NRAM: High Performance, Highly Reliable Emerging Memory

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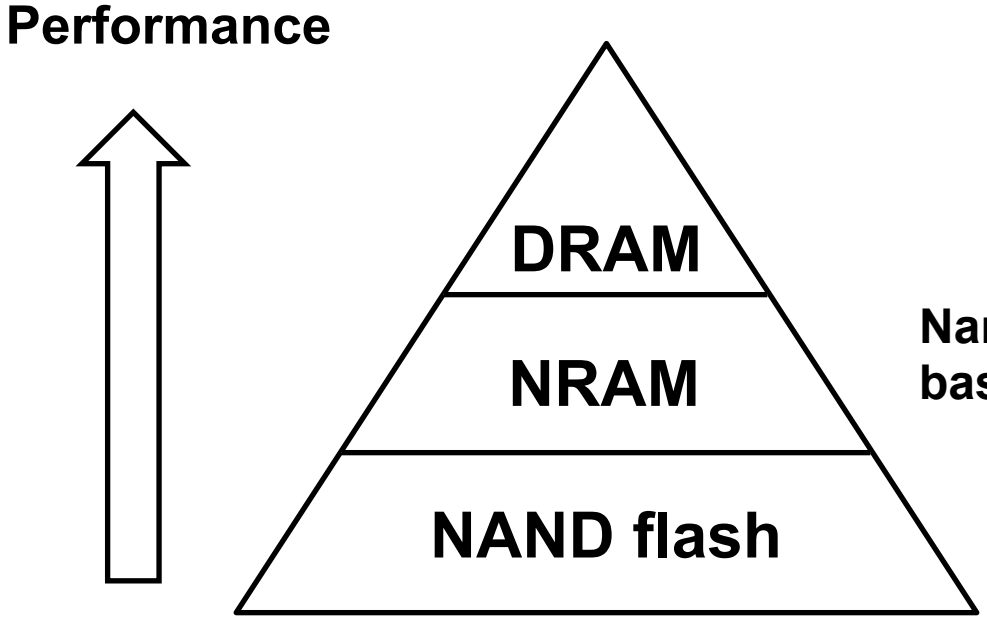
Outline

- Introduction of NRAM
- Single NRAM cell and cell array measurement setup
- NRAM characteristics
  - DC-IV curve
  - Set and reset program characteristics
  - Large on/off ratio
  - High temperature program
  - High endurance
- Conclusion

Introduction of NRAM



Nano-RAM, Carbon nanotube based resistive memory

Compare with Conventional Memories

○ = good ✕ = bad

	DRAM	NAND flash	NRAM	
Performance	○	✕	○	← 20 ns pulse [1]
Scalability	✕	○	○	← Single cell 15 nm [2]
Endurance	○	✕	○	← Single cell 10^{12} [3]
Non-volatile	✕	○	○	← 1000 years@ 85ºC [2]

