Doping of $BiScO_3$-$PbTiO_3$ Ceramics for Enhanced Properties

Alp Sehirlioglu[1], Ali Sayir[1,2] and Fred Dynys[2]

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Abstract

High-temperature piezoelectrics are a key technology for aeronautics and aerospace applications such as fuel modulation to increase the engine efficiency and decrease emissions. The principal challenge for the insertion of piezoelectric materials is the limitation on upper use temperature which is due to low Curie-Temperature (T_C) and increasing electrical conductivity. $BiScO_3$-$PbTiO_3$ (BS-PT) system is a promising candidate for improving the operating temperature for piezoelectric actuators due to its high T_C(>400ºC). Effects of Zr and Mn doping of the BS-PT ceramics have been studied and all electrical and electromechanical properties for Sc-deficient and Ti-deficient BS-PT ceramics are reported as a function of electrical field and temperature. Donor doping with Zr and Mn (in Sc deficient compositions) increased the DC-resistivity and decreased tanδ at all temperatures. Resulting ceramics exhibited saturated hysteresis loops with low losses and showed no dependence on the applied field (above twice the coercive field) and measurement frequency.

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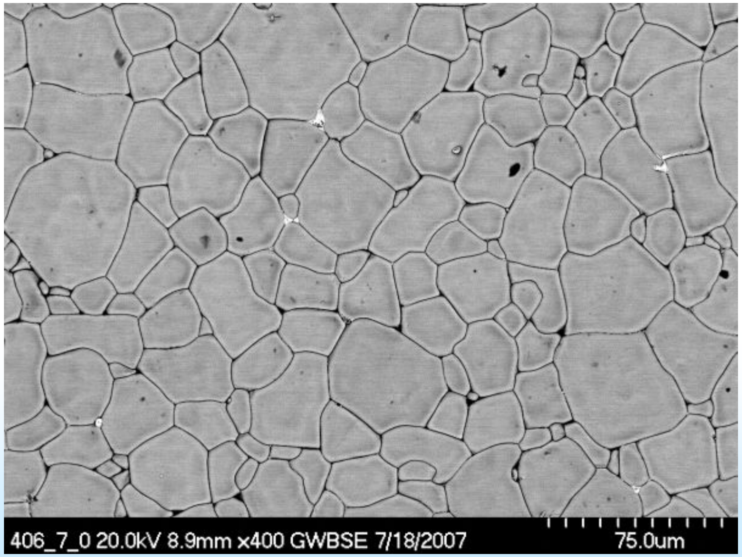
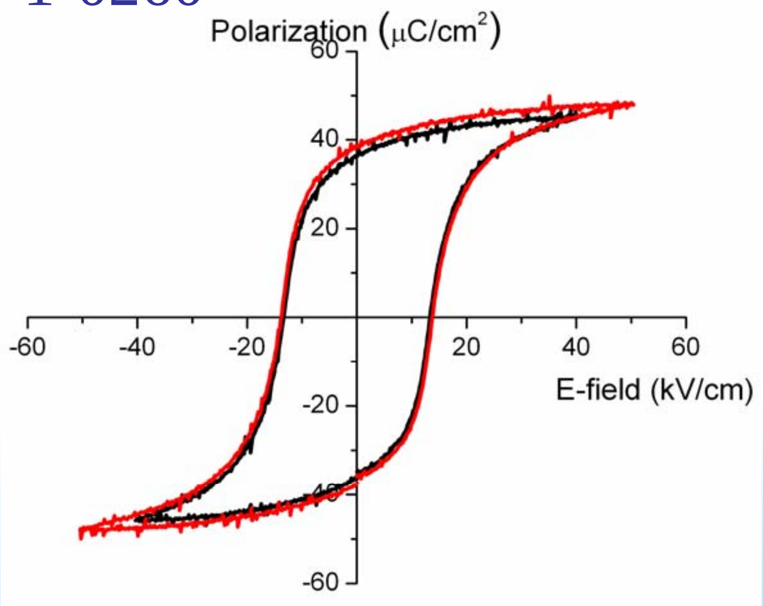




Objective

Development of high-temperature piezoelectric actuators for aeronautics and aerospace applications.

Applications

- Actuators for Aerospace and Aeronautics
  - Fuel modulation, valves, micro-positioning devices, MEMS, active damping and energy harvesting.
- Sensors
  - Pressure sensors, passive damping

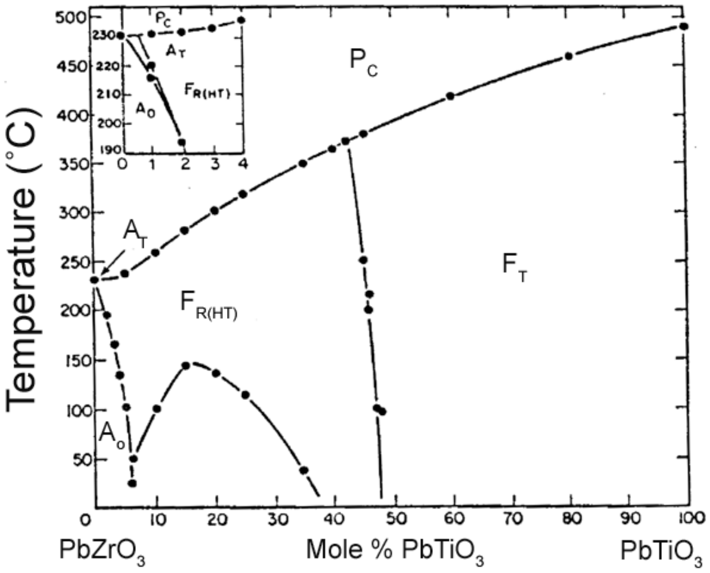
Advantages

- Fast response time
- Generate large forces
- No gears or rotating shafts, no wear and tear.

Challenges for High Temperature

- Trade off between T_C and d_{33}
- Conductivity at elevated temperatures

	T_{limit} (°C)/(°F)	d_{33} (pC/N)
PZT Type II (PZT 5A)	350 / 662	374
PMN-PT single crystals	90 / 194	>2000
$BiScO_3$-$PbTiO_3$	450 / 842	401
$La_3Ga_{5.5}Ta_{0.5}O_{14}$ single crystal	N/A	7
$Na_{0.5}Bi_{4.5}Ti_4O_5$	650 / 1202	19
$La_2Ti_2O_7$	1482 / 2700	16



B. Jaffe, W. R. Cook and H. Jaffe, Piezoelectric Ceramics, Academic Press, New York, 1971.

Approach

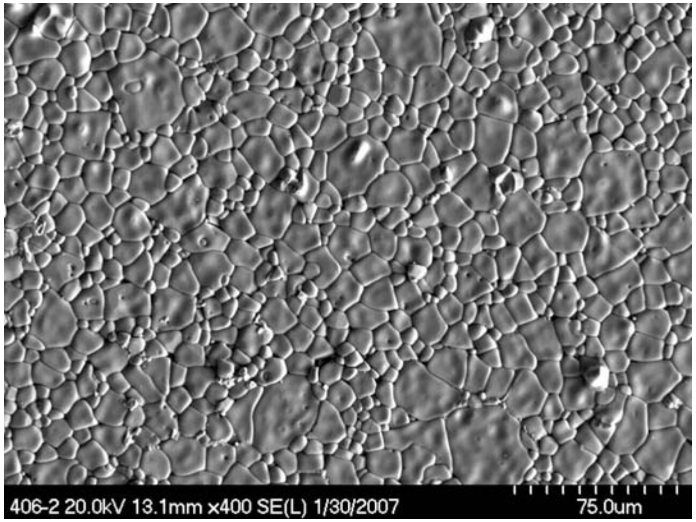
- Microstructure engineering

  Liquid phase sintering

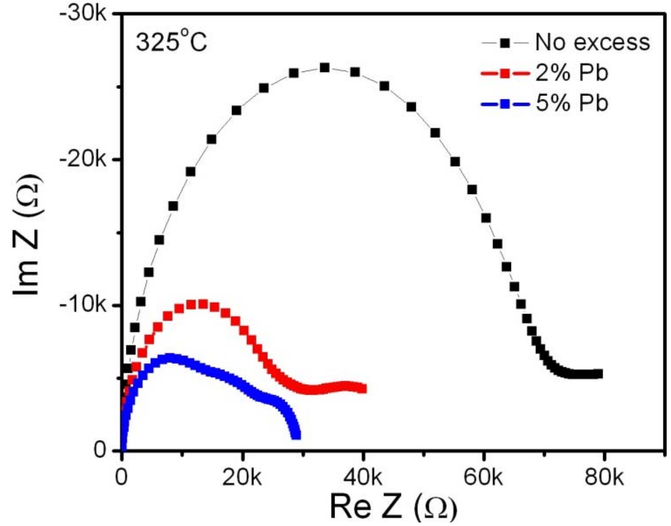
- Compositional engineering
  - Isovalent doping (Yb, In)
  - Aliovalent doping (Sr, Zr)
  - Multivalent doping (Mn)

