-01254224

HAL Id: hal-01254224

<https://hal.science/hal-01254224>

Submitted on 11 Jan 2016

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0.5-V 350-ps 28-nm FD-SOI SRAM Array with Dynamic Power-Supply 5T Cell

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Abstract—To achieve high-speed 0.5-V SRAMs, a dynamic power-supply 5T cell, and a multi-divided array with selectively-boosted 5T-cell power lines are proposed. Layout and post-layout simulation with a 28-nm planar-FD-SOI MOSFET reveal that a 4-kb array in a 128-kb core using the proposals operates at 350-ps cycle with x6 faster and x13 lower power than the counterpart 6T-cell array, while maintaining a small leakage current.

Keywords—0.5-V dynamic power-supply 5T cell, multi-divided open bit-line SRAM, selectively boosted cell-power lines.

I. INTRODUCTION

Traditional high-speed 6T-cell SRAMs are facing at least two issues, namely, voltage (V_{DD}) scaling of the cell to 0.5 V or less, and reduction of the array power. Recently, to solve the issues, a static multi-power-supply 5T cell and a multi-divided open-BL (O-BL) array [1] are proposed. However, write speed is slow due to need for high- V_t MOSFETs for low standby leakage current. In this paper, to cope with the issues, a dynamic power-supply 5T cell (D-5T) and a multi-divided array with selectively-boosted D-5T power lines are proposed, and evaluated through layout and post-layout simulation with a 28-nm planar FD-SOI MOSFET [2].

II. DYNAMIC POWER-SUPPLY 5T CELL

Fig. 1 shows the proposed D-5T. The flip-flop in D-5T operates at one set of static supply V_{DD} and V_{SS} ($= 0$ V) and the other set of dynamic supply V_{DH} ($\geq V_{DD}$) and $-V_{SL}$ (≤ 0). In the standby mode, the power lines DHL and SLL are at V_{DD} and V_{SS} , respectively. Here, it is assumed that each MOSFET has a regular V_t ($= RVT \cong 0.4$ V) so as to meet the leakage specification. In the active mode, they are positively and negatively boosted by Δ from V_{DD} and V_{SS} . Hence, for example, when a cell storing “0” with N_1 at 0 V is read, the gate-source (G-S) of on-MOSFET M_d is forward-biased by Δ for quickly driving BL with the V_t effectively reduced to $RVT - \Delta$. That of off-MOSFET M_l is reverse-biased by Δ for lower leakage current with the V_t effectively increased to $RVT + \Delta$. Those of on-and -off MOSFETs (M_{lb} and M_{db}) are forward-biased by Δ with both V_s effectively reduced to $RVT - \Delta$. Hence, although M_{lb} enables faster write operation with faster feedback of the flip-flop, M_{db} increases the leakage current. Since such leakage is accepted with the array described later, faster read and write operations are achieved.

Fig. 1 Dynamic-power supply 5T cell. P; precharge. CT₁, CT₂; contacts.

D-5T is assisted by a negative and positive boosting of WL(NPB-WL) and mid-point sensing(MID-S). The negative boosting enables to reduce $V_t(M_a)$ by δ for given leakage and V_{WL} , further enhancing the speed. Unless WL is boosted, the speed is governed by M_a , losing the above-high-speed advantage of the flip-flop. Degraded read stability due to the M_a - M_d ratio voltage increased by NPB-WL is remedied by reducing BL-precharge voltage, $V_P(BL)$, to $V_{DD}/2$, as mentioned later. Note that as long as cell nodes (N_1 , N_2) stays at V_{DD} , like in 6T, cell performances are almost governed by the flip-flop, regardless of WL and BL voltages. The $V_{DD}/2$ enables MID-S since it works as the reference voltage for “1” and “0” signal. MID-S halves the array dynamic power with halved BL-voltage swing. D-5T can be smaller than the 6T due to one MOSFET and one BL eliminated from the 6T-cell layout [3]. It affords to add a contactless column line YL with the same layer as BLs and power lines in the 6T cell, which is indispensable for a high-performance array described later.

