Spin-Transfer-Torque MRAM

D. C. Worledge, G. Hu, J. J. Nowak, D. Houssameddine, J. Bak, S. L. Brown, B. Doris, D. Edelstein, M. G. Gottwald, P. Hashemi, Q. He, D. Jeong, J. Kim, C. Kothandaraman, G. Lauer, H K Lee, N. Marchack, E. O'Sullivan, M. Reuter, R. P. Robertazzi, J. Z. Sun, T. Suwannasiri, and P. L. Trouilloud

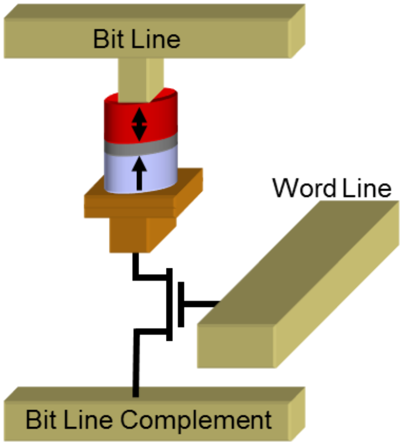
IBM-Samsung MRAM Alliance, IBM TJ Watson Research Center, Yorktown Heights, New York

Outline

- Overview of Spin Torque MRAM
- Spin Transfer Torque
- MgO Magnetoresistance
- Discovery of PMA in CoFeB|MgO
- Demonstration of perpendicular Spin Torque MRAM
- Metrology techniques

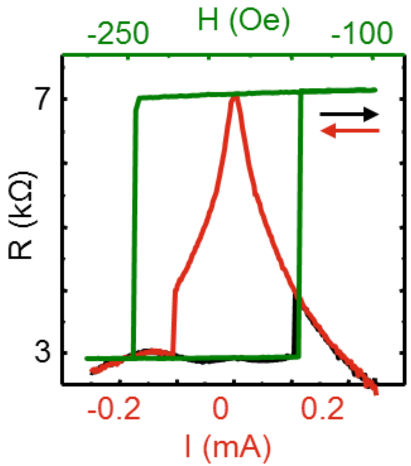
Spin Torque MRAM overview

- Switch single free layer by passing current through magnetic tunnel junction.
- Angular momentum of spin polarized current transferred to free layer.
- Switch to ‘0’ or ‘1’ by reversing current direction.
- Read and write using the same transistor, at low and high voltage.
- Must avoid read disturbs at low V and breakdown of tunnel barrier at high V.



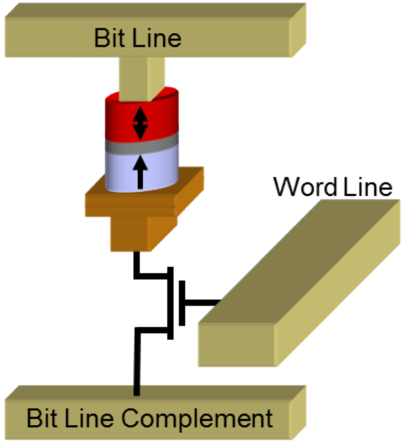
J. C. Slonczewski, Phys. Rev. B **39**, 6995 (1989).

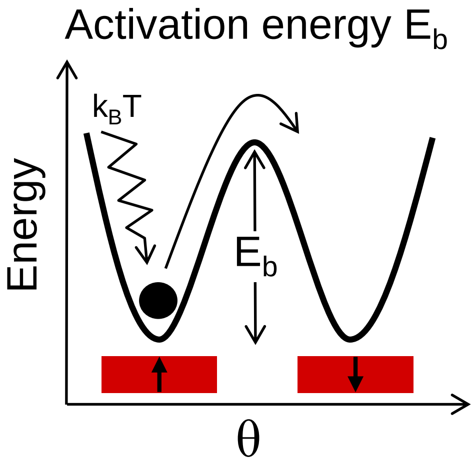
J.C. Slonczewski, J. Magn. Magn. Mater. **159**, L1-L7 (1996).



Key Attributes

- The only scalable memory (or emerging memory) that combines non-volatility with unlimited endurance.
    - No atoms are moved.
- 100,000x faster write than NAND Flash
- Simple two-terminal device embeddable in BEOL. Only ~ 3 mask adders for embedded. Compatible with standard 400 C BEOL process.
- Uses standard CMOS. No high voltage required.
- Potential for operation at high temperature, 180 C and above.
- Switching current is low and scales naturally with area ➔ dense memory.
- Applications value nonvolatility, unlimited endurance, and high speed ~ 10 ns



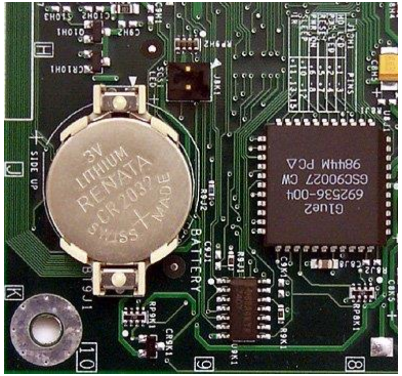


MRAM Applications

Application examples

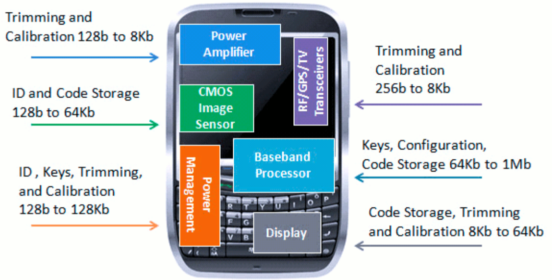
Standalone

- Replace battery-backed SRAM
- Buffer for hard disk drive
- Replace DRAM



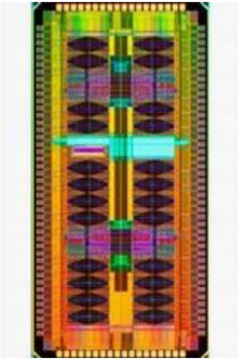
Embedded Non-volatile

- Non-volatile memory for:
  - Microcontroller program code
  - Encryption key storage
  - Trimming and calibration



Embedded Cache

- Fast dense memory for L3 cache
- Alternative to eDRAM



Key requirements

Standalone
- Lower temp process is OK
- 4 - 256 Mb and up
- 10 - 50 ns read/write
- High endurance (10^{10} - 10^{17})

