A Content Addressable Memory Using Magnetic Domain Wall Motion Cells

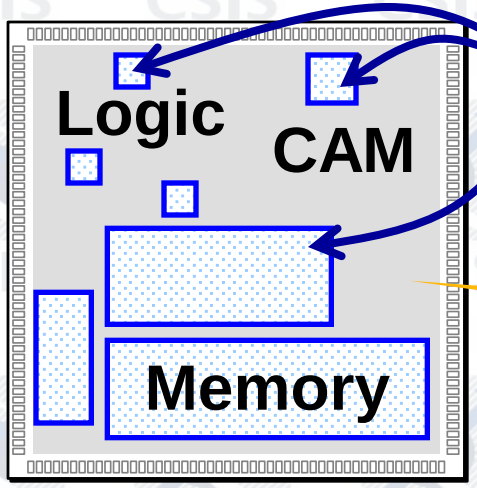
R. Nebashi[1], N. Sakimura[1], Y. Tsuji[1], S. Fukami[1],
H. Honjo[1], S. Saito[1], S. Miura[1], N. Ishiwata[1],
K. Kinoshita[1], T. Hanyu[2], T. Endoh[2], N. Kasai[2], H. Ohno[2],
and T. Sugibayashi[1]

[1] NEC Corporation, Japan
[2] Tohoku University, Japan

Outline

- Introduction
- Demonstration of Spintronics-based CAM Test Chip
  - Multi-free layer domain wall (DW) motion cell
  - Shared write transistor
- Future Challenge
  - Multi-context Spin CAM
  - Domain wall motion in CoFeB
- Summary

Motivation



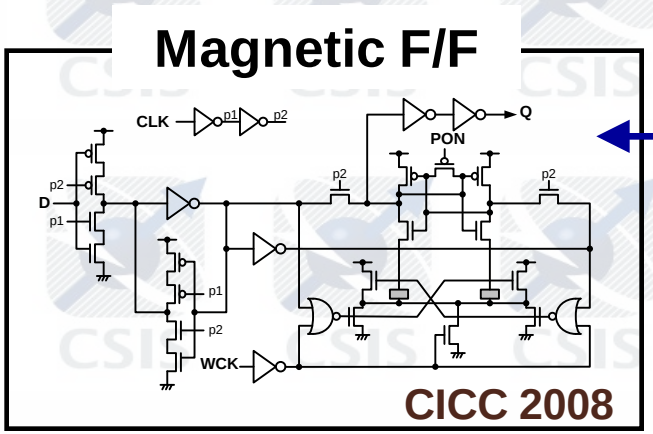
Non-volatile
storage element
(MTJ: magnetic tunnel junction)

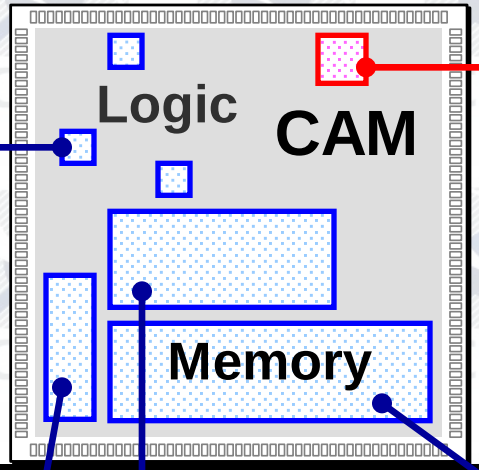
Data are retained even in
a power off state

Non-volatile Spintronics SoC with power gating

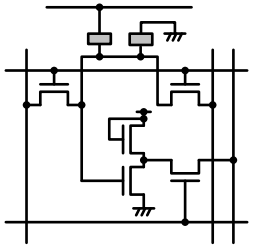
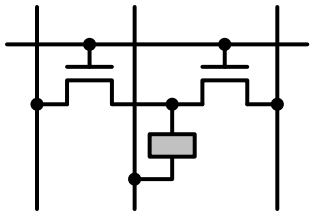
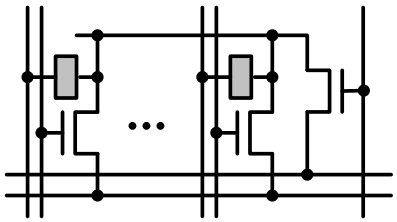
- **Reduced leakage current**
- **Small power penalty for state retention and reload**

Overview of Spintronics Core on SoC



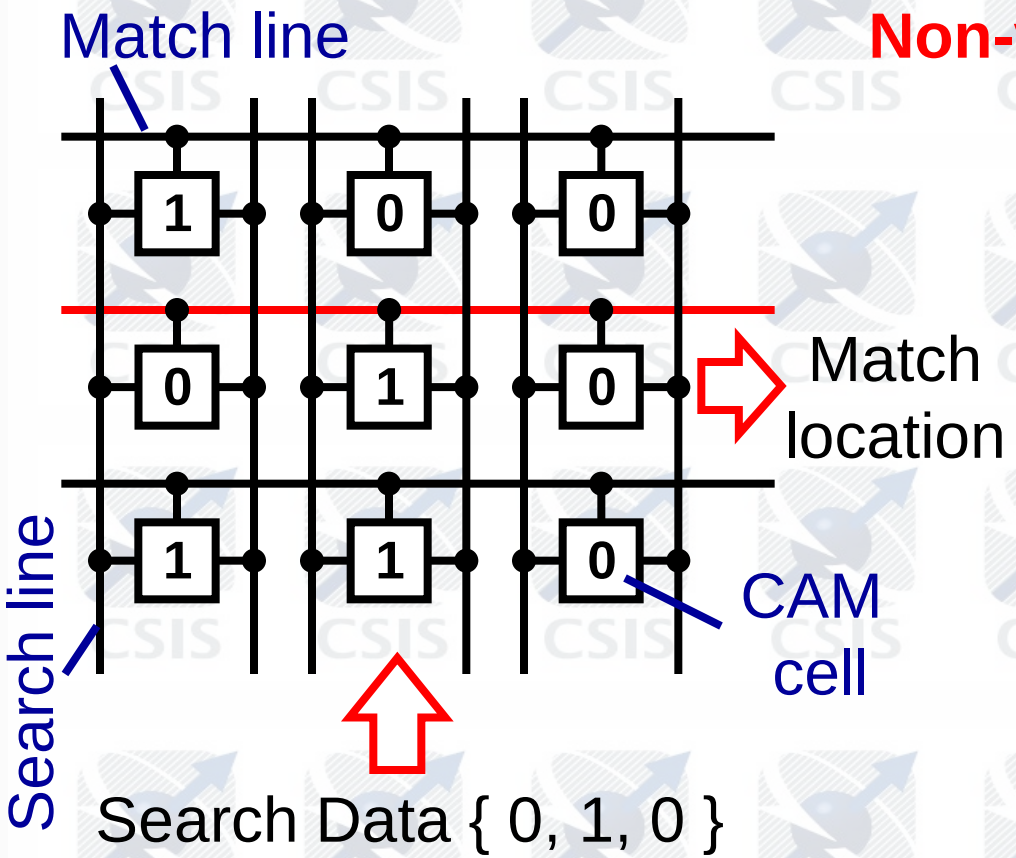


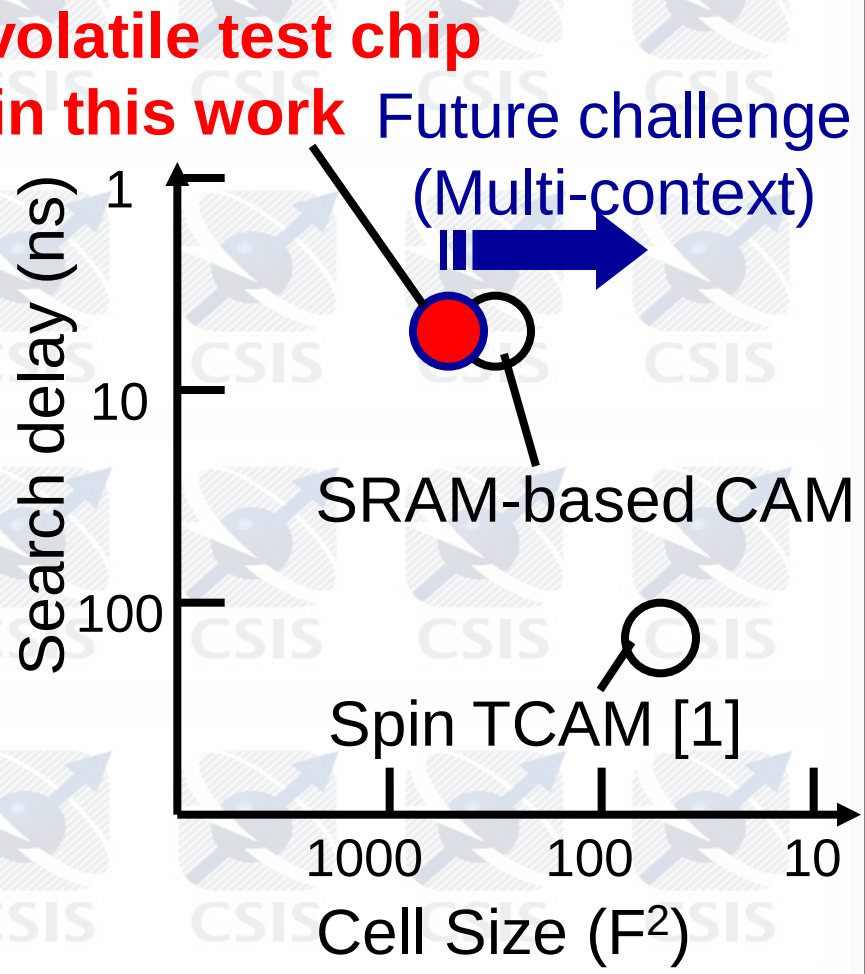
This work

Speed	~ 500 MHz	~ 200 MHz	~ 33 MHz
Capacity	Small	Medium	Large
Cell	5T2MTJ  VLSI Cir. 2006	2T1MTJ  VLSI Cir. 2006	9T8MTJ/8bit  A-SSCC 2007

