Simultaneous Measurement of the Piezoelectric, Dielectric and Resistive Current Response of Ferroelectric Capacitors by an AFM Approach

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Motivation

Non-volatile memory application of ferroelectric capacitors and ferroresisitve storage devices

A: Scaling

Characterization of nano-scaled ferroelectric capacitors
d_{33}, C, P vs. size

B: Ferroresistive storage devices

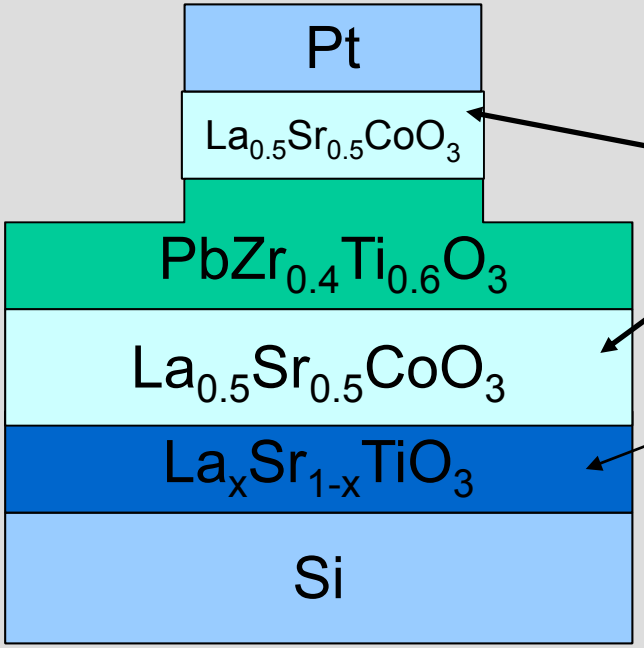
Resistive switching:
How to distinguish a ferroelectric origin from a non-ferroelectric one?

Sample Preparation

B. Liu *et al.*, APL **80**, 4801 (2002)

$PbZr_{0.4}Ti_{0.6}O_3$ epitaxial (001) oriented films were prepared by sol-gel deposition.

Capacitors were made by focused ion beam (FIB) milling having lateral sizes between 10 µm – 200 nm



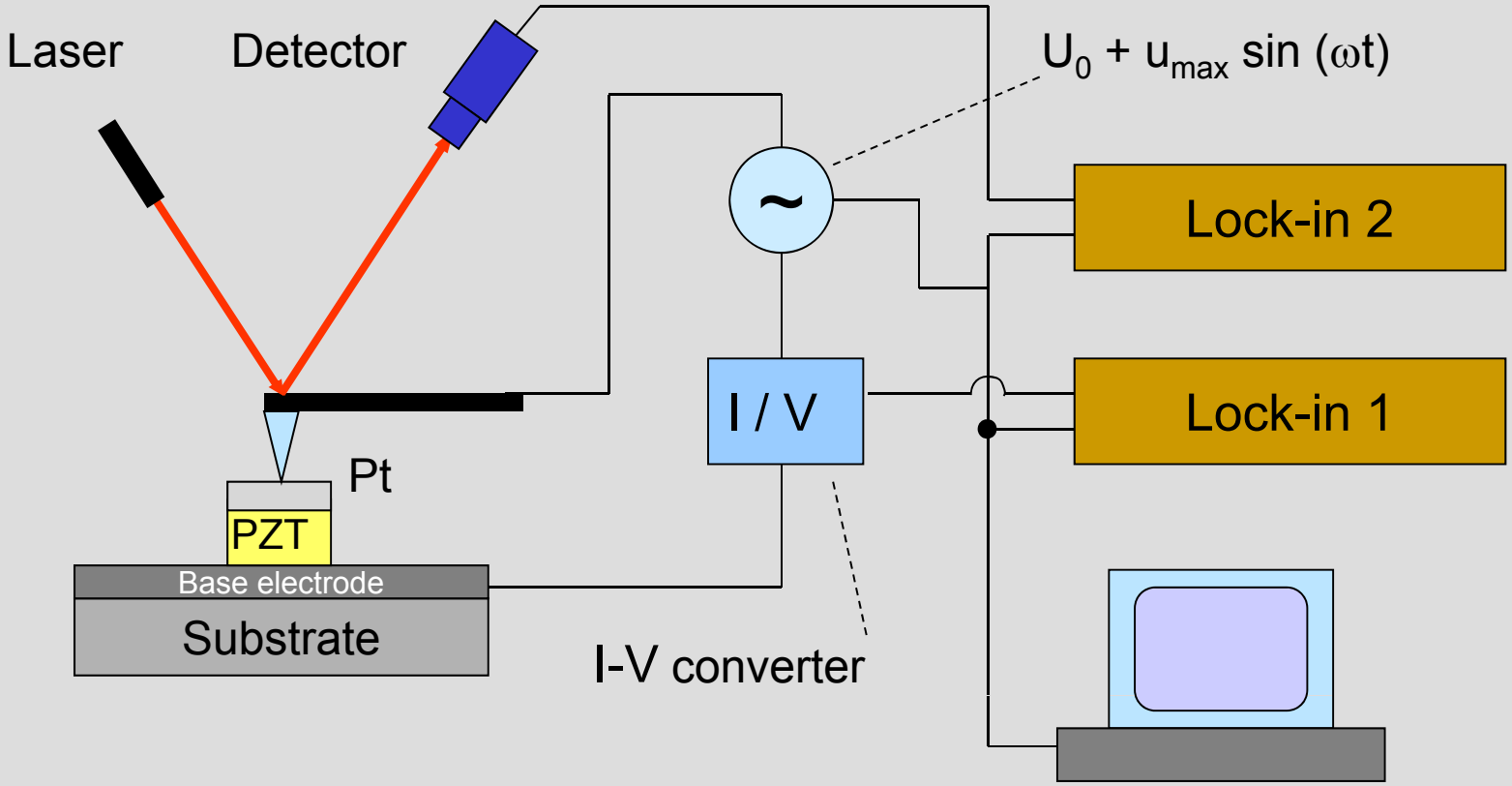
Top and base electrodes (PLD)

Epitaxial conductive template layer (MBE),

Darrell Schlom Penn State

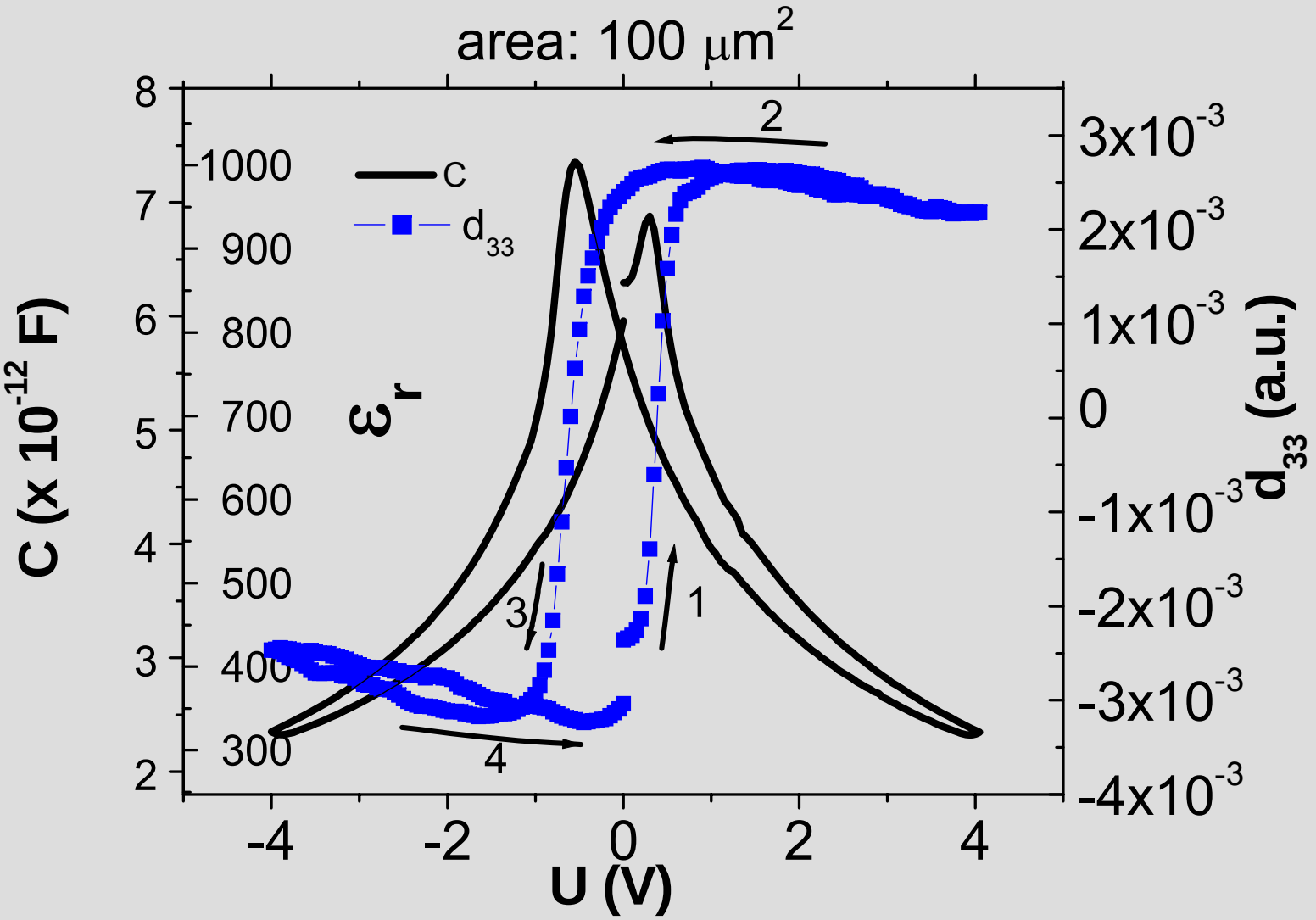
Simultaneous Measurement of different Properties