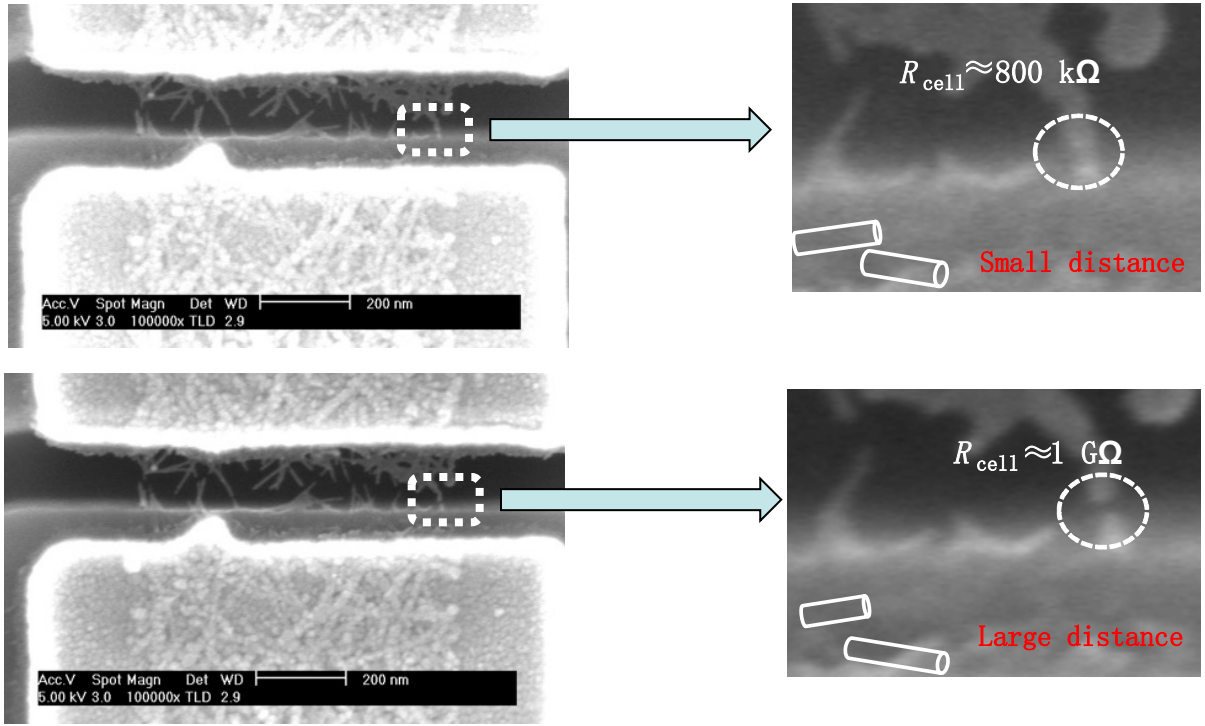
[1]. S. Ning *et al., IEEE Symp. on VLSI Technology,* Jun. 2014, pp. 96–97.
[2]. Nantero Presentation for ITRS ERD/ERM, *International Technology Roadmap for Semiconductors (ITRS),* 2013.
[3]. S. Ning *et al., IEEE Trans. on Electron Devices (TED),* vol. 62, no. 9, pp. 2837–2844, Sept. 2015.

Compare with Emerging Memories

	ReRAM [1]	PRAM [2]	NRAM [3]
Material	Al_xO_y	$Ge_2Sb_2Te_5$	Carbon nanotube (CNT)
Resistive switching on read	Filament size	Phase change	Tunneling current between CNTs
Endurance	10^8	10^9	10^{12}
Current	High	High	Low

[1]. S. Ning *et al., Solid-State Electronics*, vol. 103, pp. 64–72, Jan., 2015.
[2]. H. Y. Cheng *et al., IEEE Int. Electron Devices Meeting*, 2013, pp. 30.6.1–30.6.4.
[3]. S. Ning *et al., Symp. on VLSI Tech.*, 2014, pp. 96–97.
[4]. S. Ning *et al., Ext. Abstr. Solid State Devices and Materials (SSDM),* Oct. 2015, pp. 1198-1199.

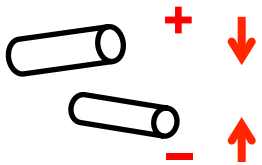
Physical Mechanism



[1]. S. Ning *et al., in VLSI Symp. Tech. Dig.,* Jun. 2014, pp. 120–121.
[2]. Nantero presentation, *Int. Tech. Roadmap for Semiconductors (ITRS)*, 2013.

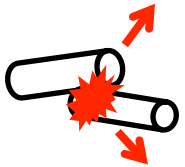
Physical Mechanism

Set: attraction force



Electrical induction

Reset: repulsive force



Heat caused phonon vibration

[1]. S. Ning *et al*., *IEEE Trans. on Electron Devices (TED),* vol. 62, no. 9, pp. 2837–2844, Sept. 2015.

