

A High Density and Low Power Cache Based on Novel SRAM Cell

Arash Azizi Mazreah¹Mohammad Taghi Manzuri²Ali Mehrparvar³¹ Islamic Azad University, Science and Research Branch, and Islamic Azad University, Sirjan Branch² Sharif University of Technology³ Islamic Azad University, Arak Branch¹ Email: aazizi@iausrjan.ac.ir² Email: manzuri@sharif.edu³ Email: mehrparvar@ieee.org

Abstract—Based on the observation that dynamic occurrence of zeros in the cache access stream and cache-resident memory values of ordinary programs exhibit a strong bias towards zero, this paper presents a novel CMOS five-transistor SRAM cell (5T SRAM cell) for very high density and low power cache applications. This cell retains its data with leakage current and positive feedback without refresh cycle. Novel 5T SRAM cell uses one word-line and one bit-line and extra read-line control. The new cell size is 17% smaller than a conventional six-transistor SRAM cell using same design rules with no performance degradation. Simulation and analytical results show purposed cell has correct operation during read/write and also the average dynamic energy consumption of new cell is 30% smaller than a six-transistor SRAM cell.

Index Terms—5T SRAM cell, Read static noise margin free, Cell current, Cell leakage, Cell area, dynamic energy consumption

I. INTRODUCTION

Due to the high demands on the portable products, energy consumption is a major concern in VLSI chip and microprocessor designs. The on-chip caches can effectively reduce the speed gap between the processor and main memory; almost modern microprocessors employ them to boost system performance. These on-chip caches are usually implemented using arrays of densely packed SRAM cells for high performance [1]. A six-transistor SRAM cell (6T SRAM cell) is conventionally used as the memory cell [2]. However, the 6T SRAM cell produces a cell size an order of magnitude larger than that of a DRAM cell, which results in a low memory density [2]. Therefore, conventional SRAMs that use the 6T SRAM cell have difficulty meeting the growing demand for a larger memory capacity in mobile applications [2].

Studies show that the power dissipated by the caches is usually a significant part of the total chip power [1]. Cache accesses consume a significant fraction (30-60%) of total energy dissipation in modern microprocessor [3]. A large portion of cache energy is dissipated in driving the bit-lines, which are heavily loaded with multiple storage cells [3]. Clearly, the caches are the most

attractive targets for power reduction [1]. Besides, in cache accesses an overwhelming majority of the write and read bits are '0'. Whereas in the conventional SRAM cell because one of two bit-lines must be discharged to low regardless of written value, the power consumption in both writing '0' and '1' are the same [1]. Also in conventional SRAM cell differential read bit-line used during read operation and consequently, one of the two bit-lines must be discharged regardless of the stored data value [3]. Therefore always there are transitions on bit-lines in both writing '0' and reading '0' and since in cache accesses an overwhelming majority of the write and read bits are "0" these cause high dynamic energy consumption during read/write operation in conventional SRAM cell.

The read static noise margin (SNM) is important parameter of SRAM cell. The read SNM of cell shows the stability of cell during read operation and further degraded by supply voltage scaling and transistor mismatch. The read operations at the low read SNM levels result in storage data destruction in SRAM cells [4].

In response to these challenges in conventional SRAM cell, our objective is to develop a read-static-noise-margin-free SRAM cell with five transistors to reduce the cell area size with performance and power consumption improvement. In designing of this new cell we exploit the strong bias towards zero at the bit level exhibited by the memory value stream of ordinary programs. The rest of this paper is organized as follows. First, Section II we describe the relation between cell current and read static noise margin in SRAM cell. Then, we propose a novel 5T SRAM cell in Section III. Next, in Section IV the energy consumption of each cache access of novel 5T SRAM cell and 6T SRAM cell investigated analytically. Section V provides circuit simulation results. Finally, we summarize the key results in Section VI.

II. READ STATIC NOISE MARGIN AND SRAM CELL CURRENT IN CONVENTIONAL SRAM CELLS

The SRAM cell current and read static noise margin (SNM) are two important parameters of SRAM cell. The

read SNM of cell shows the stability of cell during read operation and SRAM cell current determine the delay time of SRAM cell [4]. Fig.1 shows the SRAM cell current in the conventional SRAM cell. Although SRAM cell current degradation simply increases bit-line (BL) delay time, Read SNM degradation results in data destruction during Read operations [4].

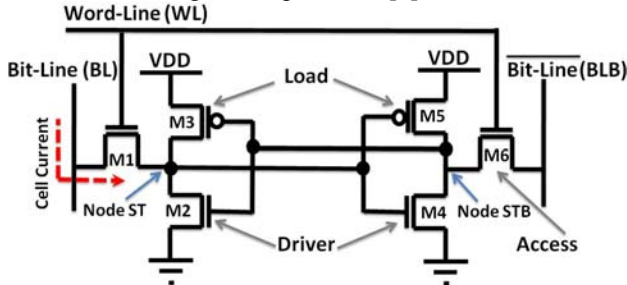


Fig. 1. SRAM cell current in 6T SRAM cell.

Both Read SNM and SRAM cell current values are highly dependent on the driving capability of the access NMOS transistor: Read SNM decreases with increases in driving capability, while SRAM cell current increases [4]. That is, the dependence of the two is in an inverse correlation [4]. Thus in conventional SRAM cell the read SNM of cell and cell current cannot adjust separately.

