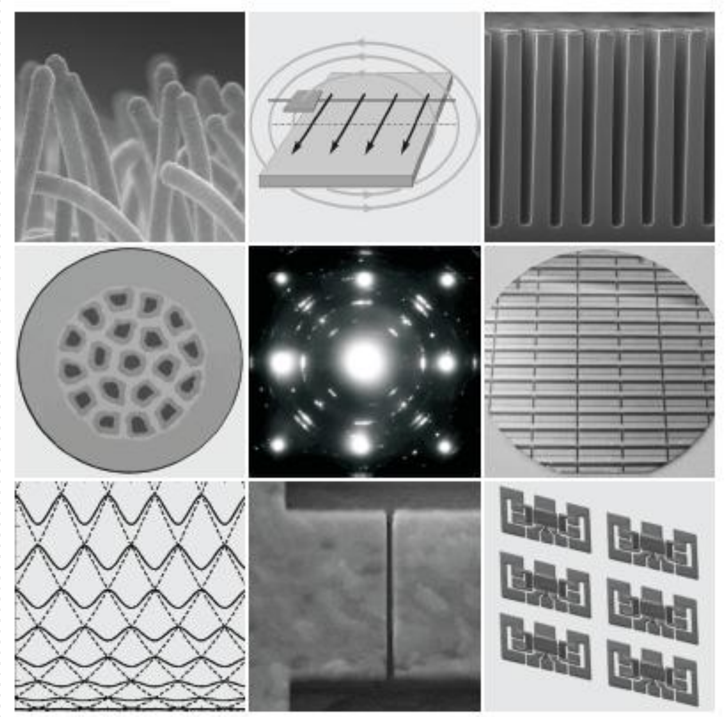
Materials for Electrical Engineering

K. Fröhlich, Slovak Academy of Sciences, Institute of Electrical Engineering



Institute of Electrical Engineering – research focus

The research and development at the Institute is focused on semiconductor, superconductor, oxide and magnetic materials, including theoretical and experimental study of their structural, optical, transport properties and devices for ***microelectronics and applied superconductivity*.**

Semiconductor science and technology:

- preparation and study of advanced materials for application in microelectronics

Outputs: materials and structures for microelectronics, high-frequency, high-power transistors, memory elements, advanced sensors of magnetic field, microwave power sensors, sensors for extremal conditions, X-ray detectors, structures for solar cells.

Superconductor science and technology:

- study and development of materials and devices for application in electric power (MgB_2, high-T_c, …)

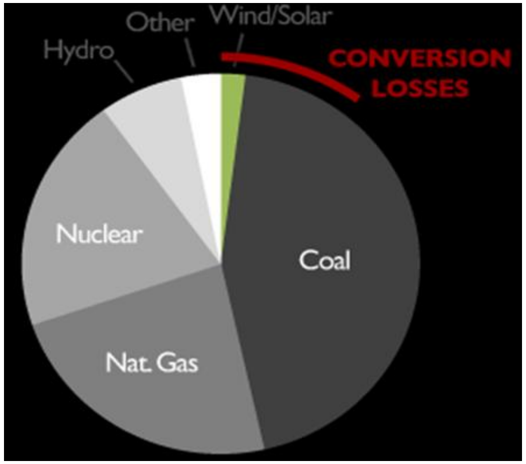
Outputs: superconducting conductors, cables, transformers and magnets.

Materials for electrical engineering: topics

- GaN based electronics for power engineering
- Future memory devices
- Sensors
- Application of atomic layer deposition
- Applied superconductivity

GaN based electronics for power engineering

GaN Switches and RF Transistors: Energy saving and data transmission



Want watts? → waste not & use **GaN-based switches**

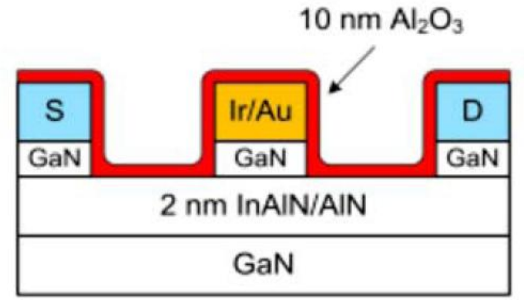
"More than 10% of all electricity is ultimately lost due to **low conversion inefficiency**. The scale of this loss exceeds the world's entire supply of renewable generation by an order of magnitude."

- Harsh environments
- High temperatures
- High power
- High efficiency
- Robust devices

GaN-based switches for voltage/current conversion:
normally-off transistors

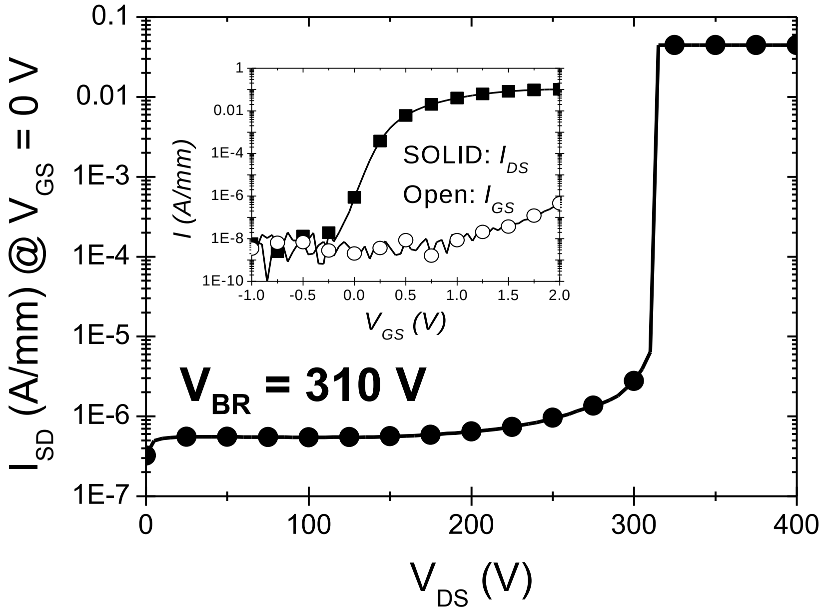
✓Automotive
✓Mobile communication
✓Radar
✓Energy distribution

