FROM RESEARCH TO INDUSTRY

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HIGHLY TUNABLE MN-DOPED PZT (PMZT) THIN FILMS FOR INTEGRATED RF DEVICES

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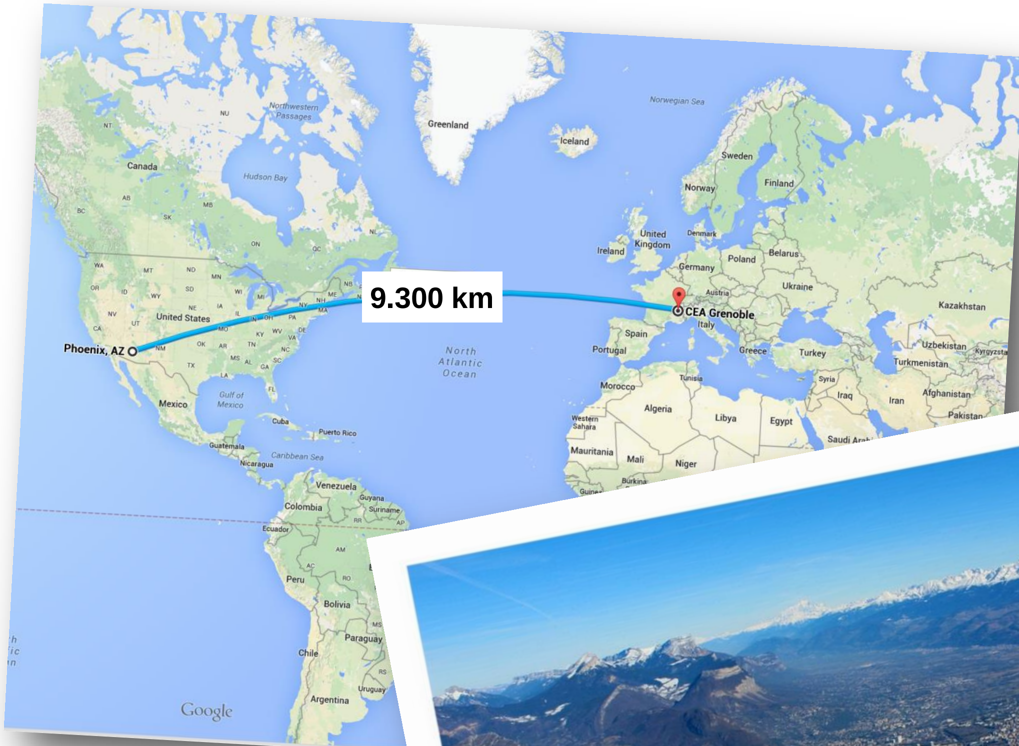
leti

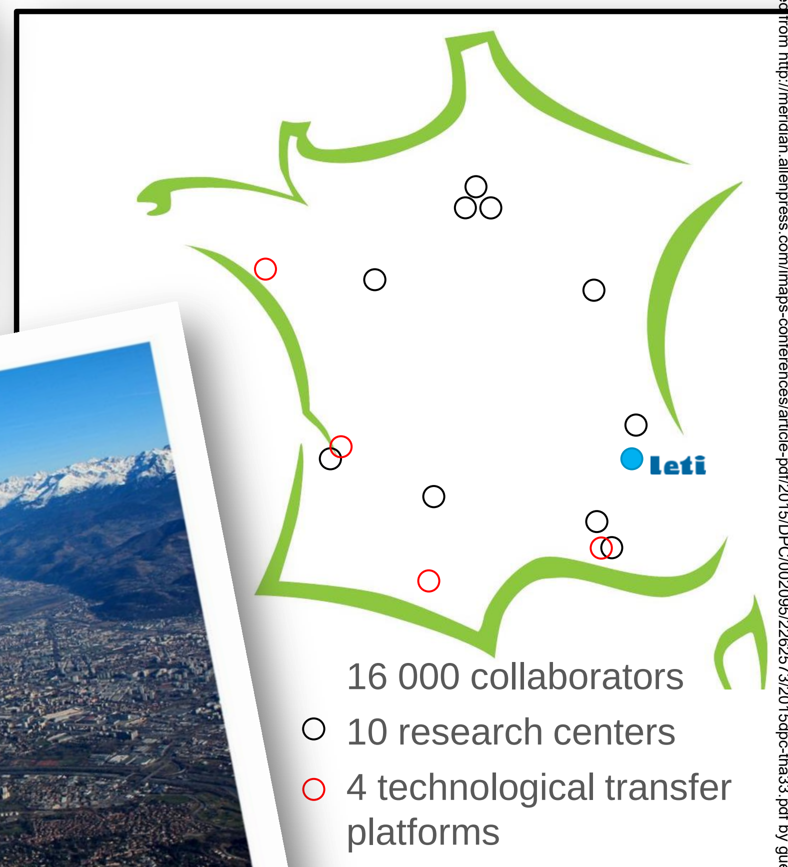
BIOGRAPHY

- **Research Engineer & WP manager at CEA Leti**
- **PhD in Physics & Engineering**
  University of Bordeaux, 2013
- **Master in Laser Physics**
  University of Bordeaux, 2009
- **Author of more than 15 publications & conferences**
- **Reviewer for leading international journals**
  Advanced Materials, Advanced Science, Applied Physics Letters, Journal of Applied Physics
- **Innovation Award**
  Safran Power Electronics Center Symposyum, 2011
- **R&D in Materials & Technologies for (Opto-)Electronics**
  Development, characterization & failure analyses of innovative devices, Electrical measurements, Physico-chemical analyses, Materials science, Ceramics, Polymers, Nanocomposites, RF applications…

CEA LETI: FLIGHT TO GRENOBLE (FRANCE)



CEA Institute founded in 1967



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CEA Institute organisation

Nuclear Energy Division	Defense and Security Division	Technological Research Division
		Leti – Electronic and information technologies
		Liten – New Energies
		List – Software

Basic Research Division (Life sciences and Physical sciences)

