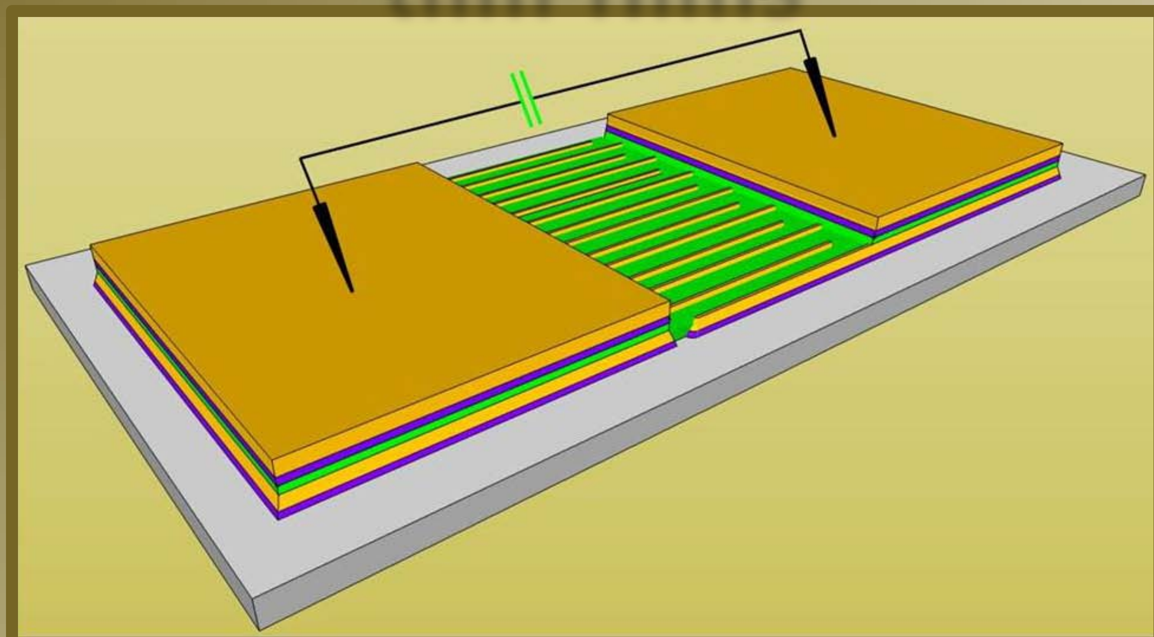
Growth and characterization of multiferroic $BiFeO_3$ thin films



Taimur Ahmed

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Outline

- Background
  - Ferromagnetics
  - Ferroelectrics
  - Multiferroics
    - $BiFeO_3$ (BFO)
- Design & modeling of dielectric response
- Device fabrication
- Characterization & Analysis
- Conclusion
- Future outlook

Background – Ferromagnetics

- Ferromagnetic materials
  - Materials retain their magnetic polarization
  - Curie-Weiss law (susceptibility is inverse dependent on Curie temperature)

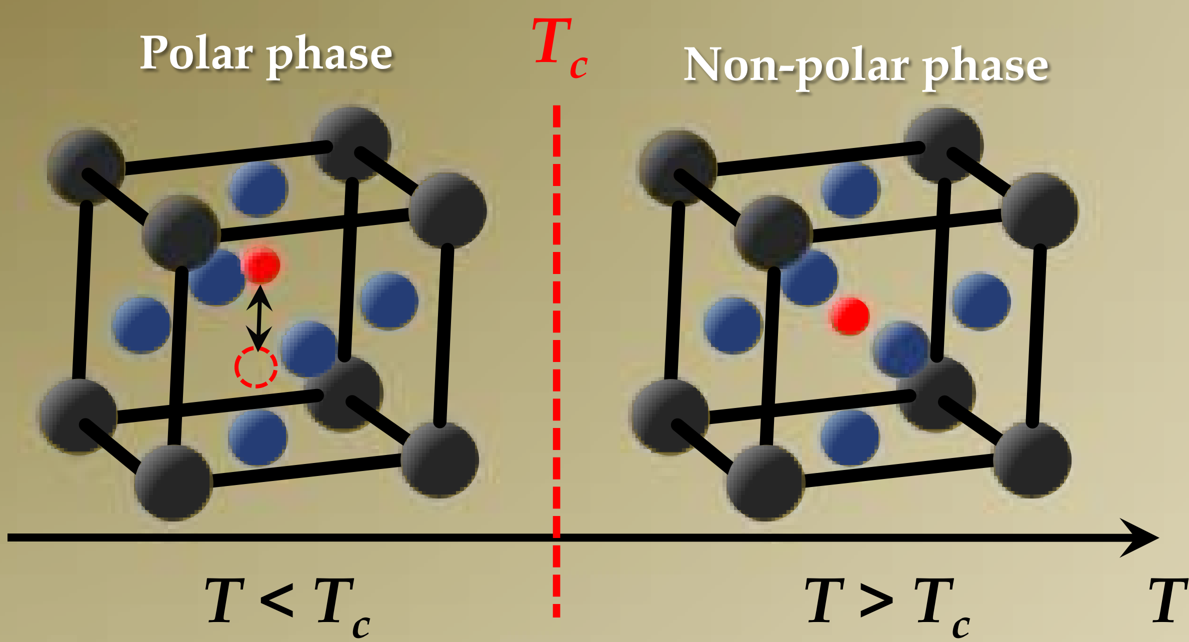
$$\chi = \frac{C}{(T - T_C)}$$

C = Curie constant of material
T = Absolute temperature
T_c = Curie temperature

- T>T_c: Ferromagnetics changes to paramagnetics
- T=T_c: Material is in phase transition

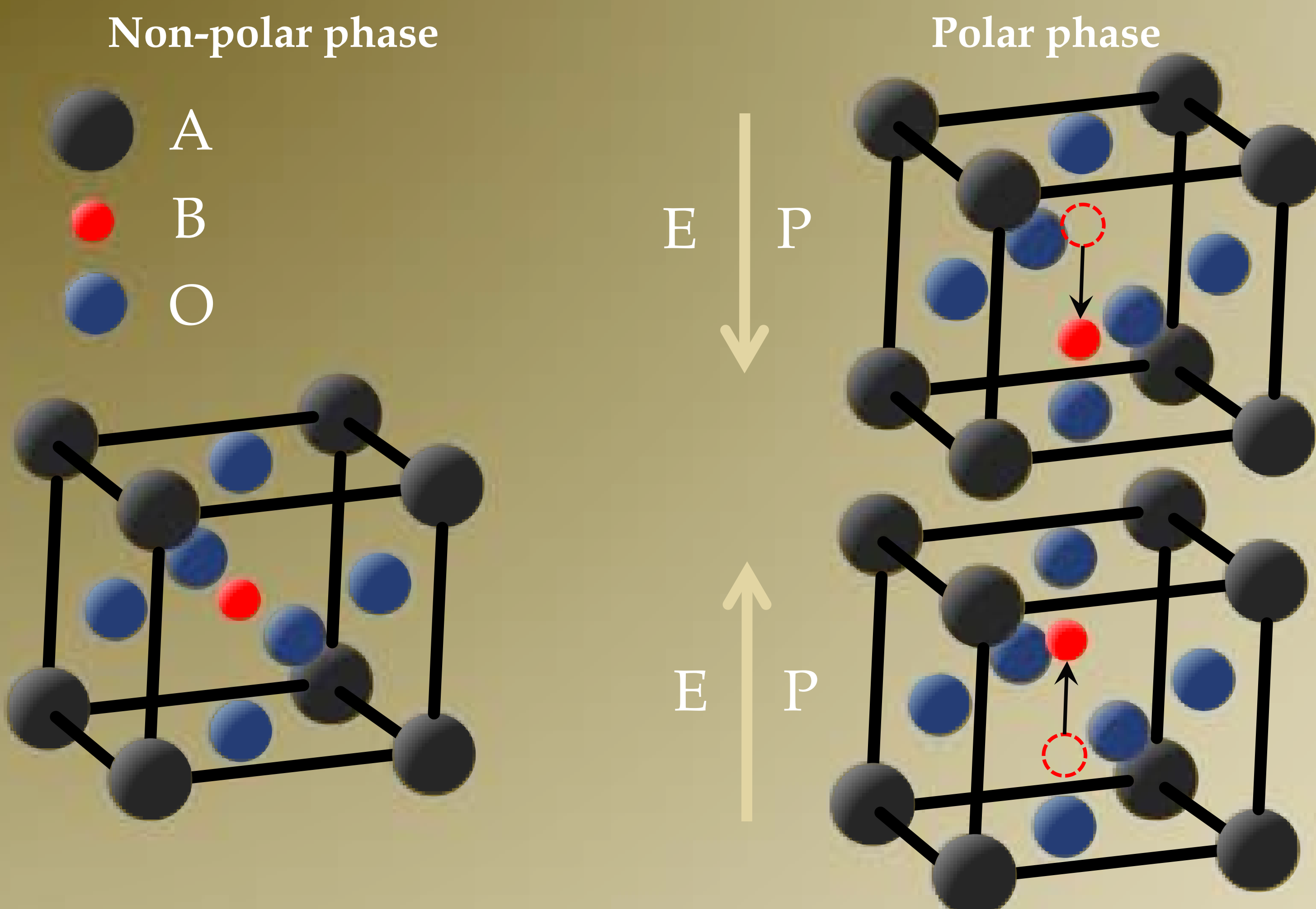
Background – Ferroelectrics

- Ferroelectric materials
  - Materials retain their electric (dipole) polarization
  - Curie temperature defines
    - Polar (ferroelectric) and non-polar (paraelectric) phase