One strategy for solving the problem of inverse correlation between SRAM cell current and read SNM is separation of data retention element and data output element. Separation of data retention element and data output element means that there will be no correlation between Read SNM and SRAM cell current. Based on this strategy, [5] presents a dual-port SRAM cell. But this cell is composed of eight transistors and has 30% greater area than that of a conventional 6T SRAM cell [4]. Another strategy is loop-cutting during read operation. Based on this strategy in [4] a read-static-noise-margin-free SRAM cell for low- V_{DD} and high speed application presented. This cell is composed of seven transistors and makes it possible to reduce the area overhead from 30% to 13% [4]. Thus this cell is with area overhead too.

To avoid inverse correlation between SRAM cell current and read SNM we proposed new five transistor SRAM cell. Our proposed cell is based on loop-cutting strategy and this observation that in ordinary programs most of the bits in caches are zeroes for both the data and instruction streams. This new cell making it possible to achieve both low- V_{DD} and high-speed operations with no area overhead.

III. CELL DESIGN CONCEPT

Fig. 2 shows a circuit equivalent to a developed 5T SRAM cell using a supply voltage of 1V in 65-nm technology node. During idle mode of cell (when read and write operation don't perform on cell) the feedback-cutting transistor (M5) is ON and N node pulled to V_{DD} by this transistor. When '1' stored in cell, M3 and M2 are ON and there is positive feedback between ST node and STB node, therefore ST node pulled to V_{DD} by M2 and STB node pulled to GND by M3. When '0' stored in cell M4 is ON and since N node maintained at V_{DD} by M5 the

STB pulled to V_{DD} , also M2 and M3 are OFF and for data retention without refresh cycle following condition must be satisfied.

$$I_{DS-M1} > I_{SD-M2} + I_{gate-M4} + I_{gate-M3}$$

For satisfying above condition when '0' stored in cell, we use leakage current of access transistors (M1), especially sub-threshold current of access transistors (M1).

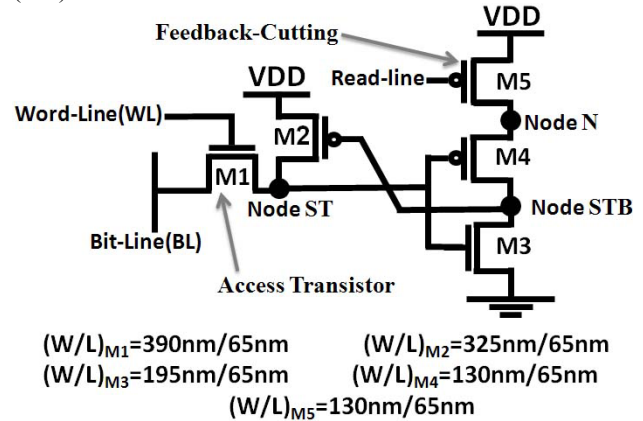


Fig. 2. New 5T SRAM cell in 65-nm technology node

For this purpose during idle mode of cell, bit-line maintained at GND and word-line maintained at V_{Idle} . Fig. 3 shows leakage current of cell during idle mode for data retention when '0' stored in cell. Most of leakage current of access transistor (M1) is sub-threshold current, since this transistor maintained in sub-threshold region. HSPICE simulation result with $V_{DD}=1V$ shows if during idle mode of cell, bit-line maintained at GND and $V_{Idle}=0.2V$ then '0' data stored in cell without refresh cycle and thus in idle mode above condition satisfied. The HSPICE parameters are obtained from the latest Predictive Technology Models (PTMs) for the technology node of 65-nm [6].

A. Read and write operation

During write operation feedback-cutting transistor is ON and N node pulled to V_{DD} by this transistor, thus in write operation read-line maintained at GND. When a write operation is issued the memory cell will go through the following steps.

1)-Bit-line driving: For a write, data drove on bit-line (BL), and then word-line (WL) asserted to V_{DD} .

2)-Cell flipping: this step includes two states as follows:

a)-Data is zero: in this state, ST node pulled down to GND by NMOS access transistor (M1), and therefore the Load transistor (M4) will be ON, and STB node will be pulled up to V_{DD} .

b)-Data is one: in this state, ST node pulled up to $V_{DD}-V_{TN}$ by NMOS access transistor (M1), and therefore the driver transistor (M3) will be ON, and STB node will be pulled down to GND, thus load transistor (M2) will be ON and positive feedback created by M2 and M3.

3)-Idle mode: At the end of write operation, cell will go to idle mode and word-line and bit-line asserted to V_{idle} and GND, respectively.

Fig. 4 shows waveform of new cell during write cycles. When a read operation is issued the memory cell will go through the following steps.

1)-Bit-line discharging: For a read, bit-line discharged to GND, and then floated.

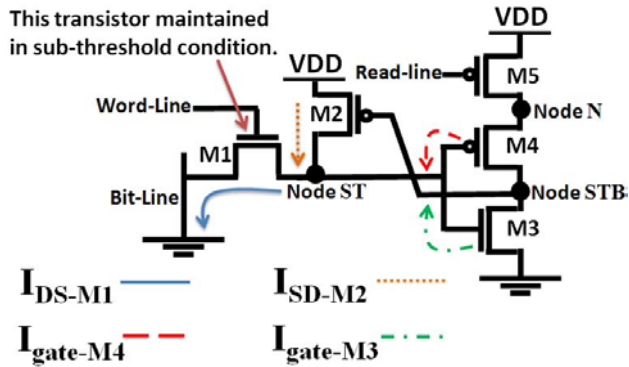


Fig. 3. Leakage current in idle mode when '0' stored in cell.