Leti → Electronics and information technologies Laboratory

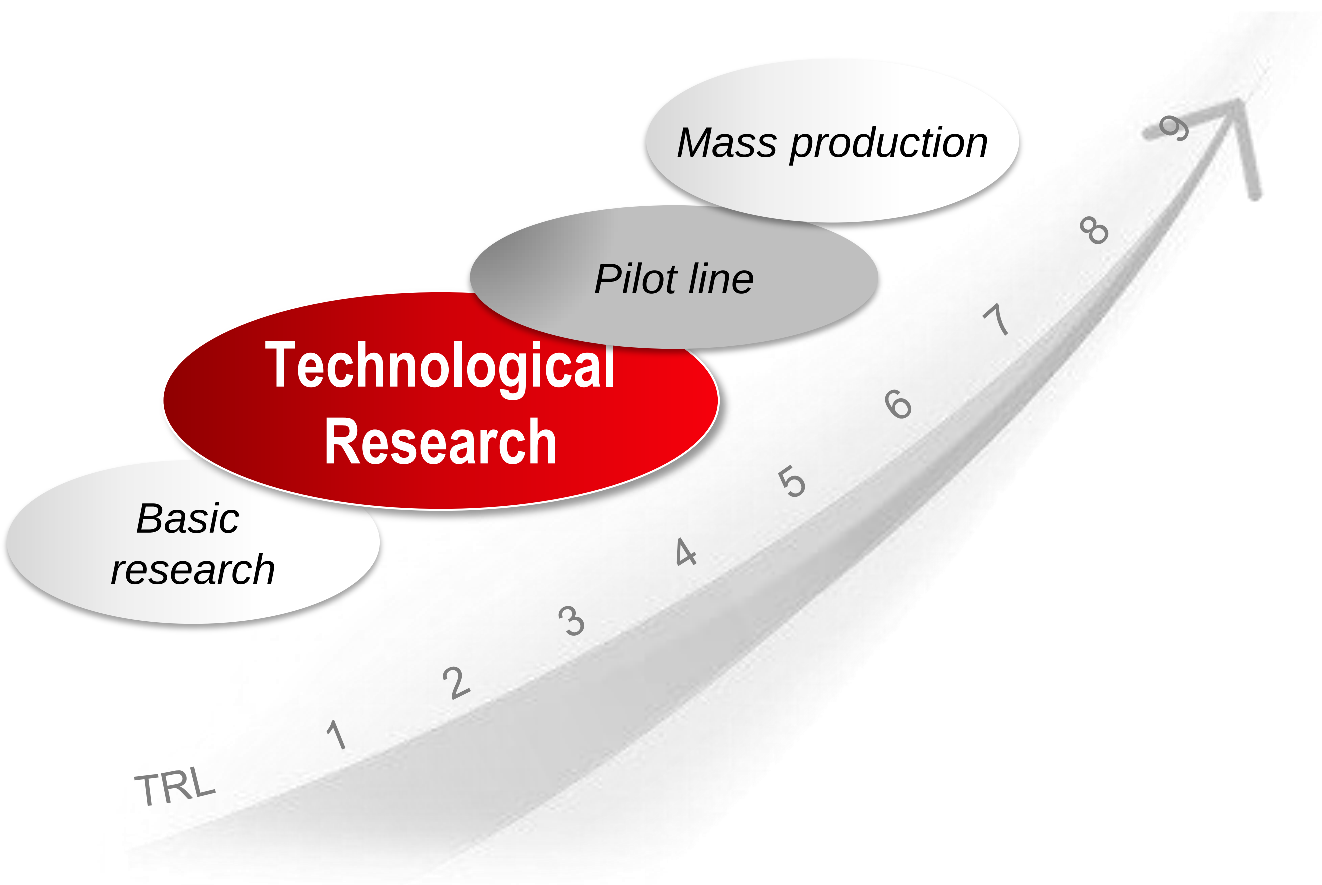
LETI KEY FIGURES

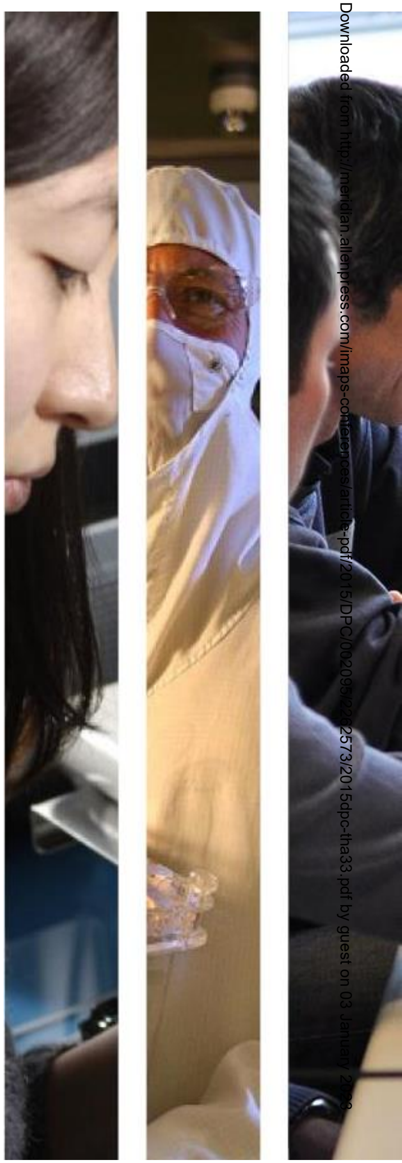
Director : Dr Marie-Noëlle Semeria

- **1,800 collaborators**
- **2,800 patents**
  40% under licensing; 311 registered in 2014
- **Budget : 318 M€**
- **91,500 sq.ft clean rooms**
  For 200 and 300 mm wafer fab, operated 24/7

LETI BUSINESS MODEL

CREATE AND TRANSFER INNOVATION TO OUR INDUSTRIAL PARTNERS





365 ON-GOING INDUSTRIAL CONTRACTS WITH FRENCH AND INTERNATIONAL COMPANIES SUCH AS:

… and also with SMI & startups.

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ELECTRONICS WITHIN SOLUTIONS

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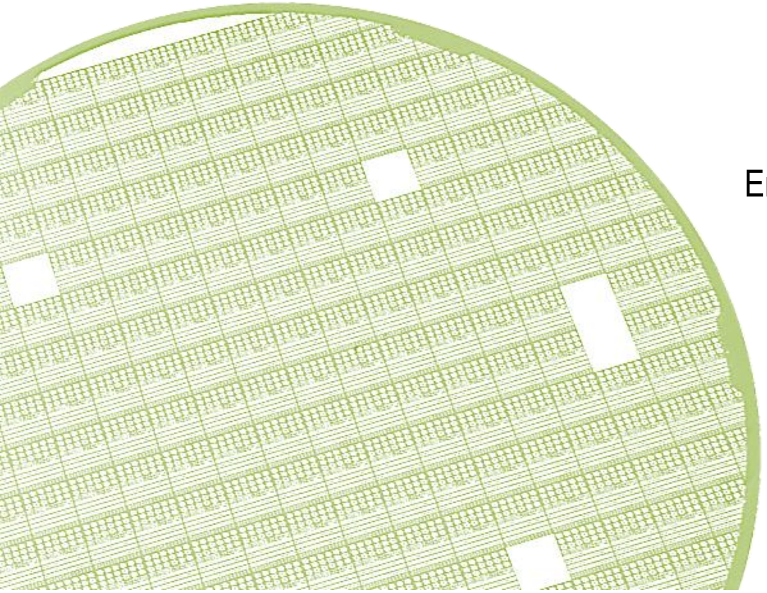
Consumer

IoT & Smart objects

Space



Energy and environment

Manufacturing

Biology and health

Transport

Safety and Security

PRESENTATION OUTLINE

Highly tunable Mn-doped PZT (PMZT) thin films for integrated RF Devices

- Context and Introduction
- Experimental Procedure
  - Fabrication of the PMZT-based MIM capacitors
  - On-wafer electrical characterization
- Performances of the PMZT-based MIM capacitors
  - Leakage currents
  - Dielectric strengths
  - RF Tunability
- Conclusion and On-going work