- Different MTJ cell is needed for different layer in memory hierarchy
- However, the best MTJ cell for CAM is not existed

Content Addressable Memory (CAM)



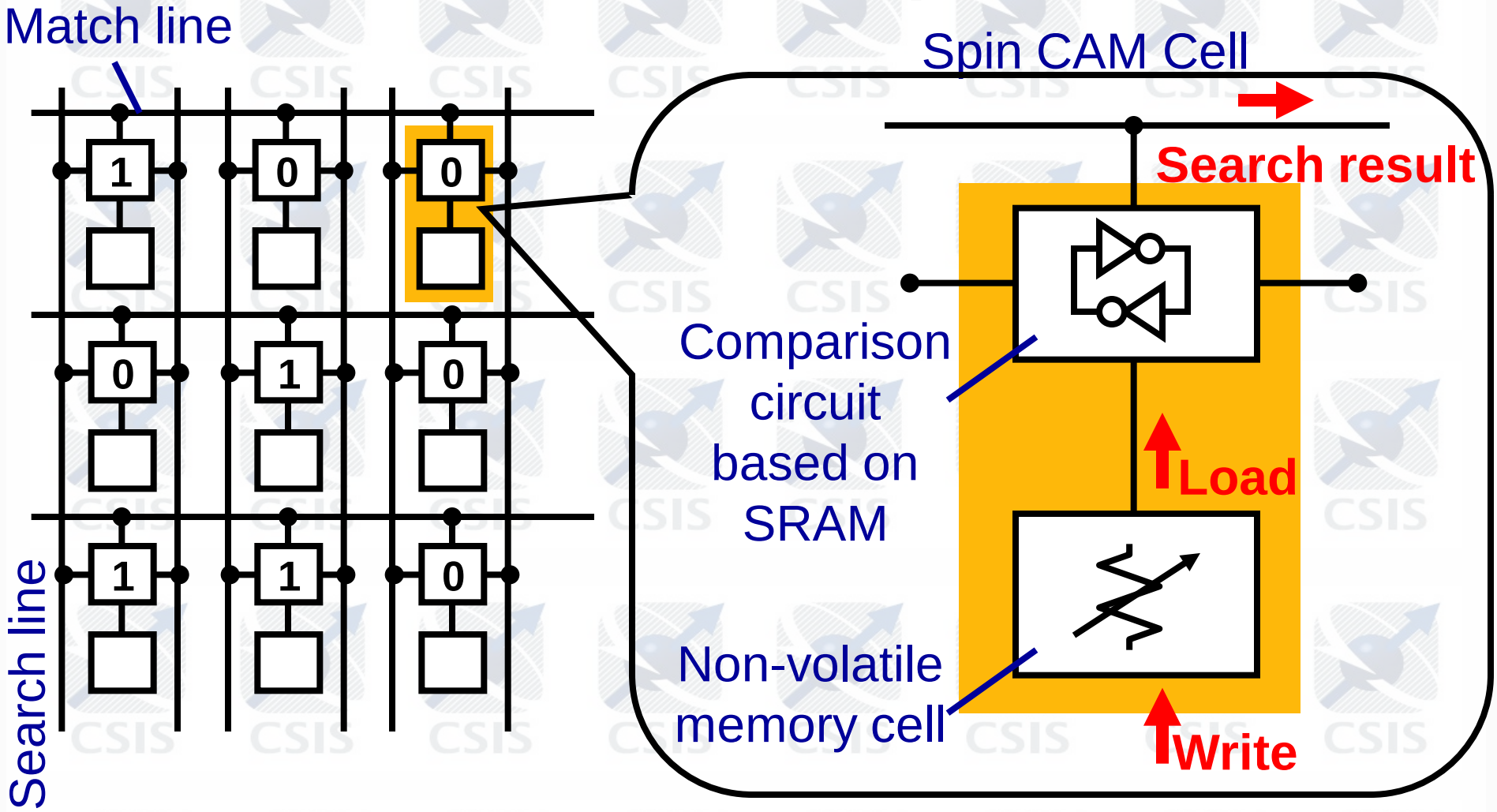


Design target

Fast search and Compact

[1] S. Matsunaga et al., APEX, 2, 023004, 2009.

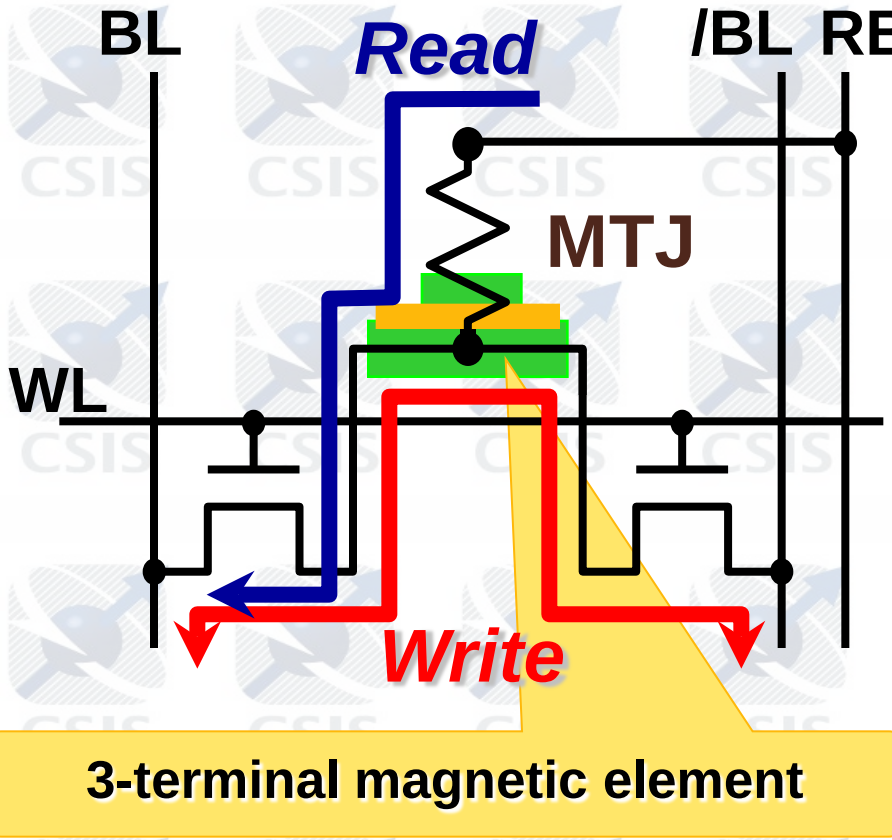
Basic Concept of Spin CAM



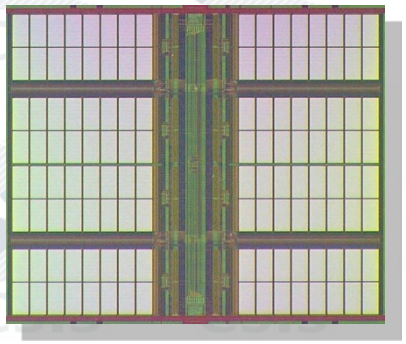
- **Once data are transferred from non-volatile memory to comparison circuit, fast search is executable**

2Tr-1MTJ Cell for High Speed R/W Operation

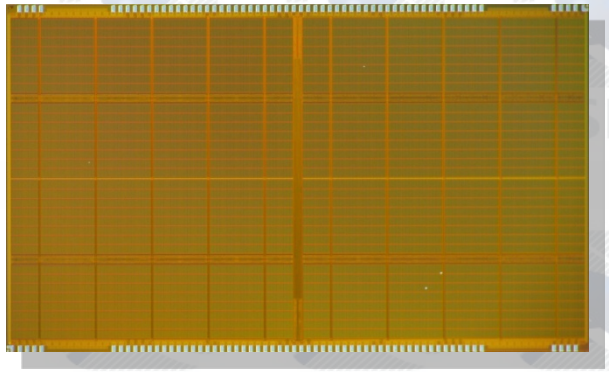
2Tr-1MTJ cell



3-terminal magnetic element



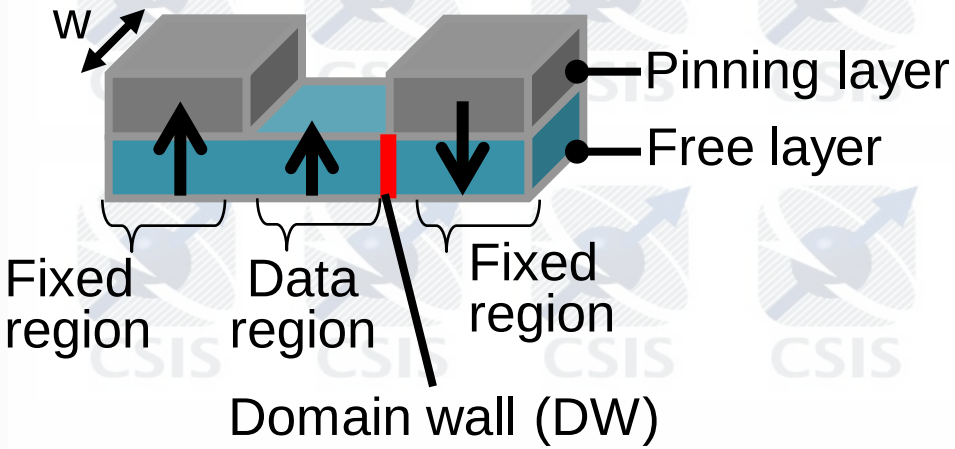
250MHz (ASSCC 2007)

