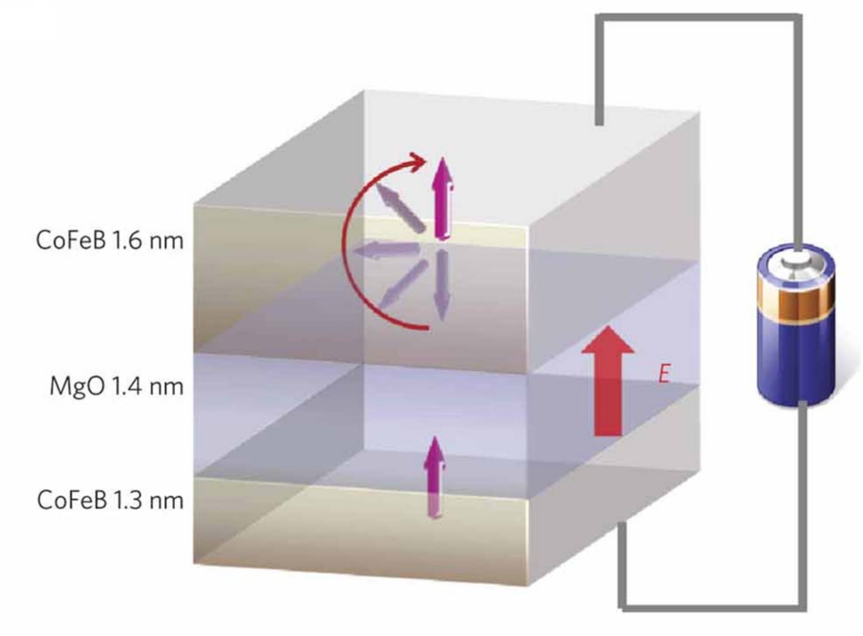
Physics 596: Journal Club

Electric field assisted switching in magnetic tunnel junctions



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Electric-field-assisted switching in magnetic tunnel junctions

Wei-Gang Wang, Mingen Li, Stephen Hageman & C. L. Chien

Summary of the topic:

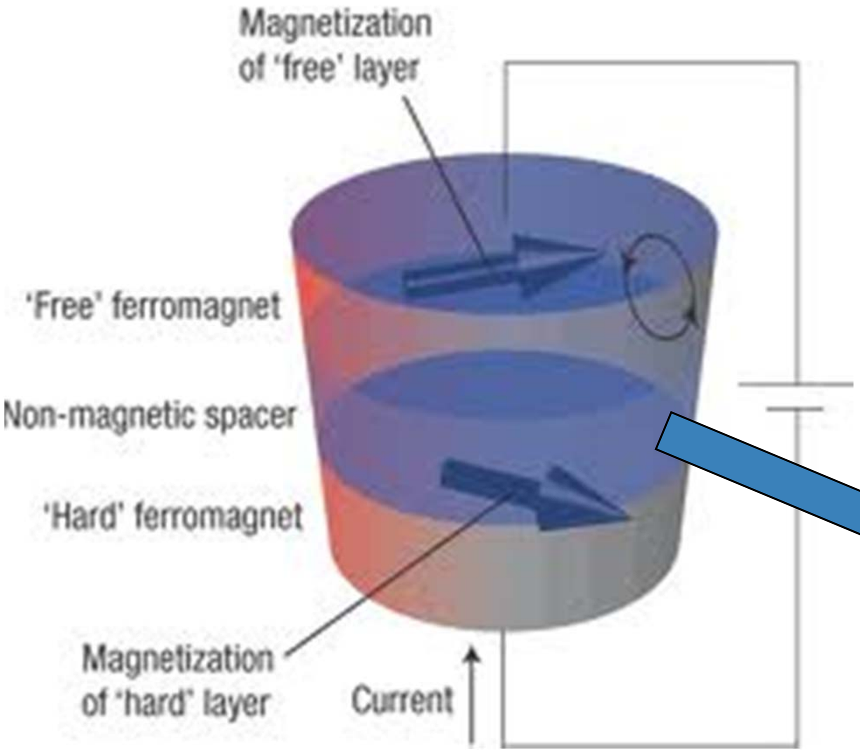
- Magnetic tunnel junctions (MTJs) based on MgO tunnel barriers are the devices of choice for **read heads**, non-volatile magnetic random access memory (MRAM) and spin logic applications

- Need a more **energy-efficient** way to manipulate the magnetization in MTJs than the existing conventional spin transfer torque (STT) effect

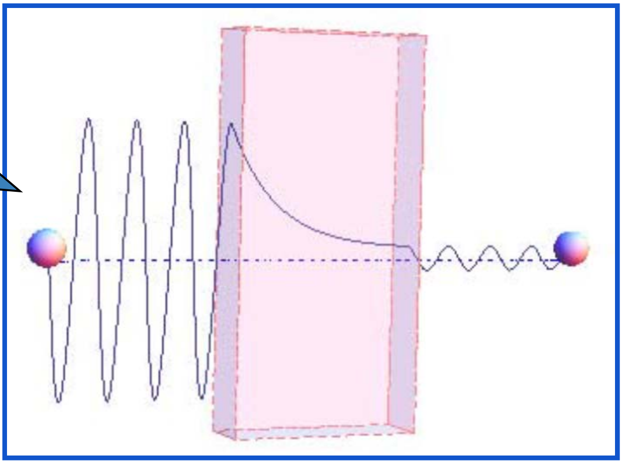
- In CoFeB/MgO/CoFeB p-MTJs, the magnetic configuration and tunnelling magnetoresistance **can be switched** at much **smaller current densities by applying electric field**

What are Magnetic Tunnel Junctions (MTJ)?

- **<u>Structure:</u>** A (MTJ) consists of two layers of magnetic metal, such as cobalt-iron, separated by an ultrathin layer of insulator, with a thickness of about 1 nm.



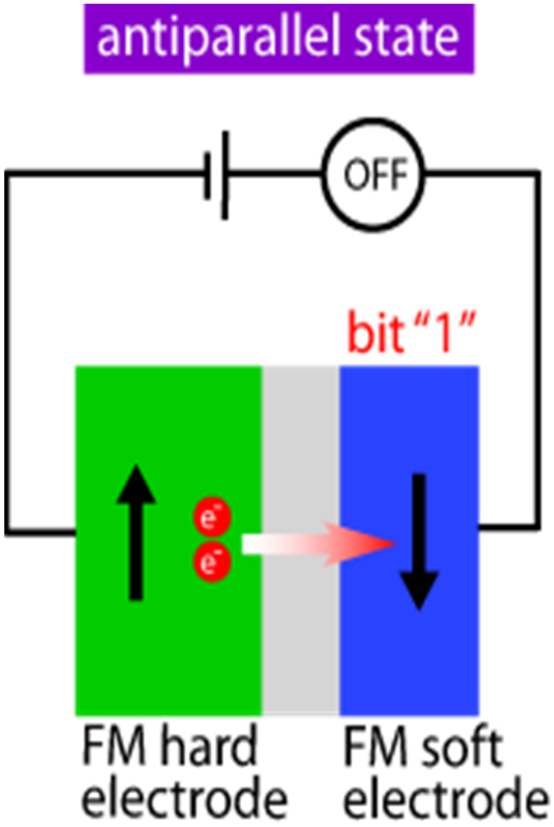
Schematic Diagram of MTJ, Maxim Tsoi, *Nature Physics* 4, 17 - 18 (2008)

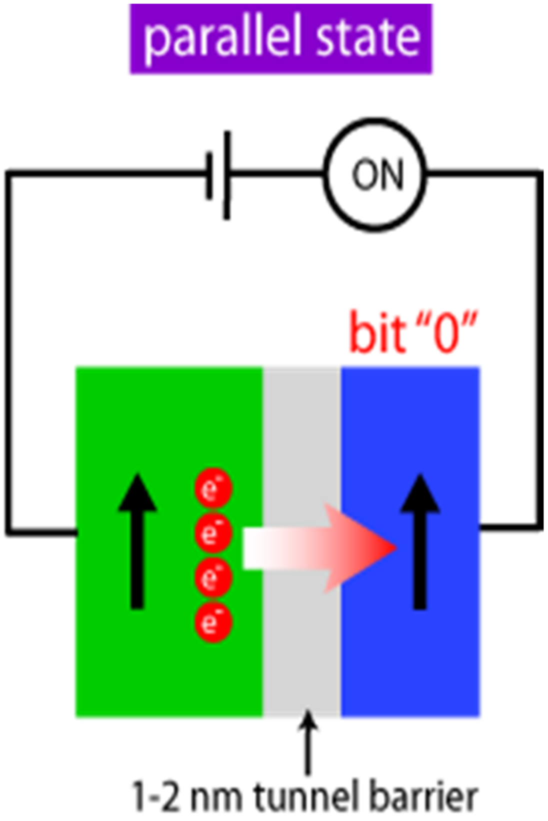


Quantum Tunneling through a potential barrier, Georgiev, D. "Q-tunnel."