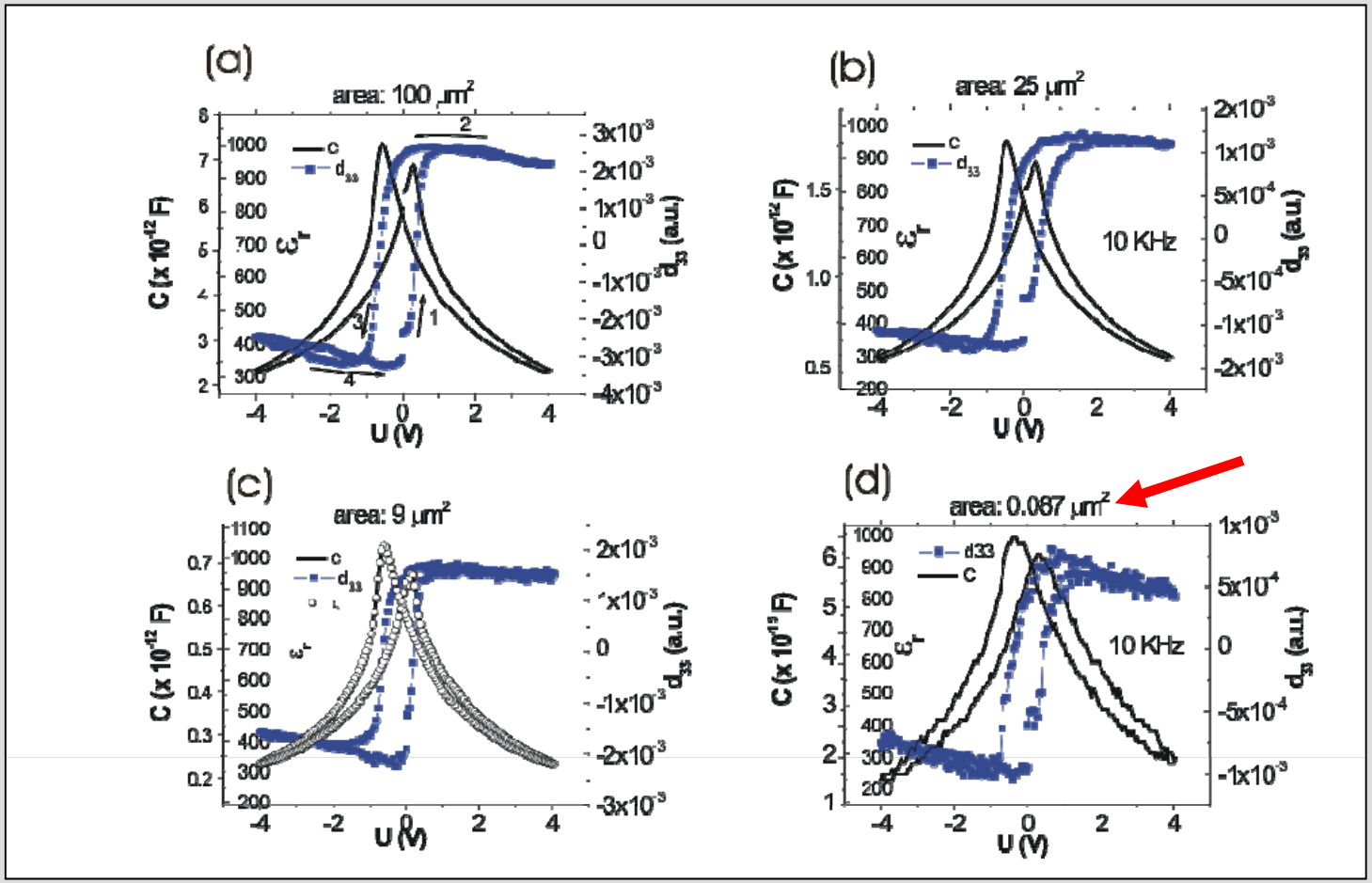
A. Petraru et al., to be published in Appl. Phys. A



To measure d_{33}, C and I (resistive) vs. bias voltage simultaneously

An Example: d33 and C vs. V

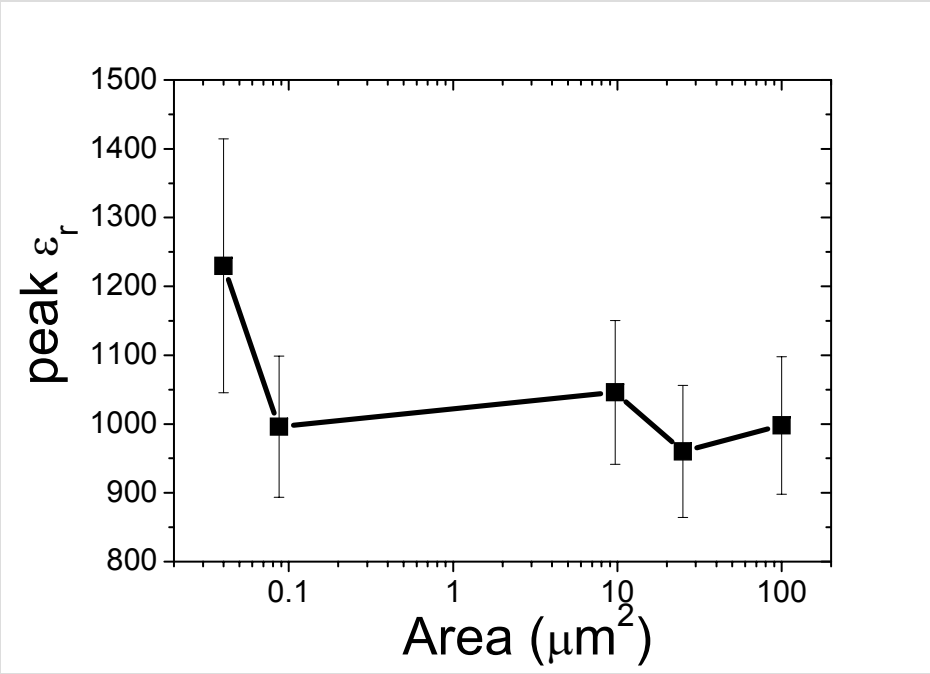




Jaehwan Oh and R. J. Nemanicha.
J.Appl. Phys. **92**, 3326, 2002.
Rui Shao, Sergei V. Kalinin, and Dawn A. Bonnell. *Appl. Phys. Lett.*, **82** 1869, 2003.
Ryan OHayre, Minhwan Lee, and Fritz B. Prinz
J.Appl. Phys. **95**, 8382, 2004.