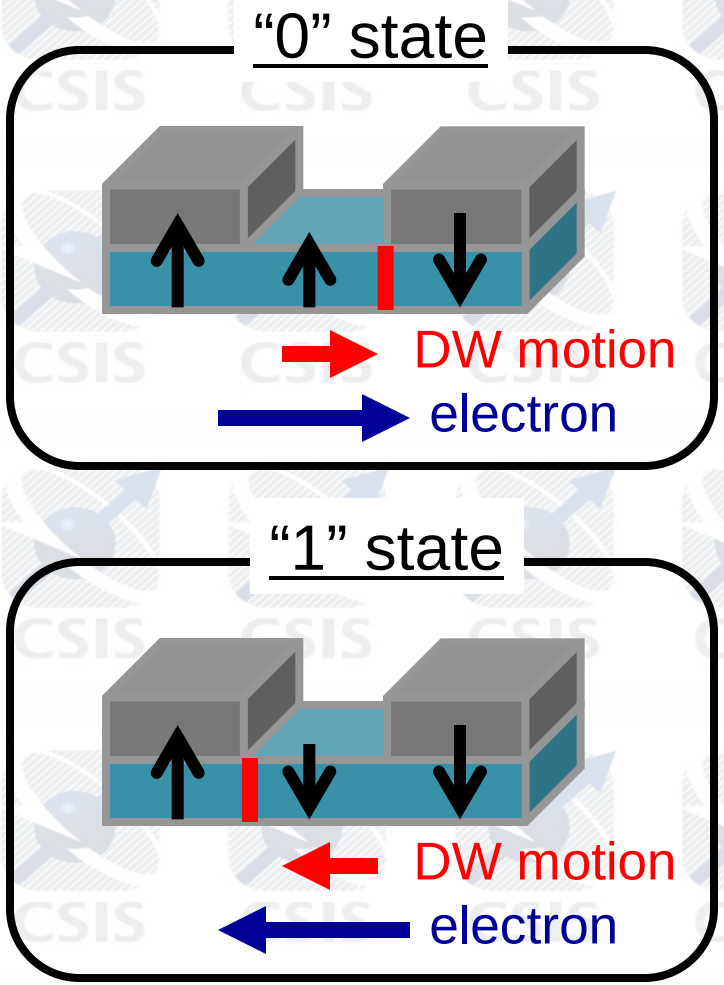


32Mbit (ISSCC 2009)

- High speed operations were demonstrated by using 3-terminal element with magnetic field writing.

Magnetic Domain Wall Motion Cell

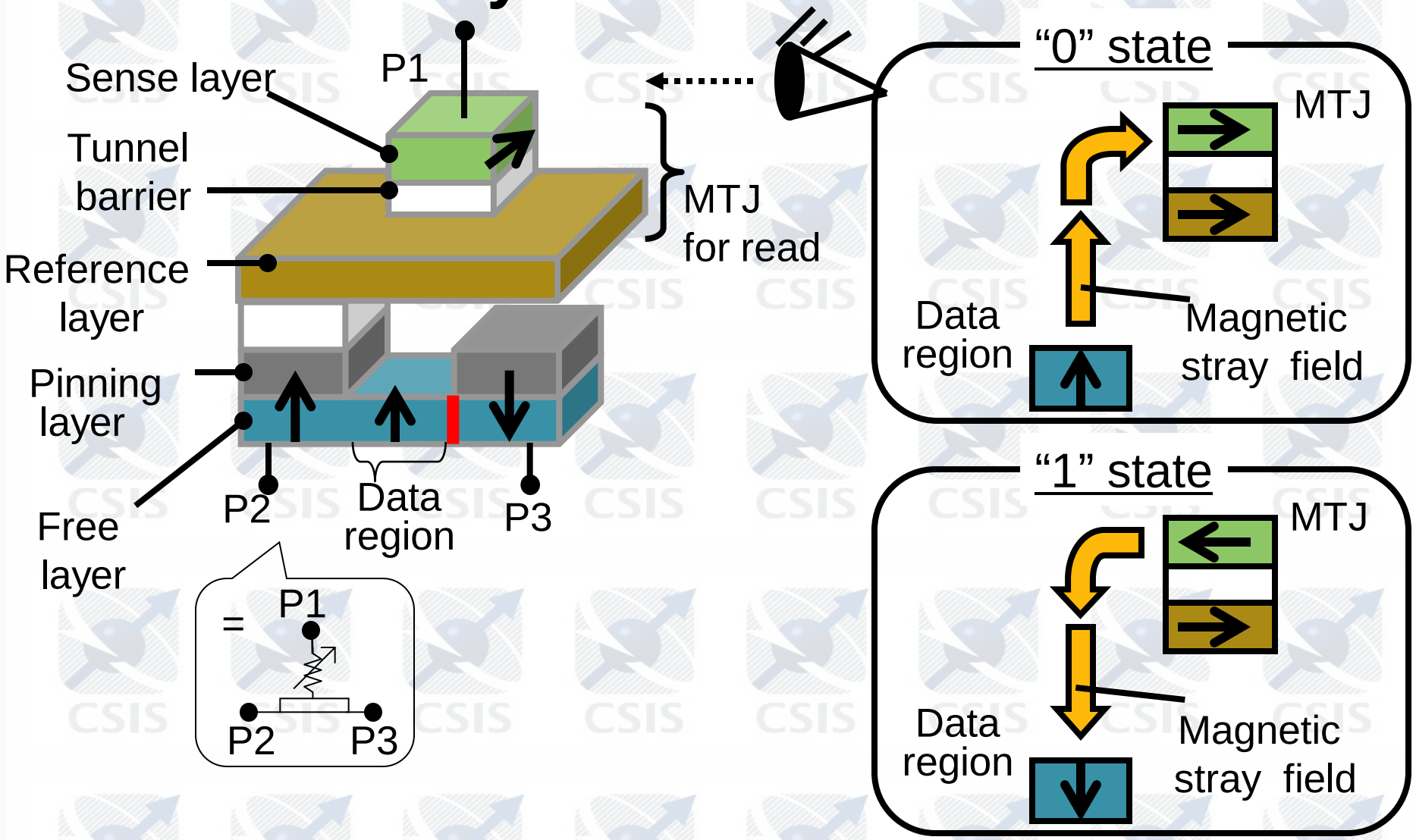




VLSI 2009

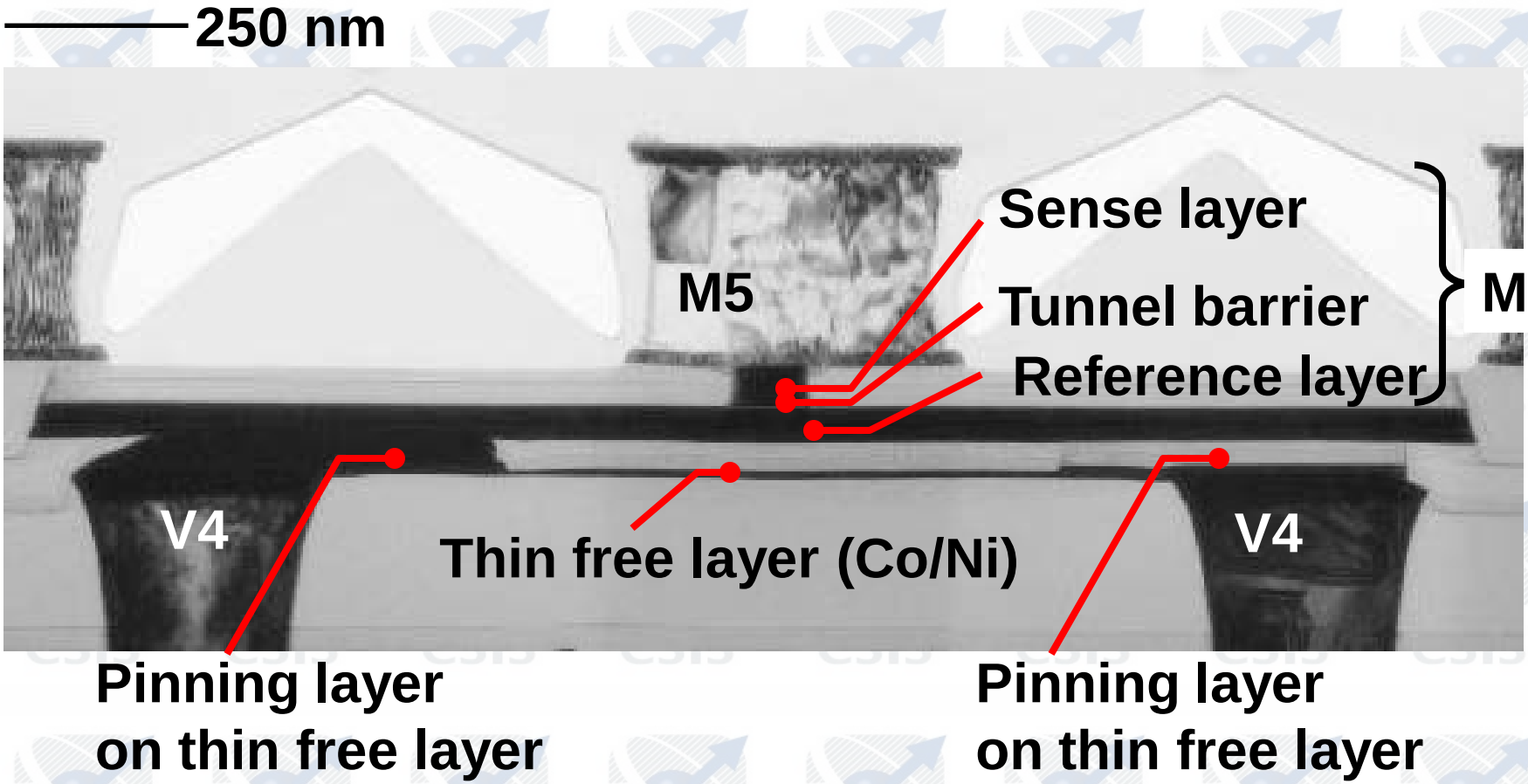
- **Low writing current (200 μA @ w = 90 nm) was obtained**