- The thin insulating layer allows electrons to tunnel through the barrier on applying a bias voltage.

How do Magnetic Tunnel Junctions Work?

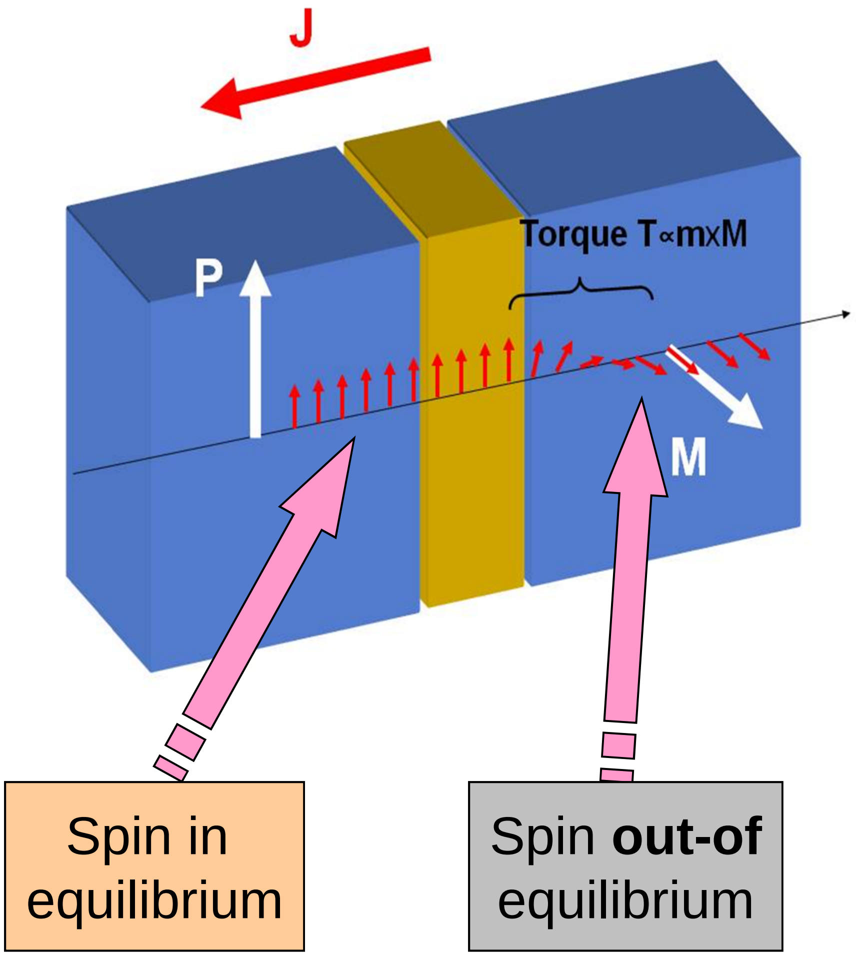




- In MTJs the tunneling current depends on the relative orientation of magnetizations of the two ferromagnetic layers, which can be changed by an applied magnetic field.

Functioning of a MTJ,
http://spam3.mdm.imm.cnr.it/background.php

Spin Transfer Torque Effect:



Spin in equilibrium

Spin **out-of** equilibrium

STT effect in MTJ

- The **Physics** underlying this mechanism:

- A torque is exerted by the out-of-equilibrium spin density on the equilibrium one

- Application:

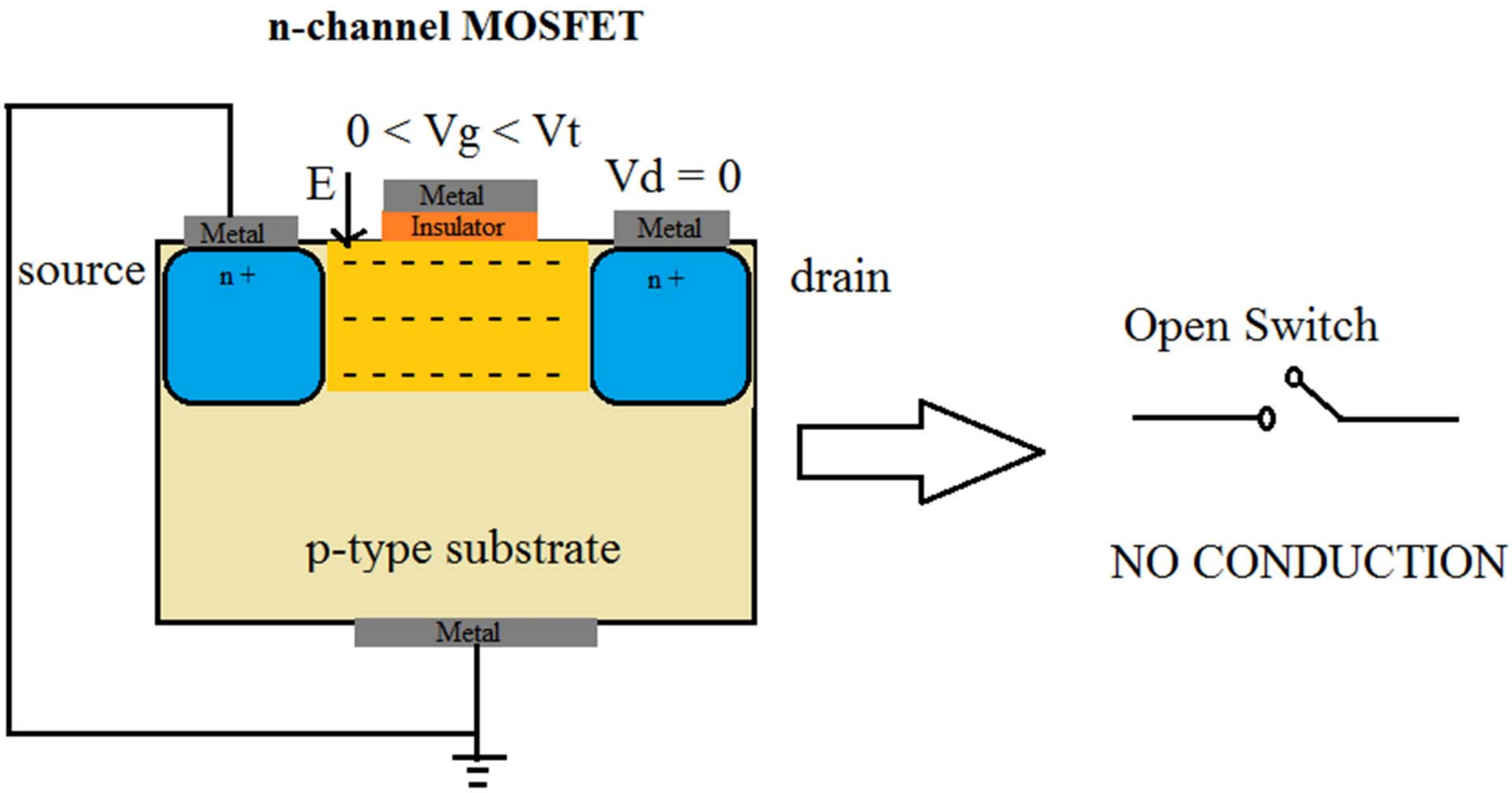
- To manipulate the orientation of a magnetic layer in a magnetic tunnel junction or spin valve by using a spin-polarized current