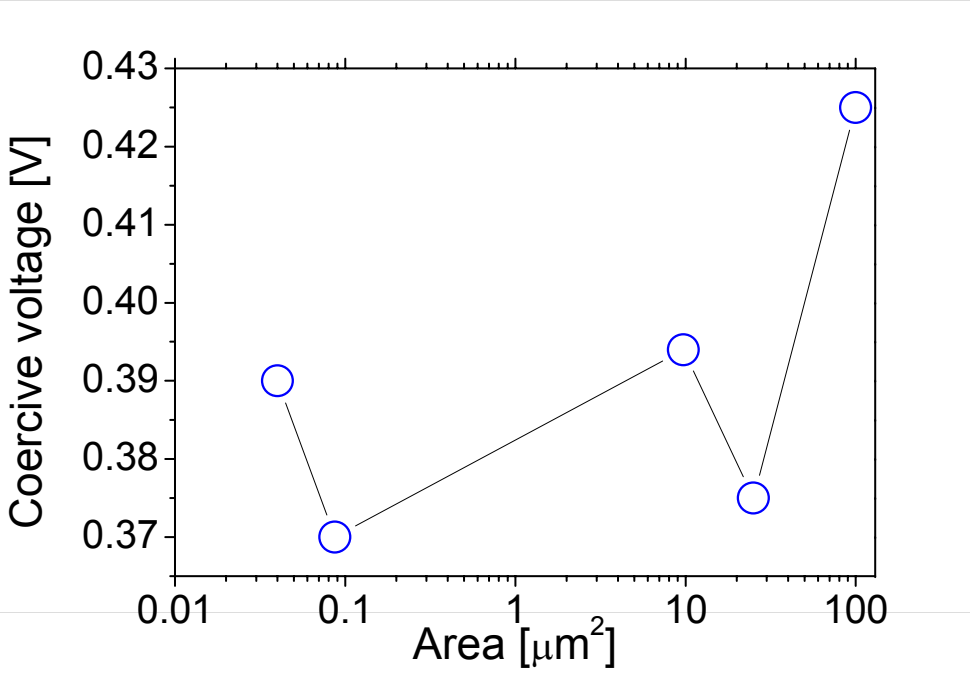
Area Dependence

Peak dielectric constant



No significant scaling of the dielectric constant.

Coercive voltage



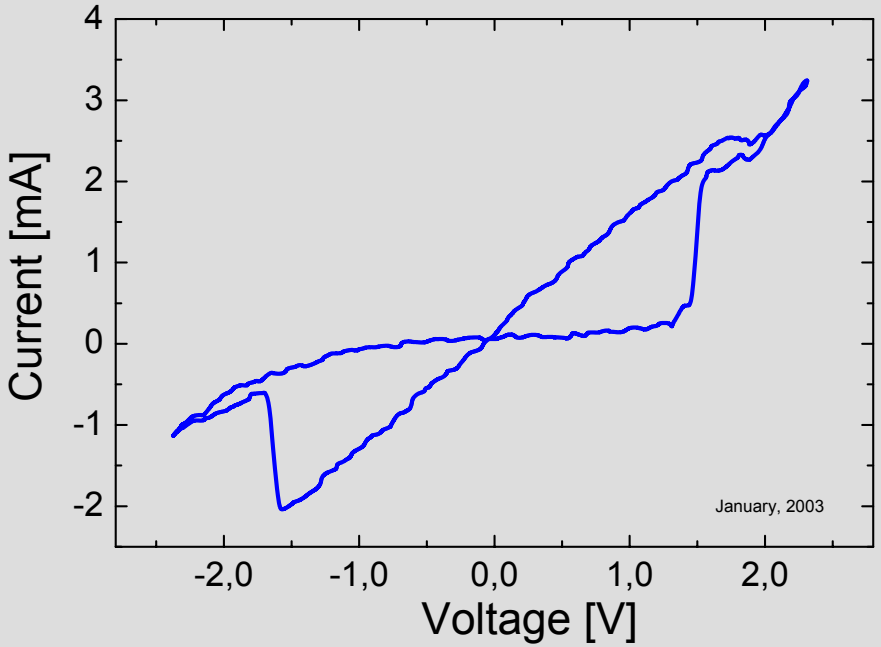
Absence of scaling of the coercive voltage.

B: Ferroresistive storage devices

Resistive switching:

How to distinguish a ferroelectric origin from a non-ferroelectric one?

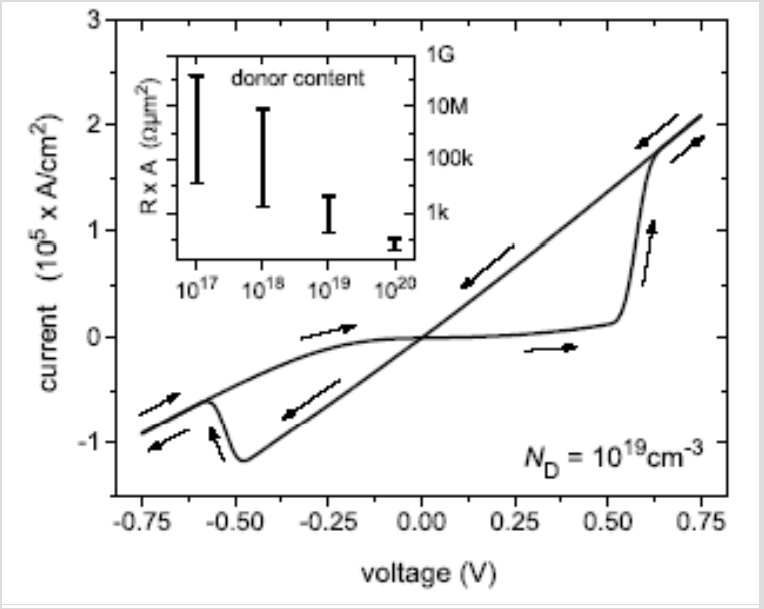
Experimental result



Thickness: 6.4 nm

Area: 3 µm²

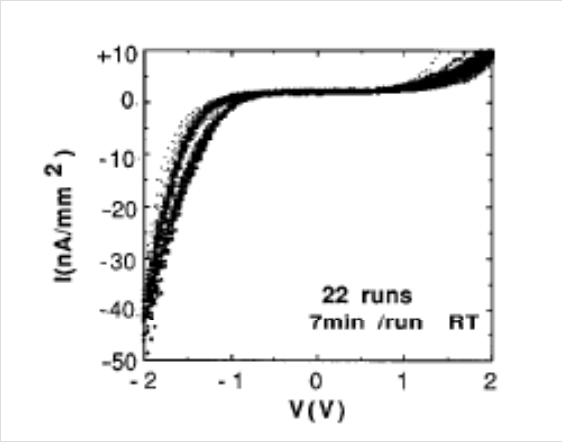
Numerical model



R. Meyer

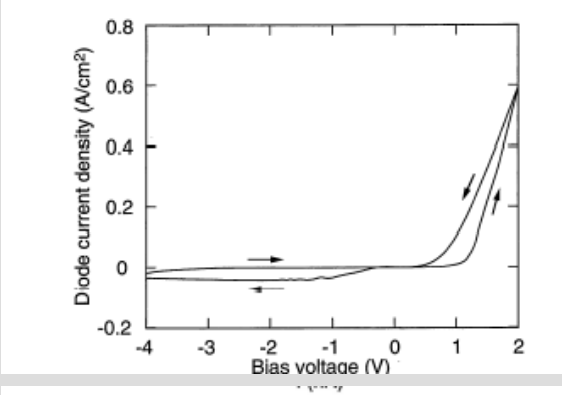
Although the curves look similar – its not a proof!

Resistive Switching observed in Ferroelectrics:

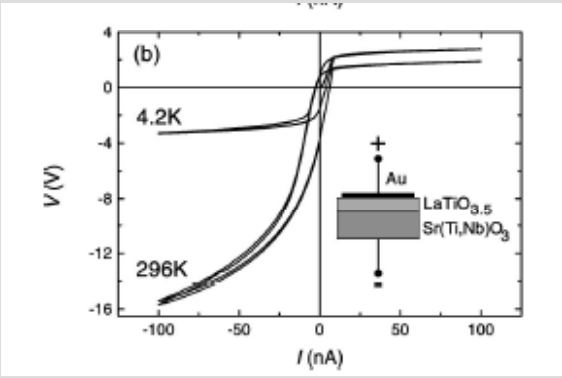


1. Complex Oxides

Reproducible memory effect in the leakage current of epitaxial ferroelectric/conductive perovskite heterostructures
Yukio Watanabe, APL **66**, 28 (1995).
Au/PLZT/LSCO

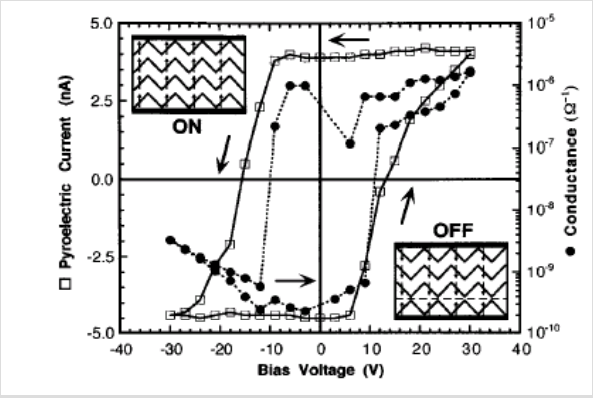


Pt-PZT-N-SrTiO3 Ferroelectric Memory Diode
K. Gotoh et al.,
Jpn. J. Appl. Phys. **35**, 39 (1996).