1st approach for normally-off GaN transistors: selective etching of GaN cap



Source-drain: 8 µm,
Gate length: 1.8 µm

V_{GS}=0, OFF-state breakdown >300 V
Inset: ON/OFF ratio at V_{GS}=2V/0V: 10^5

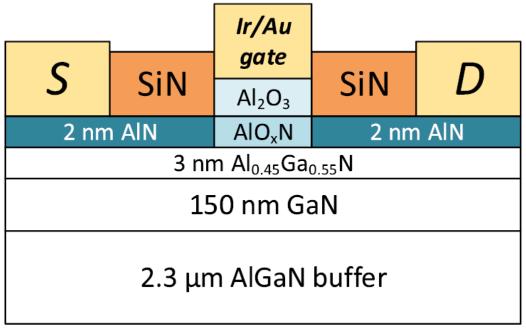


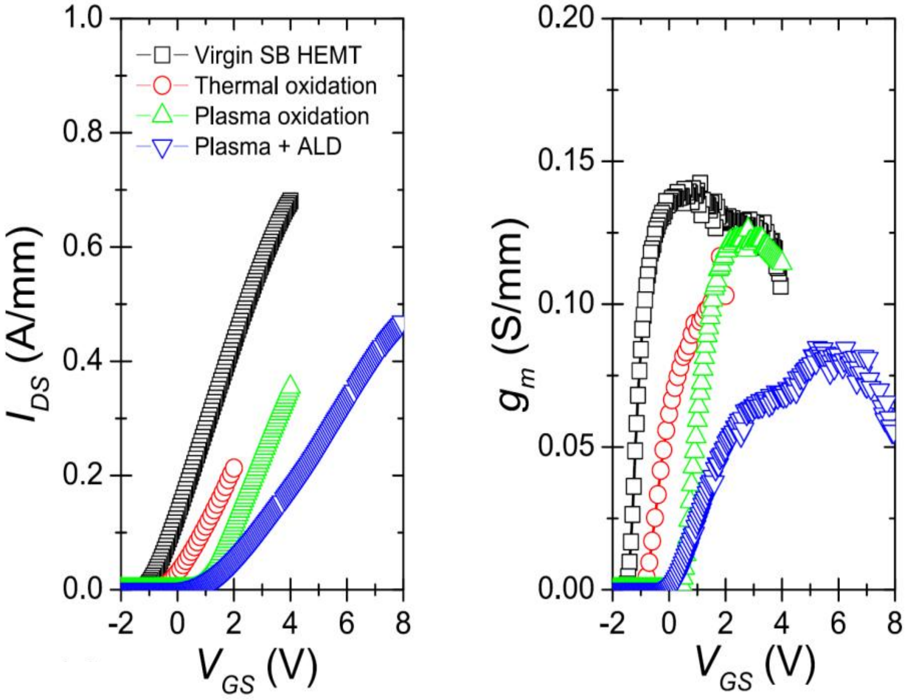
GaN cap creates a negative polarization charge increasing thus the gate effective barrier. After removal of the GaN cap at access regions the extrinsic channel becomes populated by carriers.

Passivation: Al_2O_3 growth by MOCVD at 500 °C, annealed at 700 °C.

Jurkovič, et al.: Schottky-barrier normally-off GaN/InAlN/AlN/GaN HEMT with selectively etched access region, IEEE Electron Dev. Lett. **34** (2013) 432.

2nd approach for normally-off GaN transistors : adjustment of threshold voltage by plasma oxidation and ALD overgrowth

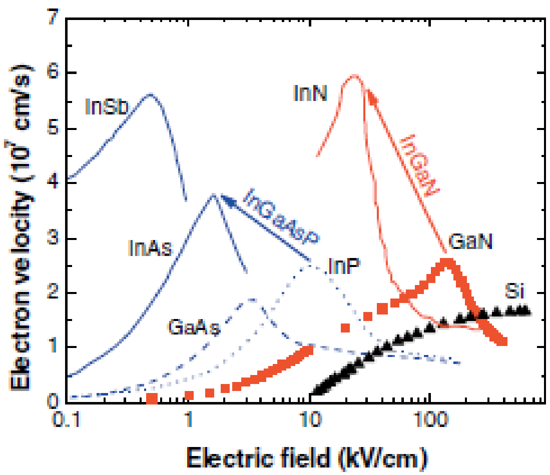




DC transfer and transconductance

D. Gregušová et al.: Adjustement of threshold voltage in AlN/AlGaN/GaN high-electron mobility transistors by plasma oxidation and Al_2O_3 atomic layer deposition overgrowth, Appl. Phys. Lett. **104** (2014) 013506

Plans for the future: InN-based electronics

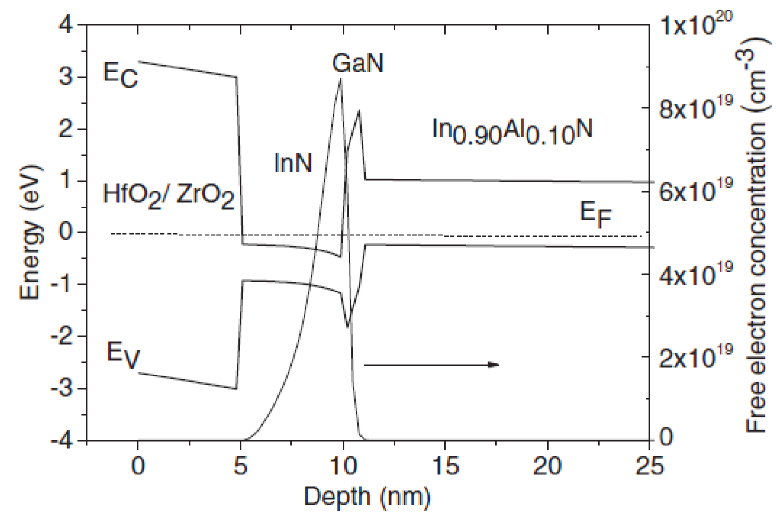


InN: Semiconductor material with the highest electron velocity among semiconductor materials.

A realistic option for "Beyond CMOS" technology (More than Moore)

New devices proposed by J. Kuzmik (IEE SAS) Applied Physics Express **5** (2012) 044101.