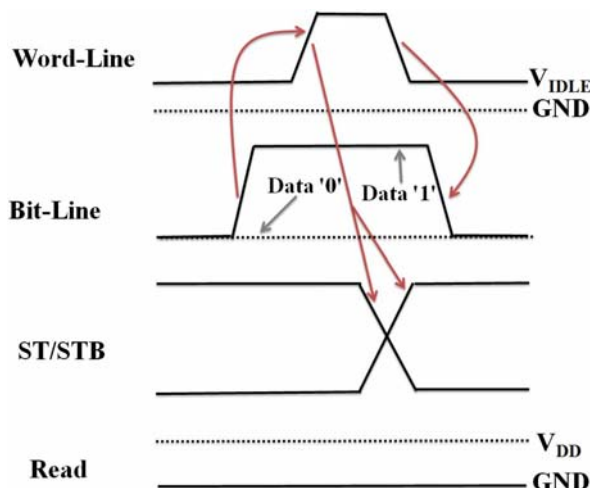


Fig. 4. Waveform of new cell during write cycle.

2)-feedback-cutting: In this step feedback-cutting transistor is OFF and thus read-line maintained at V_{DD} during read operation.

3)-Word-line activation: in this step word-line asserted to V_{DD} , and two states can be considered:

a)-Voltage of ST node is high: when voltage of ST node is high, the voltage of bit-line pulled up to high voltage by NMOS access transistor. We refer to this voltage of bit-line as $V_{BL-High}$.

b)-Voltage of ST node is low: when voltage of ST node is low, the voltage of bit-line and ST node equalized.

4)-Sensing: After word-line deactivate to V_{idle} and read-line return to GND then sense amplifier is turned on to read data on bit-line. Fig. 5 shows possible circuit schematic of sense amplifier that used for reading data from new cell.

5)-Idle mode: At the end of read operation, cell will go to idle mode and bit-line asserted to GND, respectively.

Fig. 6 shows waveform of new cell during read cycles.

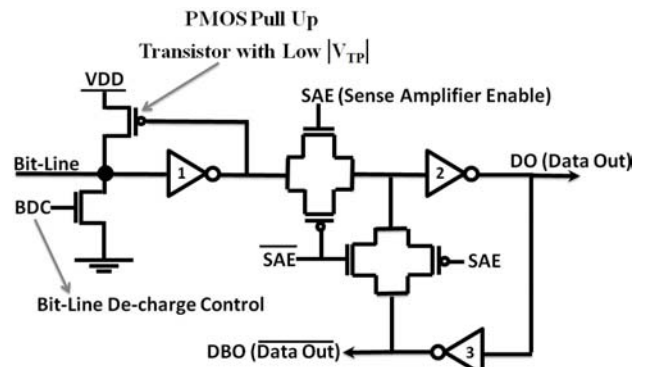


Fig. 5. Possible circuit schematic of sense amplifier.

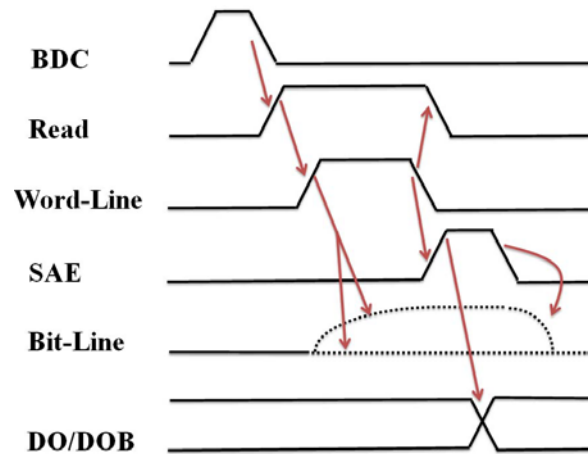


Fig. 6. Waveform of new cell during read cycle.

B. Cell area

Fig. 7 compares layout of 6T SRAM cell and 5T SRAM cell in scalable CMOS design rules. The 6T SRAM cell has the conventional layout topology and is as compact as possible. The 6T SRAM cell requires $416 \lambda^2$ area, whereas 5T SRAM cell requires $345 \lambda^2$ area. These numbers do not take into account the potential area reduction obtained by sharing with neighboring cells. Therefore the new cell size is 17% smaller than a conventional six-transistor cell using same design rules.

C. Leakage current

In one state, novel 5T SRAM cell must retains its data using the leakage current of the access transistor (when zero stored) and in the other state the 5T SRAM cell must retains its data using positive feedback (when one stored). Thus in idle mode when '1' stored in cell, there is positive feedback and M2, M3 and feedback cutting (M5) transistors are ON and access transistor maintained in sub-threshold region. In this state there is a path from

supply voltage to ground and power dissipated. Fig. 8 shows this path when '1' stored in cell.

In ordinary programs most of the bits in caches are zeroes for both the data and instruction streams. It has been shown that this behavior persists for a variety of programs under different assumptions about cache sizes, organization and instruction set architectures [7] [8]. Also in [8] from the execution traces of the SPEC2000 benchmarks on average, almost 75% and 64% of bit values are zero in the data and instruction caches, respectively. Thus most of bit values resident in the data and instruction caches are zero. Based on these observations we simulated average leakage current in idle mode of 5T SRAM cell and conventional 6T SRAM cell by using 65-nm PTM. Fig. 9 compares simulated average leakage current of 5T SRAM cell and conventional 6T SRAM cell by using 65-nm PTM, as shown in Fig. 9 the average leakage current of new cell 10% is grater than conventional 6T SRAM cell. It is quite clear, the cache based on new cell contains other component except cell array, and thus the effect of leakage current of cells on total leakage current of cache is less than 10%.