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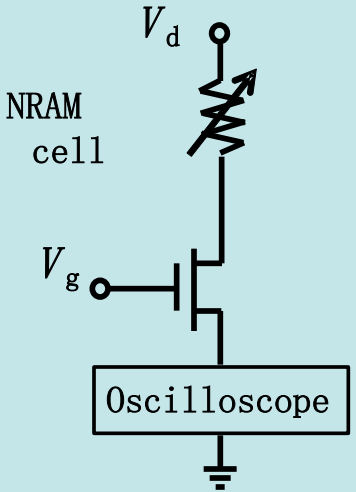
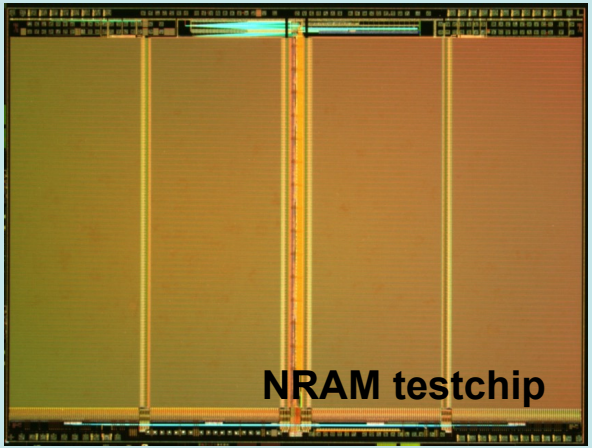
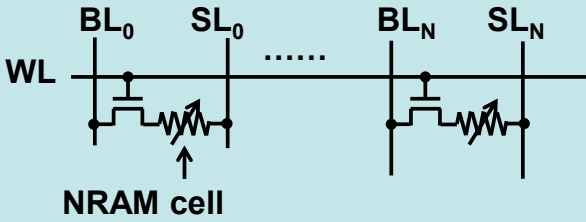
Single NRAM Cell and Cell Array Test

140 nm NRAM single cell



116 nm, 4 Mbits NRAM cell array





	BL	SL
Set voltage	$+V_{Set}$	0 V
Reset voltage	0 V	$+V_{Reset}$

[1]. S. Ning *et al.*, *IEEE Trans. on Electron Devices (TED),* vol. 62, no. 9, pp. 2837–2844, Sept. 2015.
[2]. G. Rosendale *et al., Proceedings of the European Solid-State Circuits Research Conference (ESSCIRC),* Sept. 2010, pp. 478–481.

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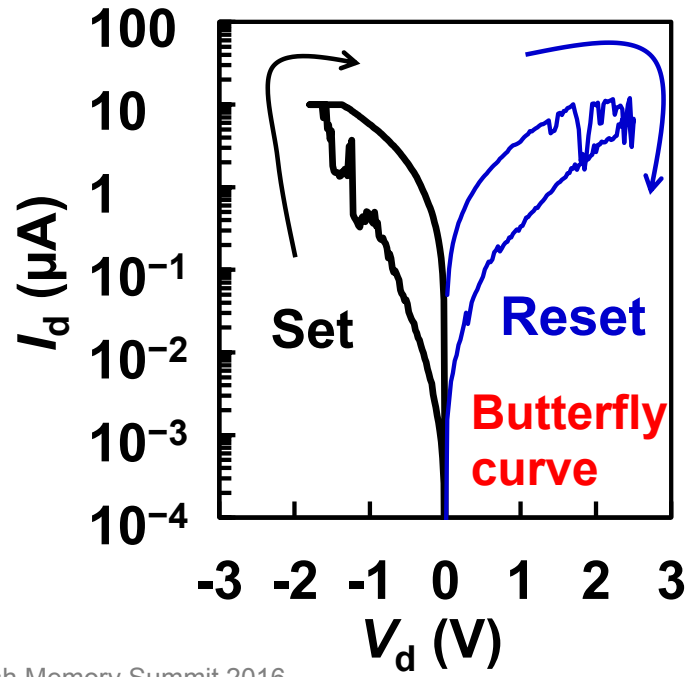
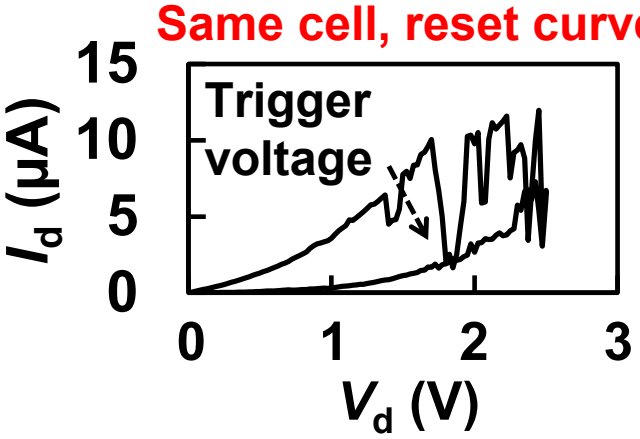
DC-IV Curve

