Spintronic devices - applications

Magnetic materials in nanoelectronics

- properties and fabrication

Lecture

M.Urbaniak

Spintronic devices - applications

1. Introduction
2. Magnetoresistive sensors
3. Magnetoresistive memories
4. Spintronic devices

Introduction

The beginnings of magnetic sound recording

- 1900 - Vladeniar Poulsen demonstrated a Telegraphone. It was a device that recorded sounds onto a steel wire [2] (many things happened before that*)
- 1935- Berlin, Fritz Pfleumer demonstrated his **Magnetophone**. It used a cellulose acetate tape coated with soft iron powder.

image from: http://www.theregister.co.uk/Print/2013/09/09/history_of_magnetic_tape_part_one/

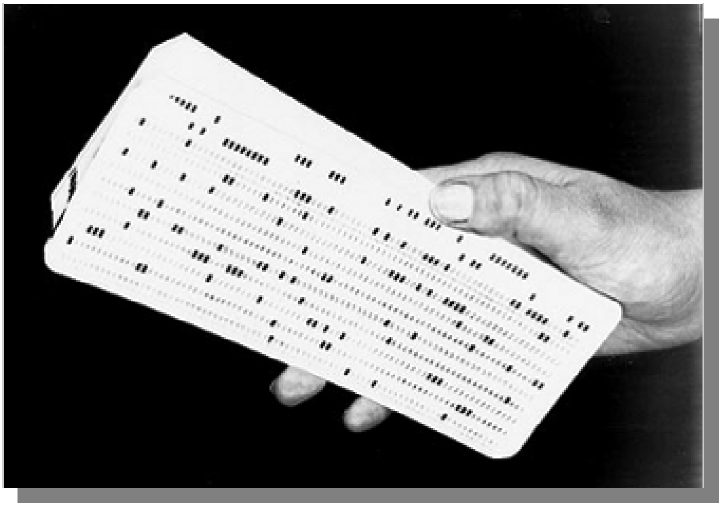
*http://www.theregister.co.uk/Print/2013/09/09/history_of_magnetic_tape_part_one/

Introduction

The beginnings of magnetic sound recording

- 1952 – IBM markets magnetic tape drive reading 7,500 cps (character per second)

image from: http://www-03.ibm.com/ibm/history/exhibits/storage/storage_PH001.html



IBM punched card
approx. 133 cps

- tape of approx. 13 mm width
- six tracks of data running parallel to the length of the tape (seventh track used for reading and writing checking of the other six)

image from: http://www-03.ibm.com/ibm/history/exhibits/701/701_1415bx26.html

Introduction

Tapes are not gone yet

- storage media on tape are still in use
- they provide high capacity for relatively low price
- the data transfer ration reaches 160 MB/s (as of 2014)

FujiFilm Ultrium cartridge

- 2.5 TB capacity
- over 30 years archival life
- 2176 data tracks per 12.56 mm tape width - tracks separation approx. 6μm
- each cartridge is equipped with EEPROM memory "*to record cartridge load/unload history and easily monitor the cartridge health.*" - from http://www.fujifilmusa.com

image from: http://www.fujifilmusa.com/products/tape_data_storage/midrange_tape/lto/lto_ultrium_6/index.html#product-views

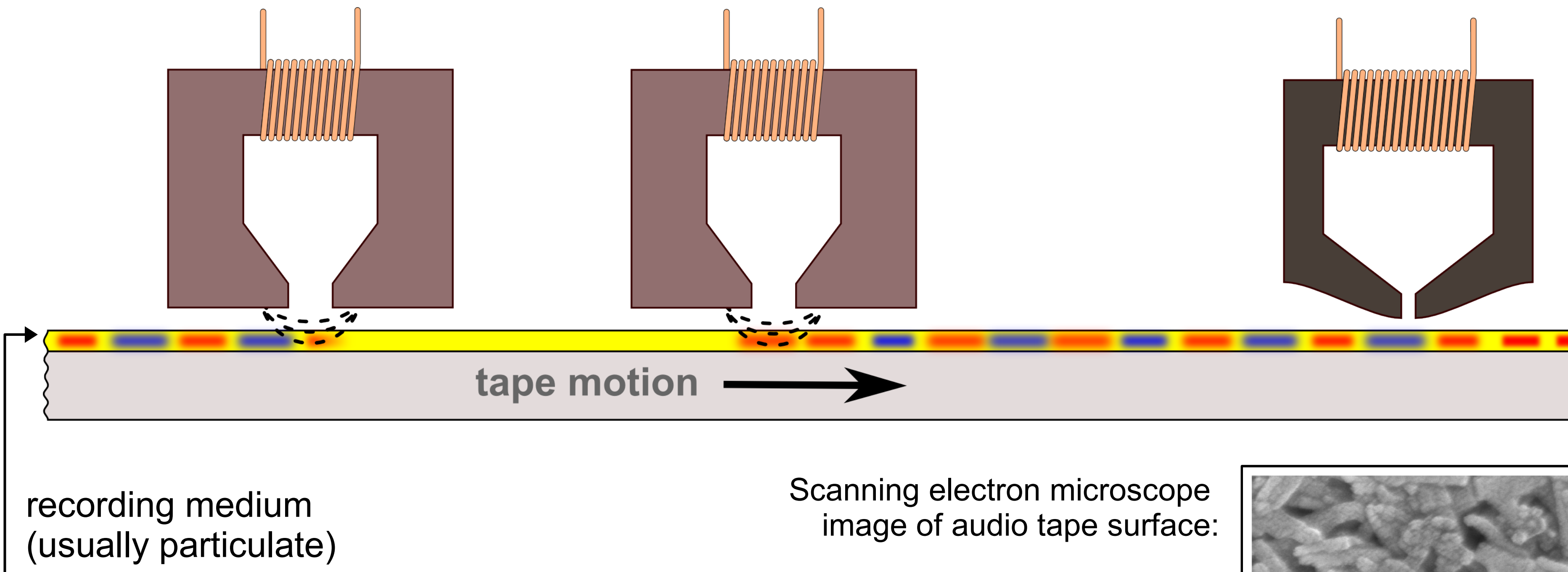
Introduction

Basic audio recording [2,3]

erase head – ac field (frequency several times higher than max. audio frequency) demagnetizes the tape; as the part of the tape moves away from the head the field gradually decreases

write head – audio frequency voltage generates magnetic field – stray fields magnetize the tape

read (reproduce) inductive **head** – stray fields from the tape magnetize the yoke; the varying audio signal is detected by magnetic induction principle; usually the coil has more turns than write head



Scanning electron microscope image of audio tape surface:

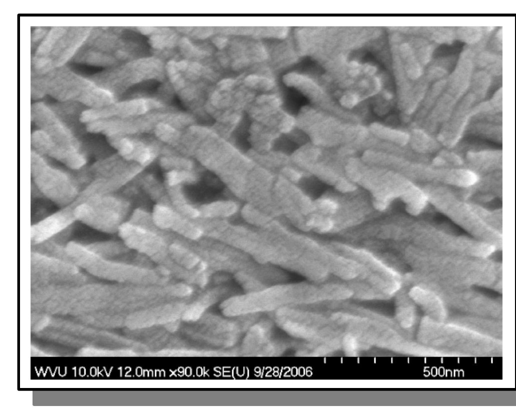
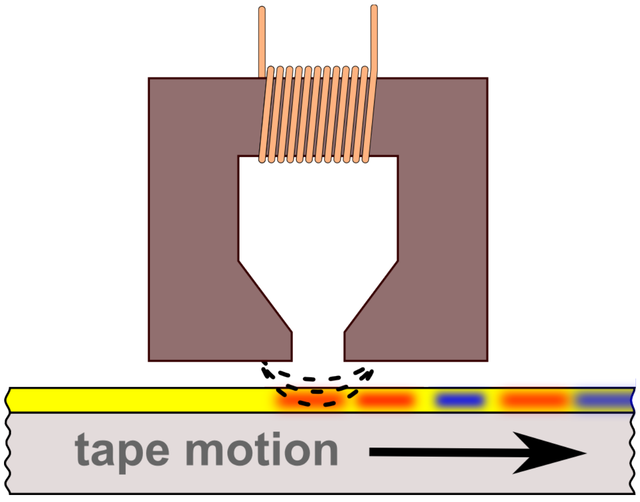


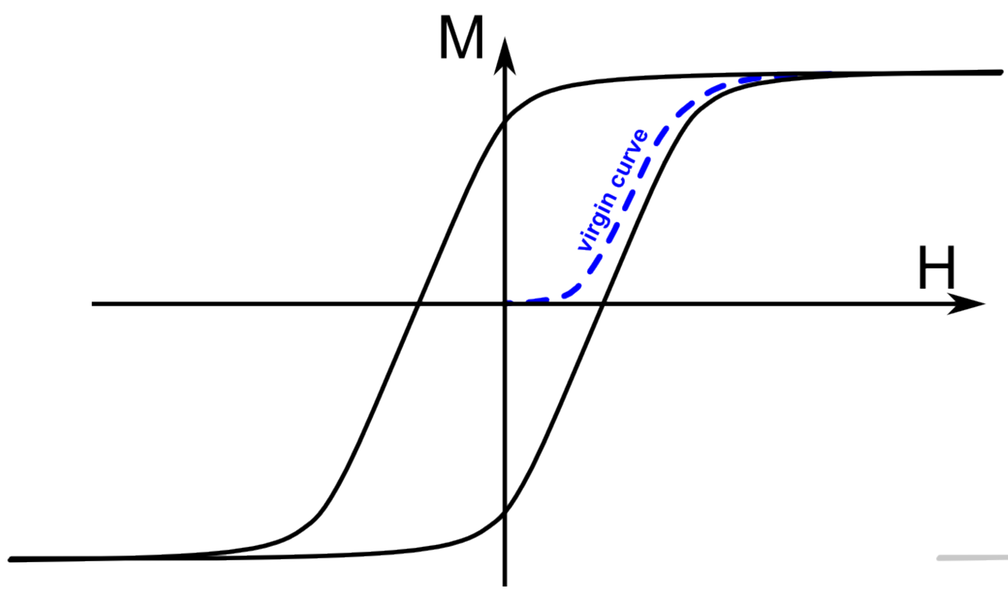
image from: T.R. Ferrett, Data Recovery from Magnetic Media Using Magnetic Force Microscopy, thesis, Morgantown, West Virginia 2008

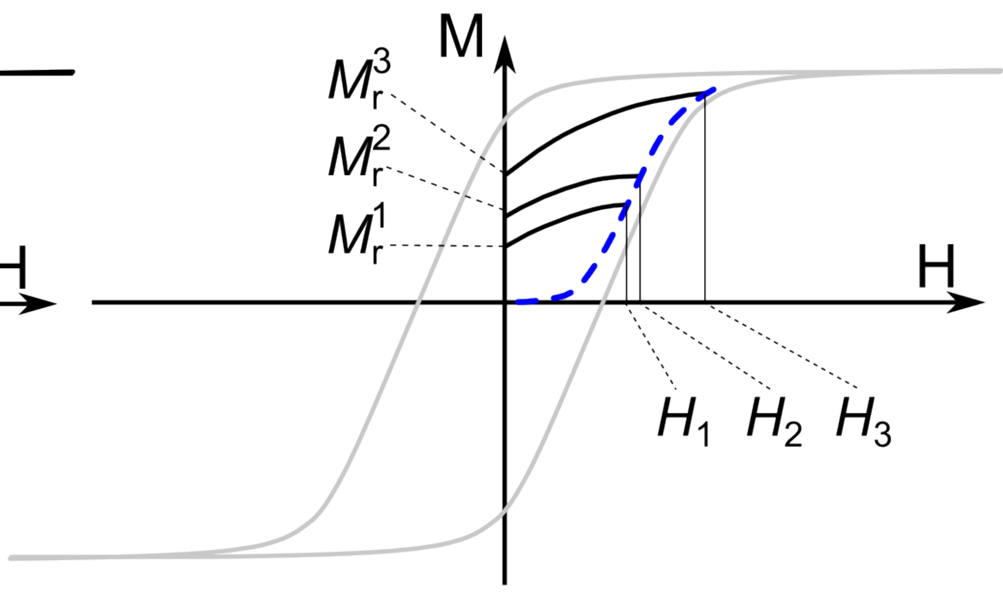
Introduction

Basic audio recording [2,3]*



- after the erase procedure the tape has approx. zero magnetization (it is in a demagnetized state)
- when afterward the magnetic field increases the magnetization traces the virgin curve
- when the tape moves away from the write head the magnetization settles at $M_r(H_{max})$ value, where H_{max} is the maximum field acting on a given part of the tape

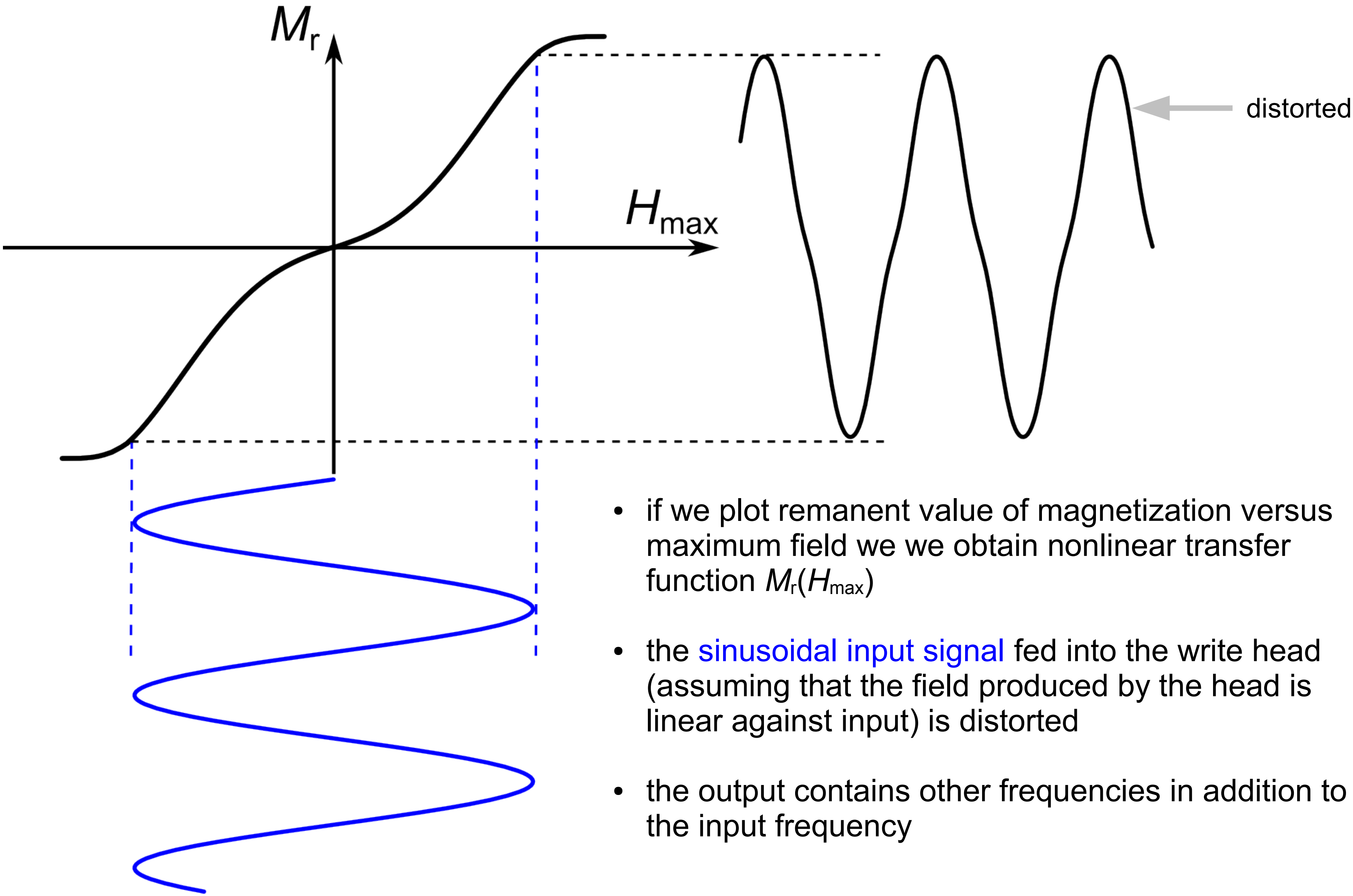




*we assume that no bias field is present

Introduction

Basic audio recording [2,3]*

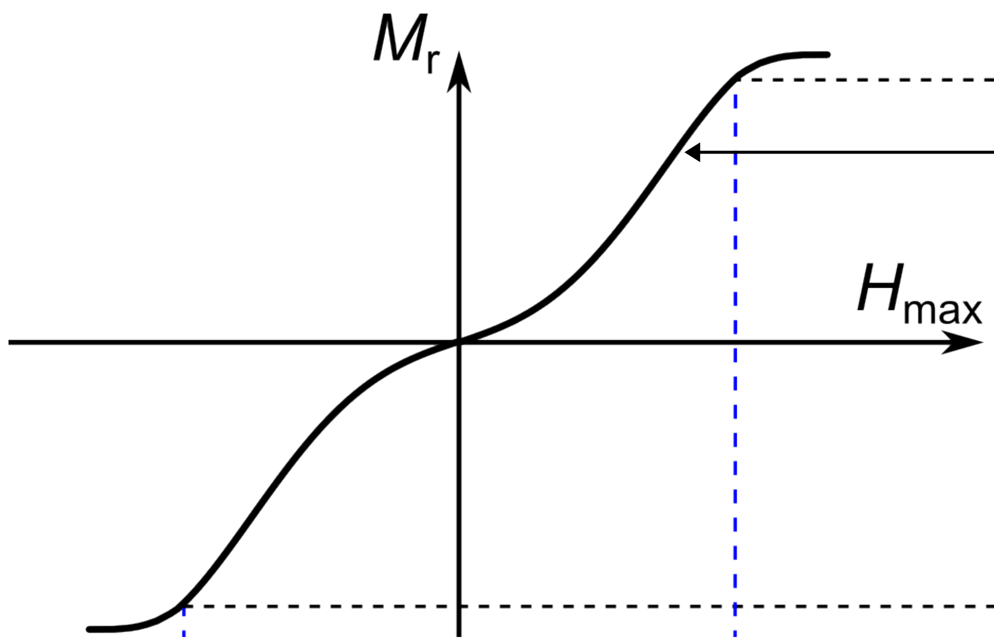


- if we plot remanent value of magnetization versus maximum field we we obtain nonlinear transfer function $M_r(H_{max})$
- the sinusoidal input signal fed into the write head (assuming that the field produced by the head is linear against input) is distorted
- the output contains other frequencies in addition to the input frequency

*we assume that no bias field is present

Introduction

Basic audio recording [2,3]



- nonlinearity in the transfer characteristics can be strongly diminished by using bias techniques [4]
- the constant voltage can be added to the audio signal moving the input to a linear part of $M_r(H_{max})$ dependence
- such bias introduces however a constant background of magnetization in the tape resulting in a strong noise on play-back and other problems...[4]

- one remedy to the nonlinearity problems is to use a high frequency bias (a frequency several times that AF of an audio signal) which linearizes the transfer curve [2,3,4]
- the hf-bias reduces distortion, signal-to-noise ratio (SNR) and the natural tape hiss [2]

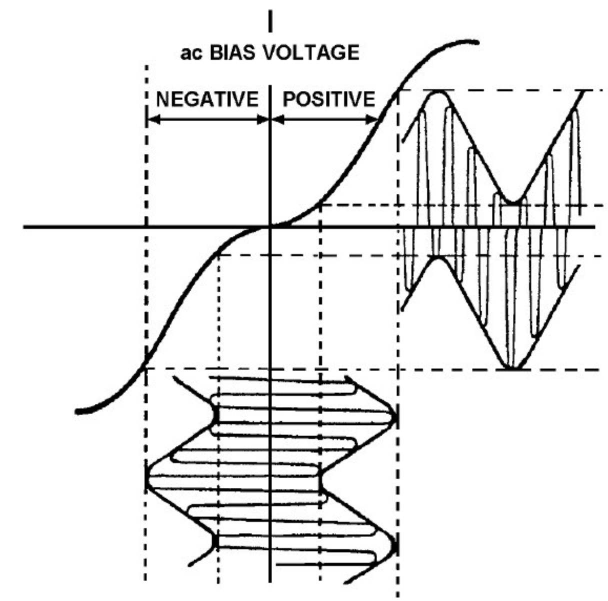


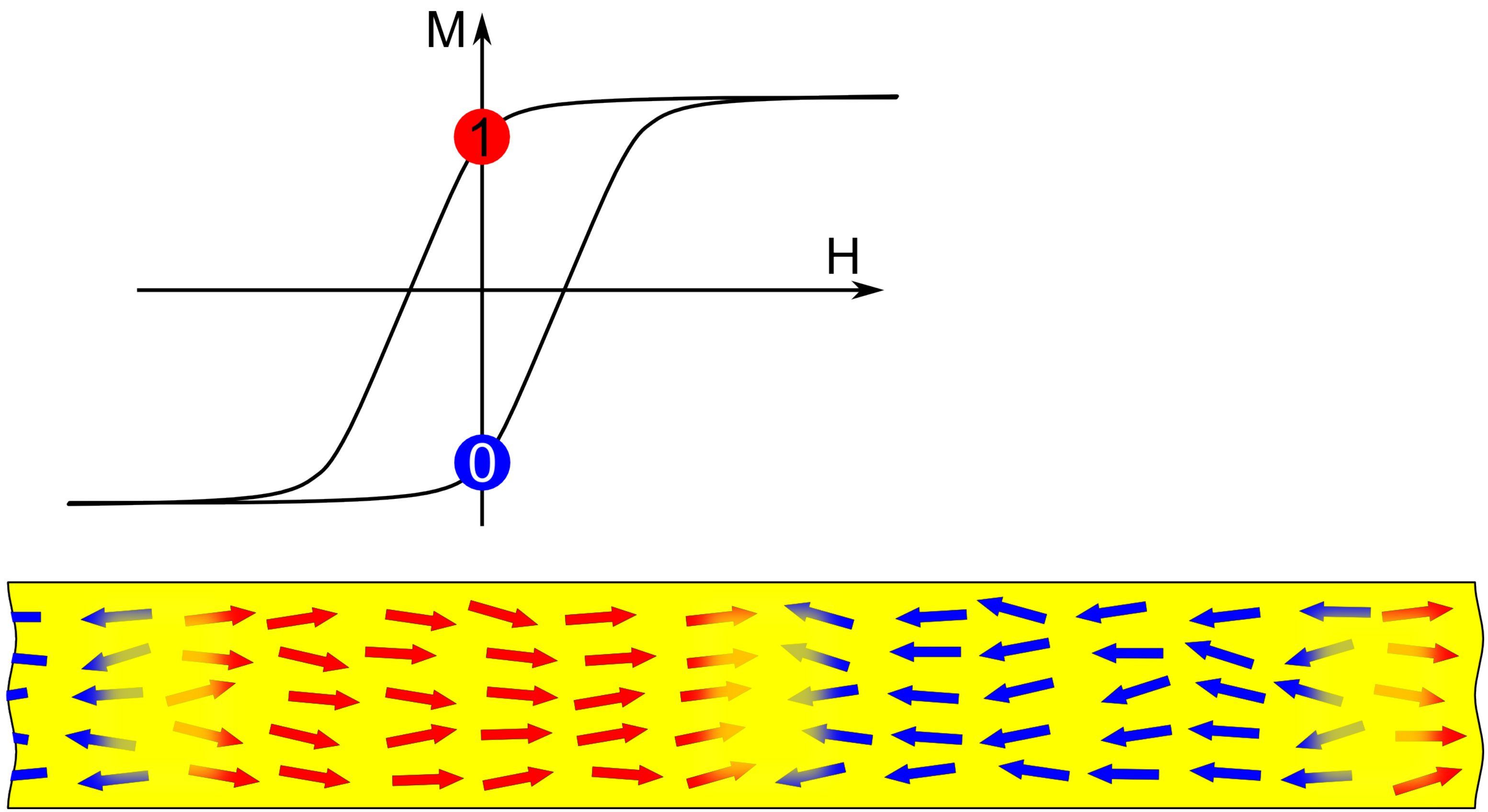
Figure 1-3.—Magnetic recording with ac bias voltage.