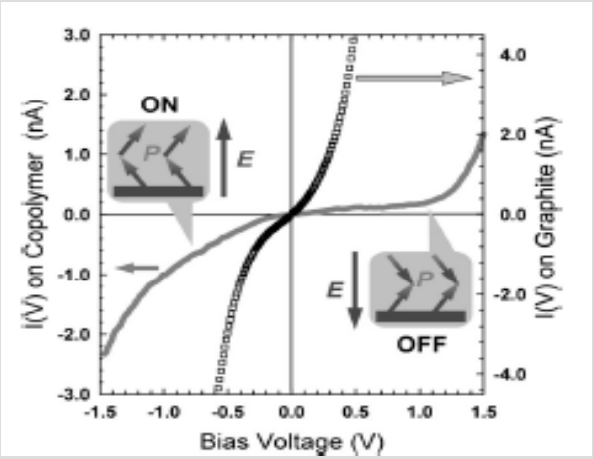


Transport properties of $LaTiO_3$ films and heterostructures
A. Schmehl, APL **82**, 3077 (2003).

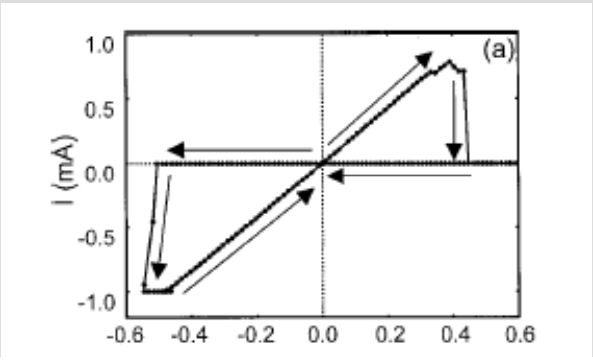
2. Non-Oxide (Ferroelectric) Materials



Novel switching phenomena in ferroelectric Langmuir–Blodgett films
A. Bune et al., APL **67**, 3975 (1995).



Nanoscale polarization manipulation and conductance switching in **ultrathin films** of a ferroelectric copolymer
Hongwei Qu,et al., APL **82** 4322 (2003).

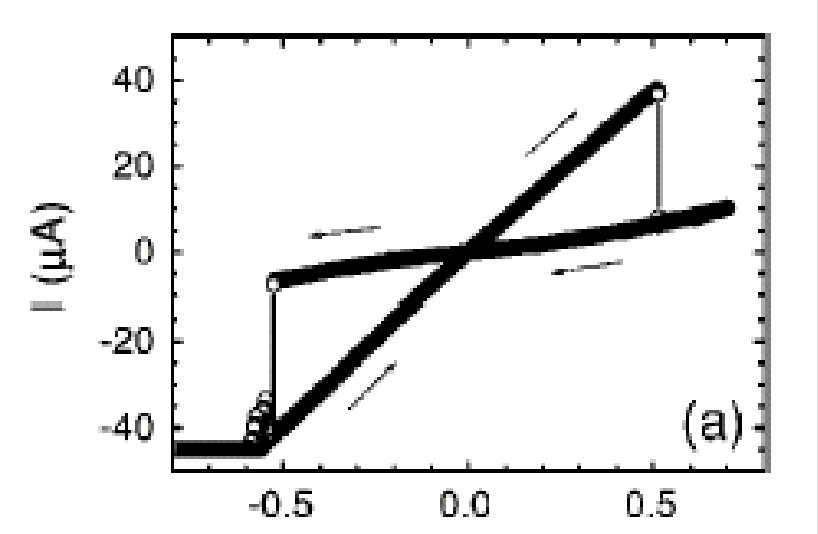


Non-volatile memory cells based on $Zn_xCd_{1-x}S$ ferroelectric Schottky diodes
P. van der Sluis, Appl. Phys, Lett., **82**, 4089 (2003).
Erratum: APL 2004

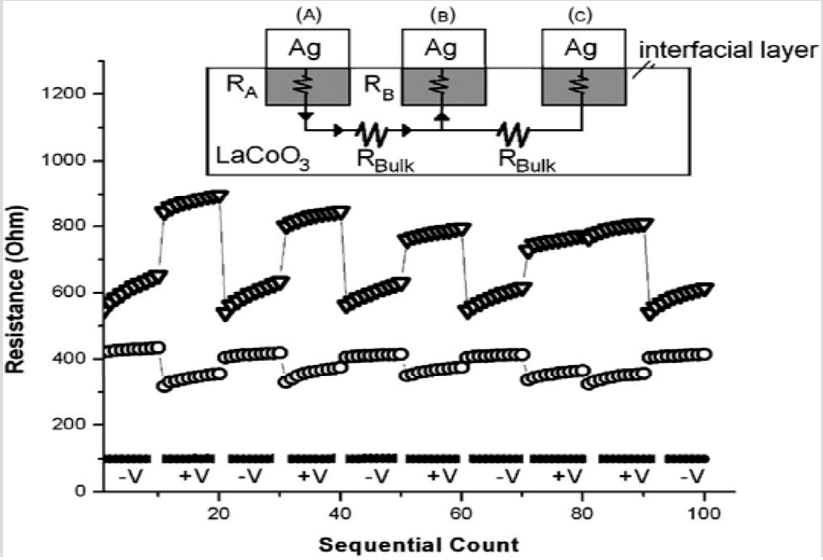
Theoretical background not clear!

Resistive Switching (non-ferroelectric oxides)