CONTEXT AND INTRODUCTION

INTRODUCTION TO PASSIVE COMPONENTS

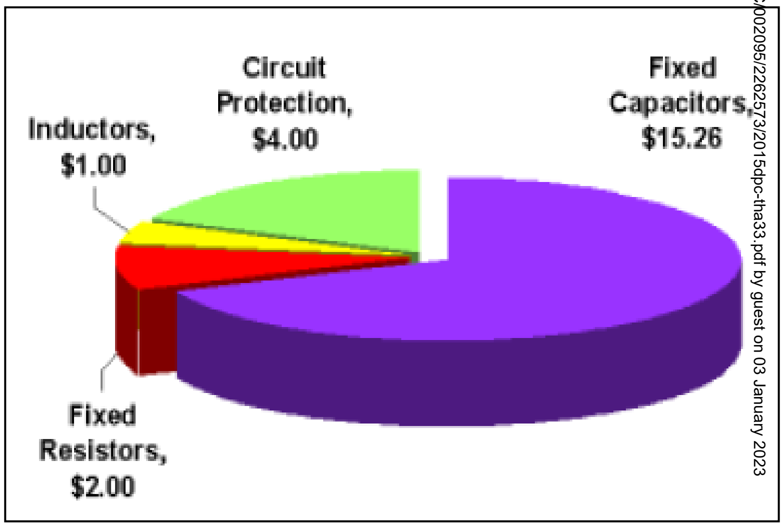
System	Total Passives	Total Ics	Ratio
CELLULAR PHONES			
Ericsson DH338 Digital	359	25	14:1
Ericsson E237 Analog	243	14	17:1
Philips PR93 Analog	283	11	25:1
Nokia 2110 Digital	432	21	20:1
Motorola Md 1.8 GHz	389	27	14:1
Casio PH-250	373	29	13:1
Motorola StarTAC	993	45	22:1
Matsushita NTT DOCOMO 1	492	30	16:1
COMPUTERS			
Apple Portable Logic Board	184	24	8:1
Apple G4	457	42	11:1

IC = integrated circuit

J. Andresakis *et al.*, Ohmega Technologies

- **Average ratio PC/IC : 20:1**

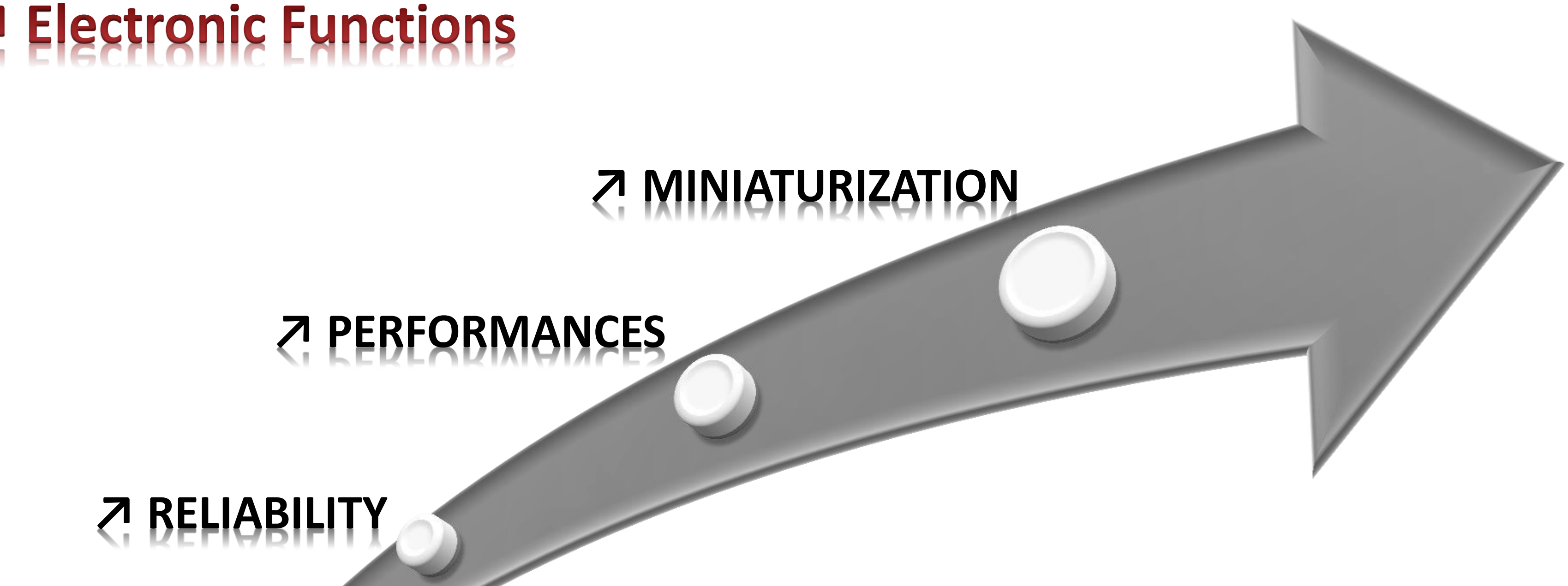
- **Capacitors : 75% of the world passive market**



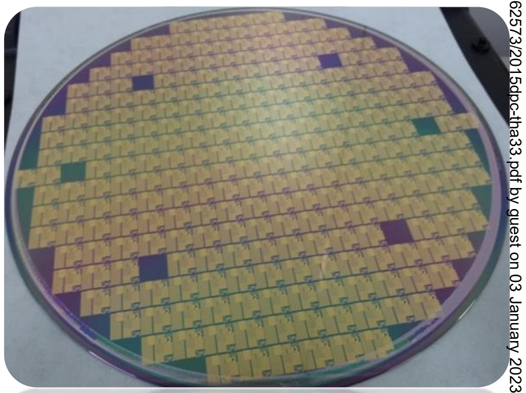
World passive market ($billions)
Source : INEMI 2004