Outline

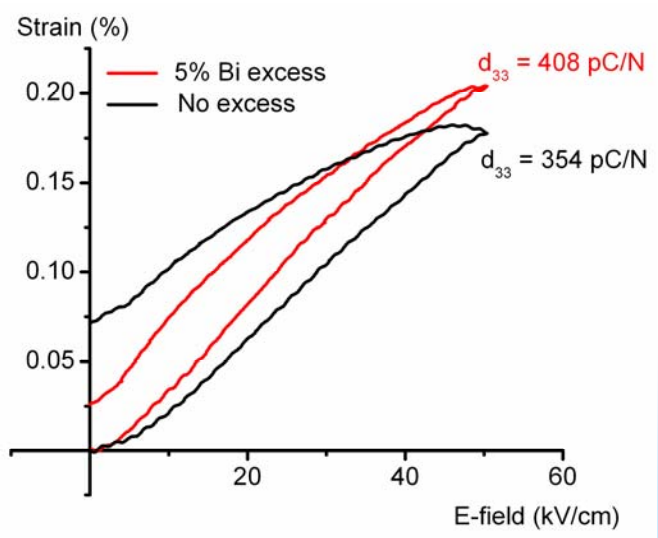
Liquid phase sintering



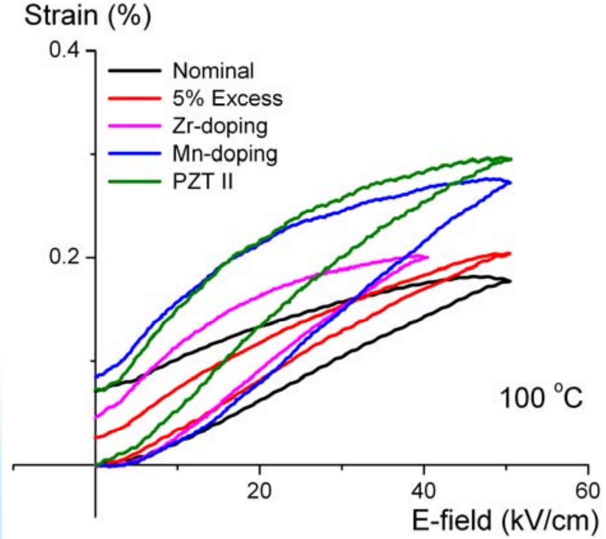
Effects of excess Pb and Bi



Electromechanical properties



Compositional modifications



Processing of BS-PT

Raw materials (Bi_2O_3, PbO, Sc_2O_3, TiO_2) ← Dopants

↓

Ball milling (15hrs)

↓

Drying (stirred)

↓

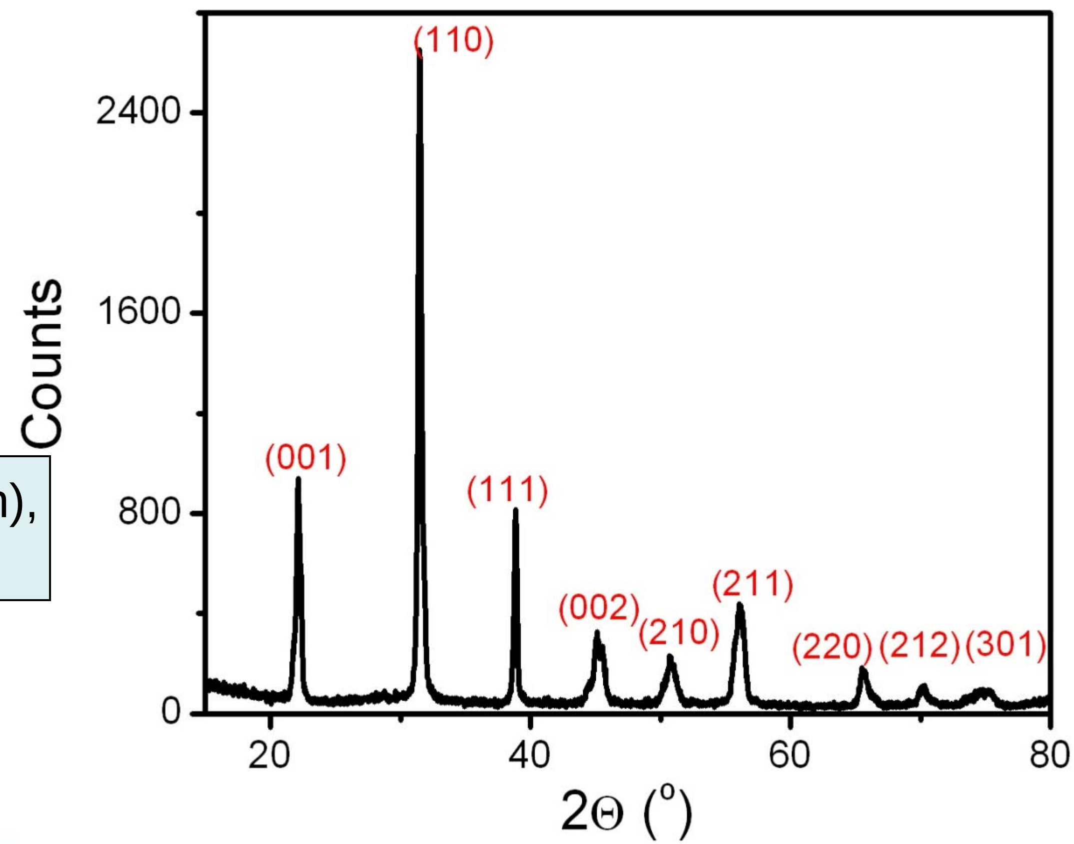
Calcination (750^{o}C, 3hrs, 5^{o}C/min), in air