Multi-free Layer Domain Wall Motion Cell

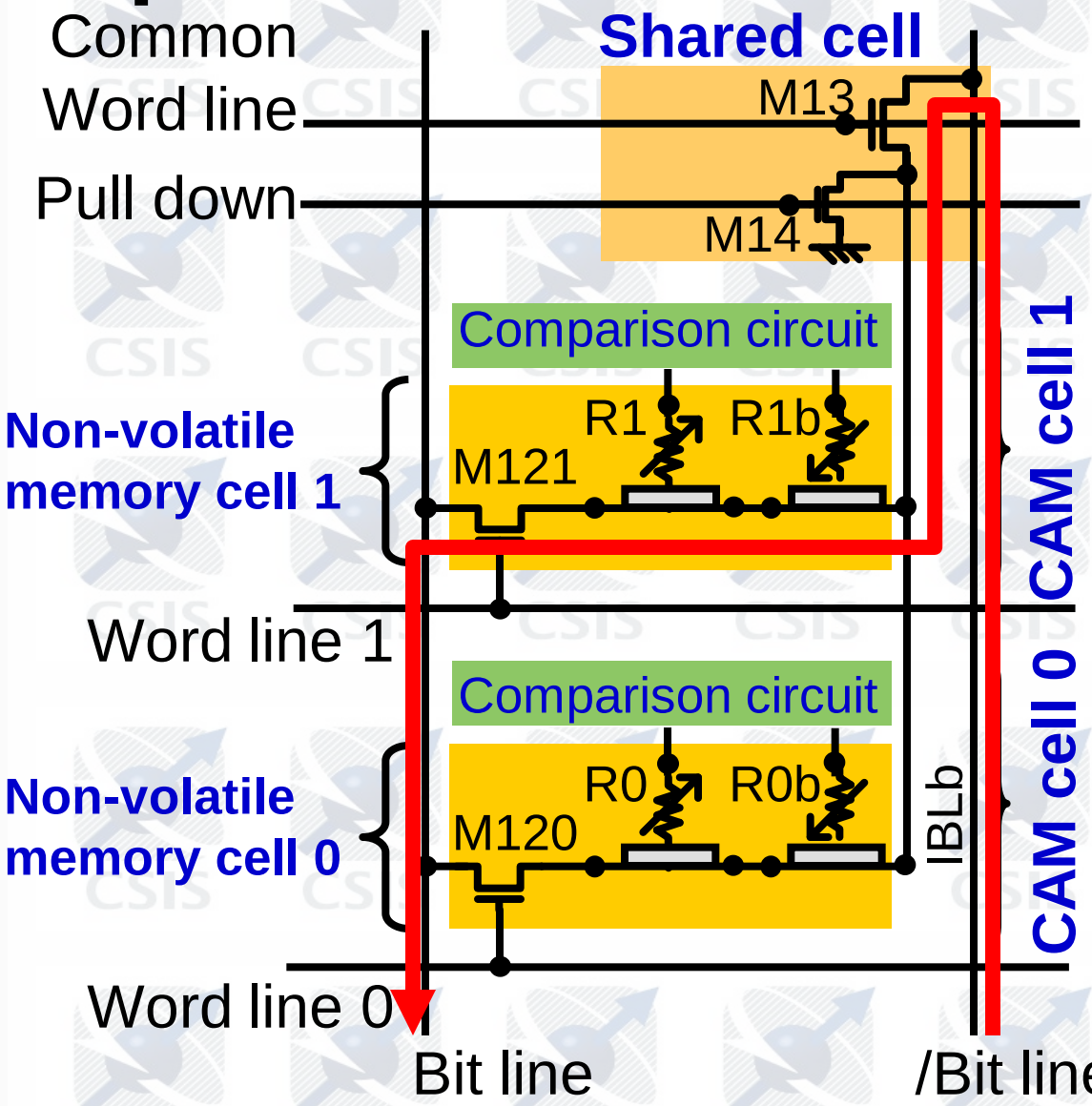


- **Fast read operation and low writing current were obtained**

Multi-free layer Domain Wall Motion Cell



Spin CAM with Shared Write Transistor

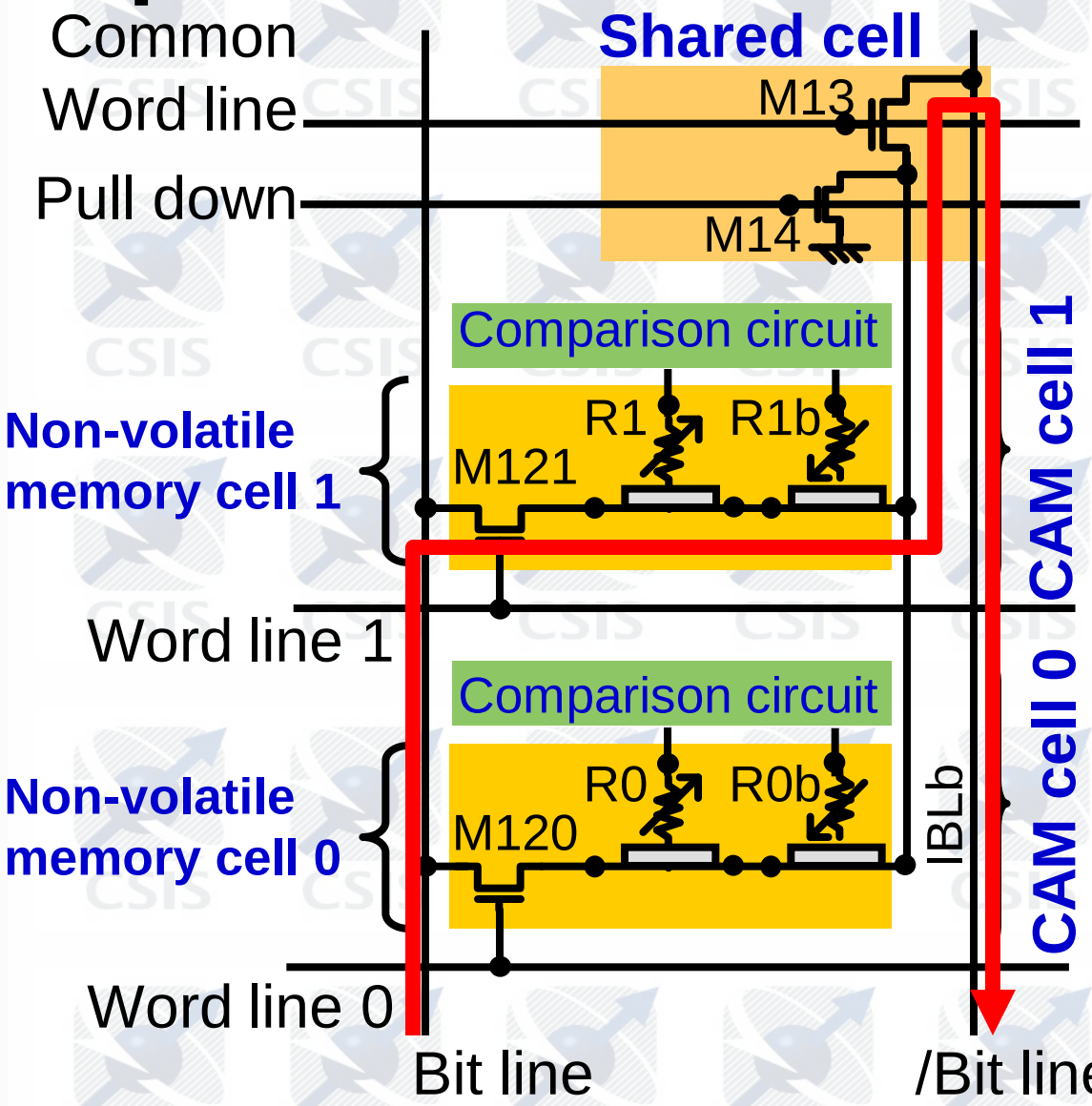


- 3-terminal elements (R1 and R1b) share write transistor (M13, M121)
- CAM cells share write transistor (M13)