Embedded Non-volatile
- 400C process required
- 1 kb – 16 Mb
- Relaxed performance requirement
- Endurance: 10^6 writes/bit

Embedded Cache
- 400C process required
- 4 - 256 Mb and up
- 1 - 2 ns read/write
- Unlimited endurance (10^{19})

Increasing difficulty

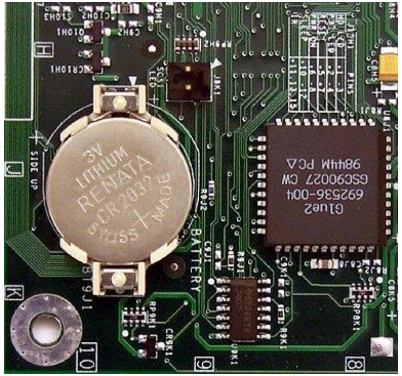
MRAM Applications

Application examples

Key requirements

Standalone

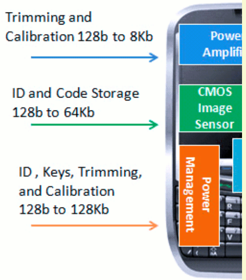
- Replace battery-backed SRAM
- Buffer for hard disk drive
- Replace DRAM



- Lower temp process is OK
- 4 - 256 Mb and up
- 10 - 50 ns read/write
- High endurance (10^{10} - 10^{17})

Embedde

- Non-volatile r
  - Microcontr
  - Encryption
  - Trimming a



- 400C proces
- 1 kb – 16 Mb
- Relaxed perf
- Endurance: 1

Mobile embedded

Replace SRAM for low performance, low power applications

- Wearable electronics
- Co-processors
- Internet of Things

- 400C process required
- 1 ~ 64 Mb
- 10 ns read/write
- Unlimited endurance (10^{18})

edded Cache

- dense memory for L3 e
- native to eDRAM

- process required
- 6 Mb and up
- ns read/write
- nited endurance (10^{19})

Increasing d

Key Advances in Spin-Transfer-Torque MRAM

Device

1974

Slonczewski (IBM) invents magnetic tunnel junction.

1995

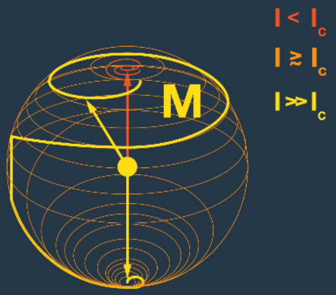
Moodera (MIT) and Miyazaki (Tohoku U.) demonstrate first room temperature magnetic tunnel junctions.

Magnetic Tunnel Junction

Write

1996

Slonczewski (IBM) invents spin-transfer-torque switching.

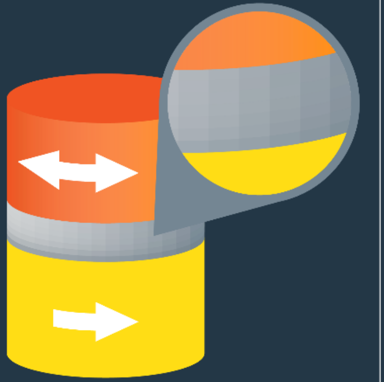


Spin Transfer Torque

Read

2004

Parkin (IBM) and Yuasa (AIST) publish discovery of high magneto-resistance in MgO tunnel junctions.

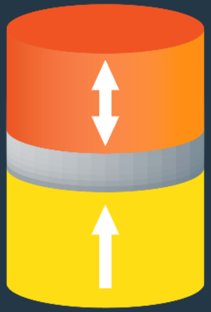


MgO Tunnel Barriers

Scaling

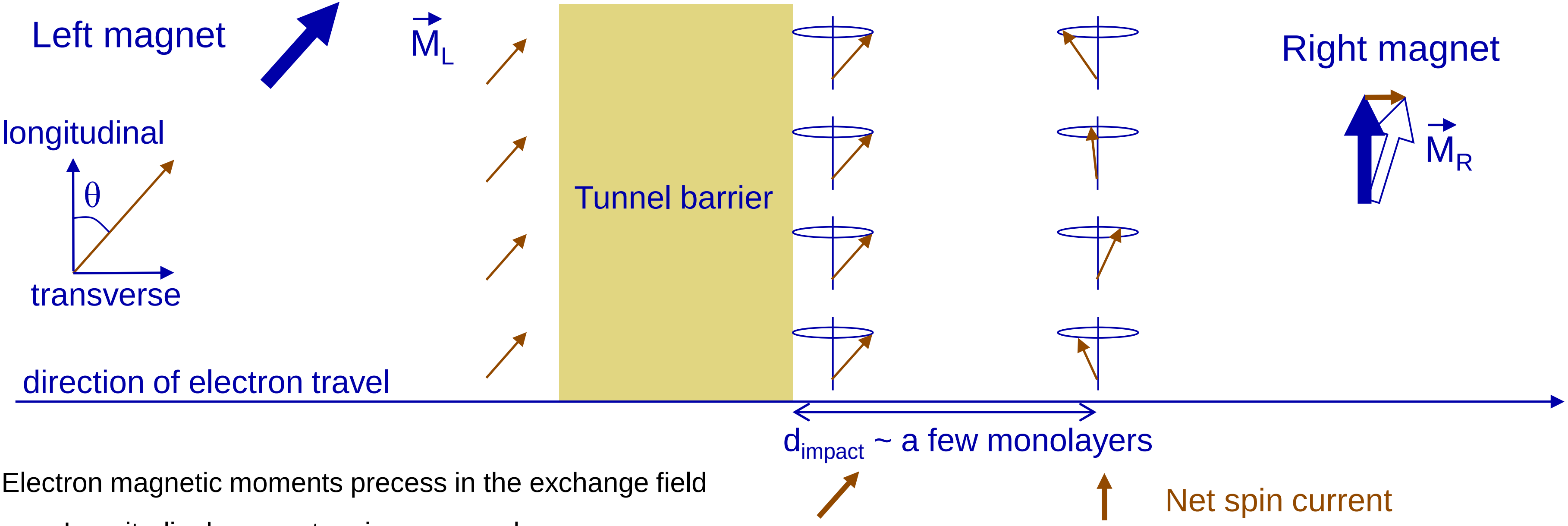
2010

Worledge (IBM) and Ohno (Tohoku U.) demonstrate first perpendicular CoFeB tunnel junctions.