5 nm HfO_2/ ZrO_2
5 nm InN
0.3-1 nm GaN
$In_{1-x}Al_xN$ buffer, x = 0.1 – 0.3
Substrate



III-N Semiconductors: IEE SAS in EU Framework Programmes

ULTRAGAN – Future Emerging Technology project, InAlN/(In)GaN Heterostructure Technology for Ultra-high Power Microwave Transistor, 2005-2008

MORGaN, Materials for Robust Gallium Nitride, Integrated Project, 2008 - 2011

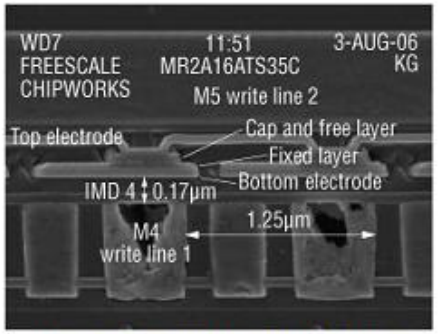
HipoSwitch, GaN-based normally-off high power switching transistor for efficient power converters, 2011 – 2014

Role of IEE SAS in projects: Engineering of the GaN-based heterostructure,
Dielectrics for passivation and gate insulation

Future memory devices

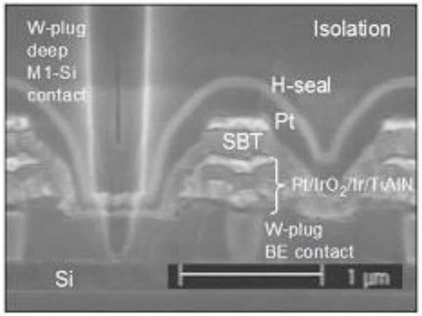
Emerging non-volatile memory concepts

MRAM



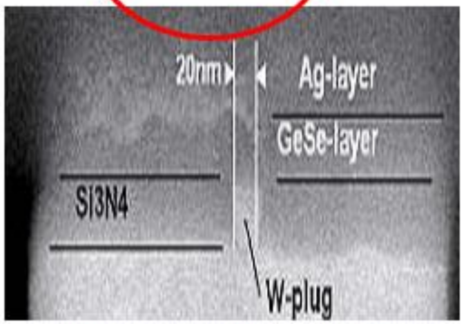
http://images.pennnet.com/articles/sst/thm/th_239818.jpg

FeRAM



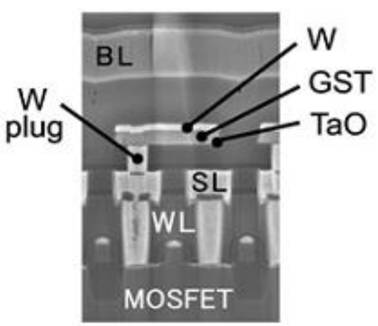
www.imec.be/wwwinter/mediacenter/en/SR2005/html/afbeeldingen/SR019F1.jpg

RRAM



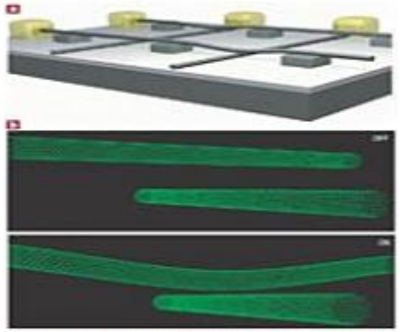
Kund, M. *et al. IEDM Tech. Digest*, 754–757 (2005).

PCM



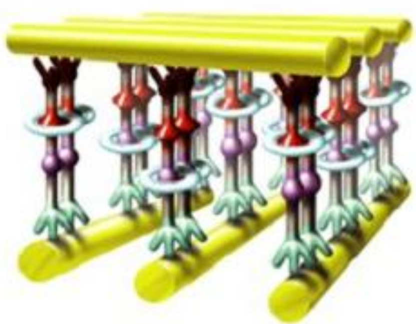
www.hitachi.com/New/cnews/061211.jpg

CNT



www.nature.com/nmat/journal/v6/n11/thumbs/nmat2028-f2.jpg

Molecular



http://research.chem.psu.edu/mallouk/science_wires/782-1-thumb.gif

etc.

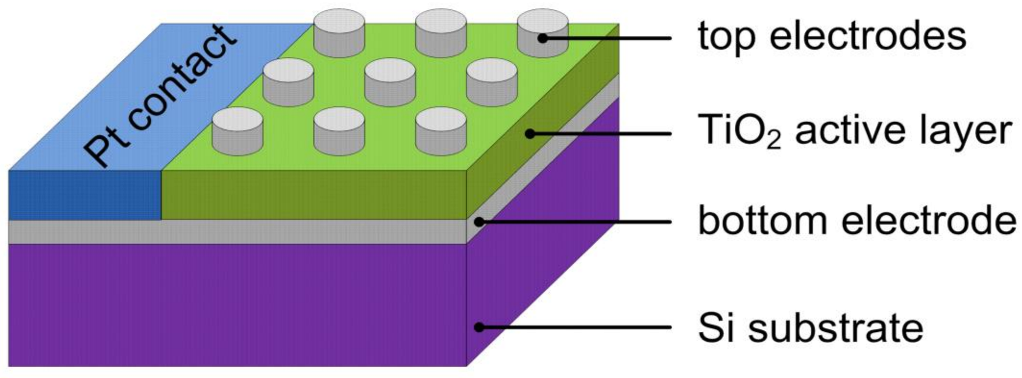
Oxide-based resistive switching random access memory

Requirements

R. Waser, R. Dittmann, G. Staikov, K. Szot, Adv. Mat. **21**, 2632 (2009)

Endurance:	> 10^7 cylces (Flash 10^3 … 10^7)
Resistance ratio:	R_{OFF} / R_{ON} > 10
READ current:	I_{ON} approx. 1 µA (due to periphery circuit) approx. 10^4 A/cm^2 (for 100nm x 100nm cells)
Scalability:	F < 22 nm and/or 3-D stacking
Write voltage:	approx. 1 … 5 V (Flash > 5 V)
Read voltage:	0.1 … 0.5 V
Write speed:	< 100 ns (Flash > 10 µs)
Retention:	> 10 yrs