→Cell area reduced

Write current Iw (0)

Spin CAM with Shared Write Transistor

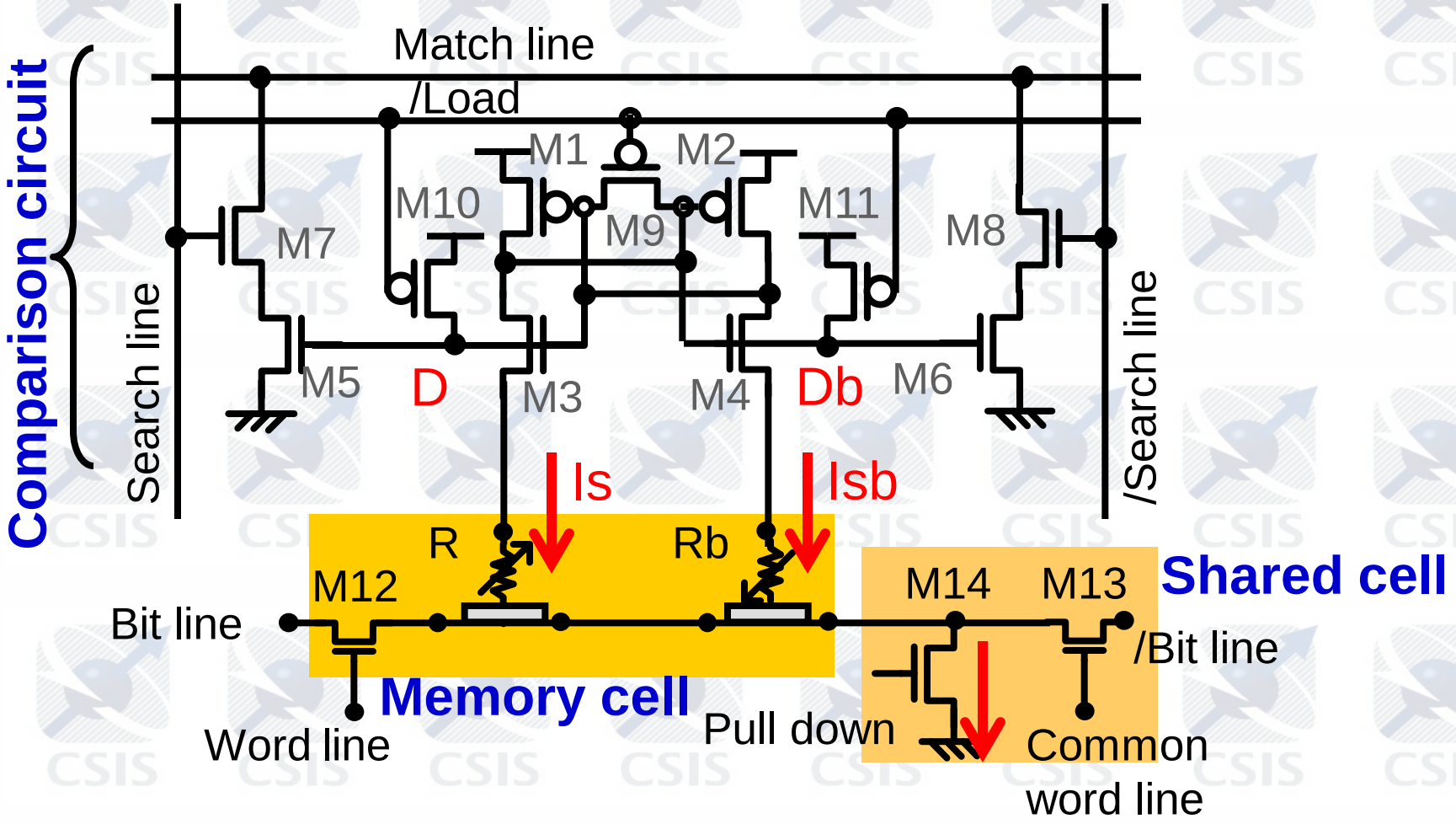


- 3-terminal elements (R1 and R1b) share write transistor (M13, M121)
- CAM cells share write transistor (M13)

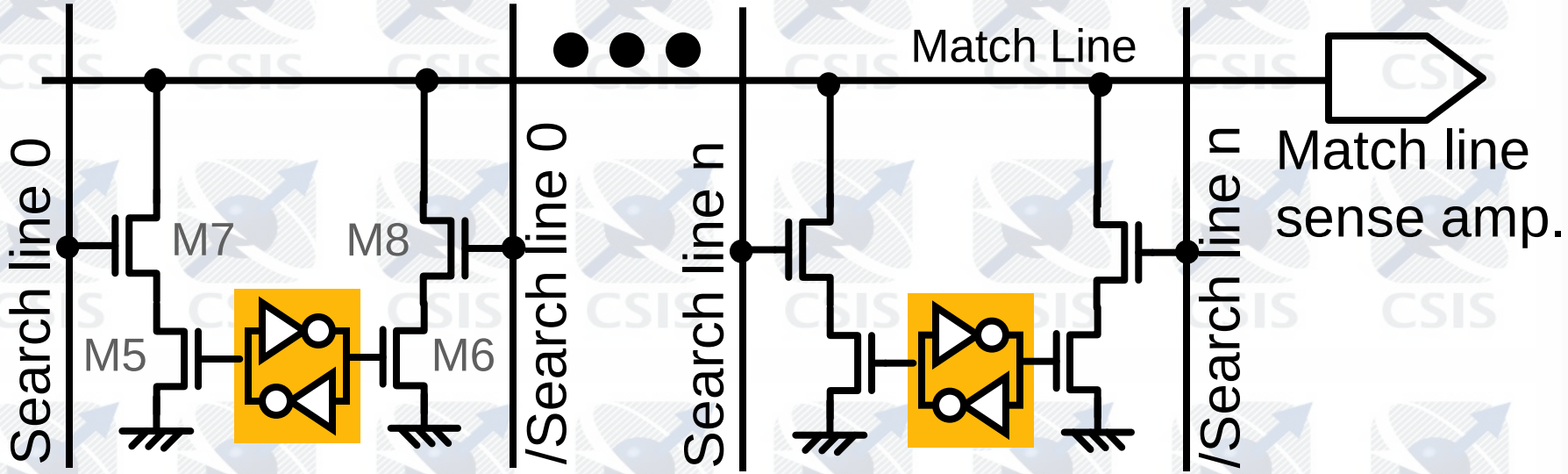
→Cell area reduced

Write current Iw (1)

Load Operation of Spin CAM



Search Operation of Spin CAM



(search operation)