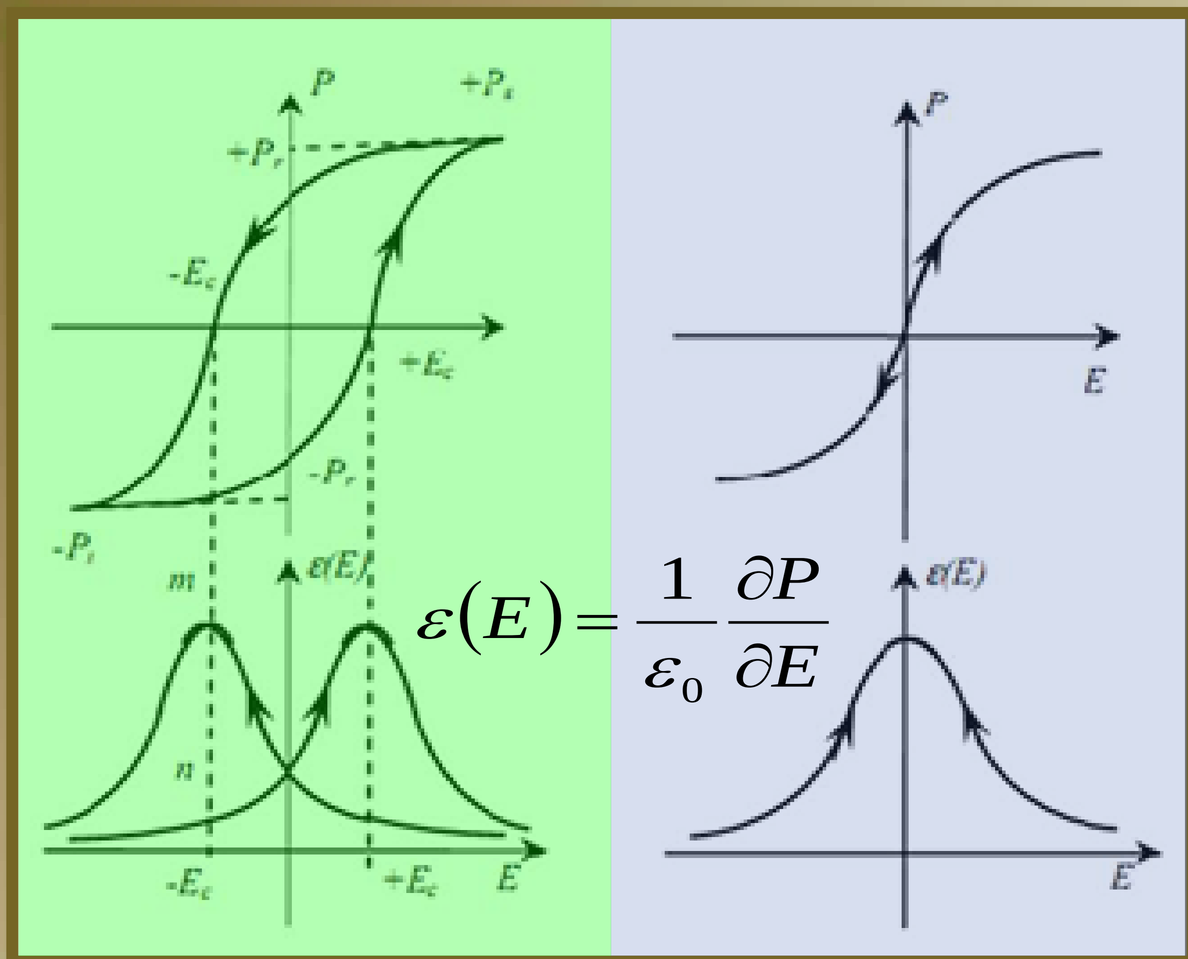
Background – Ferroelectrics

Perovskite - ABO_3



Background – Ferroelectrics

Polar phase **Non-polar phase**



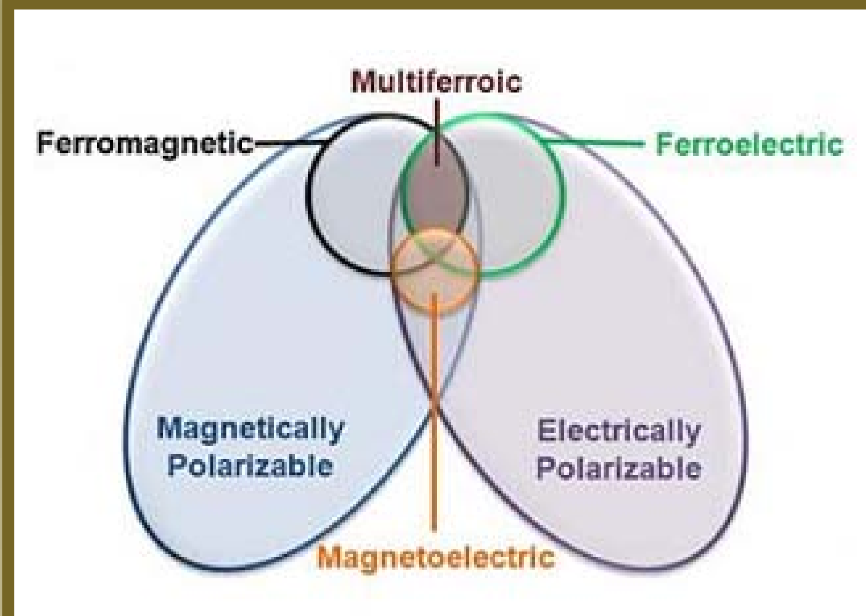
$$\varepsilon(E) = \frac{1}{\varepsilon_0}\frac{\partial P}{\partial E}$$

S. Gevorgian. Springer, 2009.

Background – Multiferroics

- Hans Schmid (1990):
  "A material that combines two (or more) of the primary ferroic orders in one phase"

ME = Ferromagnetic
+
Ferroelectric



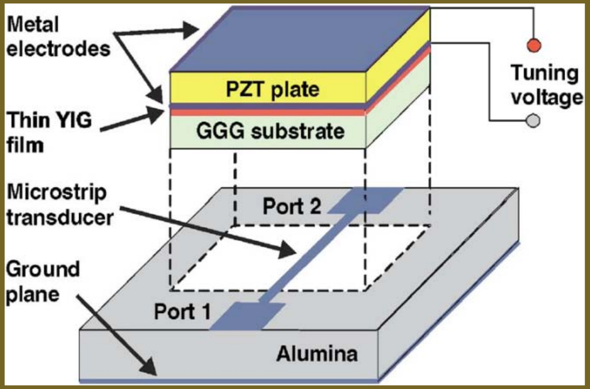
- In practice often:

Multiferroic = Magnetoelectric

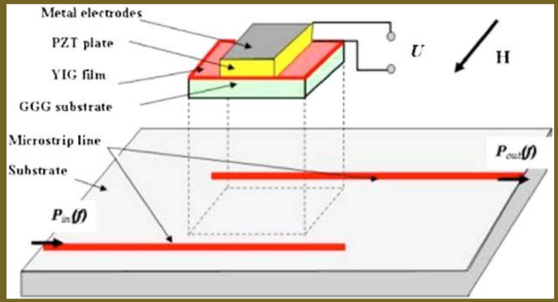
L. W. Martin et al. Mater. Sci. Eng., R, 68(4-6):89-133, May 2010.

Device Level Applications

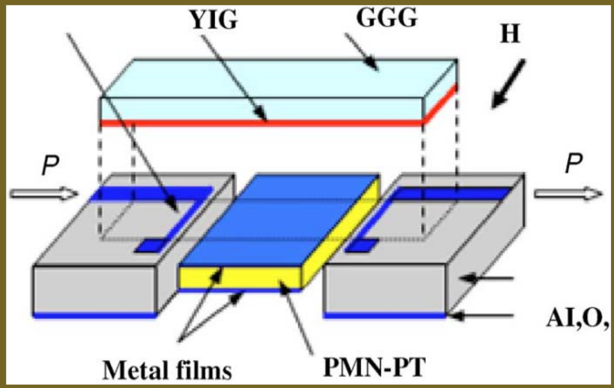
Tunable resonator



Tunable filter



Tunable phase shifter/delay line

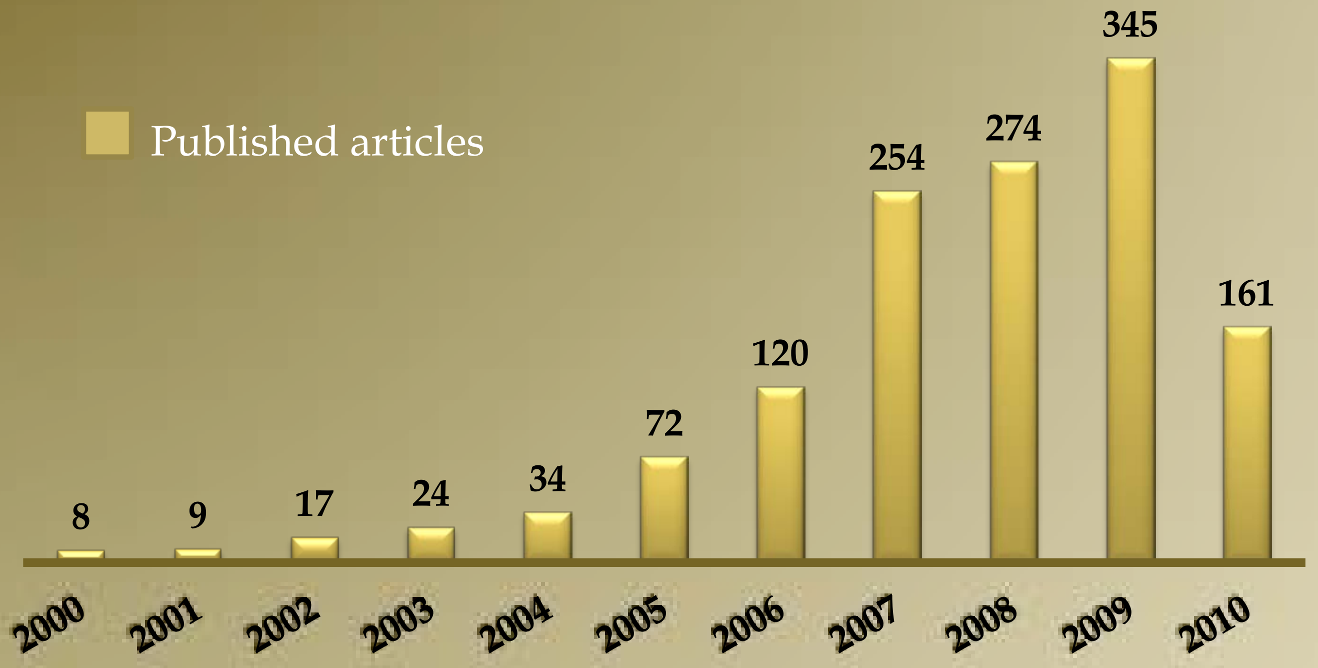


- Magnetoelectric memories
- Magneto-mechanical actuators
- Tunable microwave devices
- Sensors

Adapted from: Ce-Wen Nan et al., J. Appl. Phys., 103, 03101 (2008)

Background – $BiFeO_3$

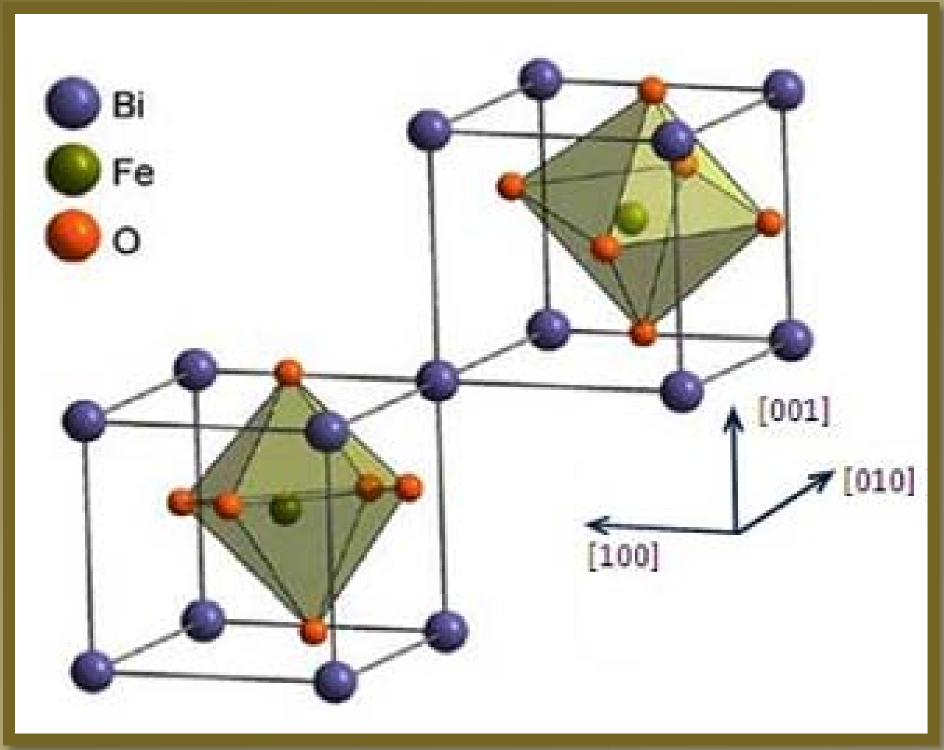
- Bismuth ferrite – $BiFeO_3$ (BFO)
  - High Curie temperature, T_C (850ºC)



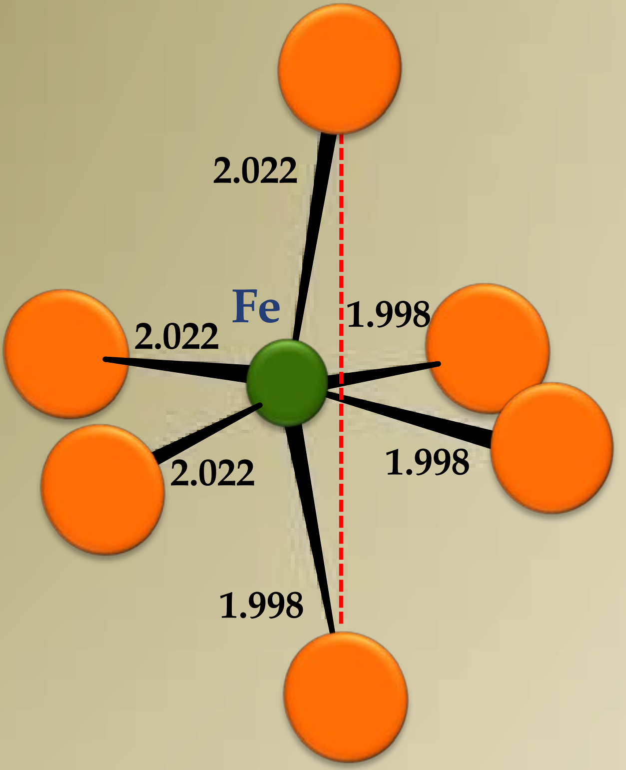
Data collected from: www.webofknowledge.com June 2010.