- **http://faculty.kaust.edu.sa/sites/aurelienmanchon/Pages/ResearchInterests.aspx**

- To achieve a more **energy-efficient** way to manipulate the magnetization in MTJs:
- **Use ELECTRIC FIELD SWITCHING**

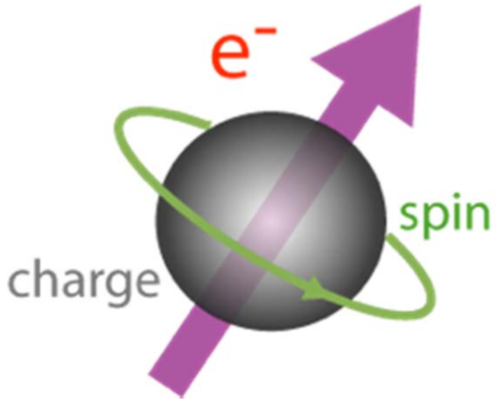
What is E-field switching?

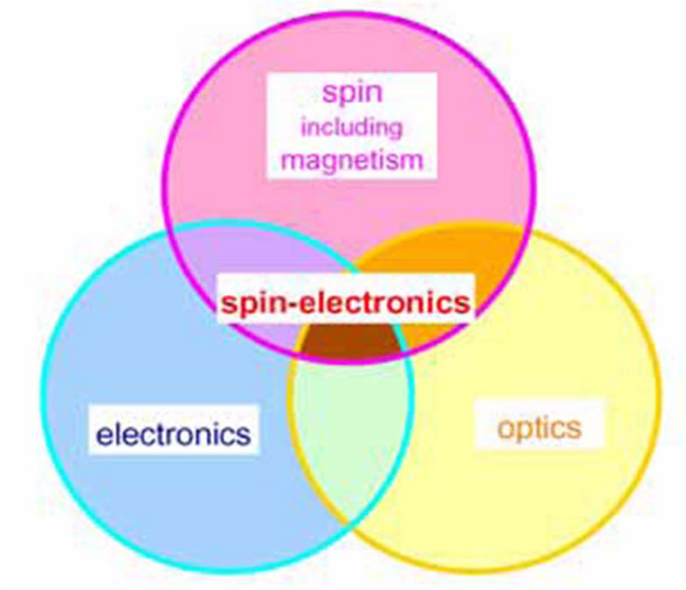
Model Example: Basic operation of the n-channel metal-oxide semiconductor (MOS) transistor



Why It’s Useful to Incorporate Spin:

- **Standard Si CMOS technology:**
- Limitations due to Scale oxide thickness, gate length**: challenges due to lithography and oxide leakage**
- ***Semiconductor: uses 2 degrees of freedom***
- ***Spin-based Electronics: uses 4 degrees of freedom***





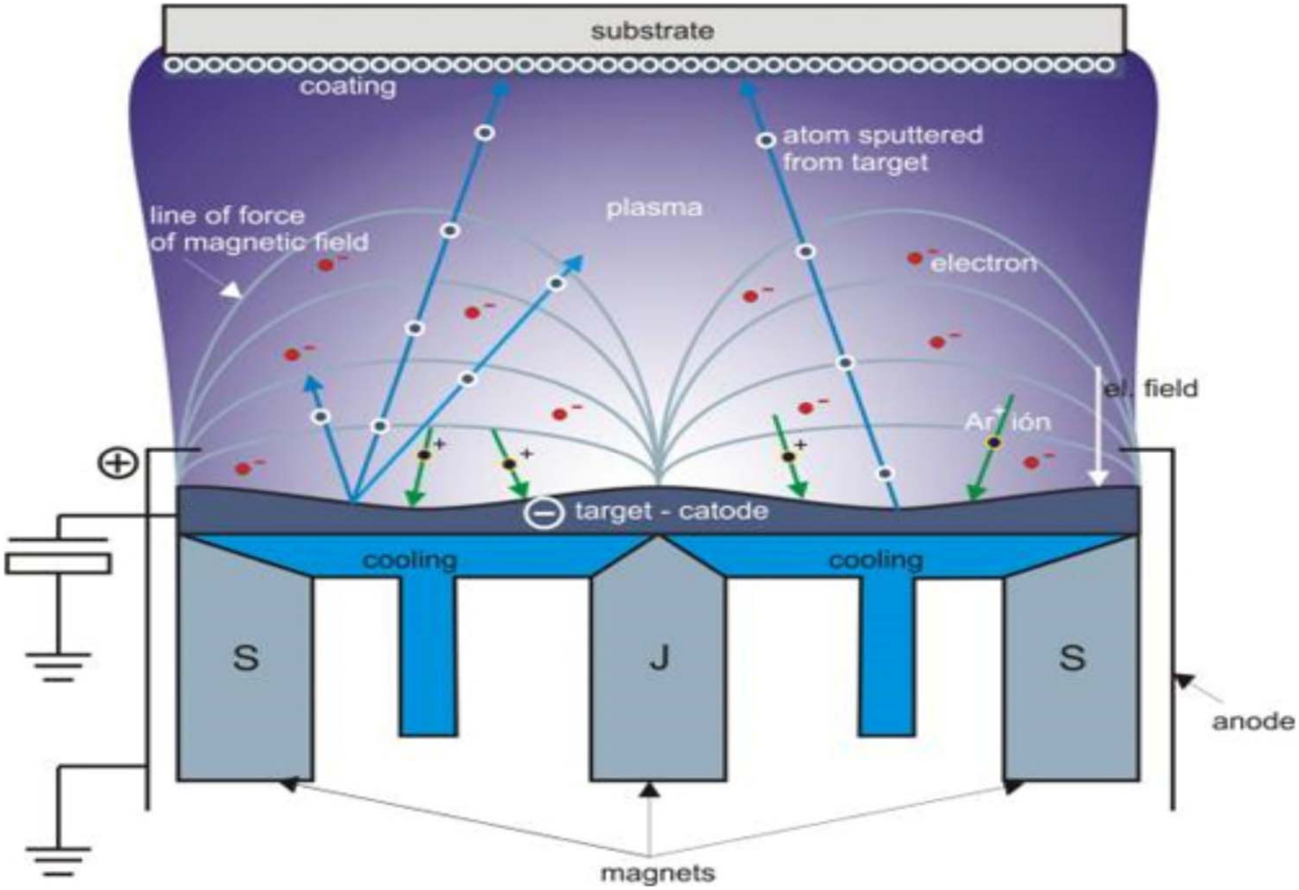
Basic Attributes of Spin:

Electron’s spin origin from its intrinsic ***Angular Momentum***;

Two spin states: ***spin up*** and ***spin down***;