CAPACITOR TECHNOLOGY TRENDS

↗ Electronic Functions

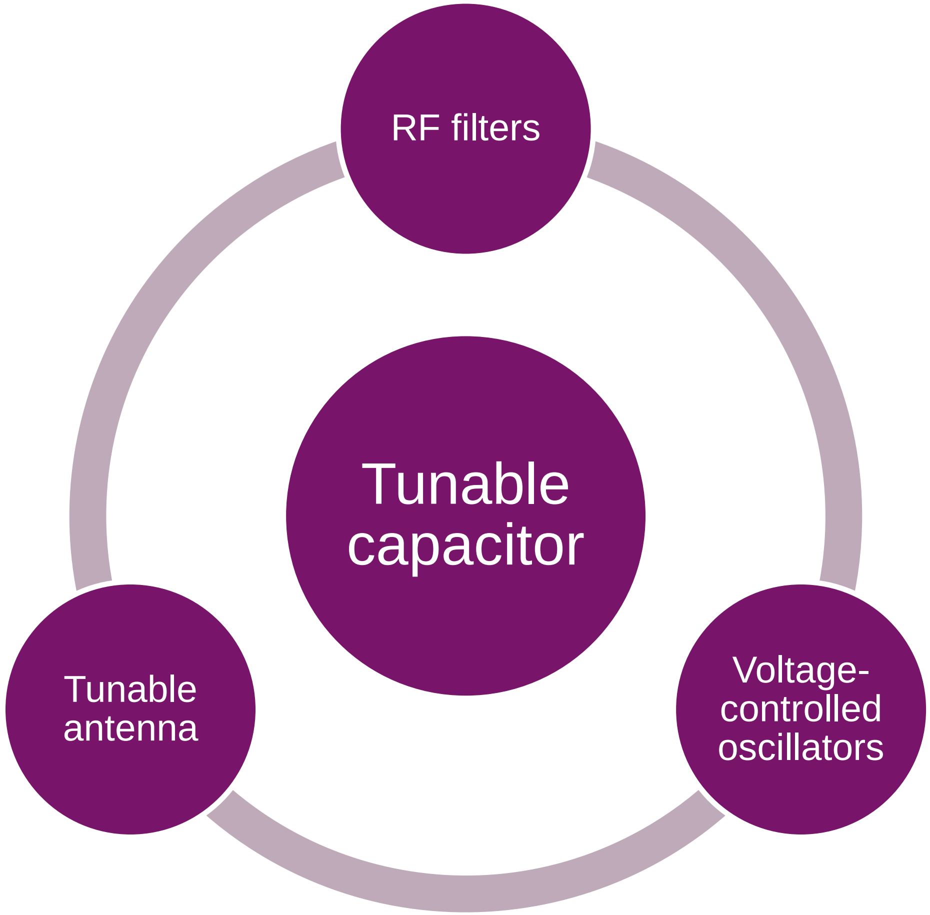


➢ **Integrated capacitors**

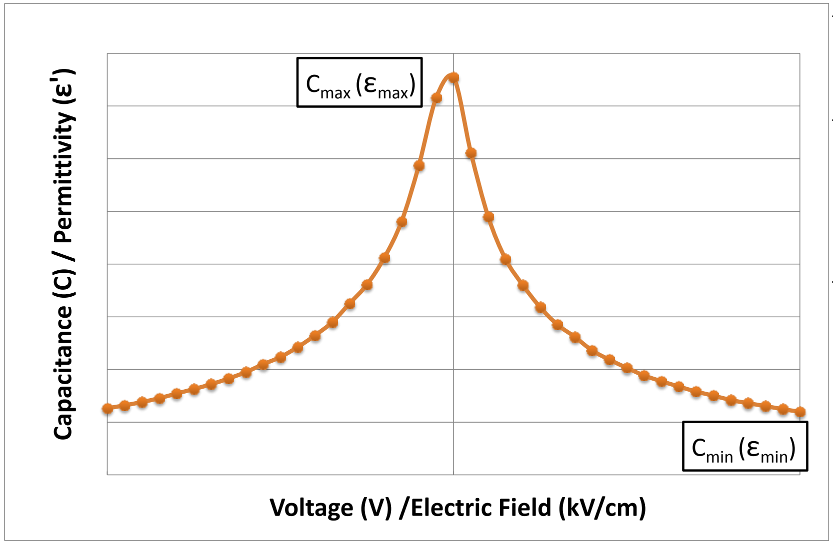


INTRODUCTION TO TUNABLE CAPACITORS

Tunable capacitors applications



Tunability definition



$$T = \frac{C^{max} - C^{min}}{C^{max}} \ [\%] \ @V$$

TUNABLE CAPACITOR REQUIREMENTS

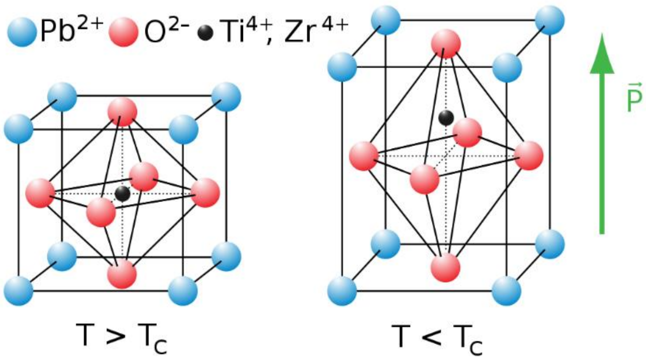
Low leakage currents	High tunability under voltage	High quality factor	Low-cost

➢ **Ferroelectric thin films**

PZT & DOPED-PZT THIN FILMS FOR TUNABLE CAPACITORS

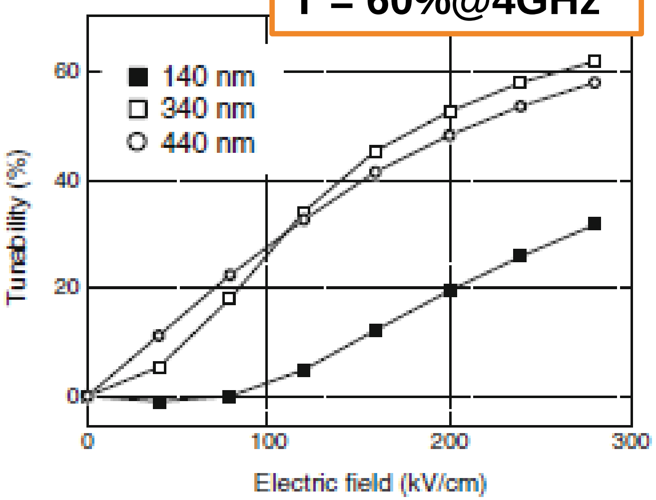
PZT

(Lead Zirconate Titanate)



Source: Rex Garland, Stanford University

T = 60%@4GHz

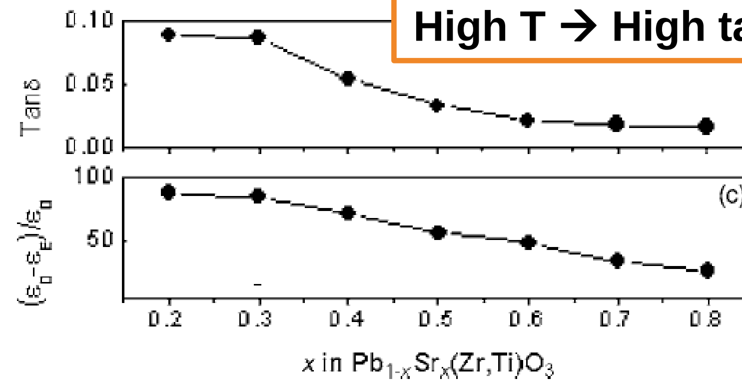


D. Min *et al.*, *J. Electrocer.*, 2012.

Doped-PZT

Strontium doped-PZT

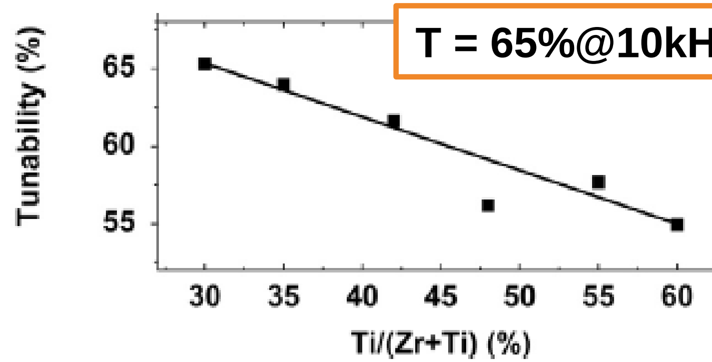
High T → High tan δ



Qi-Yue Shao *et. al.*, *J. of App. Phys.*, 2006

Lanthanum doped-PZT

T = 65%@10kHz



Zhongqiang Hu *et al.*, *Cer. Int.*,2014

Performances unsuitable for tunable capacitors

THIS WORK

Manganese (Mn) doped-PZT → PMZT

with different amounts of dopants (0% - 3% Mn)