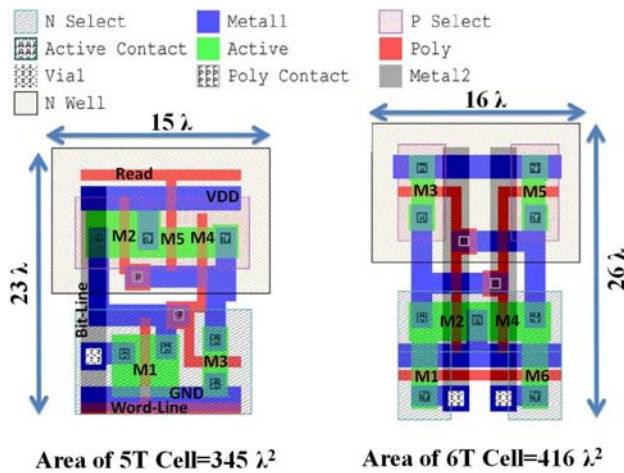


Fig. 7. Layout comparison of 5T cell and 6T cell.

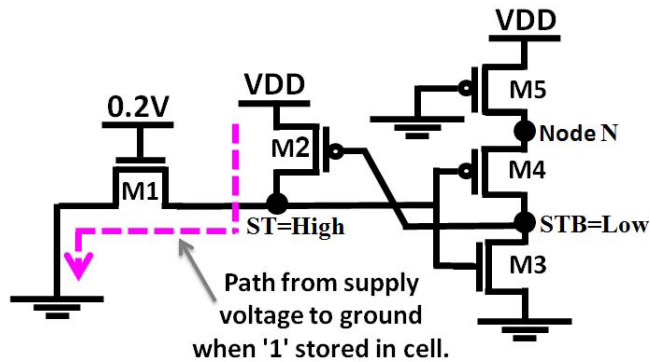


Fig. 8. Path from supply voltage to ground when '1' stored in cell.

IV. DYNAMIC ENERGY CONSUMPTION

In a cache, the major dynamic energy consuming components are bit-lines, word-lines, sense amplifiers,

decoders and output drivers [1]. In general, the bit-lines are the most power consuming component [1]. Therefore energy consumption during cache access consumed due to the transitions occur during read/write operation, and thus during each cache access a certain amount of energy is drawn from the power supply and dissipated. The energy consumption of each cache access depends on type of cache access (read or write).

When the capacitor C_L charged by a transistor from GND to V_{DD} and then discharged to GND by another transistor or same transistor, amount of energy is drawn from the power supply and dissipated, equals $C_L V_{DD}^2$ [9]. The stored energy on the capacitor C_L with voltage V_C

equals $\frac{1}{2} C_L V_C^2$. Thus each time the capacitor C_L charged

from V_C to V_{DD} by a transistor and then discharged to V_C by another transistor, amount of energy drawn from the power supply and dissipated, obtained by following expression.

$$E_{Supply} = C_L (V_{DD}^2 - V_C^2) \quad (1)$$

In following dynamic energy consumption in each cache access of 5T and 6T SRAM cell investigated analytically, and since sense amplifiers, decoders and output drivers in cache based on 5T cell and 6T cell approximately have same dynamic energy consumption and dynamic energy consumption of decoders and output drivers didn't depend on type of cell (5T or 6T) we ignore the dynamic energy consumption due to sense amplifiers, decoders and output drivers. Also symbols and parameters that we use throughout our analytical modeling are listed in Table 1.

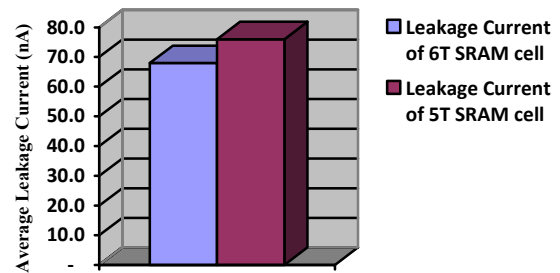


Fig. 9. Average leakage current comparison of 5T SRAM cell and 6T SRAM cell with the 65-nm PTM.

A. Capacitance in 5T SRAM cell and 6T SRAM cell

Fig. 10 shows a column and a row of cache based on novel 5T cell and basic 6T cell. According to this figure we can write following expression.

$$C_{BL-5T} = C_{Junction-Access-5T} + C_{Interconnect-BL-5T} \quad (2)$$

$$C_{WL-5T} = C_{Gate-Access-5T} + C_{Interconnect-WL-5T} \quad (3)$$

$$C_{Read-5T} = C_{Gate-Feedback-Cutting} + C_{Interconnect-Read} \quad (4)$$

$$C_{BL-6T} = C_{BLB-6T} = C_{Junction-Access-6T} + C_{Interconnect-BL-6T} \quad (5)$$

$$C_{WL-6T} = C_{Gate-Access-6T} + C_{Interconnect-WL-6T} \quad (6)$$

B. Dynamic energy consumption of conventional 6T SRAM cell

When a write operation is issued, a cache based on 6T SRAM cell will go through the following steps:

- 1)-Bit-line driving: For a write operation, this bit-line driving performed by turning on proper write buffer. After this step, the bit-line pair will be forced into full-swing logic level and then word-line asserted to V_{DD} [10].
- 2)-Cell flipping: If the value of the stored bit in the cell is the opposite to the value being written, then the cell flipping process will take place [10].
- 3)-Pre-charging: At the end of the write operation, word-line pulled to GND and bit-line pair pre-charged to V_{DD} [10].

