Scaling Effects on Ferro-Electrics: Application in Nanoelectronics and Characterization

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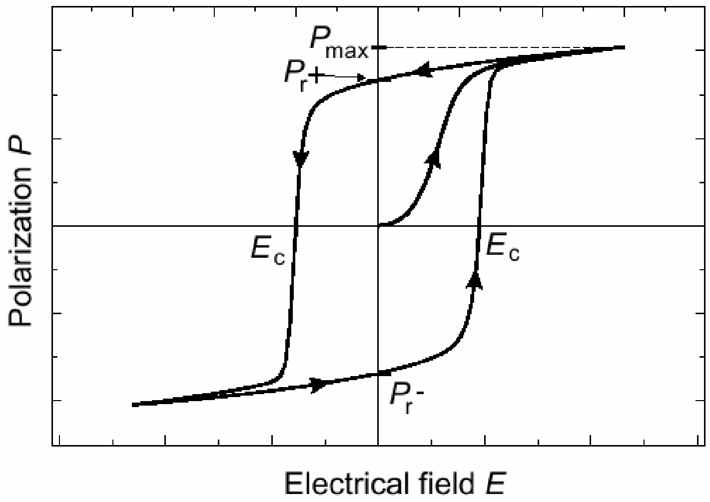
Introduction: ferroelectricity

Ferroelectrics: dielectrics crystals which a spontaneous electric polarization due to atomic deplacement in the crystal structure

The direction of polarization can be reoriented by an external electricl field:

=> domains where the spontaneous polarization is parallel

=> hysteresis loops



Direction polarization can be used to store information: memories

Bit 0: Pr-

Bit 1: Pr+

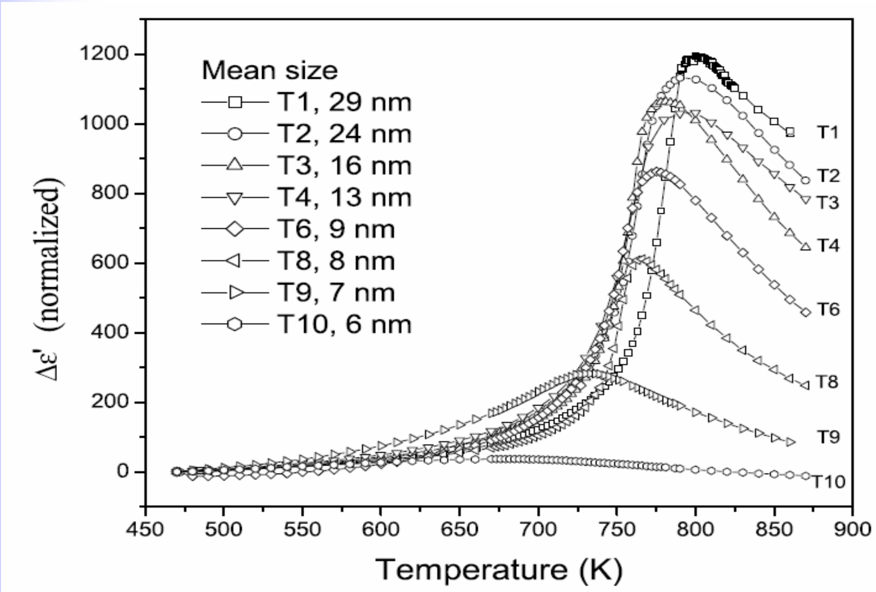
2 atomic stable positions in the crystal field

=> Non volatile data storage device

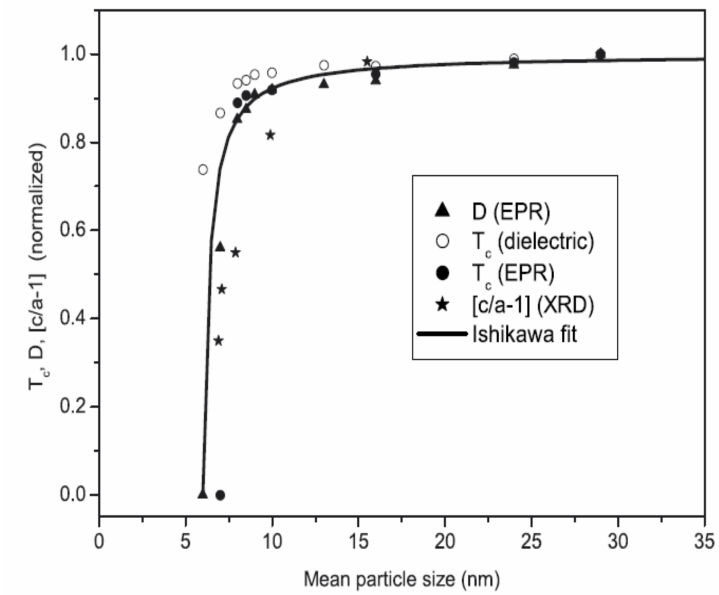
Nano-ferroelectric: properties

At nano-scale, strong influence of the surface energy, depolarization field, etc.

=> Modification of polarization, dielectric constant, Curie temperature, etc.



E. Erdem et al.,
J. Phys.: Condens. Matter **18,** 3861 (2006)



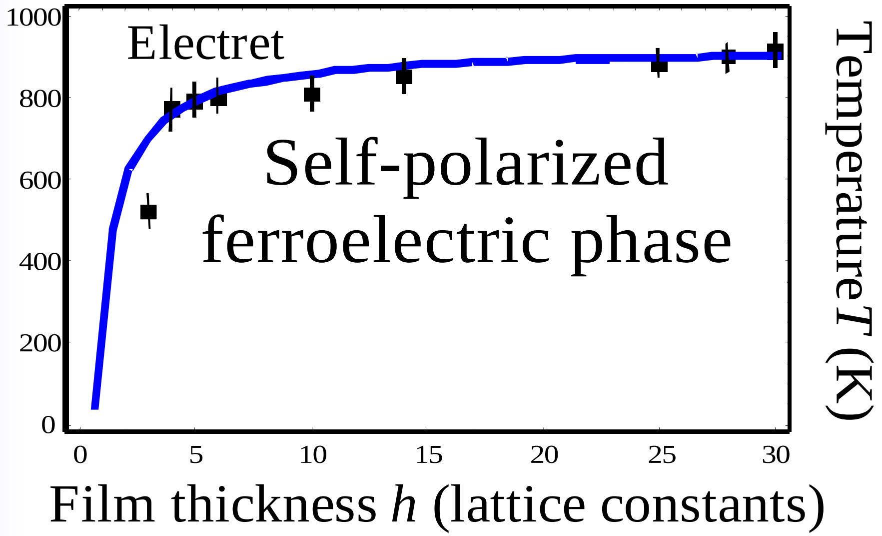
What is the critical thickness to observe ferroelectricity in thin films?

Nano-ferroelectric: still ferroelectric?

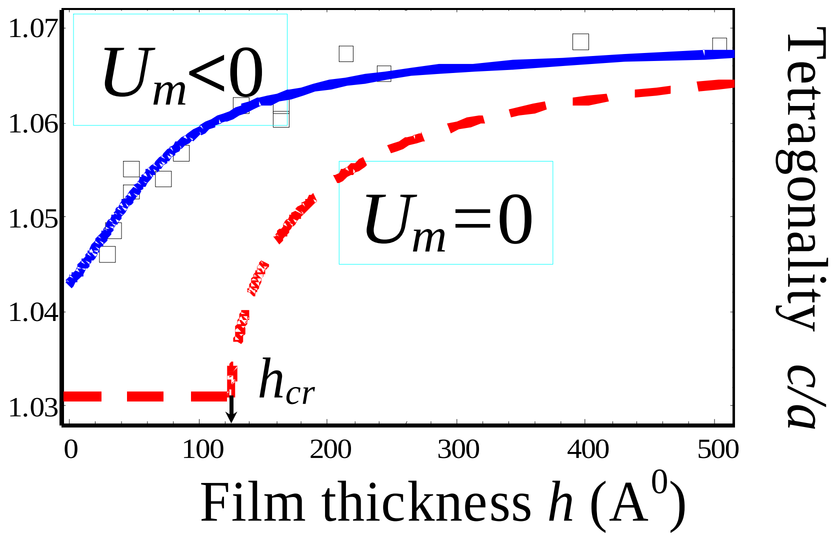
Deformation of the film due to mismatch between the parameters of the film and substrate $U_m = (b - a)/b$ (a, b are their lattice constants) induce built-in electric field.