right image from: Navy Electricity and Electronics Training Series Module 23—Magnetic Recording NAVEDTRA 14195, 1998, prepared by CTMC(SS) M.C. Georgo

Introduction

Digital magnetic recording [2]

- data is stored on the tape by magnetizing the tape to the saturation
- there are two possible states of the given tape area depending on the polarization of the input signal from the write head
- the states can represent digital data used by computers



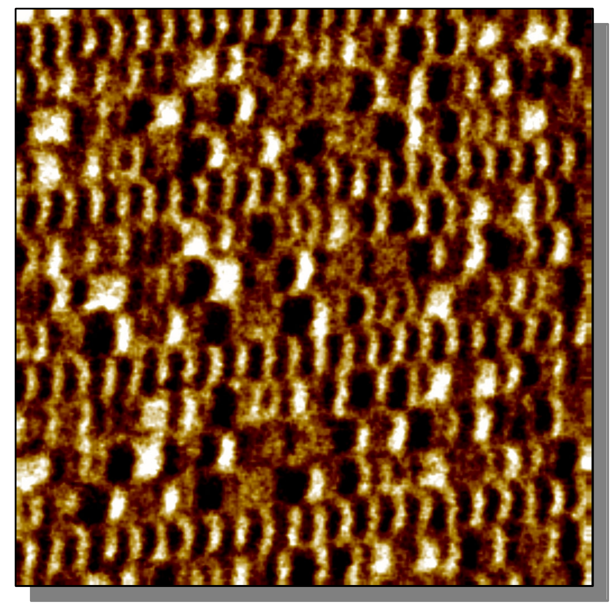
Introduction

Digital magnetic recording [2]

- reading of data from the tape/disk can be performed with inductive head as previously shown for audio recording or with magnetoresistive heads using anisotropic magnetoresistance (AMR) or the giant magnetoresistance (GMR)

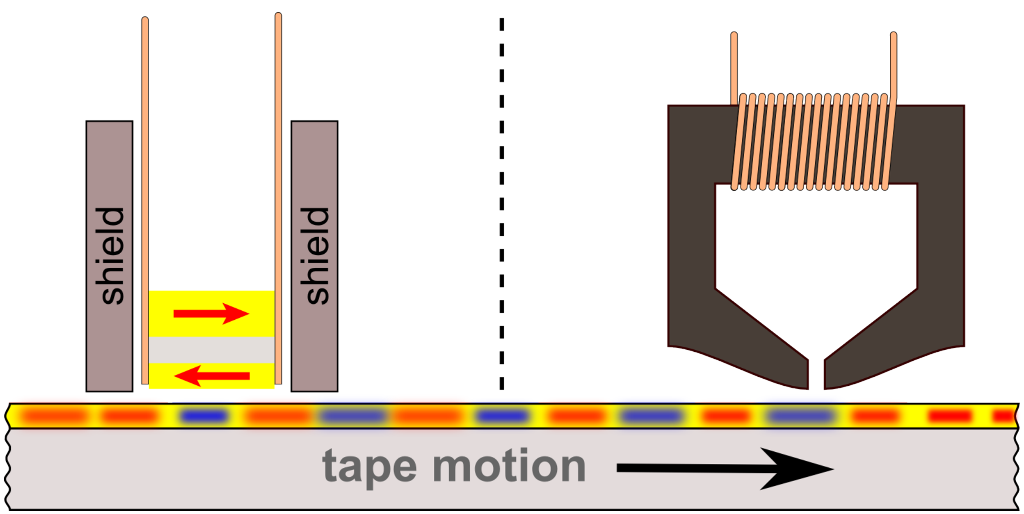
magnetoresistive read heads

- AMR heads – the available output decreases as the thickness of the device gets smaller (to be able to read narrower bits); the AMR heads were introduced first for the read-out of tapes
- **GMR heads** – high voltage even if the thickness of the device is small
- signal does not depend on relative velocity storage medium - head



Magnetic domains of High-density HDD media (2×2µm²)

image from: parkafm.co.jp/AFM_gallery/AFM_gallery_view.php?id=231&word=Magnetic%20Materials



read (reproduce) inductive **head**

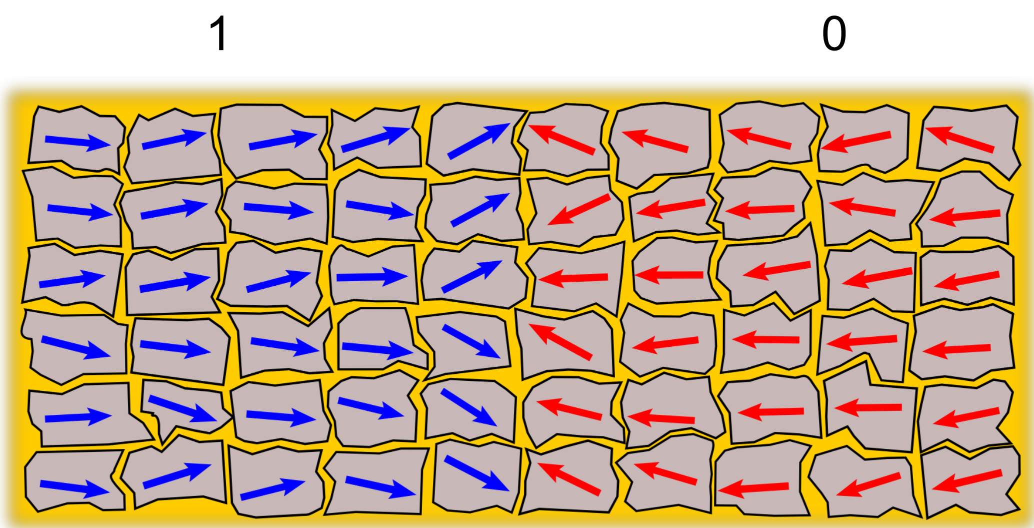
stray fields from the tape magnetize the yoke; the varying audio signal is detected by magnetic induction principle; usually the coil has more turns than write head

- signal depends on the relative velocity storage medium - head

Introduction

Where are the bits?

- in digital recording (longitudinal or perpendicular) bits are written into the tape/disc in the form of areas of different orientation of magnetic moments
- usually "single" magnetized area encompasses many grains (on the order of 10^3); the more grains the more sharp transition between neighboring magnetized areas can be achieved



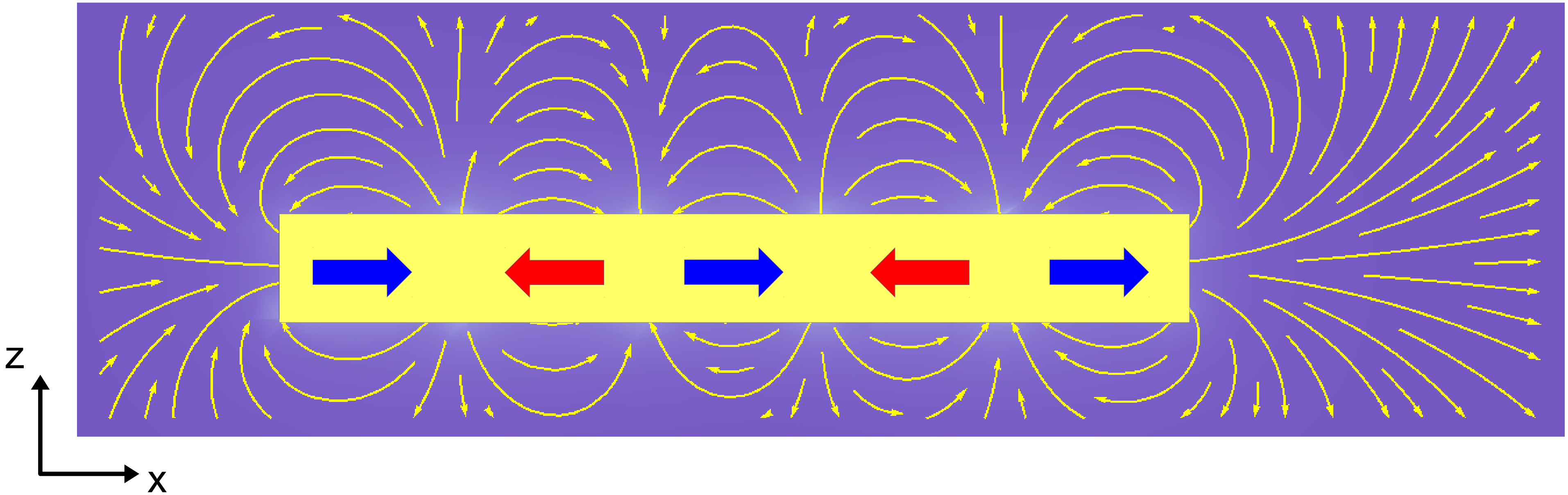
- for years the increase in the storage density (number of bits that can be stored on unit surface) was achieved mainly by a decrease of grain size
- if grains approach superparamagnetic limit* (several nanometers in size, depending on material, grain shape etc.) the recorded information becomes unstable due to thermal fluctuations of magnetic moments
- patterned media are the solution to this problem

*see for example my 6th lecture from 2012

Introduction

Where are the bits?

- the magnetic field produced by a line of magnetized "bits" is characterized by changes of field direction corresponding to transition between areas of opposite magnetic moments direction



Note:

- magnetic induction (***B***) lines are schematic and simplified
- they are calculated assuming that the track (the area of the storage medium where the bits are stored [2]) consists of parallelepiped with magnetization exactly parallel to x-axis (in-plane) which is constant throughout the whole "bit"; in real system the magnetization direction in transition areas between bits may strongly deviate from that direction
- it is assumed too, that "bits" are infinitely extended in the direction perpendicular to the plane of the image (y-direction) – this allows the use of simple expressions

Introduction

Where are the bits?

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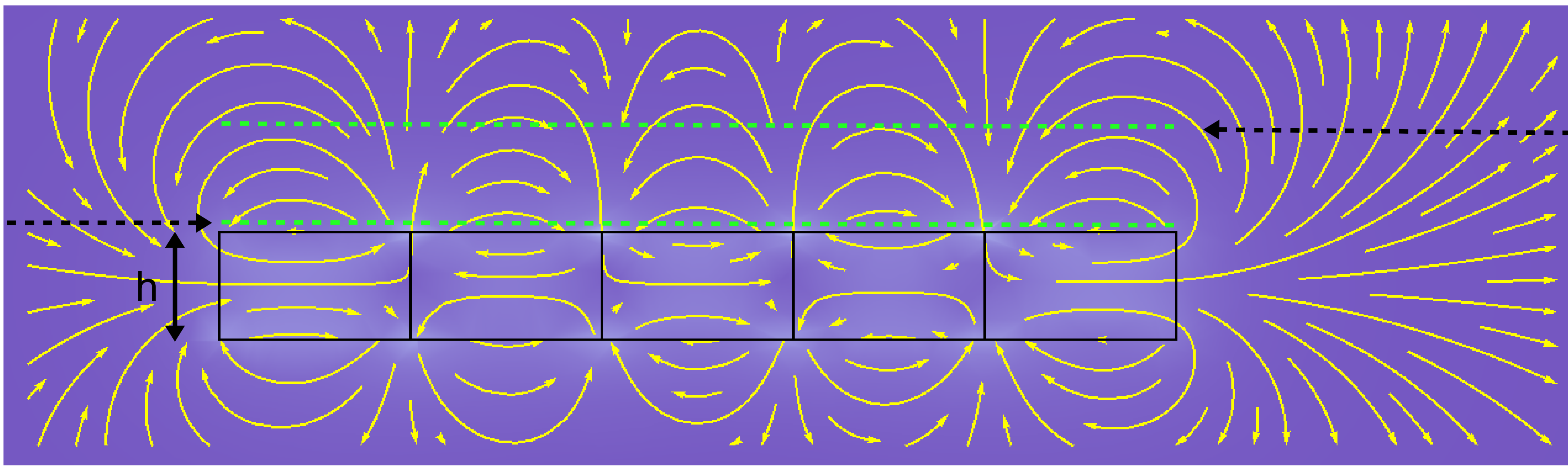
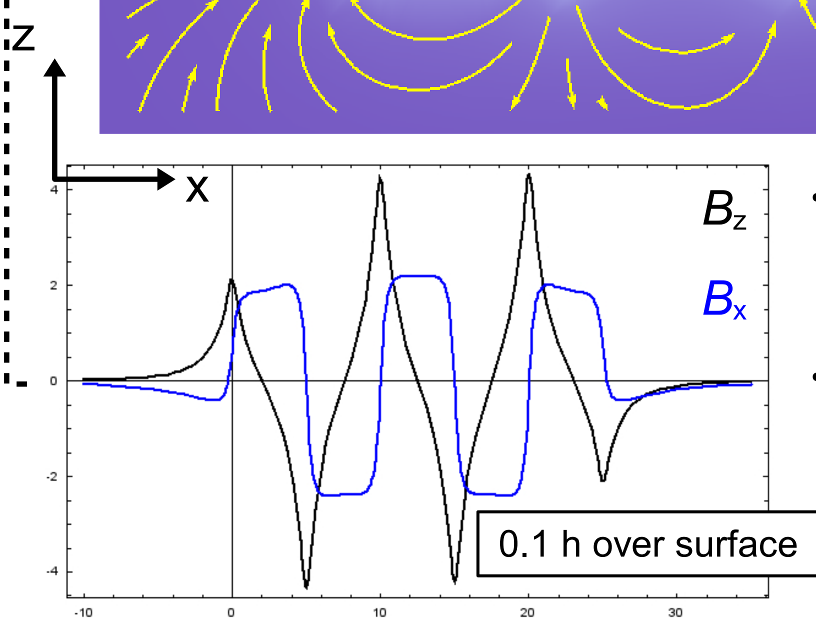
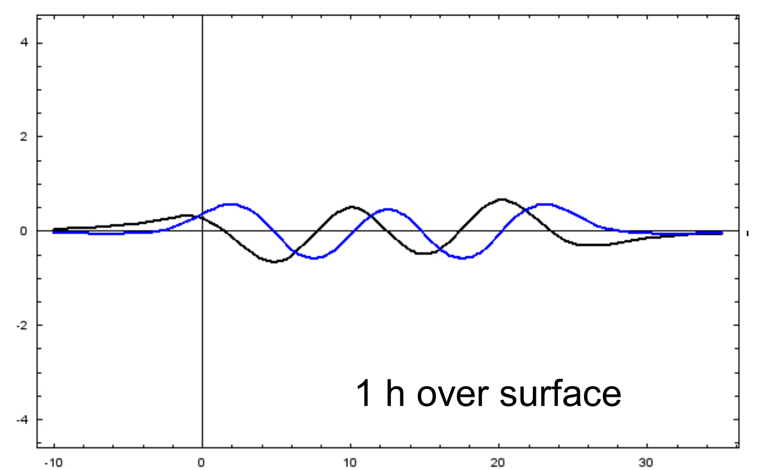




- magnetic induction strongly decreases with the distance from the surface of the storage medium
- B_x component of magnetic induction <u>changes sign</u> in the vicinity of the transition between oppositely magnetized regions



Introduction

Where are the bits?

- due to the strong dependence of the stray field strength on the vertical distance from the medium the gap between the reading head and the tape/disc must decrease with increasing bit density

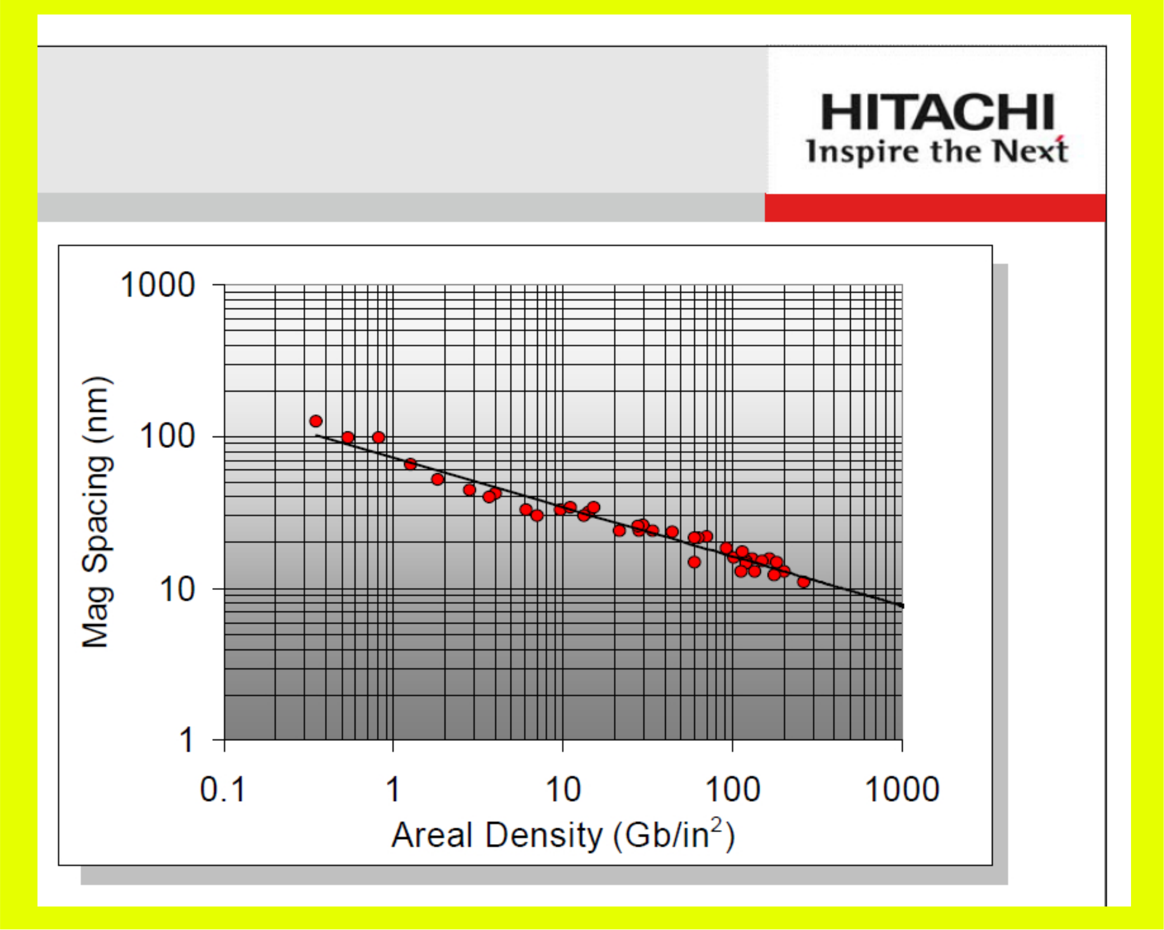
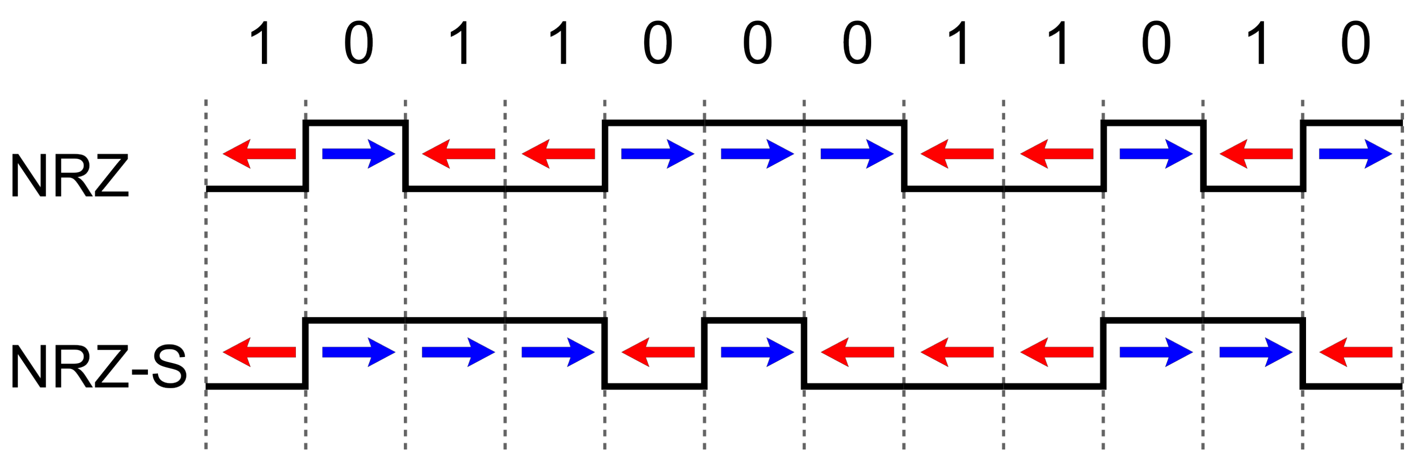


image from: R. New, The Future of Magnetic Recording Technology, lecture from April 11, 2008, Hitachi Global Storage Technologies

Introduction

Where are the bits?