Thus based on above writing process, when a write operation performed on a cache with 6T SRAM cell following transitions occur on word-line and bit-lines.

1-Word-line charged from GND to V_{DD} and then discharged to GND. Consequently amount of energy drawn from power supply and dissipated is $C_{WL-6T}V_{DD}^2$.

2-BL or BLB from V_{DD} discharged to GND and then charged to V_{DD} . Consequently amount of energy drawn from power supply and dissipated is $C_{BL-6T}V_{DD}^2$.

Therefore, when caches based on 6T SRAM cell accesses with write operation amount of energy is drawn from power supply and dissipated approximately obtained by following analytical expression.

$$E_{Write-cache-6T} = C_{WL-6T}V_{DD}^2 + C_{BL-6T}V_{DD}^2 \quad (7)$$

When a read operation is issued a cache based on 6T SRAM cell will go through the following steps:

- 1)-Word-line activation: At this step word-line asserted to V_{DD} and access transistors connect cell to their bit-lines [10].
- 2) - Bit-line deriving: After word-line asserted to high voltage, the target cell connected to their bit-lines. The so-called cell current through a drive transistor of target cell will discharge voltage of BL or BLB to V_{BL-Low} [10].
- 3)-In this step sense amplifier is enabled to read data on bit-lines [10].
- 4)-At the end of read operation word-line return to GND and bit-line pair per-charged to V_{DD} [10].

Thus based on above reading process, when a read operation performed on cache with 6T SRAM cell following transitions occur on word-line and bit-lines:

1-Word-line charged from GND to V_{DD} and then discharged to GND. Consequently amount of energy drawn from power supply and dissipated is $C_{WL-6T}V_{DD}^2$.

2-BL or BLB from V_{DD} discharged to V_{BL-LOW} and then charged to V_{DD} . Consequently amount of energy drawn

from power supply and dissipated is

$$C_{BL-6T}(V_{DD}^2 - V_{BL-LOW}^2).$$

Therefore, when a read operation performed on a cache based on 6T SRAM cell amount of energy is drawn from power supply and dissipated approximately obtained by following analytical expression.

$$E_{Read-cache-6T} = C_{WL-6T}V_{DD}^2 + C_{BL-6T}(V_{DD}^2 - V_{BL-LOW}^2) \quad (8)$$

In the instruction cache, because all accesses are cache reads, cache writes only occur in case of misses. In the data cache, the cache writes also arise in the execution of STORE instruction besides the cache misses [1]. The proportion of cache writes to reads is about 1: 2 in data cache [11]. Thus based on these observations in worst case 33% of accesses are write and 67% are read and the average dynamic energy consumption in a cache access can be estimated by following expression.

$$E_{Access-cache-6T} = 0.33 \times E_{Write-cache-6T} + 0.67 \times E_{Read-cache-6T} \quad (9)$$

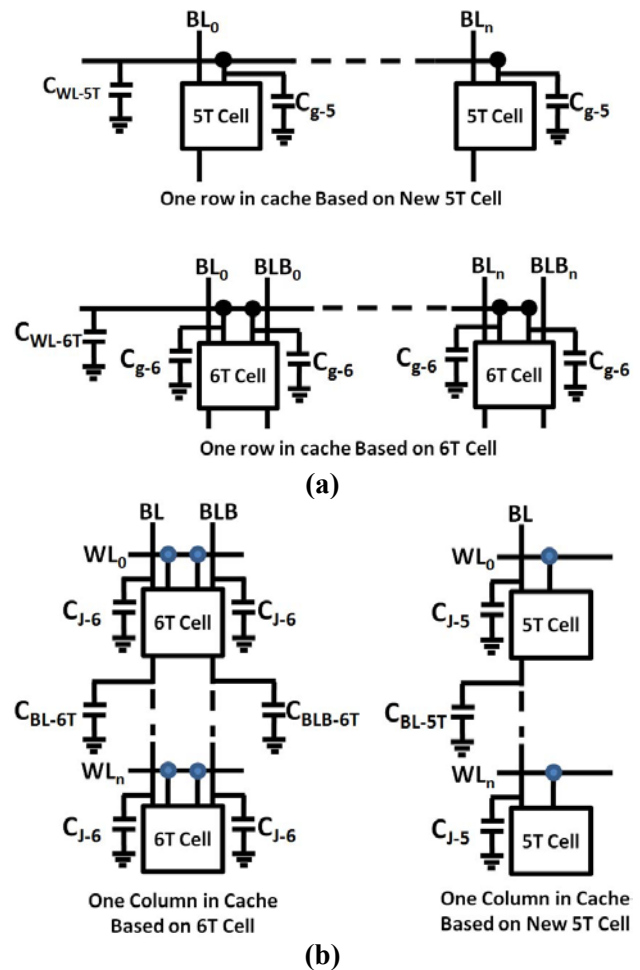


Fig. 10. A row and a column of cache based on new 5T cell and a cache based on 6T cell.

C. Dynamic energy consumption of novel 4T-SRAM cell

Based on read and write operation described in Section 3, when write operation is issued depending on the value must be stored in the cell, there are two cases in write energy consumption: one is write '0' and the other is write '1'.

a)-In the case of write '0' following transitions occur on word-line.

1-Word-line charged by a transistor from V_{Idle} to V_{DD} and then discharged to V_{Idle} . Consequently amount of energy drawn from power supply and dissipated is $C_{WL-5T}(V_{DD}^2 - V_{Idle}^2)$.