=> This field lead to electret state in thinner film.

$PbTiO_3$ film on $SrTiO_3$ substrate



$PbTiO_3$ film on $SrTiO_3$: Nb substrate



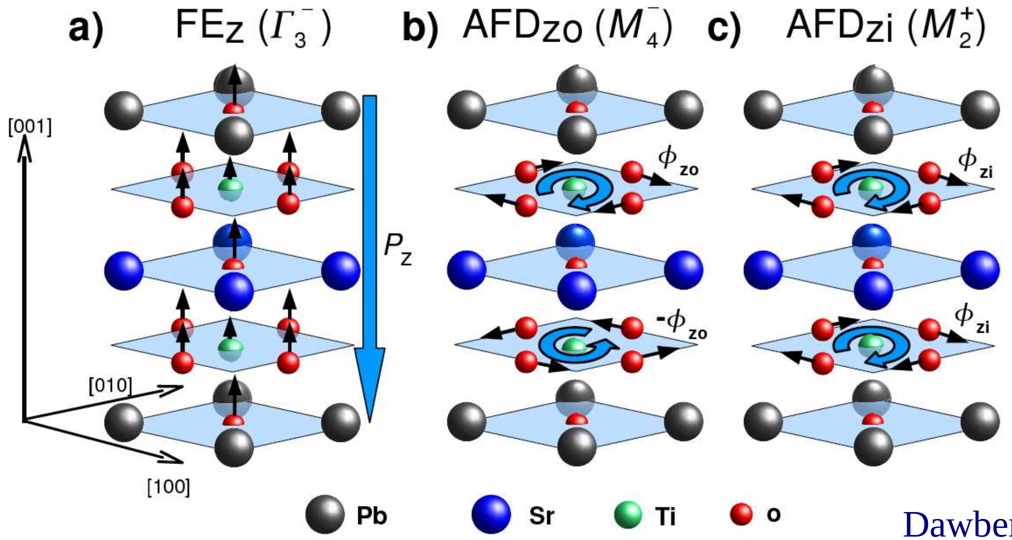
Glinchuk M.D., Morozovska A.N., Eliseev E.A., J. Appl. Phys. **99**, 114102 (2006)

Triscone's group (Geneva): measurement of ferroelectricity down to 2.4 nm (PZT film) at room temperature.

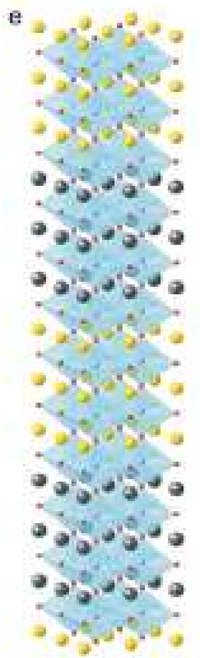
Nano-ferroelectric: new properties

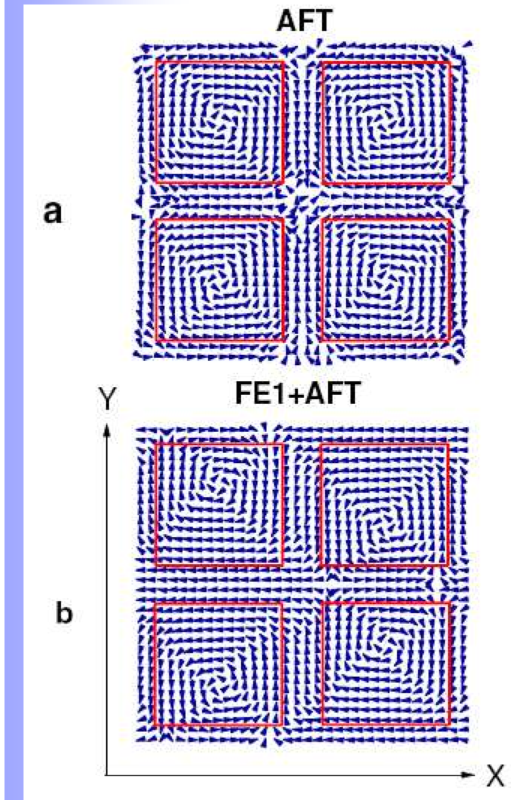
However new properties absent in bulk materials appear in nano-ferroelectrics.

Superlattices of $SrTiO_3$ and $PbTiO_3$ => Unusual polarization behaviour, modification of T_c...



Dawber, PRL 95 (2005)





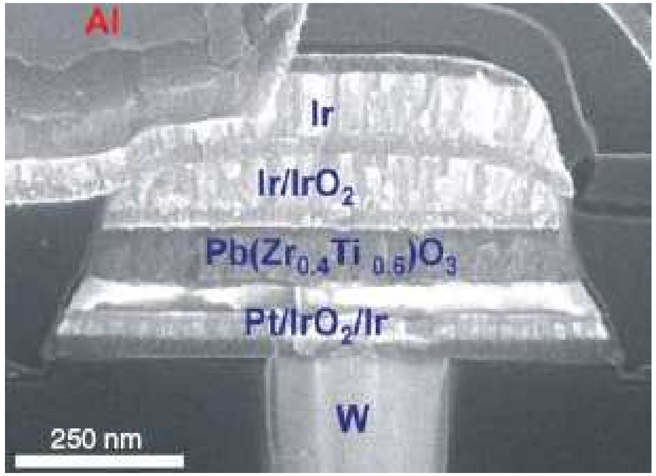
Recent effort to predict properties of nano-ferroelectrics using *ab initio* models
Groups of Vanderbilt, Resta, Krakauer, etc.

Polarization vortex in ferroelectric ABO_3 dots by Virtual Crystal Approximation (VCA)
Bellaiche, PRL 97 (2006)

Ferroelectric Radoom Access Memories: similar to DRAM but with a ferroelectric layer instead of a dielectric layer

Non volatile memories: data storage through the remnant polarization

Commercial production already at 350 nm (Fujitsu) and 130 nm (Texas Instrument)



32 Mb SAMSUNG FeRAM

	SRAM*1	DRAM*2	EEPROM*3	FLASH*4	FRAM*5
Memory type	Volatile back-up	Volatile	Non-volatile	Non-volatile	Non-volatile
Cell structure	6T	1T/1C	2T	1T	1T/1C 2T/2C
Read cycle (ns)	12	70	200	70	110
Internal write voltage (V)	3.3	3.3	20 (supply voltage 3.3V)	12 (supply voltage 3.3V)	3.3
Write cycle	12ns	70ns	3ms	1 sec.	110ns
Data write	Overwrite	Overwrite	Erase + Write	Erase + Write	Overwrite
Data erase	Unnecessary	Unnecessary	Byte (64 byte page)	Sector (8K/16K/32K/64K)	Unnecessary
Endurance	∞	∞	1E5	1E5	1E10 to 1E12
Stand-by current (μA)	7	1,000	20	5	5
Read operation current (mA)	40	80	5	12	4
Write operation current (mA)	40	80	8	35	4

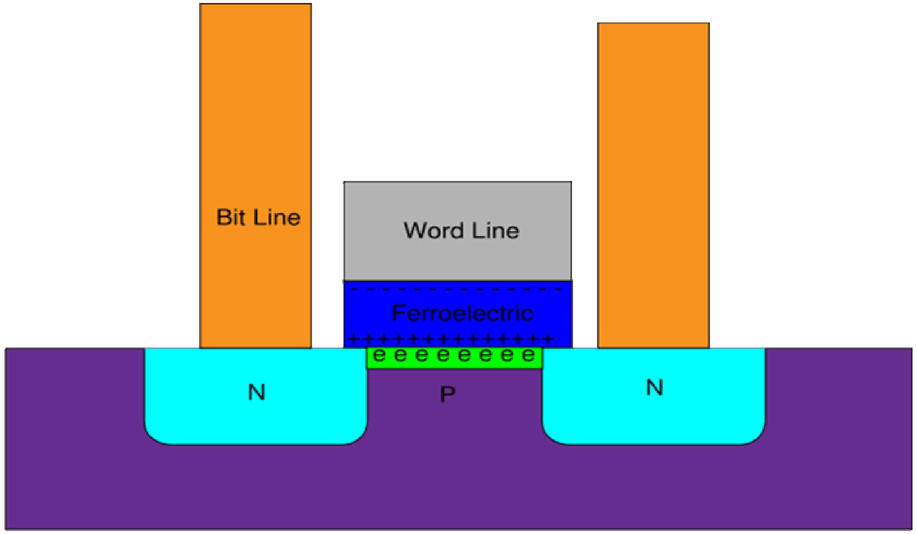
Notes: *1: 512K × 8bit *2: 2M × 8bit *3: 8K × 8bit *4: 1M × 8bit *5: 8K × 8bit