↓

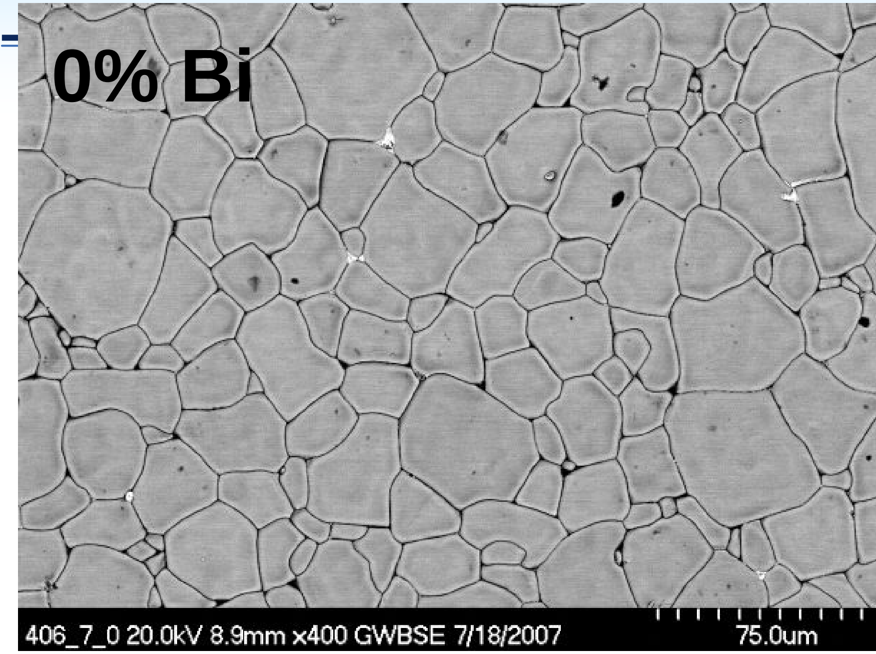
Ball milling (6hrs) ← Excess addition

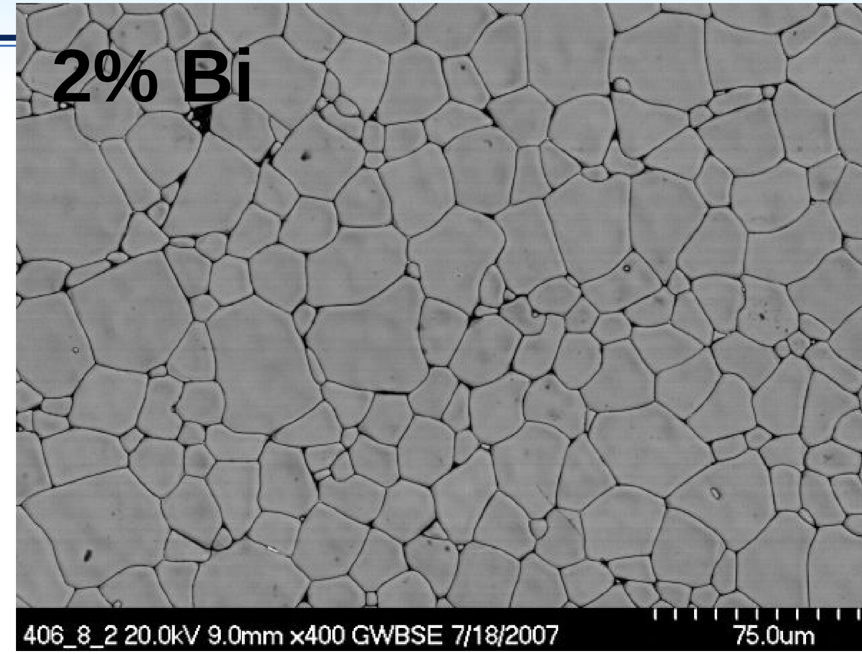
↓

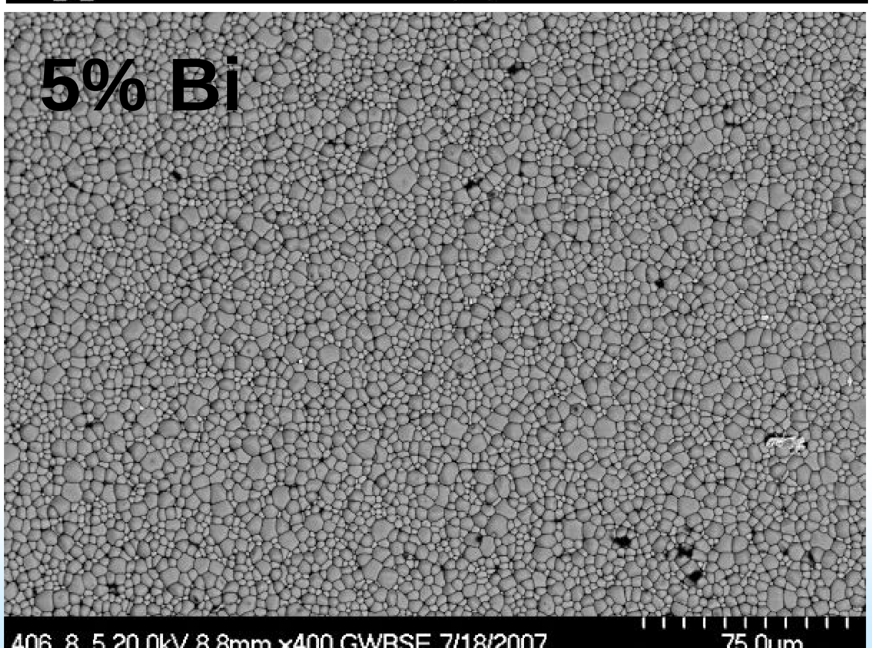
Pressing → Sintering (1100^{o}C, 1hr, 5^{o}C/min), in air