BiFeO$_3$: Crystal structure

Distorted Rhombohedral Perovskite



Oxygen octahedron



Adapted from: C. Michel et al. Solid State Commun., 7(9), 1969.

$BiFeO_3$ films: Challenges

- Leakage current
  - Non-stoichiometric thin films (Bi depletion)
  - Microstructural defects (grain boundaries *etc.*)

- Weak magnetoelectric coupling

Objective

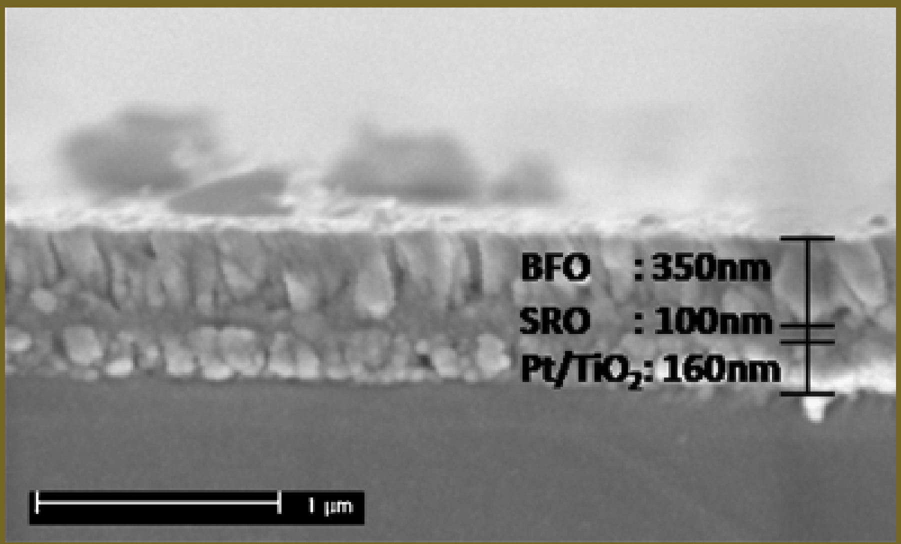
- Optimization of growth temperature of $BiFeO_3$ (BFO) thin films
  - To have stoichiometric thin films
  - To have low leakage current

Outline

- Background
- Design & modeling
  - Design configurations
    - Grain structure of $BiFeO_3$ films
    - Parallel plate configuration
    - Co-planar configuration
    - Co-planar configuration with buried ID electrode
  - Permittivity models
- Device fabrication
- Characterization & Analysis
- Conclusion

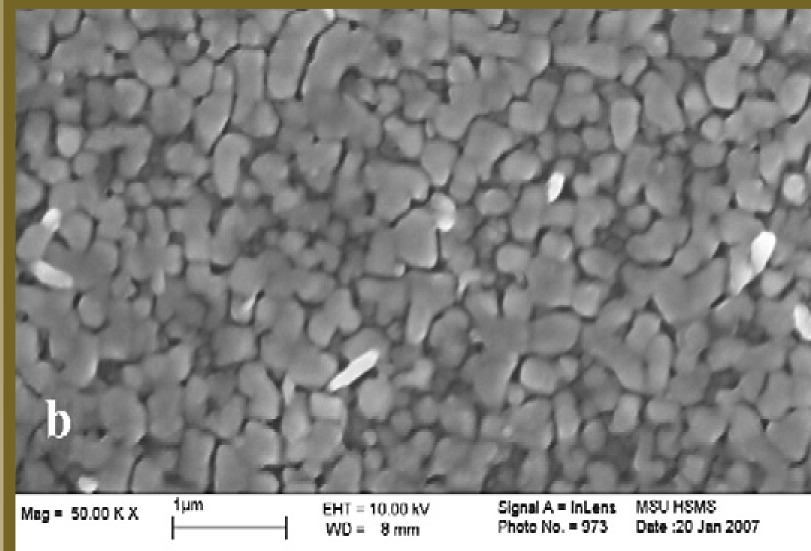
Grain structure of $BiFeO_3$ films

RF sputtering



R. Zheng et al. *J. Am. Ceram. Soc.* 91 (2008) 463.

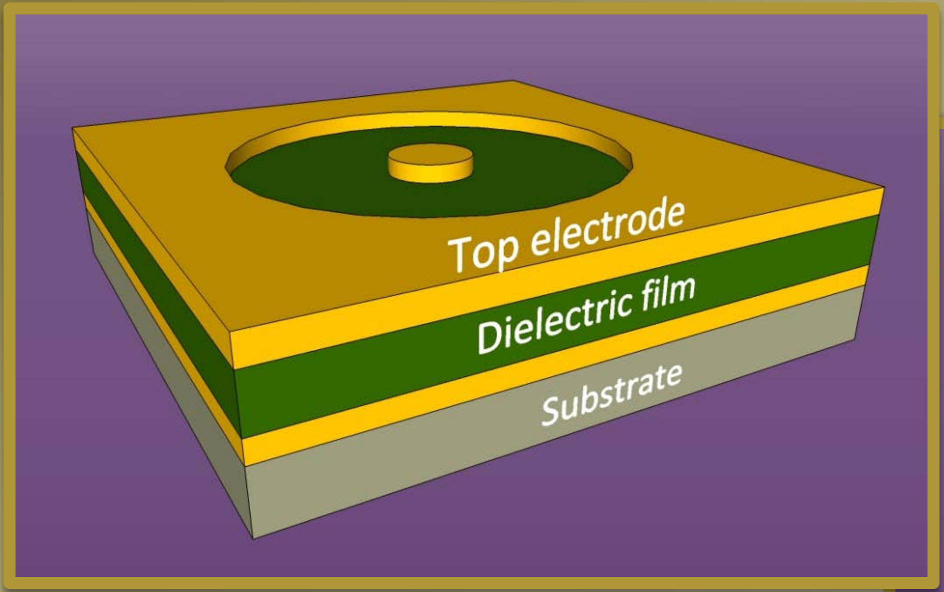
MOCVD

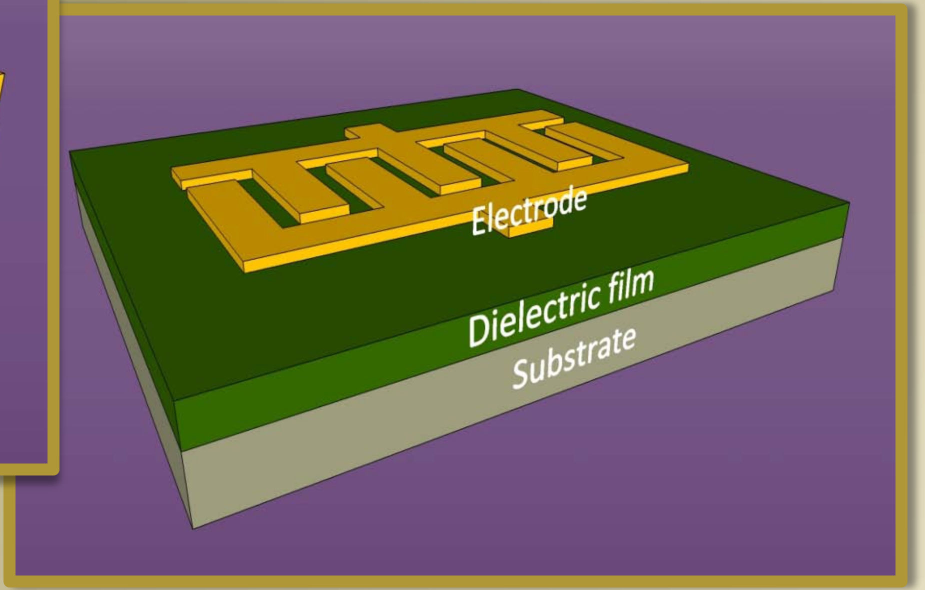


M.S. Kartavtseva et al. *Surface and Coatings Technology 201* (2007) 9149.

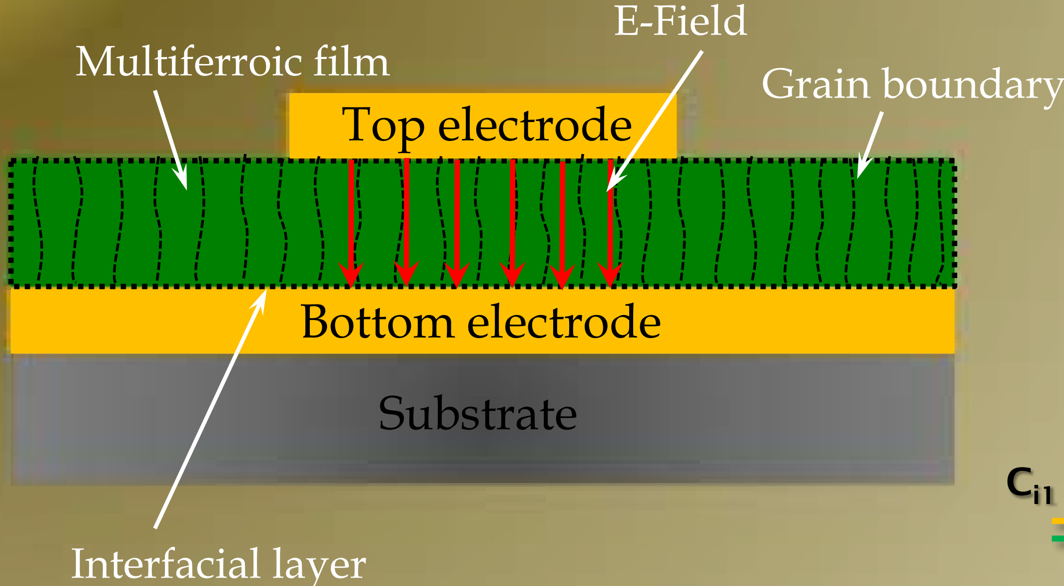
Design & modeling of dielectric response

- Design configurations
  - Parallel plate configuration
  - Co-planar inter digital (ID) configuration