EXPERIMENTAL PROCEDURE

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SOL-GEL PROCESS

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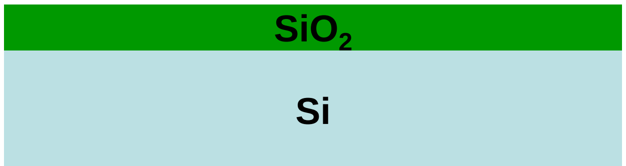
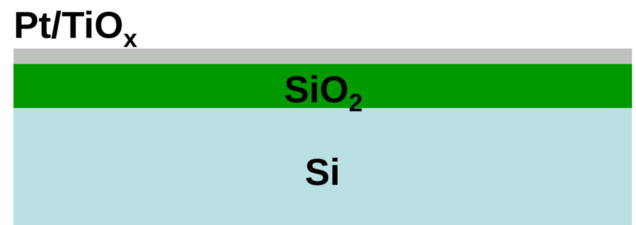
1



- Si wafer (200 mm)
- Si thermal oxidation → SiO_2

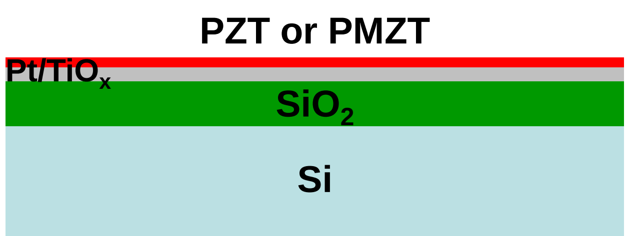
2



- Ti deposition by PVD (10nm)
- Ti thermal oxidation → TiO_2
- PVD deposition of Pt (100nm)

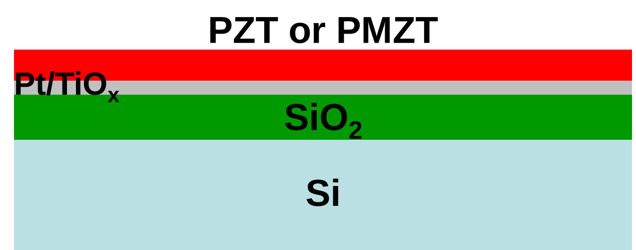
  → Bottom Electrode

3



- Spin-coating deposition of 1 P(M)ZT layer
  - Drying: air/130°C/5min (hot plate)
  - Pyrolysis: air/350°C/5min (hot plate)
  - Crystallization: 0_2/700°C/1min (RTA)

4

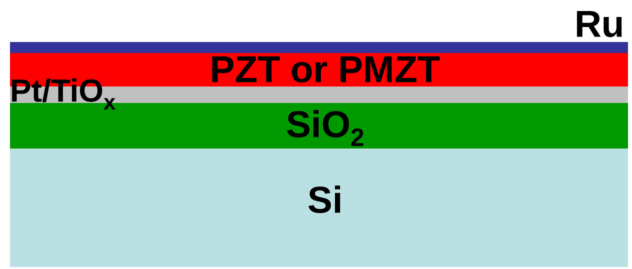


- Spin-coating deposition of 3 P(M)ZT layers
  - Drying: air/130°C/5min (hot plate)
  - Pyrolysis: air/350°C/5min (hot plate)
  - Crystallization: 0_2/700°C/1min (RTA)

Sol-gel process → Low cost compared to PVD or ALD deposition

MIM CAPACITORS FABRICATION PROCESS

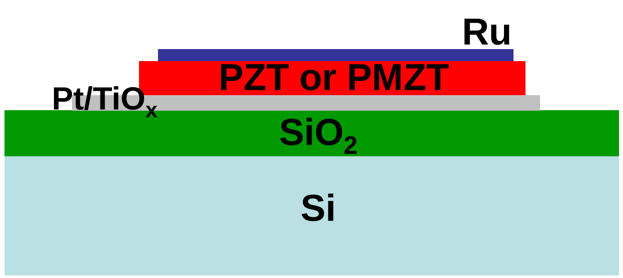
1



- Ru (Ruthenium) deposition by PVD (10nm)

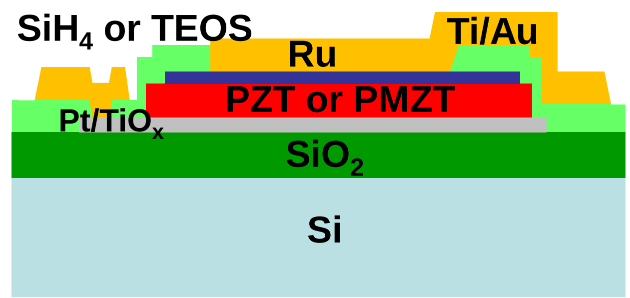
→ Top Electrode

2



- Ru etching (1st photolithography level)
- PZT etching (2nd photolithography level)
- Pt etching (3rd photolithography level)

3

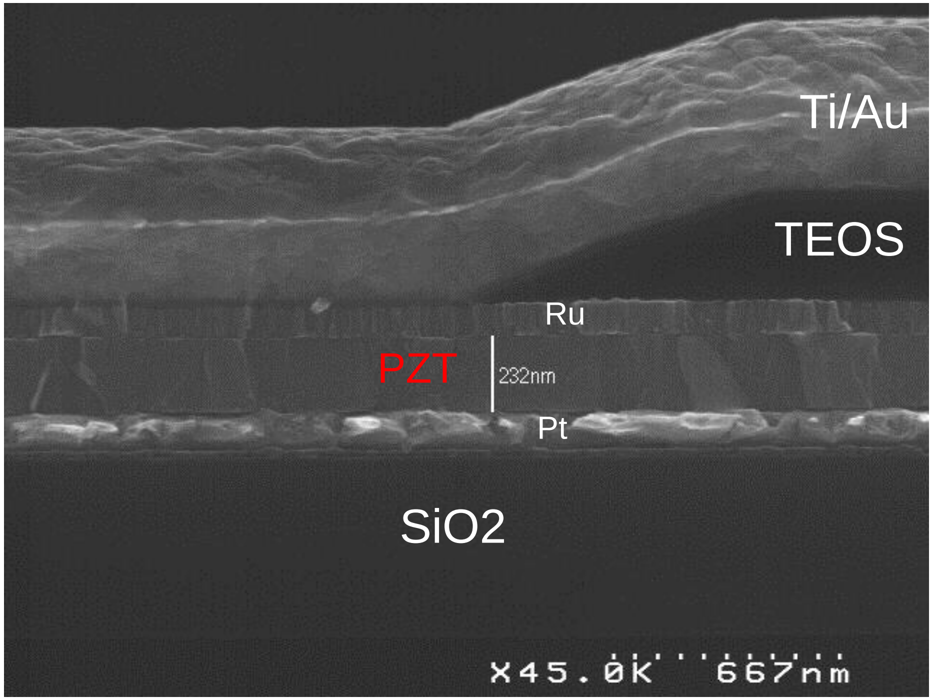


- Passivation: PECVD deposition of TEOS
- TEOS etching (4th photolithography level)
- Deposition and etching of Au/Ti contacts (5th photolithography level)