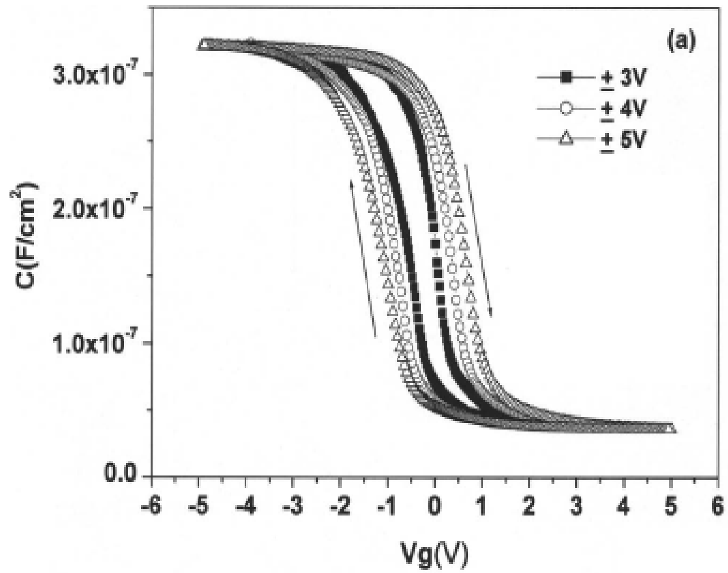
Same functionnality as Flash Memories but:

Lower power usage
Faster write performance
Greater maximum of cycles

Nano-ferro devices: FeFET

Ferroelectric Field Effect Transistor: similar to MOSFET, the gate oxide is a ferroelectric





Depending on remnant polarization, electrons are depleted or accumulated

Non volatile memories

Decrease of **stand-by loss** (« vampire power »)

Only few perovskite oxides (big class of ferroelectric materials) are suitable for growth on silicon

Nano-fabrication: Top-down

From 2D film to 1D dots:

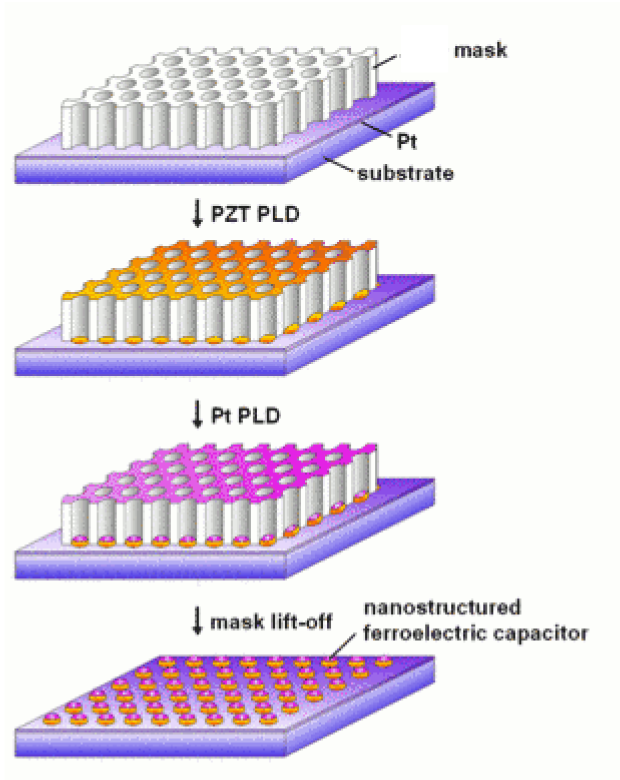
Focused Ion Beam etching, e-beam lithography, imprint

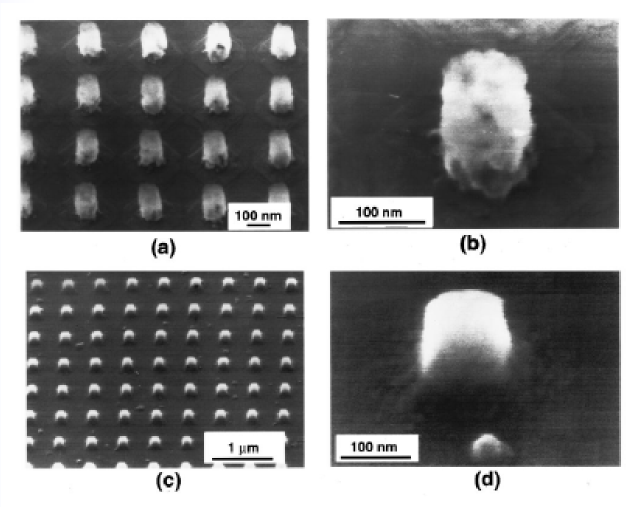
High-precision positioning

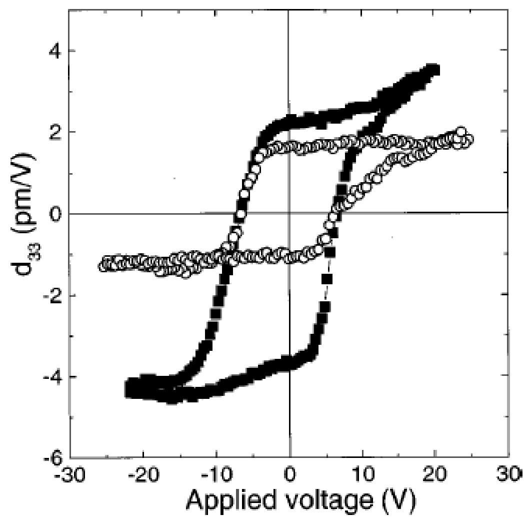
Size control but limited in resolution

Damage the nano-structures (layer ~10 nm)

Time-consuming







M. Alexe, Appl. Phys. Lett. 75, 1999

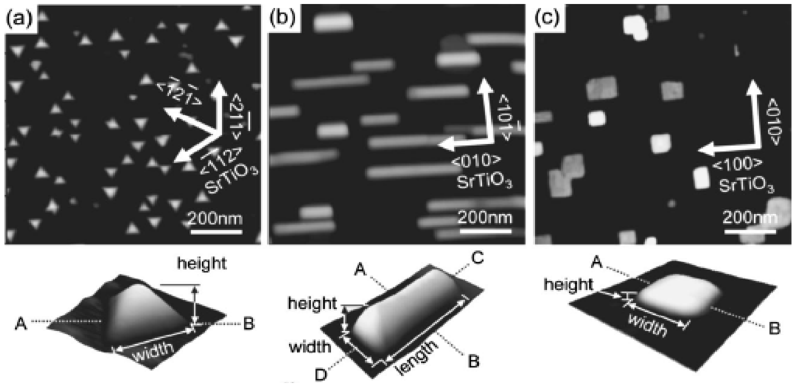
Self-assembled process:

Formation of arrays of ferroelectric nano-crystals on a substrate

As for semi-conductor quantum dots growth, balance between interface, substrate and film energies