Perpendicular Magnetization

How Spin-Transfer Torque Works



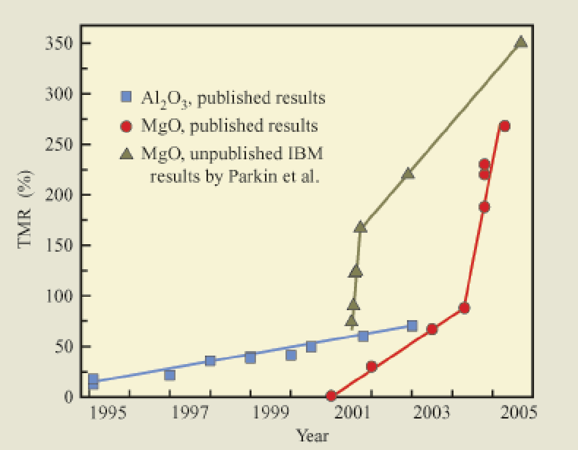
- Electron magnetic moments precess in the exchange field
  - Longitudinal momentum is conserved
  - Transverse momentum oscillates rapidly
- A beam of electrons rapidly dephases
  - Transverse momentum sums to zero
- Conservation of angular momentum ➔ momentum is absorbed by right magnet
  - Torque ~ sinθ

J. C. Slonczewski, Phys. Rev. B **39**, 6995 (1989).

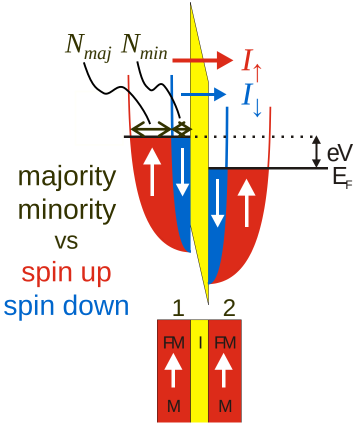
Tunnel magnetoresistance (TMR)

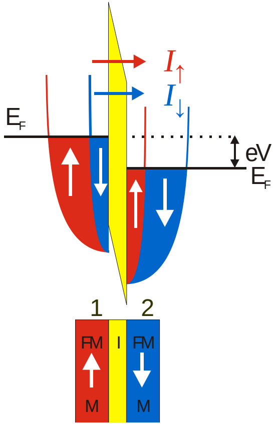
$$R(\theta) = \frac{R_\perp}{1 + P_1 P_2 \cos\theta}$$

- The resistance of two magnetic layers separated by a thin insulating tunnel barrier depends on the relative magnetic orientations.
- Caused by the difference between up- and down-spin densities of states.
- TMR has been used in hard disk drive products since 2005, and MRAM products since 2006.



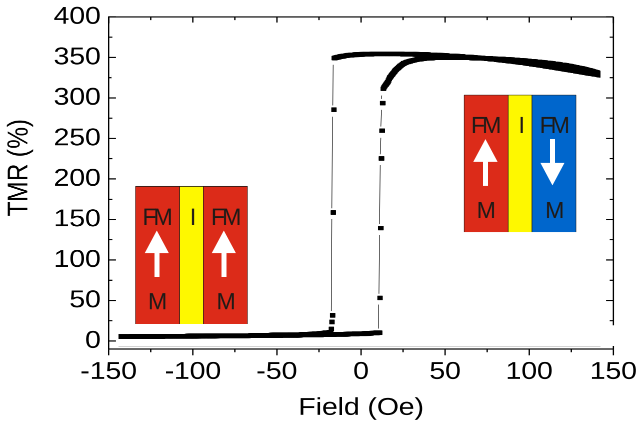
J.S. Moodera, et al., Phys. Rev. Lett. **74**, 3273 (1995).
S.S.P. Parkin, et al., Nat. Mater. **3**, 862 (2004).
S. Yuasa, et al., Nat. Mater. **3**, 868 (2004).





$$MR = \frac{R_{AP} - R_P}{R_P} = \frac{2P_1P_2}{1 - P_1P_2}$$

$$\text{with } P = \frac{N_{maj} - N_{\min}}{N_{maj} + N_{\min}}$$

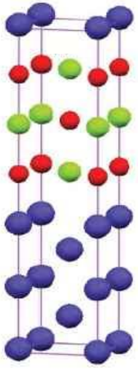


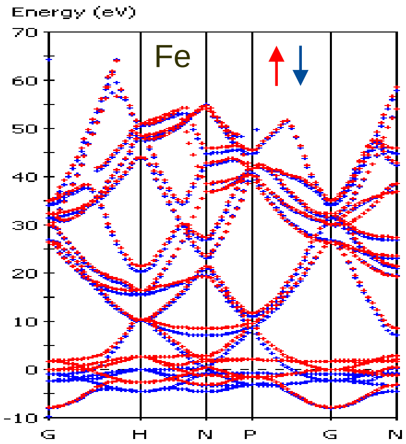
$I_P \sim N_{1maj} N_{2maj} + N_{1min} N_{2min}$ $\qquad$ $I_{AP} \sim N_{1maj} N_{2min} + N_{1min} N_{2maj}$