Process on 200mm wafers ready for mass production

THIN FILMS CHARACTERIZATION

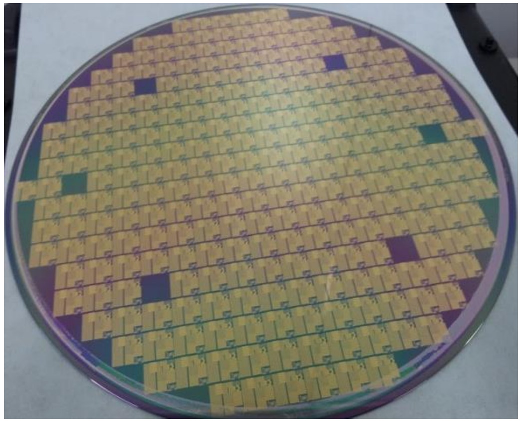
- **Thin film deposition:** Ellipsometry measurements (49 points) :
  - P(M)ZT thickness ~ 225 nm
  - Thickness uniformity ± 3 %
  - Roughness ~ 1.5 nm
- **5th photolithography level:** Cross-sectional Scanning Electron Microscopy (SEM)



Good wafer-to-wafer uniformity → Reproducible process

ELECTRICAL MEASUREMENTS (1/3)

Wafer-level electrical characterization



- Leakage currents
- Breakdown voltages (dielectric strengths)
- RF Tunability

Wafer-level characterization facilities at CEA LETI

Cascade PAV	Cascade S300	Karl Zuss PA300
		

ATMOSPHERE(S)

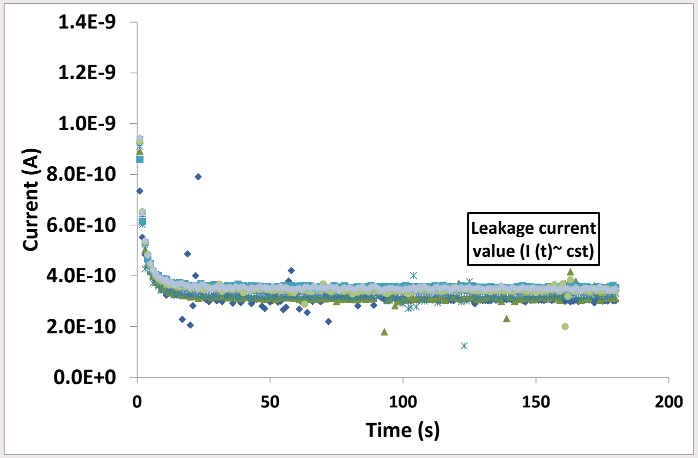
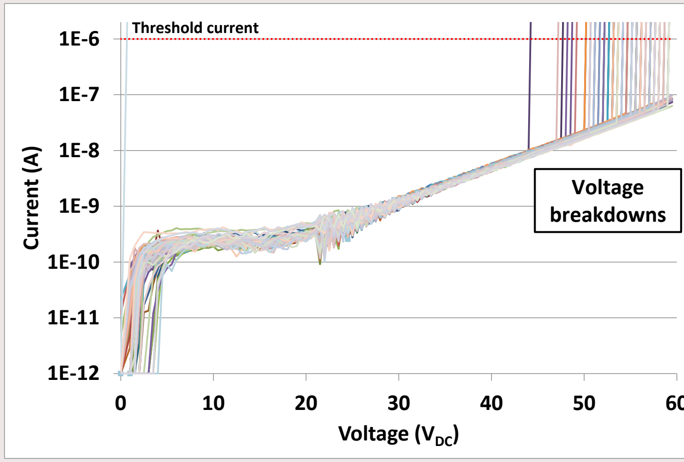
AIR

NITROGEN

VACUUM

PROBERS

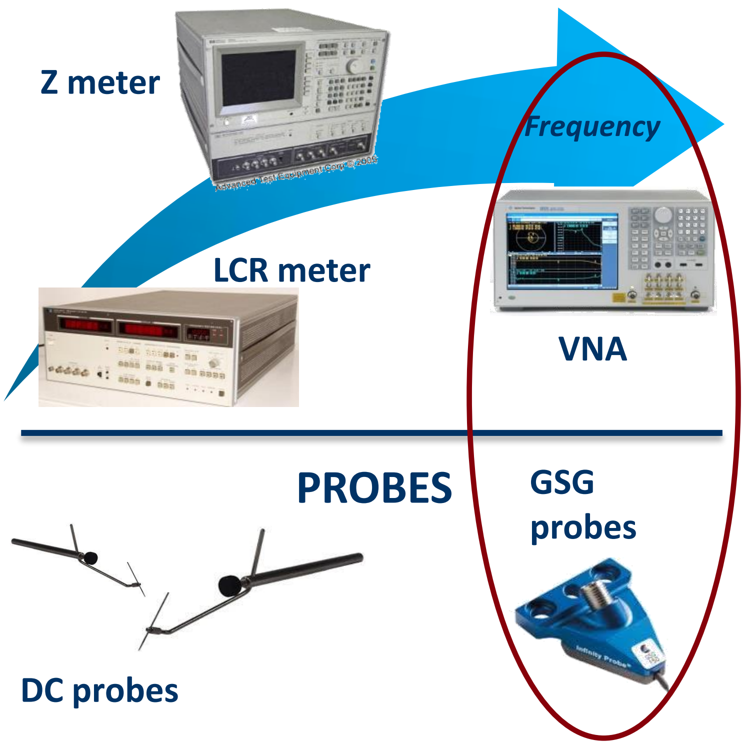
ELECTRICAL MEASUREMENTS (2/3)

Methods	Current vs time, I(t), under an applied electric field	Linear Ramp Voltage Stress measurements (LRVS)
Measurements	Leakage currents	Breakdown voltages
Instruments	Keithley 2410	Keithley 2410
Conditions	10 points, Time: 180s, Applied voltages: ± 5, 10, 20, 30, 40V_{DC}	90 points, Voltage ramp: 1V/s, Threshold current: 1µA
Typical results		

ELECTRICAL MEASUREMENTS (3/3)

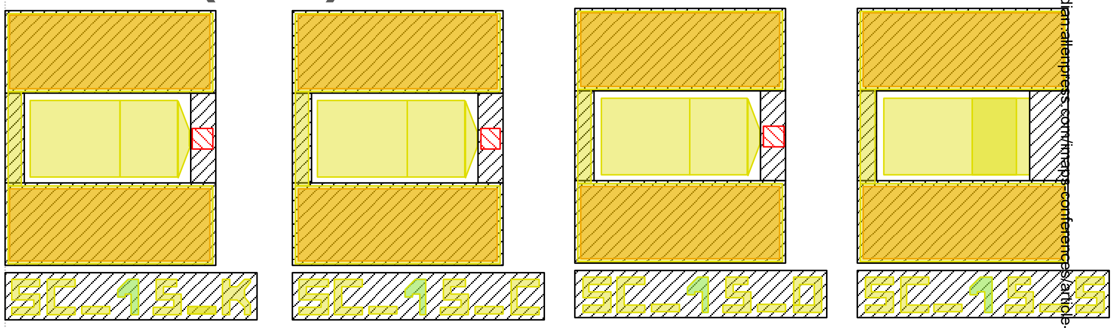
Tunability/C(V) characterization

INSTRUMENTS



Devices under test (DUT)