Avoid the processing damage during FIB patterning

Smaller dimensions structures than those obtained with top-down processes



PbTiO$_3$ grown on SrTiO$_3$ with different crystalline orientations

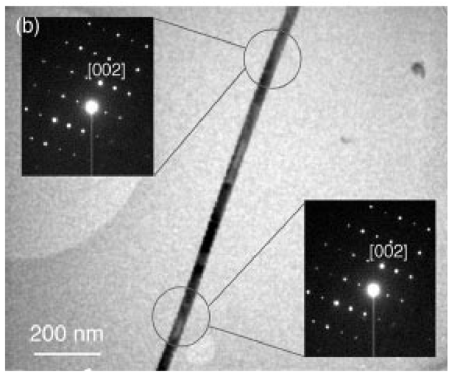
Nomura, Appl. Phys. Lett. 86, 2005

Nano-wires fabrication:

Hydro-thermal decomposition of bimetallic precursor

Well-isolated single-crystalline BaTiO$_3$ rods with diameters from 5 to 60 nm and several µm-long

Park, Adv. Mat. 15, 2003



Nanoscale characterization: AFM

The AFM as a tool for electric characterization at the nanoscale :

A conductive tip can => **a nanometric electrode**

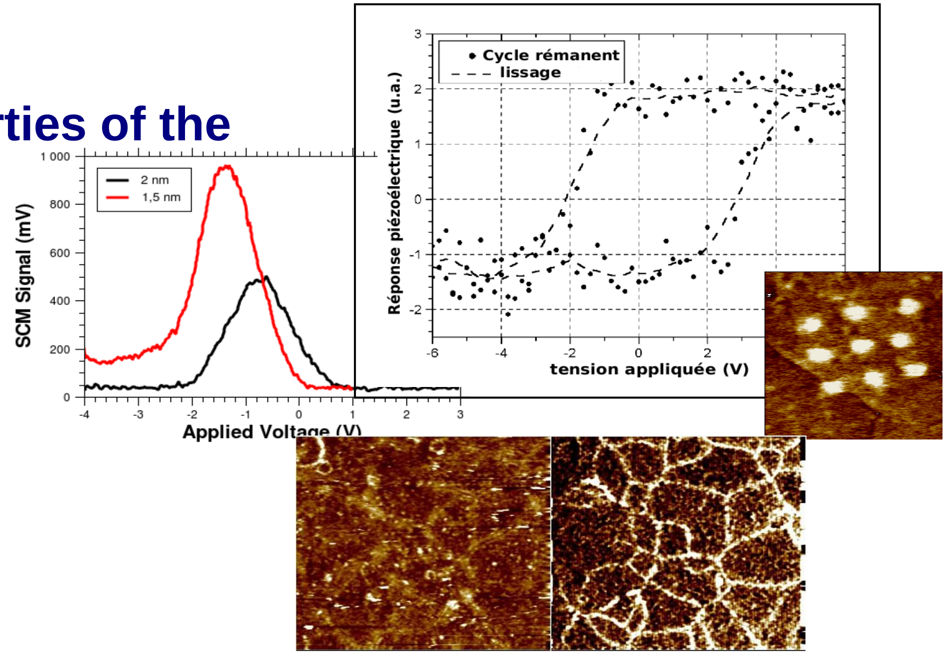
Piezoelectric motion controller => **positioning** with a nanometric resolution

Examples :

- Electric Force Microscopy (**EFM** : electric field)
- Kelvin Force Microscopy (**KFM** : potential)

Characterization of the electrical properties of the dielectrics and ferroelectrics:

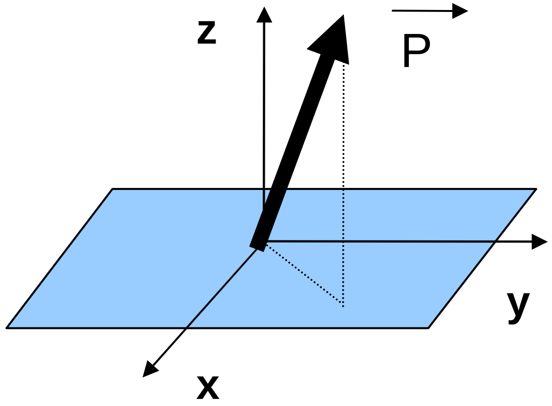
- **Current measurements**
- **Capacitive measurements**
- **Piezoelectric measurements**



Piezoresponse Force Microscopy

Numerous size effects are expected in ferroelectrics materials :

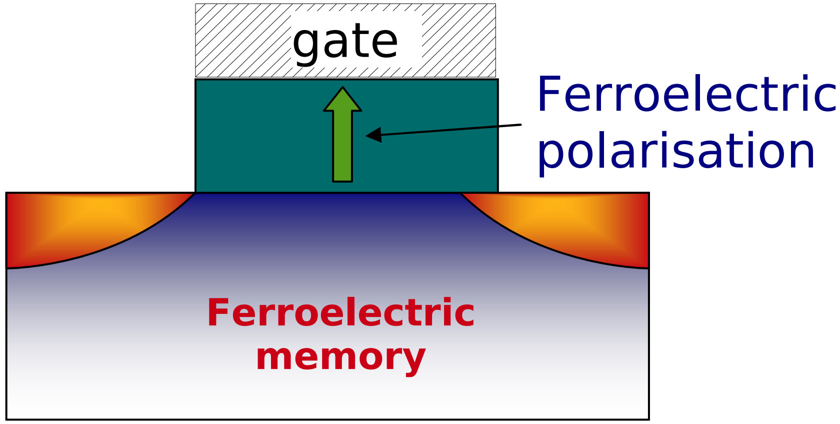
- Coercive voltages
- Remnant polarisation
- Dielectric constant
- Smallest domain size ?
- Smallest thickness allowing ferroelectricity ?
- Piezoelectric constants



Must be measured at the nanoscale

The reduction of the size of devices using ferroelectric layers is a challenging problem for characterization

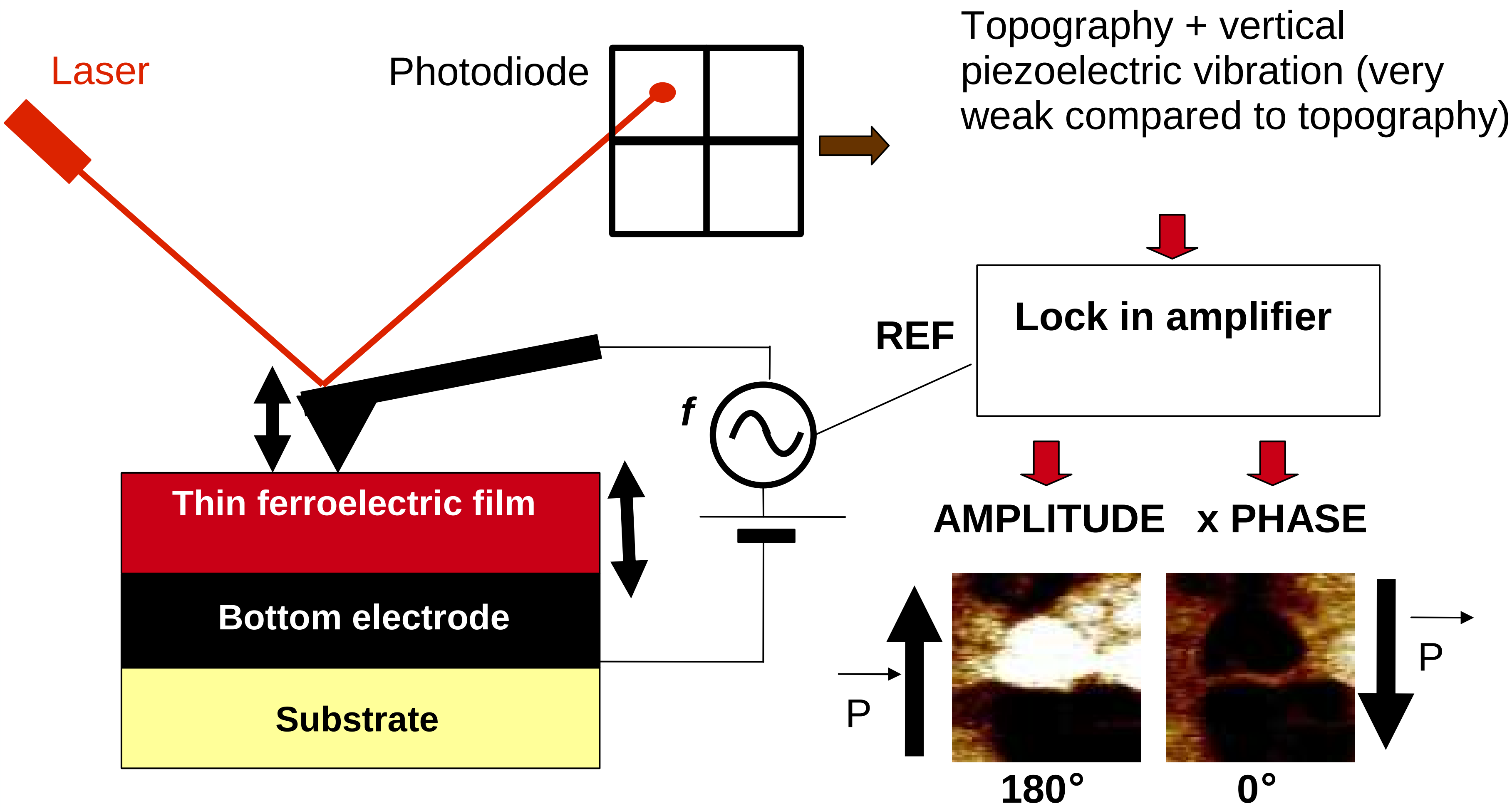
Characterization provides crucial feed back to growers