Fig. 2 shows parameters used for cell-evaluation. At $V_t(M_{lb})/V_t(M_{db}) = 342/468$ mV, speeds become higher with higher V_{DH} and V_{SL} (see Fig. 3), as expected. Write operation becomes particularly faster with smaller ΔV_t due to faster feedback of the flip-flop. Here, ΔV_t denotes a deviation from the above V_s . The write recovery is also fast, enabling fast write cycle time (see Fig. 4). In contrast, the 6T cell using non-

Fig. 2 (a) Typical design parameters of 5T cell and 6T cell[3], and (b) speed definitions, exemplified by $t_R(1)$ for “1” read and $t_W(0)$ for “0” write.

Fig. 3 Speeds for (a) V_{DH}/V_{SL} for $\Delta V_t = 0$ mV, and (b) ΔV_t for $V_{DH}/V_{SL} = 0.7/0.2$ V. $V_t(M_{lb}) = 342\text{mV} + \Delta V_t$, and $V_t(M_{db}) = 468\text{mV} + \Delta V_t$.

Fig. 4 Write waveforms of (a) D-5T and (b) 6T for various WL-pulse widths. $V_{DH}/V_{SL} = 0.7/0.2V$ and $\Delta V_t = 0$ mV for D-5T.

Fig. 5 Read stability for (a) V_{DH}/V_{SL} at $\Delta V_t = 0$, and (b) ΔV_t at $V_{DH}/V_{SL} = 0.7/0.2$ V.

Fig. 6 Leakage current for (a) V_{DH}/V_{SL} at $\Delta V_t = 0$, and (b) ΔV_t at $V_{DH}/V_{SL} = 0.7/0.2$ V. $V_t(M_{lb}) = 342mV + \Delta V_t$, and $V_t(M_{db}) = 468mV + \Delta V_t$.

boosted WL and V_{DD} -BL precharging is slow. Fig. 5 depicts the dynamic read stability, evaluated with actual relevant circuits (Figs. 5(a) and (b)) with a BL-capacitance C_B of 20 fF and WL-pulse width of 300 ps. The shadowed area is for non-destructive read-out (NDRO) region for “1” and “0” read, while the white area for destructive read-out (DRO) region. Obviously, at $V_P(BL) = V_{DD}/2$ (HVP), D-5T is stable over a wide range of V_{DH}/V_{SL} or ΔV_t . For $V_P(BL) = V_{DD}(FVP)$, however, NDRO is not ensured at $V_{DH}/V_{SL} > 0.6/0.1V$ or $\Delta V_t < 70$ mV, since the M_{lb} - M_{db} inverter tends to more easily flip at the regions. Hence, HVP is mandatory to NDRO. Fig. 6 shows leakage characteristics. The major source of leakage is M_{lb} or M_{db} at a high- V_{DH}/V_{SL} or small- ΔV_t region while M_1 or M_d at a low V_{DH}/V_{SL} or large- ΔV_t region. The resultant large leakage of M_{lb} or M_{db} is accepted with the following array.

III. SELECTIVELY-BOOSTED CELL-POWER-LINE ARRAY

Fig. 7 shows an O-BL 4-kb unit array [1] divided into four pairs of sub-arrays (PMA₀-PMA₃), only one of which is activated for low power. The division is achieved without substantial area increase by sharing a large column block (YDEC&DRV) with the PMAs, and leaving column selection to the YL. After equalizing all pairs of BLs, LIOs, and GIOs to $V_{DD}/2$, a signal is read out to the read and write circuit (RWC) through relevant switches (e.g., My_0 and My_{0b} , My_1 and My_{1b} , and SW_0), and then amplified by RWC, referring to $V_{DD}/2$ at /GIOs. V_{DH} , $V_{SL} (= \delta = 0.2$ V), $V_{DD}/2$, and $V_{WL} (= V_{YL} = 1$ V) are assumed to be from on-chip voltage converters which are well established in DRAMs [4]. Additional area and power by V_{DH} and V_{SL} converters are expected to be insignificant at a 128-kb core level, due to the small voltage swings and small leakage current.