Deembedding structures



Square shaped Disc shaped Open Short

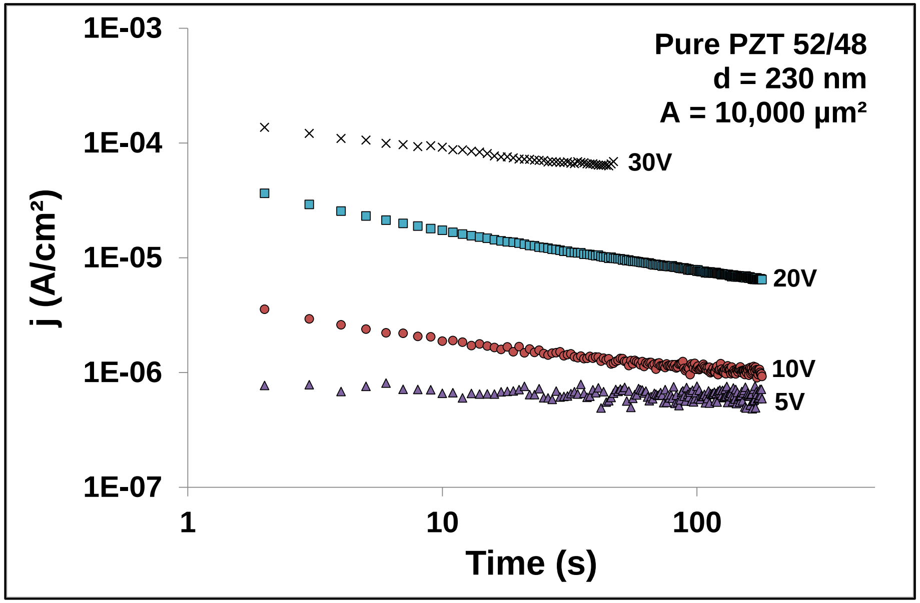
1. S_{11} parameters measurements [100MHz:4GHz] under applied voltage [0V:+20V]
2. Impedance calculation
3. Deembedding
4. Capacitance vs voltage/Tunability extraction

$$T = \frac{C_{eff}^{0V} - C_{eff}^{20V}}{C_{eff}^{0V}} \, [\%] \quad \text{or} \quad T = \frac{C_{eff}^{0V}}{C_{eff}^{20V}} : 1 \, [no\ unit]$$

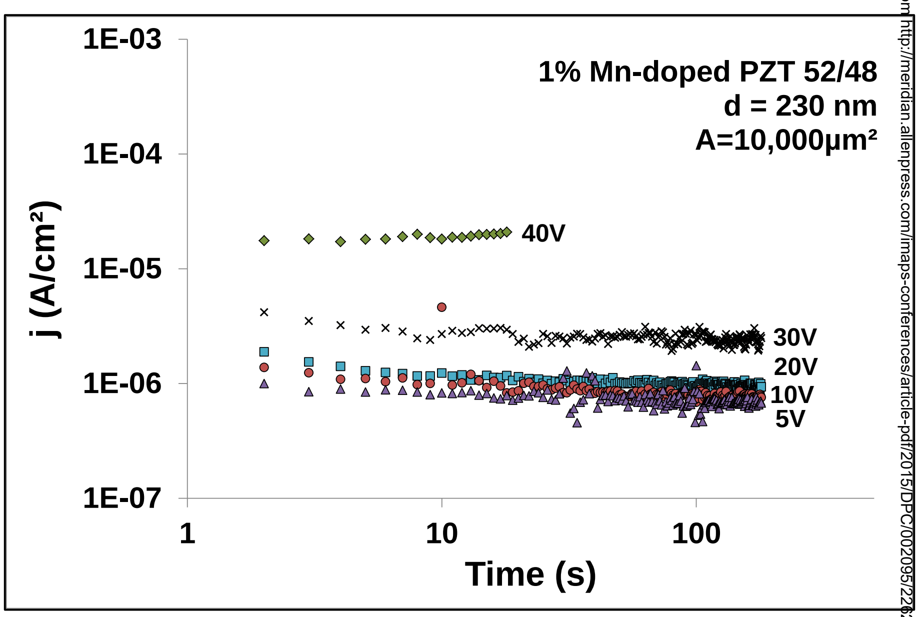
RESULTS AND DISCUSSION

LEAKAGE CURRENTS

PZT



PMZT 1%



Curie-von Schweider power law:

$$J(t) \propto t^{-n}$$

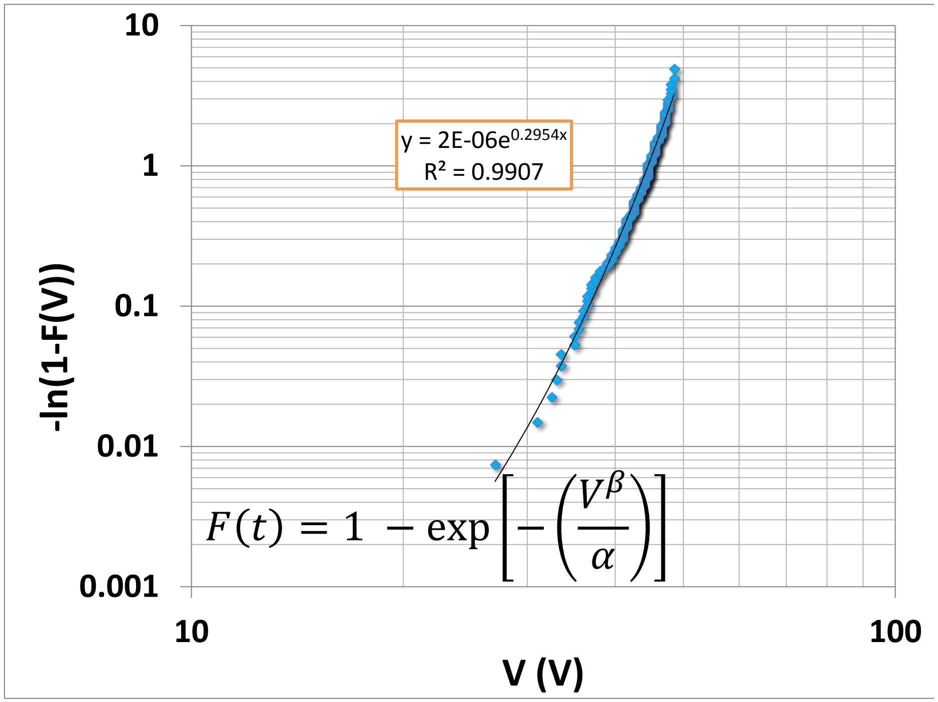
→ Space-charge relaxation mechanisms or trapping of charge carriers

→ Complementary measurements at various temperature required to determine conduction mechanisms