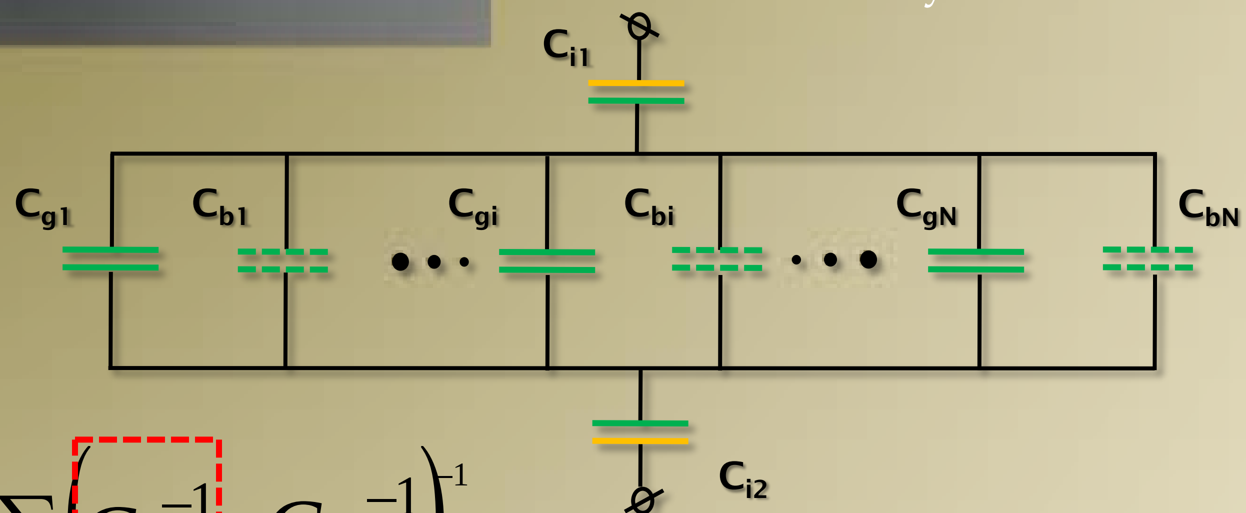
Parallel plate configuration



C_b = Capacitance of grain boundaries

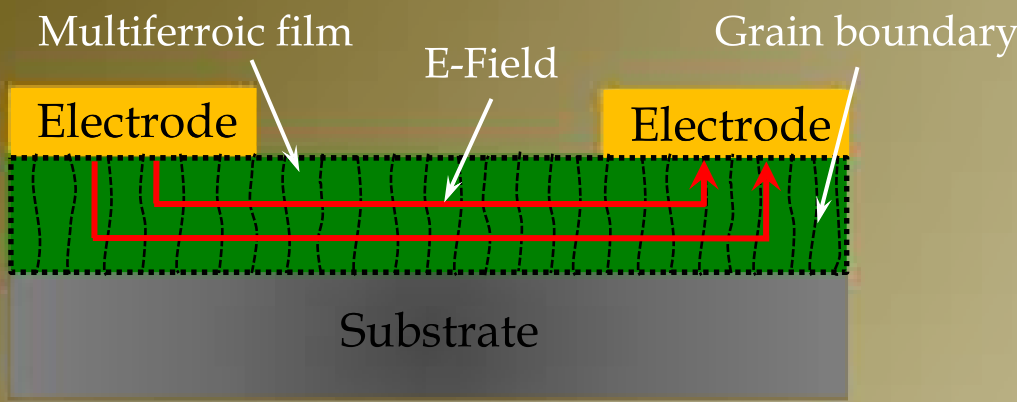
C_g = Capacitance of grains

C_i = Capacitance of interface layers



$$C_{eq} = \sum C_b + \sum \left(C_i^{-1} + C_g^{-1} \right)^{-1}$$

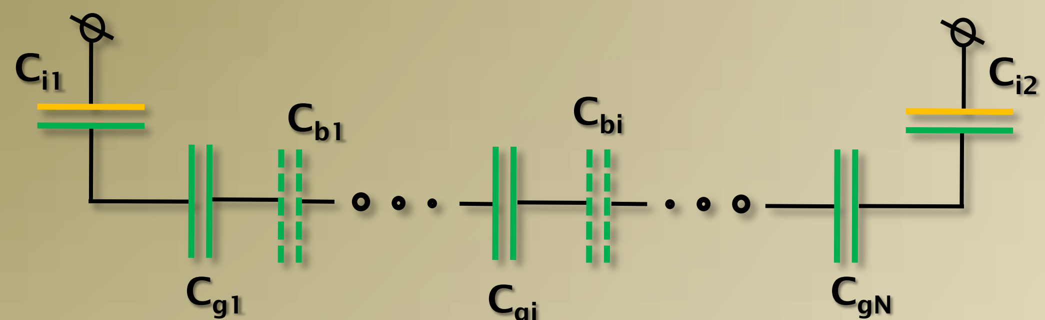
Co-planar configuration



C_b = Capacitance of grain boundaries

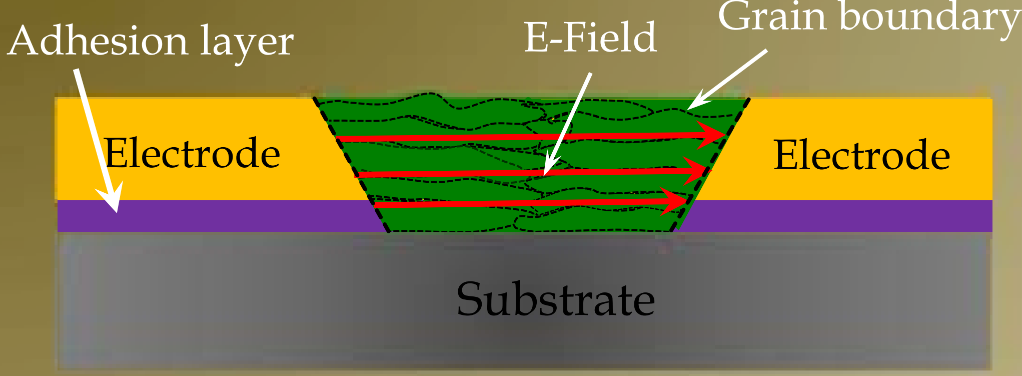
C_g = Capacitance of grains

C_i = Capacitance of interface layers



$$C_{eq}^{-1} = \sum C_b^{-1} + \sum C_i^{-1} + \sum C_g^{-1}$$

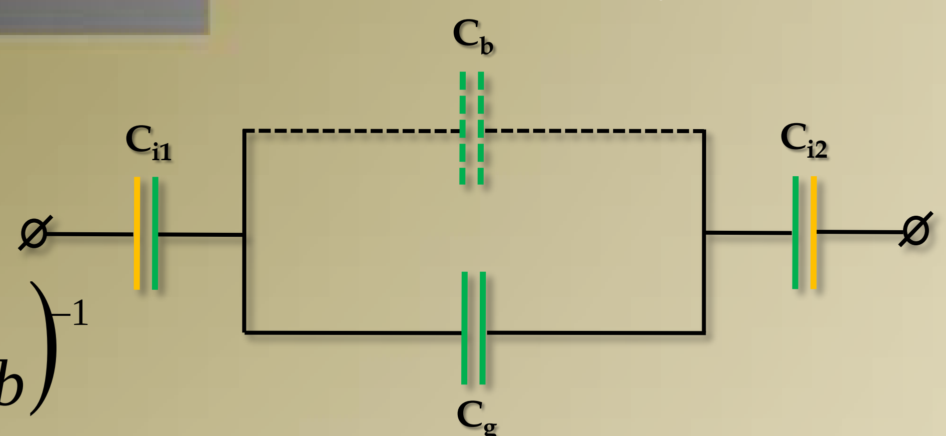
Co-planar configuration: buried electrodes



C_b = Capacitance of grain boundaries

C_g = Capacitance of grains

C_i = Capacitance of interface layers



$$C_{eq}^{-1} = \sum C_i^{-1} + \sum \left(C_{g+b}\right)^{-1}$$

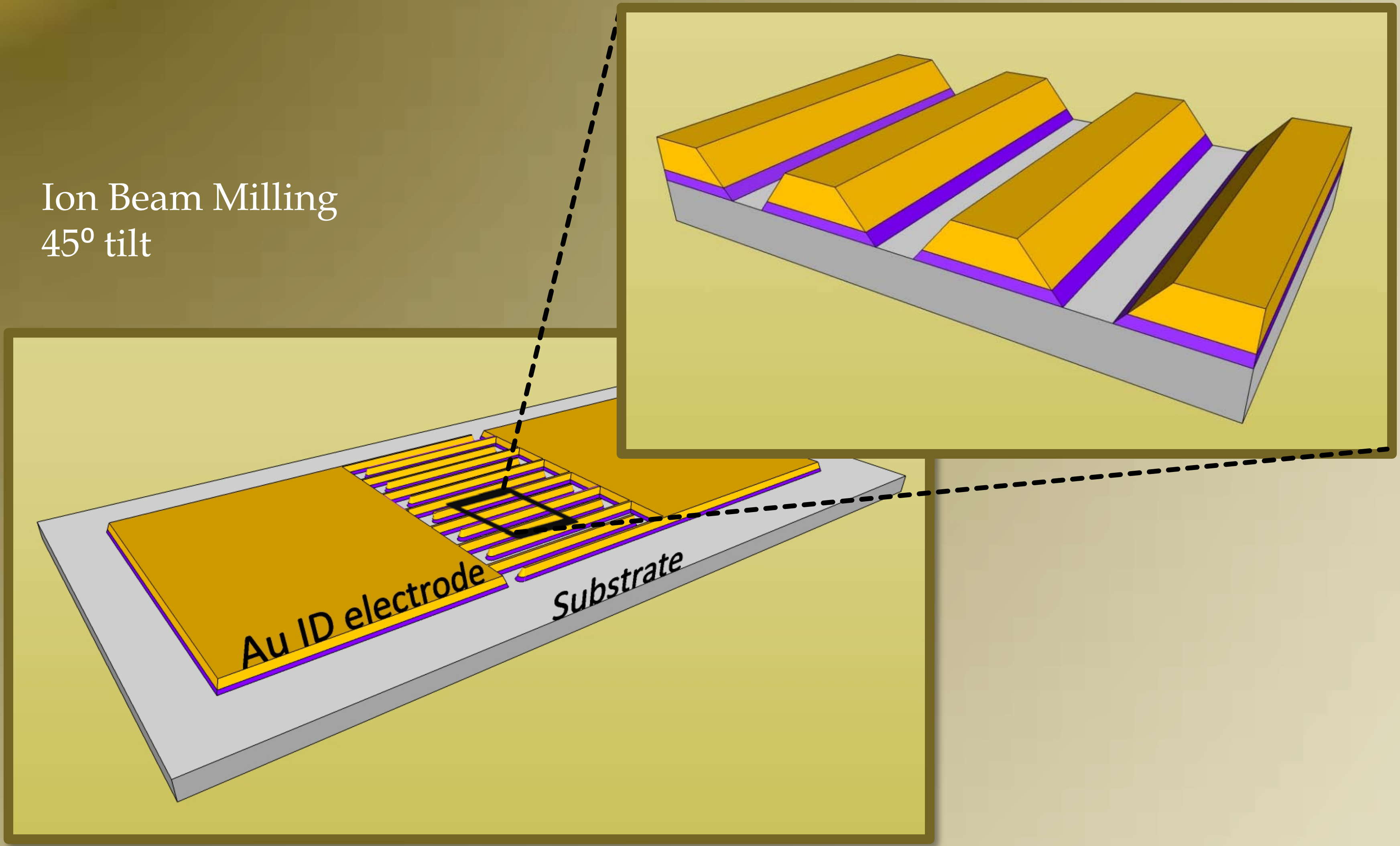
$$C_{eq}^{-1} \approx \sum C_g^{-1}$$

Outline

- Objective
- Background
- Design & modeling of dielectric response
- Device micro fabrication
  - Patterning of IDC electrodes
  - BFO thin film growth (PLD)
  - Contact pads deposition
- Characterization & Analysis
- Conclusion
- Future outlook