PFM: principle

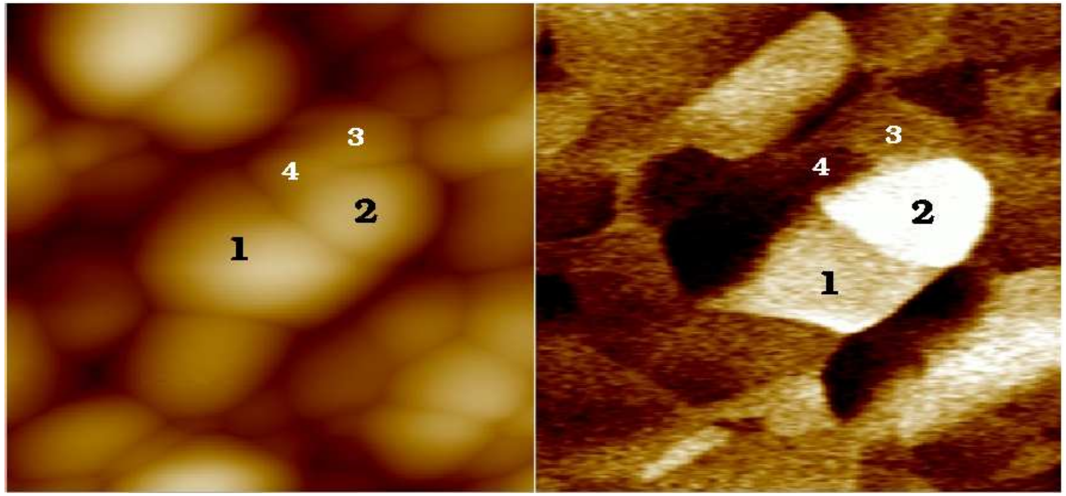
Inverse piezoelectric effect => vibration of the surface due to the application of an alternating voltage.

All ferroelectrics are piezoelectric



Antiparallel domains vibrate with an opposite phase

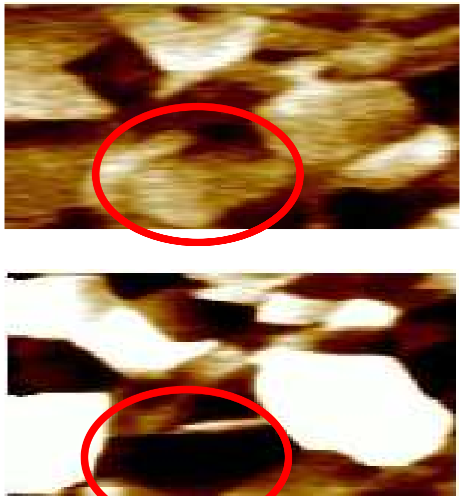
Quasi 3-D mapping of domains



Mapping of ferroelectric domains (component **perpendicular** to the surface) in **$LiNbO_3$.** The spatial resolution is nanometric.

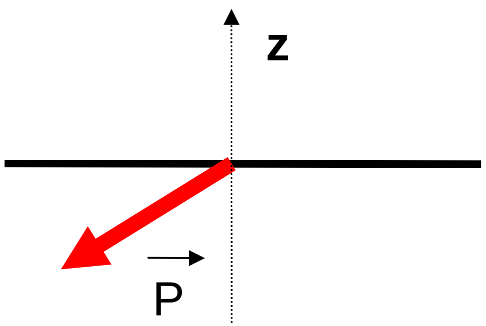
B. Gautier, V. Bornand, Thin Solid Films 515(4-5):1592, 2006

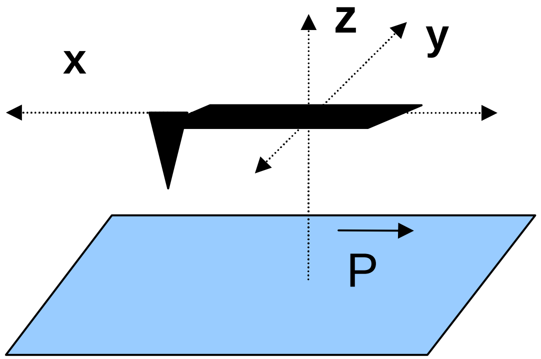
out of-plane



in-plane

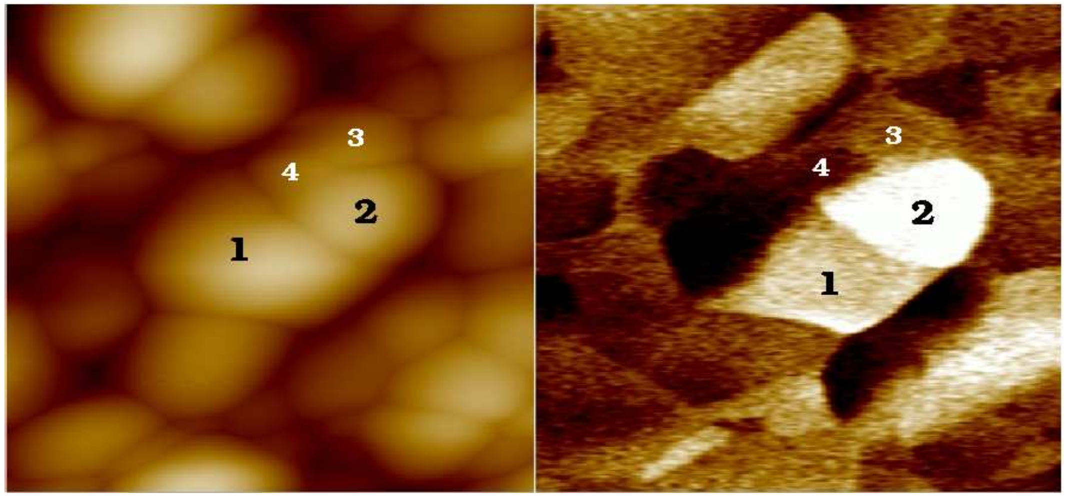
The **in-plane** component in the y-direction is also accessible





The in-plane component parallel to the cantilever (x direction) remains inaccessible

Quasi 3-D mapping of domains



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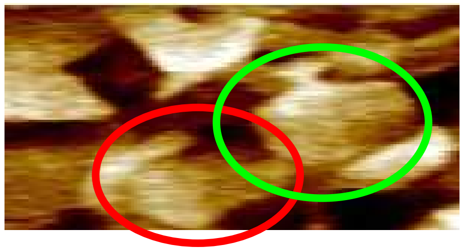
out of-plane