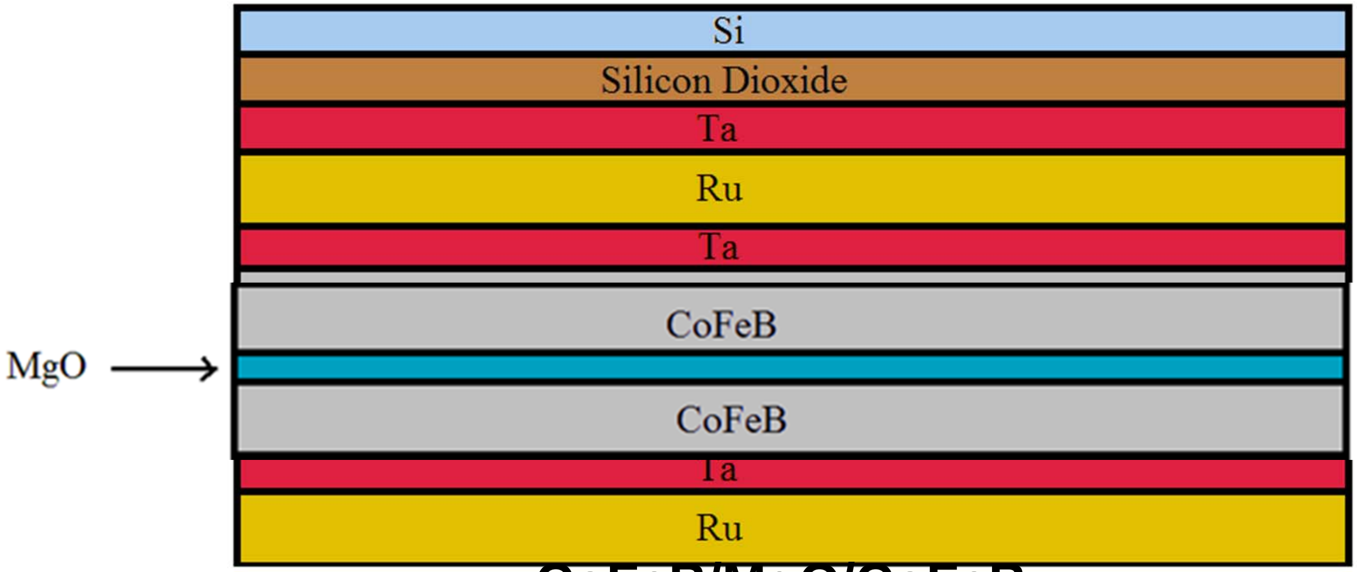
In magnetic fields, electrons with spin up and down have two different energies.

The Magnetron sputtering system:



- Magnetron Sputtering unit, http://www.umms.sav.sk/index.php?ID=415&pg=8.

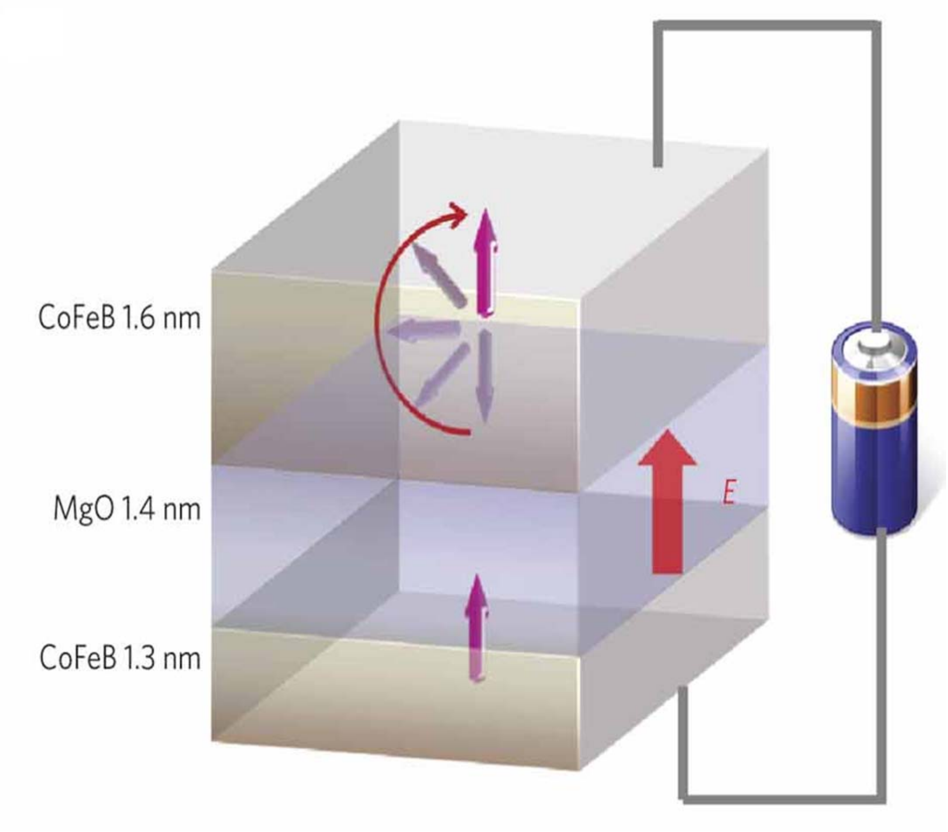
Fabrication of the MTJ:



CoFeB/MgO/CoFeB

- The films were deposited in a multi-source ultrahigh-vacuum magnetron sputtering system with the base vacuum of 3×10^{-9} torr.
- MTJs in circular shapes with diameter (D) ranging from 400nm to 50 nm were fabricated and measured by the four-probe method on a probe station at room temperature.

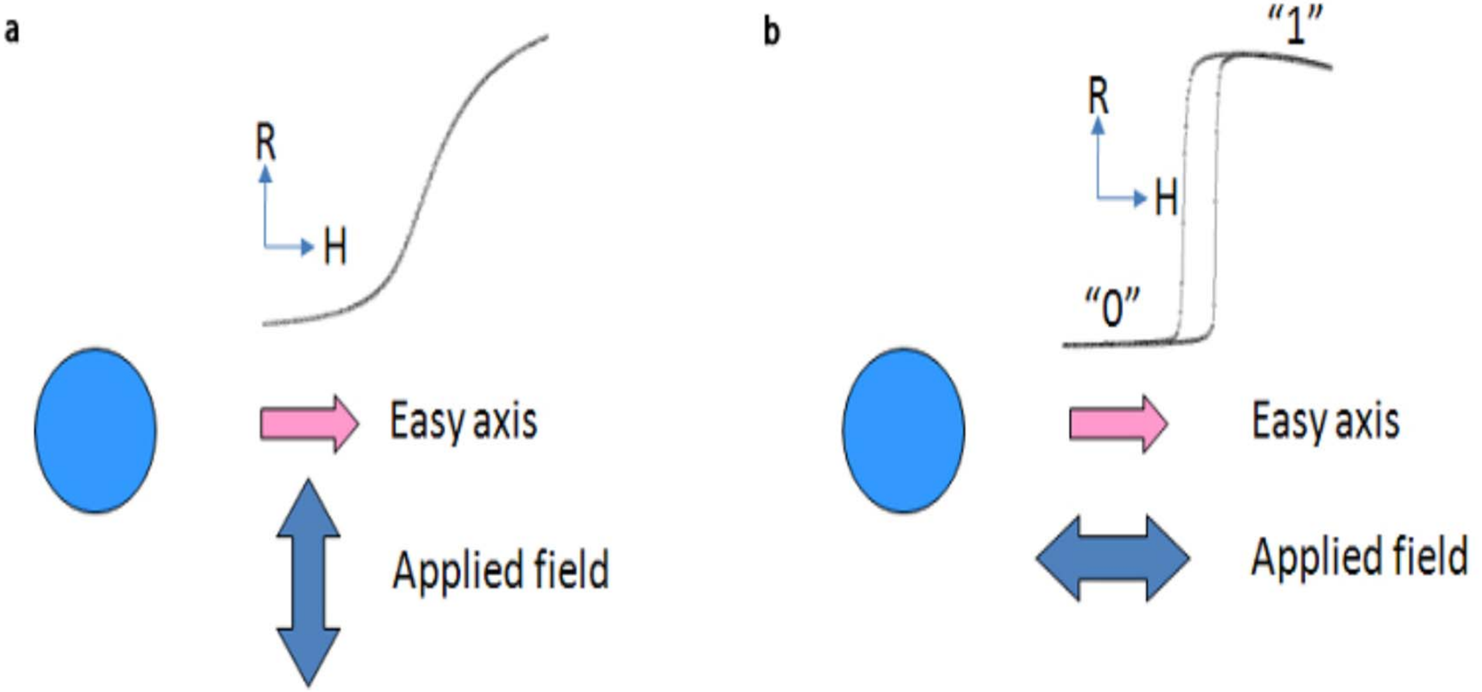
Structure and functionality of the fabricated device
(Top and Bottom electrodes behave differently)



The fabricated MTJ (Wang et al.)