ID electrode patterning

Ion Beam Milling
45º tilt



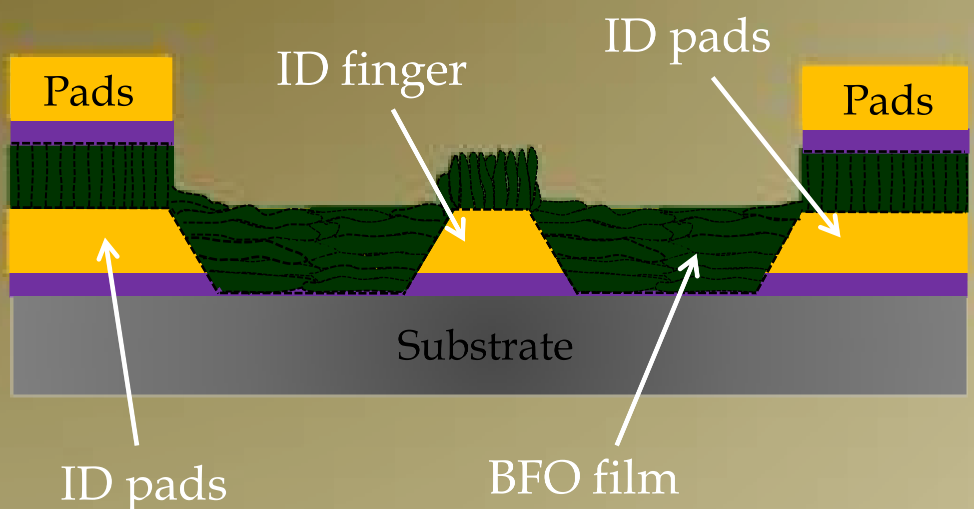
$BiFeO_3$ thin film growth

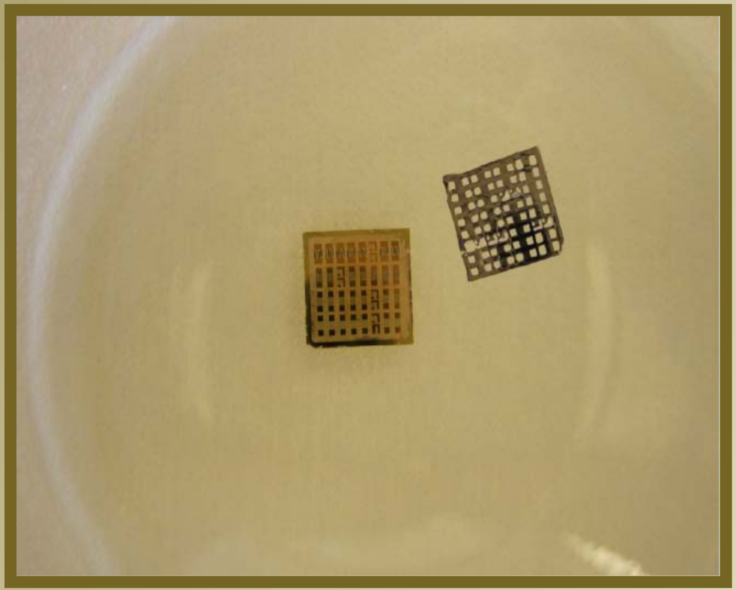
- Pulsed Laser Deposition (PLD)

Parameters	Comments
Laser source	KrF
Laser wavelength	248 nm
Energy	1.5 mJ/cm^2
Target	$Bi_{1.1}FeO_3$
Oxygen pressure	1 x 10^{-2} mbar
Repetition rate	10 Hz
Substrate	Au/Ti/SiO_2
Substrate temperature	**500^0C -750^0C**
Substrate-target distance	6cm

Contact pad deposition & lift-off

E-beam evaporator
Ti: 50 nm
Au: 500 nm

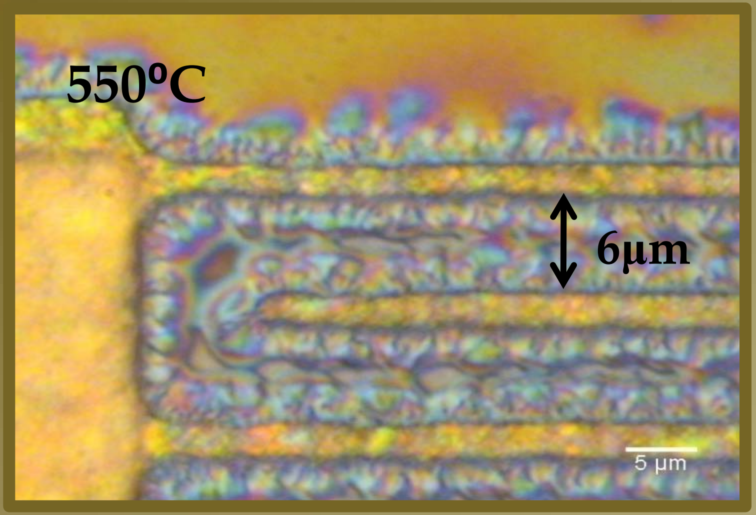


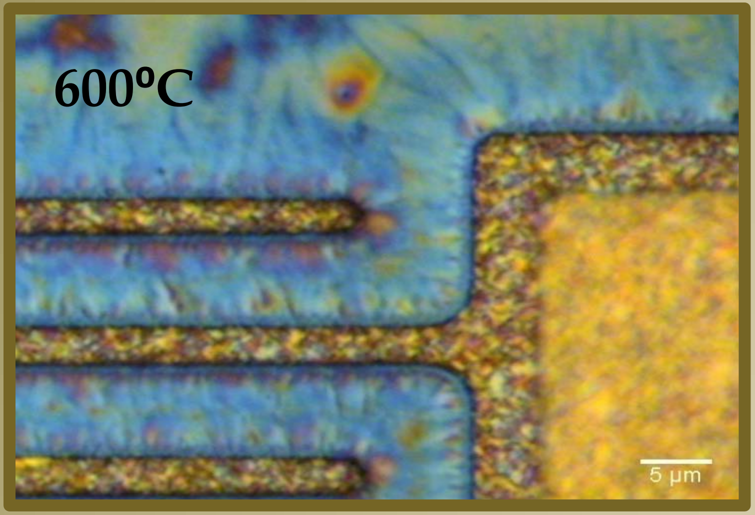


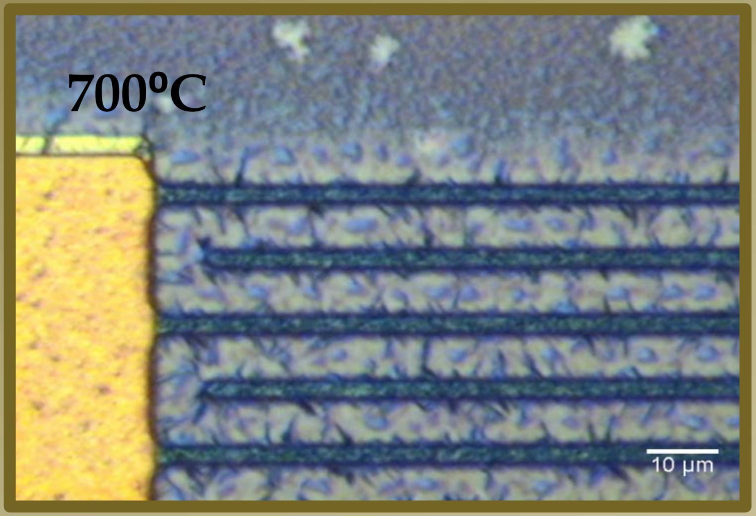
Outline

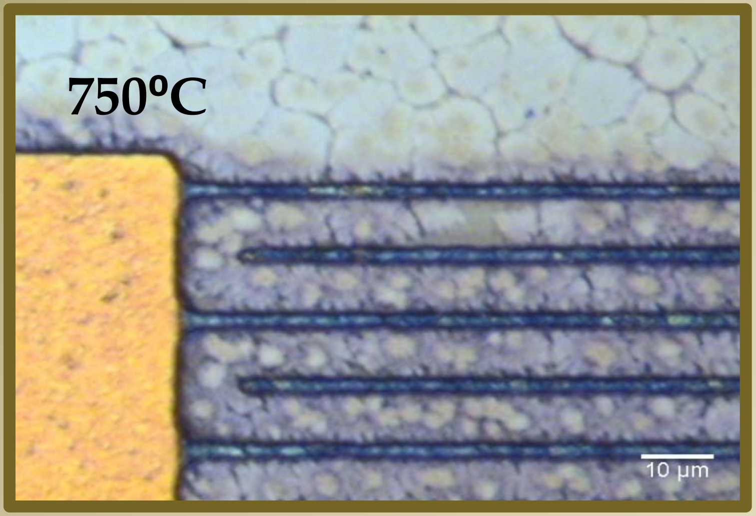
- Background
- Design & modeling of dielectric response
- Device fabrication
- Characterization & Analysis
  - Microstructure of deposited thin films
  - Dielectric response
  - Magnetoelectric response
- Conclusion