Pt (TE)/HfO_2 (5 nm)/TiN (BE) planar structures: experimental configuration

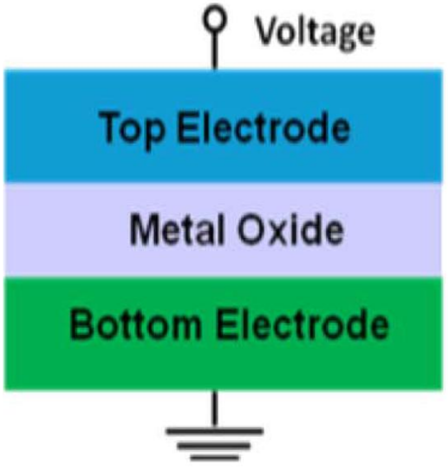


Pt (shadow mask) 100x100 μm²

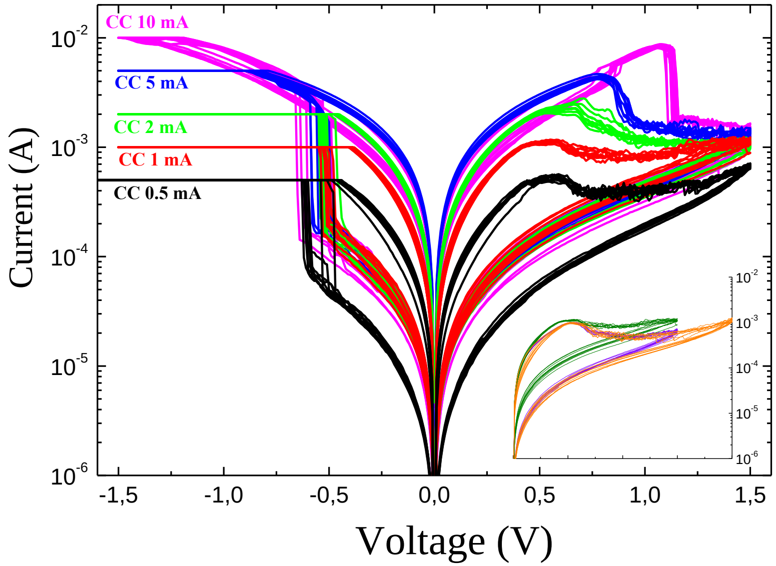
TiO_2, HfO_2 by ALD

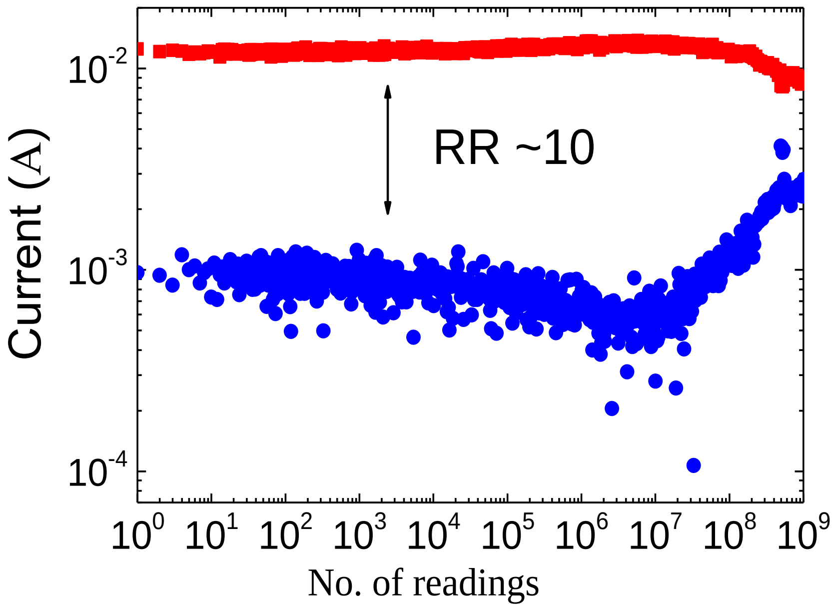
TiN

- Measurement of the virgin I-V curve, forming
- Resistive switching loop measurement
- Pulsed resitive switching measurement, endurance



Bipolar resistive switching in Pt (TE)/HfO_2 (5 nm)/TiN (BE) planar structures





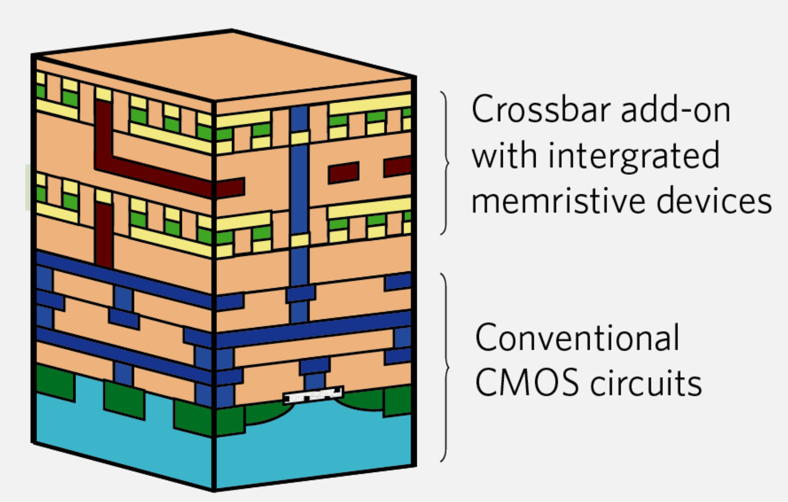
- Stable dc resistive switching loops
- I_{on}/I_{off} @ 0.2V ≈ 90
- control of the operating current by current compliance
- more than 10^7 readings in pulsed regime

HfO$_2$-based MIM structures exhibit promising properties for memory application

Future prospects of resistive switching

Adavantages

- High scalability of the resistivity switching based memory cells
- Fast speed (~ ns)
- Relatively simple technology
- Multilevel capability



Possible future applications

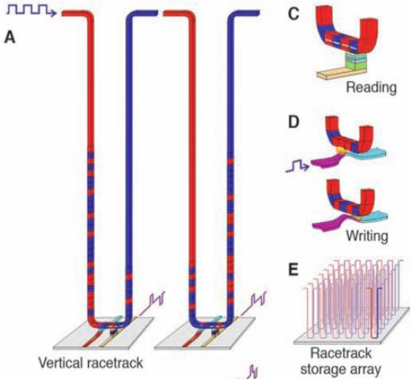
- Embedded memory
- High density memory arrays
- Logic application
- Neuromorphic computing

Nanoscale high-density RRAM are expected to revolutionize existing data storage hierarchy in future high-speed information systems because they feature superior performance, high storage capability and non volatile character.