- in electronics, in the presence of external disturbances (noise), to register the change of a quantity (voltage) is faster than to determine its value
- consequently the "bits" are read not as a value of the magnetic field associated with a magnetized region but as its change
- this is equally true for the read-out with inductive heads where the signal is proportional to the tape/disc speed as well as for magnetoresistive heads (AMR, GMR, TMR) where the resistance is read out as a voltage from a field sensor [5]
- there are many ways of encoding data by series of flux reversals [2,6]; here two examples:



Non-Return-to-Zero (NRZ) encoding

- the polarity of the writing signal changes when incoming data changes from 1 to 0 or vice versa [2]
- the writing device must remember the state before the last polarity change

Non-Return-to-Zero-Space (NRZ-S) encoding

- write signal (and thus the magnetic polarization of tape/disc area) changes when the incoming bit is zero
- no change of write signal when incoming bit is one
- offers better protection from error than NRZ

Introduction

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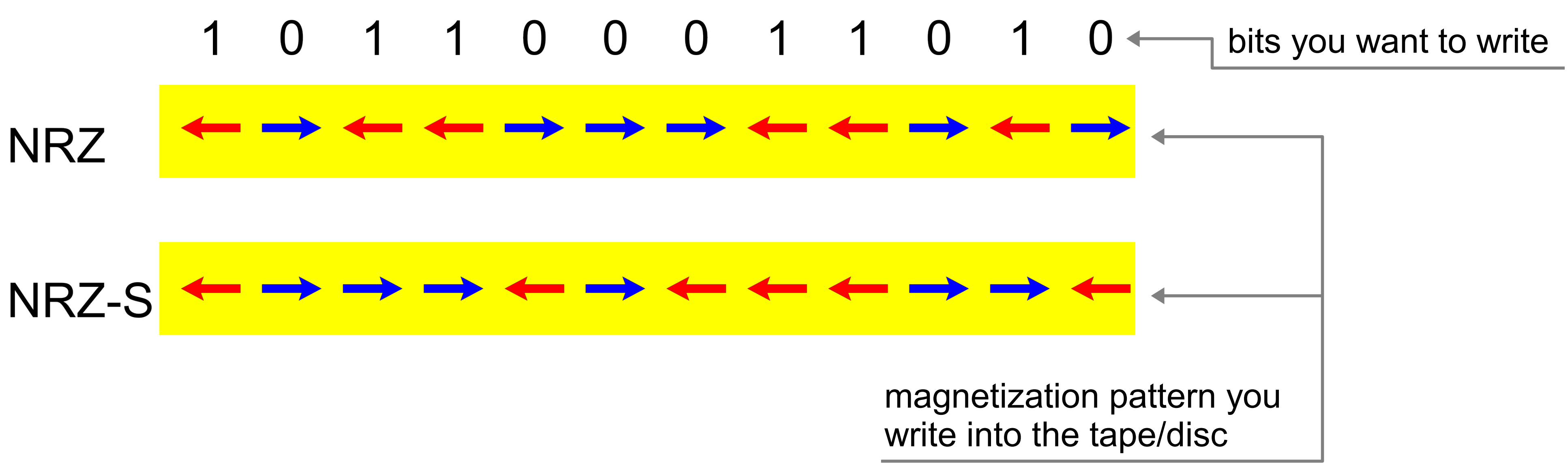


Introduction

RKKY coupling and saturation field

- in a general case of unlike layers (different magnetization, anisotropy energy, anisotropy direction etc.) coupled by interlayer coupling (see previous lecture) there are no analytic expressions available for a direct comparison with the experiment
- for "simple" cases the expressions describing the hysteresis loop can be found in literature [10,11]
- for the simplest case of two identical layers the saturation field can be found as follows:

The expression for the energy of the bilayer (each layer has moment *M*) is given by

$$E=-BM\left(\cos(\theta_1)+\cos(\theta_2)\right)-J\cos(\theta_1-\theta_2)$$

Zeeman energy

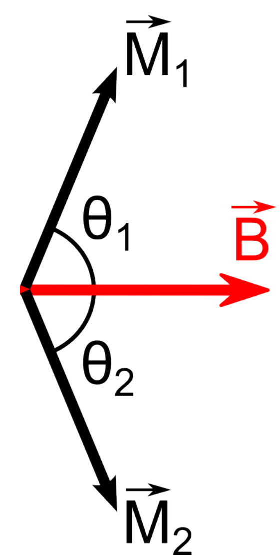
RKKY coupling energy; positive J favors parallel orientation of magnetic moments

an angle between moment direction and field direction θ (θ=0)

From symmetry considerations it follows that:

$$\theta_2=-\theta_1$$

$$E=-BM\left[\cos(\theta_1)+\cos(-\theta_1)\right]-J\cos(2\theta_1)=-2BM\cos(\theta_1)-J\left[\cos^2(\theta_1)-1\right]$$



For first derivative with respect to θ_1 we have:

$$\frac{\partial E}{\partial\theta_1}=2BM\sin(\theta_1)+4J\cos(\theta_1)\sin(\theta_1)$$

Equating that to zero, and dividing by $\sin(\theta_1)$*, we get:

$$2BM=-4J\cos(\theta_1)$$

*we can do that as long as $\sin(\theta_1)\neq 0$,i.e., below saturation

Introduction

- We are interested in the case of AF coupling* (J<0) and want to find the $\theta_1(\mu_0 H)$:

$$\cos(\theta_1) = \frac{M}{2J} B$$

- It follows that $\theta_1=0$ [$\cos(\theta_1)=1$], i.e., saturation is achieved for:

$$B_s = \mu_0 H_s = \frac{2J}{M}$$

Note that the saturation field is proportional to the coupling energy – it can be used to estimate J

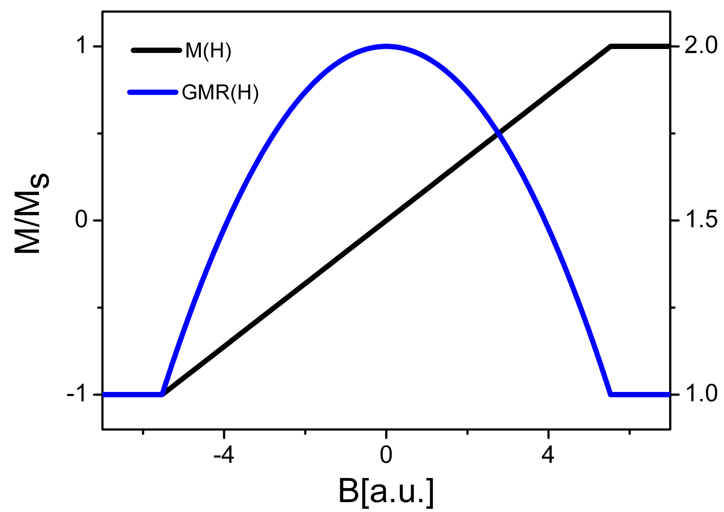
- Since $M \cdot \cos(\theta_1)$ gives the component of the magnetic moment parallel to the direction of the magnetic field we see that:

$$M_B(B) = \frac{M^2}{2J} B \propto B$$

but note too, that because both moments are positioned symmetrically about the field direction the resistance of GMR system is not proportional to the external field

$$R(B) \propto \cos(2\theta_1) = 2\cos^2(\theta_1) - 1 \propto \cos^2(\theta_1)$$

$$R(B) \propto \frac{M^2}{4J^2} B^2 \propto B^2$$



*if the coupling is ferromagnetic (F) the moments are always parallel (provided no magnetic anisotropy is present!)

Introduction

- Note that in the case of multilayers composed of identical layers the saturation field is expressed by a different equation [10] (the effective coupling is doubled):

$$B_s = \mu_0 H_s = \frac{4J}{M}$$

Note that the shape of the hysteresis/magnetoresistive loop depends on the number of layers (**n**); if the number of layers is even the boundary effects persist even for infinite number of layers

- If the anisotropy is present shapes of hysteresis loops can be complicated and strongly **n**-dependend, at least for small **n**:

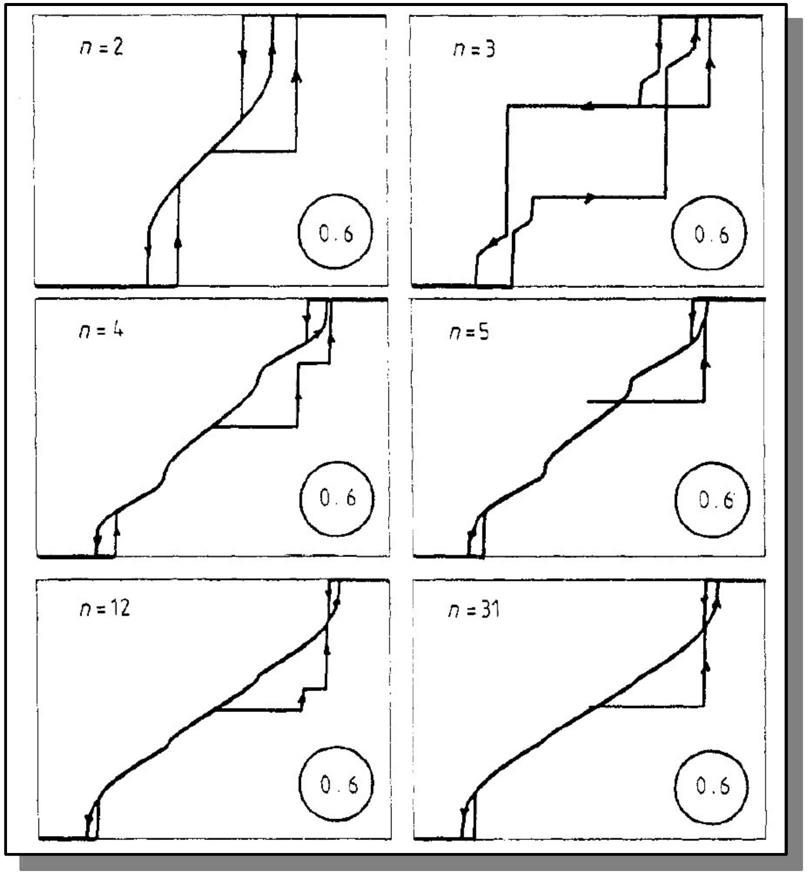


Figure 27. Initial magnetization curves and hysteresis loops obtained in the case of cubic anisotropy with k=0.6 for six different values of the number of layers: n=2,3,4,5,12,31.

image from: B. Dieny, J. P. Gavigan, J. P. Rebouillant, J. Phys.: Condens. Matter **2**, 159 (1990)

Introduction

Field sensitivity of magnetoresistance

- from the previous lecture we know that the RKKY-like interlayer coupling strongly decrease with the spacer thickness t_s
- the saturation field of the GMR effect depends consequently on t_s, but the GMR amplitude decreases with t_s too.

The field sensitivity of the magnetoresistance is defined as:

$$S=\frac{\Delta R}{R\Delta H}\quad [\%/A/m], \qquad \text{or} \quad [\%/Oe]$$

In practice, using GMR stacks as field strength sensors, one is usually interested in the sensitivity in a linear part of the dependence

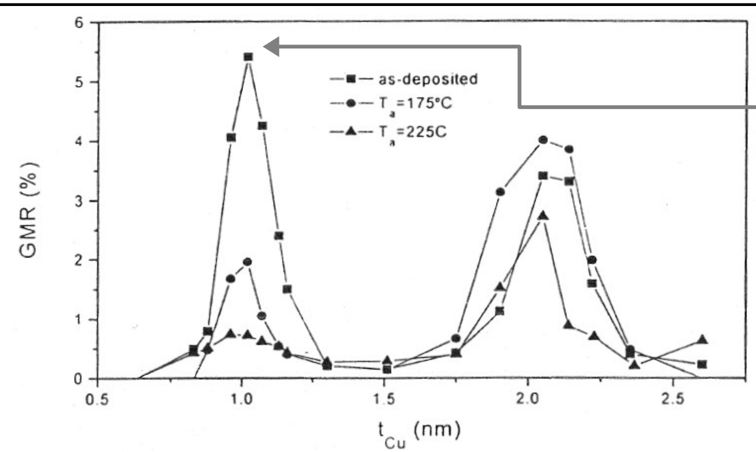


Fig. 1. GMR as a function of the Cu sublayer thickness for the as deposited and annealed samples.

Si(100)/Cu(20nm)[$Ni_{83}Fe_{17}$(2nm)/Cu(t

high GMR, low sensitivity

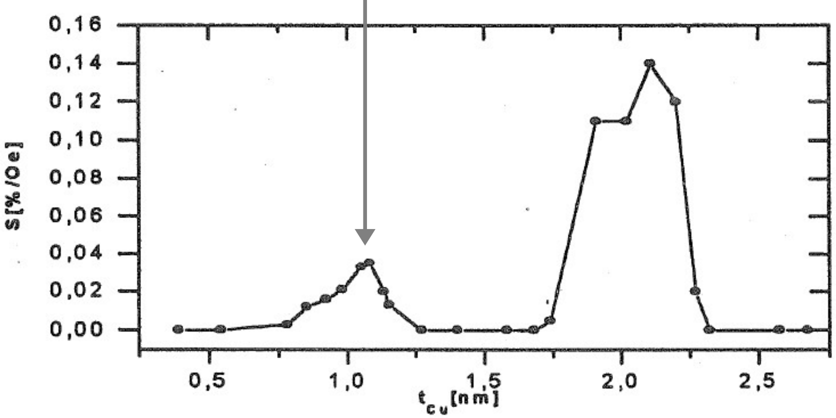


Fig. 1. Cu thickness dependence of GMR field sensitivity S for MIs with t_{Py} = 2 nm (external magnetic field and sensing current parallel to easy axis direction)

image from: F. Stobiecki, T. Luciński, R. Gontarz, M. Urbaniak, Materials Science Forum 287, 513 (1998)

image from: M. Urbaniak, T. Luciński, F. Stobiecki, Molecular Physics Reports **21**, 167 (1998)

Introduction

Field sensitivity of magnetoresistance

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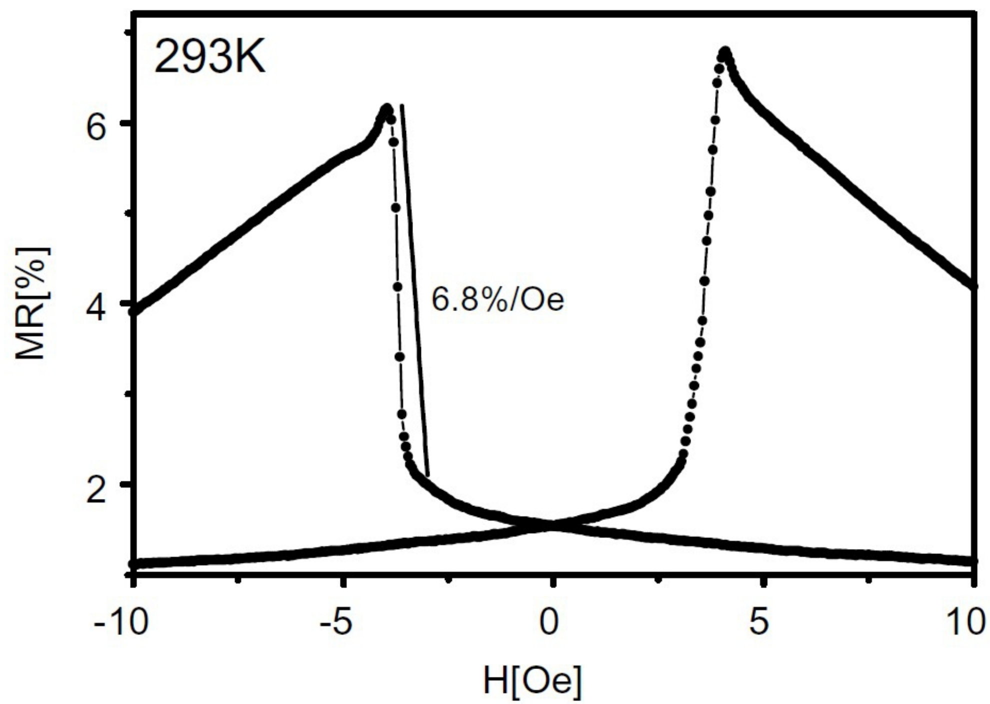


Fig. 5. Low field region of magnetoresistance for the same sample as demonstrated in Fig. 3 (0 Deg curve). The thick straight line indicates the slope of GMR(H) dependence.

- the highest sensitivities in GMR ,and TMR, systems are obtained with spin-valves or pseudo spin-valves

glass/[Py(2 nm)/$Cu_{0.85}Ag_{0.1}Au_{0.05}$(2.5 nm)/Co(0.75 nm)/$Cu_{0.85}Ag_{0.1}Au_{0.05}$(2.5 nm)]$_{10}$

image from: M. Urbaniak, T. Luciński, F. Stobiecki, A. Hütten, G. Reiss, J. Magn. Magn. Mater. **239**, 288 (2002)

GMR sensors

Field magnitude sensors

- the most important characteristics of field sensors are sensitivity and linear range
- in many applications the linearity is not important as only the resistance change between two defined states is measured: presence of an object/current, direction of the field, angle of rotation

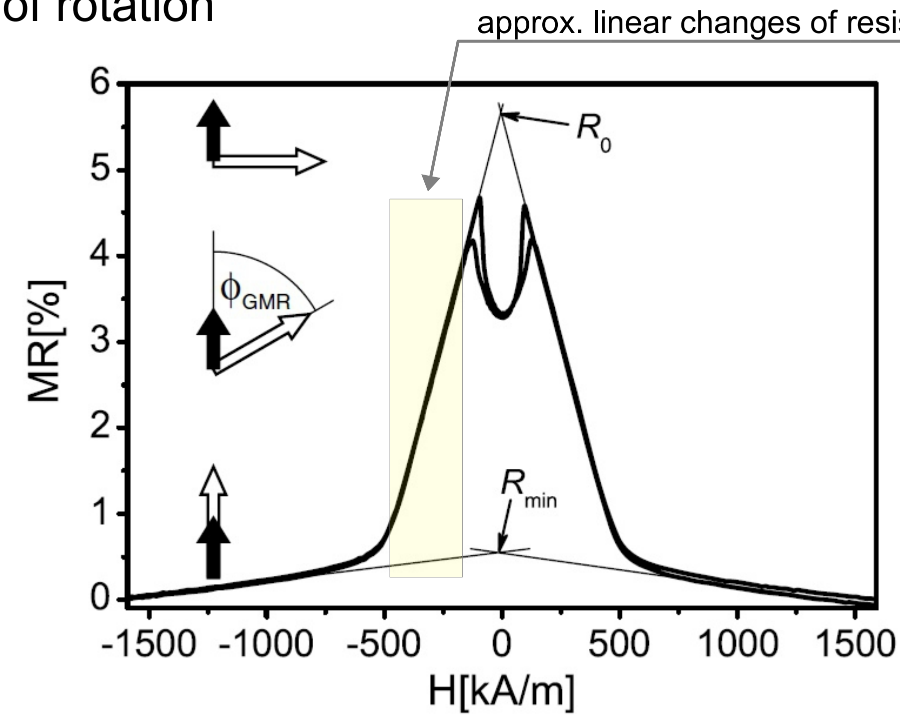


Figure 3. Exemplary *MR*(*H*) dependence measured for $[Ni_{80}Fe_{20}(2\ nm)/Au(2.4\ nm)/Co(1.2\ nm))/Au(2.4\ nm)]_{10}$ ML. AMR is less than 0.1%. The meanings of R_{min} and R_0 are explained in the text. The drawing presents the dependence of resistance *R* on the angle ϕ_{GMR}: *R* is minimal when ϕ_{GMR} is zero.

- the resistance change in the “linear” range of the *R*(*H*) dependence is related to the reversal of the NiFe layer
- the saturation field (approx. 500 kA/m) is determined by the shape anisotropy of NiFe layers
- in hysteretic range, not useful for applications, both Co and NiFe layers magnetization directions change

image from: M. Urbaniak, F. Stobiecki, B. Szymański, M Kopcewicz, J. Phys. Condens. Matter **20**, 085208 (2008)

GMR sensors

Field magnitude sensors with memory [24]

- (Au-2 nm/Co^S-wedge-0.6-1.2 nm/Au-2 nm/Co^H-0.6 nm/Au-2 nm) GMR layer deposited on Si(100) substrate
- wedged Co layer shows a monotonic decrease of the coercive field with increasing thickness – the contribution of the perpendicular surface anisotropy diminishes
- if the sample is magnetically saturated with external field and consequently the field of reversed polarity is applied the reversal starts where the coercive field is lower – thicker Co: the domain wall moves from there to the thinner end of the wedge
- at the same time the magnetization of the second layer remains unchanged – through the GMR effect this leads to the increase of the resistance of the stack (measured between contacts 1 and 9)

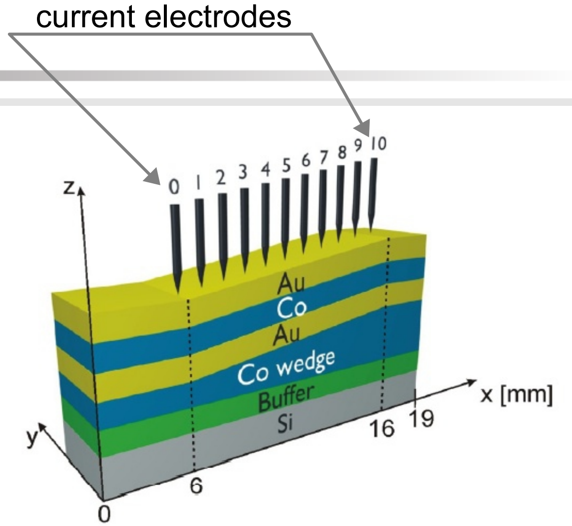
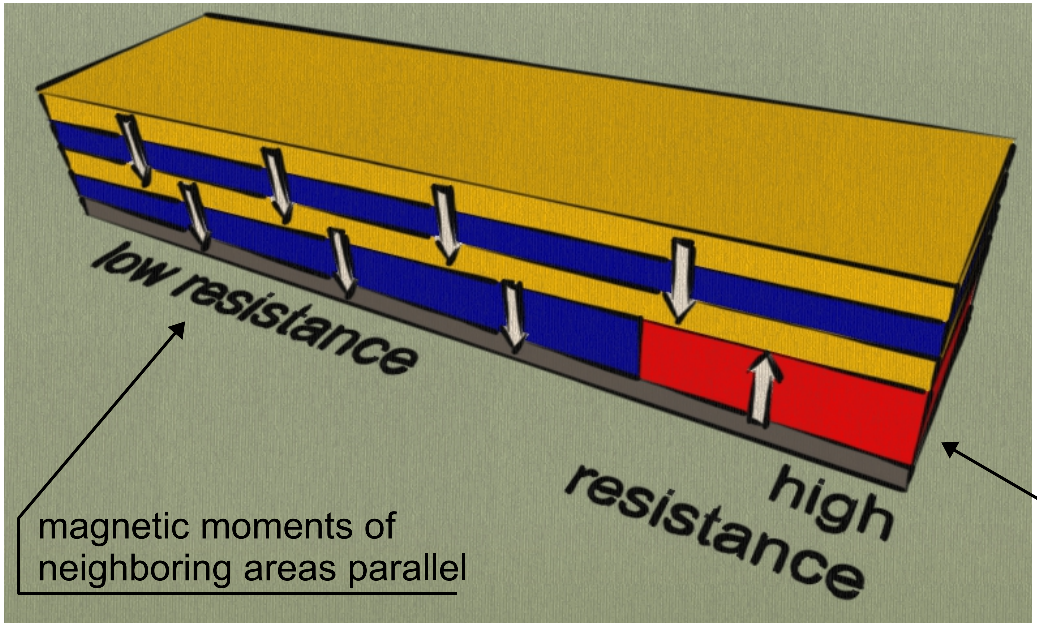


FIG. 1. Schematic representation of the spin valve structure and arrangement of contacts for magnetoresistance measurements.

image from: M. Matczak *et al.*, Appl. Phys. Lett. **100**, 162402 (2012) [24]

$$K_{eff} = K_V + \frac{K_S}{t_{Co}}$$



GMR sensors

Field magnitude sensors with memory [24]

- the resistance of the stack after the removal of magnetic field (at remanence) is a linear function of the maximum applied field (as long as it does not exceed the maximum coercive field of the Co wedge layer)
- the magnetoresistance is about 2% giving the sensitivity of about 0.37%/(kA/m) (0.03%/Oe); the value can be increased if thinner buffer and capping layers are used

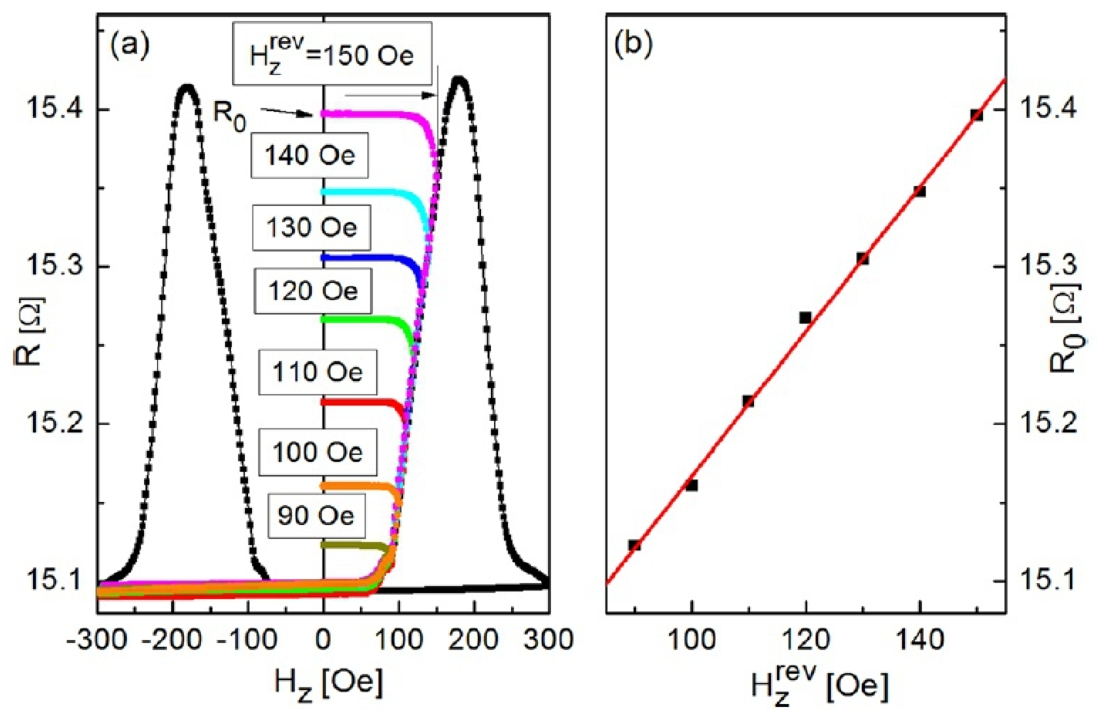


FIG. 4. (a) Major and minor magnetoresistance loops of the spin valve system. Minor loops have been taken with different values of H_z as described in the text. (b) Remanent resistance of the sample as a function of H_z.