Thus in this case the energy consumption estimated by following expression.

$$E_{Write-0-cache-5T} = C_{WL-5T}(V_{DD}^2 - V_{Idle}^2) \quad (10)$$

b)-In the case of write '1' following transitions occur on word-line and bit-line.

1-Word-line charged by a transistor from V_{Idle} to V_{DD} and then discharged to V_{Idle} . Consequently amount of energy drawn from power supply and dissipated is $C_{WL-5T}(V_{DD}^2 - V_{Idle}^2)$.

2-BL charged by a transistor from GND to V_{DD} and then discharged to GND. Consequently amount of energy drawn from power supply and dissipated is $C_{BL-5T}V_{DD}^2$.

Thus in this case the energy consumption estimated by following expression.

$$E_{Write-1-cache-5T} = C_{WL-5T}(V_{DD}^2 - V_{Idle}^2) + C_{BL-5T}V_{DD}^2 \quad (11)$$

In [1] from the execution traces of the SPEC2000 benchmarks around 85% of the instruction write bits are '0' and over 90% of the data write bits are '0'. Therefore, in worst case when a write operation performed on cache with novel 5T SRAM cell on average amount of energy is drawn from power supply and dissipated approximately obtained by following analytical expression.

$$E_{Write-cache-5T} = 0.85 \times E_{Write-0-cache-5T} + 0.15 \times E_{Write-1-cache-5T} \quad (12)$$

When the read operation is issued depending on the value stored in the cell, there are two cases in read energy consumption: one is read '0' and the other is read '1'.

a)-In the case of read '0' following transition occur on word-line and read-line.

1- Word-line charged by a transistor from V_{Idle} to V_{DD} and then discharged to V_{Idle} . Consequently amount of energy drawn from power supply and dissipated is $C_{WL-5T}(V_{DD}^2 - V_{Idle}^2)$.

2- Read-line charged by a transistor from GND to V_{DD} and then discharged to GND. Consequently amount of energy drawn from power supply and dissipated is $C_{Read-5T}V_{DD}^2$.

Thus in this case the energy consumption estimated by following expression.

$$E_{Read-0-cache-5T} = C_{WL-5T}(V_{DD}^2 - V_{Idle}^2) + C_{Read-5T}V_{DD}^2 \quad (13)$$

b)-In the case of read '1' following transitions occur on word-line1 and BLB.

TABLE I.
SUMMARY OF NOTATIONS USED IN THE ANALYTICAL MODEL.

| Symbol | Parameter |
|--|---|
| C_{g-6T}, C_{g-5T} | Gate capacitance of access transistor 6T and 5T SRAM cell |
| C_{J-6T}, C_{J-5T} | junction capacitance of access transistor 6T and 5T SRAM cell |
| $C_{Junction-Access-5T}, C_{Junction-Access-6T}$ | Load capacitance due to junction capacitance of access transistors connected to bit-line |
| $C_{Interconnect-BL-5T}, C_{Interconnect-BL-6T}$ | Load capacitance due metal of bit-line |
| $C_{Gate-Access-5T}, C_{Gate-Access-6T}$ | Load capacitance due to gate capacitance of access transistors connected to word-line |
| $C_{Interconnect-WL-5T}, C_{Interconnect-WL-6T}$ | Load capacitance due metal or poly of word-line |
| $C_{Gate-Feedback-Cutting}$ | Load capacitance due to gate capacitance of feedback-cutting transistors connected to read-line |
| $C_{Interconnect-Read}$ | Load capacitance due metal or poly of read-line |
| C_{BL-6T}, C_{BL-5T} | BL capacitance of a cache based on 6T and 5T SRAM cell |
| $C_{Read-5T}$ | Read-line capacitance of a cache based on 5T SRAM cell |
| C_{WL-5T}, C_{WL-6T} | Word-line capacitance of a cache based on 5T and 6T SRAM cell |
| C_{BLB-6T} | BLB capacitance of a cache based on 6T SRAM Cell |
| V_{DD} | Supply voltage |
| V_{BL-Low} | Voltage of BL or BLB during read operation in a cache based on 6T Cell |
| $V_{BL-High}$ | Voltage of BL during read operation in a cache based on 5T SRAM Cell |
| V_{Idle} | Voltage of word-line during idle mode in 5T SRAM Cell |
| $E_{Write-Cache-6T}$ | Average Energy consumption of write operation in cache based on 6T SRAM Cell |
| $E_{Read-Cache-6T}$ | Average Energy consumption of read operation in cache based on 6T SRAM Cell |
| $E_{Access-Cache-6T}$ | Average Energy consumption during cache access in cache based on 6T SRAM Cell |
| $E_{Write-0-Cache-5T}$ | Energy consumption of writing zeros in cache based on 5T SRAM Cell |
| $E_{Write-1-Cache-5T}$ | Energy consumption of writing ones in cache based on 5T SRAM Cell |
| $E_{Read-0-Cache-5T}$ | Energy consumption of reading zeros in cache based on 5T SRAM Cell |
| $E_{Write-1-Cache-5T}$ | Energy consumption of reading ones in cache based on 5T SRAM Cell |
| $E_{Write-Cache-5T}$ | Average Energy consumption of write operation in cache based on 5T SRAM Cell |
| $E_{Read-Cache-5T}$ | Average Energy consumption of read operation in cache based on 5T SRAM Cell |
| $E_{Access-Cache-5T}$ | Average Energy consumption during cache access in cache based on 5T SRAM Cell |

1- Word-line charged by a transistor from V_{Idle} to V_{DD} and then discharged to V_{Idle} . Consequently amount of energy drawn from power supply and dissipated is $C_{WL-5T}(V_{DD}^2 - V_{Idle}^2)$.

