A new concept of light-matter coupling: rearranging ferroelectric domains with light

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Some aspects of ferro-piezoelectric materials

About the application of piezoelectricity ...

Actuators

In microelectronics (positioning systems), nanotechnology (scanning probe microscopes), optical technologies (adaptive systems), information technologies (inkjet heads), consumer products (camera autofocus) ...

Ultrasound generation

In medical industry (ultrasound, non-intrusive probes), structural analysis (non-destructive testing), fishing and military industries (SONAR) ...

Sensors

In energy industry (gas and liquid flow meters), transport (accelerometers) ...

Energy harvesting

In self-powered systems (traffic signaling, sensor networks, ...

High piezoelectricity and low losses

Large piezoelectricity

All applications requires electric contact!

TALK SUMMARY

- Some aspects of ferro-piezoelectric materials
- Moving ferroelectric domain walls with light
- Photo-detector and photo-actuator effects
- Origin of the phenomenon
- Summary
Some aspects of ferro-piezoelectric materials

What is a ferroelectric material? The case of perovskite ferroelectrics.

A material showing spontaneous polarization that is able to be switched by applying an electric field.

Non ferroelectric (cubic) phase

Ferroelectric (tetragonal phase)

The ferroelectricity is a property strongly related to the crystallographic structure.

This is more complex in a bulk material!
Some aspects of ferro-piezoelectric materials

How is a bulk ferroelectric?

Domain walls are formed to minimize the stress (elastic energy) ...

... also for minimizing the electric energy.

Domain structure is usually complex!
Some aspects of ferro-piezoelectric materials

Origin of the high piezoelectric response: a simplified vision

\[ d \propto \varepsilon P_r \]
\[ \varepsilon = \frac{dP}{dE} \]

The polarization variation should be large

- **Polarization rotation and/or extension**
  - **Intrinsic effect**

- **Motion of domain walls**
  - **Extrinsic effect**

Crystalline and domain structures determine piezoelectric response!

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Material selection

A “well-known” ferroelectric material: BaTiO$_3$ (BTO) crystal

Well-defined tetragonal structure at room temperature.

- Top–seeded solution growth (TSSG)
- by PI-KEM (UK)
- 5 x 5 x 0.5 mm$^3$
- (100) orientation (in-plane)
Domains structure characterization

**Confocal Raman microscopy (CRM)**

CRM coupled with AFM

One Raman spectra corresponds to a crystallographic orientation; that is, a polarization orientation.

A superficial approach ... although better than other techniques
Domains structure characterization

Resolving the domain structure

A-domains (red): polarization in-plane

C-domains (blue): polarization out-of-plane

B-domains (green): polarization in- and out-of-plane

B-domains appear for stress release and charge compensation.
**Domains structure characterization**

*Resolving the domain structure*

**A-domains (red):**
polarization in-plane

**C-domains (blue):**
polarization out-of-plane

**B-domains (green):**
polarization in- and out-of-plane

**B-domains** appear for stress release and charge compensation.
Domains structure characterization

Quantifying different domain structure regions

Can this regions be detected by XRD?

- (100) → (h00)
- (001) → (00l)
High-resolution synchrotron X-ray diffraction (HR-SXRD)

SpLine CRG BM25 beamline:
- X-ray beam wavelength: 0.5636 Å (22 keV)
- Spot size: 0.5 mm x 0.5 mm
- Step size of 0.0025° (resolution of ~10^{-4} Å)

A powerful technique!
Domains structure characterization

**Change in the domain structure by HR-SXRD**

Changes in the same crystal region could be detected!

*Nature Photonic 12, 29-32 (2018)*
Moving ferroelectric domain walls with light

Reversible optically-induced domain structure change

The relative percent of C-domain enhances in a reversible fashion!

A proof of domain wall motion!

Nature Photonic 12, 29-32 (2018)
Moving ferroelectric domain walls with light

Reversible optically-induced domain structure change

The relative percent of in-plane B-domain also increases as a result of the domain rearrangement!

This observation is possible thanks to the HR of the XRD.

Nature Photonic 12, 29-32 (2018)
Photo-detector effect

**Light-induced change of macroscopic dielectric permittivity**

\[ \text{Normalized } \varepsilon' \]

\[ \text{Frequency (Hz)} \]

- **Lights on/off**
- **Illumination conditions**

Wavelength independent in the tested range.

We can experiment with the cheaper light source!

Since dielectric constant changes, other related properties must also change!!

*Nature Photonic* 12, 29-32 (2018)

Photo-detector effect

*Power dependence: tuning dielectric constant*

- Linear dependence: Great for sensor applications!
- Capacitance can be adjusted by light power control!!

Photo-actuator effect

Light-induced nanoactuation

A photo-controlled nanoactuator!!

ACS Appl. Mater. Interfaces, to be published.
Photo-actuator effect

Light-activated nanoactuation at the macroscopic scale

Contact profilometry images reproduces AFM results but at the macroscopic scale.

Optical triggering and mechanical actuation can be done in different areas: cooperative nature of the phenomenon.

A macroscopic nanoactuator!

ACS Appl. Mater. Interfaces, to be published.

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Origin of the phenomenon

**Physical mechanism**

Light induces self-organization of symmetry breaking of domain walls.

A reversible manifestation of photostriction!

*Nature Photonic* 12, 29-32 (2018)
Many questions ... but we have some important answers

- It is well-known that ferroelectrics are photostrictive materials that manifest macroscopic deformation as a result of photovoltaic plus converse piezoelectric effects.

- Photovoltaic effect requires light wavelength below material bandgap (ultraviolet for BTO).

Photovoltaic and thermal effects can be discarded!
Origin of the phenomenon

The role of the charged domain walls (CDWs)

In order to improve the photo-response, the occurrence of CDWs should be maximized by domain engineering.

Origin of the phenomenon

The role of the CDWs

Energy bands bend at CDWs, thereby decreasing locally the energy band-gap.

Low energy photons may interact with the electron gas in the CDWs.

Nature Comm. 3, 748 (2012)
Nature Comm. 4, 1808 (2013)

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- HR-SXRD is a powerful tool to resolve change in the domain structure in ferroelectric crystals at the macroscopic level.

- It is possible to achieve a reversible optical change of ferroelectric domains configuration.

- This effect leads to the tuning of macroscopic polarization and its related properties by means of low energy visible light (a non-contact external control).

- The optical control of macroscopic polarization may enable us to establish a paradigm for a new generation of ferroelectric-based photo-detectors and photo-actuators.

**Future works: .... a lot to do!!**
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