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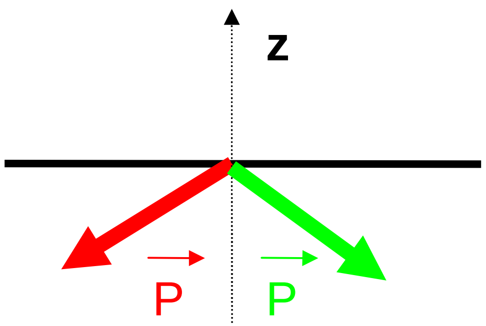
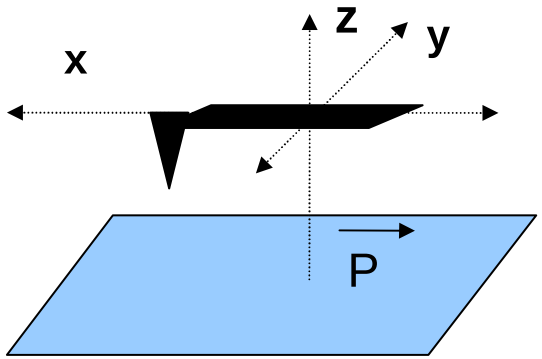
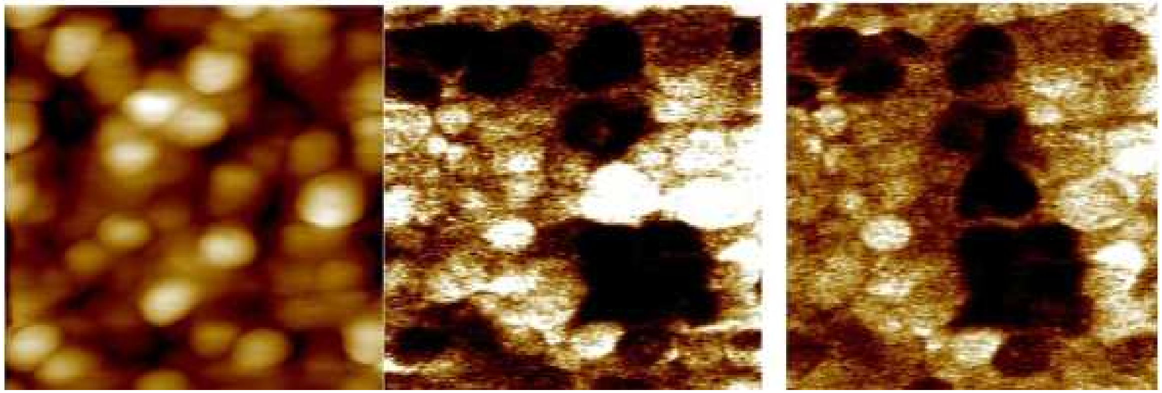




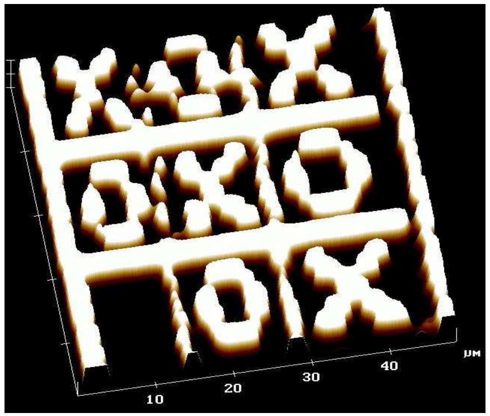
The in-plane component parallel to the cantilever (x direction) remains inaccessible

Creation of domains



Local switching
of the polarisation by applying a sufficient voltage between the tip and the sample (here □10 V)

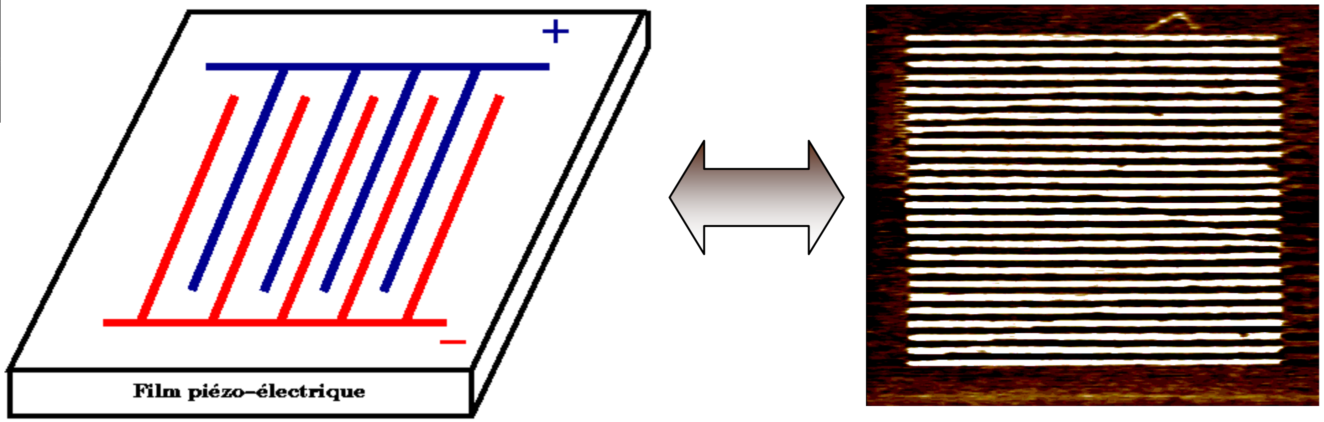
C. Thiebaud, D. Charraut, B. Gautier, J.C. Labrune, Ann. Chim. ScL Mat, 26:145 (2001)



Creation of any polarisation pattern
Applications for the Surface Acoustic Waves Devices (SAW)
=> replacement of the top electrodes