Single cell bi-polar program



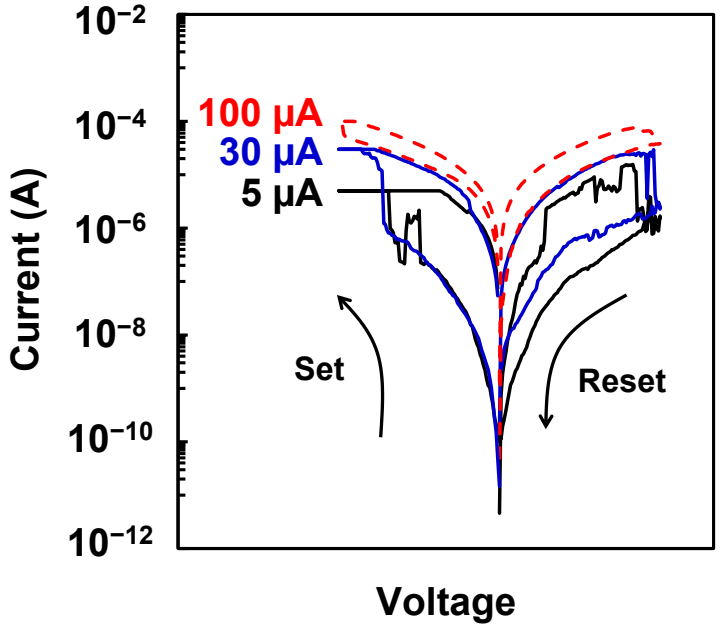
Current vibration due to long term voltage stress on CNTs



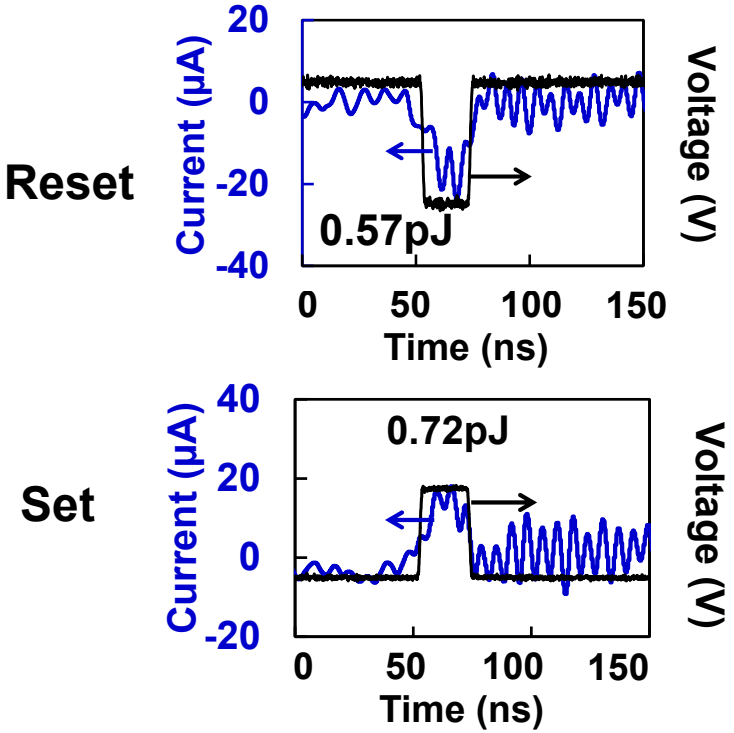
[1]. S. Ning *et al.*, *IEEE Symp. on VLSI Technology,* Jun. 2014, pp. 96–97.