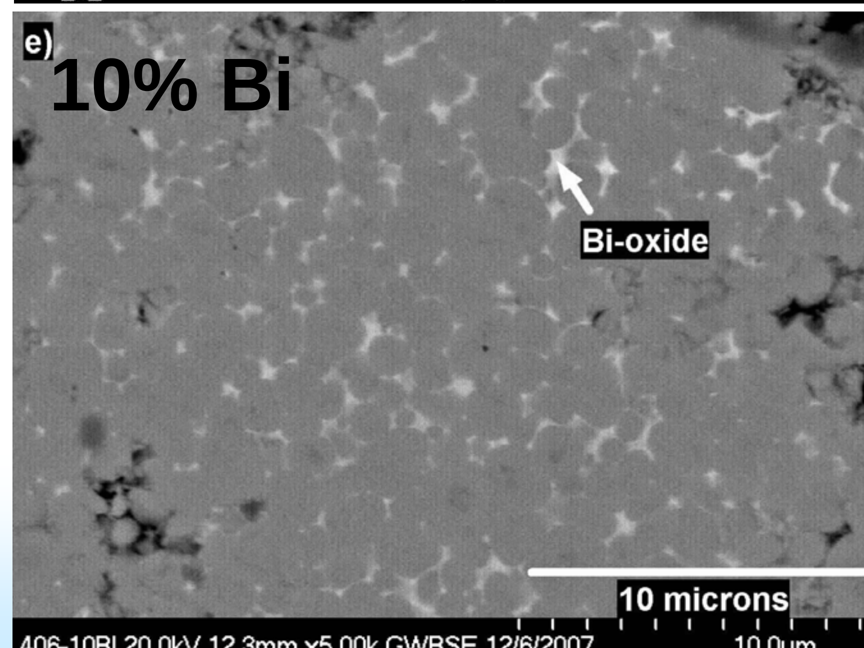


Effect of Bi on microstructure

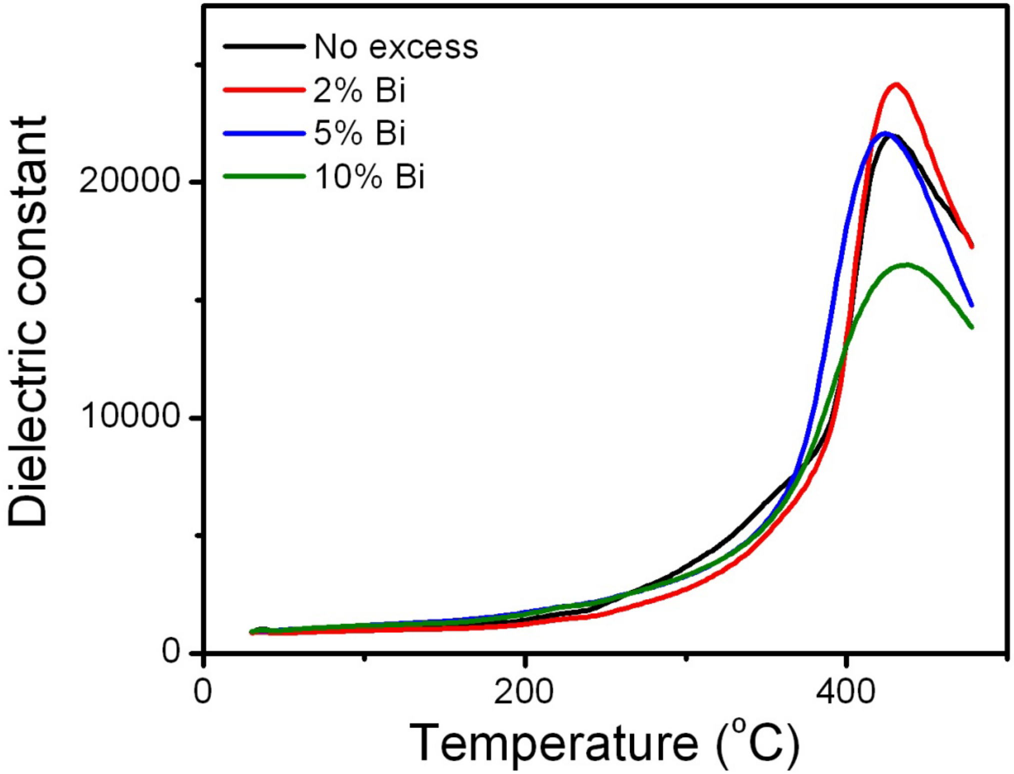




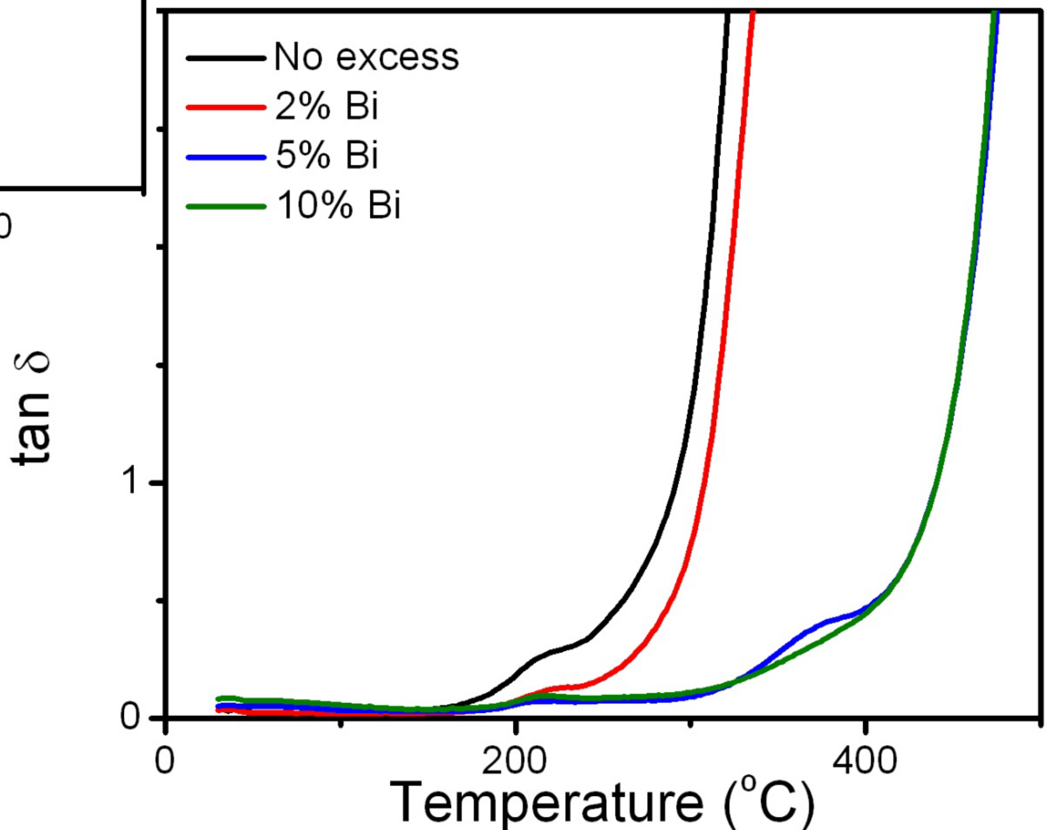




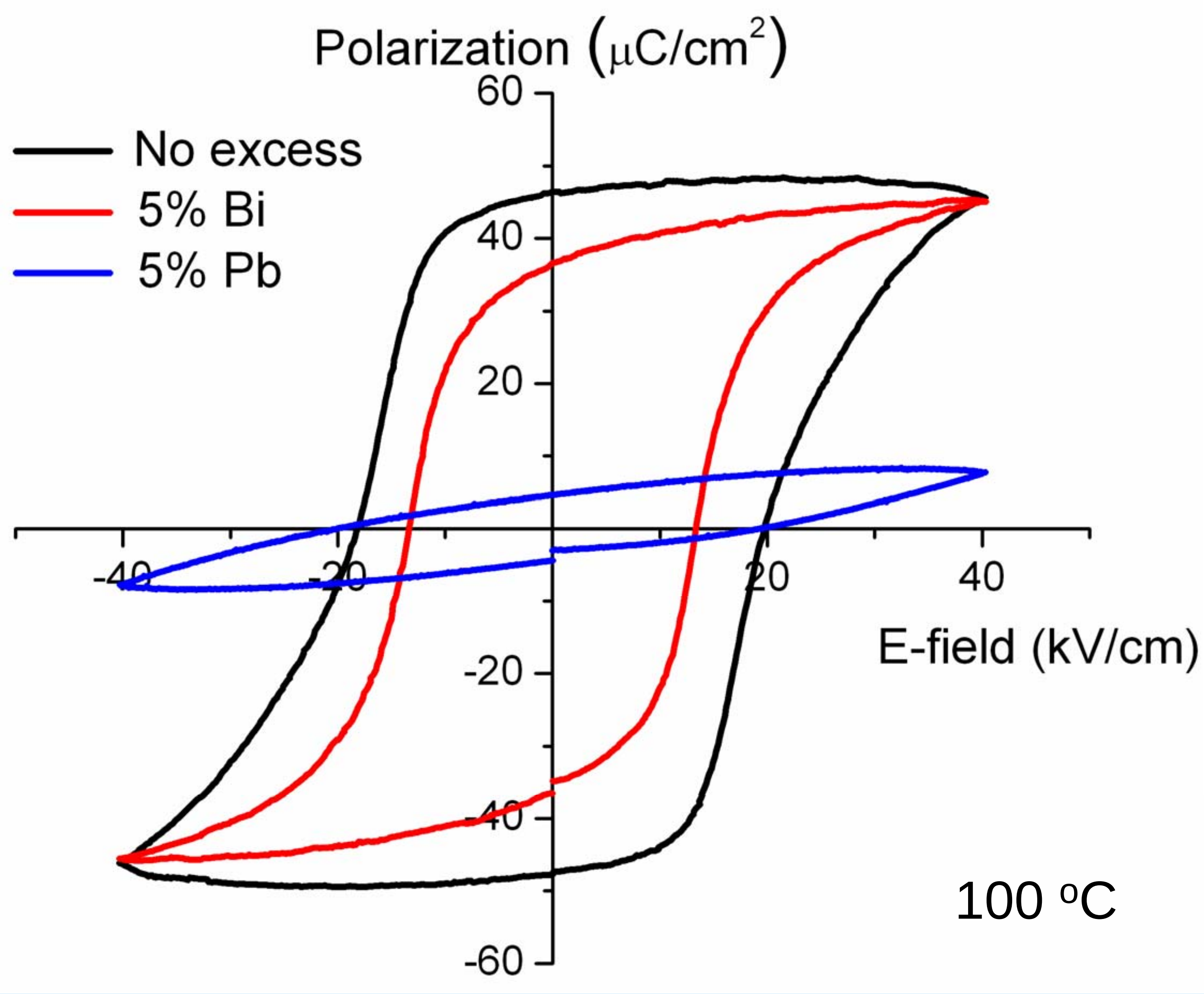
Effects of Bi in BS-PT



1 kHz, 0.5 V/mm ac, in air

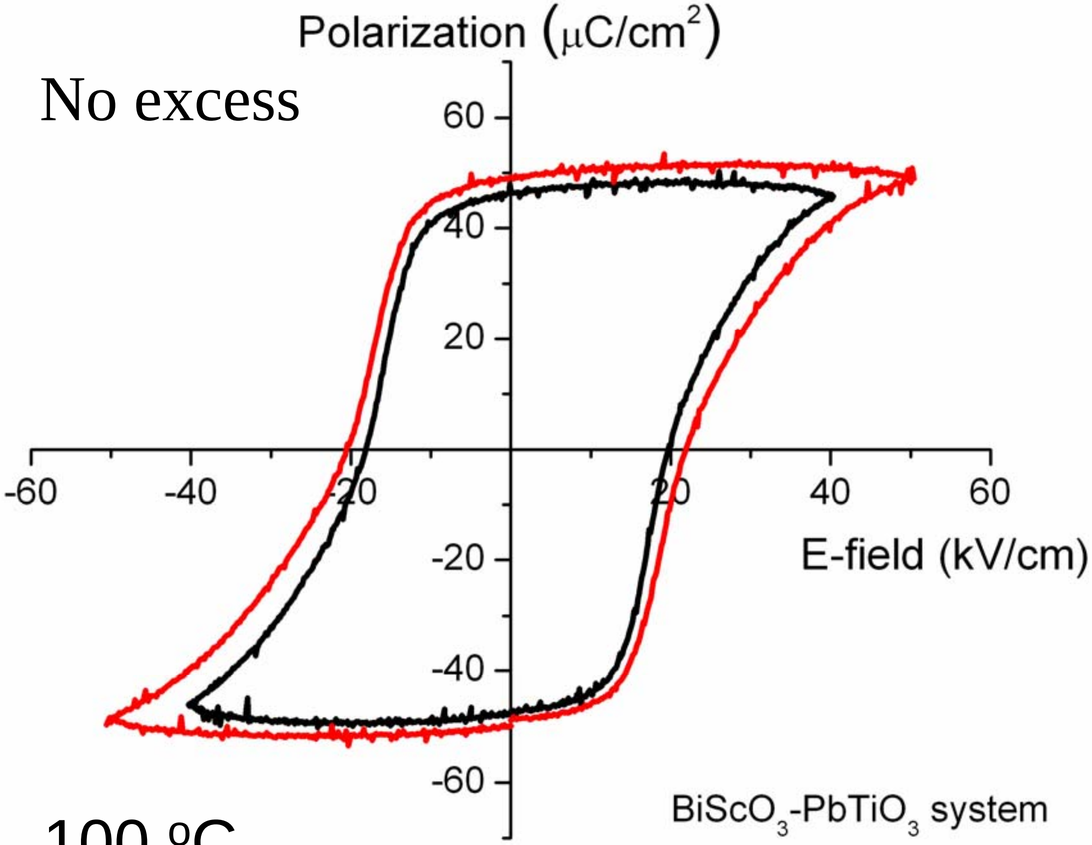