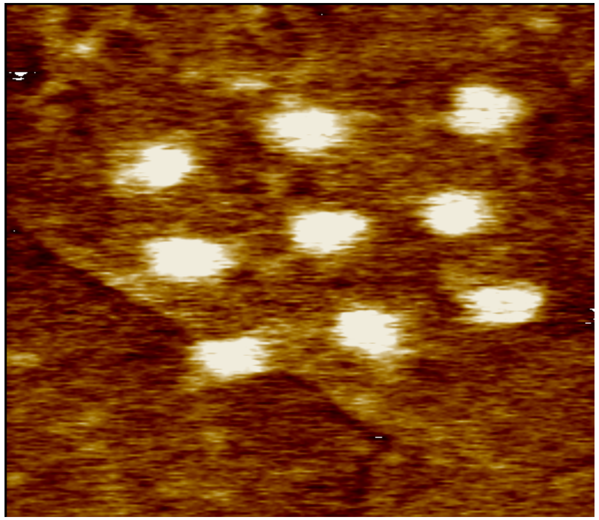
$$f \sim \frac{V_R}{T}$$

=> 20 Ghz
T= 200 nm

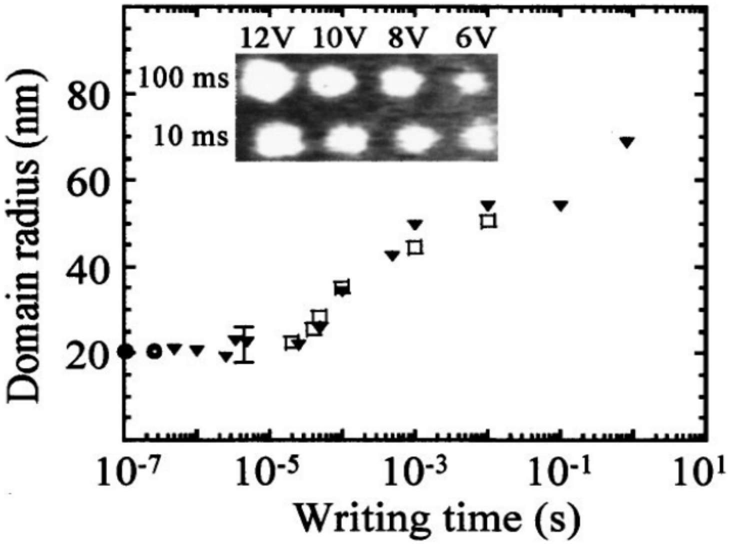


S. Ballandras, B. Gautier, D. Hauden and J.-C. Labrune.
Patent USA – Canada - Europe 0009246, 2001.

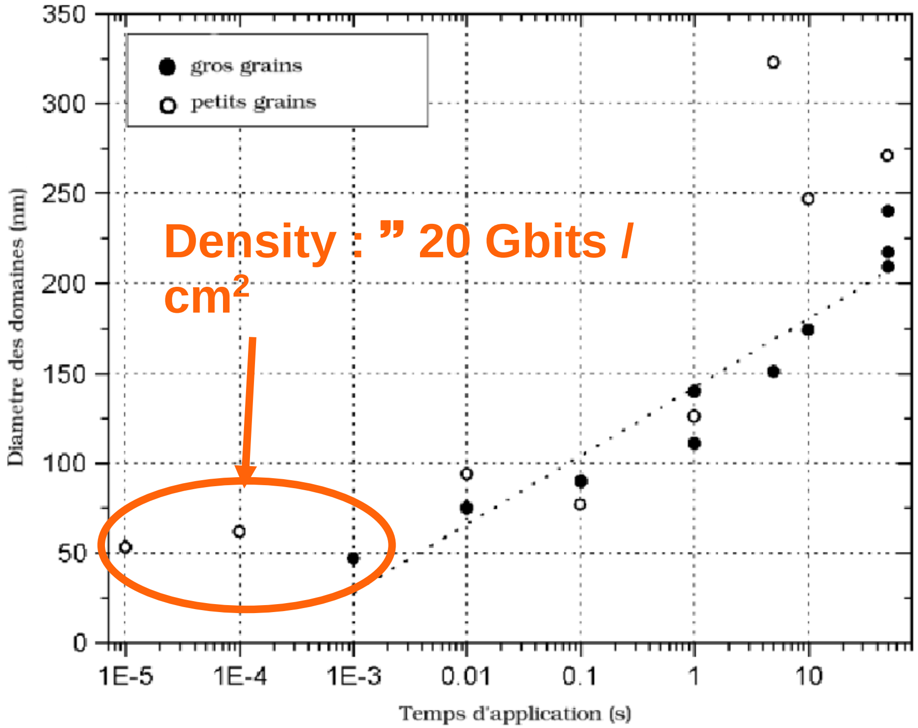
Applications for ferroelectric memories



Microstructure of the film, voltage amplitude, duration, geometry... influence the final size of the domain => density of integration of the final device



P. Paruch et al. Appl. Phys. Lett., Vol. 79, No. 4, 23 (2001)

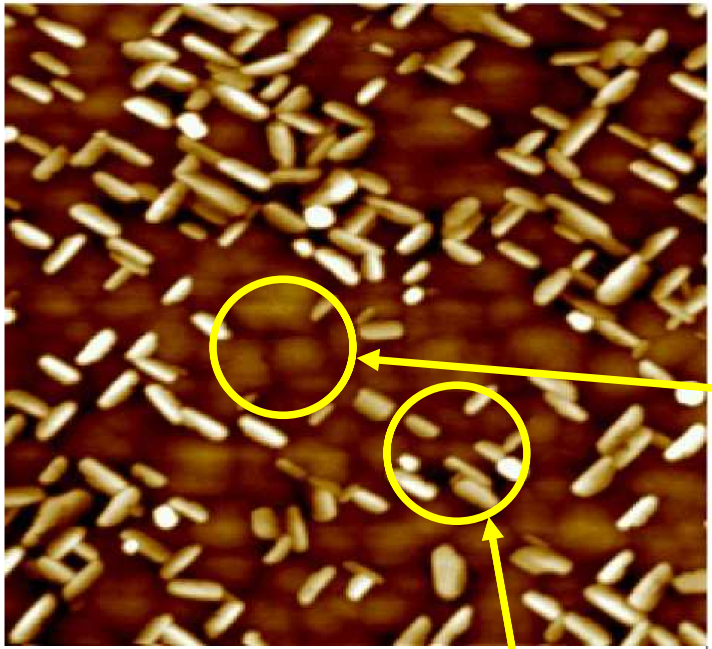


Evolution of the domain size with the duration of the voltage pulse

B. Gautier, C. Soyer, E. Cattan, D. Remiens and J.-C. Labrune Integrated Ferroelectrics 269:219, 2002

Hysteresis loops

PFM allows to test a very small area of the film with **piezoelectric** hysteresis loops => test of the ferroelectric **nature** of the film

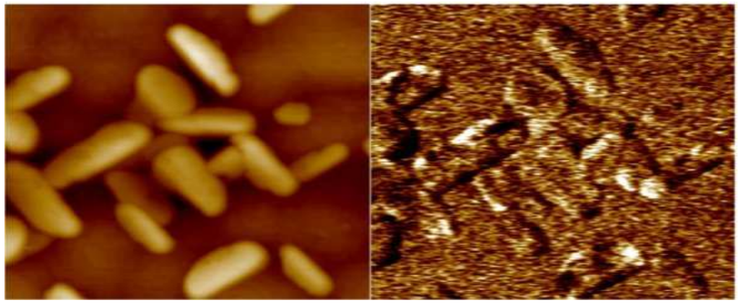


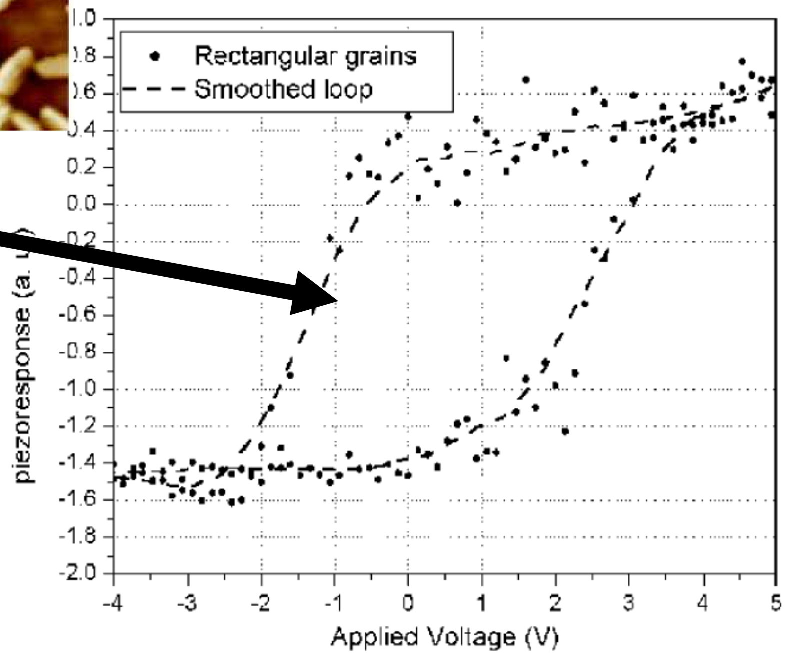
3 microns

<001> Direction

<115> Direction

Local piezoelectric hysteresis loops (here on a $SrBi_2Nb_2O_9$ thin film), **only** on the <115> regions of the film



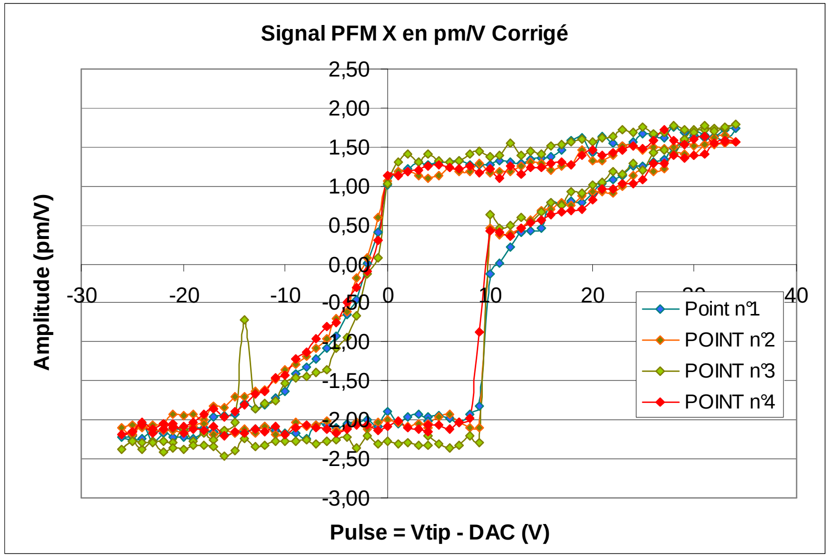


B. Gautier, Jean-Rene Duclere, and Marylin Guilloux-Viry Appl. Surf. Sci. 217:107, 2003
J.-R. Duclère, **,** M. Guilloux-Viry, A. Perrin, and B. Gautier:, Ann. Phys. 13(1-2):35, 2004