2- Read-line charged by a transistor from GND to V_{DD} and then discharged to GND. Consequently amount of energy drawn from power supply and dissipated is $C_{Read-5T}V_{DD}^2$.

3-BL charged by a transistor from GND to $V_{BL-High}$ and then discharged to GND. Consequently amount of energy drawn from power supply and dissipated is $C_{BL-5T}V_{BL-High}^2$.

Thus in this case the energy consumption estimated by following expression.

$$E_{Read-1-cache-5T} = C_{WL-5T}(V_{DD}^2 - V_{Idle}^2) + C_{Read-5T}V_{DD}^2 + C_{Read-5T}V_{DD}^2 \quad (14)$$

Over 70% of the bits that are read from the cache are zeros [3]. Therefore, when a read operation performed on cache with novel 4T SRAM cell on average amount of energy is drawn from power supply and dissipated approximately obtained by following analytical expression.

$$E_{Read-cache-5T} = 0.7 \times E_{Read-0-cache-5T} + 0.3 \times E_{Read-1-cache-5T} \quad (15)$$

As mentioned above, around 33% of accesses are writing and 67% are reading. Thus in cache with new 5T cell, we can estimate worst case average dynamic energy consumption of cache access by following expression.

$$E_{Access-cache-5T} = 0.33 \times E_{Write-cache-5T} + 0.67 \times E_{Read-cache-5T} \quad (16)$$

D. Dynamic energy consumption Comparison

Fig. 11 shows the average dynamic energy consumption in a cache access of novel SRAM cell and 6T SRAM cell by using parameter values listed in Table 2. As shown in Fig. 11 the average dynamic energy consumption in cache accesses of cache based on novel SRAM cell is %30 smaller than cache based on 6T SRAM cell. For this reduction there are two obvious reasons as follows. First, in writing and reading zero of new cell there is not any change on bit-line since bit-line maintained at GND in idle mode. Therefore the energy consumption of writing and reading zero are smaller than writing and reading one. Second, reading '0' or writing '0' occurs more frequently than reading '1' or writing '1'.

V. EXPERIMENTAL RESULTS

To verify correct operation of new 5T SRAM cell and comparison with 6T SRAM cell, we simulate a 5T SRAM cell and 6T SRAM cell using HSPICE with 1V for supply voltage also the HSPICE parameters are obtained from the latest Predictive Technology Models

(PTMs) for the technology node of 65-nm [6]. Based on layouts shown in Fig. 7, and with using Tanner L-Edit CAD tool we extract the HSPICE Netlist of novel 5T SRAM cell and 6T SRAM cell. Also based on layouts shown in Fig. 7, all parasitic capacitances and resistances of bit-lines, word-lines are included in the circuit simulation. For testing the correctness of a read and write operation of new 5T SRAM cell, following scenario applied to new 5T SRAM cell:

- Writing '0' in to new cell and then read it.
- Writing '1' in to new cell and then read it.

Fig. 12 and Fig. 13 show simulated waveform with applying above scenario. As shown in Fig. 12 when '0' read from new 5T cell there is not any read noise on ST node but as shown in Fig. 13 when '1' read from new 5T cell, ST node pulled to low voltage, because Bit-line floated at GND during read operation. Since during read operation feedback-cutting transistor is OFF, consequently there is not any relation between ST node and STB node and finally injected noise by access transistor during reading '1' removed by core of cell.

Based on simulation results and analytical results of previous sections, Table 3 compares the novel 5T SRAM cell and Basic 6T SRAM cell. The average cache access delay is defined as the average elapsed time for performing read or writes operation without including write buffer delay and sense amplifier delay. Also the static noise margin (SNM) is defined as the maximum value of DC disturbances that can be tolerated before the cell's storage value is flipped [12].

As shown in Table 3 the new 5T cell is 20% faster than 6T cell. For this speed improvement there are two obvious reasons as follows. First, in new 5T cell there is not any relation between read SNM and cell current. Thus we can increase the cell current of new cell without any read SNM degradation. Whereas in 6T cell any increasing the cell current for speed improvement resulting read data destruction. Second, W/L of access transistor of new cell selected greater than W/L of access transistors of 6T cell for speed improvement. Therefore the cell current of new 5T cell is higher than 6T cell and this resulting faster transition on ST and STB node and bit-line.

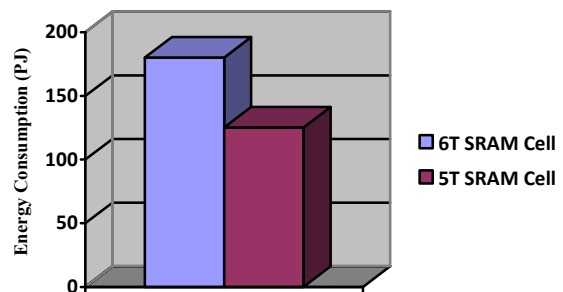


Fig. 11. Average dynamic energy consumption of a cache with 5T SRAM cell and with 6T SRAM cell.