Ferroelectric and piezoelectric properties

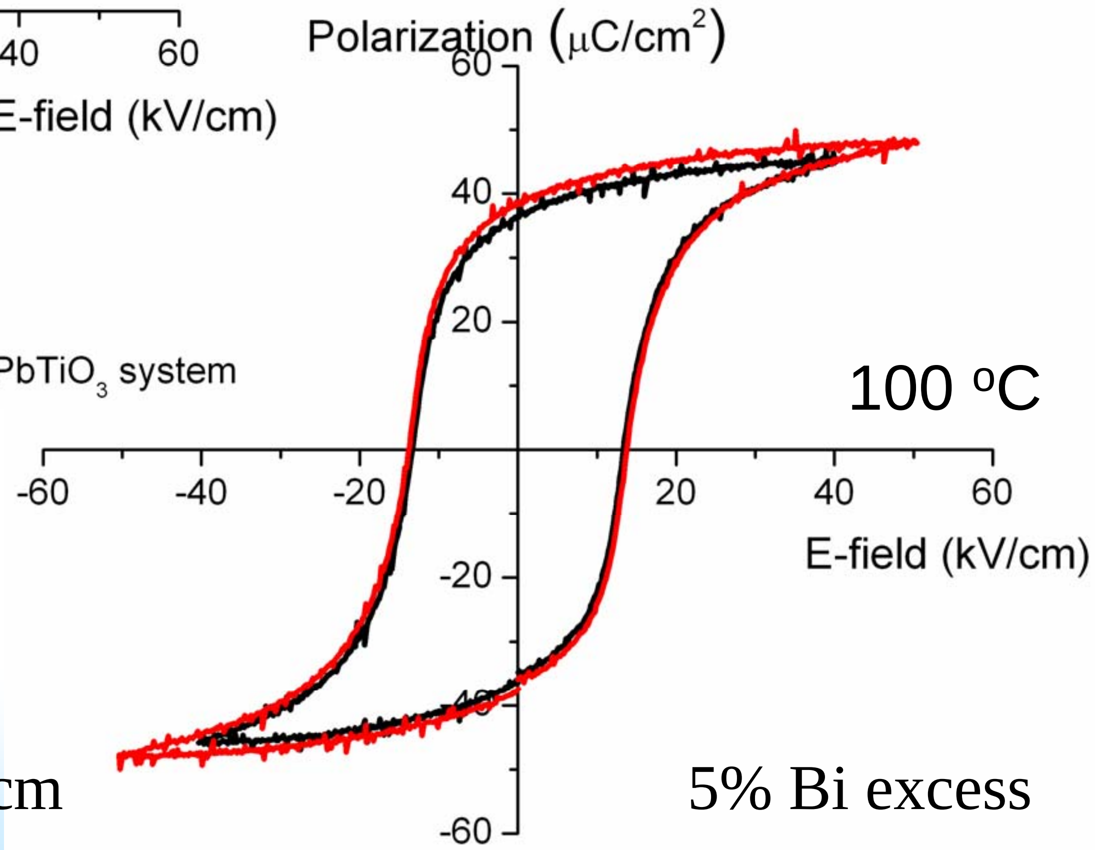


Ferroelectric Properties

No excess



100 °C

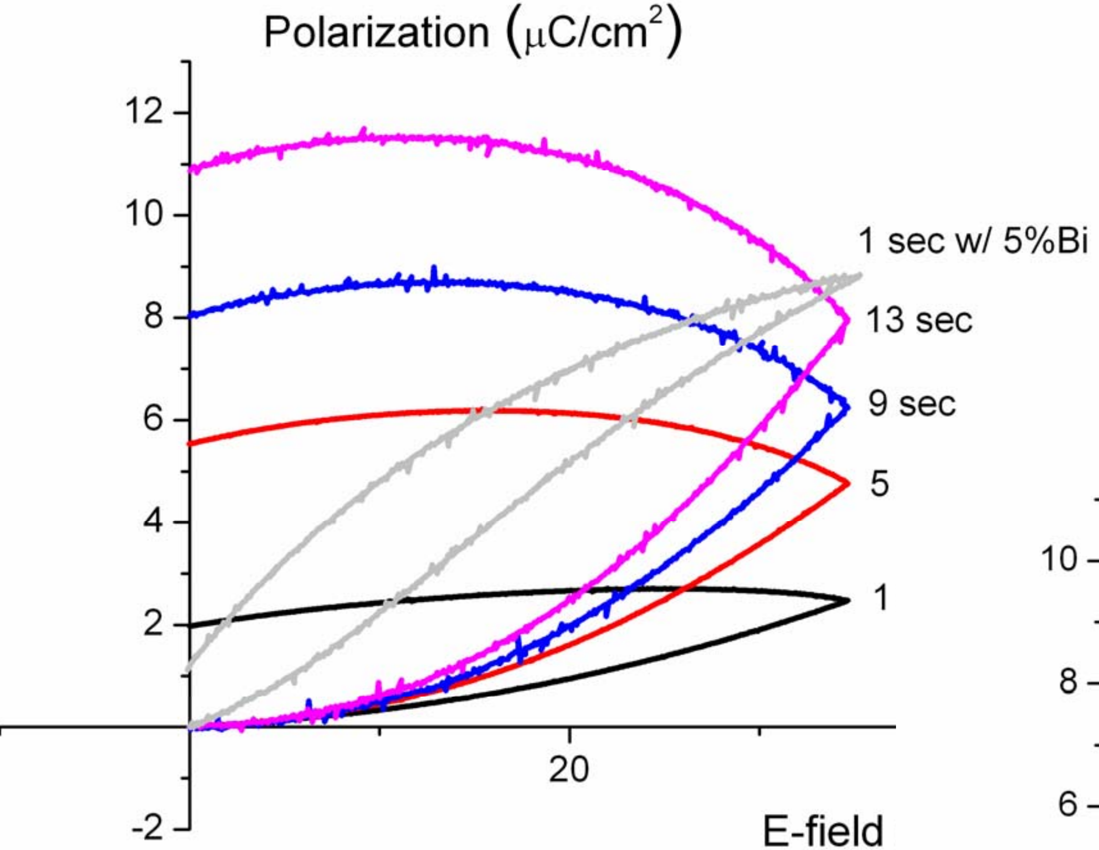


100 °C

E_C = 13.5 kV/cm

5% Bi excess

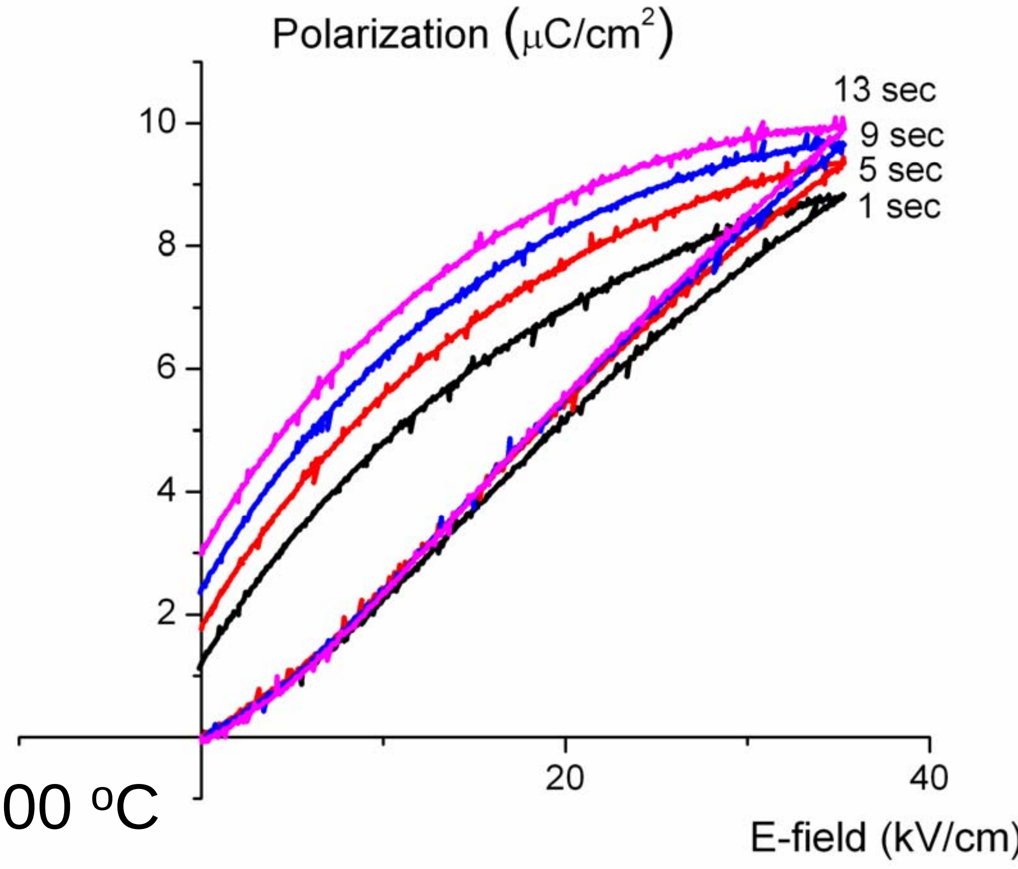
Unipolar frequency dependence



100 °C

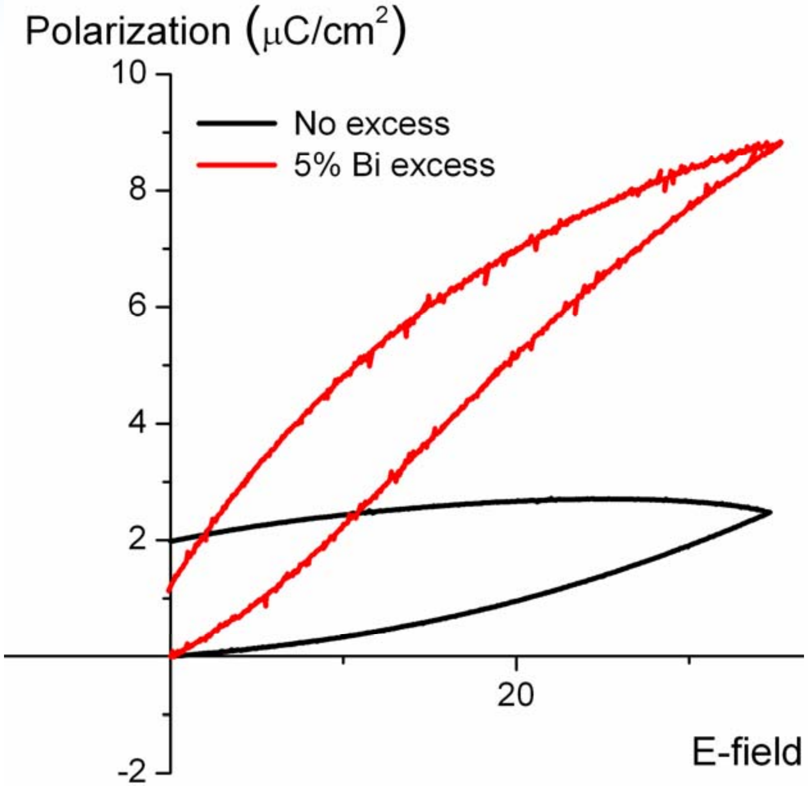