Institute of Electrical Engineering – Ferromagnetic memories

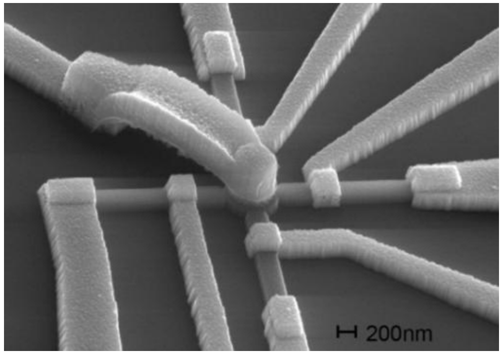
"Racetrack" memory

Parkin Science 2008



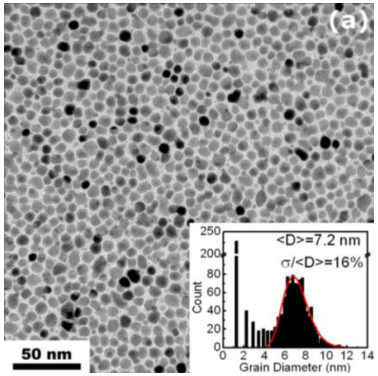
MRAM

Mark PRL 2011



Bit-pattern media

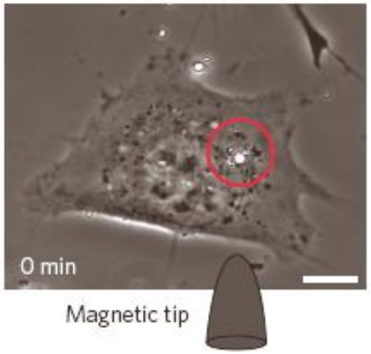
Mosendz JAP 2012 (Hitachi)



Advantages: reliability , scalability, non-volatility

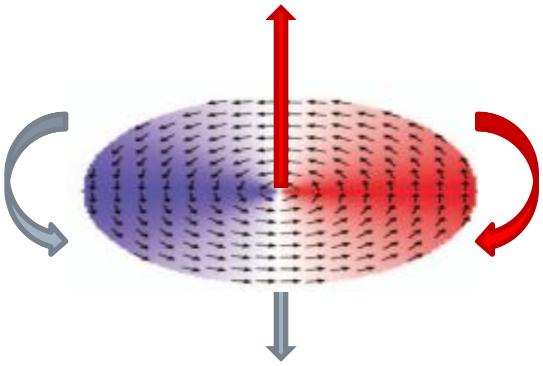
Our aims:

- *Develop fast bit pattern media for processors*
- *Develop MFM with spatial resolution < 10 nm*



Nanomagnets for bit-pattern media

Nanomagnets in 4 vortex states -
defined by polarity and chirality



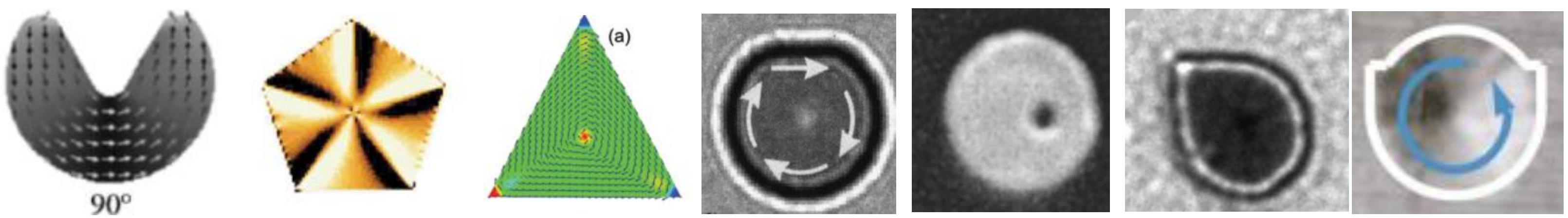
Advantages

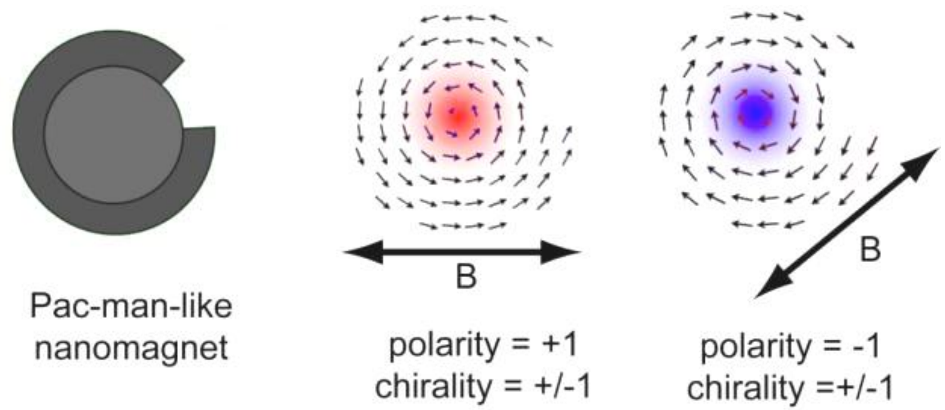
1. Gives 4 possible magnetic states - 2 bits
2. Weak interaction between neighbours
3. Sub-100 nm elements – show clearly defined states

Task:

How to write /read polarity/chirality easily for sub-100 nm nanomagnets

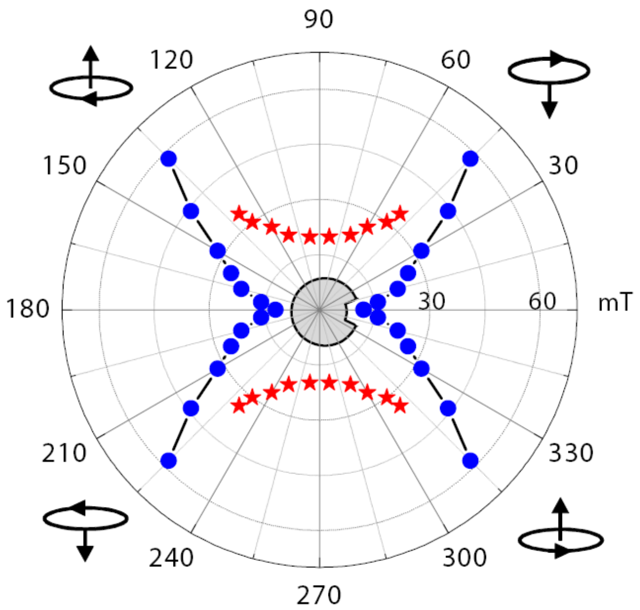
Setting chirality/polarity in magnetic nanodots



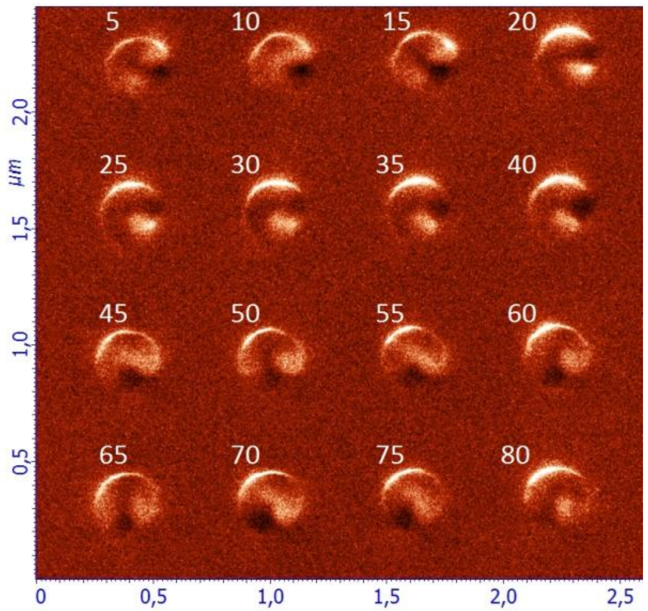


Angular dependence of vortex nucleation field

Calculations



Experiment



Cambel PRB 2011, Tóbik PRB 2012

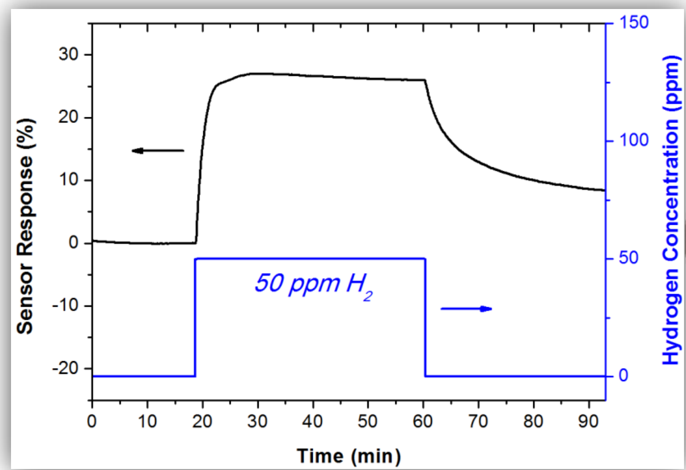
Šoltýs et al. MNE 2012

- *Each quadrant gives one state for d = 70 nm- defined by symmetries of PL and **B***
- *Experiments for d = 200 nm (right) support calculations*

Sensors

Institute of Electrical Engineering – Sensor of hydrogen

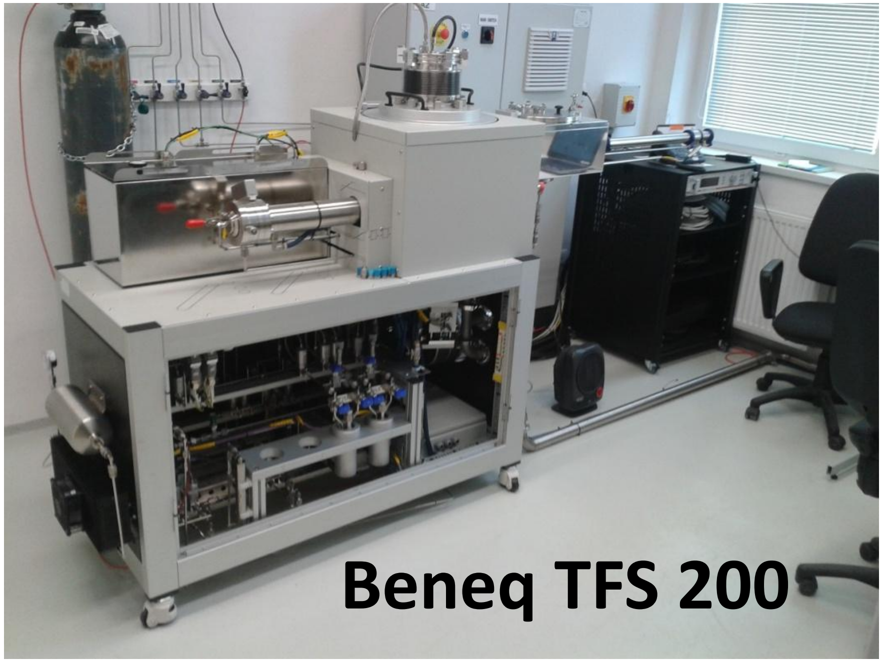
Hydrogen sensor based on polyaniline treated in oxygen plasma



Kunzo, P., Lobotka, P., Micusik, M. & Kovacova, E., Sensors and Actuators B: Chemical 171–172 (2012) p. 838–845