Beck et *al.,* APL **77**, 139 (2000),
IBM-Zürich, based on SRO/SrZrO3:Cr/SRO

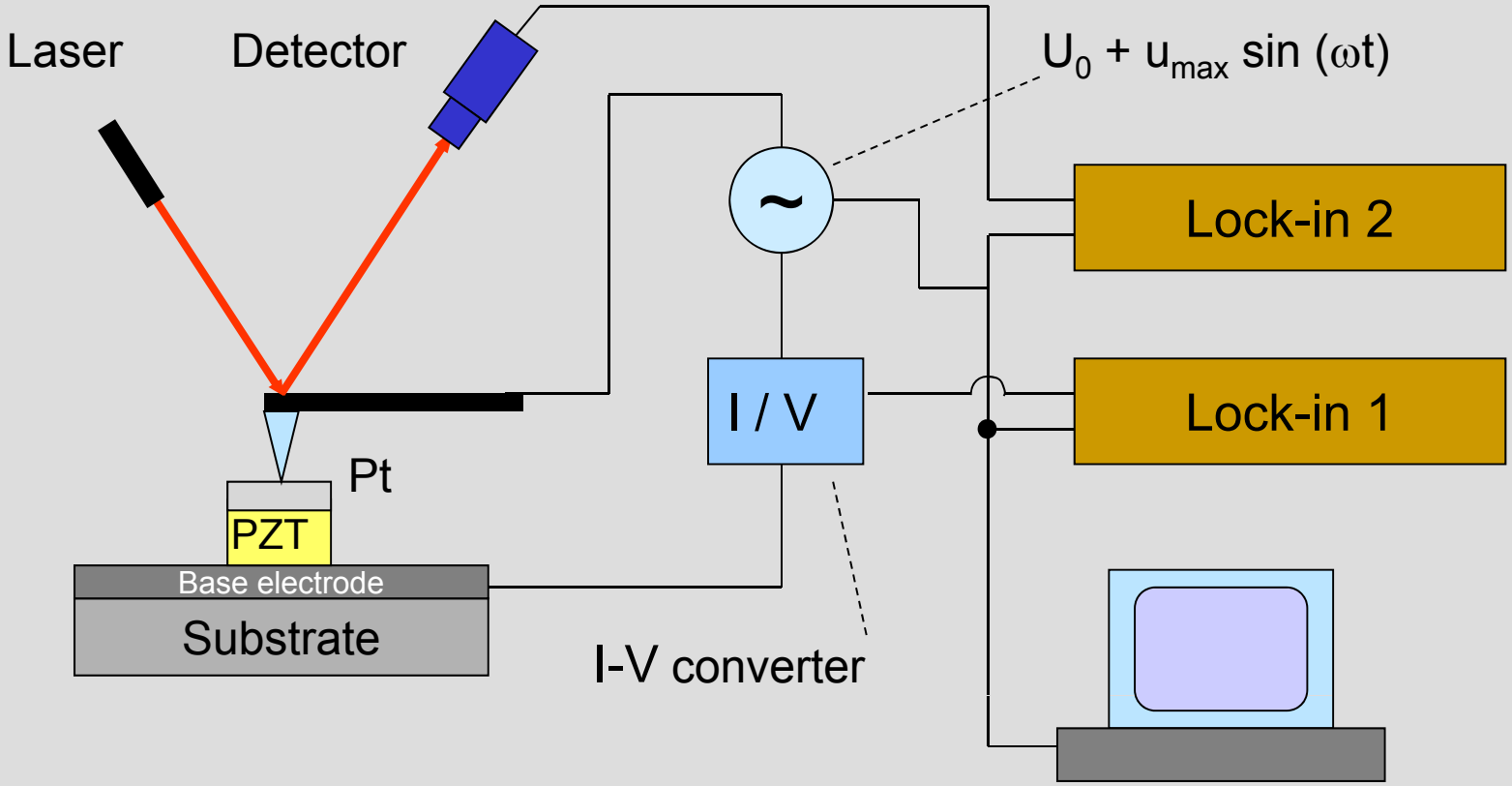


S. Tsui, et *al.,* APL **85**, 317 (2004)
$Ag/LaCoO_3/LaAlO_3$ (interface effect)



Simultaneous Measurement of different Properties

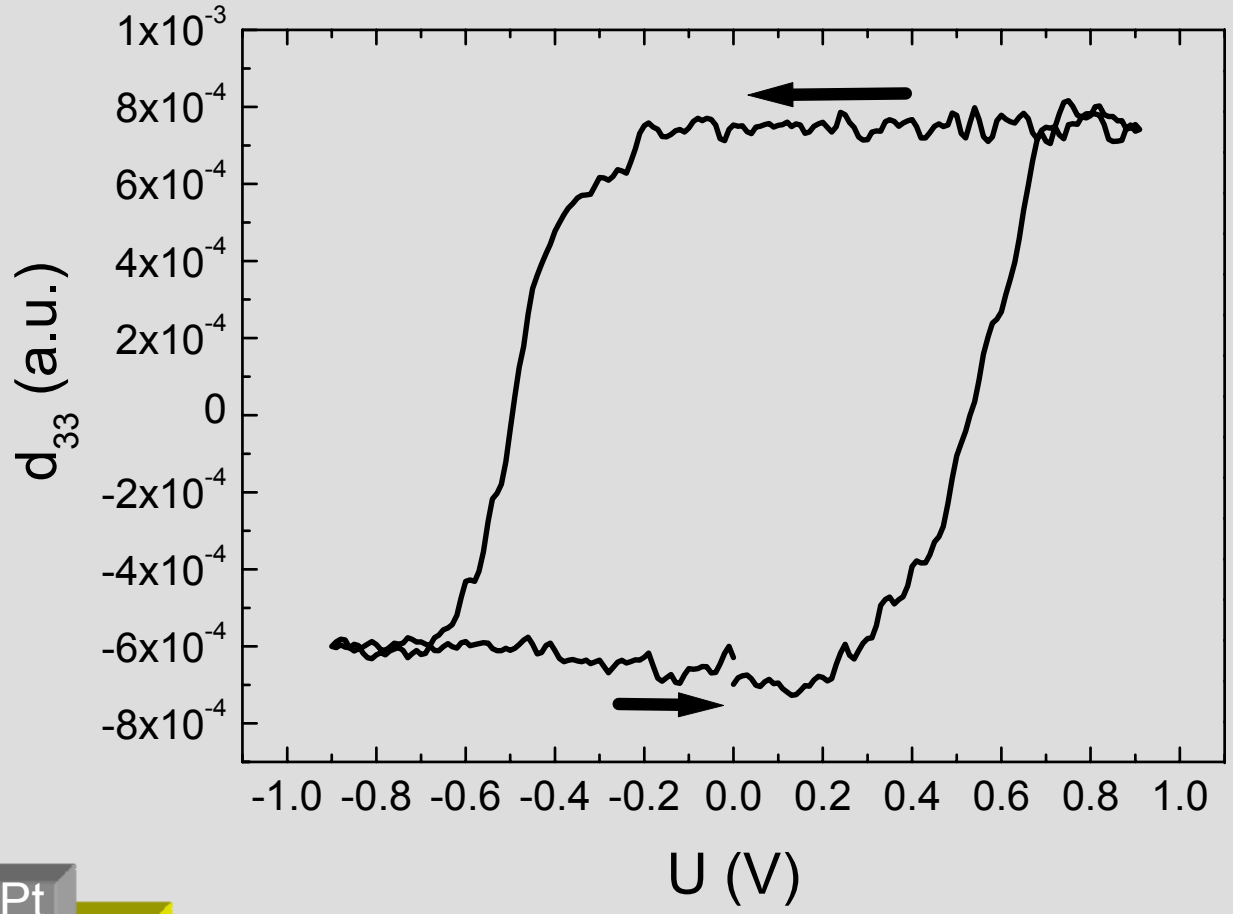
A. Petraru et al., to be published in Appl. Phys. A