- The low- and high-resistance states are those with parallel and antiparallel magnetizations with the switching fields at the coercivity of the two ferromagnetic electrodes.
- The bottom electrode switches at a higher magnetic field and more sharply than the top electrode, (thickness-dependence study).

The R vs H of the spin-valve is linear in the sensor configuration, and hysteretic in memory configuration



- (a) Sensor Configuration

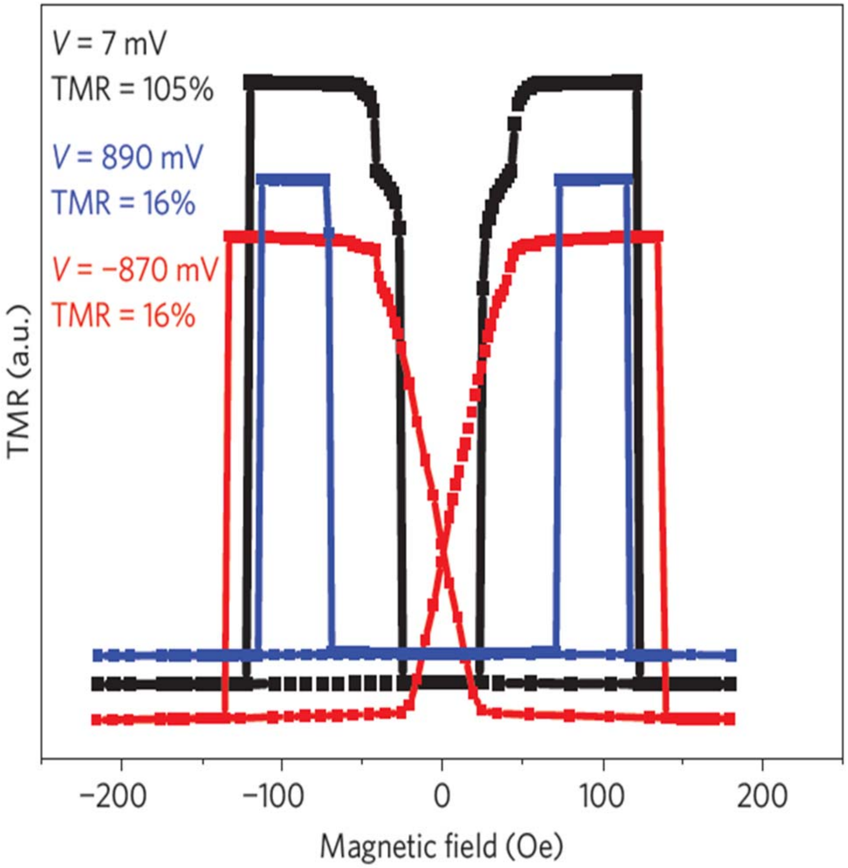
- (b) Memory Configuration

- Two configurations of the MTJ: Shen, W. (Ph.D. dissertation, Brown University, 2007).

Magnetic field dependence of the tunnel magneto-resistance (TMR) of the device

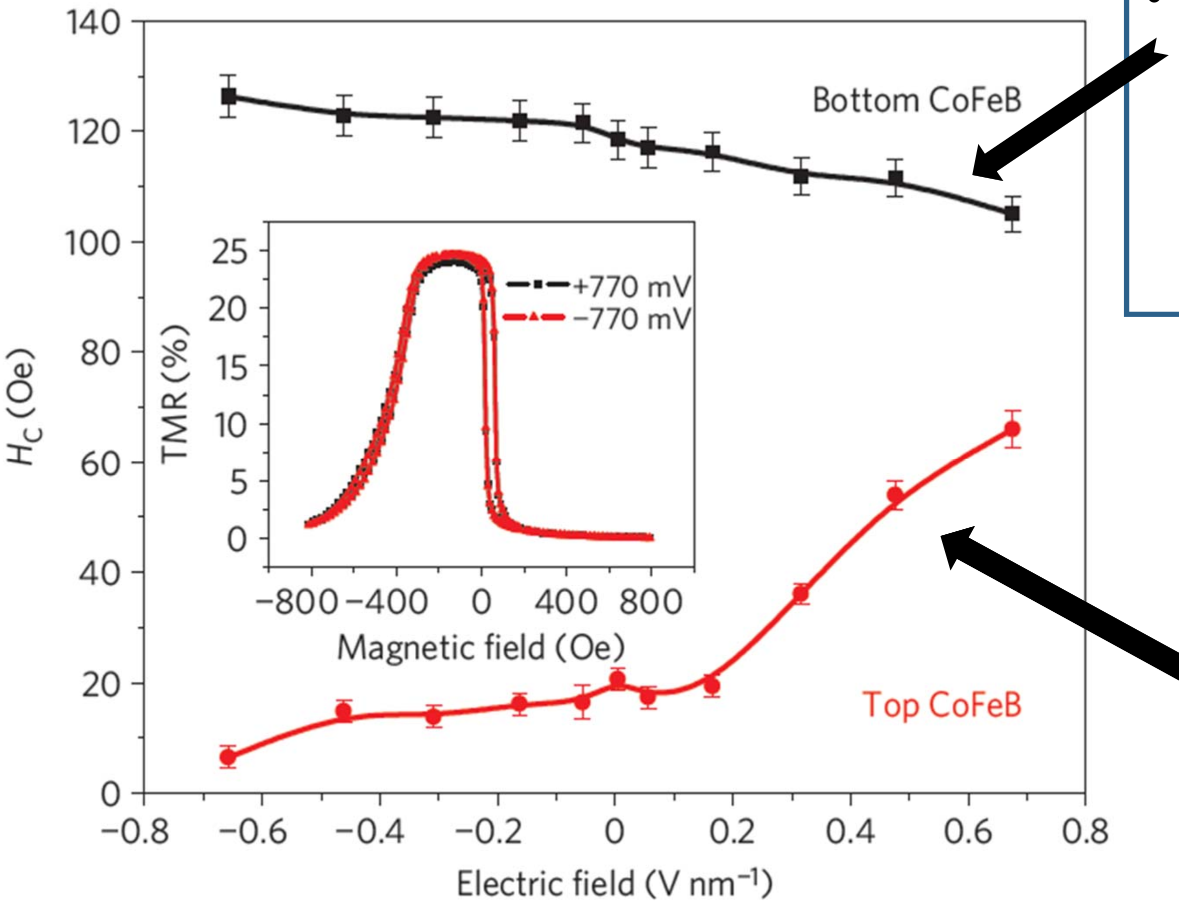
- Switching characteristics of the MTJ **depend explicitly on the bias voltage** V(bias), its value as well as its sign

- The effect of electric field can be directly studied by **d.c. resistance**, with a small voltage of a fraction of a volt., owing to the unique combination of **interfacial perpendicular anisotropy** and **spin-dependent tunnelling** at the CoFeB/MgO interfaces



TMR vs. Magnetic Field in devices studied (Wang et al.)