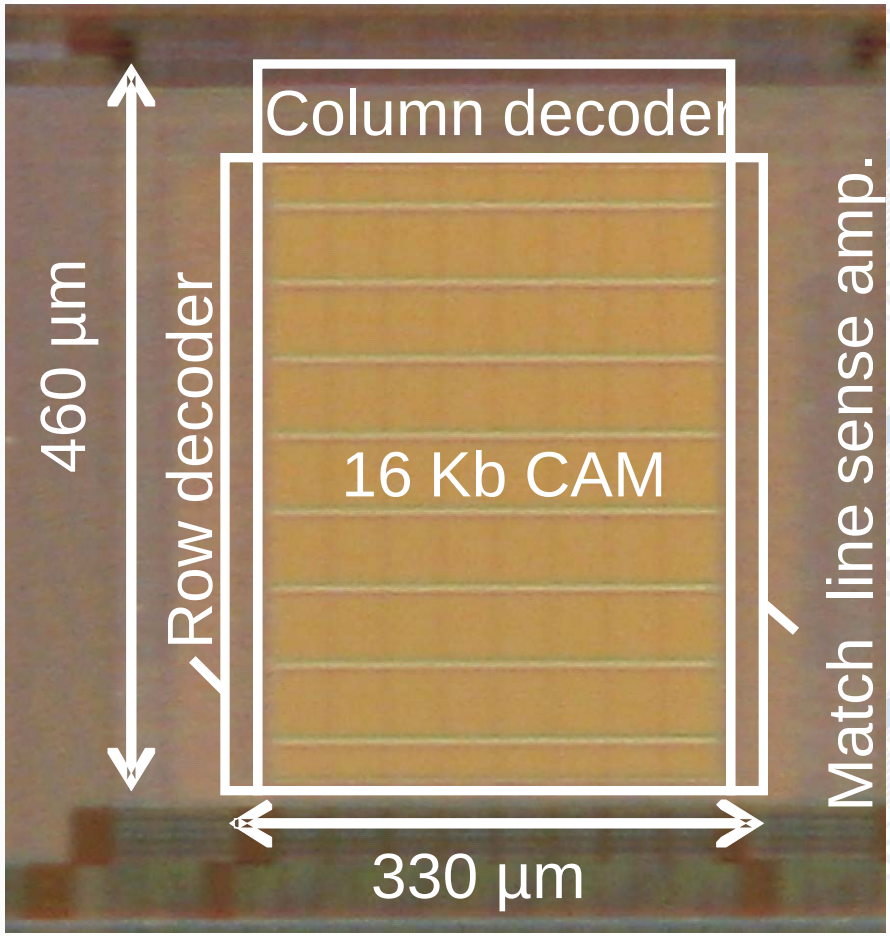
1. Search line precharged to Gnd

2. Match line precharged to Vdd

3. Match line evaluate

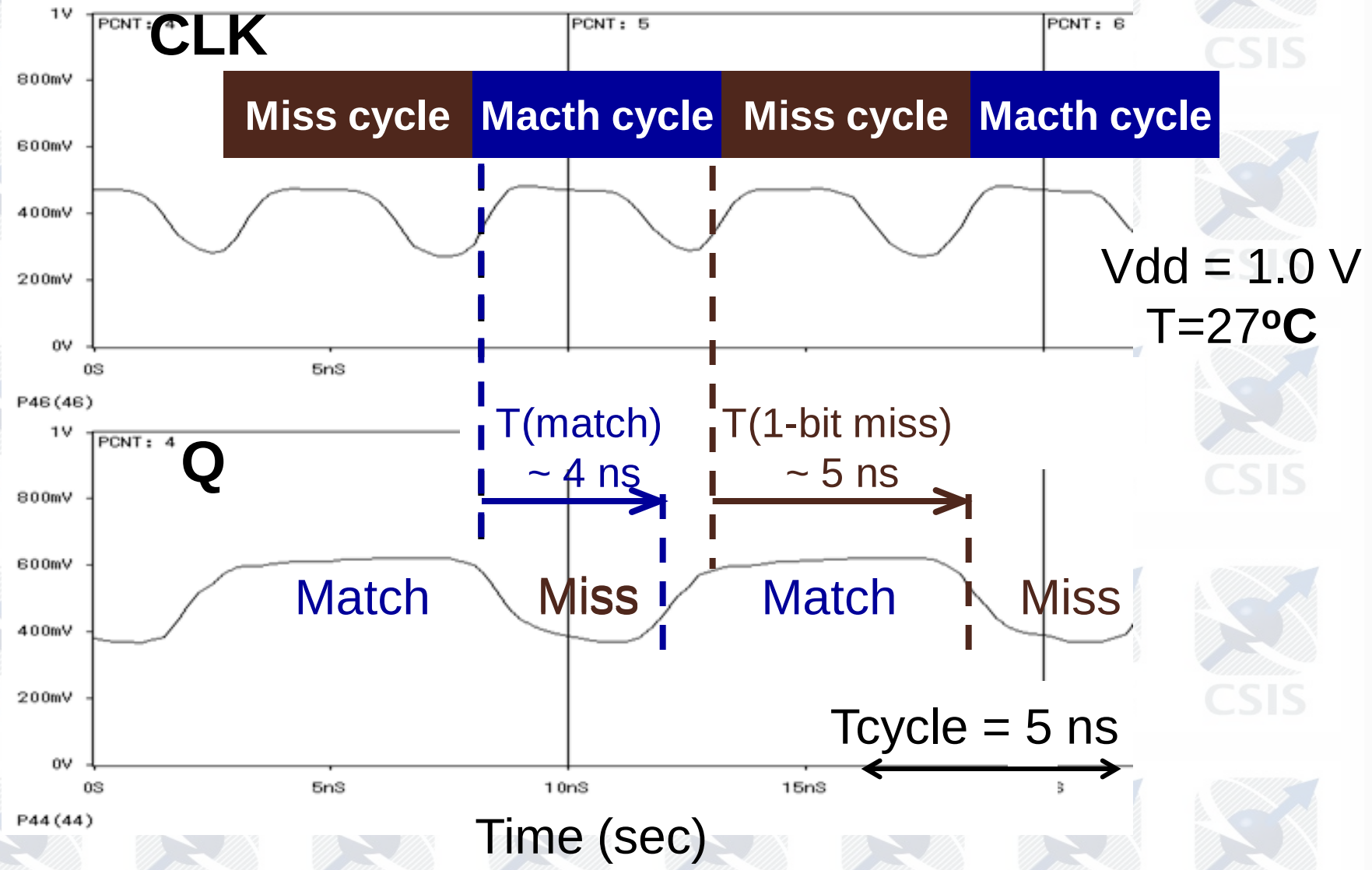
- **Search operation is executed in same way as conventional SRAM-based CAM**
- **Search speed is comparable to SRAM-based CAM**

16-Kbit Spin-CAM Test Chip

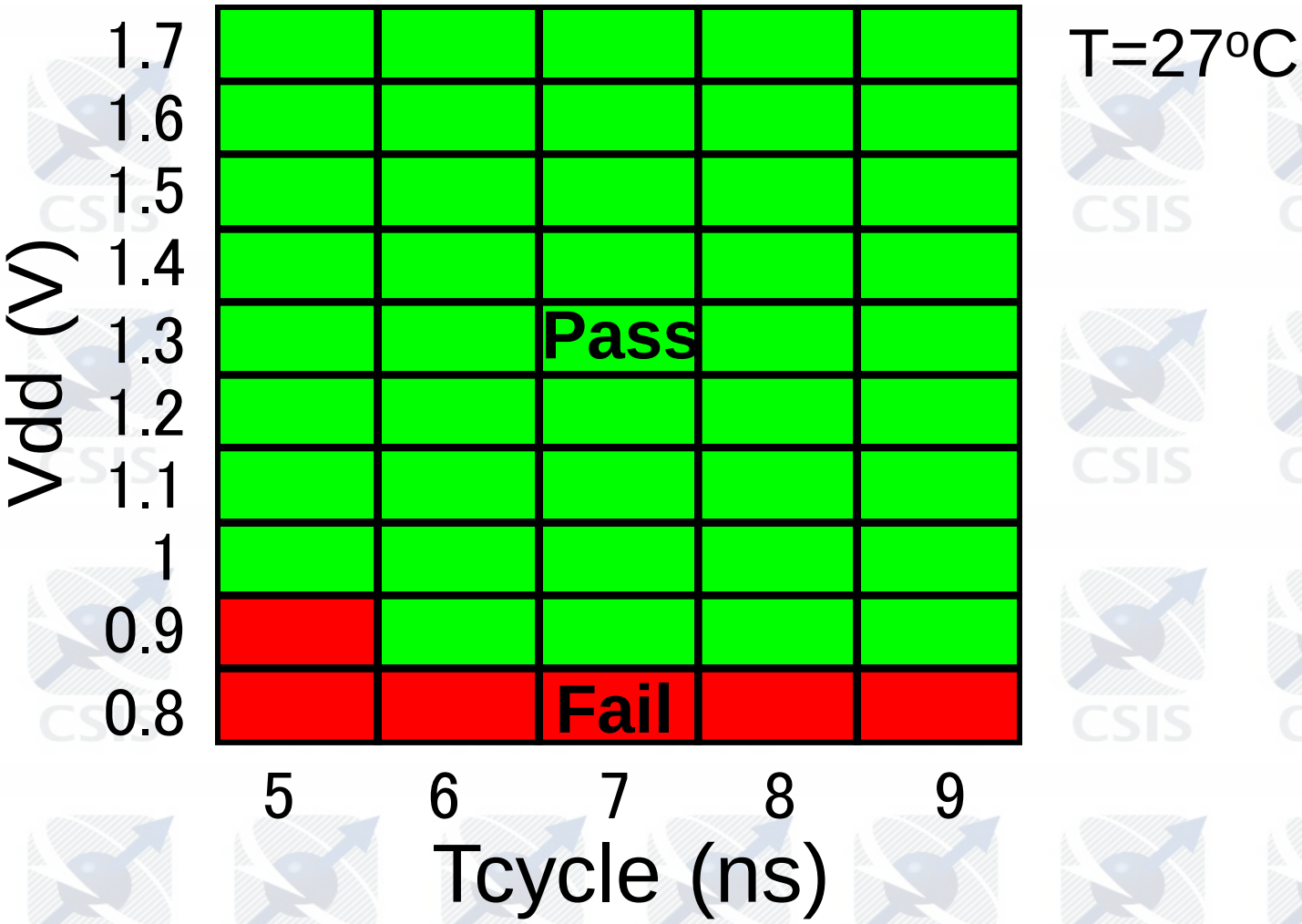


Technology	90 nm CMOS + DW Process
Cell size	6.6 um^2/bit
Organization	128 word x 128 bit
Supply voltage	1.0 V
Search cycle time	5 ns