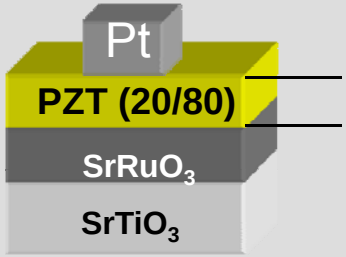


To measure d_{33}, C and I (resistive) vs. bias voltage simultaneously

Resistive Switching and Ferroelectricity

d_{33} vs. Bias

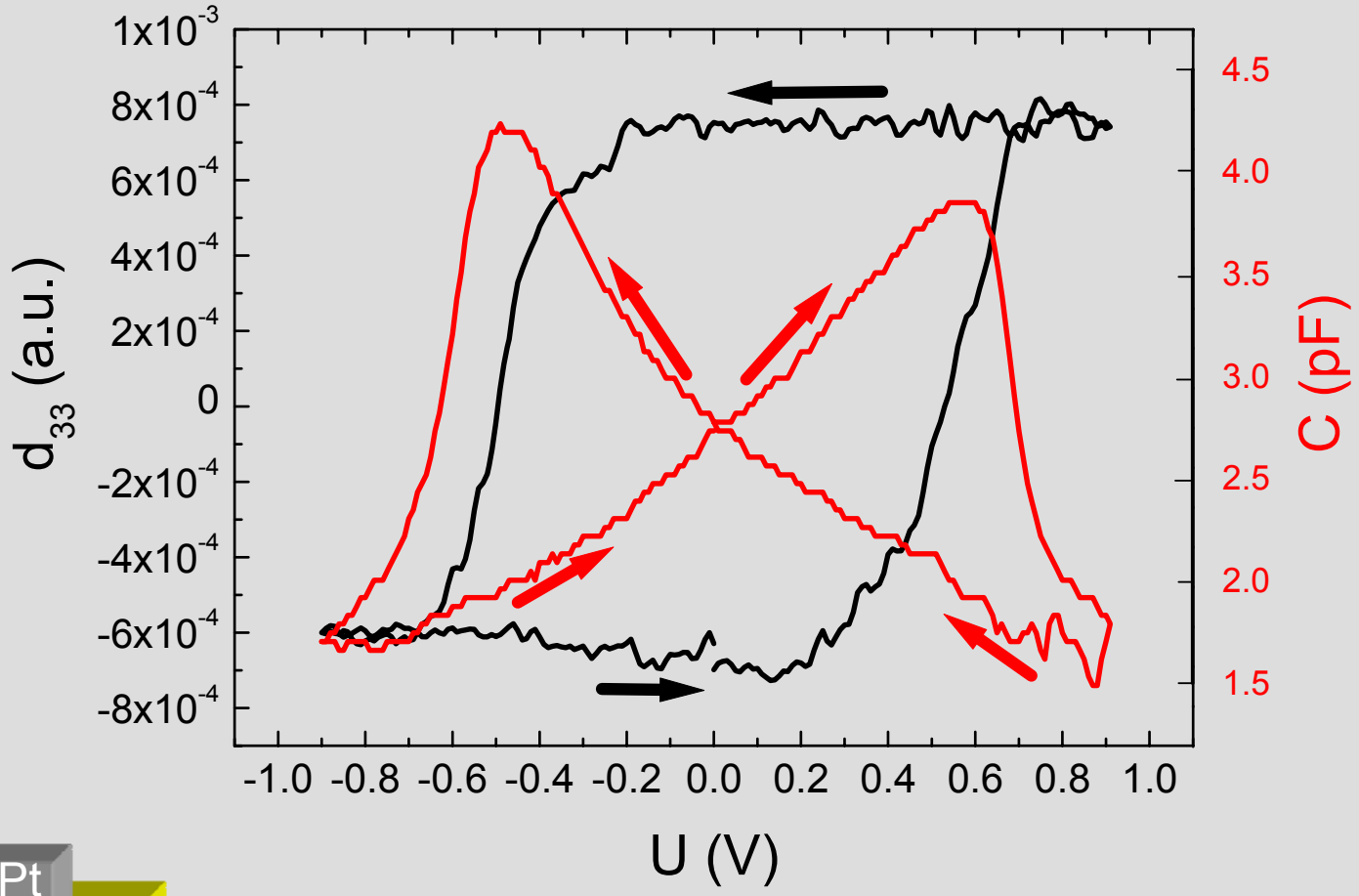


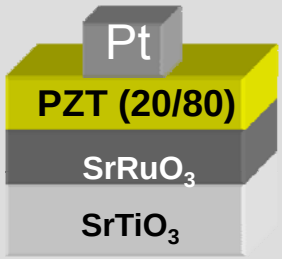


Thickness: 30 nm

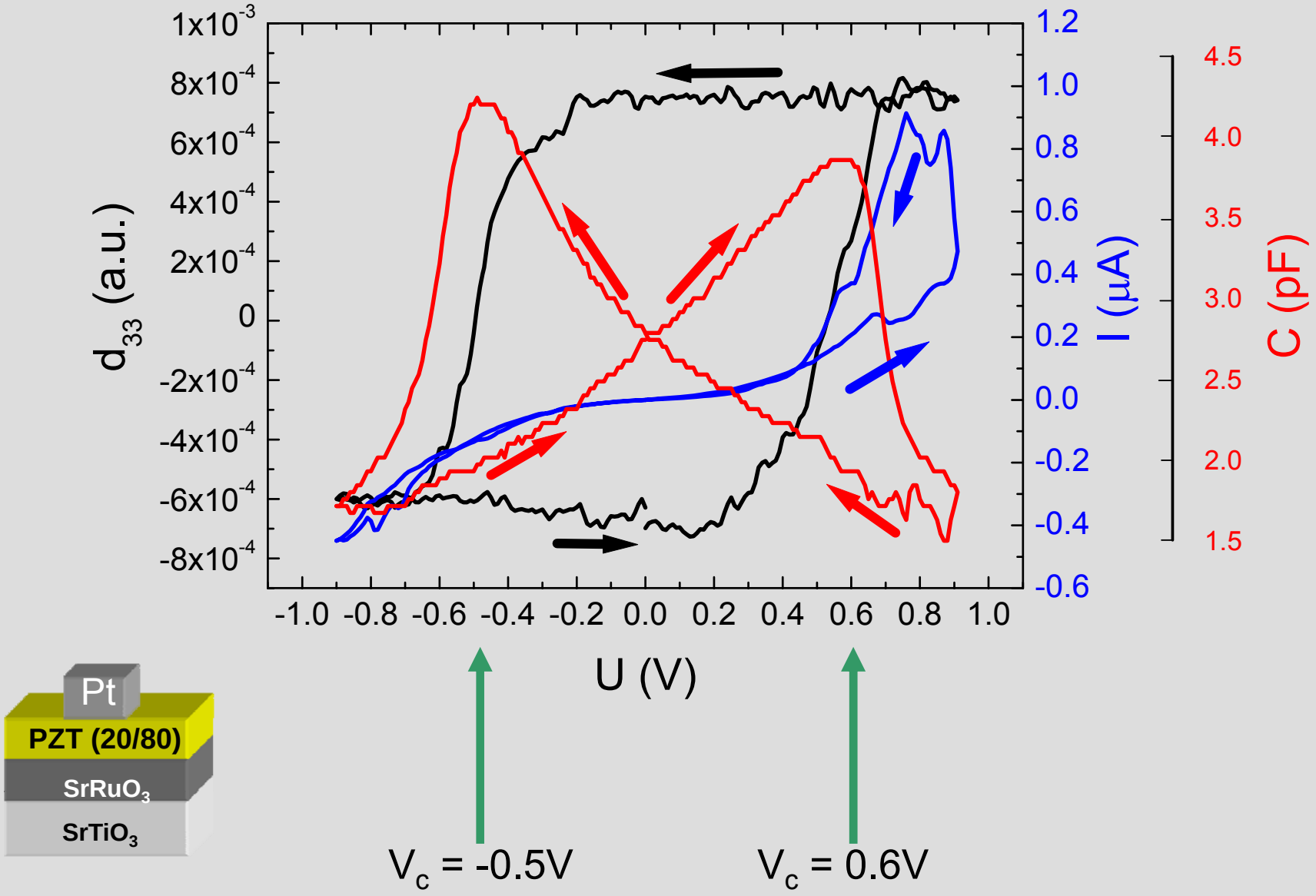
Area: 3 μm²

Resistive Switching and Ferroelectricity
d_{33}, C vs. Bias

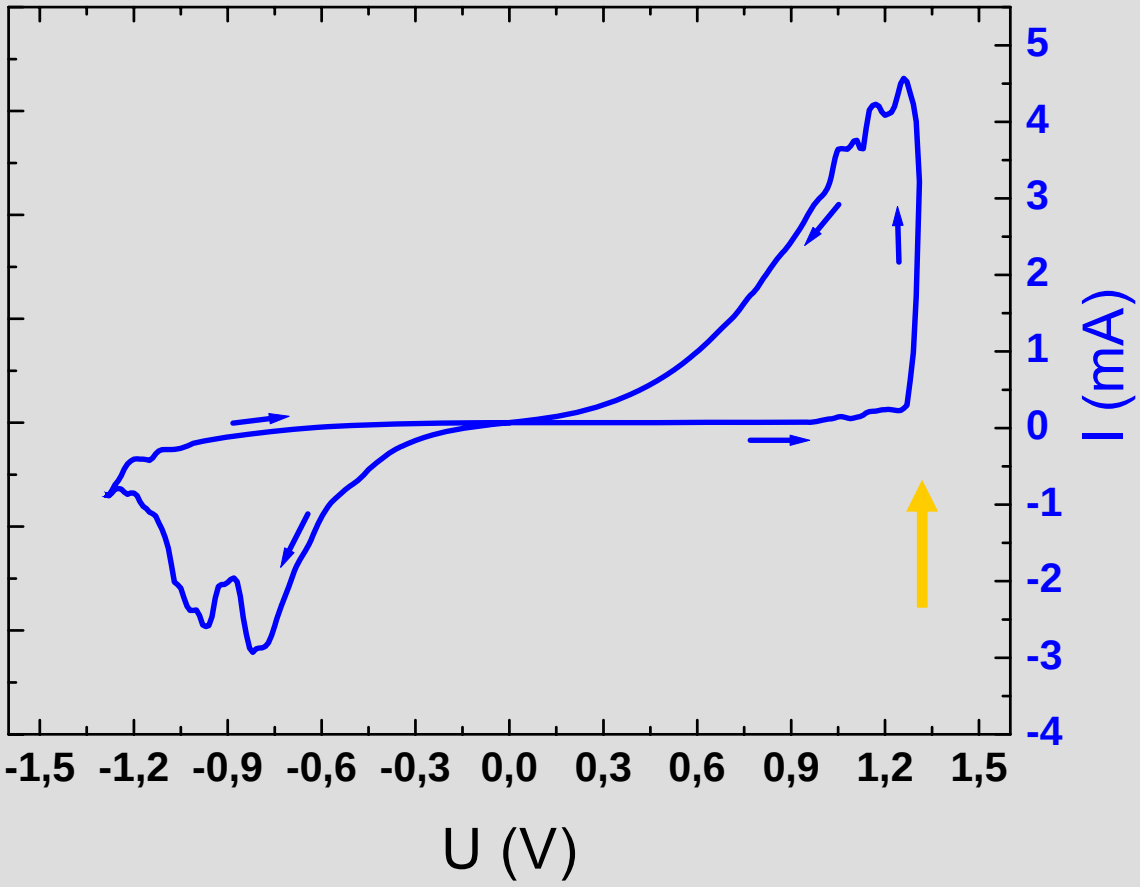