Top and bottom electrodes of the MTJ behave oppositely under the bias Electric field

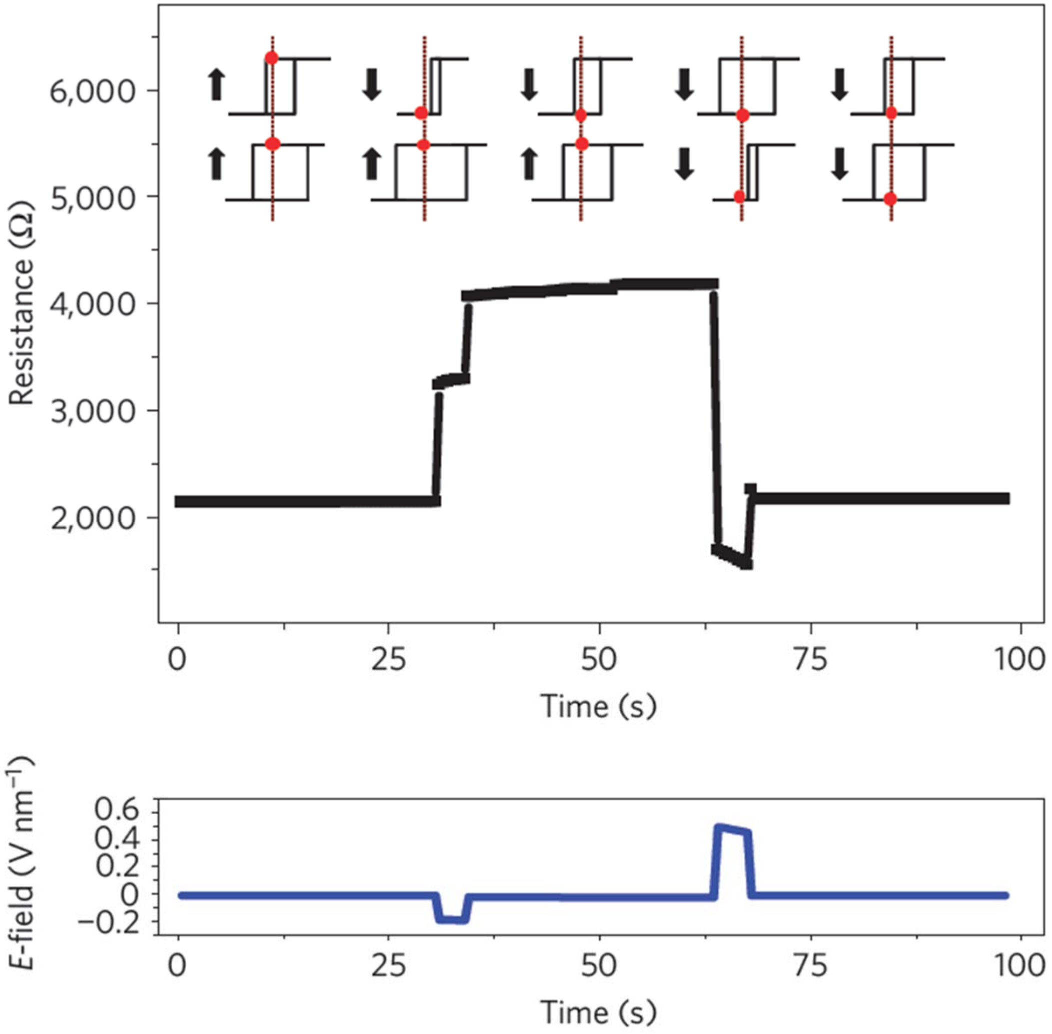


Coercivity vs. Electric Field in devices studied (Wang et al.)

- For the bottom electrode, coercivity H_C depends quasi-linearly on E_{bias}

- The top electrode exhibits the opposite dependence, where coercivity H_C increases with increasing E_{bias}.

Manipulation of giant tunnelling resistance by electric field



- <u>To flip states of the MTJ:</u>

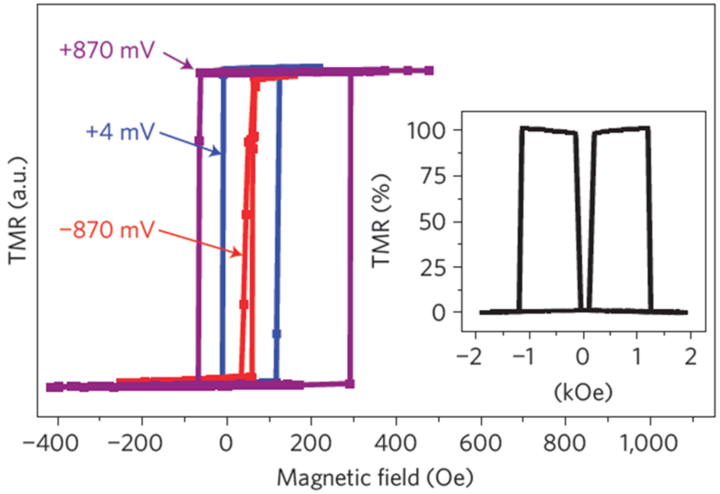
- Change low-resistance to the high-resistance state
- Accomplished by negative voltage pulse

- <u>For reversible switching:</u>

- Use a positive voltage pulse.

Manipulation of GMR by Electric Field in devices studied (Wang et al.)

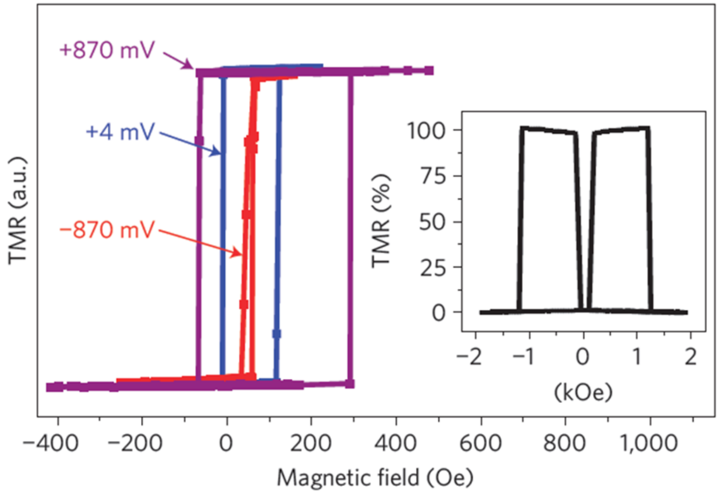
Electric-field-induced unipolar switching

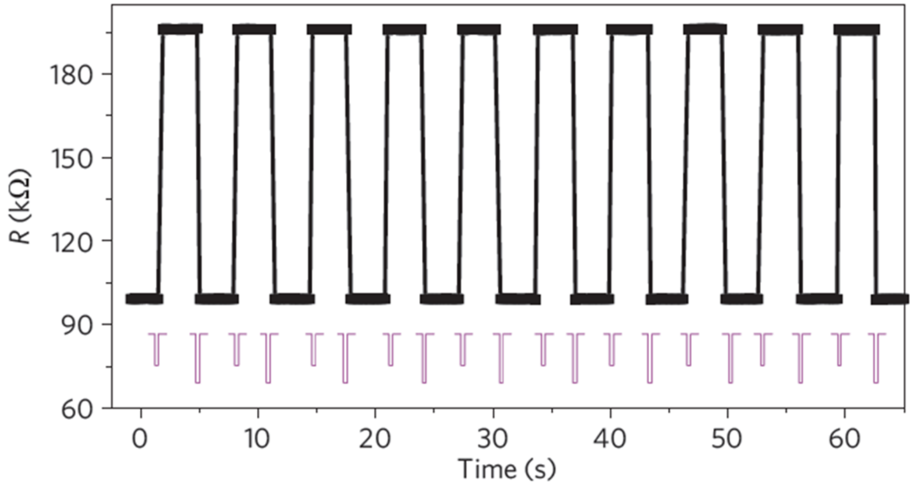


TMR vs Magnetic Field in devices studied (Wang et al.)