For a given leakage current of array, the smaller the number of activated cells, the larger the allowable leakage current per activated cell, enabling faster write operation. In fact, the array meets the requirement if the multi-divided array is utilized. In principle, the number is reduced to 1/64 if one of 16 sets of the power lines (DHL and SLL) running in the BL direction is selected by a YL, and one-fourth each set divided into four, as in the figure, is selected by row addresses. The selection is performed by 3D selection, namely, activating a selected YL and a selected power-driver block PD of the four (PD₀-PD₃) placed at the divisions. The PD outputs block power lines, BDH and BSL, to activate the row selector SLB composed of many selector SLs, each of which is controlled by the YL and the set of BDH and BSL. Fig. 8 depicts selection-relevant circuits. A dual LIO and dual GIO structure is adopted to accommodate an SL in the BL pitch under two kinds of shared contacts (Fig. 1). Thus, for example, one set of DHL₀ and DHL₁, and SLL₀₁, both of which connect 128 cells, are boosted by YL₀ and the set of BDH₀ and BSL₀ from PD₀. The number, however, is effectively 64 for a 128-kb array with 32-b data-in data-out organization. Leakage per cell in the active mode is thus reduced from 540 pA to 71.4 pA (i.e., only 11% larger than the standby leakage) at $\Delta V_t = 0$, as shown in Fig. 6, assuming that leakage current of a non-activated cell is 64 pA. The area penalty of SL is only 6% of the cell. Fig. 9 illustrates the

Fig. 7 4-kb unit array in 128-kb array with activating only PMA₀. HVP: $V_{DD}/2$ precharger and equalizer.

layout of the 4-kb unit array and waveforms by post-layout simulation, showing a fast cycle of 350 ps enabled by fast write recovery, as expected. DHL- and SLL-waveforms are slightly deformed but quickly controlled. Indeed, as summarized in Fig. 10, the 5T-cell array is much faster than the 6T cell array due to excellent cell speeds and the small total capacitance $C_T(R)$ of the read path thanks to the multi-divided array. The cycle time is x6 faster because the 6T array is as slow as 2 ns. The active power is reduced to 1/13 that of the 6T-cell array thanks to the small power-related total capacitance $C_T(P)$ due to the partial activation of the array, and halved voltage swing on BLs, $\Delta V(BL)$. Here, no division for the 6T-cell array is assumed because the YL is not available. If divided with the same process, the array is intolerably large.

Archit. of 4-kb unit array $V_{DD}=0.5\text{ V}$, $V_{DH}=0.7\text{ V}$, $V_{SL}=0.2\text{V}$.	5T	6T	Remarks
Cell size	928x306nm ²	928x306nm ²	Cell in Fig. 1
C _T (R)	15.8fF	37.6fF	simulated
t _R (0)/t _R (1)	179/176ps	≅ 1,887ps ^{*1}	^{*1} (C _T (R)/C _B)t _R (cell)
t _w (0)/t _w (1)	172/178ps	≅ 331ps ^{*2}	^{*2} t _w (6T)+102ps
t _{cmin} (ratio)	350ps(1)	≅ 2,058ps ^{*3} (5.9)	^{*3} t _R (array)+171ps
C _T (P)/ΔV(BL)	85ff/0.25V	536ff/0.5V	
P _{act} (ratio)	1/12.6	1	worst V _t -variation
Leak _{stb} /Leak _{act}	262/293nA	220/220nA	

Fig. 10 Performances of 4-kb unit arrays in 128-kb core. Simulated for 5T-cell array, while calculated for the 6T-cell array.

IV. CONCLUSION

To achieve high-speed 0.5-V SRAMs, a dynamic power-supply 5T cell, and a multi-divided array with selectively-boosted 5T-cell power lines were proposed. Layout and post-layout simulation with a 28-nm planar-FD-SOI MOSFET revealed that a 4-kb array in a 128-kb core using the proposals operates at 350-ps cycle with x6 faster and x13 lower power than the counterpart 6T-cell array, while maintaining a small leakage current.

ACKNOWLEDGEMENT

The authors thank Circuit Multi Projects (CMP), Grenoble, France for providing the FD-SOI 28nm design kit (DK), and STMicroelectronics, Crolles, France for the DK support.

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