Measured 5-ns Search Waveform



Measured Search Cycle Time



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- Future Challenge
  - Multi-context Spin CAM
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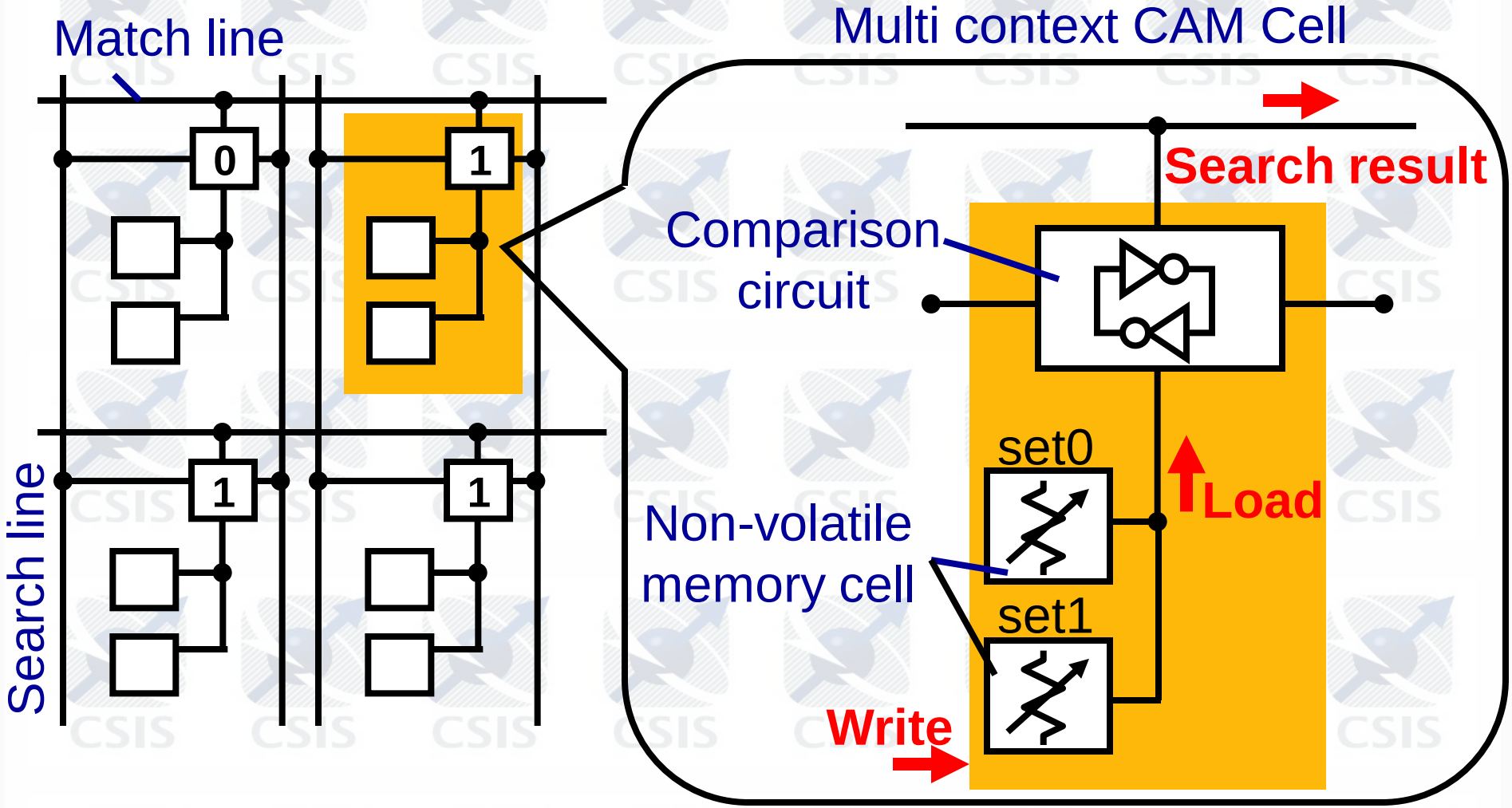
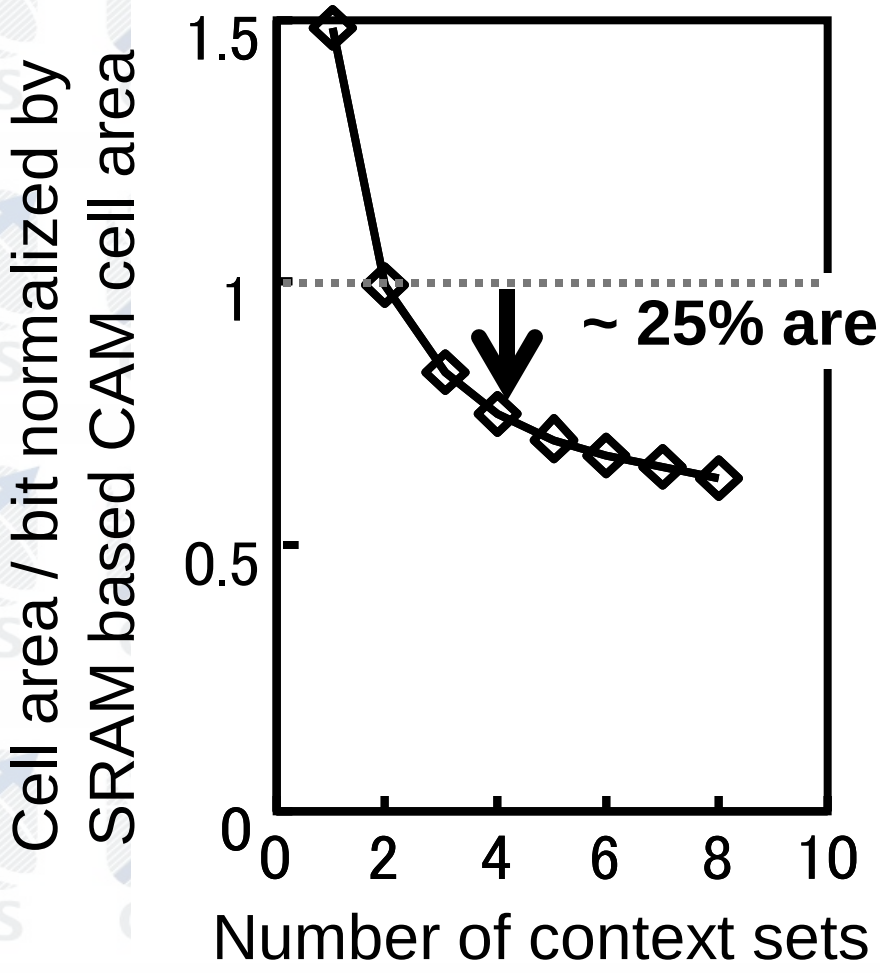
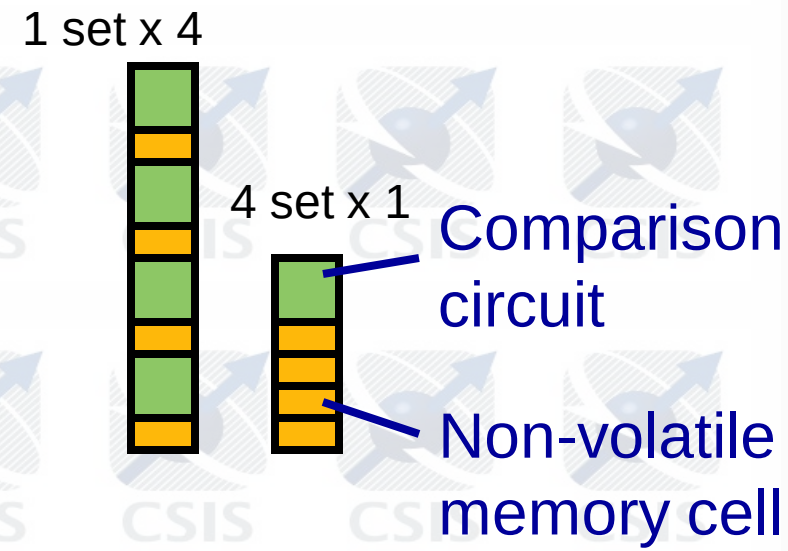
Basic Concept of Multi-context CAM



- **Non-volatile memory cells share comparison circuit → cell efficiency improves**