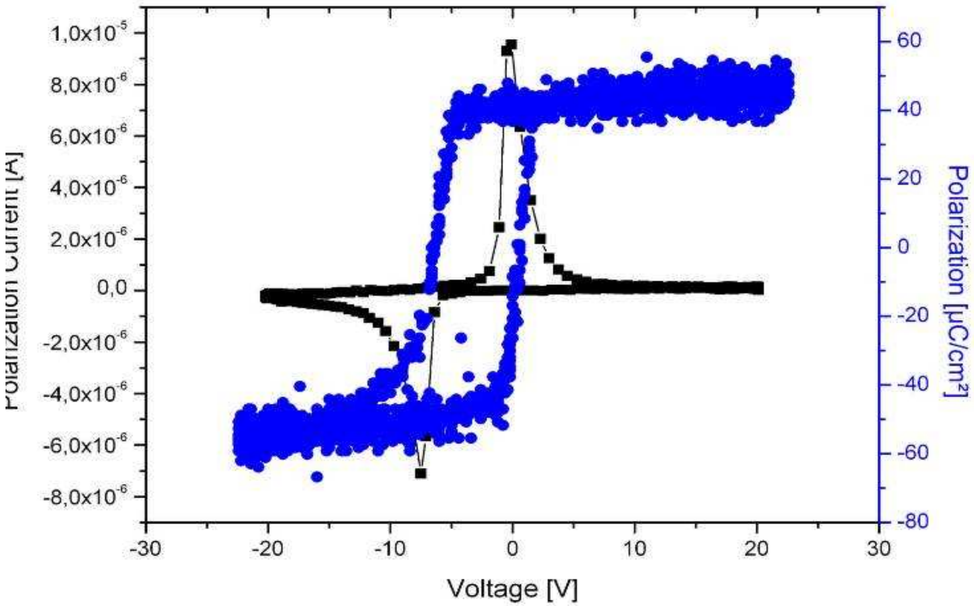
Comparison macro – nano characterization

Ferroelectric memories : orientation must be perpendicular to the surface = > Smart-Cut™ technology.

One explanation for the back-switching of the domains : **imprint**



Hysteresis loops performed by PFM : a strong imprint is recorded (shift of the loop toward positive voltages). Courtesy A. Brugère.

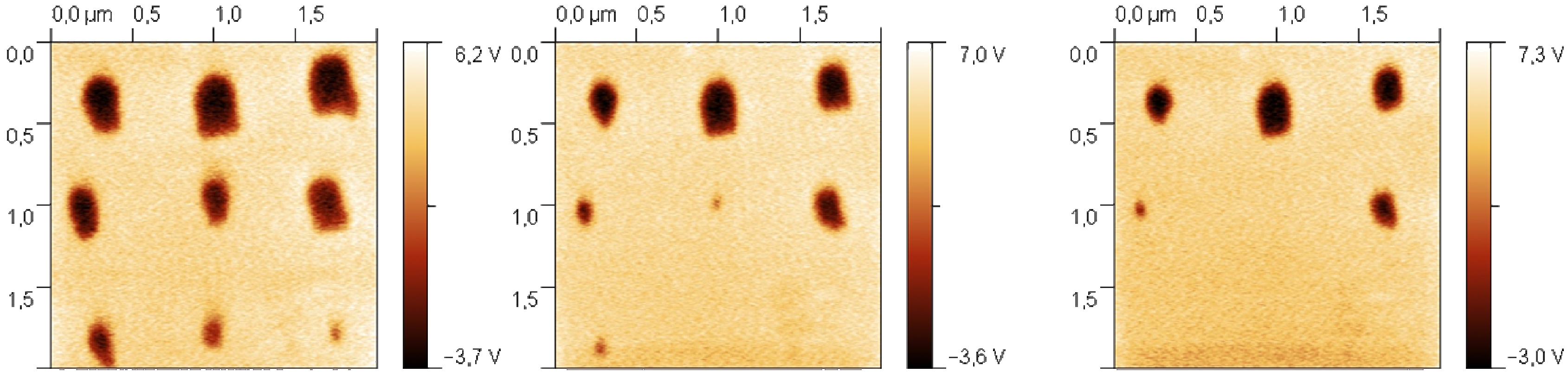


Hysteresis loops performed by a Sawyer-Tower circuit (polarisation and current) : the same imprint is found (voltage applied on the sample and not on the tip as for PFM). Courtesy J.S. Moulet.

=> Reliable information provided by the PFM mode

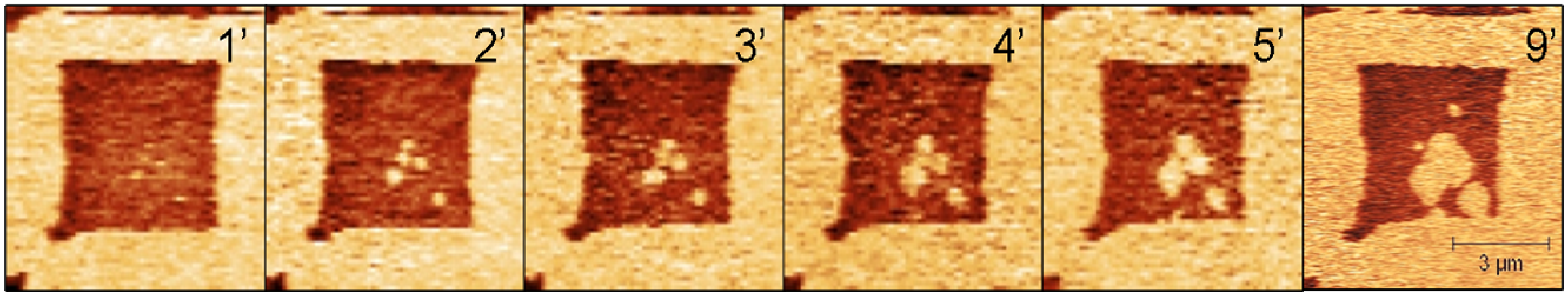
Dynamic behaviour of domains

Example of $LiTaO_3$ (LTO)



5 V offset is applied during PFM measure-ments

Images : A. Brugère, CEA



Domains written with voltage pulses of different amplitude and duration in a thin film (e~120 nm) of $LiTaO_3$ (LTO) obtained by Smart-Cut™ (sample from SOITEC, Grenoble) : depending on their size, the domains flip back to a preferential state. Below : domains flip back even after uniform polarisation of a large area. The flip back phenomenon seems to start from « seeds »

=> application to the fatigue of ferroelectric layers

Conclusions

Nano-ferroelectrics high density memories are of major interest

It leads to challenging understanding and simulation of the properties of such materials at nanoscale

Piezoresponse Force Microscopy (PFM) is a very powerful tool to investigate the ferroelectric and piezoelectric nature of thin films and monocrystals at the nanoscale.

It allows to probe the **dynamic behaviour** of ferroelectric domains => e.g. fatigue phenomena at the nanoscale

PFM is in some cases the only way to probe the ferroelectric nature of a surface (heterogeneous surfaces, nanostructures...).

The **same apparatus** is used to read and write ferroelectric domains – any polarisation pattern can be written with a resolution of several tens of nanometers.

Thanks to:

Antoine BRUGERE (CEA, Grenoble), Serge GIDON (CEA, Grenoble) Jean-Sébastien MOULET (LTFC-SOITEC, Grenoble), Emmanuel DEFAY (CEA/LETI, Grenoble), Veronique BORNAND (Univ. Montpellier 2), J.R. Duclère (Univ. Limoges), Jean-Luc MAURICE (Thalès, Palaiseau), Gang NIU (INL, Lyon), Octavian LIGOR (INL, Lyon), Wael HOURANI (INL, Lyon), Guillaume SAINT-GIRONS (INL, Lyon), Guy HOLLINGER (INL, Lyon)

Thank you for your attention