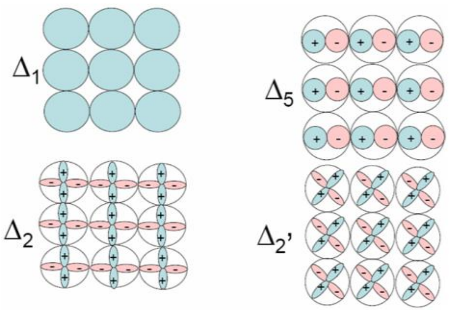
Symmetry filtering in MgO

$$P = \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow}$$

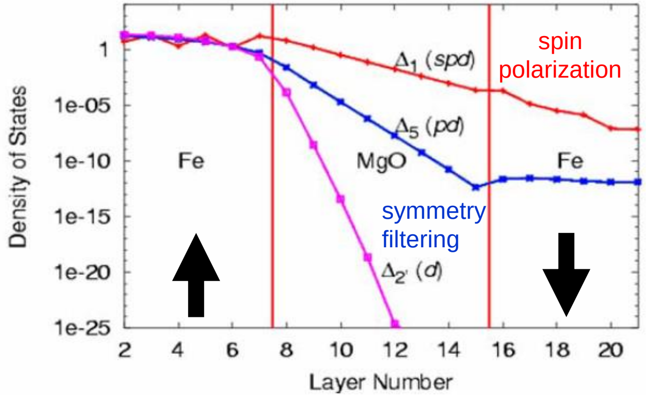
- Typical 'spaghetti' band diagram – how can we ever hope for high spin polarization?
- For 001 MgO (rock salt structure) and 001 BCC electrodes, organize bands by symmetry:
  - Δ_1 (s, pz, dz^2), Δ_5 (px, py, dxz, dyz), Δ_2, $\Delta_{2'}$.
- Tunneling probability ~ exp(-2κd). It turns out κ depends on symmetry: $\kappa_{\Delta 1} < \kappa_{\Delta 5} < \kappa_{\Delta 2} < \kappa_{\Delta 2'}$.
- Hence only the Δ_1 band makes it through the barrier – it is the only band that matters.
- 001 BCC Fe and CoFe have ~100% spin-polarization of Δ_1 bands ➔ high MR.
- Requirements are 001 MgO, 001 BCC CoFe, low defects, low oxidation of CoFe.





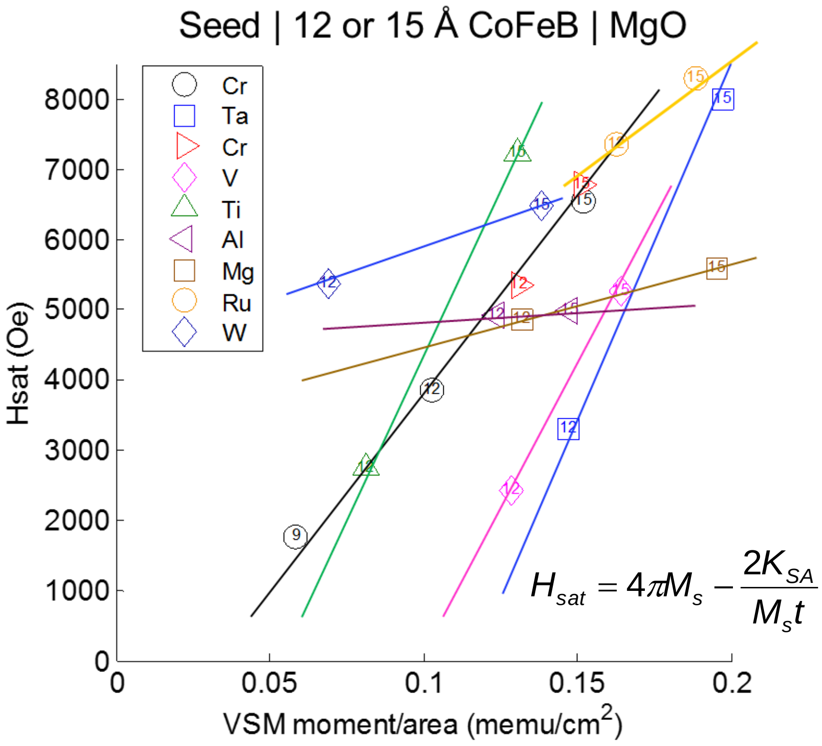


Two dimensional symmetries of a square lattice.



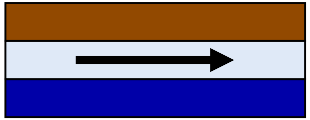
W. H. Butler, Sci. Technol. Adv. Mater. 9 014106 (2008)

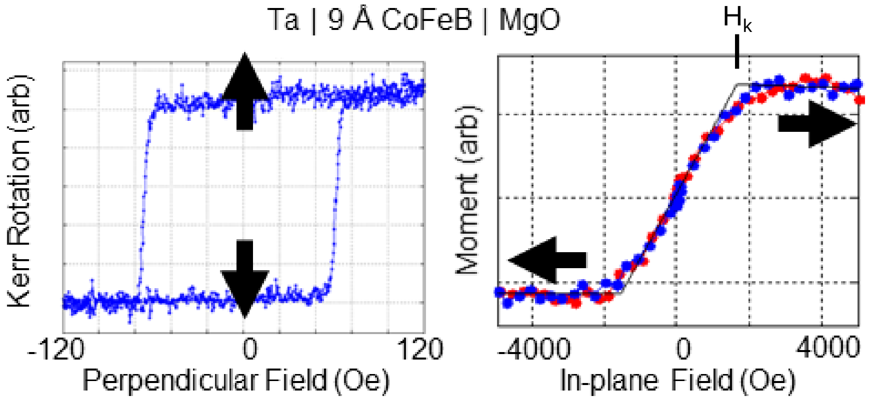
Search for a new perpendicular materials system



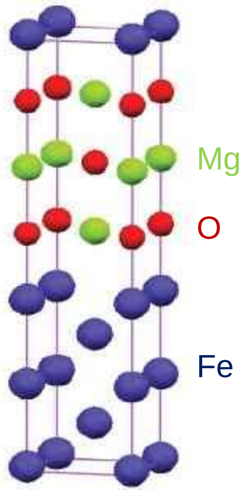
- Fixed MgO & CoFeB, and varied seed layer to search for signs of PMA.
- Used in-plane films with kerr measurement of H_{sat} for fast turnaround
- Searched many metals, oxides, and nitrides for seed layer.
- Ta is best choice.
  - Surprising, since Ta is what everyone has used for many years.
  - Difference is to make CoFeB thin!