Microstructure
As-deposited films

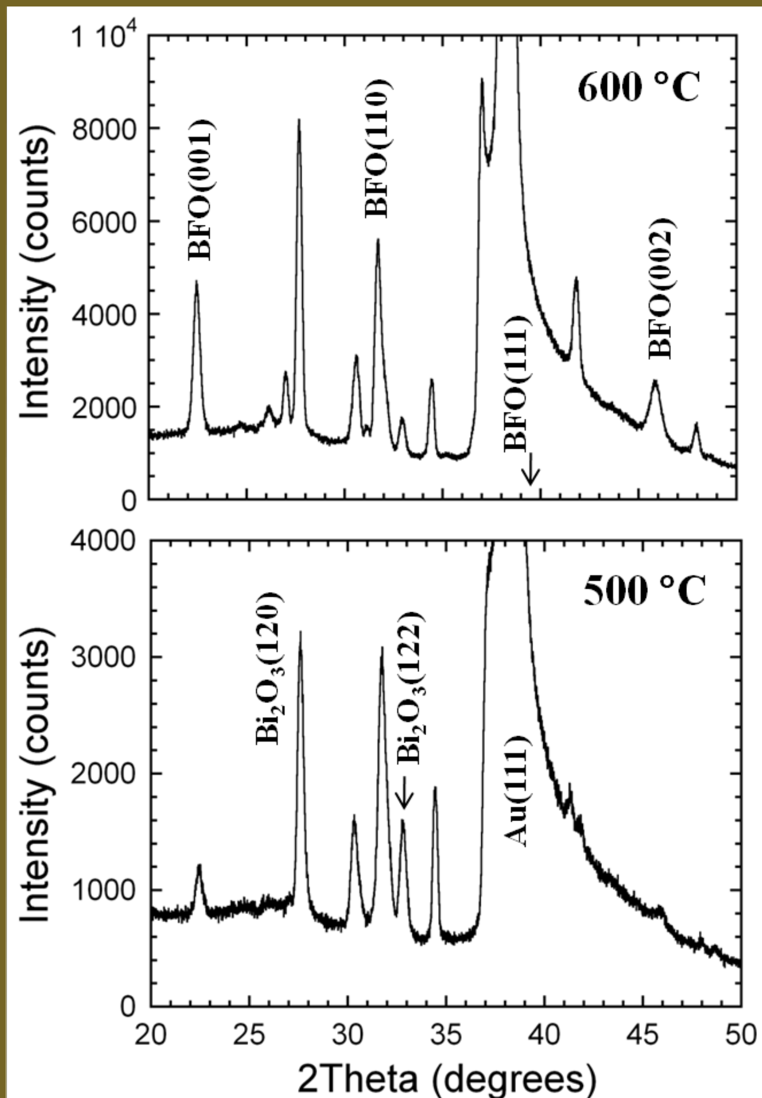




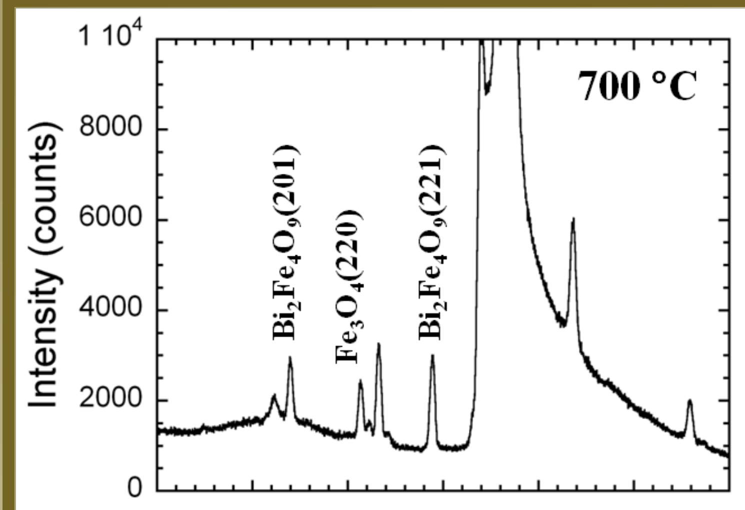




Stoichiometry
As-deposited films

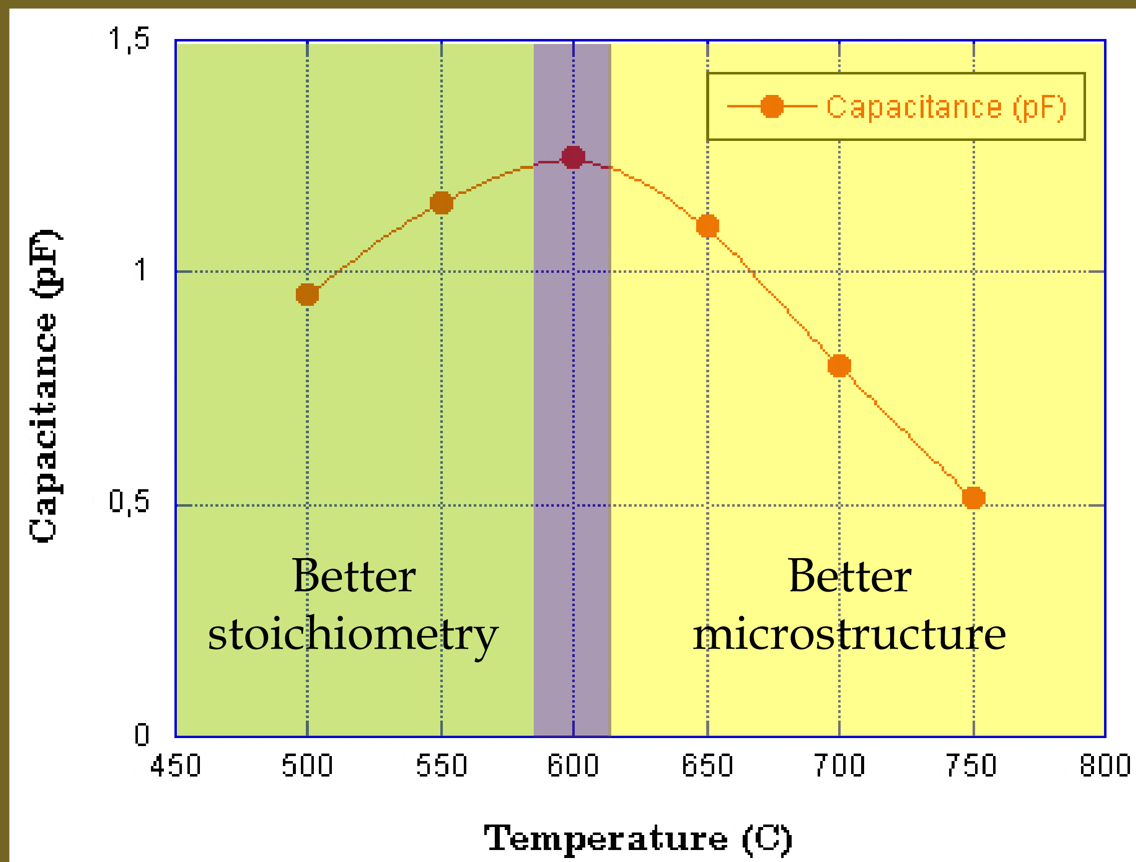


XRD Spectra



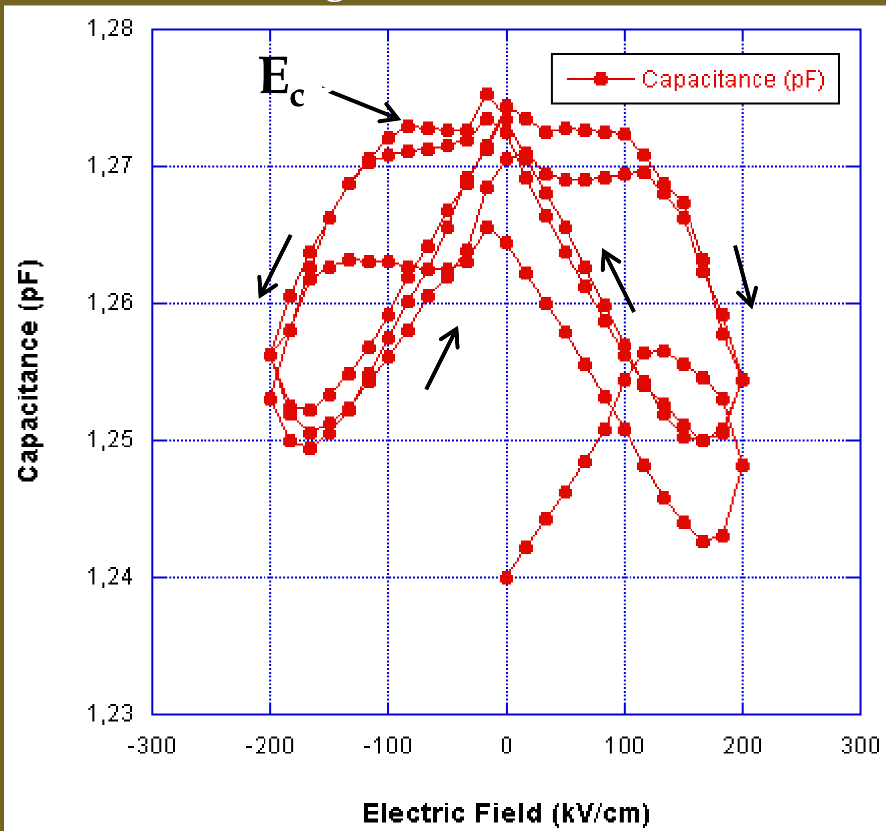
Dielectric Response

As – deposited BFO thin films



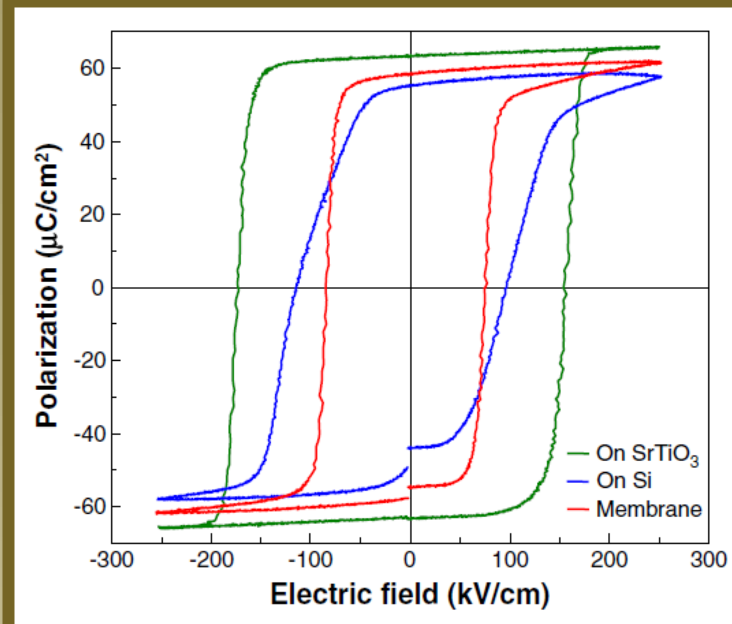
C(V) response

$T_g = 600^0C$



80kV/cm

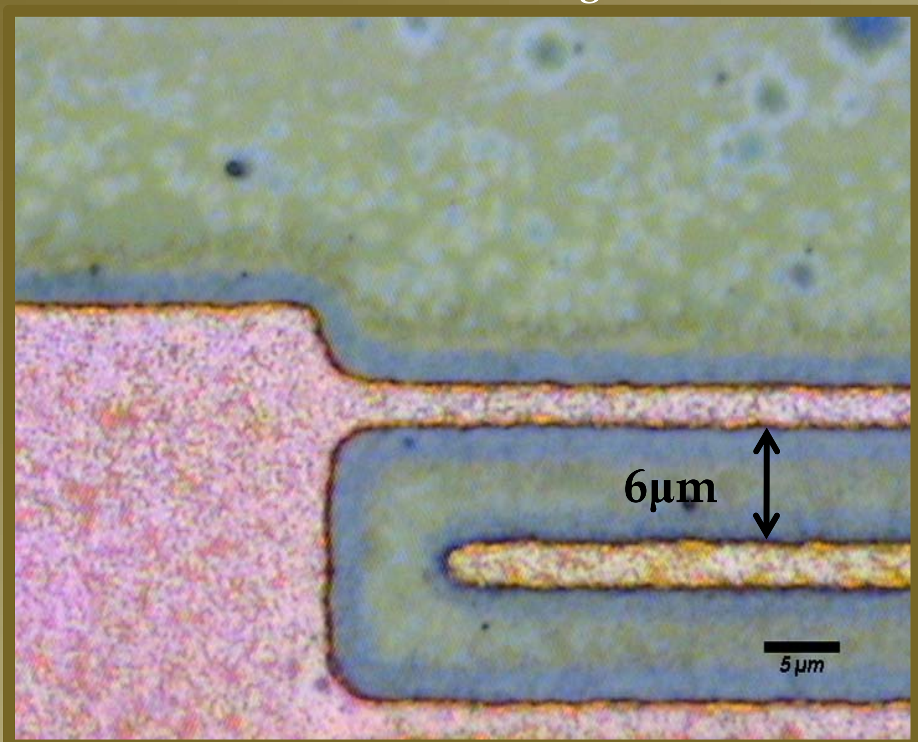
Epitaxial $BiFeO_3$ thin films

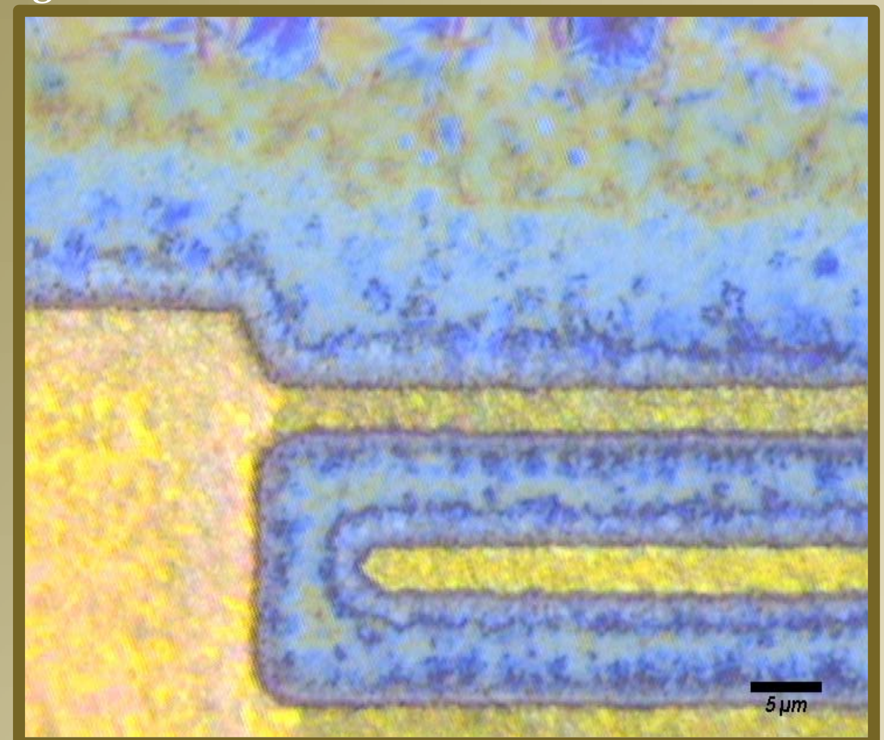


H. W. Jang et al. Phys. Rev. Lett. 01 (2008) 107602-1