No excess

5% Bi excess



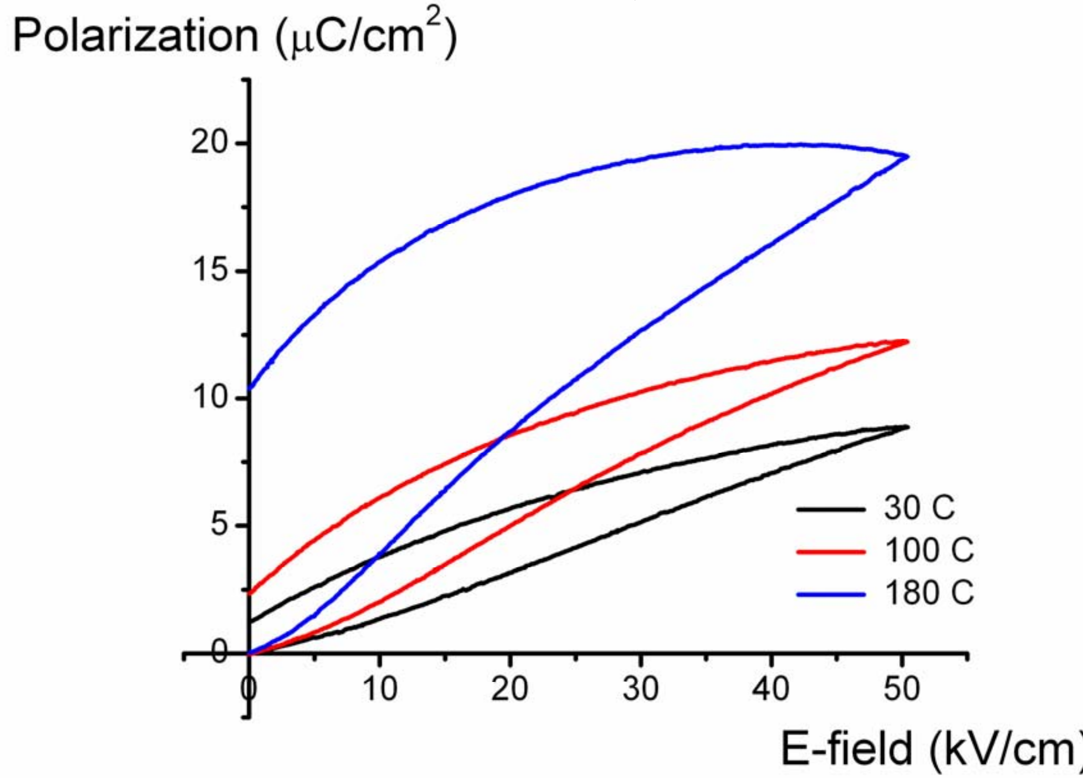
100 °C

Unipolar polarization

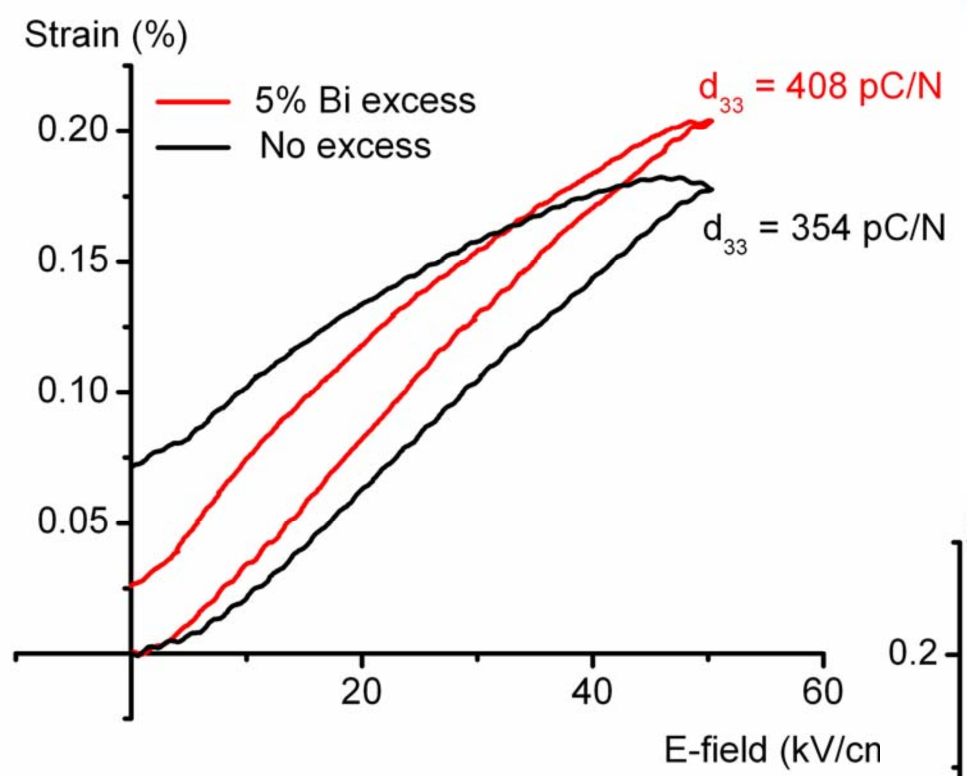


5% Bi

100 ^{o}C

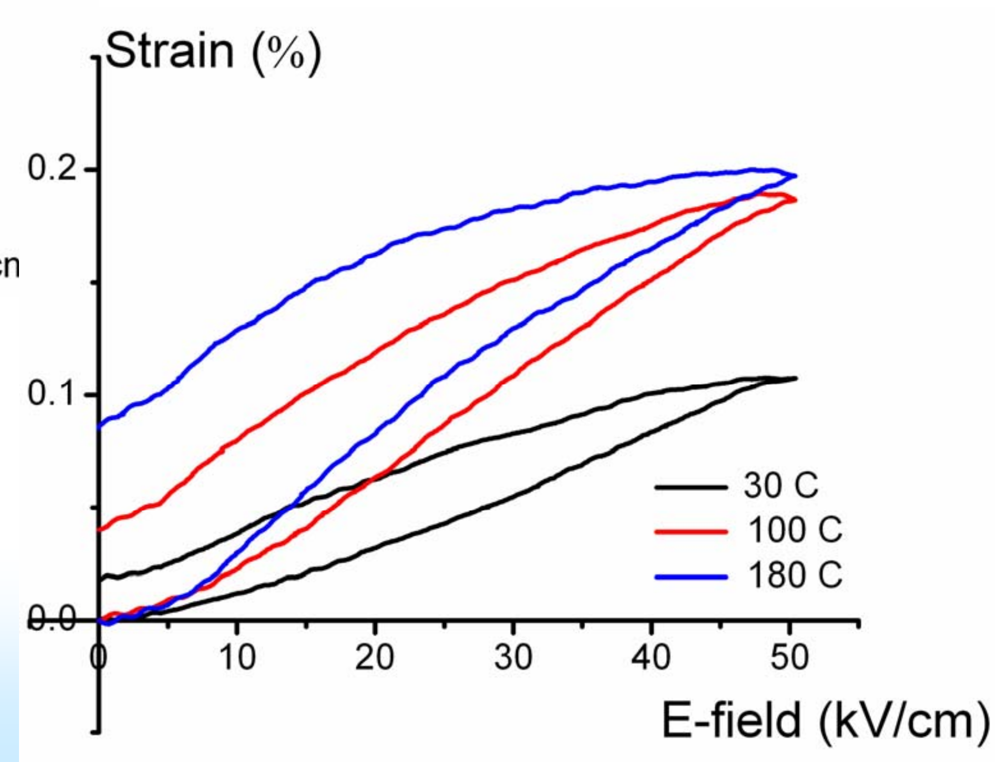


Piezoelectric coefficient

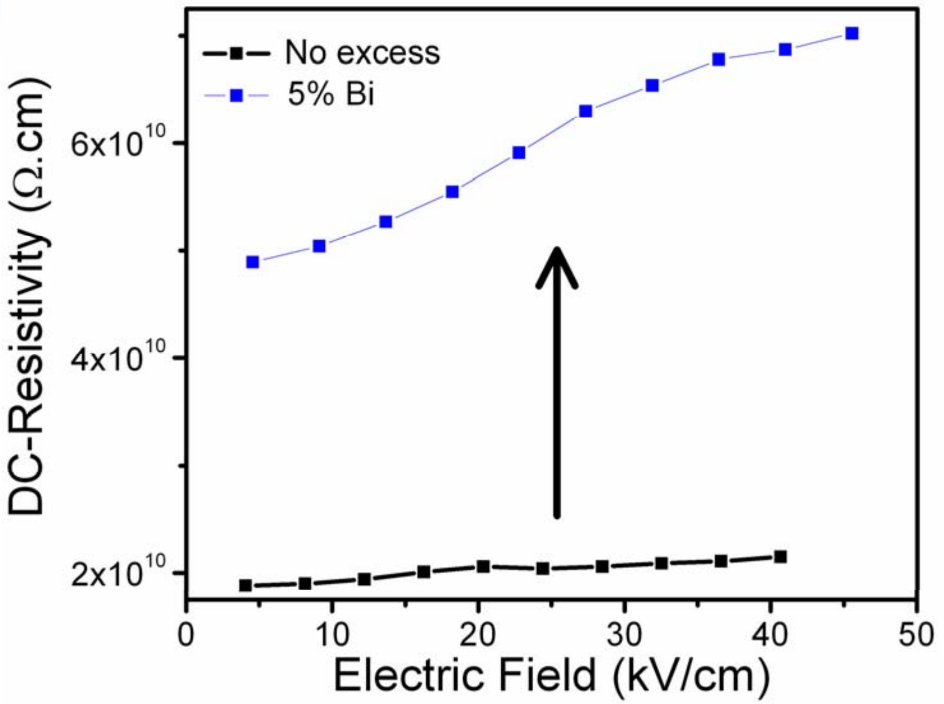


100 ^{o}C

5% Bi