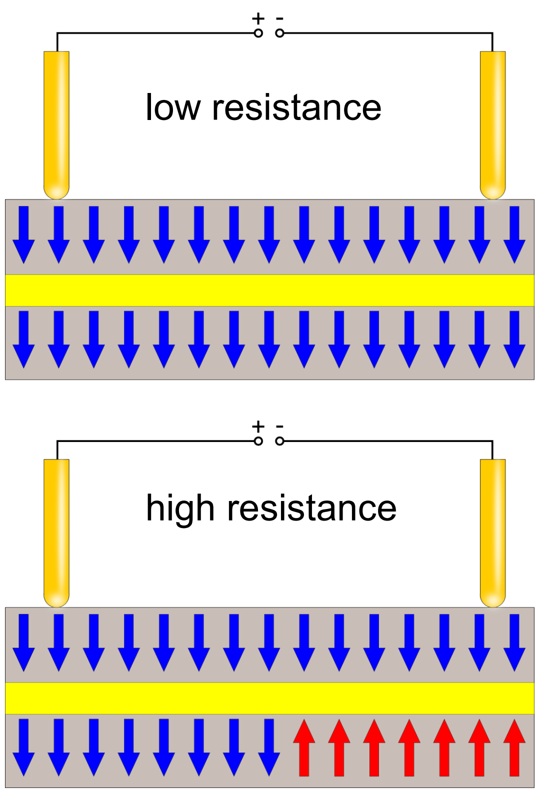


image from: M. Matczak *et at.*, Appl. Phys. Lett. **100**, 162402 (2012) [24]

GMR sensors

Angle sensor

- to fabricate a sensor of magnetic field direction one can use a single spin valve (the direction of magnetic moment of one layer is approximately fixed*); it is assumed that the magnetic moment of the free layer is parallel to the field direction
- in practice to improve performance bridge configuration of sensors is used
- $V_{GMR}(\theta)$?

$$R_1(\theta_1)=R_0-\Delta R\cos(\theta_1)=R_0-\Delta R\cos(\theta)$$
$$R_2(\theta_2)=R_0-\Delta R\cos(\theta_2)=R_0+\Delta R\cos(\theta)$$

- similarly for R_3 and R_4
- the current through the R_1 and R_3 resistors (GMR sensors) is given by:

$$I_{13}=U/(R_1+R_3)$$

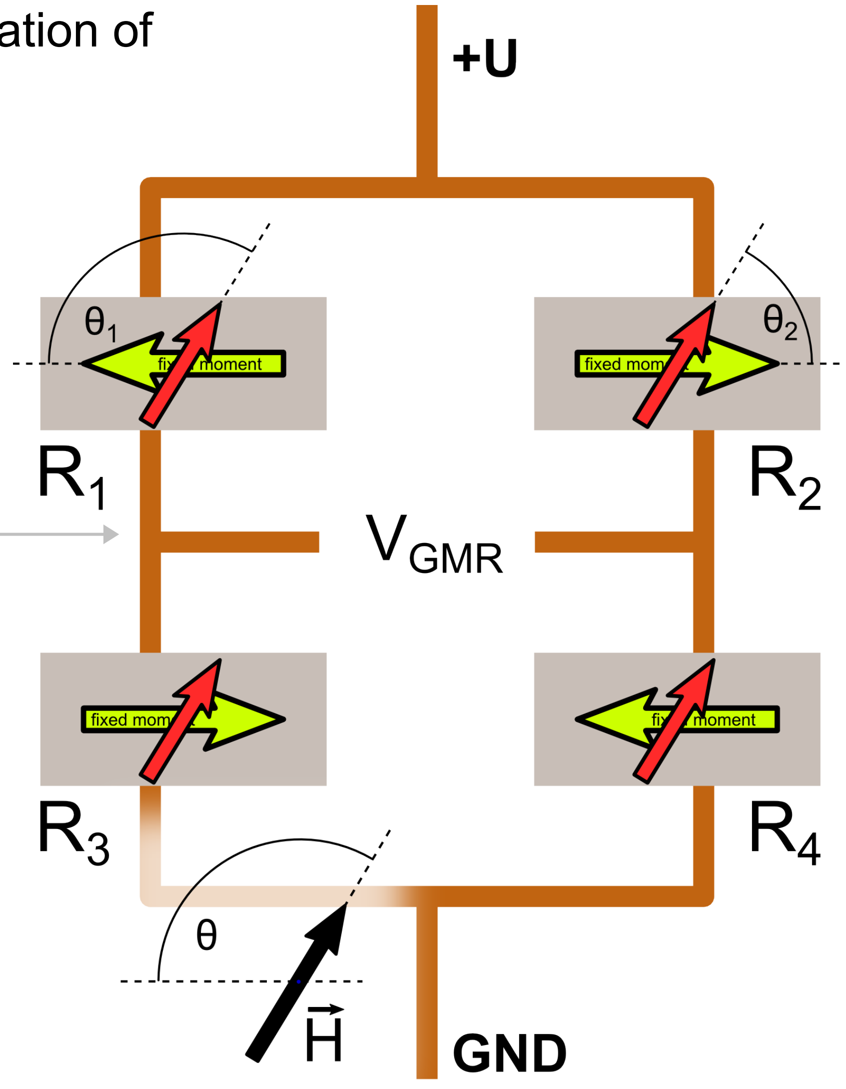
U -sensor input voltage

- the voltage above the resistor R_3 is given by:

$$U_3=R_3 I_{13}=U R_3/(R_1+R_3)$$

- and for bridge output we have:

$$V_{GMR}=R_3 I_{13}-R_4 I_{24}=\frac{(R_2 R_3-R_1 R_4)}{(R_1+R_3)(R_2+R_4)}U$$



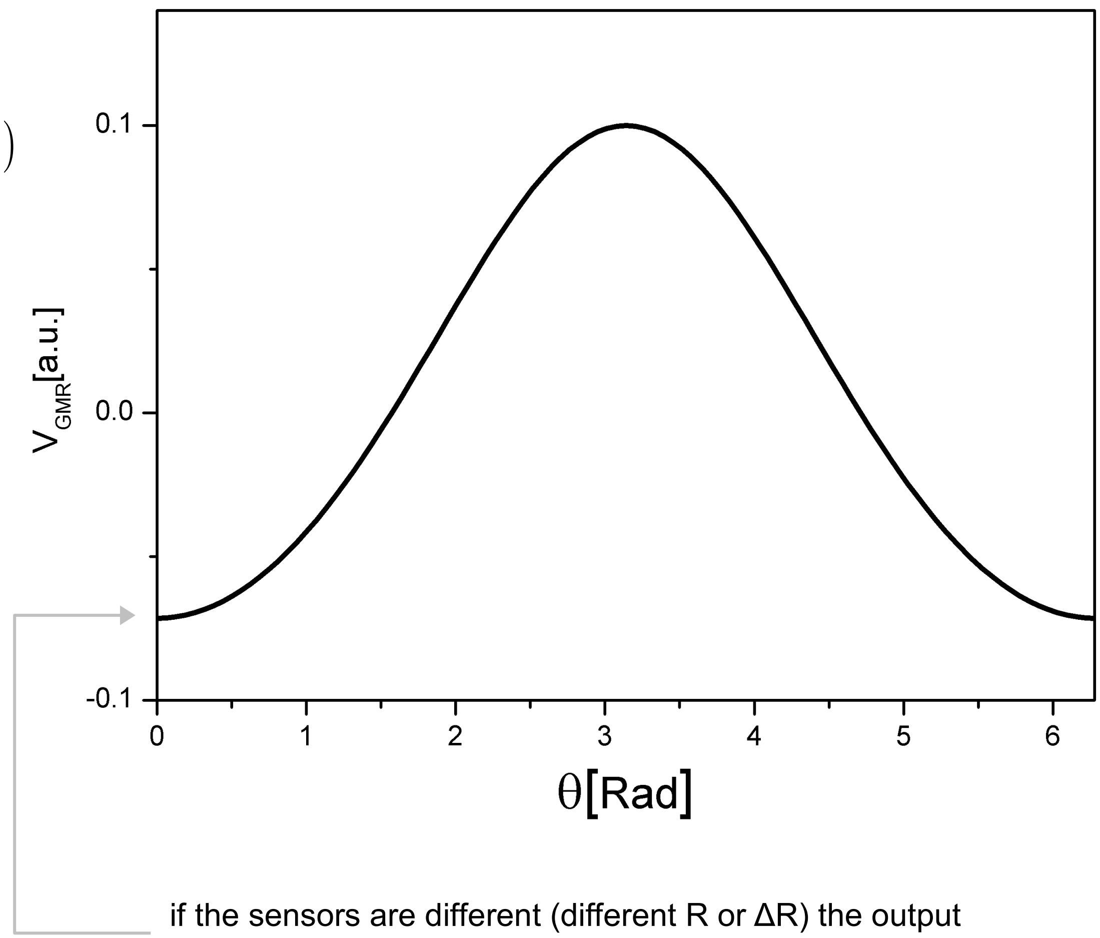
*the sensor can operate within a limited field range; at higher fields moment of a reference layer starts to depart from the “fixed” direction

GMR sensors

- and for bridge output we have:

$$V_{GMR}=\frac{(R_2R_3-R_1R_4)}{(R_1+R_3)(R_2+R_4)}U=\frac{\Delta R}{R_0}U\cos(\theta)$$

- note that the output is ambiguous function of the field angle
- to obtain the unambiguous output for 360° it is necessary to use other sensor/bridge with differently oriented fixed layers in spin valves



if the sensors are different (different R or ΔR) the output may be not symmetric relative to 0.

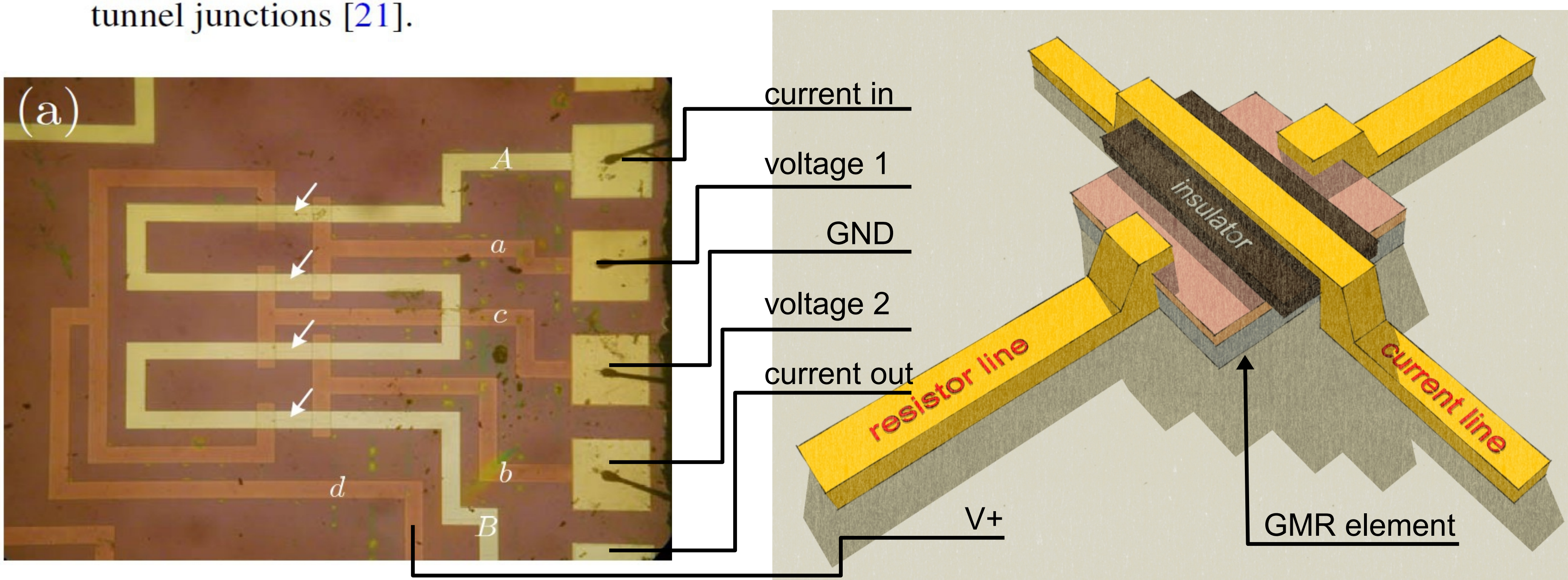
Using the bridge has the advantage of shifting the measured voltage (sensor output) from some finite value, for a single magnetoresitive element, to near zero region; the whole available measuring range of a voltmeter can be utilized which in case of analog-to-digital converters increases resolution of the sensor.

GMR sensors

GMR current sensors [8]

- the field produced by a current flowing through the wire/strap can be sensed with magnetoresistive elements
- they offer better sensitivity as compared to Hall effect based sensors
- the sensors are fabricated so that the current conductor is integrated into the device [8]

Figure 5. IC current meters. The function scheme and nomenclature can be found in Figure 2. Arrows indicate real magnetoresistor locations. (a) Spin-valve [45], (b) Magnetic tunnel junctions [21].



left image from: C. Reig, M-D. Cubells-Beltrán, D. R. Muñoz, Sensors **9**, 7919 (2009)

GMR sensors

GMR based sensors with storage functionality [9]

- in some applications the angle detection capability should extend to n turns of the field (n×360°). The applications could be in: steering wheels (up to 5 turns), potentiometers and "motor feedback systems for industrial applications" which require thousands of turns
- the devices of n-turn capability could be used for one turn applications to achieve better resolution

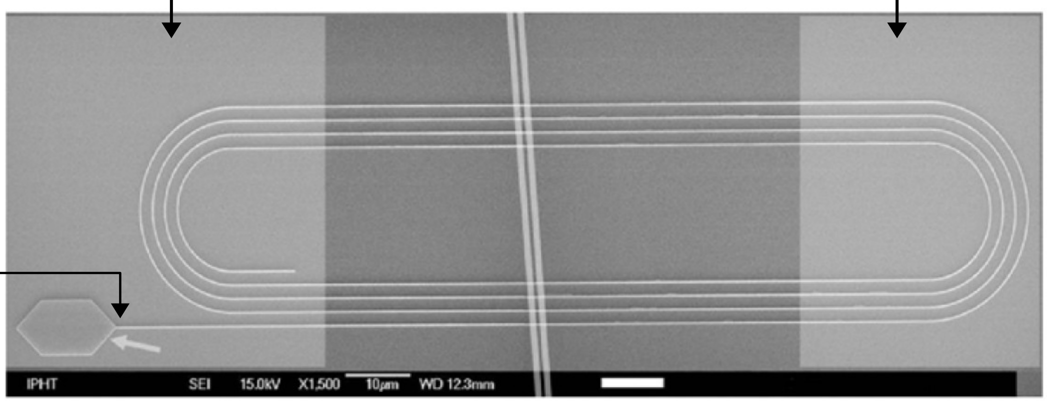


Figure 22. Composed picture of two SEM micrographs, showing the right and the left part of a multiturn counter with four turns. The middle part of the straight stripes with a length of approximately 380 μm is cut out. Al contact pads covering the curved regions of the spiral are seen as overlaid bright gray areas. They are used as electrical contacts. The arrow (lower left) is directed to the enlarged area responsible for the generation of the domain walls.

- spiral fabricated (lithography) from seed layer/7IrMn/2.5Co90Fe10/0.8Ru/2.5Co90Fe10/2/0.8Co90Fe10/20Ni81Fe19/5TaN (all thicknesses in nm) GMR stack
- the resistance of the spiral changes with the number of domain walls "injected" into the wire
- 360 Deg domain walls are pushed into the wire/stack as the external magnetic field rotates; one rotation generates one wall

image from: R. Weiss, R. Mattheis, G. Reiss, Meas. Sci. Technol. **24**, 082001 (2013)

GMR sensors

Magnetic beads detection with GMR

- patterned NiFeCo 6nm[Cu 2.1nm/NiFeCo 1.5nm]×10/ Ta 100nm GMR sensors (≈10%@8kA/m) deposited on Si substrate
- superparamagnetic MyOne beads (1 μm diameter) were deposited on sensors from a suspension (sinking speed in water is about 0.5μm/s [24])

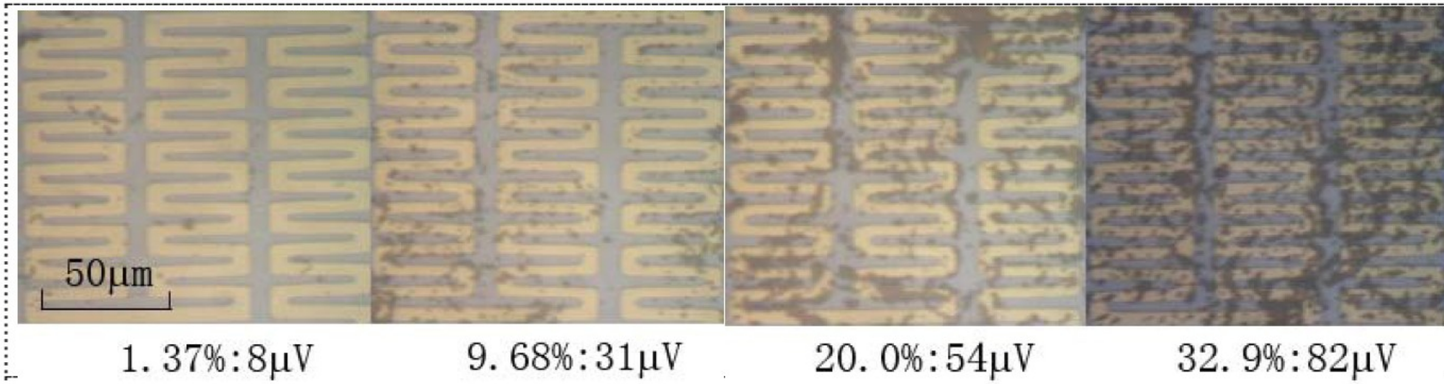
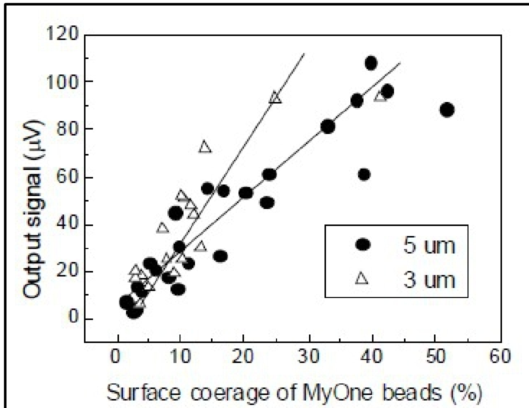
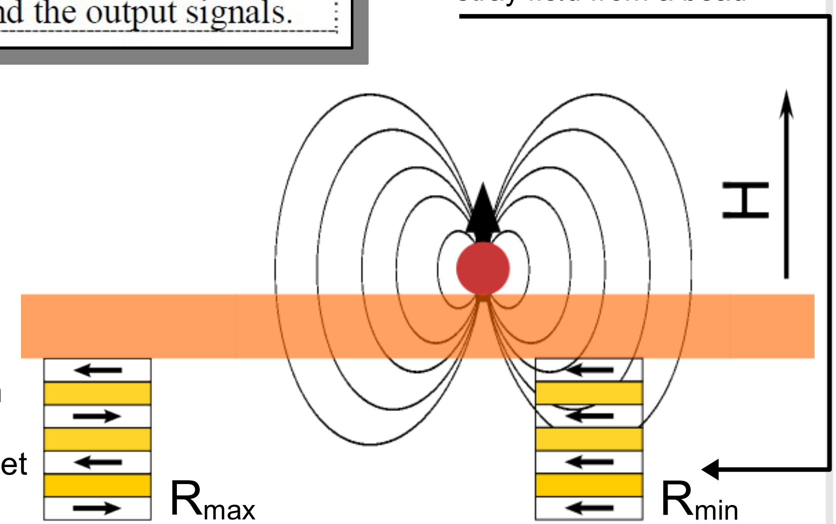


Figure 3. The images of the MyOne beads on the surface of sensing area and the output signals.



The dependence of the output signal on the surface coverage of MyOne beads. Normal **240 Oe** field applied to induce net magnetic moment of beads.

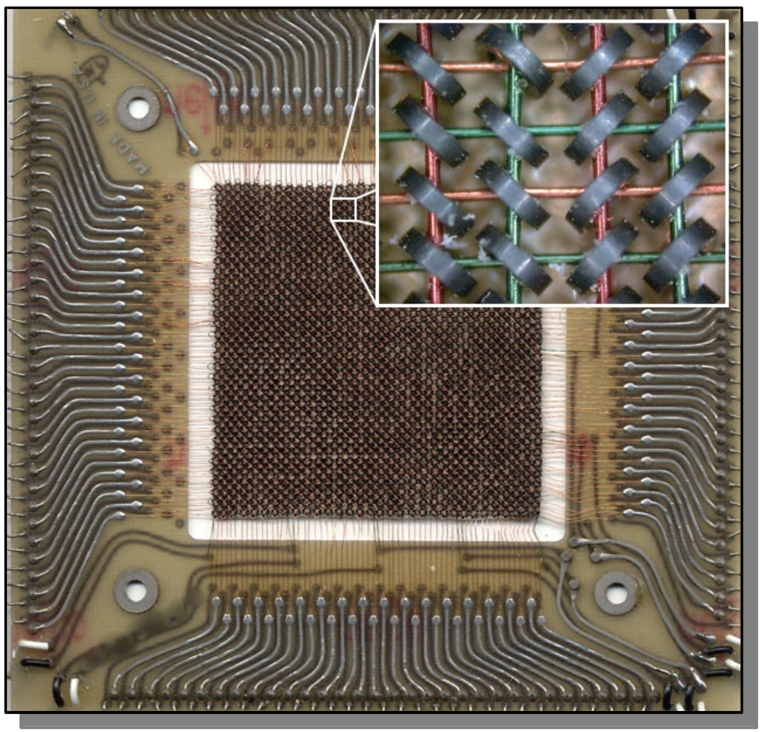
the resistance of that part of the sensor is reduced due to a presence of stray field from a bead



images from: J. Feng, Y.Q. Wang, F.Q. Li, H.P Shi, X. Chen, Journal of Physics: Conference Series **263**, 012002 (2011)

Magnetoresistive memory

- First magnetic random assess memories used ferrite rings to store bits of data; that type of memories was in use from the sixties up to the eighties of XX century.
- To write a bit the magnetization of the cores was switched by a combined action of currents flowing in wires woven through the toroids and the readout was performed by registering the voltage induced in a sensing line (wire) by the application of the definite impulse in writing wires: if the read impulse results in the reversal of the magnetization the high voltage is induced in a sense wire otherwise only small voltage is detected.
- in core memory the readout is destructive



Random access ferrite core memory (RAM) from 1961. Size of the card : 10.8cm x 10.8cm (6.5 inch), capacity : 1024 bits.