Microstructure
Ex-situ annealed films

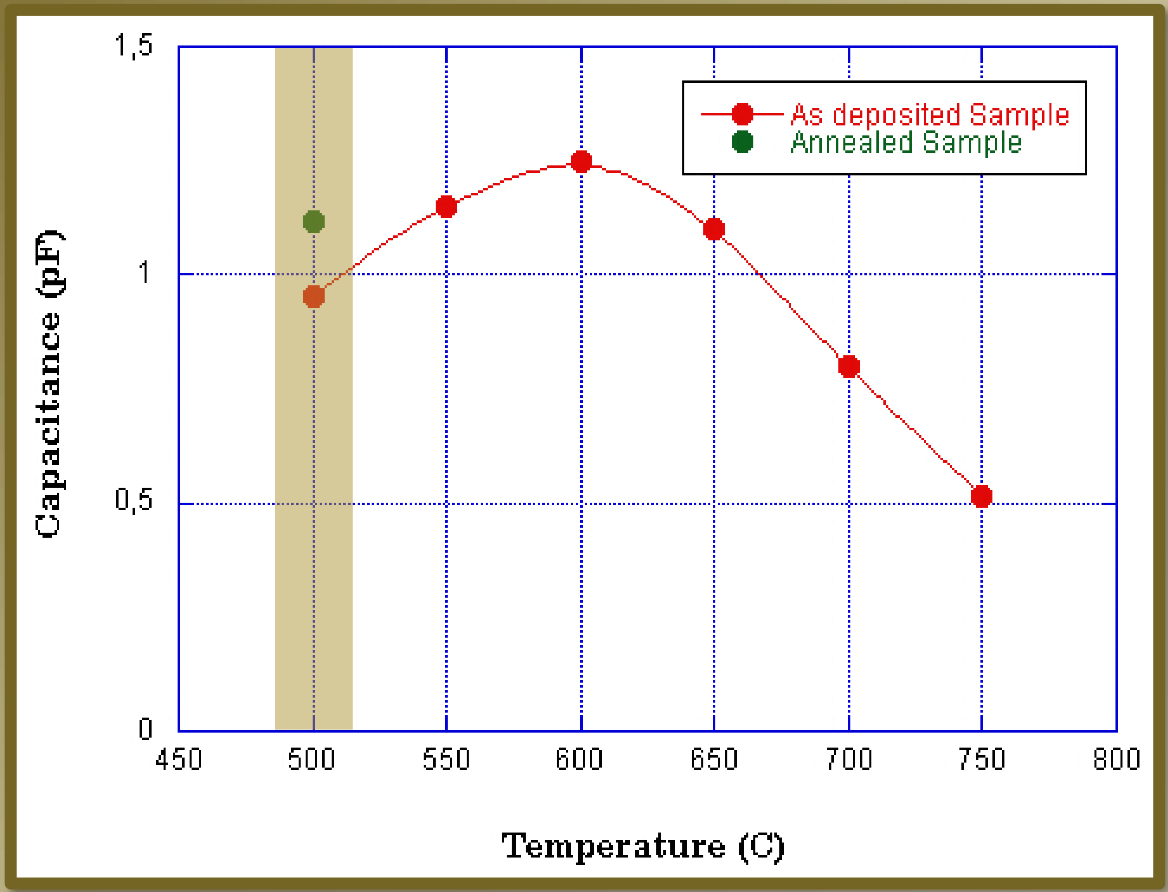
As deposited T_g = 500^{0}C **T_g =500^{0}C & Annealed at 700^{0}C**





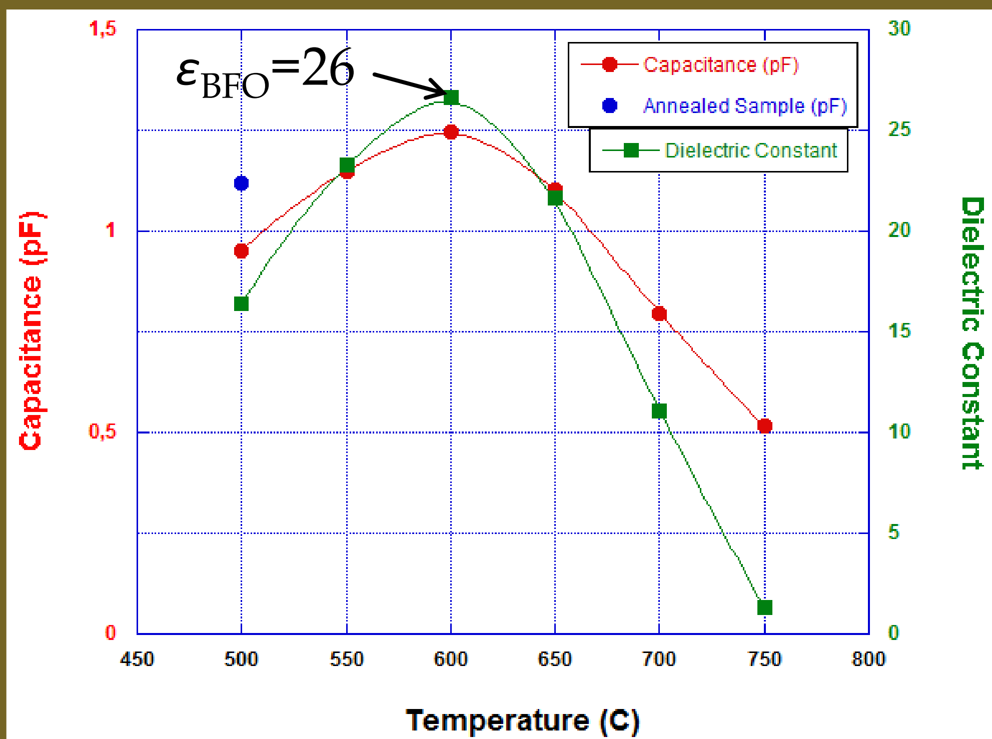
Dielectric Response

Ex – situ annealed (700^{0}C) BFO thin film

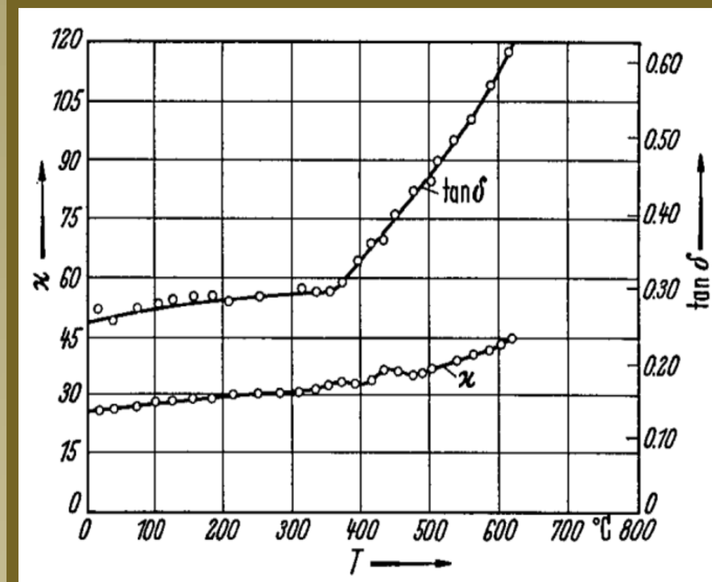


Dielectric Response

Dielectric constant (Farnell's model)



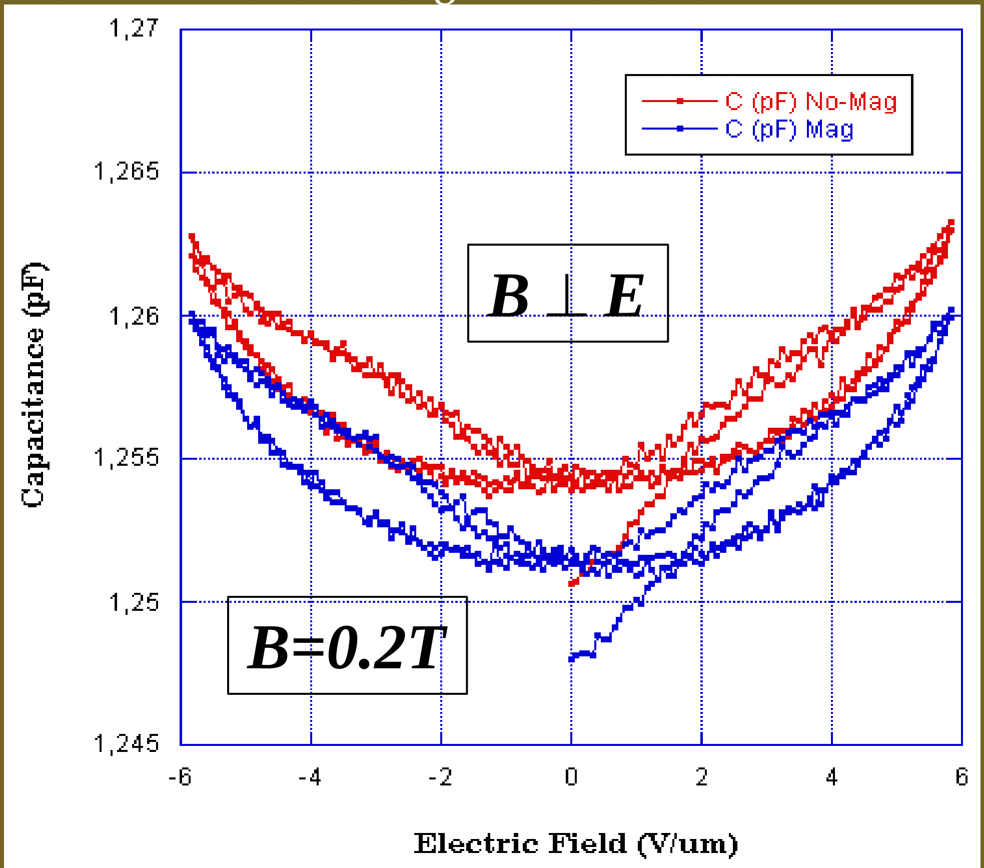
Bulk $BiFeO_3$ ceramic



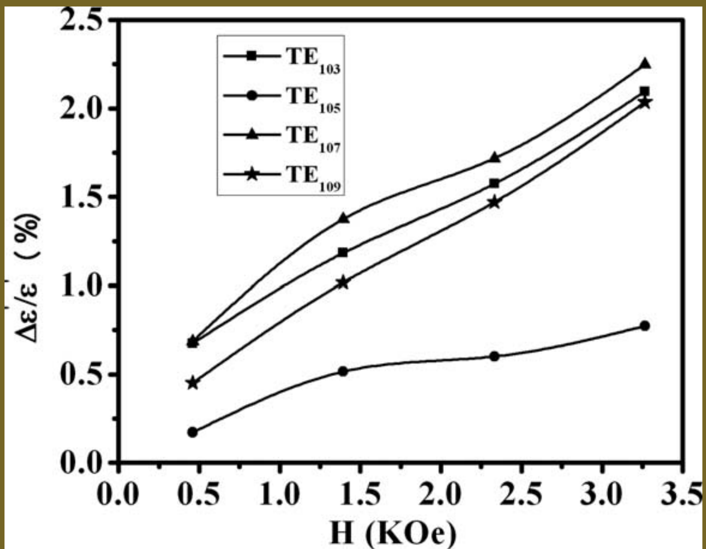
Yu.E. Roginskaya, et al. Sov. Phys. JETP, 23 (1966) 47