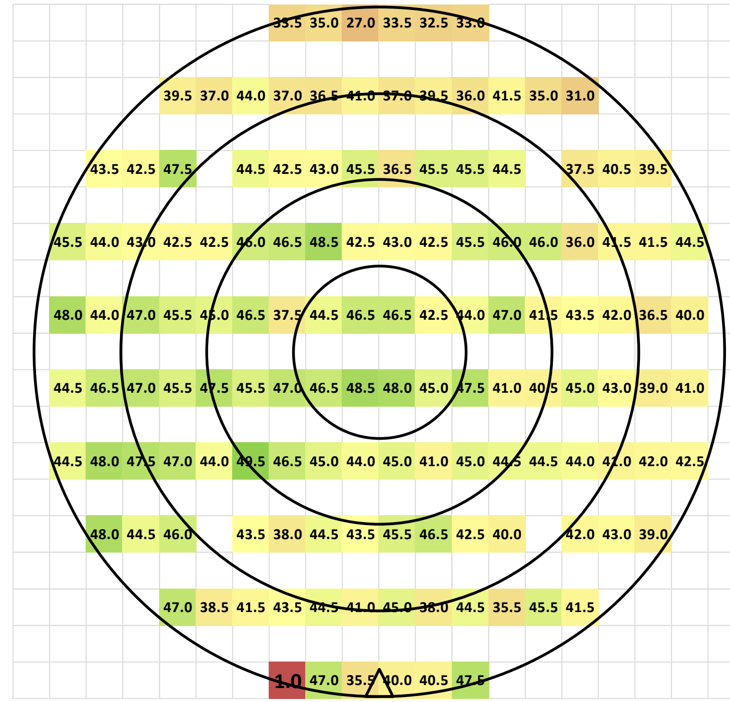
Relatively low leakage currents

BREAKDOWN VOLTAGES

Weibull distribution



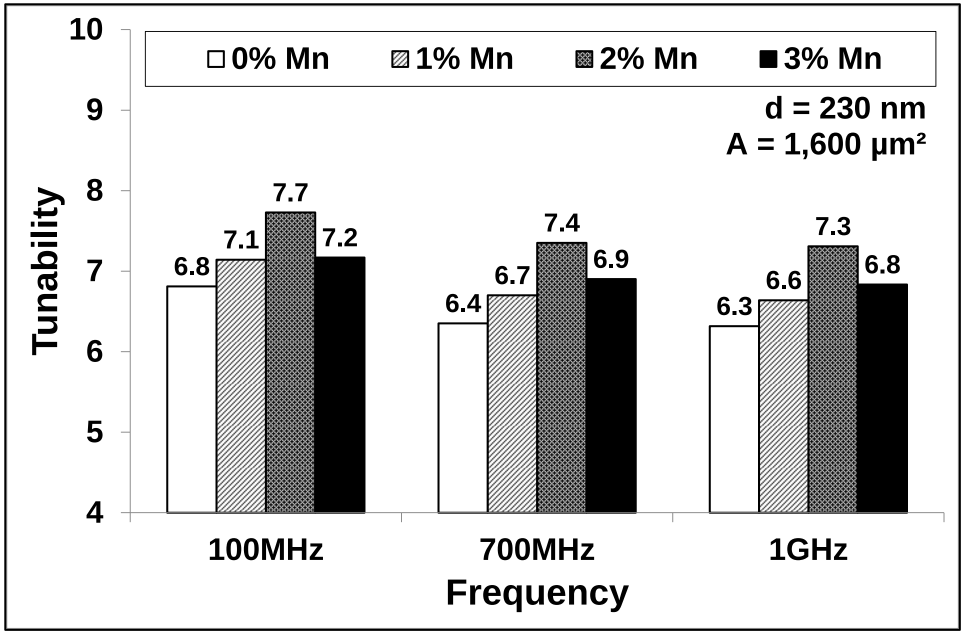
Breakdown voltage cartography



% Mn	0%	1%	2%	3%
Breakdown voltage (V)	44.5	44.9	56.6	55.4
Dielectric strength (MV/cm)	1.9	2.0	2.5	2.4

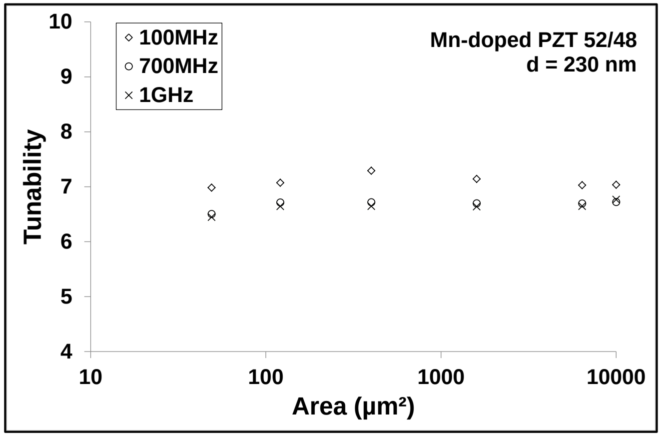
High dielectric strengthes

RF PROPERTIES (1/2)



- No specific law for the tunability variation as a function of the doping ratio
- **Highest tunability of 7.7:1@100MHz achieved with the PMZT doped with 2% Mn.**
- PZT & PMZT tunability is constant regardless of the capacitor area.

- **Enhanced tunability of both the PZT and the PMZT thin films were obtained**
- Tunability remains constant while the frequency increases from 100MHz to 1GHz.



- **tan δ <0.1 ~ to the state of the art for PZT-derived materials**

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RF PROPERTIES (2/2)

Dielectric tunability of various material

MATERIAL	T (%)	FREQUENCY	VOLTAGE (V)	REF.
BST	71.0	500MHz	9	A. Tombak *et al.*, 2002
BST	65.0	1MHz	8	B.H. Park *et al.*, 2000
BSKT	77.0	100kHz	12	C. Koppole *et al.*, 2013
PCT	70.0	1kHz	30	M.L. Calzad *et al.*, 2005
PZT	60.0	4GHz	13	D. Min *et al.*, 2012
PZT	69.3	1kHz	18	J. Wu *et al.*, 2008
PSZT	48.0	1MHz	15	Q.Y. Shao *et al.*, 2006
PLZT	65.0	10kHz	14	Z. Hu *et al.*, 2014
PZT	**84.1**	**1GHz**	**20**	**This work**
PMZT (2%Mn)	**84.9**	**1GHz**	**20**	**This work**

One of the highest reported tunability

FACTORS INFLUENCING THE TUNABILITY

Processing and integration factors

- Deposition technique,
- Curing processes (post-annealing, T°C,…),
- Electrodes & substrate materials,

Films and material properties

- Crystal structures
- Porosity
- Impurities
- Dead layer thickness
- Film thickness

Capacitor tunability

Variation with applied voltage & frequency

CONCLUSION & ON-GOING WORK

SUMMARY

- PMZT-based MIM capacitors have been manufactured using a low cost process ready for mass production
- Low leakage current density (which decreases by 1 to 2 orders of magnitude by modifying PZT with Mn @30V).
- High dielectric strengths achieving 2.5MV/cm
- Outstanding tunability as high as 85% (~7.5:1) @1GHz at 870kV/cm

  → among the highest ones reported in the literature for PZT-derived thin films, but also for other ferroelectric materials (such as BST tunability ~ 5:1)
- Mn-doped PZT thin films are promising candidates for RF tunable capacitors.

ON-GOING WORK

On PMZT

- Microstructural analyses such as XRD analyses to determine the crystal structure
- Current measurements at various temperature to identify the conduction mechanisms
- …

Characterization of other doped-PZT thin films

THANK YOU.

Work performed in the frame of TOURS 2015, project supported by the French program “Programme de l’économie numérique des Investissements d’Avenir”