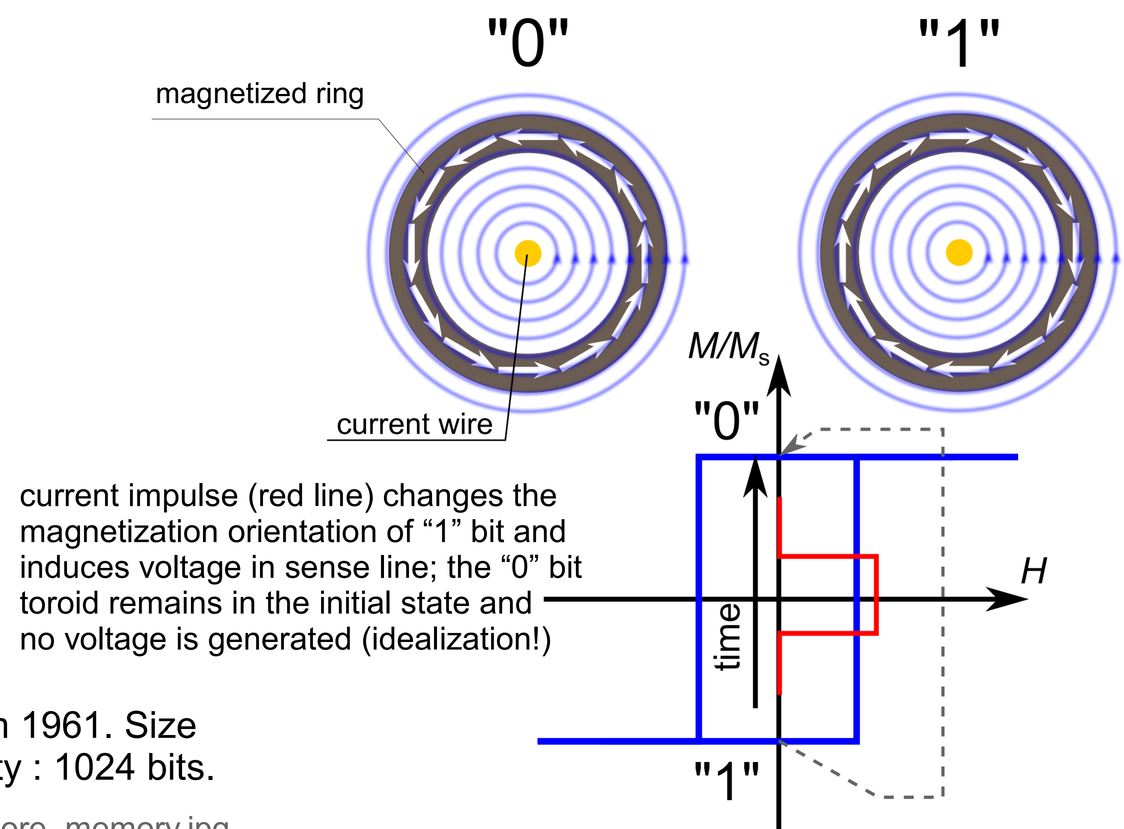
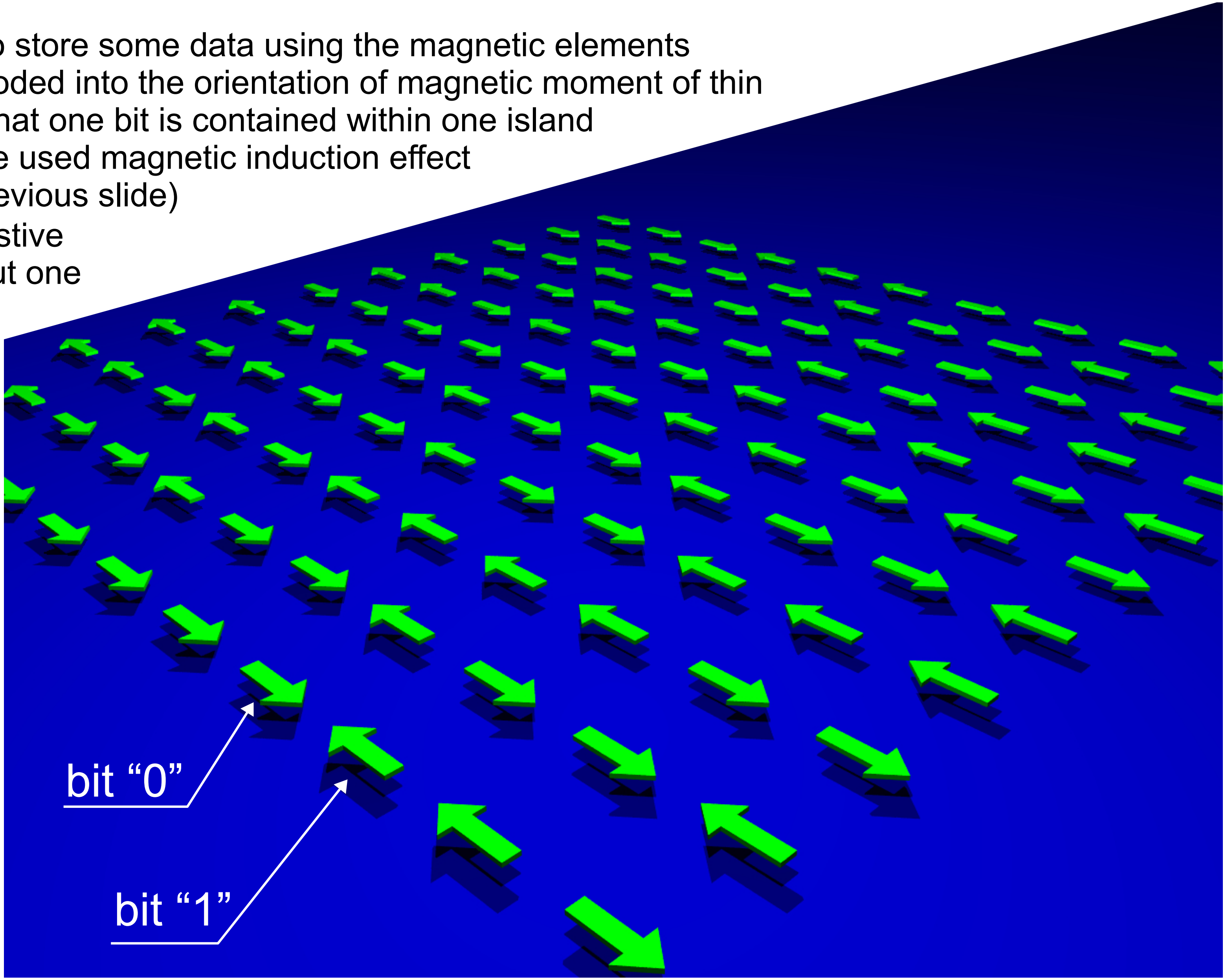


image from: Wikimedia Commons; author Orion 8, Ferrite_core_memory.jpg

Magnetoresistive memory

MRAM – magnetoresistive random access memory

- suppose we want to store some data using the magnetic elements
- the bits can be encoded into the orientation of magnetic moment of thin films patterned so that one bit is contained within one island
- to read the data one used magnetic induction effect in core memory (previous slide)
- to use magnetoresistive effect in the read-out one needs additional magnetic layers



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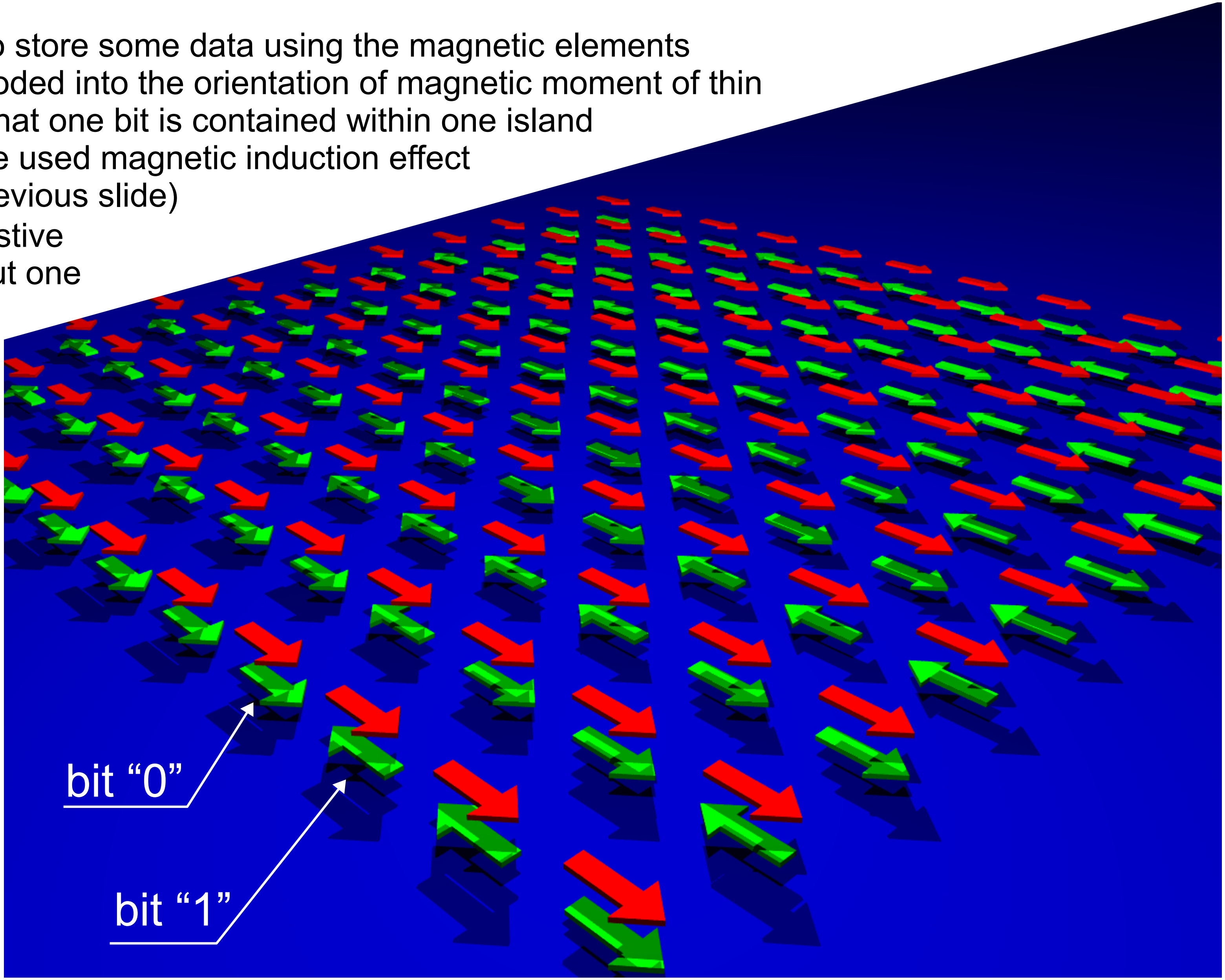
- to read the data one used magnetic induction effect in core memory (previous slide)
- to use magnetoresistive effect in the read-out one needs additional magnetic layers

Using spin-valve principle one can determine the orientation of **green** moments by measuring the resistance of the stack containing both types of layers.

Red layers have higher coercive field due to exchange coupling to a antiferromagnet.



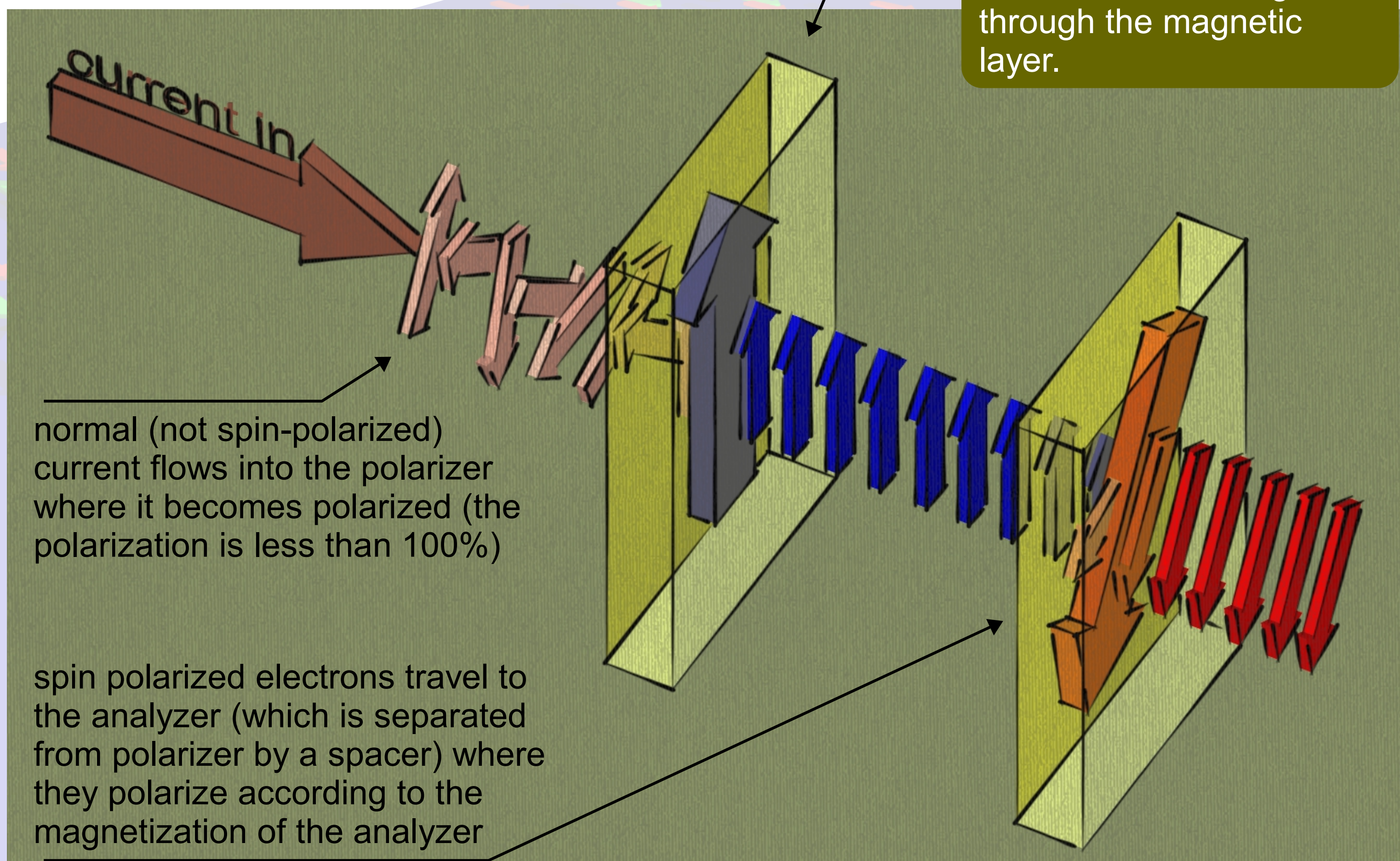
Magnetoresistive memory

polarizer is usually thicker than analyzer or is coupled to a antiferromagnet "*in order that magnetic dynamics are excited in one magnetic layer but not both*" [17]

MRAM – magnetoresistive random access memory

- writing of data into the single memory element requires either the application of a magnetic field which is strong enough to reverse the magnetic moment of the free layer (**green**) or the use of a spin torque transfer effect to achieve the same effect
- the memories utilizing the latter effect are called STT-MRAM*
- this types of memories are more attractive than memories using magnetic field for magnetization switching because they do not require additional field conductors and energy required to switch the single bit is lower

Spin polarized current can apply a torque to a ferromagnet as electrons gain or loose angular momentum traveling through the magnetic layer.



*whether you expand that abbreviation as spin torque transfer [16] MRAM or spin transfer torque [15] seems to be a matter of taste.

Magnetoresistive memory

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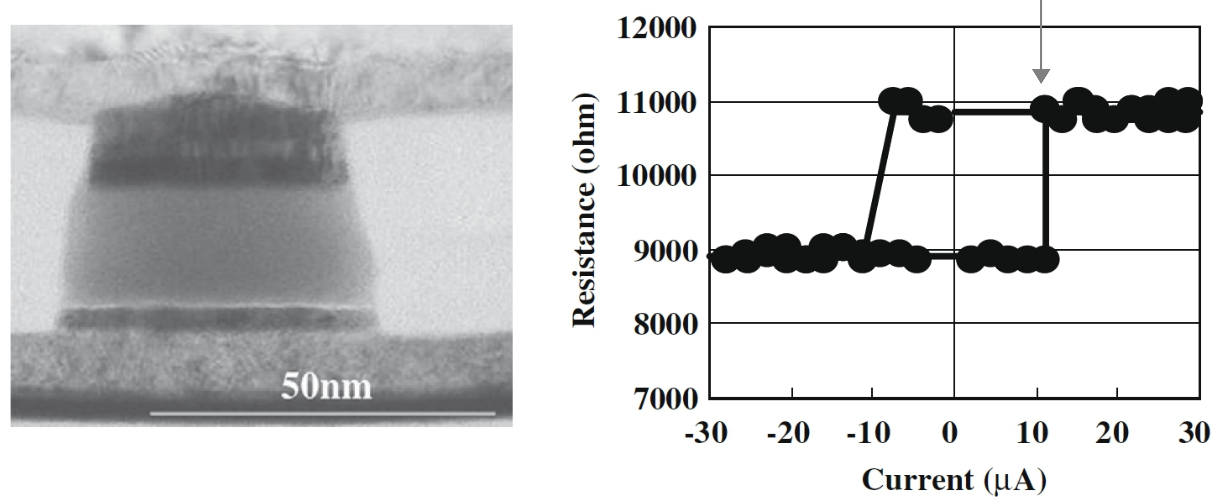
about 5×10^9 Am^{-2}

image from [17]: *H. Yoda et al. / Current Applied Physics 10 (2010) e87–e89*



(a) A TEM image (b) A hysterics curve

Fig. 2. A TEM image and small critical switching currents of an MTJ with an Fe alloy storage layer.

spin-polarize current can be used to reverse the magnetization!

*whether you expand that abbreviation as spin torque transfer [16] MRAM or spin transfer torque [15] seems to be matter of taste.

Magnetoresistive memory

MRAM – magnetoresistive random access memory

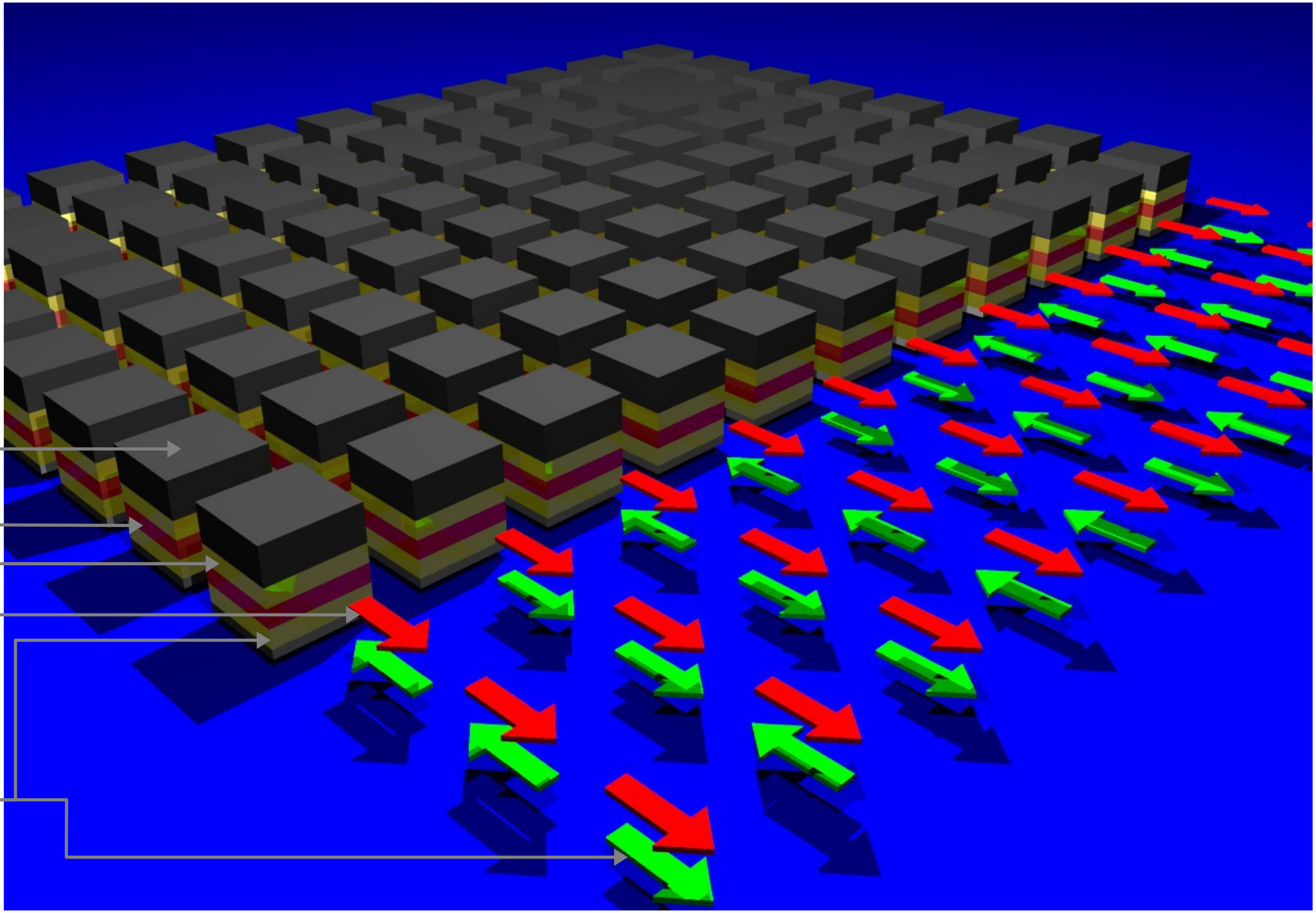
- in each spin valve the hard layer is fixed, i.e., its magnetization does not change orientation during writing or readout
- STT MRAM

antiferromagnet providing exchange bias (to fix the magnetic moment of a “hard” layer

nonmagnetic, conducting (GMR) or not (TMR) spacer decoupling ferromagnetic layers (yellow)