- The minor loops of the TMR curve are shown here, with the zero-voltage full TMR curve shown in the inset.
- The coercivity of the top CoFeB shows dramatic change under different bias voltages.
- It is 70 Oe at near-zero bias, and increases almost 2.5-fold to 172 Oe at DC bias of + 870mV and reduces to 8 Oe at bias of - 870 mV.

Electric-field-induced unipolar switching





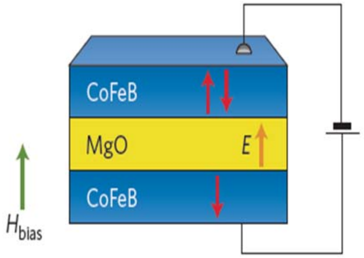
- This MTJ can be **reversibly switched** by consecutive negative pulses as shown here.
- A series of 200 ms pulses with alternating amplitude of V1 (-0:9 V) and V2 (-1:5 V) were sent to the MTJ every 3 s.

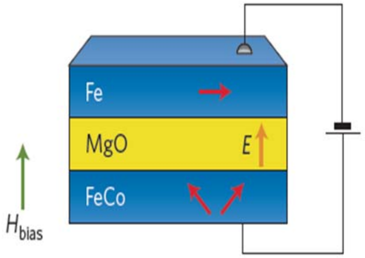
- After each switching pulse the resistance is monitored at 10 mV. We can clearly see that the MTJ is **consistently switched** by these **unipolar pulses**, as opposed to the bipolar pulses used in the usual STT effect.

Switching by negative pulses in devices studied (Wang et al.)

Key Points of the Paper

- ✓ In CoFeB/MgO/CoFeB p-MTJs, the magnetic configuration and tunnelling magnetoresistance **can be switched** at much **smaller current densities by applying electric field**.



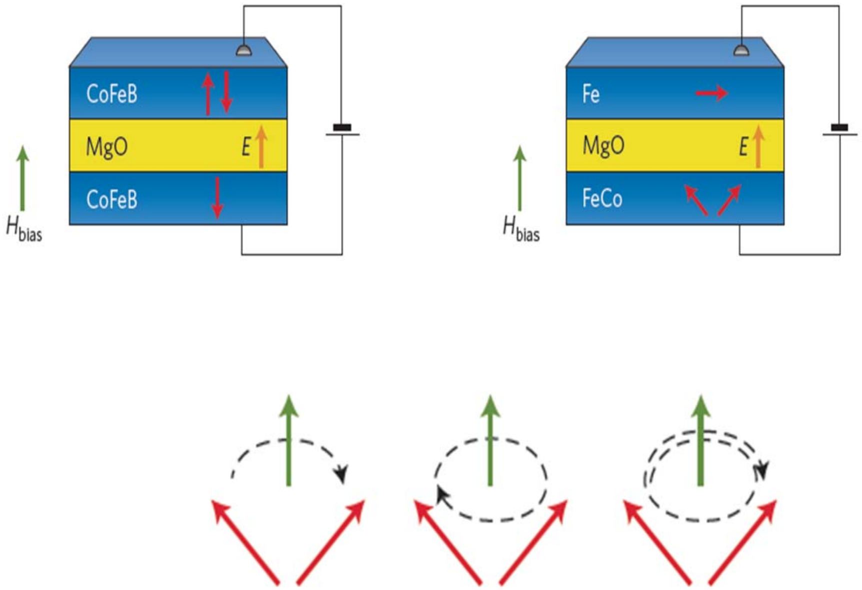


NATURE MATERIALS, Vol 12, Jan 2012

Key Points of the Paper

✓ In CoFeB/MgO/CoFeB p-MTJs, the magnetic configuration and tunnelling magnetoresistance **can be switched** at much **smaller current densities by applying electric field**.

✓ **Reversible switching** is possible if the direction of biasing magnetic field is changed.



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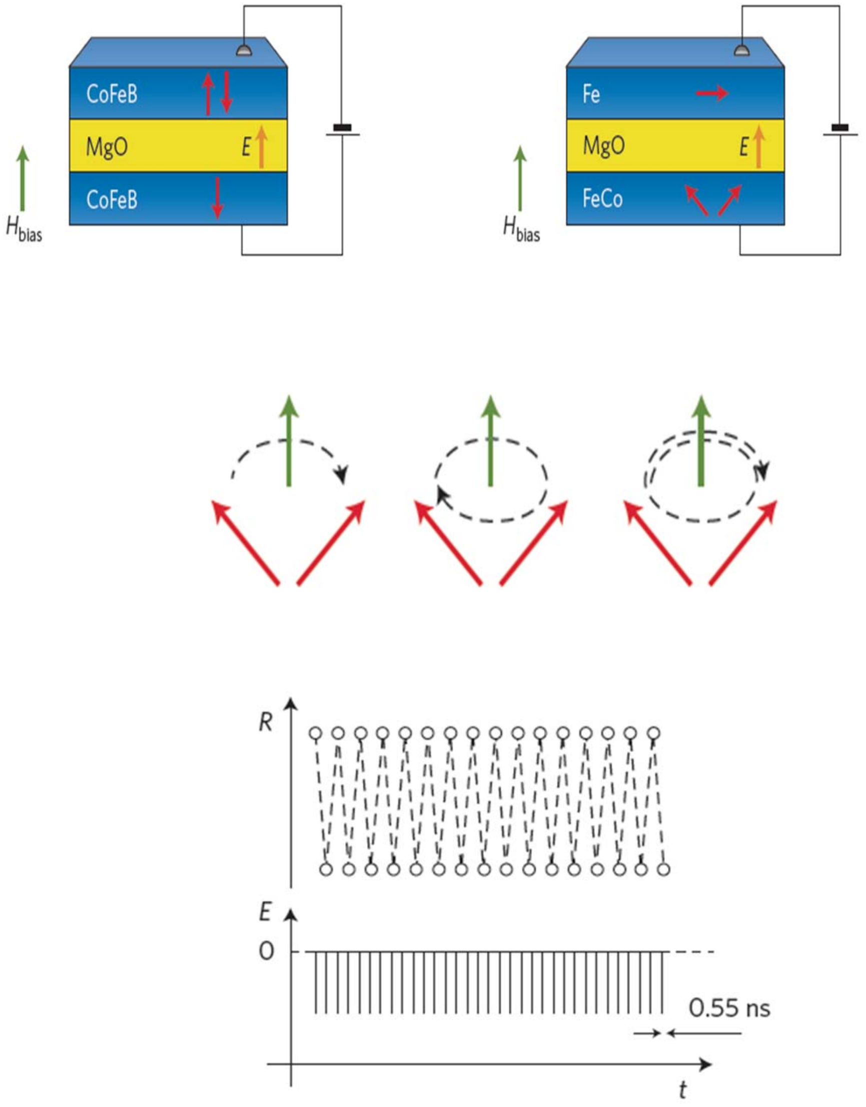
Key Points of the Paper

- ✓ In CoFeB/MgO/CoFeB p-MTJs, the magnetic configuration and tunnelling magnetoresistance **can be switched** at much **smaller current densities by applying electric field**.
- ✓ **Reversible switching** is possible if the direction of biasing magnetic field is changed.
- ✓ Crucial step towards **voltage-controlled** spintronic devices such as ultralow-energy MRAM and logic elements.