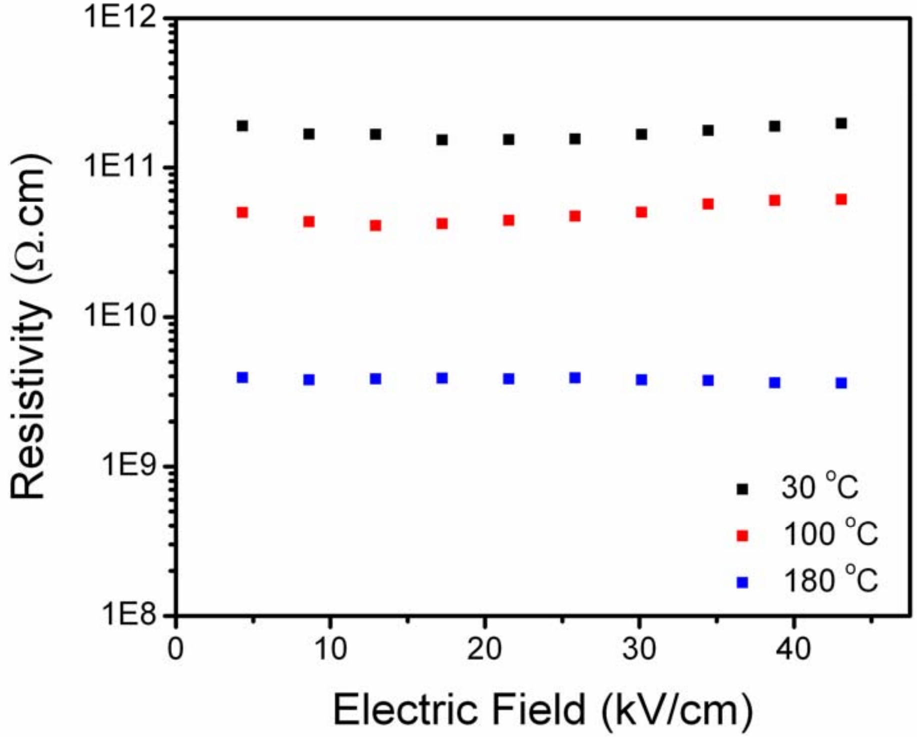


High field resistivity

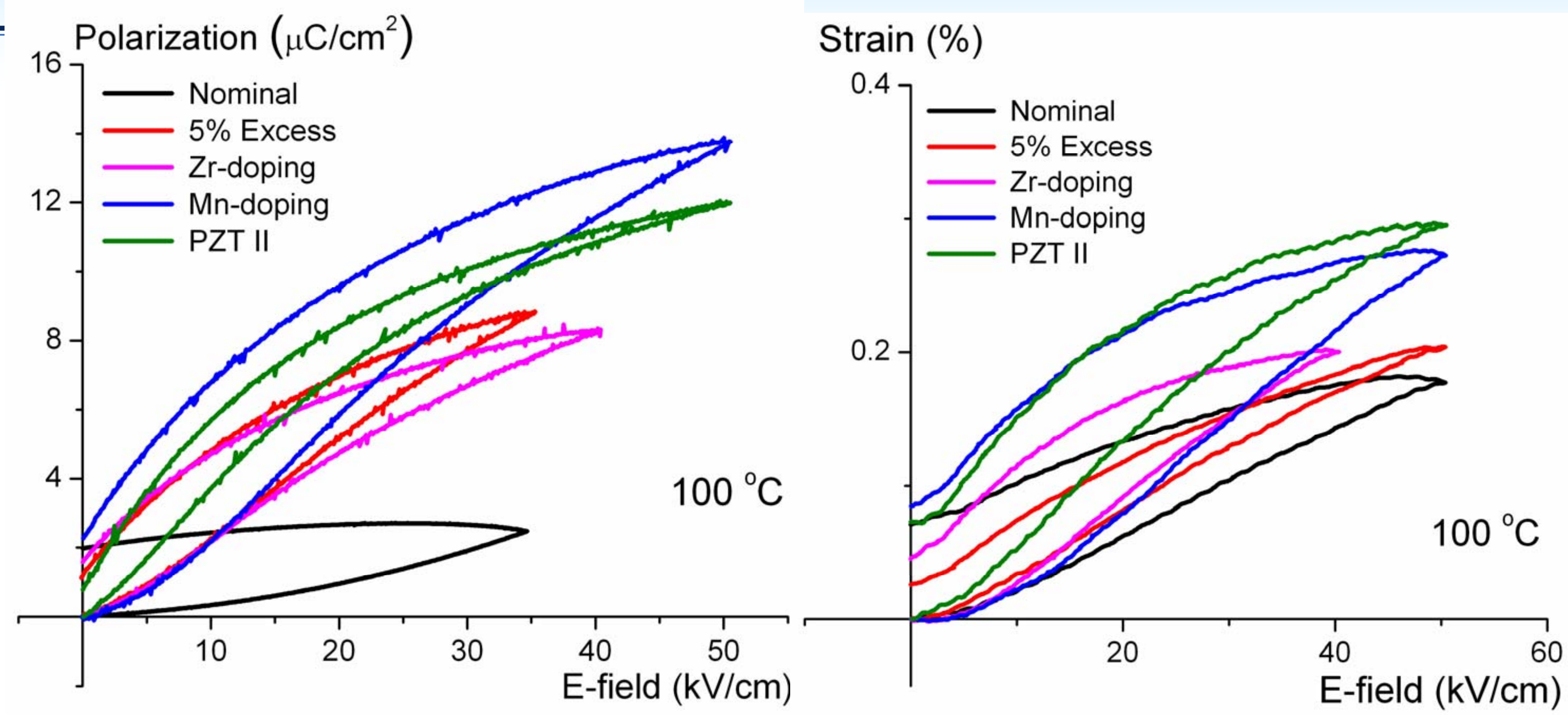


100 °C

5% Bi



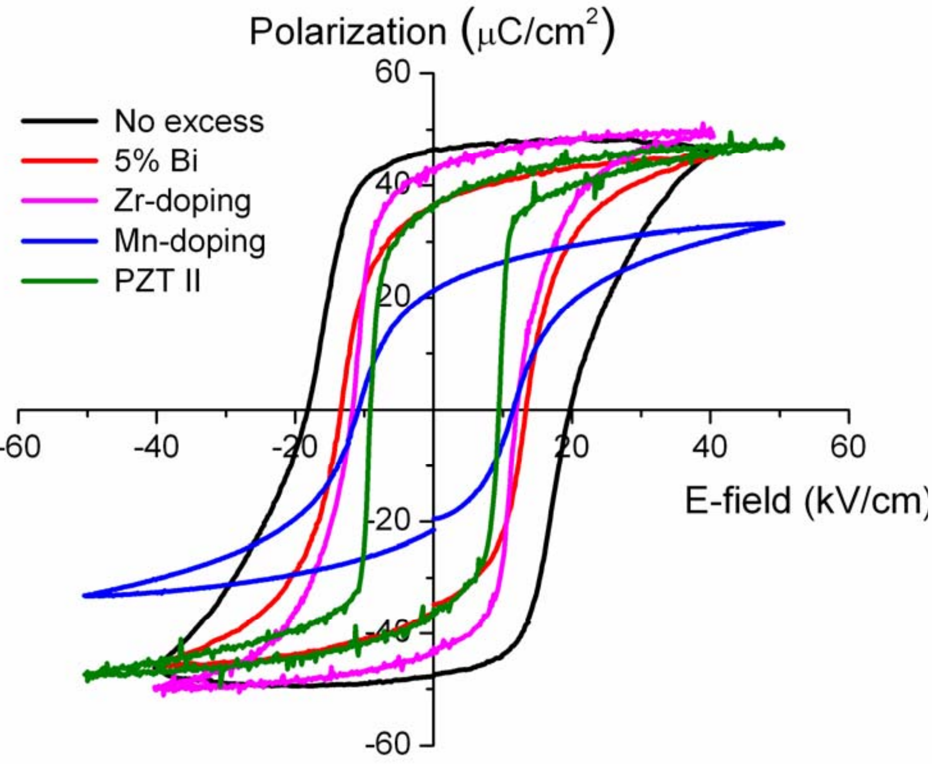
Doping comparison

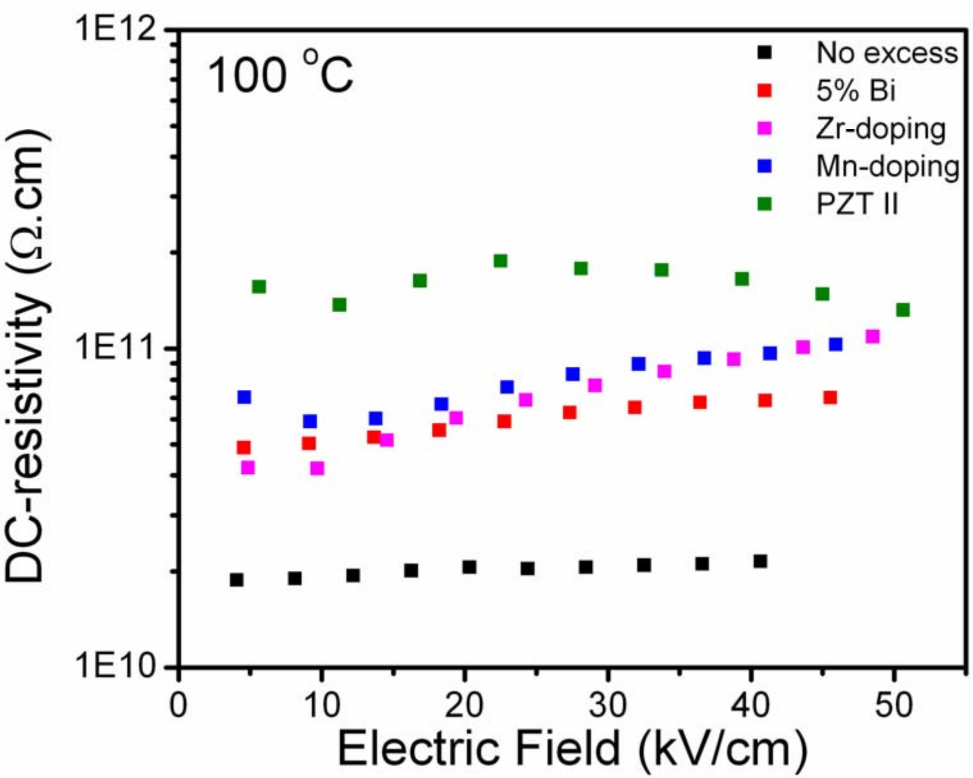


	Nominal	5% Bi	Zr-doping	Mn-doping	PZT II
$d\varepsilon_{max}/dE_{max}$ (pm/V)	354	408	500	542	585