magnetically hard layer is used as a reference

magnetically soft layer is used to store data



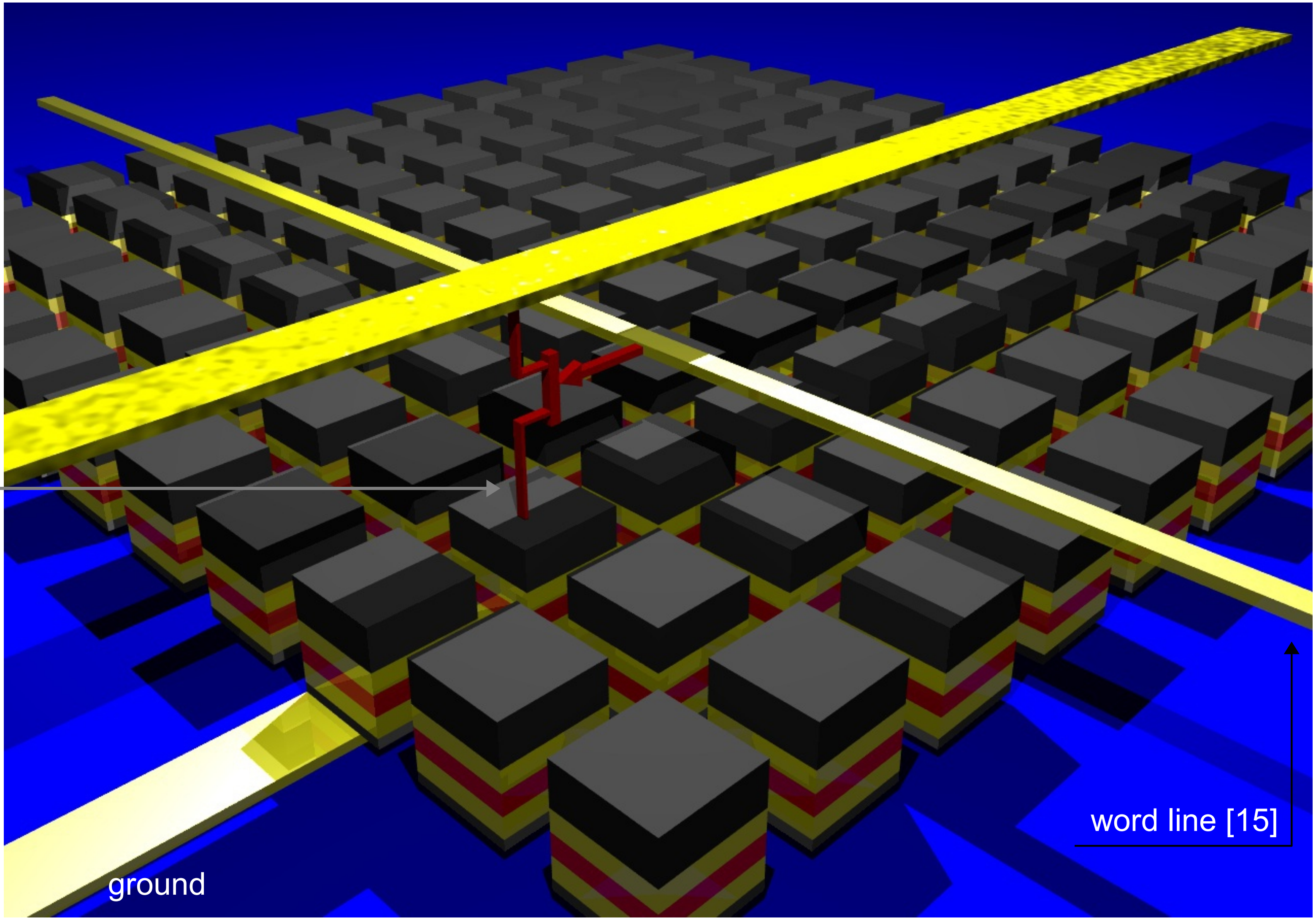
Magnetoresistive memory

MRAM – magnetoresistive random access memory

- to read the resistance of a given cell the resistance between the appropriate column and row is measured [18]. There are numerous sensing schemes which can be used to decide whether the given resistance corresponds to “0” or “1”. Some of the schemes involve comparing resistance with a reference cell of a know state [18].

the MOS-FET transistors are used to avoid current shunting effects, i.e., flow of the current through other than the selected cell [18]

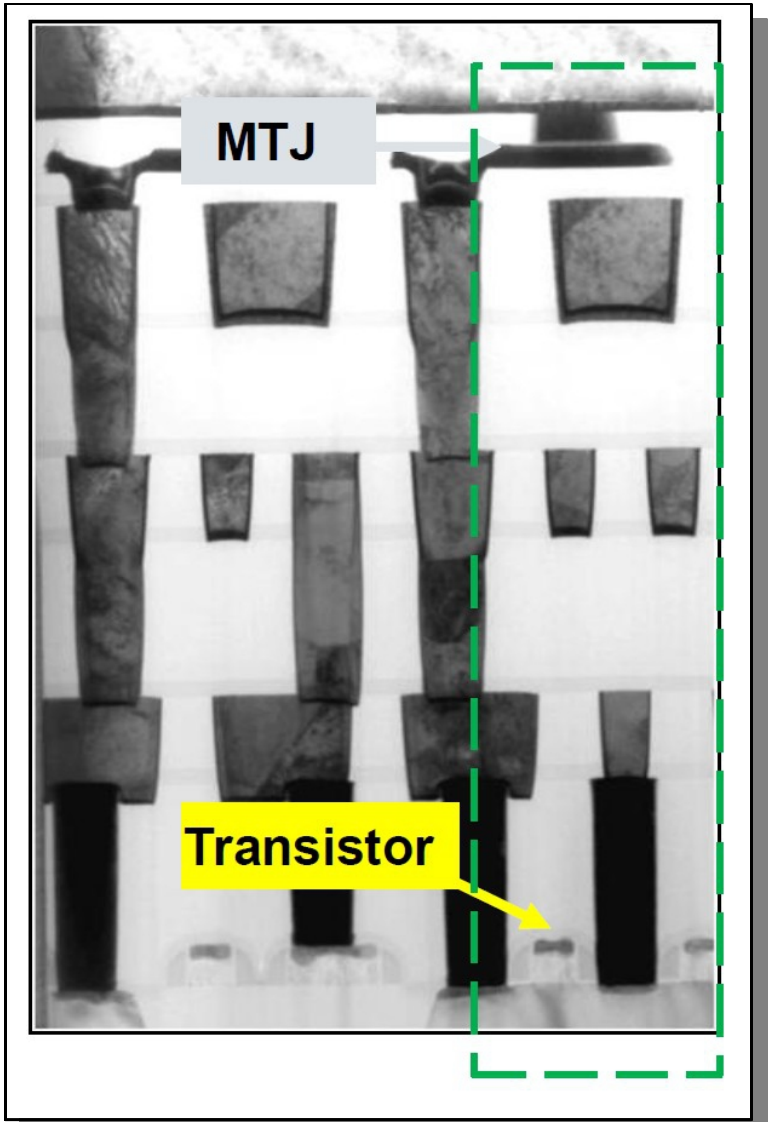
the sensing or writing current flows through selected cell, to a ground, only if the column-select transistor is on [15]



Magnetoresistive memory

MRAM – magnetoresistive random access memory

***Everspin** Toggle MRAM Technology*



Cross section and top view of the fragment of MTJ memory cell

Everspin:

- data not changed if external magnetic field is below 2 kA/m*
- if the memory is inactive or data is being read the data is preserved if the external magnetic field is below 8 kA/m (≈0.01T) [20]

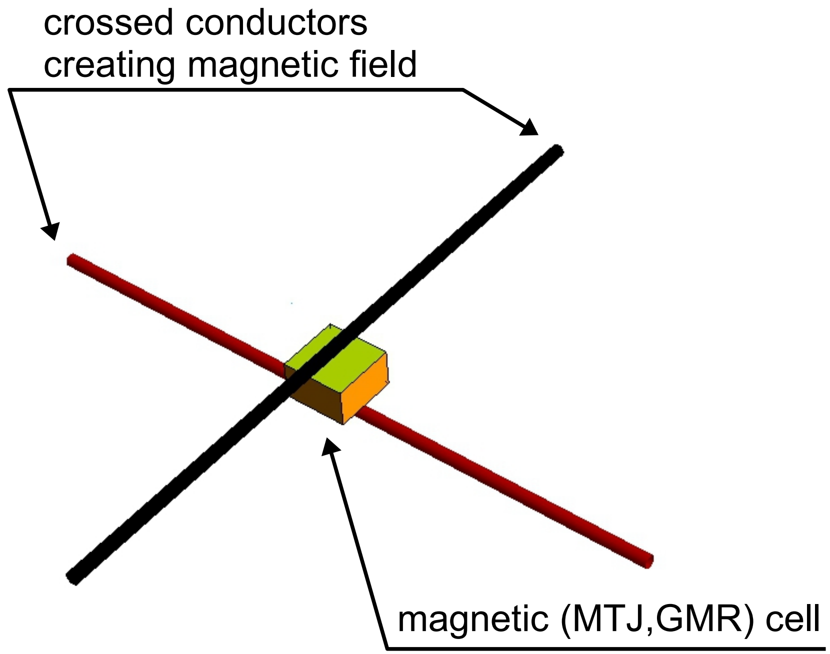
images from: http://everspin.com/CES2012/CES_2012_Everspin_Slide_Show.pdf

*total intensity of earth magnetic field is of the order of 40 A/m at middle latitudes (nationalatlas.gov/articles/geology/a_geomag.html)

Magnetoresistive memory

MRAM – magnetic field

- to produce the magnetic field which is spatially selective different arrangements of conductors can be used; the most obvious is the use of crossed conductors (usually stripes):



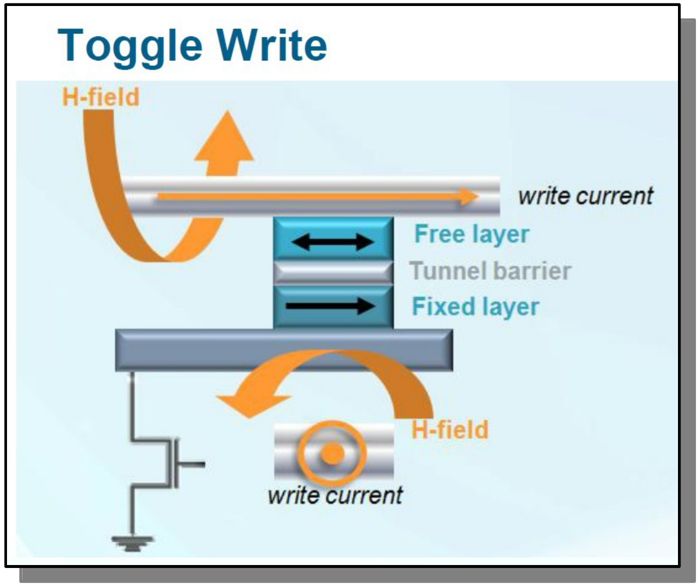
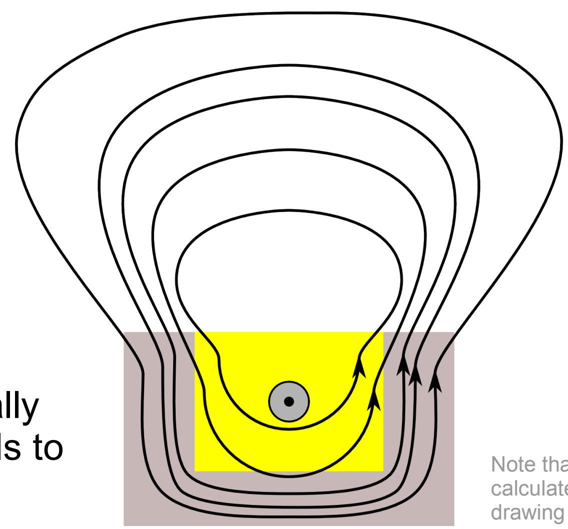


image from: http://everspin.com/CES2012/CES_2012_Everspin_Slide_Show.pdf

in practice the field conductors are usually cladded with soft ferromagnetic materials to concentrate the magnetic flux [21]

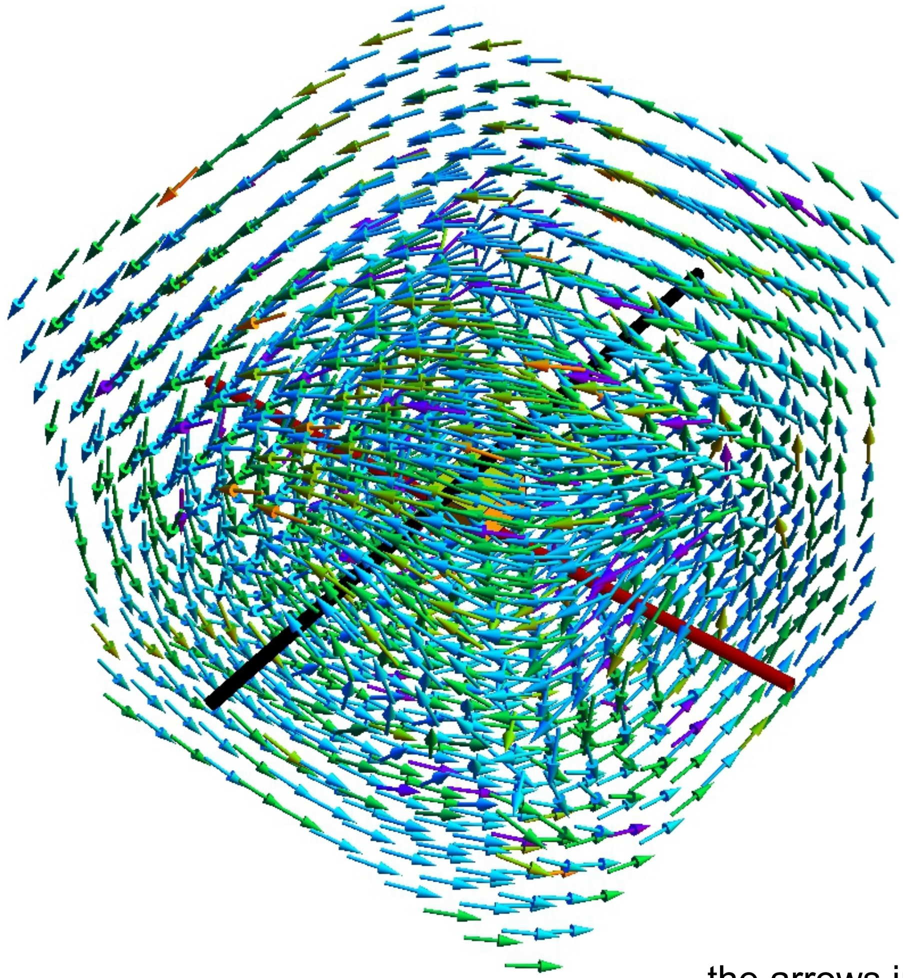


Note that the field lines were not calculated – it is just a schematic drawing

Magnetoresistive memory

MRAM – magnetic field

- to produce the magnetic field which is spatially selective different arrangements of conductors can be used; the most obvious is the use of crossed conductors (usually stripes):



- the magnetic field created by the single line is too weak to switch the magnetization of the free layer
- combined action of two conductors creates the field which is strong enough switch the moment direction of the memory cell

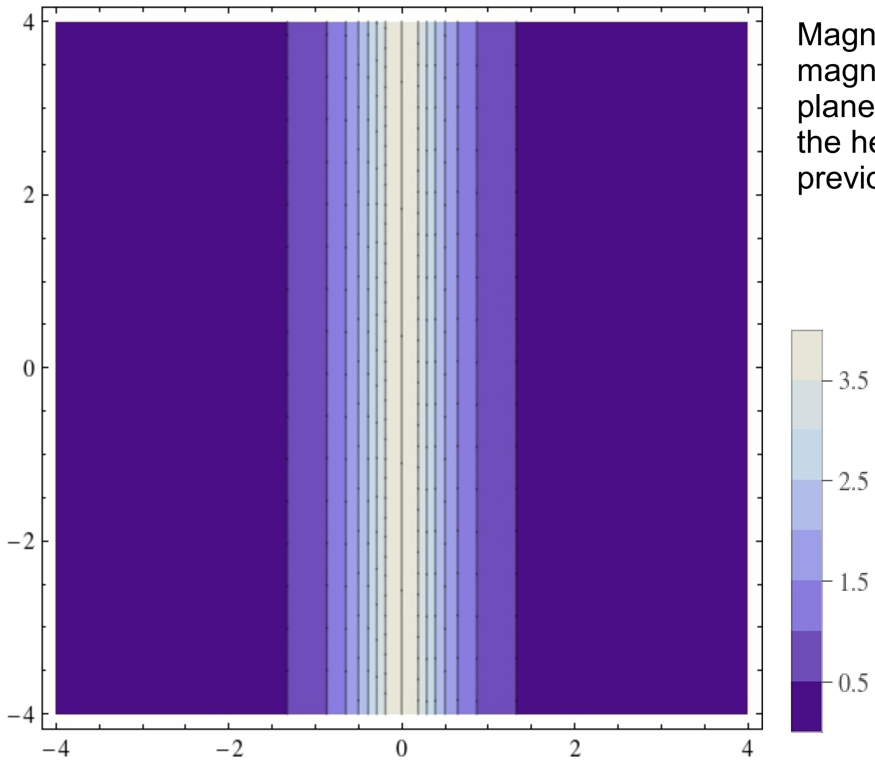
the arrows in the left graph show the direction of magnetic field but not its magnitude; calculated for line conductors with zero diameter carrying the same current*

*if one shows the field produced by stripes it would be less inhomogeneous but more difficult for me to calculate

Magnetoresistive memory

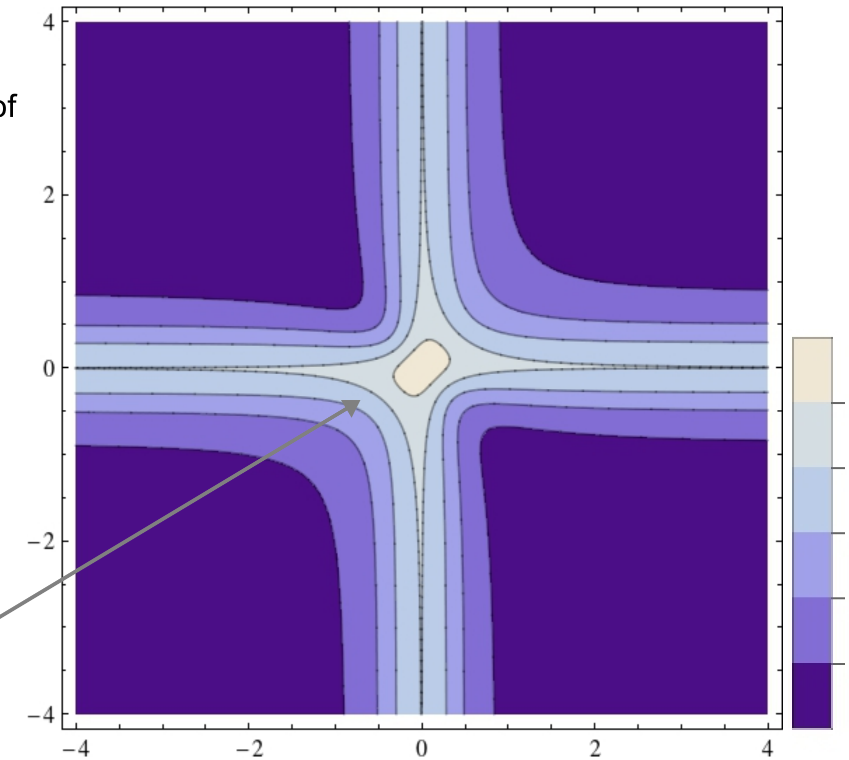
MRAM – magnetic field

- to produce the magnetic field which is spatially selective different arrangements of conductors can be used; the most obvious is the use of crossed conductors (usually stripes):



one wire

Magnetic field magnitude in the mid-plane of the cell (half of the height) shown on previous slides



two crossed wires

note the small area with highest field values

Magnetic field magnitude shown in the right panel is not axiosymmetric because the mid-plane of the cell is not midway between the wires

Magnetoresistive memory

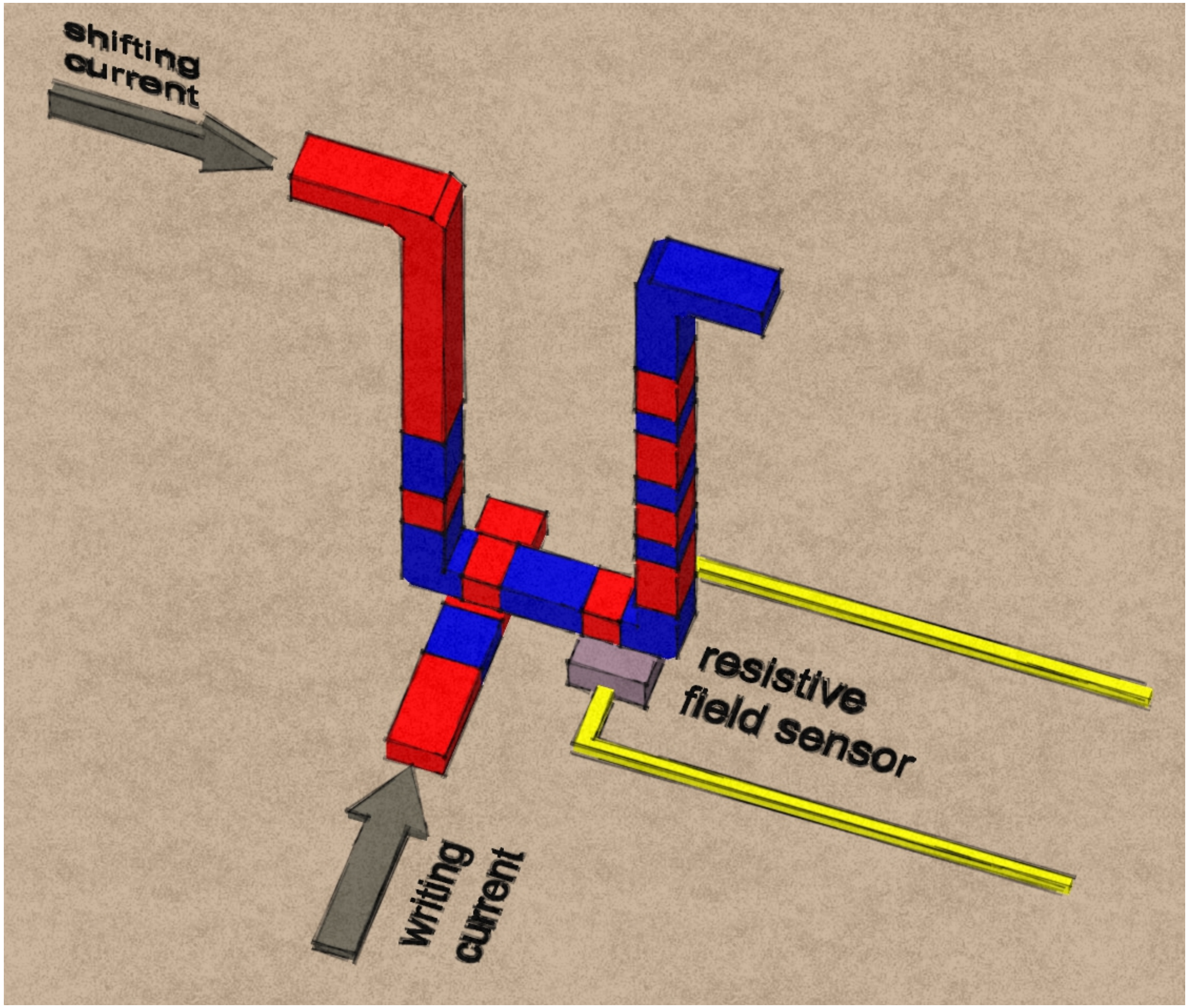
MRAM versus other random access memories (adapted from J. Heidecker [19])

	SRAM	DRAM	NOR Flash	MTJ-MRAM	STT-MRAM
access time[ns]	<1 ns	260 ps	25 ns	35 ns	<10ns (?)
endurance (write cycles)	infinite	infinite	10^5	infinite	infinite
retention	0 (volatile)	0 (volatile)	>10 yrs	>20 yrs	>20 yrs
cell size (F^2)	100	8	6	10	<4 (?)