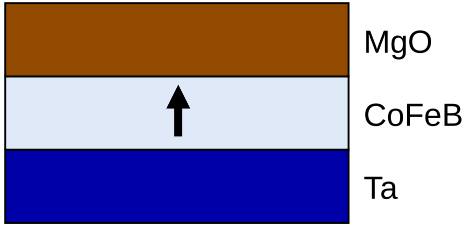
D. C. Worledge, et al., unpublished 2009
D. C. Worledge, US Patent US8536668

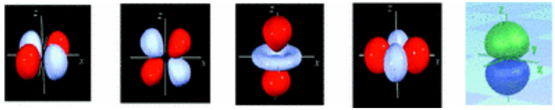




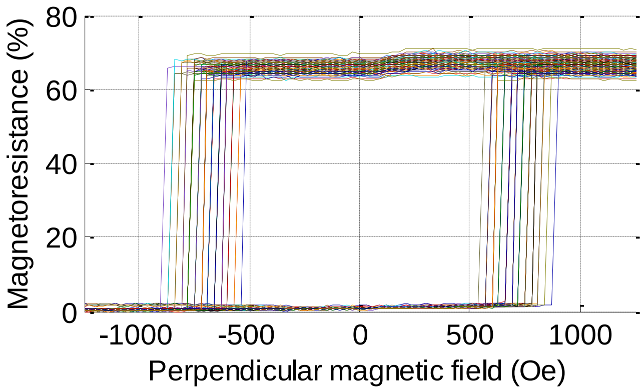
Perpendicular Ta | CoFeB | MgO



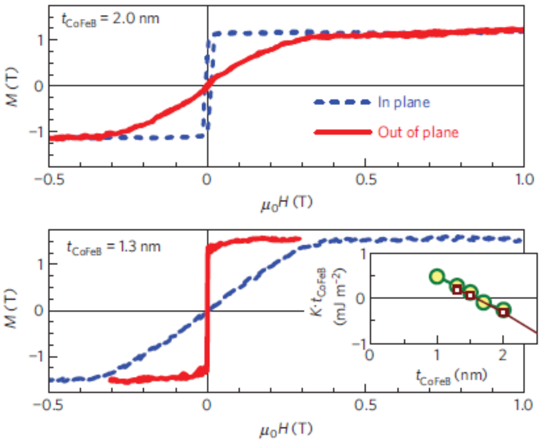




D. C. Worledge, et al., Proc. IEDM Tech. Dig. p296 (2010).



S. Ikeda, et al., Nature Mater. **9**, 721 (2010).

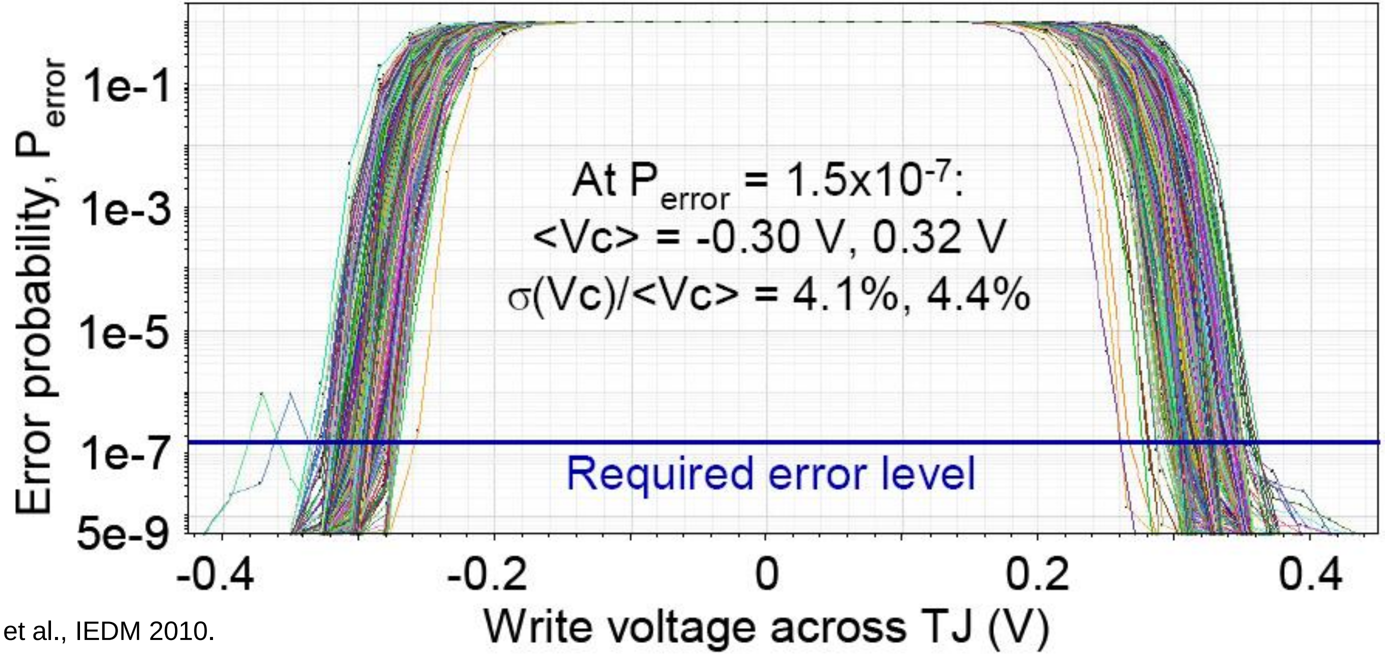


- Interfacial anisotropy at CoFeB|MgO interface
  - Theory suggests due to Fe-O bonding at interface

    H. X. Yang, M. Chshiev, B. Dieny, et al., Phys. Rev. B **84**, 054401 (2011).
  - Earlier work with Pt seeds also shows this anisotropy at CoFeB|MgO interface.

    B. Rodmacq, S. Auffret, B. Dieny, et al., J. Appl. Phys. **93**, 7513 (2003).
  - Role of Ta simply to absorb B?
- Ta|CoFeB|MgO is already the preferred system for high MR
- Also discovered by Ohno group.