PZT II by Piezo Kinetics, Inc

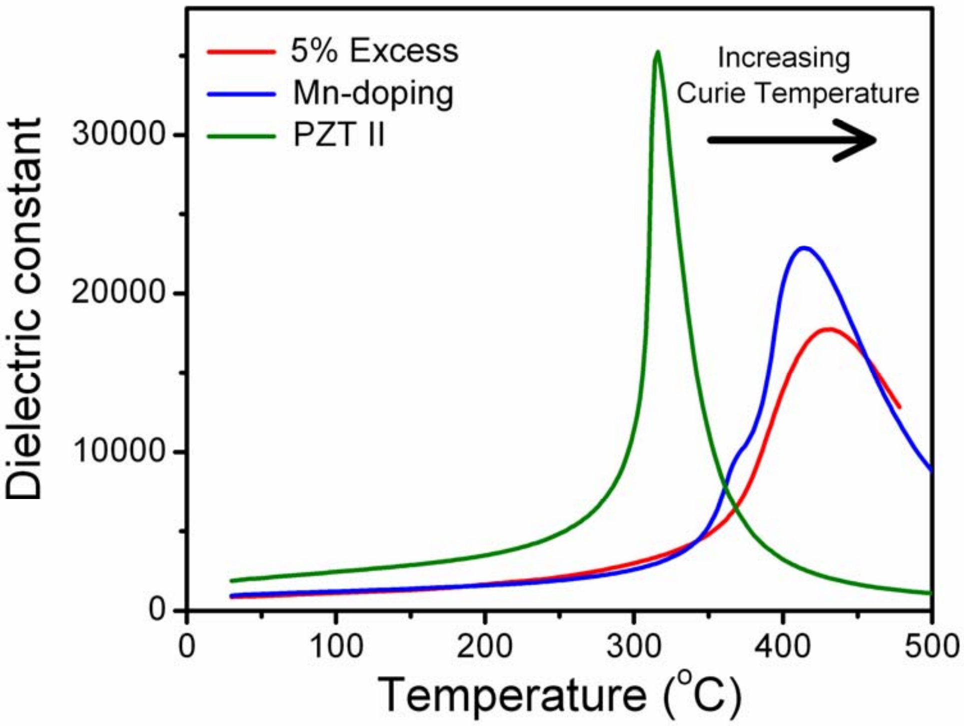
Doping comparison (2)



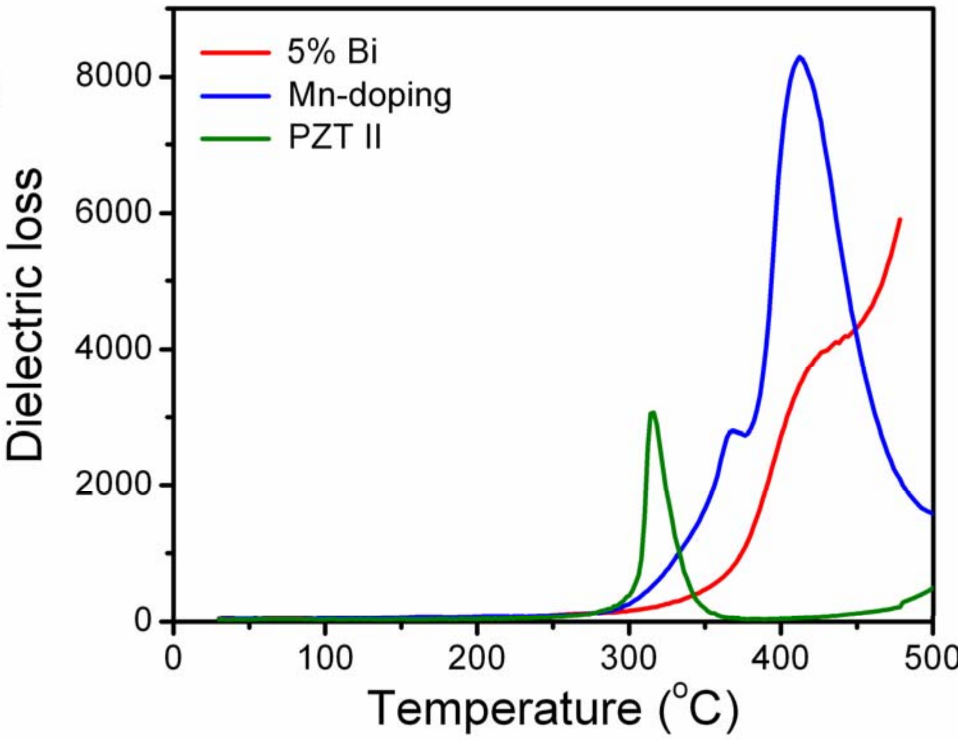


	Nominal	5% Bi	Zr-doping	Mn-doping	PZT II
P_r ($\mu C/cm^2$)	46.4	36.6	43	21.3	36.4
E_C (kV/cm)	19	13.3	11.8	11.2	9.25

Doping comparison (3)



	5% Bi	Mn-doping	PZT II
T_C (°C)	432	414	316



$$\in'' = \in' \times \tan \delta$$

$\in'$ = Dielectric constant

$\in''$ = Dielectric loss

$\tan \delta$ = Loss tangent

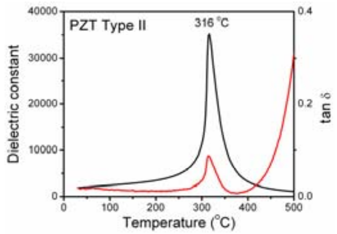
Materials for high temperature actuators

FA 9550-06-1-0260

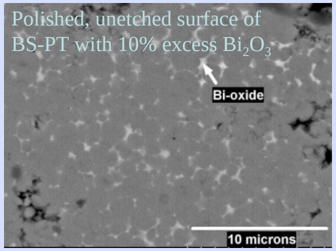
STATUS QUO

Now mature PZT system is limited up to 180°C for the upper use temperature

- *Higher Curie Temperature is needed*
- *Lower conductivity at elevated temperatures is required*



NEW INSIGHTS

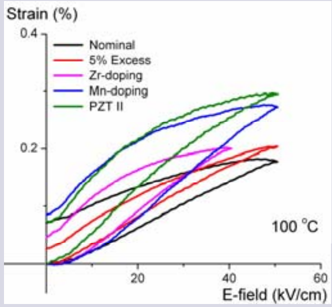


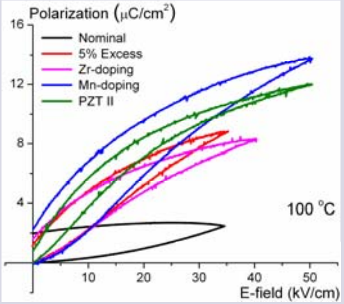
$BiScO_3$-$PbTiO_3$ (BS-PT) has high Curie temperature and large piezoelectric coefficients

It is promising to be operational at higher temperatures than PZT via microstructural and compositional refining

MAIN ACHIEVEMENT:

Piezoelectric activity in the level of state of the art materials have been achieved.





HOW IT WORKS:

$BiScO_3$-$PbTiO_3$ ceramics have been improved by concurrent engineering of::

- **Microstructure**: Optimized microstructure via liquid phase sintering[1] and decreased the high field and high temperature losses.[2]
- **Composition:** Modified the composition by isovalent and aliovalent doping to increase the electro-mechanical properties.

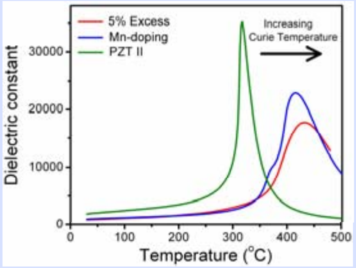
ASSUMPTIONS AND LIMITATIONS:

- Needs further optimization through combination of the two approaches and multi-doping strategies.
- The developed material needs to be demonstrated as a part of an actuator

[1] Journal of the American Ceramic Society, *accepted*

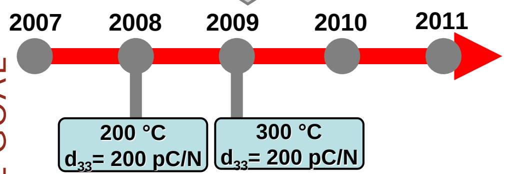
[2] Journal of Applied Physics, *submitted*

QUANTITATIVE IMPACT



- Increased Curie temperature more than 100 °C.
- Matched the induced-strain levels and high field DC-resistivity, and enhanced polarizability in compasion with the state of the art piezoelectrics (PZT-Type II).

END-OF-PHASE GOAL



Build piezoelectric stack-actuators for high temperature applications

- *Optimize the composition and microstructure*
- *Develop necessary electrodes, leads and encapsulation material*

High temperature piezoelectrics enable active combustion control in jet engines that can increase engine efficiency and reduce emissions