F- minimum lithographic pitch [16]

Alternative magnetic memories

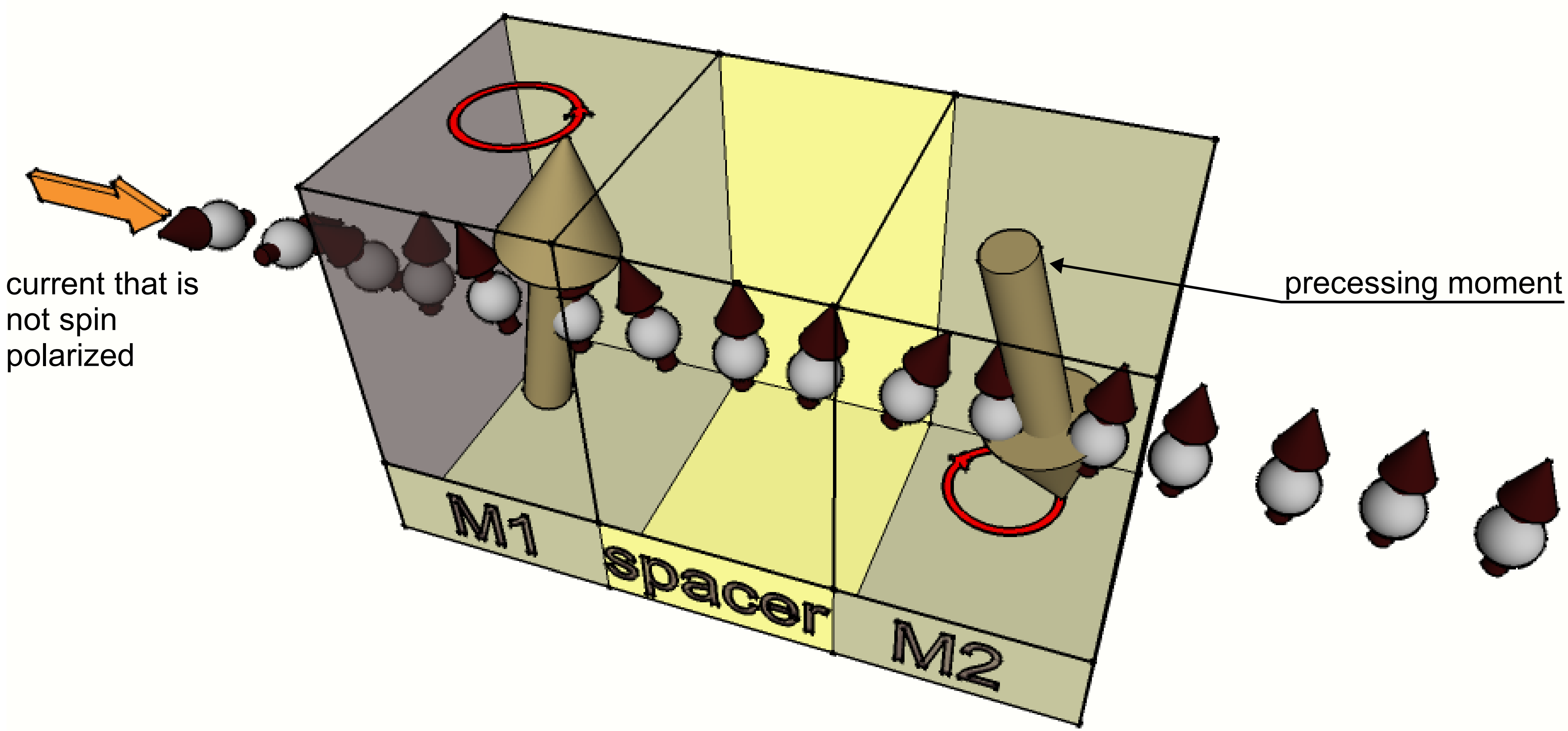
Racetrack memory – S.S. Parkin, IBM



- the memory is of the shift register type – no direct access to bit
- the information is written into the “racetrack” by the stray fields of the domains controlled by the writing current
- to read the data the consecutive bits are moved by the shifting current to be detected by the resistive sensor (GMR, TMR)
- the resistive sensor detects stray fields of the domain walls
- the domain walls are pinned with the notches in the track (the wall stays preferentially between the notches because its length, and thus the energy, is lower there)
- the memory needs one transistor for some 100 bits [22]

Spintronic devices

Spin-torque wave generators*
In 1996 J. Slonczewski predicted that the current flowing between two ferromagnetic layers may induce a steady precession of the moments or novel form of switching of magnetization [27]. The latter effect has already found application in STT-MRAM. The first effect is, among others, being investigated with a hope of fabricating novel microwave generators [28].



*STO – Spin Torque Oscillator

Spintronic devices

Landau-Lifshitz-Gilbert (LLG) equation of spin motion

- The change of angular momentum ***J*** of a rigid body under the influence of the torque is given by:

$$\vec{\tau}=\frac{d\vec{J}}{dt}$$

- The torque acting on magnetic moment in magnetic field is: $\vec{\tau}=\vec{m}\times\vec{B}$
- With gyromagnetic ratio defined as $\gamma=\frac{|\vec{m}|}{|\vec{J}|}$ we get:

For an electron we have:

$$\vec{m}_e=-g_e\frac{e}{2m}\vec{S}$$

$$\frac{d\vec{m}}{dt}=\gamma\vec{m}\times\vec{B}$$

This equation can be used to describe motion of the electron's magnetic moment. The electron itself is fixed in space.

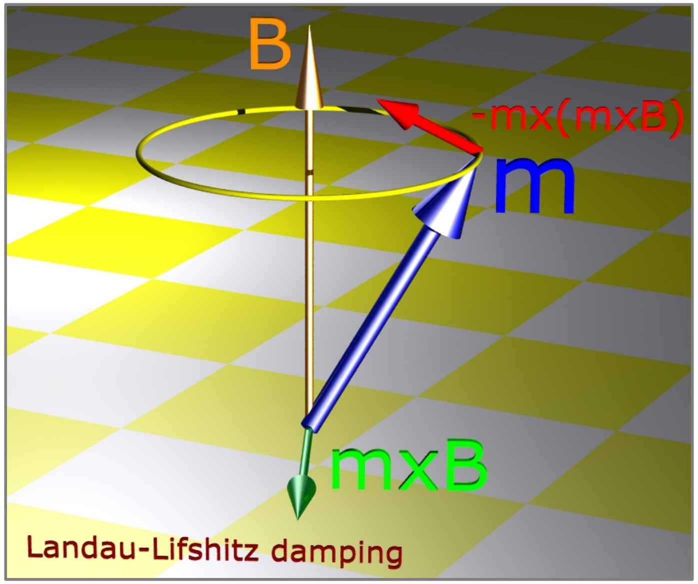
- Landau and Lifshitz have introduced **a damping term** to the precession equation:

$$\frac{d\vec{m}}{dt}=\gamma\,\vec{m}\times\vec{B}-\frac{\alpha_L}{|\vec{m}|}(\vec{m}\times(\vec{m}\times\vec{B})), \qquad (1)$$

where α_L is a dimensionless parameter [29].

Spintronic devices

Landau-Lifshitz-Gilbert (LLG) equation of spin motion



- As can be seen the damping vector is directed toward ***B*** and vanishes when ***m*** and ***B*** become parallel.
- As can be seen from Eq. (1) the acceleration of ***m*** towards ***B*** is greater the higher the damping constant α_L. Gilbert [32] pointed out that this is nonphysical and that Eq. (1) can be used for small damping only [29].
- He introduced other phenomenological form of equation which can be used for arbitrary damping. Damping is introduced as dissipative term [30] of the effective field acting on the moment*:

$$\vec{B} \rightarrow \vec{B} - \eta \frac{d\vec{m}}{dt} \qquad (2)$$

Landau-Lifshitz-Gilbert equation

$$\frac{d\vec{m}}{dt} = \frac{\gamma}{(1+\alpha^2)} \vec{m} \times \vec{B} - \frac{\alpha}{(1+\alpha^2)} \frac{\gamma}{|\vec{m}|} \vec{m} \times \vec{m} \times \vec{B}$$

exchange energy density*

- In general the magnetic induction should be replaced by the effective field $\boldsymbol{B}_{eff}$ [33, p.178]:

$$\vec{B}_{eff} = \mu_0 \left(\frac{C}{M^2} \left[(\nabla M_x)^2 + (\nabla M_y)^2 + (\nabla M_z)^2 \right] + \vec{H} + \frac{\partial}{\partial \vec{m}} E_{anisotropy} \right)$$

to be read as:

$$\frac{\partial}{\partial \vec{m}} f = \hat{x} \frac{\partial}{\partial m_x} f + \hat{y} \frac{\partial}{\partial m_y} f + \hat{z} \frac{\partial}{\partial m_z} f$$

*for more details see my lecture no.8 from 2012

Spintronic devices

Landau-Lifshitz-Gilbert (LLG) equation with spin torque

- by including an additional term LLG equation can be extended to phenomenologically describe the influence of spin polarized current on magnetization dynamics [27,31,34]
- in the simplest case of two magnetic layers, with magnetic moment of one of them fixed the motion of magnetic moment can be approximately given by the equation [31]:

$$\frac{d\vec{m}_{free}}{dt} = -\mu_0 \gamma \vec{m}_{free} \times \vec{H}_{eff} - \mu_o \gamma \alpha \vec{m}_{free} \times (\vec{m}_{free} \times \vec{H}_{eff}) + \frac{\varepsilon J_{injected} \hbar}{e l_z 2} \frac{\gamma}{M_{s1}} m_{free} \times (\vec{m}_{free} \times \vec{m}_{fix})$$

ε -current polarization

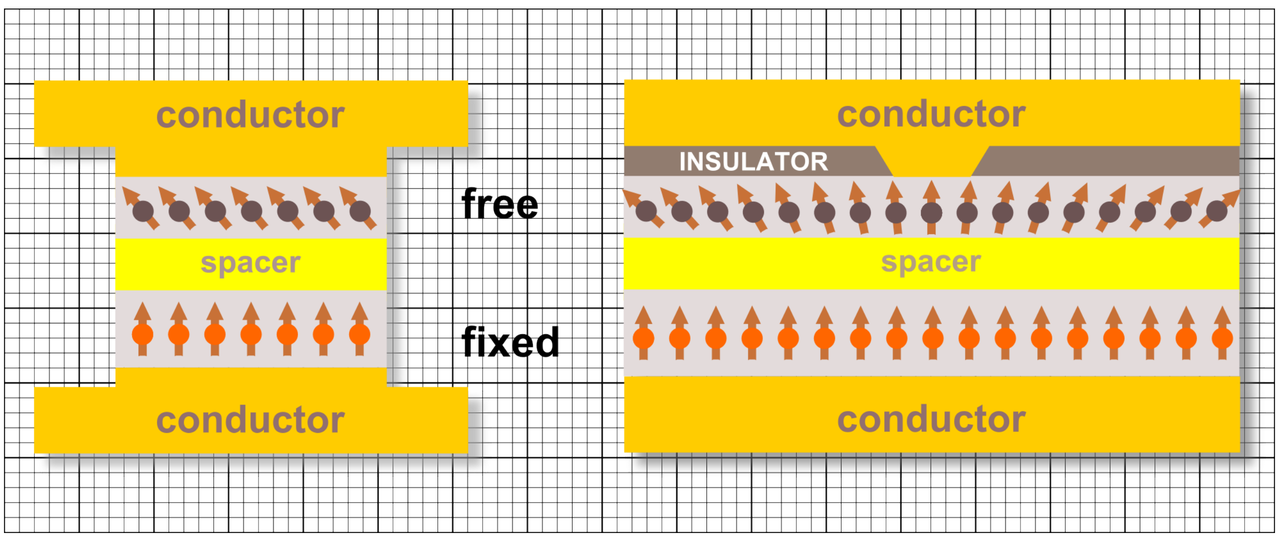
$J_{injected}$ -current density (of the order of 10^{10}-10^{11} Am^{-2})

l_z -thickness of the free layer

M_{s1} -magnetization of the free layer

Note that spin-current injection can result in the spin-waves generation especially in nanocontact configuration where the area into which spin current is being pumped is coupled by the exchange interaction with the rest of the film [31]

nanopillar



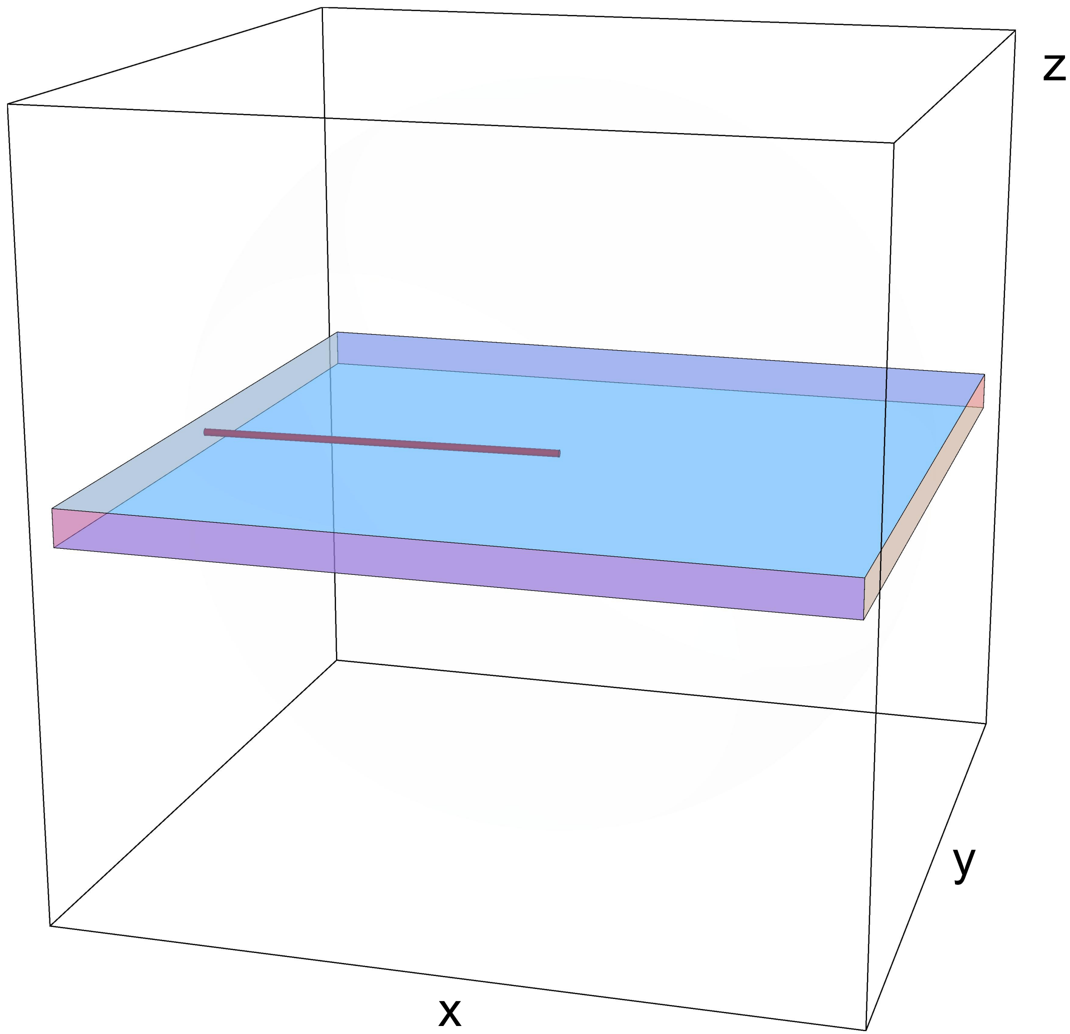
nanocontact [31]

- spin waves
- lower FWHM of emitted power
- edge defects associated with patterning are mitigated
- no parasitic dipolar coupling between free and fixed layer

Spintronic devices

Switching of thin film magnetic moment - macrospin approximation

- one magnetic moment under combined influence of magnetic field and spin-polarized current [17]

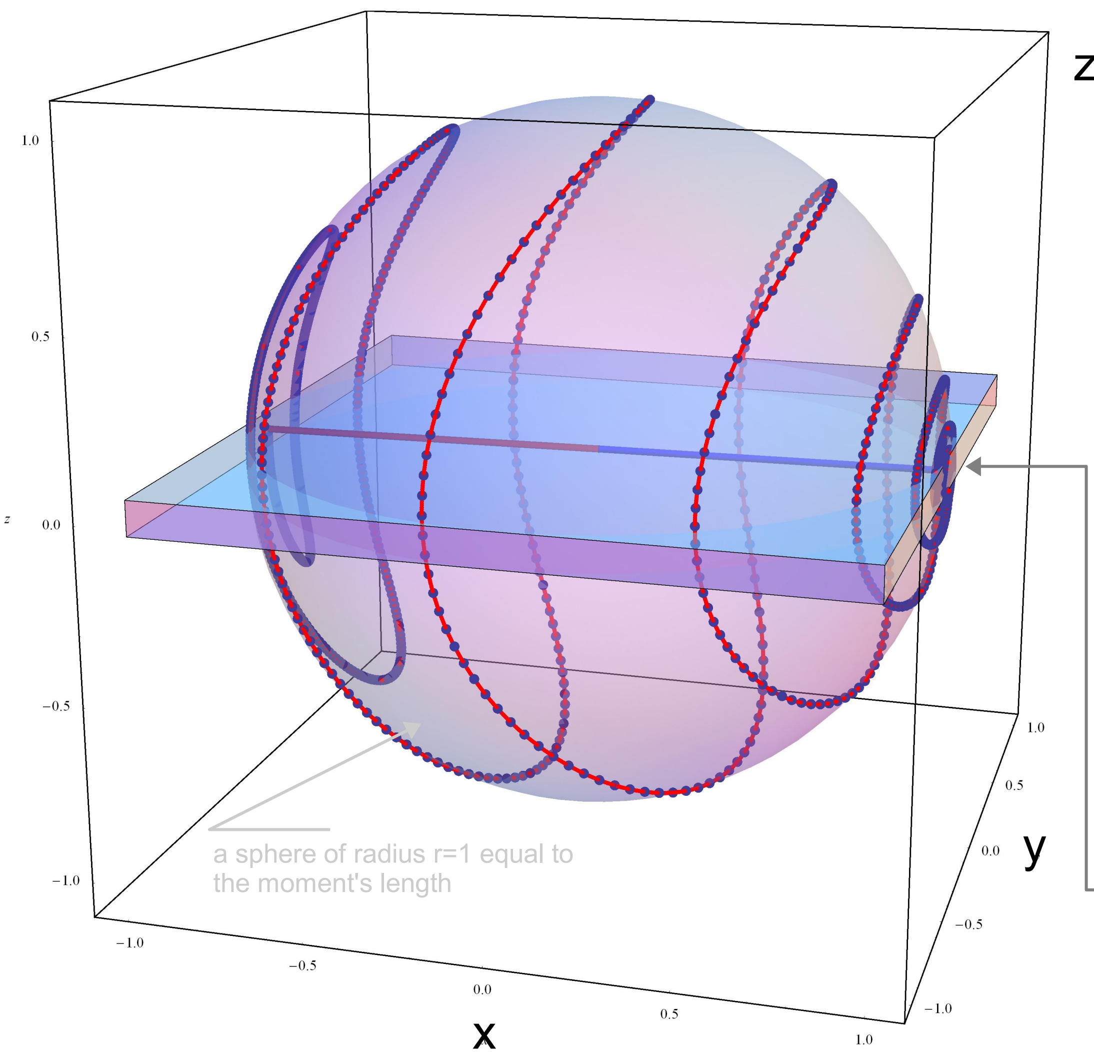


- the magnetic moment (red line) points initially in (-0.95,-0.05,0) direction (if it pointed exactly in -x direction it would not reverses under the action of the field directed in +x direction*)
- thin film is infinite in the x,y-plane so the moment experiences shape anisotropy with demagnetizing field, equal to z-component of magnetization, which tends to keep the moment in the plane of the film

*in real film the thermal fluctuations are enough to initiate the reversal

Spintronic devices

Switching of thin film magnetic moment - macrospin approximation



- after (instantaneous) application of the field in +x direction the moment precesses to its final position (blue line)

- blue dots mark equal time intervals
- parameters:

initial moment direction: (-0.95,-0.05,0)
H=(1,0,0)
damping =0.1
current=0
saturation reached* after 13436 dt**

**dt - time step used in simulation

*after which time step (all steps equal) the magnetic moment for the first time points along the field direction to within 1 deg of arc

Spintronic devices

Switching of thin film magnetic moment - macrospin approximation

Mathematica 6 code to get the previous and following graphs:

```
 ClearAll[Mi,Hx,Hy,Hz,Current,alfa,anizo,S];
M={Mi[[1]],Mi[[2]],Mi[[3]]};
Spin={S[[1]],S[[2]],S[[3]]};
He={Hx,Hy,Hz-anizo Mi[[3]]};(*thin film-arbitrary field direction*)(*anizo=1 - cienkawarstwa; anizo=0 - isotropic sphere - no magnetic anisotropy*)

Md=Sqrt[M.M];
 dMtodt=- Cross[M,He] - alfa  Cross[M, Cross[M, He]]+Current  Cross[M,Cross[M,Spin]];(*this gives the set of equation describing time evolution of the magnetic moment orientation
which I have inserted into the k-loop below*)
```

first evaluate the first cell and do not worry about "*Part specification Mi[[1]] is longer than depth of object.*" etc.