Application of atomic layer deposition

Preparation of HfO_2, TiO_2 and Al_2O_3 films by atomic layer deposition



- thermal, CC plasma, ozone ALD
- up to 200 mm wafers
- liquid source: Al_2O_3 (TMA), H_2O)
- hot source 300 °C: (TiO_2, HfO_2)
- load-lock
- deposition temperature: 100 - 300 °C

Main advantages of ALD:

Low deposition temperature, conformal growth, precise control of the thickness

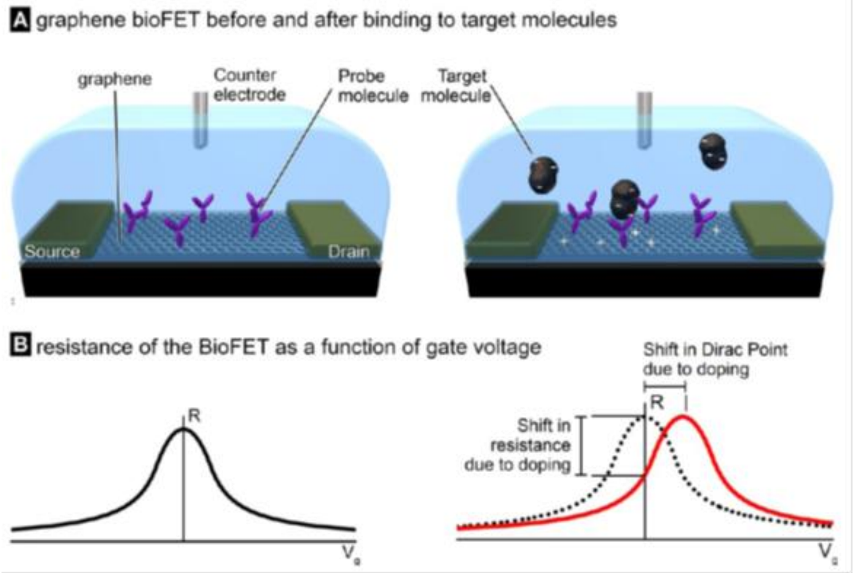
GaN-based transistors gate insulation and passivation

Graphene based devices,

FET, bio-FET sensor

Technological steps:

- Preparation of graphene, CVD
- Ohmic contacts, vacuum evaporation
- gate oxide film by atomic layer deposition
- Gate deposition
- Processing of the sensor
- Funcionalisation of the graphene surface



Resistive switching (memory applications)

Water splitting (nano energy)

Applied superconductivity

Experimental Realization of a Magnetic Cloak

Fedor Gömöry,[1] Mykola Solovyov,[1] Ján Šouc,[1] Carles Navau,[2] Jordi Prat-Camps,[2] Alvaro Sanchez[2]*

23 MARCH 2012 VOL 335 **SCIENCE** www.sciencemag.org

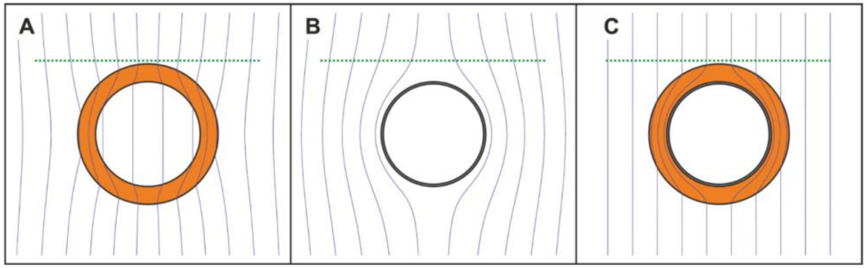


Fig. 1. Calculated field lines for (**A**) a single cylindrical magnetic shell with $\mu = 3.54$, attracting fields and having some field penetration in its interior; (**B**) a single cylindrical superconducting shell with $\mu = 0$ repelling field lines; and (**C**) a cylindrical bilayer with an inner superconducting layer ($\mu = 0$) of interior (exterior) radius of $R_0 = 0.96\ R_1$ (R_1) and an outer magnetic layer with $R_2/R_1 = 1.34$ with $\mu_2 = 3.54$, fulfilling Eq. 1. These values are chosen to approximate those used in the experiments. Green dotted lines denote the measuring lines in the experiments.

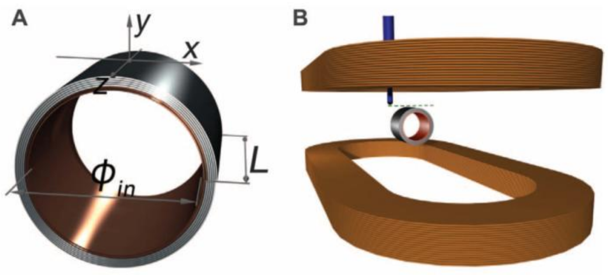


Fig. 2. (**A**) Scheme of the experimental magnetic cloak consisting of two shells: The inner one (brown) is made of several turns of superconducting tape, and several turns of tape with ferromagnetic properties create the outer shell (gray). In our case, length L = 12 mm and diameter ϕ_{in} = 12.5 mm. Preparation of such structure requires a cylindrical former (not shown in the image). (**B**) Experimental setup for mapping the magnetic field in the vicinity of the magnetic cloak. The magnetic field is generated by a pair of race-track coils wound from Cu wire (brown). The Hall probe is mounted on the bottom of the holder rod (blue).

Superconductivity

may be the only technology able to achieve a radical reduction of the head mass

Light MgB_2

MgB_2 is a **light and cheap** material formable into **filamentary wires,** which is commercially available in **long-lengths** (..km).