Low Program Current

Single cell DC $I_{compliance}$ = 5 µA, 30 µA, and 100 µA



Single cell AC I_{peak} < 20 µA



[1]. S. Ning *et al.*, *IEEE Trans. on Electron Devices (TED),* vol. 62, no. 9, pp. 2837–2844, Sept. 2015.
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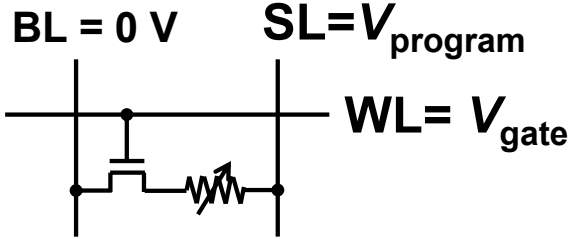
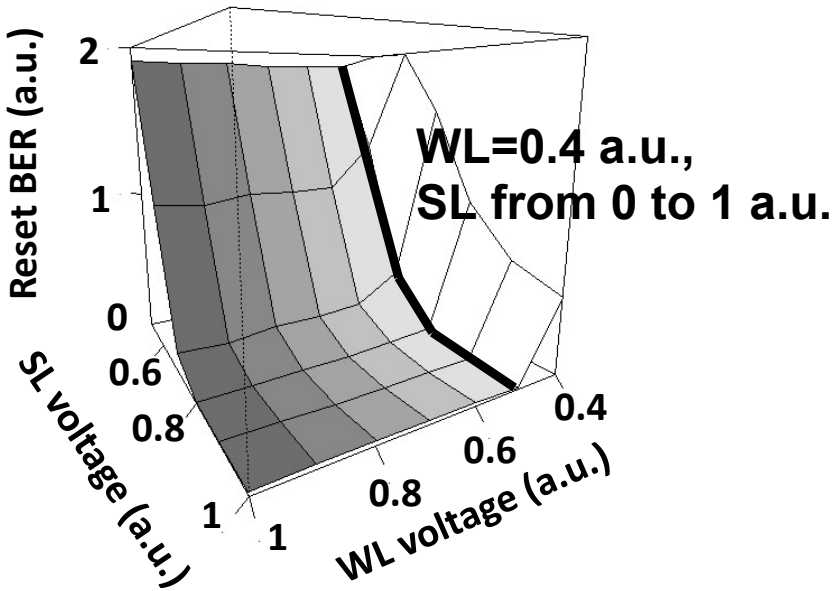
Reset Characteristic

- **Cell array measurement, Reset is driven by both voltage and current**

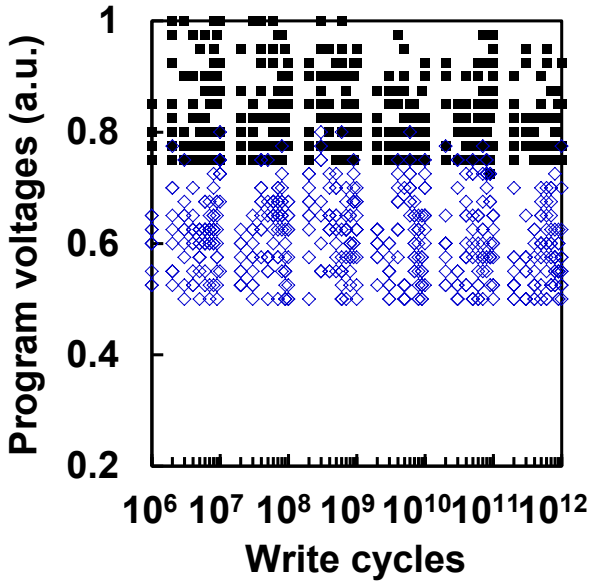




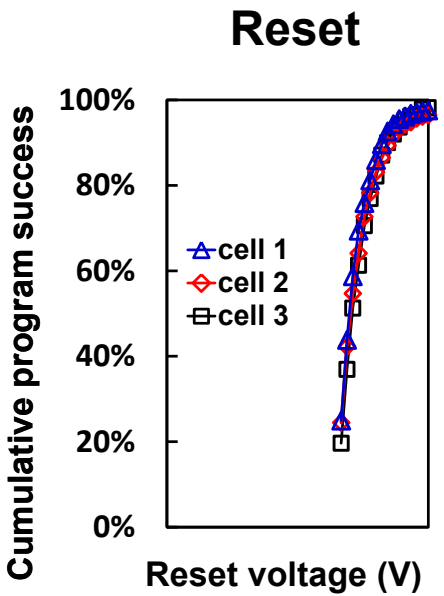
[1]. S. Ning *et al.*, *Ext. Abstr. Solid State Devices and Materials (SSDM),* Oct. 2015, pp. 1198-1199.