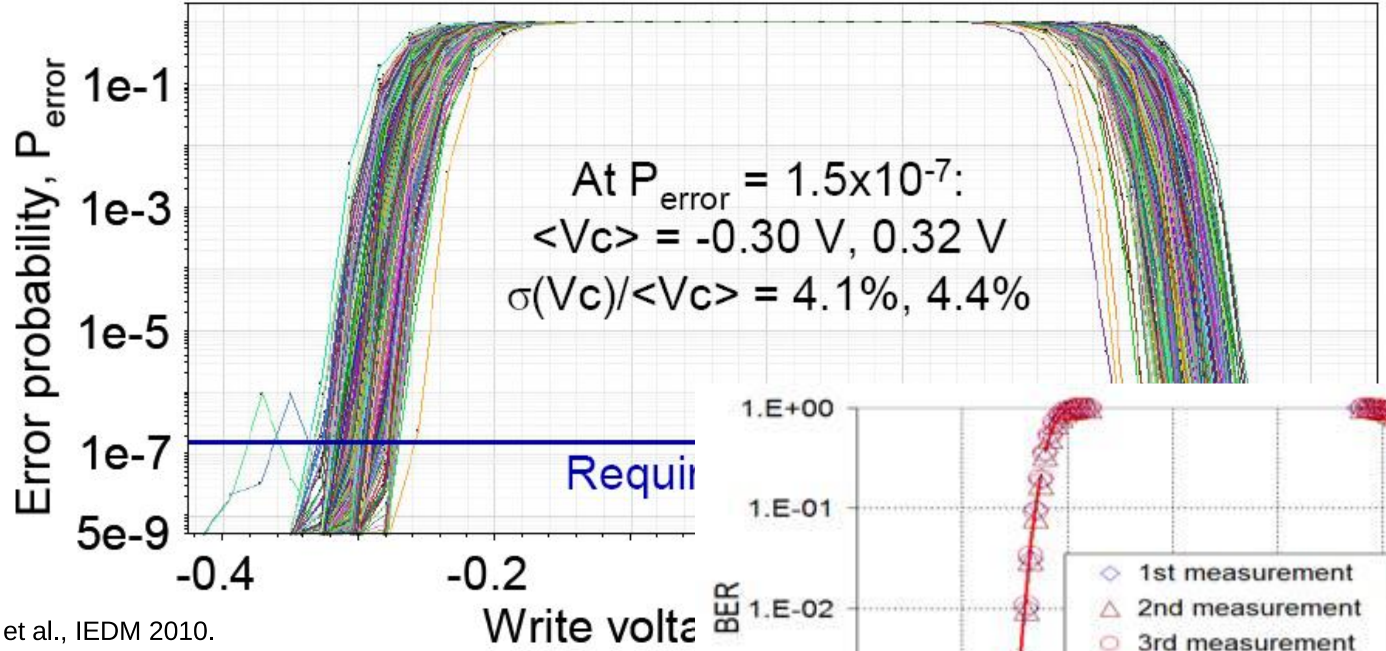
First Demonstration of Reliable Spin Torque Writing



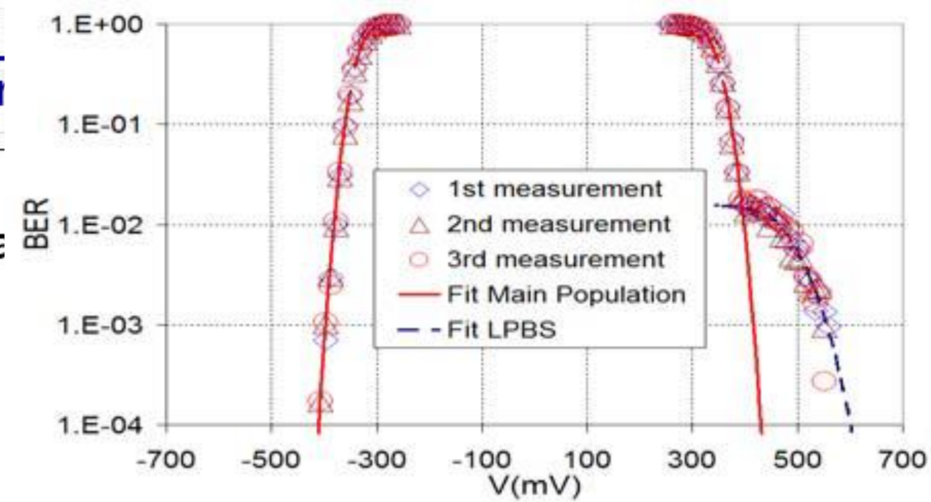
D. C. Worledge, et al., IEDM 2010.

- Every bit has a probability of a write error, on every write cycle ➔ inherent to spin torque
- 498 devices, 120 nm diameter. 100 ns pulses. External field H_{offset} = 28 Oe applied.
- No anomalous switching at 10^{-2} – 10^{-3} level like that seen for in-plane junctions.

First Demonstration of Reliable Spin Torque Writing



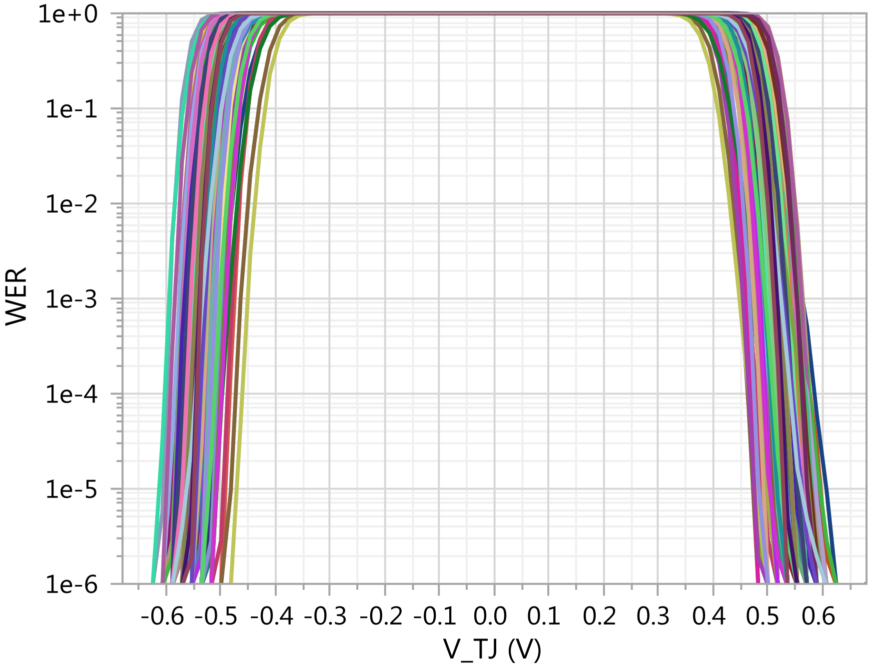
D. C. Worledge, et al., IEDM 2010.