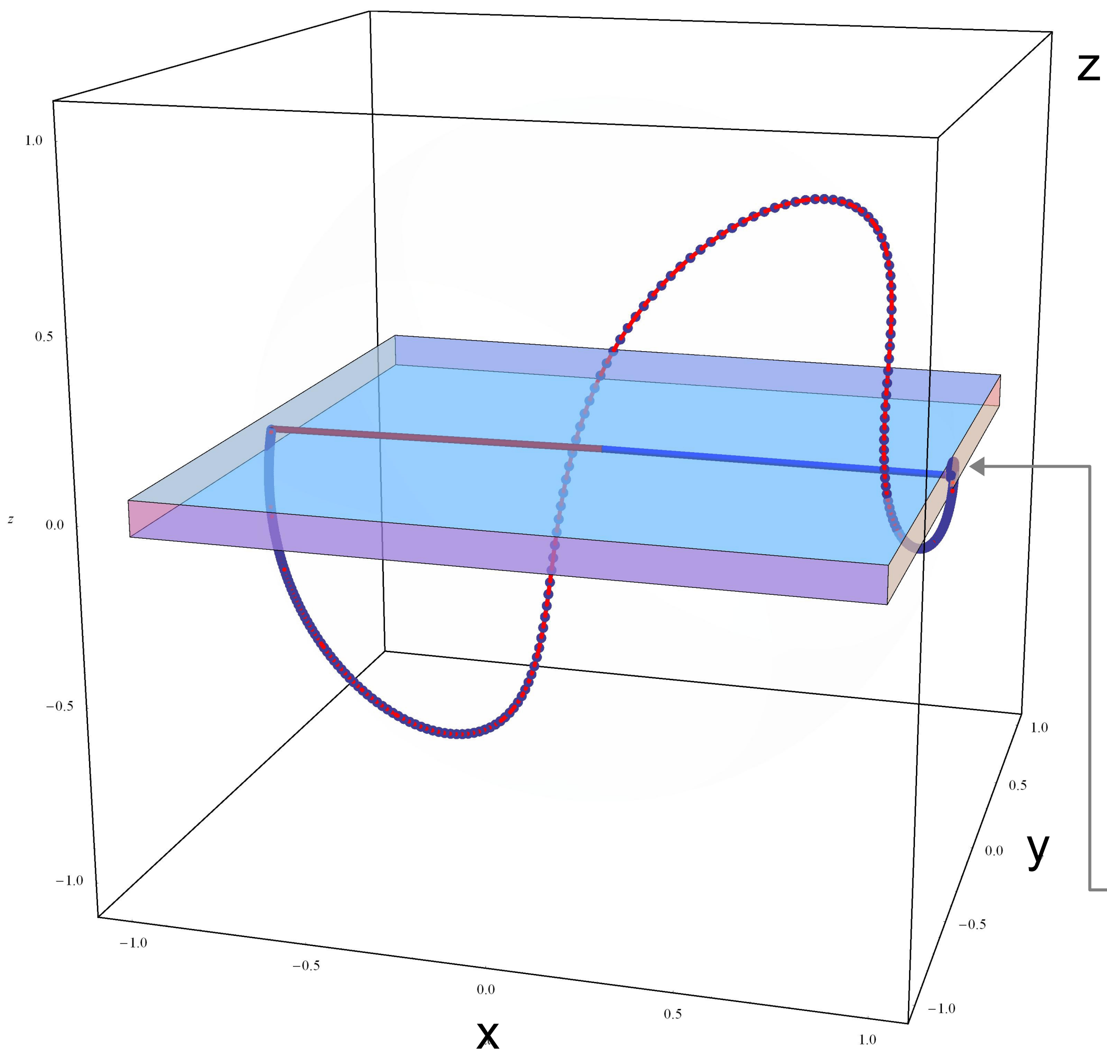
——————————————————————— cell border

```
  ilepunktow=14000;(*number of points- time intervals*)
orientacjamomentu=Table[{0,0,0},{i,1,ilepunktow-1}];
dt=0.01;(*time step*)
alfa=0.1;
anizo=1; (*anizo=0;-sphere*)
Hvalue=1;(*field value*)
Hx=1;(*components relative*)
Hy=0;
Hz=0;
Ha=Sqrt[Hx^2+Hy^2+Hz^2]/Hvalue;
Hx=Hx/Ha;
Hy=Hy/Ha;
Hz=Hz/Ha;

Mi={-0.95,-0.05,0};(*initial moment orientation*)
moment=Sqrt[Mi.Mi];(*moment's length*)
Mi=Mi*(1/moment);
Current=0; (*current*)
(*spin-current orientation:*)
S={-1,0,0};

wy3=Graphics3D[{RGBColor[1,0,0],Cylinder[{{0,0,0},1*{Mi[[1]],Mi[[2]],Mi[[3]]}},0.01]}];(*line of initial moment orientation*)

licznik=0;

gamma=2;
timemultiplier=1/(moment gamma (1+alfa^2));

coile=10;(*co ile punktow stawiac marker*)
macierzznacznikow=Table[{0,0,0},{i,1,Floor[ilepunktow/coile]-1}];
licznik=1;
l=1;
pp=0;(*print only once*)
For[k=1,k<ilepunktow,k++,

 Mi[[1]]=Mi[[1]]+dt timemultiplier dMtodt[[1]];
 Mi[[2]]=Mi[[2]]+dt timemultiplier dMtodt[[2]];
 Mi[[3]]=Mi[[3]]+dt timemultiplier dMtodt[[3]];

 (*adjust the M length - to take care of numeric errore:*)
 temp=Sqrt[Mi.Mi];
 Mi[[1]]=Mi[[1]]/temp;Mi[[2]]=Mi[[2]]/temp;Mi[[2]]=Mi[[2]]/temp;


 orientacjamomentu[[k,1]]=Mi[[1]];orientacjamomentu[[k,2]]=Mi[[2]];orientacjamomentu[[k,3]]=Mi[[3]];

 (*angle A between the moment and the field direction*)
 kos=(Mi[[1]]*Hx+Mi[[2]]*Hy+Mi[[3]]*Hz)/Hvalue;
 If[Abs[kos]>=0.999847 && pp==0,(*about 1 degree of arc*)
  {Print["Field direction reached after ",k, " dt"];
   pp=1;}
  ]


  (*the markers on the orbit are placed every coile-th iteration of k*)
  If[licznik<coile,licznik=licznik+1,{licznik=1;
   macierzznacznikow[[l,1]]=orientacjamomentu[[k,1]];
   macierzznacznikow[[l,2]]=orientacjamomentu[[k,2]];
   macierzznacznikow[[l,3]]=orientacjamomentu[[k,3]];

   l++}
  ]


 ]


wy1=ListPointPlot3D[orientacjamomentu, PlotRange->{{-1.1,1.1},{-1.1,1.1},{-1.1,1.1}}, BoxRatios->{1,1,1},AxesLabel->{x,y,z},PlotStyle->{Red},BoxStyle->Directive[Thickness[0.004]]];


wy4=ListPointPlot3D[macierzznacznikow, PlotRange->{{-1.1,1.1},{-1.1,1.1},{-1.1,1.1}},AxesStyle->{Thick}, BoxRatios->{1,1,1},PlotStyle->PointSize[Large],AxesLabel->{X,Y,Z},ImageSize->600,ViewPoint->{Pi,Pi/2,2}];
wy2=Graphics3D[{Opacity[0.3],Sphere[{0,0,0},1]}];
warstwa=Graphics3D[{Opacity[0.5],Cuboid[{1,1,0-0.05},{-1,-1,0.05}]}];
wy5=Graphics3D[{RGBColor[0,0,1],Cylinder[{{0,0,0},1*{Mi[[1]],Mi[[2]],Mi[[3]]}},0.01]}];(*final moment direction*)
wy3=Show[wy1,wy4,wy3,wy2,wy5,warstwa,ImageSize->800,ViewVector->{2,-7,2}(*relative to the center*),ViewCenter->{0.5,0.5,0.5},ImageMargins->20,BoxStyle->{AbsoluteThickness[4],RGBColor[0,0,0]}]
(*Export["D:\\yourfolder\\image.jpg",wy3,ImageResolution->300]*)
```

then evaluate the second cell; to get the graph for other parameters (damping, field direction, current etc.) the first cell need not to be evaluated again

Spintronic devices

Switching of thin film magnetic moment - macrospin approximation



- after (instantaneous) application of the field in +x direction the moment precesses to its final position (blue line)

- blue dots mark equal time intervals
- parameters:

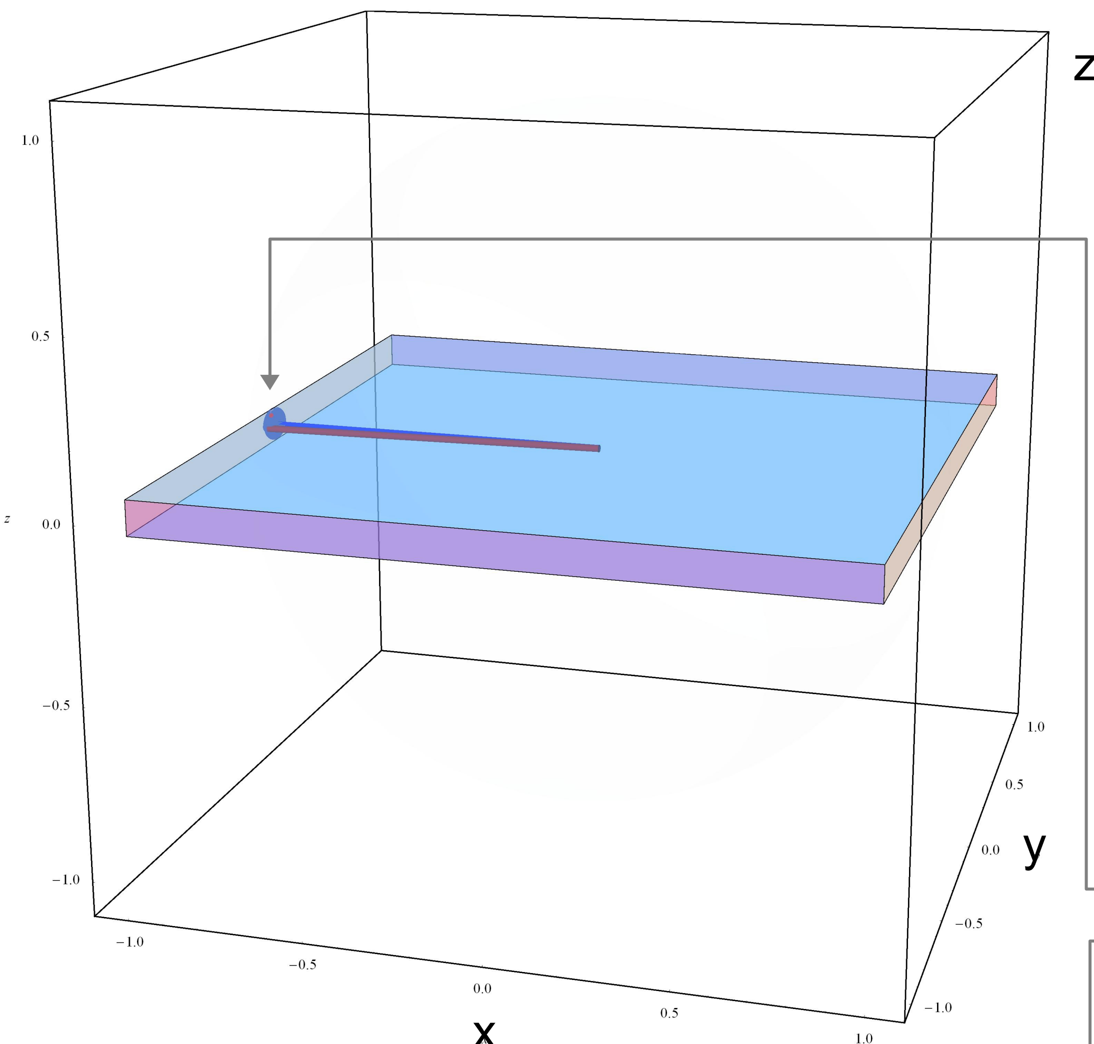
initial moment direction: (-0.95,-0.05,0)
H=(1,0,0)
damping =**0.5** stronger damping
current=0
saturation reached* after **3140** dt – note that the moment switched in a shorter time in spite of higher damping constant

final position of the moment

*after which time step (all steps equal) the magnetic moment for the first time points along the field direction to within 1 deg of arc

Spintronic devices

Switching of thin film magnetic moment - macrospin approximation



- after (instantaneous) application of the field in +x direction the moment precesses to its final position (blue line)

- blue dots mark equal time intervals
- parameters:

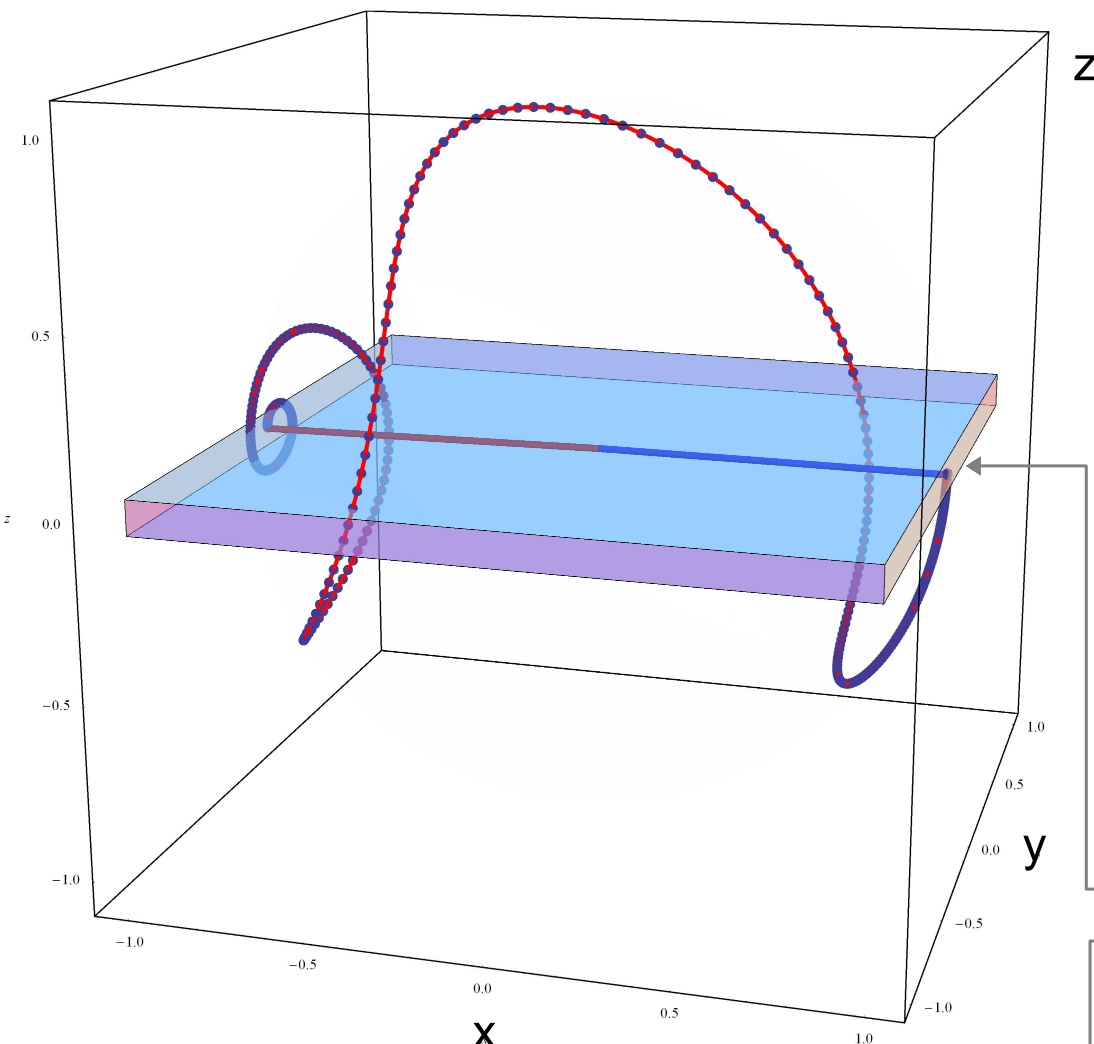
initial moment direction: (-0.95,-0.05,0)
H=(-1,0,0)
damping =**0.5**
current=**0.1 with spin orientation favoring the reversal of the moment to +x direction**
note that the current is too small influence the reversal

final position of the moment

The spin current is ON now

Spintronic devices

Switching of thin film magnetic moment - macrospin approximation



- action of the current exceeds the influence of the field and the moment reverses

- blue dots mark equal time intervals
- parameters:

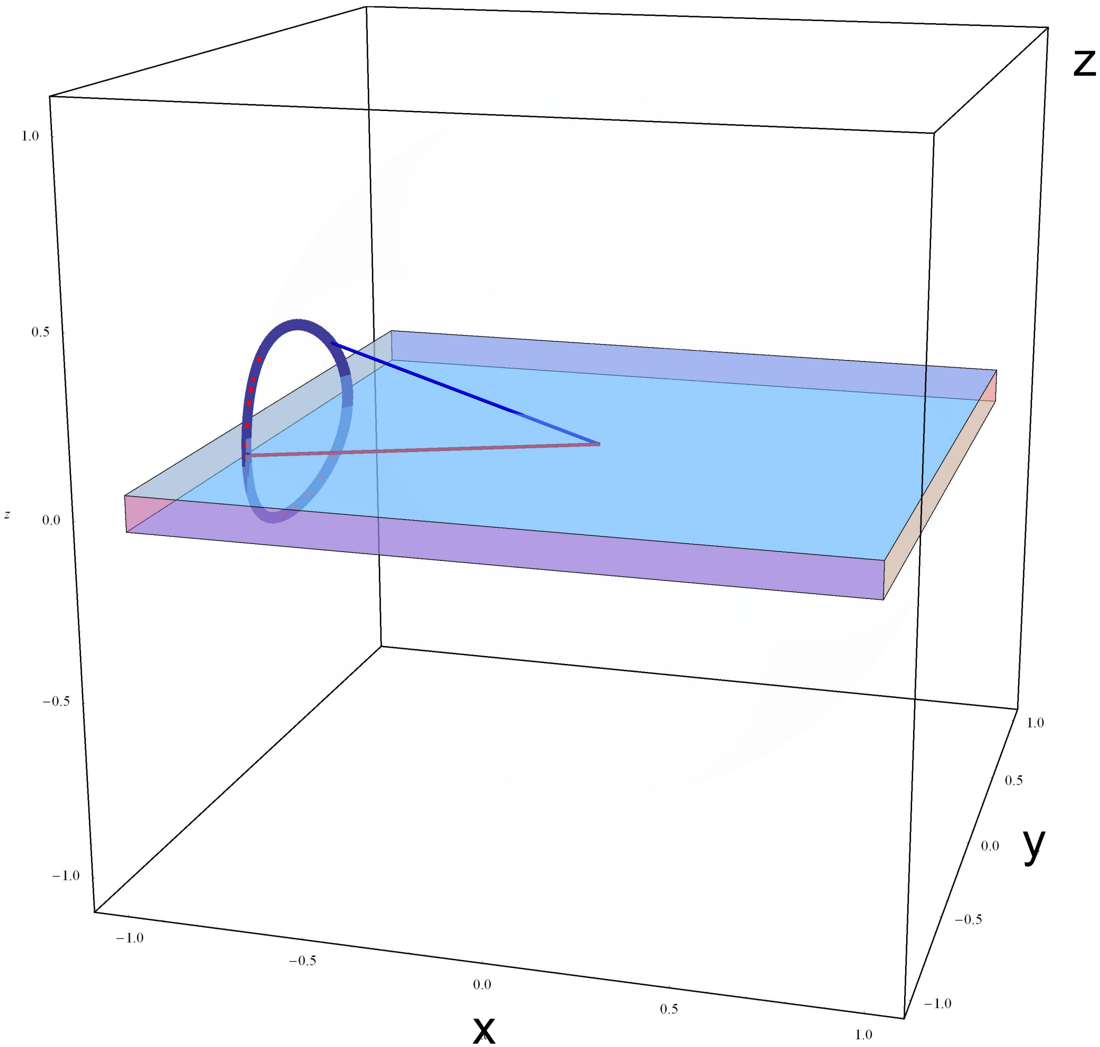
initial moment direction: (-0.95,-0.05,0)
H=(-1,0,0)
damping =**0.5**
current=**0.5** with spin orientation favoring the reversal of the moment to +x direction
saturation reached* after **3846** dt

final position of the moment

The spin current was high enough for the switching of the moment to take place

Spintronic devices

Switching of thin film magnetic moment - macrospin approximation



- the precession of magnetic moment can be used to generate microwaves through the effect of GMR [17]

- blue dots mark equal time intervals
- parameters:

initial moment direction: (-0.95,-0.4,0)
H=(-1,0,0)
damping =**0.5**
current=**0.149** with spin orientation favoring the reversal of the moment to +x direction
action of the current balances the damping and the moment performs **steady precession**

Spintronic devices

Spin-torque generators*

In 1996 J. Slonczewski predicted that the current flowing between two ferromagnetic layers may induce a steady precession of the moments or novel form of switching of magnetization [27]. The latter effect has already found application in STT-MRAM. The first effect is, among others, being investigated with a hope of fabricating novel microwave generators [28].

sputter-deposited multilayer stacks consisting of 2 nm CoFe (FM1)/4 nm Cu/4 nm CoFe (FM2)

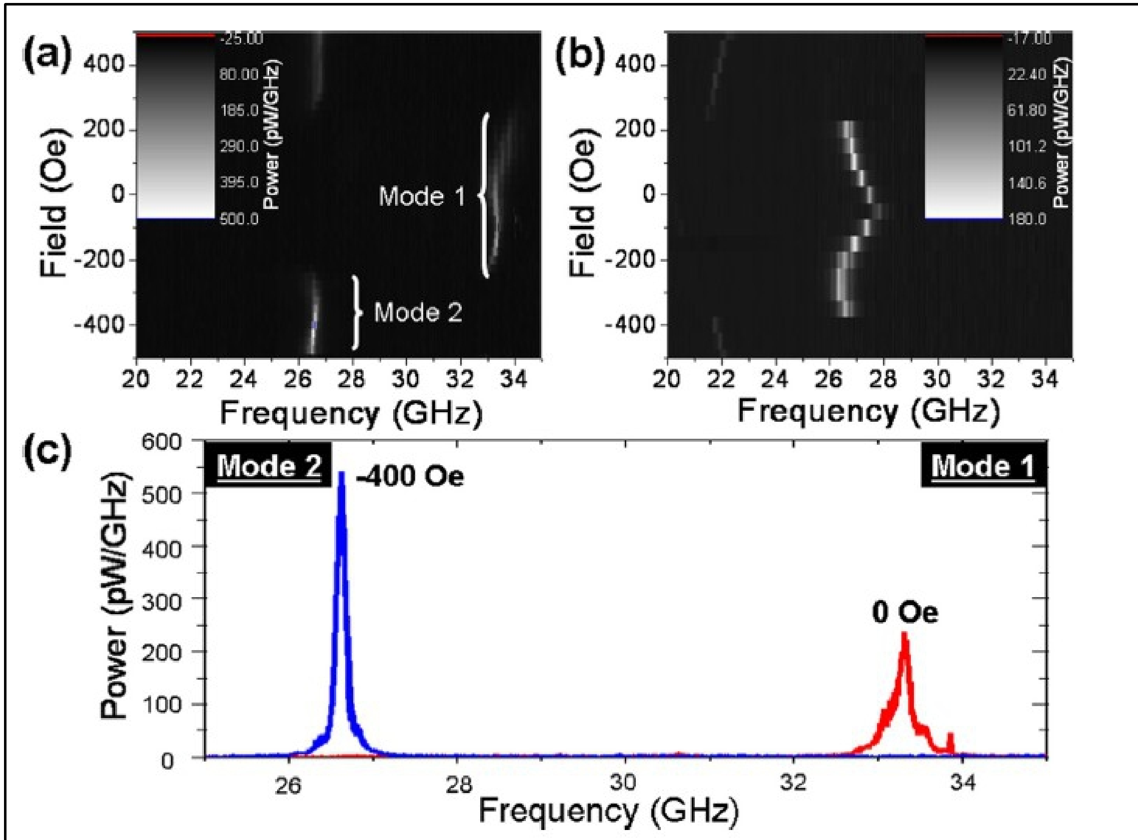


FIG. 2. High frequency phase diagram for STO device 1 (a) and device 2 (b) depicting the two field regimes corresponding to optical (mode 1) and acoustic (mode 2) oscillation modes for the two ferromagnets. (c) Power spectral density for the oscillator in (a) at 0 and −400 Oe, showing well defined spectral peaks with large output powers at different ultrahigh frequencies. The integrated powers of the spectral peaks are 72.4 pW at Ha = 0 Oe and 128.5 pW at Ha = −400 Oe, and we observe a hop of ~6.5 GHz between modes.

- bias current ~0.7mA
- both magnetic layers precess
- the precession and power generation is observed **in zero external magnetic field**

image from: P.M. Braganca, K. Pi, R. Zakai, J.R. Childress, B.A. Gurney, Applied Physics Letters **103**, 232407 (2013)

*STO – Spin Torque Oscillator

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- POV-Ray www.povray.org
- Blender www.blender.org
- SketchUp sketchup.com.pl

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