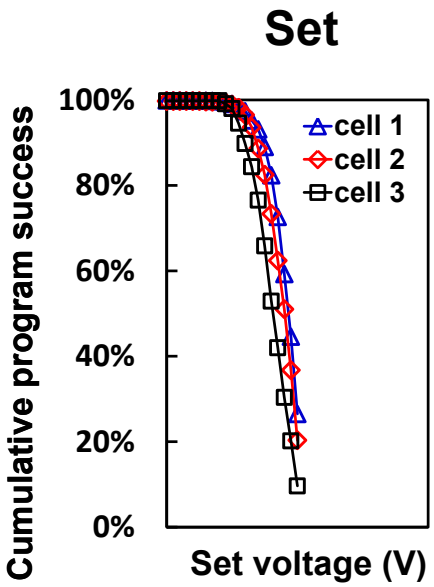
Set and Reset Voltages

- Use incremental pulse programing on single cell
  - ■ Reset voltage
  - ◇ Set voltage (absolute value)



- Three randomly chosen NRAM cells





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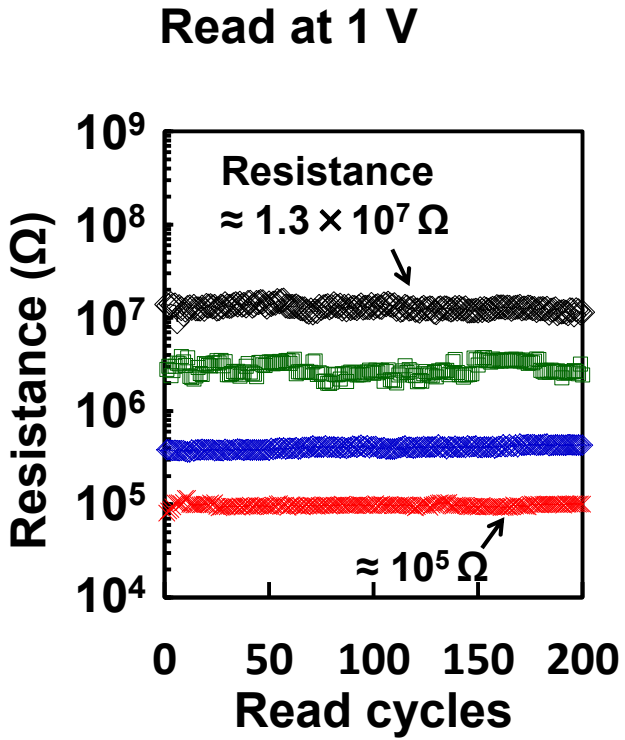
Large On/Off Ratio

- **Single cell measurement**

  > 100 times on/off ratio

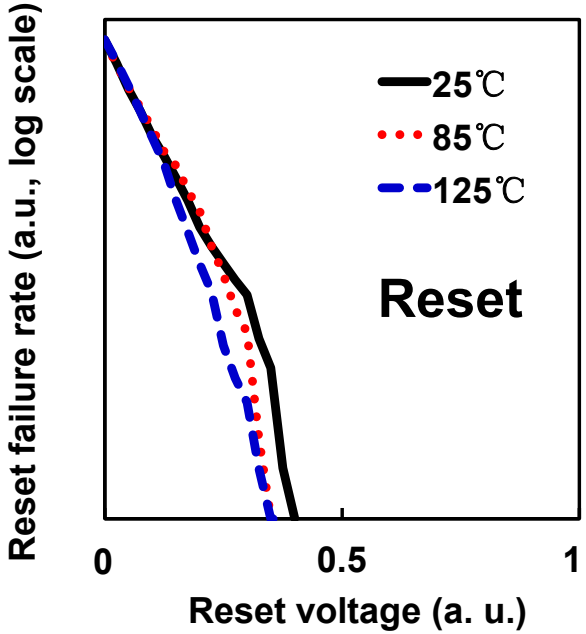
  Possible for multi-level cell (MLC)