- Compare to previous in-plane results
    - ‘Ballooning’

Tai Min, et al., IEEE Trans. Mag. 46, 2322 (2010).

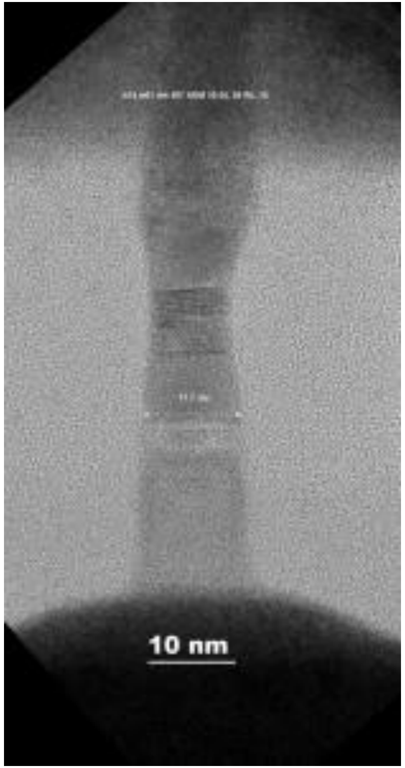
Reliable 10 ns writing is possible now

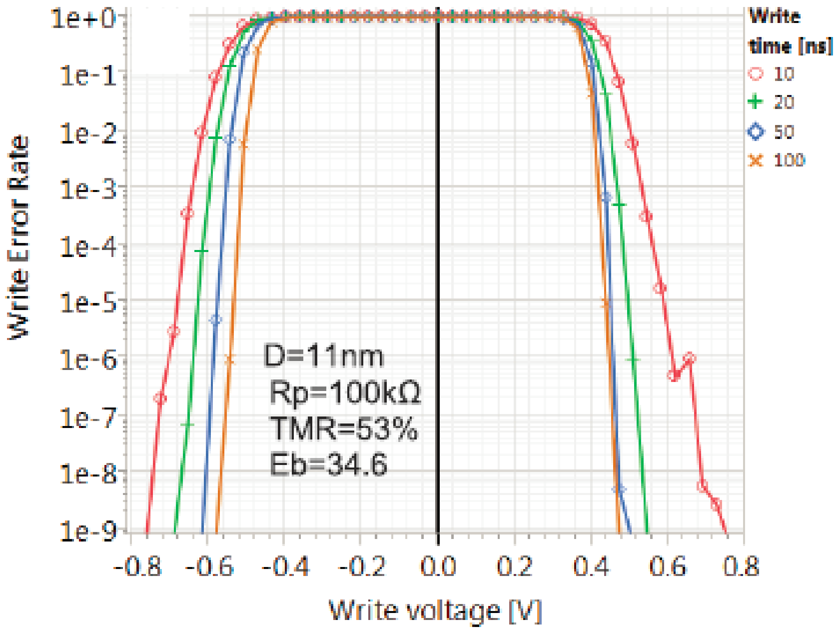


- 256 devices, 39 nm diameter, 10 ns pulses, no external field, R_{min} = 6.6 kΩ, E_b = 63 kT, I_{c1e-6} = 83 uA
- Compared to 2010 IEDM paper: 10x faster, 4x lower power, 4x denser, 7x larger Hc

Scaling down to 11 nm

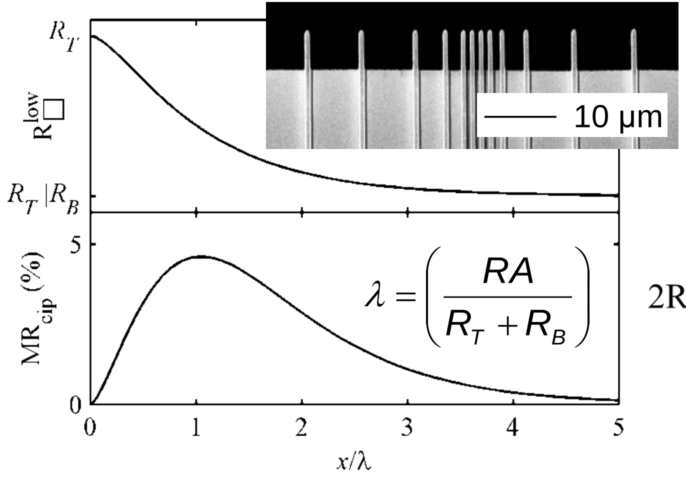
J. J. Nowak, et al., IEEE Mag. Lett., **7**, 3102604 (2016)

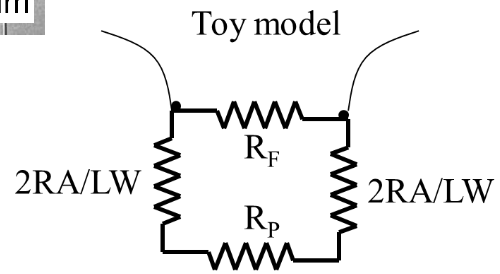


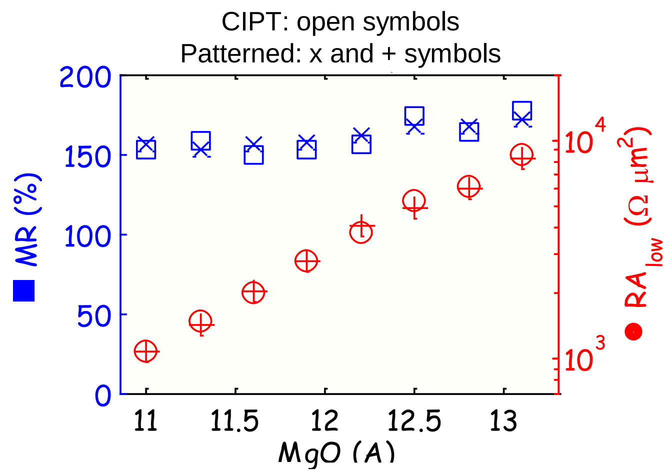


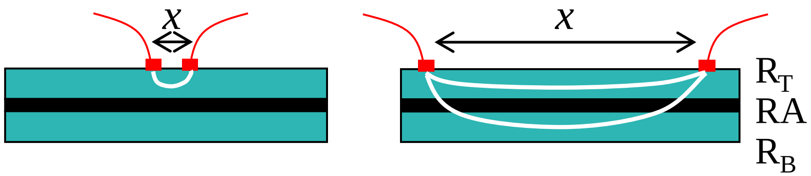
- Spin torque physics works well down to 11 nm
- WER = 7e-10 demonstrated in 7.5 uA
- Write current scales well with area