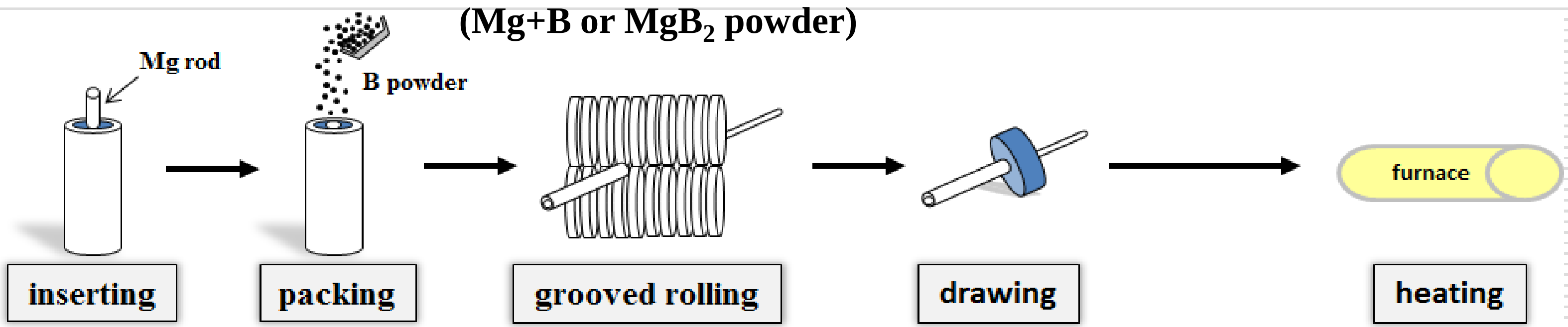
Needs for application for Energy:

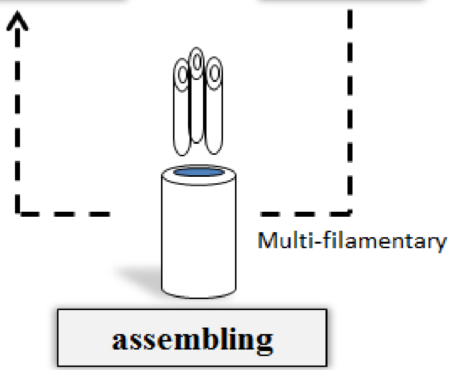
High **engineering current densities** (in **low magnetic fields**)

Light and **stable** MgB_2 conductors

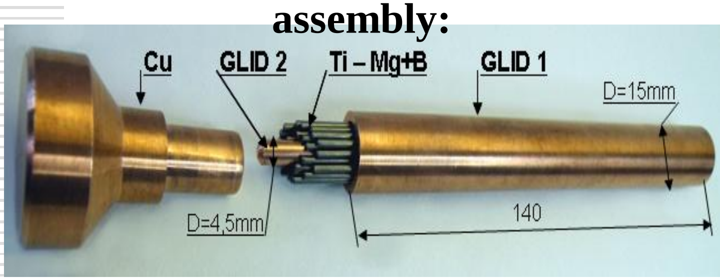
MgB_2 cables – current **up scaling**, bending **degradation**

AC losses – twisting, cabling





Example of our multi-core billet assembly:

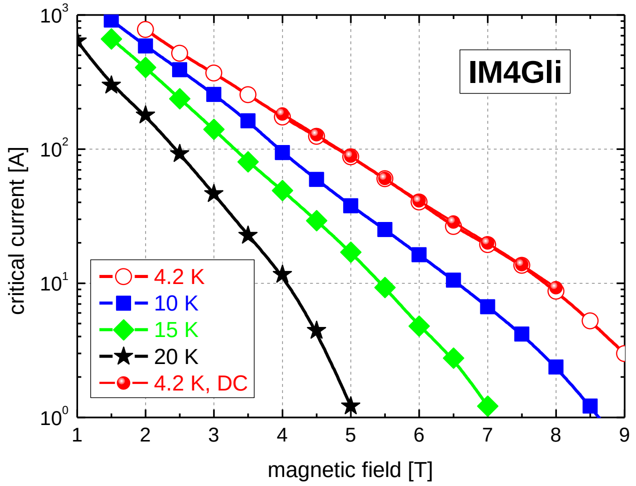


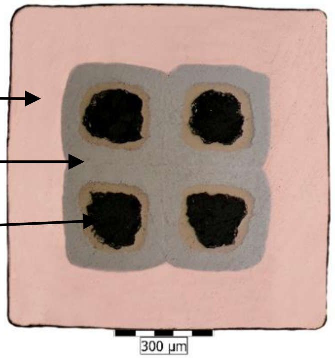
Final heat treatment:
640-850°C/0.5-1h
MgB_2 phase creation

HE **D** **RS** **FR** **TAR**

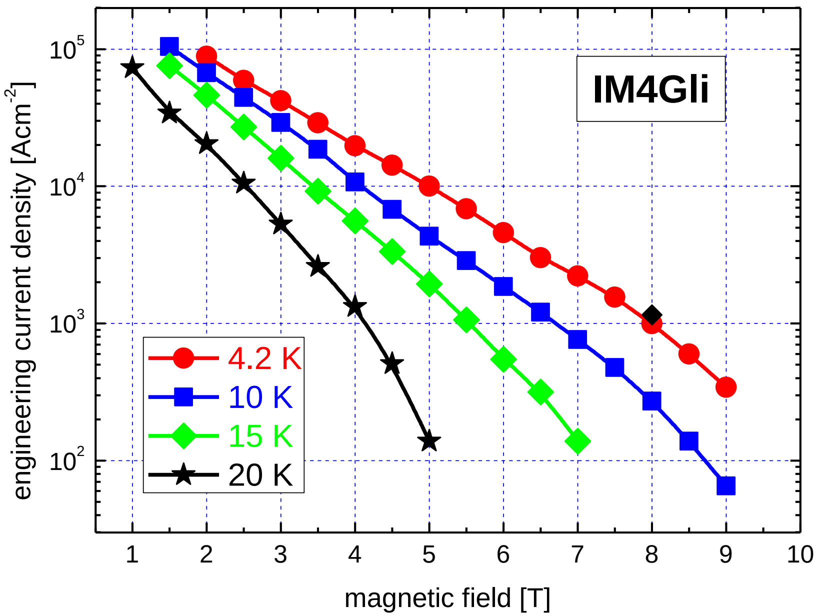
Extrusion (**HE**), Drawing (**D**), Rotary swaging (**RS**), Rolling: flat- (**FR**), groove- (**GR**) or two-axial

I_c measured by pulse currents:





Deformed by HE + TAR



Application limit

$J_e \geq 10^4$ Acm^{-2}

10^4 Acm^{-2} < 2.5 T for 20 K

10^4 Acm^{-2} < 5.0 T for 4.2 K

Increase of the cooperation with China research institutions is highly desirable

Thank you for your attention