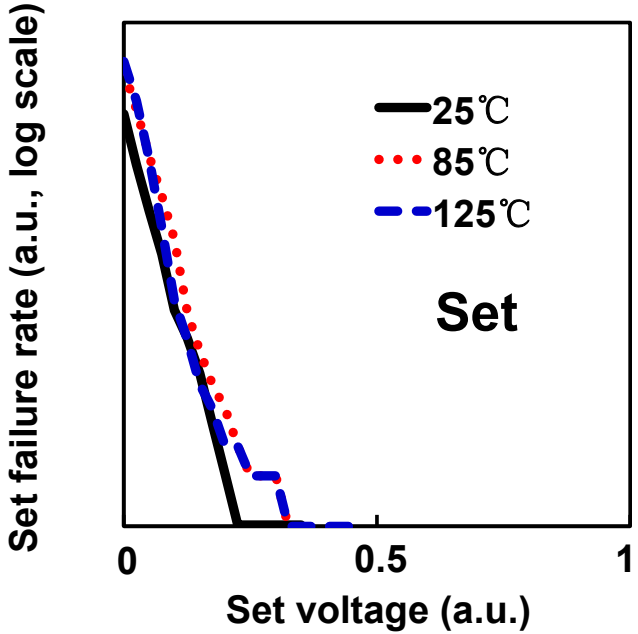


[1]. S. Ning *et al.*, *IEEE Symp. on VLSI Technology,* Jun. 2014, pp. 96–97.

High Temperature Program

- **Single cell measurement, stable program voltage at different temperatures**





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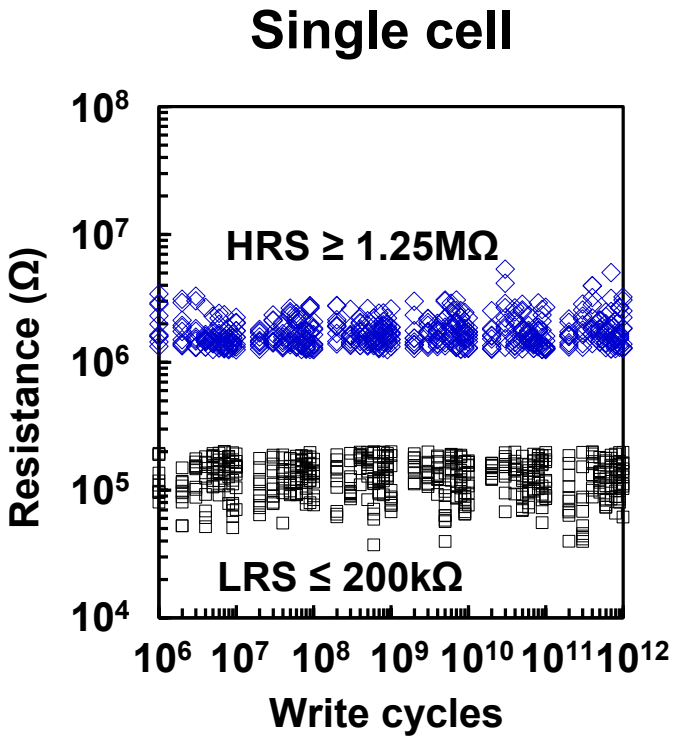
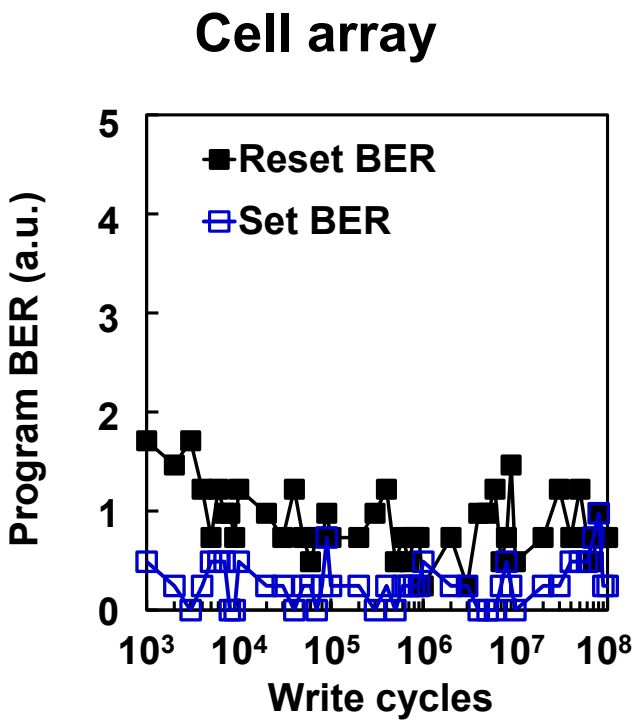
High Endurance