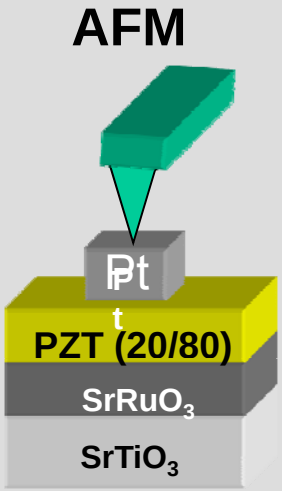


Resistive Switching and Ferroelectricity
d_{33}, C, $I_{res.}$ vs. Bias

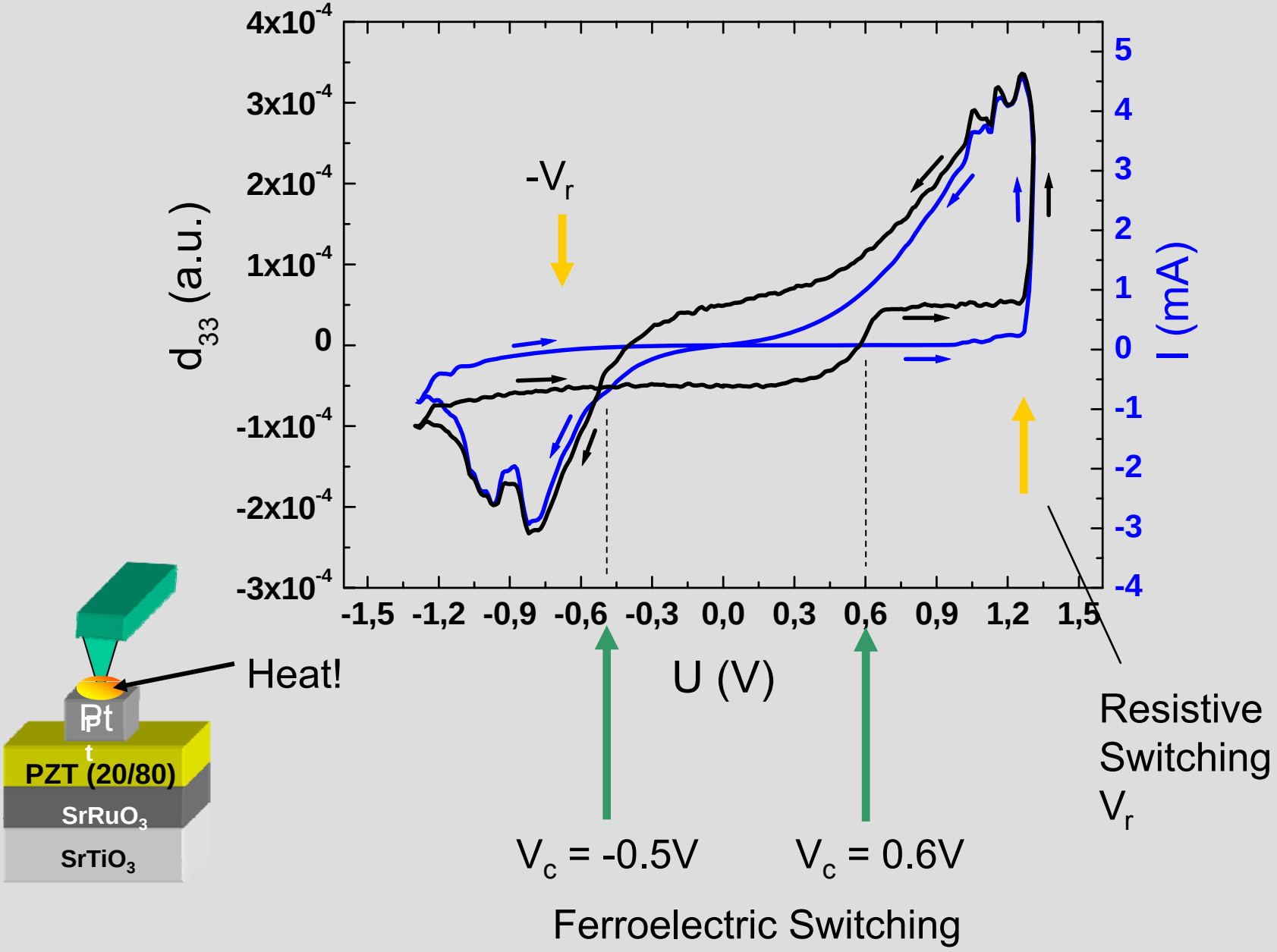


Increase Bias Voltage…

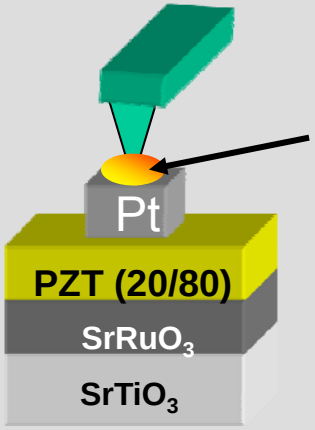




Resistive Switching and Ferroelectricity



Resistive Switching and Ferroelectricity



Current density high enough for heat generation?

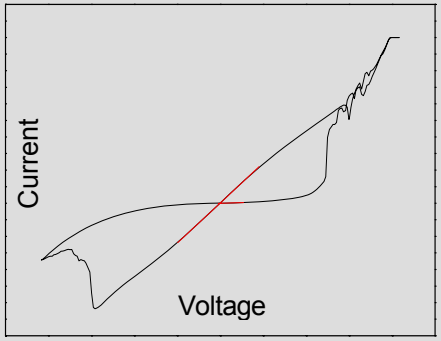
Estimation: $I = 10\ \mu A$, $r_{tip} = 5\ nm$