Current-In-Plane Tunneling







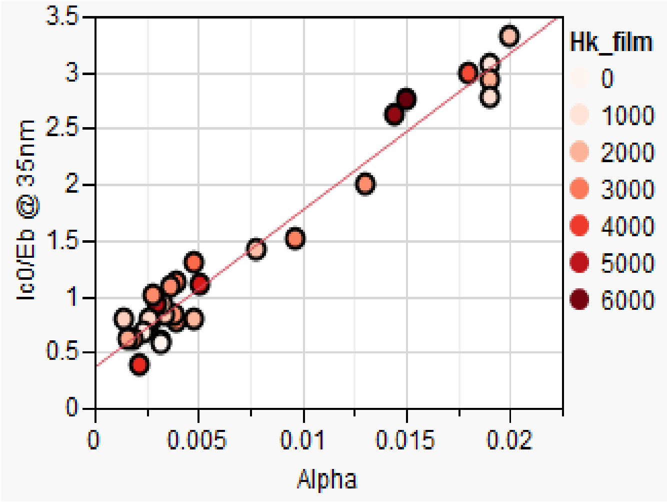


D.C. Worledge and P.L. Trouilloud, Appl Phys. Lett**. 83,** 84 (2003).

- Measures MR and RA of un-patterned blanket wafers (no processing required).
- About 1 minute per wafer.
- Uses four-point microprobe resistance measurements as a function of probe spacing, in a magnetic field.

Blanket film damping constant

- Magnetic damping, α (Gilbert damping): magnetic moment damps down in $1/\alpha$ precession cycles.
- For 35nm devices, I_{c0}/E_b increases linearly with blanket film damping constant, as predicted by the single domain model.
- Ferromagnetic resonance (FMR) technique – increase sensitivity, decrease measurement time, measure patterned devices.

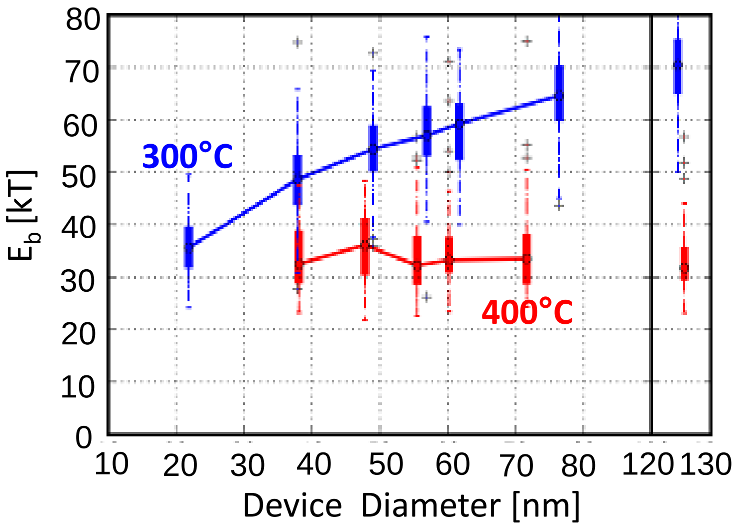


$$I_{c0} = \frac{4e}{\hbar}\alpha\frac{1+P_{free}P_{ref}}{P_{ref}}E_b$$

G. Hu,et al., Proc. IEDM Tech. Dig. p38-3 (2017)

Blanket film exchange stiffness A_{ex} measurement

- Magnetic tunnel junctions don't behave like single-domain particles
- Sub-volume excitation (only part of the junction dominates the switching process)
- Exchange stiffness, A_{ex}, measures how strongly magnetic the material is



J. Z. Sun, et al., PRB **84**, 064413 (2011)
J. Z. Sun, et al., JAP **111**, 07C711 (2012)

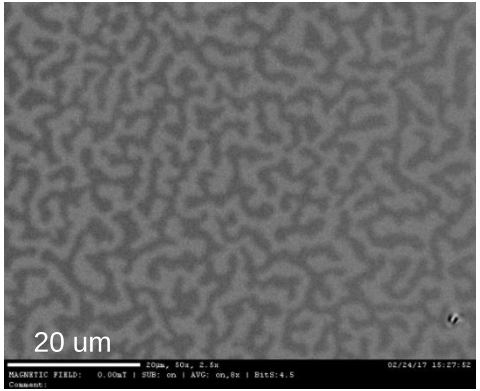
$$H_K = \frac{2K_{eff}}{\mu_0 M_S}$$

$$D_P = 1.91 * t * e^{\frac{\pi D_0}{t}}$$

$$D_0 = \frac{\gamma_W}{\mu_0 (M_S)^2}$$

$$\gamma_W = 4\sqrt{A_S K_{eff}}$$

Domain patterns measured in Kerr microscope



M. Yamanouchi, et al., *IEEE Magnetics Letters*, vol. 2, pp. 30030, 2011.

Wish List for new metrology techniques for STT-MRAM

- New metrology techniques for routine blanket film characterization
  - For example, damping and exchange stiffness
- New metrology techniques for nano-meter scale blanket film characterization (beyond TEM)
  - Sources of distributions
  - Process-induced damage
- Direct measurement of H_k, damping, and exchange stiffness on patterned devices
- New metrology techniques or methodologies to address other key device performance parameters like breakdown and WER ballooning.

Major remaining issues for advanced MRAM products

- PMA tunnel junctions with high MR > 400% at low RA
- Reliable low current switching at $I_{c10ns} < 10$ uA
- Reliable fast switching at < 2 ns
- On-pitch etching

Summary

- Spin Transfer Torque due to spin dephasing
- High magnetoresistance using MgO tunnel barriers due to symmetry filtering
- Perpendicular materials for scaling: Thin CoFeB with magnetic anisotropy from MgO interface
- Reliable writing demonstrated
- Scaling down to 11 nm junction: switches in 7.5 uA at write-error-rate = 7e-10
- Fast switching demonstrated down to 10 ns