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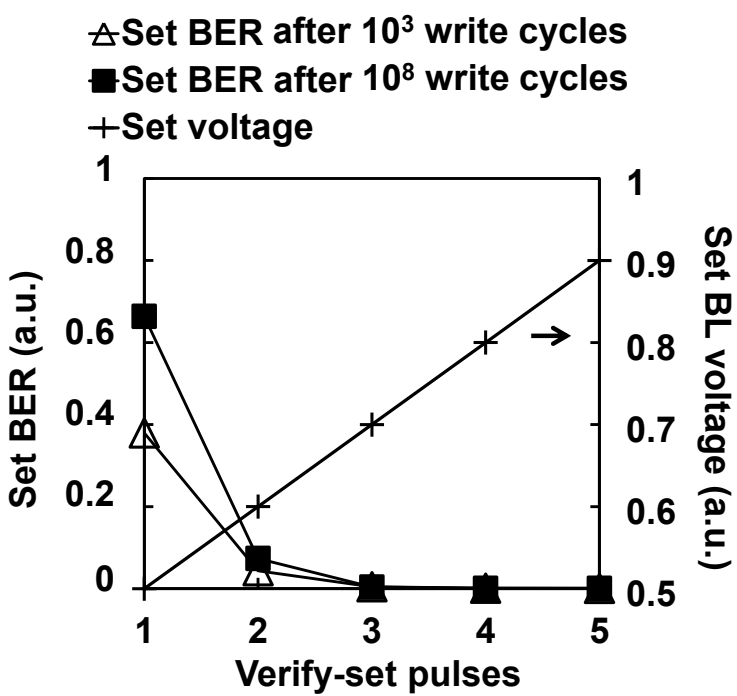
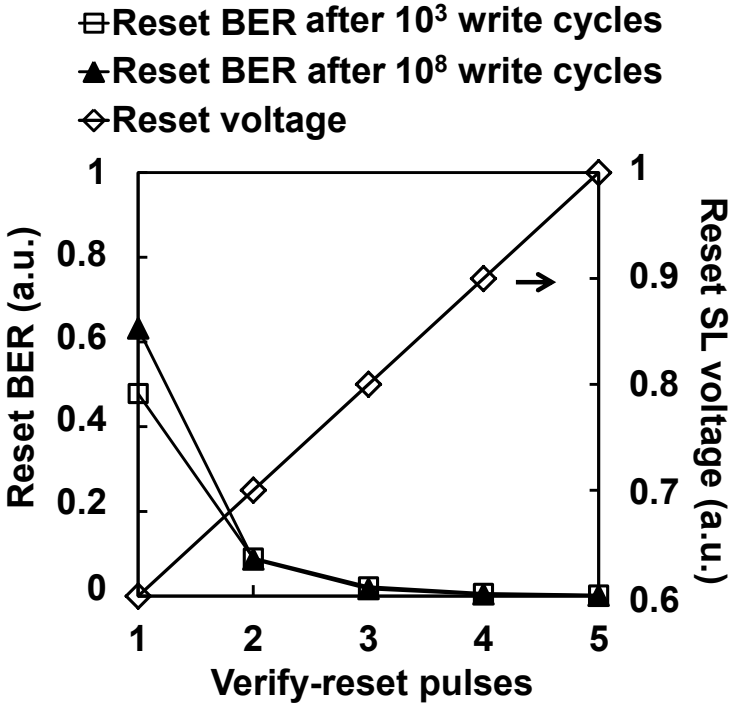
High Endurance

- **Cell array does not wear-out after 10^8 write cycles**





[1]. S. Ning *et al., Japanese Journal of Applied Physics (JJAP),* vol. 55, no. 4S, 2016.
[2]. S. Ning *et al., Ext. Abstr. Solid State Devices and Materials (SSDM),* Oct. 2015, pp. 1198-1199.

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Conclusion

- NRAM is an emerging nonvolatile memory cell which has performance between DRAM and NAND flash.
- Compared with other emerging nonvolatile memories, NRAM has competitive characteristics, including, lower program current, large on/off ratio, large endurance, high temperature stability and long retention time.