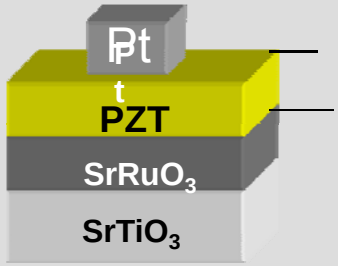
$J = I/A$

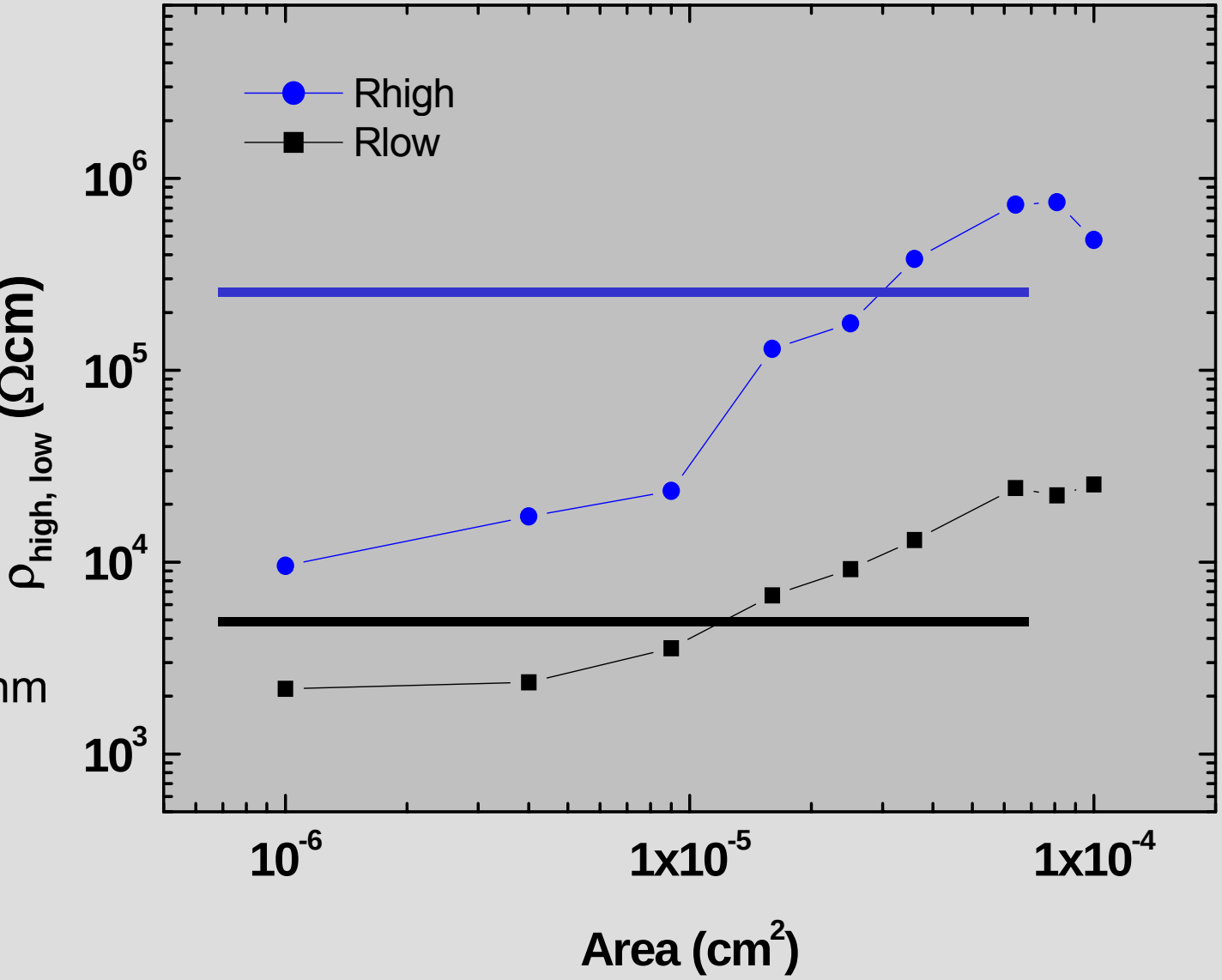
$J = 1.5 \times 10^7\ A/cm^2$

If current > 10 µA,
heating affects cantilever deflection

Resistive Switching caused by Ferroelectricity?

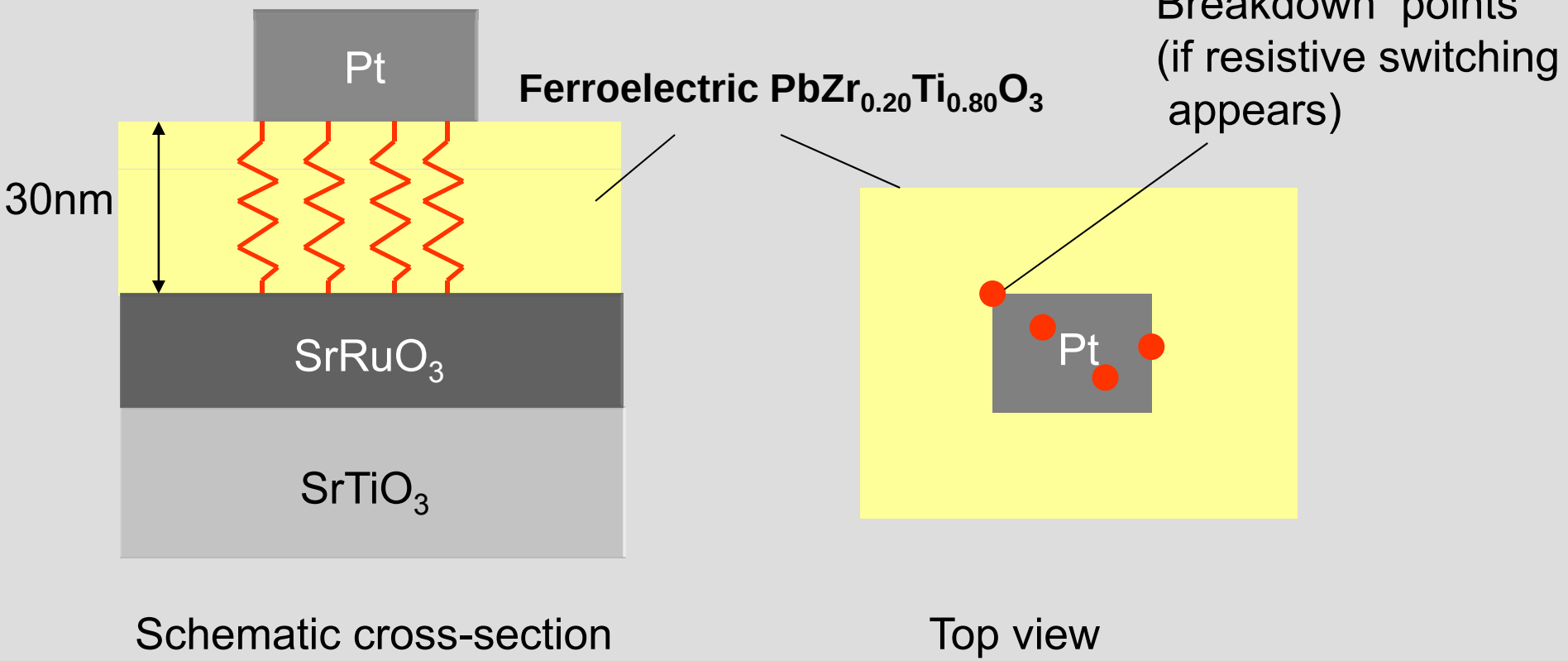






Resistive Switching: Filament Model

K. Szot, FZ Jülich



D. M. Schaadt et *al.*, J. of Vacuum Science & Technology B **22**, 2030 (2004)

K. Szot et al. Switching the electrical resistance of individual dislocations in single-crystalline SrTiO3, to be published in Nature Materials

Resistive Switching: Filament Model

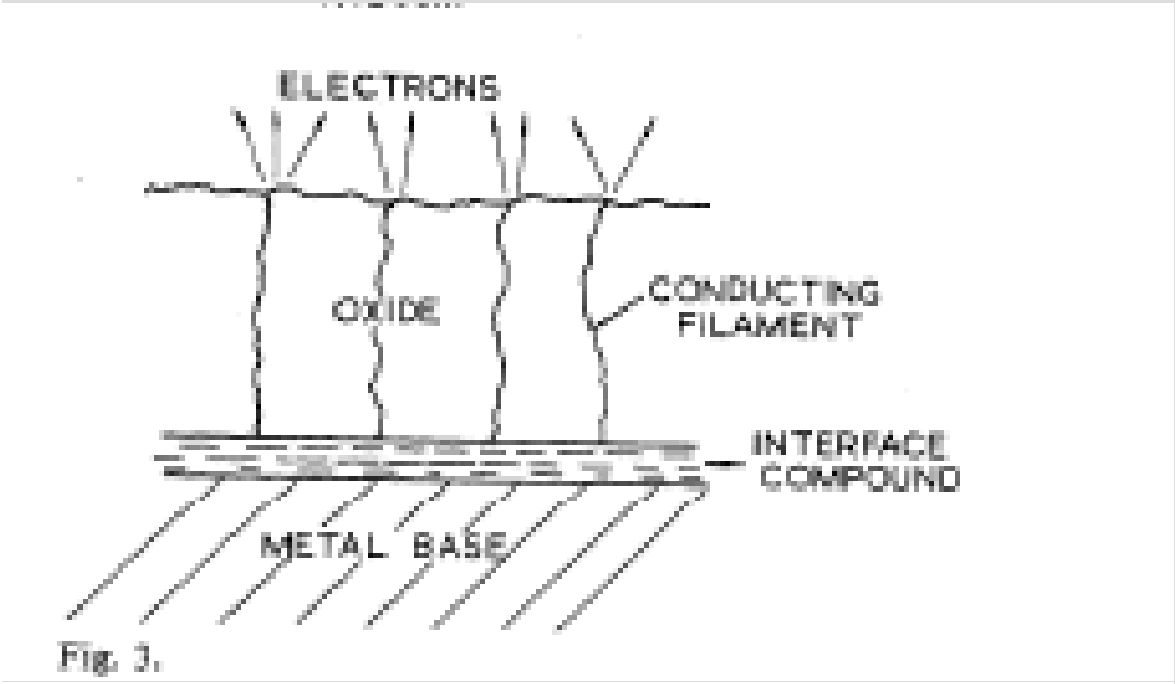


Fig. 3.

G. Dearnaley
A. M. Stoneham and
D. V. Morgan
Rep. Prog. Phys.
33, 1129 (1970).

G. Dearnaley,
Thin Solid Films **3**, 1161 (1969).

Summary

Simultaneous acquirement of the *C(V)* characteristics, I(V) and piezoresponse d_{33} (V) of ferroelectric devices using a conductive AFM

Lateral size scaling of ferroelectric capacitors:

- we find no significant scaling of the dielectric constant with the lateral size down to 200 nm
- we do not find a significant variation in the tunability of the dielectric constant;
- absence of scaling of the coercive voltage (and hence coercive field) with lateral dimensions.

Resistive switching in ferroelectric materials:

- in case of resistive switching we are able to distinguish a ferroelectric from a non-ferroelectric origin

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University of Aachen (RWTH)
Research Center Jülich
„Displacive and Conductive Phenomena in Ferroelectric Thin Films: Scaling effects and switching properties“.