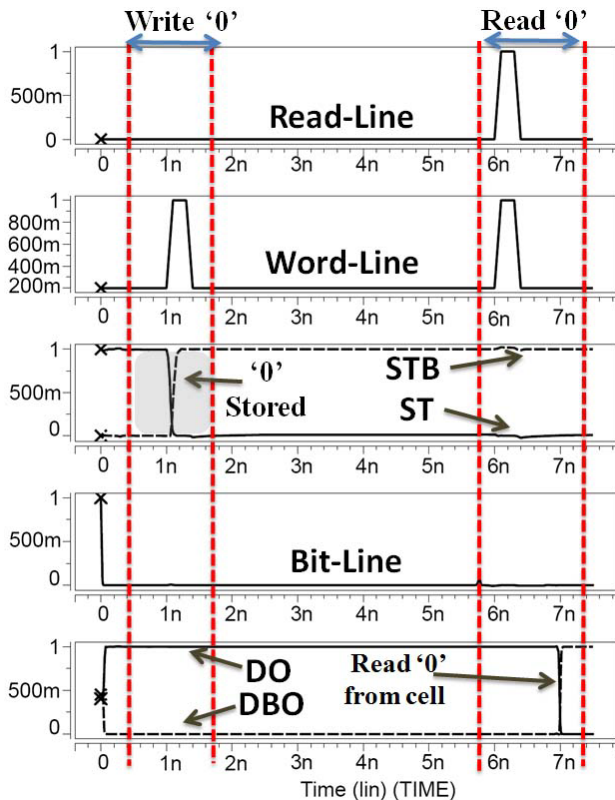


Fig. 12. Simulated waveform for writing '0' and read it.

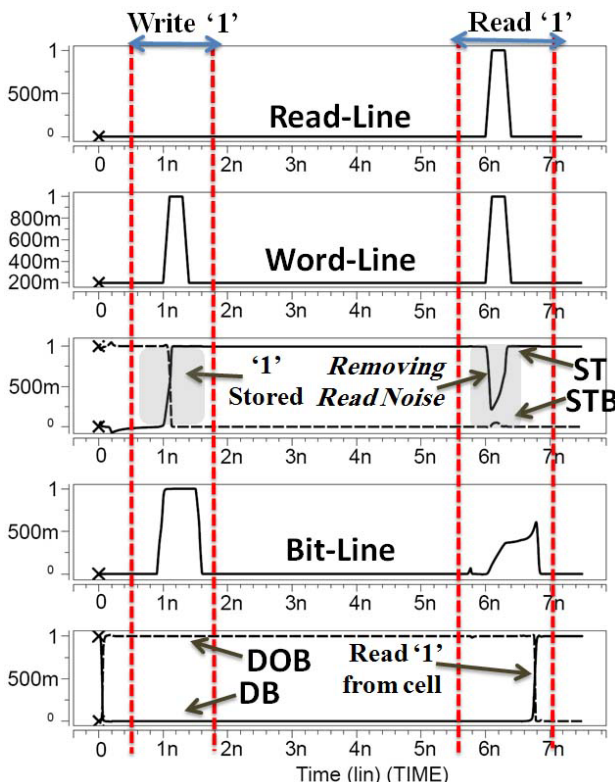


Fig. 13. Simulated waveform for writing '1' and read it.

VI. CONCLUSION

With the aim of achieving a high density and low power cache, we developed a 5T SRAM cell. The key observations behind our design are that dynamic occurrence of zeros in the cache access stream and cache-

resident memory values of ordinary programs exhibit a strong bias towards zero. New cell retains its data with leakage current when there is not any positive feedback. In same design rules proposed cell area is 17% smaller than 6T SRAM cell with 20% speed improvement. Dynamic energy consumption during cache access of new cell is 30% smaller than 6T SRAM cell but the proposed cell is with 10% cell leakage current penalty.

TABLE II.
PARAMETER VALUES USED IN ANALYTICAL EXPRESSIONS.

| Symbol | Value |
|-------------------------|--------|
| C_{WL-6T} | 0.8pF |
| C_{WL-5T} | 0.9pF |
| C_{BL-6T}, C_{BLB-6T} | 1.35pF |
| C_{BL-4T} | 1.5pF |
| V_{DD} | 1V |
| V_{Idle} | 0.3V |
| V_{BL-Low} | 0.7V |
| $V_{BL-High}$ | 0.5V |

TABLE III.
PERFORMANCE COMPARISONS OF SRAM CELLS

| Metrics | 6T SRAM Cell | 5T SRAM Cell |
|--|--------------|--------------|
| Average Cache Access Delay | 180ps | 143ps |
| Static Noise Margin | 0.45V | 0.5V |
| Average Leakage Current | 68nA | 76nA |
| Average Dynamic Energy Consumption in Cache Access | 180pJ | 125pJ |
| Read Static Noise Margin | 0.3V | Free |

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Arash Azizi Mazreah received the B.S. degree in computer hardware engineering and M.S. degree in computer system architecture engineering in 2005 and 2007 respectively. Currently he is a Ph.D. candidate in computer system architecture engineering at Islamic Azad University, Science and Research Branch and faculty of Islamic Azad

University, Sirjan branch. His major research experiences and interests include low power digital system design, high speed SRAM, and VLSI testing and high density VLSI system design.



Mohammad Taghi Manzuri received his B.S. and M.S. in Electrical Engineering from Sharif University of Technology, Iran, in 1984 and 1988, respectively; and Ph.D. in Electrical and Computer Engineering from Vienna University of Technology, Austria, in 1995. Currently, he is an associate professor in Computer Engineering Department of Sharif University of

Technology, Tehran, Iran. His main research interests include digital signal processing, robotics, image processing, and data communications.



Ali Mehrparvar received the B.S. degree in computer hardware engineering in 2002. Currently he is a M.S. candidate in computer system architecture engineering. His major research experiences and interests include interests include low power digital system design, high speed SRAM, and VLSI testing and high density VLSI system design.