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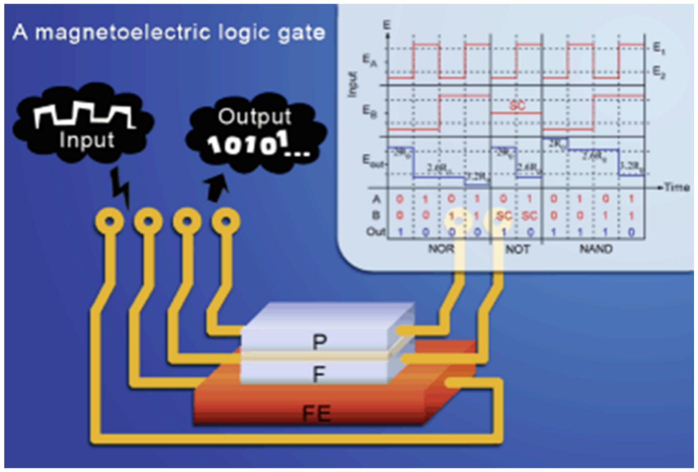
Advantages over existing MTJ technology

Advantages

- Ultralow energy switching in MTJ.

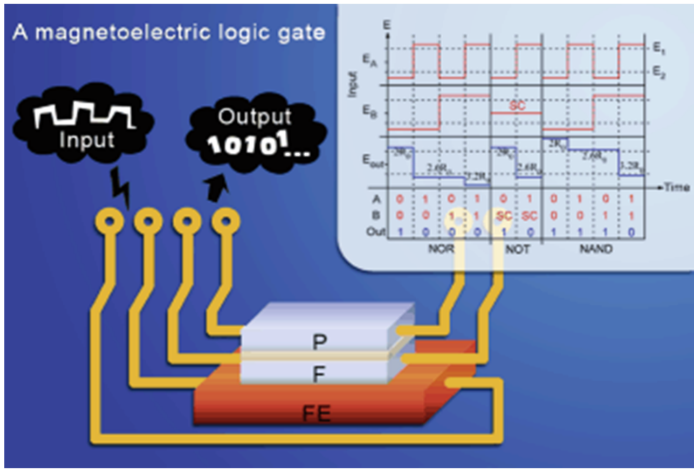


From PPS-rapid, Wiley

Advantages over existing MTJ technology

Advantages

- Ultralow energy switching in MTJ.
- New avenue for exploring other voltage-controlled spintronic devices.



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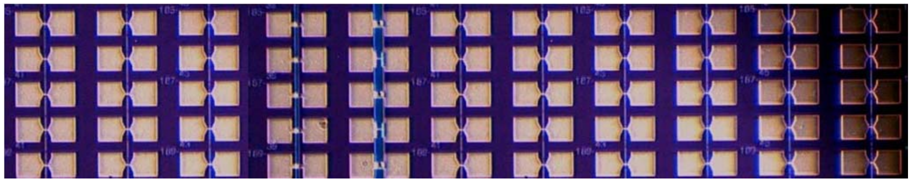


From Wang’s group

Our Analysis

- The magnetic configuration and tunnelling magnetoresistance can be switched at much smaller current densities, due to the direct effect of the E field on the PMA of the CoFeB layers
- Important for voltage-controlled spintronic devices such as ultralow-energy magnetic random access memory and logic elements.

- Less energy expense in magnetoresistance for data storage

From: thedailygreen.com

Our Analysis

- The magnetic configuration and tunnelling magnetoresistance can be switched at much smaller current densities, due to the direct effect of the E field on the PMA of the CoFeB layers

- Important for voltage-controlled spintronic devices such as ultralow-energy magnetic random access memory and logic elements.

From: Artist Control

- More electric-field control of magnetization

Tracking the advance of the article

From: Nol-tec

✓ 23 citations

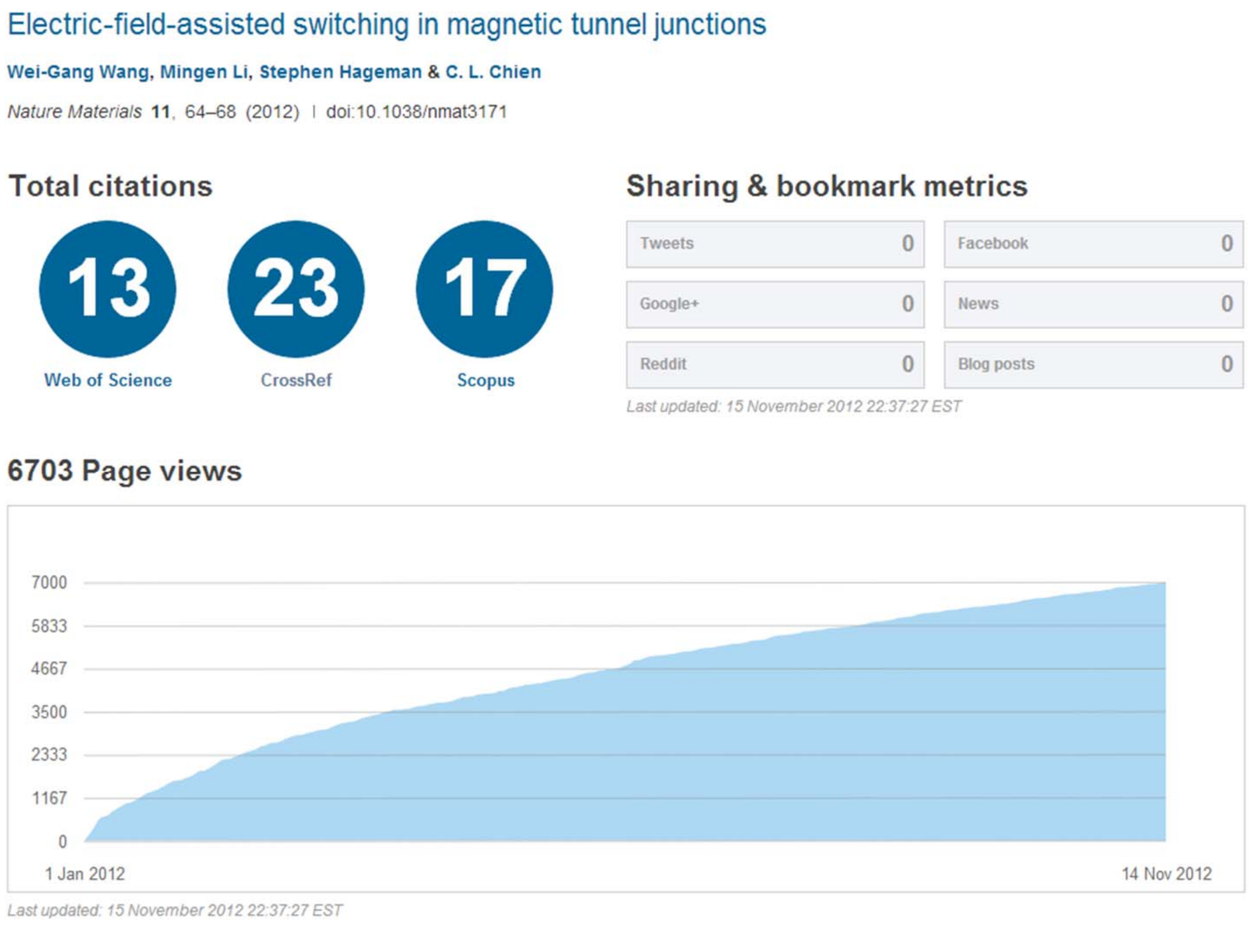
✓ Only 5 of those have been cited

✓ Most recent November 5th

✓ First citation was in the same journal: Very recent state of the art of Spintronics. (Cited 4 times, most cited)

From: SCOPUS WEB OF KNOWLEDGE, ARXIV, NATURE

Tracking the advance of the article



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From: NATURE MATERIALS

Evolution of the field

- Size dependence of spin-torque induced magnetic switching in CoFeB-based perpendicular MTJ
- Reducing spin torque switching current density by boron insertion into a CoFeB free layer of a magnetic tunnel junction
- MTJ with iron dusting layer free-tunnel barrier
- Some patents:
    - Magnetic oscillations driven by the spin Hall effect in 3 terminal MTJ device
    - Method of writing to MTJs by increasing applying voltage level
    - Dual MTJs sensor with a longitudinal bias stack

Thank You !