Magnetoelectric response

T_g=600⁰C



BiFeO$_3$/quartz substrate



F. B. A. Ahad, *J. Appl. Phys.* 105, 07D912 (2009)

ME tunability = Δε/ε =0.21%

Outline

- Background
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- Characterization & Analysis
- Conclusion

Conclusions

- Effect of T_g on BFO films growth
  - Strong dependence on film's microstructure and stoichiometry
- BFO films grown over Au IDC electrodes
  - Improved microstructure/large in-plane grains
  - Reduced parasitics/less grain boundaries
- Permittivity (26), E_c (80kV/cm) and ME tunability of 0.21% by 0.2 T @ T_g=600^{0}C are close to bulk BFO

Conclusions

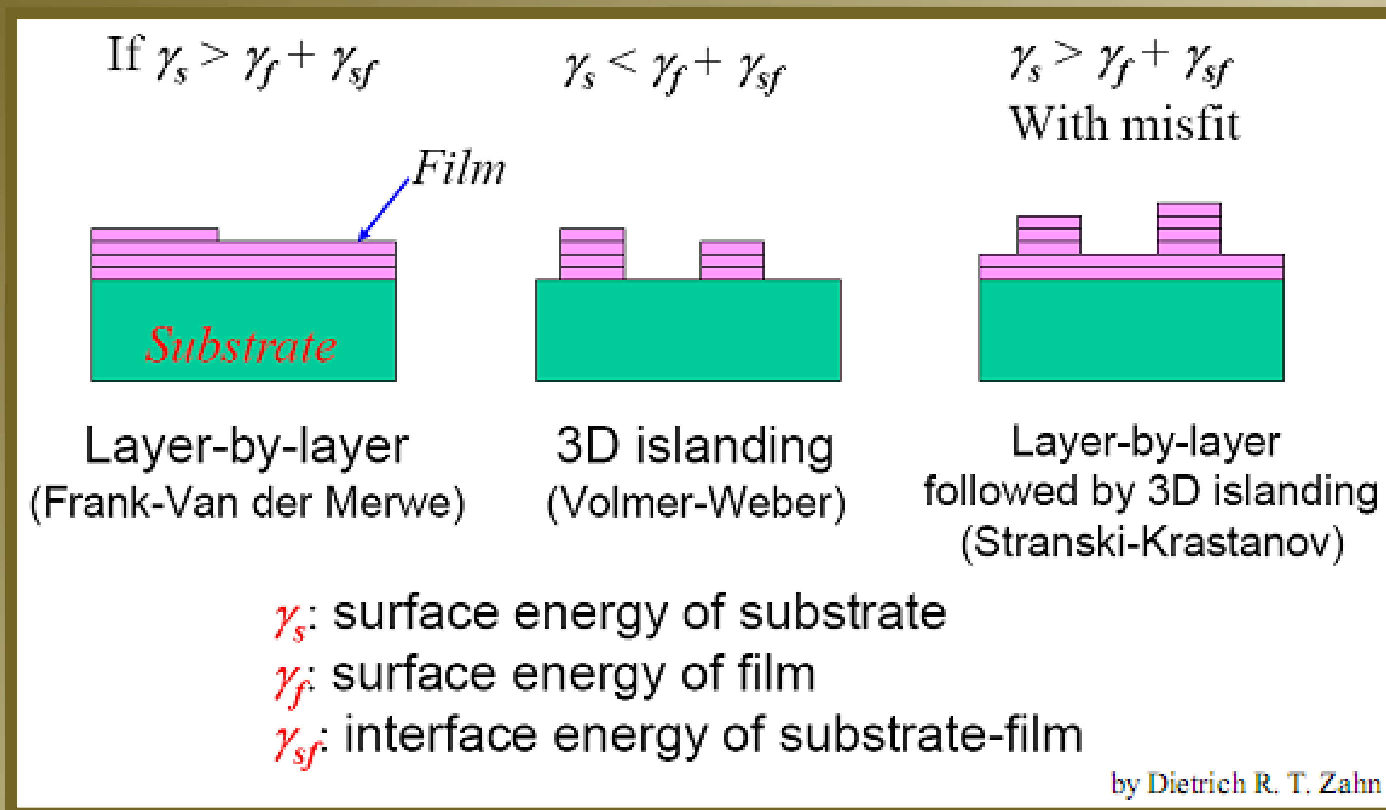
- Post deposition ex-situ annealing results higher permittivity than as-deposited films
  - Improved microstructure/Increased grain size
  - Simultaneously preserving stoichiometry

Journal Publications

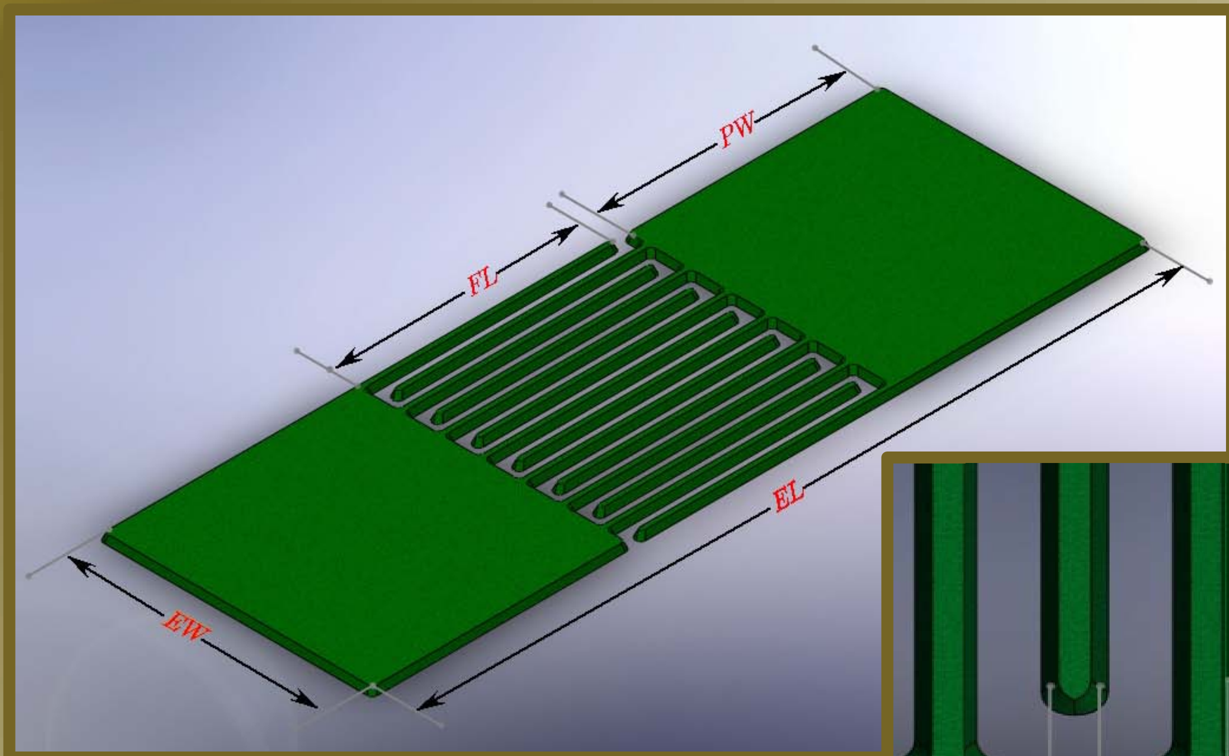
- **Taimur Ahmed**, A. Vorobiev, S. Gevorgian, "*Growth temperature dependent dielectric properties of BiFeO3 thin films deposited on silica glass substrates*" Thin Solid Films, 520 (13) pp. 4470-4474 (2012).

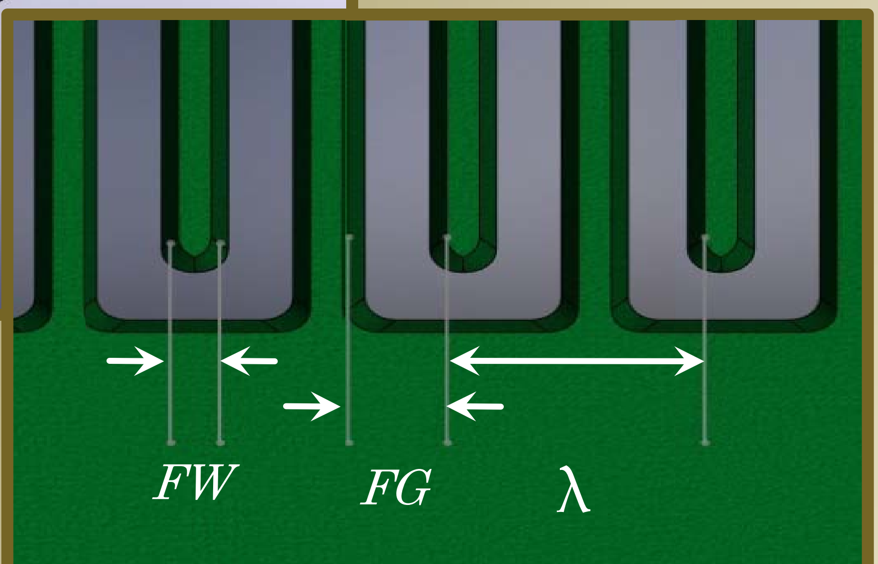
- A. Vorobiev, **Taimur Ahmed**, S. Gevorgian, "*Microwave response of BiFeO3 films in parallel-plate capacitors*" Integrated Ferroelectrics, 134 pp. 111-117 (2010).

PLD: Film nucleation and growth



Permittivity model





Permittivity model

- Farnell's model

$$\varepsilon_{BFO} = \frac{\left(C - K\varepsilon_S\right)}{K + \left\{0.29\left(\frac{h}{L}\right)^{-1.5} - 1\right\}}$$

$$K = 6.5\left(\frac{FW}{L}\right)^2 + 1.08\left(\frac{FW}{L}\right) + 2.37$$

C = Measured capacitance
ε_s= Dielectric constant of substrate (SiO_2)
L = (FW + FG)

	Parameters	Dimensions (μm)
FL	Finger length	700
FW	Finger width	3
FG	Finger gap	6
h	Finger/electrode thickness	0.55
P	Number of finger pairs	25