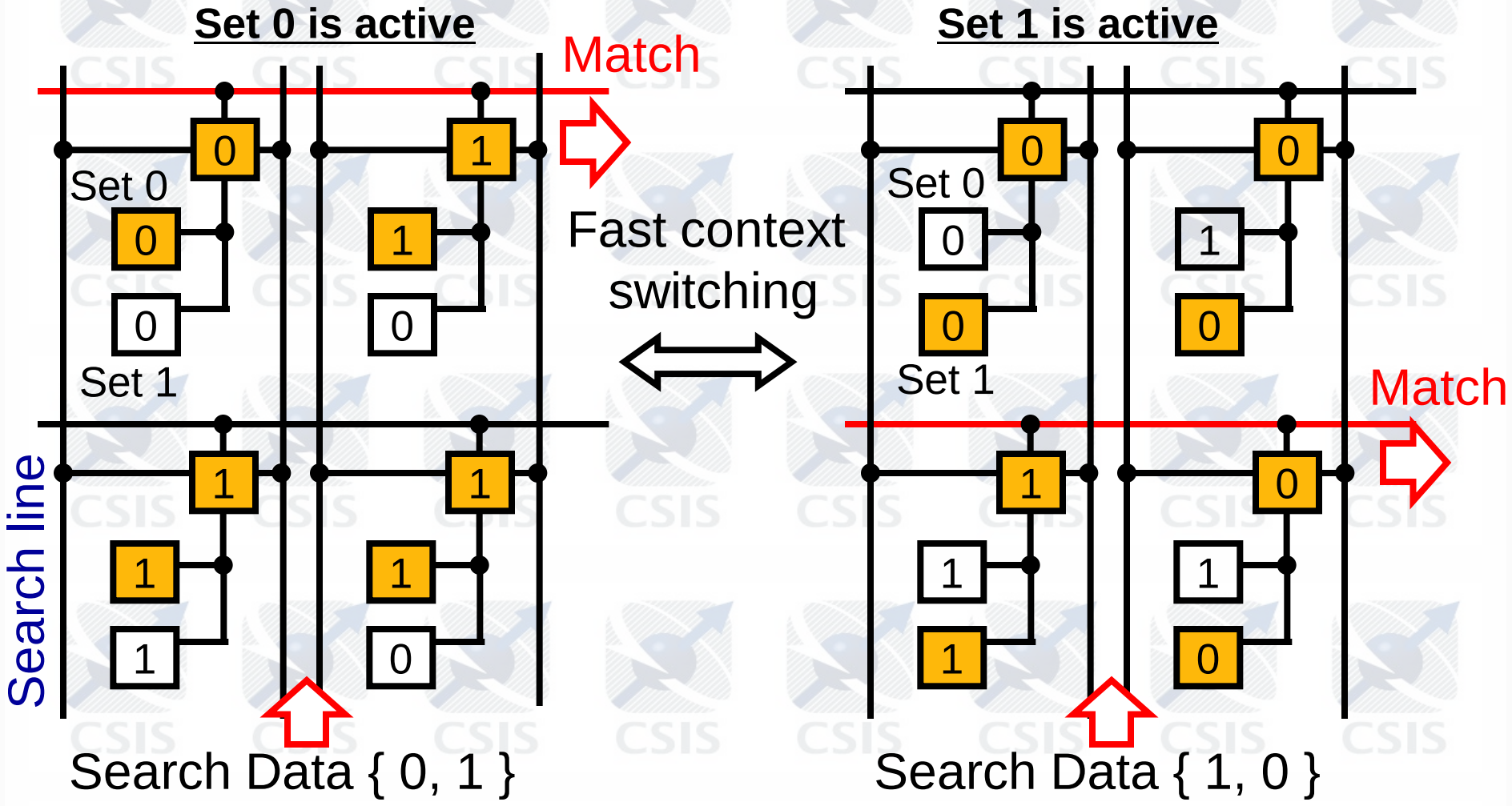
Reduced Area of Multi-context CAM





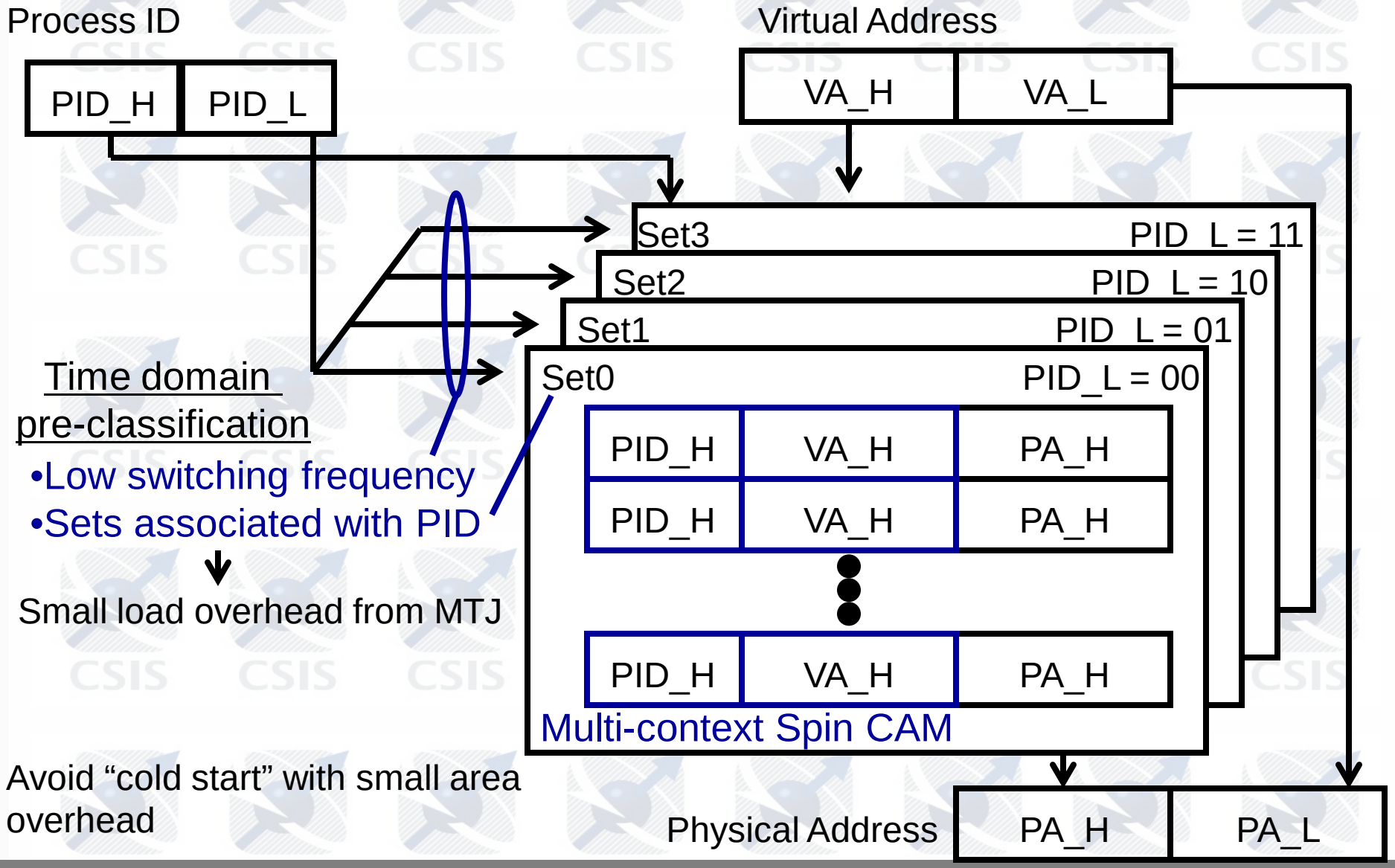
- **A 25% reduction in effective cell area was estimated with the CAM compared to an SRAM based CAM**

Search Operation of Multi-context CAM

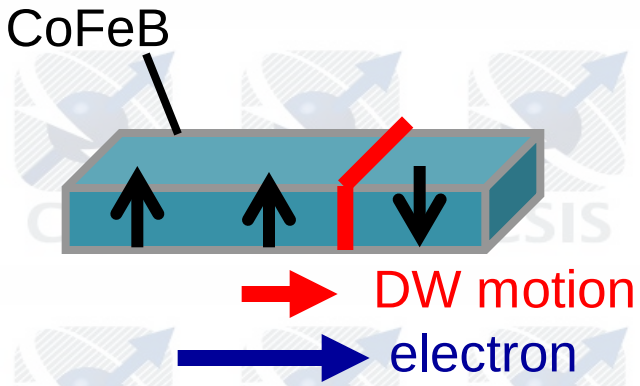


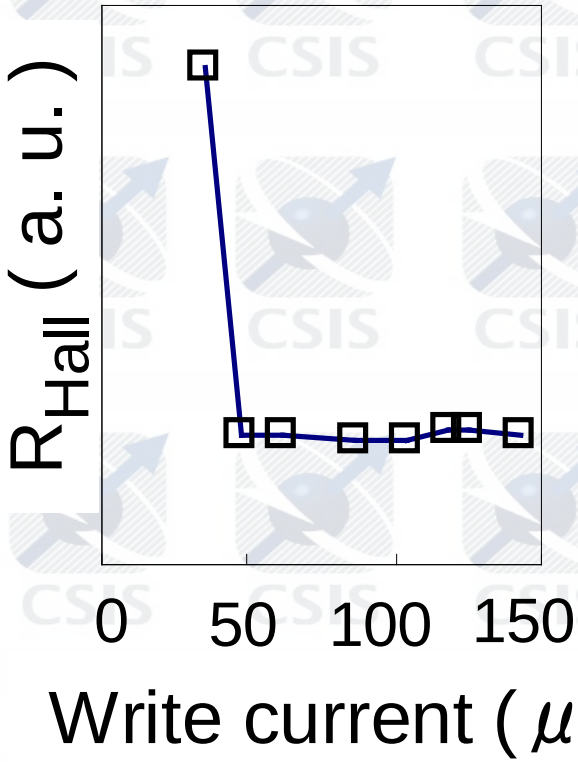
- **Fast context switching**
- **Context switching cause increased overhead in power and delay**

Application Example : Translation Look-aside Buffer



Domain Wall Motion in CoFeB





S. Fukami , Intermag 2011, GC-02.

- **Domain wall moves with ~ 50 μA current in CoFeB**
- **Future challenge is optimization and integration**

Summary

- 16-Kb Spin CAM test chip
  - 5-ns search operation
- Multi-free layer domain wall (DW) cell
  - Fast read operation and small writing current
- 3-terminal device with shared write transistor
  - 6.6-μm^2/bit cell area
- Multi-context Spin CAM
  - 25 % effective cell area reduction comparable to SRAM-based CAM
- Domain wall motion in CoFeB
  - Domain wall moves with ~ 50 μA current