Piezoelectricity & Its Applications

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Overview My Research Interests

Sustainable Materials and Renewable Technologies (SMART) Lab

- High Temperature Thermoelectric Power Generation
- Oxides and Nitrides Nanostructures for Energy Related Applications
- Novel TE, and PV/TE Hybrid Devices
Nitrides/Oxides for High Temperature TE Applications

Multi-length Scale Nanostructure to Decouple Electron and Phonon Transport

InGaN-GaN superlattice

Novelty of the work
• Controllable unique thermoelectric properties of superlattice nanoinclusion
• Introduce GPa stress to tune the thermoelectric properties of the host
• Bulk materials for large-scale applications

Z Liu, et. al, Scientific Reports, 6, 19537, 2016
B. Kuckgok, et al, AIP advances, 6, 025305, 2016

Funding: NSF CAREER Project
15% increase of energy efficiency can be achieved using TE Devices at 1200K
Flexible TE Devices for Self-Powered Sensors

Self-powered smart contact lens

Contact lens (flexible material)
Optically transparent array(s) of doped ZnO (thermoelectric elements)

Ambient temperature (cold side)
Electron flow
Heat flow out of eye
Sampling/sensing
Drug/chemical delivery

Wireless communication

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Engineering Novel Composites for Civil Infrastructures

Effect of Fiber Surface Functionalization on Composites Properties

Develop High-Strength/ Low-density Green Composite by Using Natural Fibers with Reclaimed High Density Polyethylene (HDPE) Matrix

- Tensile strength 60.2 MPa; Flexural strength: 58.2 MPa
- Tensile strength reached up to 80% of E-glass fiber Composites

N. Lu et al, Advanced Materials Research, 415,2012, 666-670
Outline

- What is Piezoelectricity
- Applications of Piezoelectricity
- Fundamental Mechanisms
- Best Piezoelectric Materials
- Leading Research Groups in This Area
- Challenges
What is Piezoelectricity

- Piezoelectricity – Convert mechanical energy into electrical current flow.
- Discovered by French Physicists Pierre and Jacques Curie in 1880

- Generally exhibited in crystal materials with no inversion symmetry
- The first practical application for piezoelectric devices was sonar during the World War I.
What is Piezoelectricity

- Bending materials to generate electricity
- Apply voltage to deform materials
The Direct Effect: Generator

- **Compression**
  Effect: Decrease in volume and it has a voltage with the same polarity as the material

- **Tension**
  Effect: Increase in volume and it has a voltage with opposite polarity as the material
The Inverse Piezoelectric Effect

- If the applied voltage has the same polarity then the material expands.
- If the applied voltage has the opposite polarity then the material contracts.
What are some applications?

NASA Applications
• Electro-optical Device Technologies
• Precise positioning
• Switches

Multifunctional Membranes
• Antennas
• Reflectors
• Smart skins
• Tuning and positioning inflatable structures

Biomedical
• Portable Artificial organs
• Lightweight fetal heart monitor
• Ultrasonic imaging
• Tissue engineering
Piezoelectric Applications

- Capture the energy created by the runners on special exercise machines - Green Microgym in Portland, Oregon cut energy bills by 60%.

- Using piezoelectric technology under the dance floor - Club Watt in Rotterdam, Holland.

- Power a pair of night vision goggles used by soldiers.

- Just one minute of walking generates enough energy to power a mobile phone for 30 minutes.

Piezoelectricity in Civil Engineering Applications

- In 2006, Japan East Railway Company installed piezoelectric floors in an exit gate of their Tokyo Station. The 6 m² piezoelectric floor was reported to generate a maximum energy of 10KW s per day.

- In a pilot study carried out by Innowattech Ltd. in association with Technion Israel Institute of Technology, a 10-m stretch of piezoelectric generators were placed under a highway in Israel in 2009. The reported average power output was 2KWh, and the obtained energy was stored in a battery beside the road.

- Trains in the UK to provide energy to power sensors to monitor the condition of wheel bearings.

East Japan Railway Company, Demonstration experiment of the power generating floor at Tokyo Station
Why Piezoelectric?

With piezoelectric nanogenerators:

✓ Mechanical-movement energy - Body or muscle movement or blood pressure
✓ Vibration energy - Acoustic or ultrasonic waves
✓ Hydraulic energy - The flow of body fluids or blood, the contraction of blood vessels, or dynamic fluid in nature.
✓ The microelectromechanical systems microgenerator - Mostly built on a piezoelectric thin-film cantilever

Piezoelectric Nano-Generators

Zinc oxide nanowire

Relaxed, the nanowire generates no voltage

Voltmeter

Bending the nanowire produces an electrical potential

[7]

FIG. 1. Number of publications on piezoelectric, electromagnetic, and electrostatic energy harvesters in Web of Science between years 2003 and 2013.
Fundamental Mechanisms

- Crystal materials have no inversion symmetry, so there is high presence of electric dipole moments in solids, such as perovskite crystal.

- It may either be induced for ions on crystal lattice sites with asymmetric charge surroundings (as in BaTiO$_3$ and PZTs) or may directly be carried by molecular groups (such as sugar cane).

- For example, a 1 cm$^3$ cube of quartz with 2 kN (500 lbf) of correctly applied force can produce a voltage of 12.5 kV.
Fundamental Mechanisms

- Above a critical temperature, the Curie point, each polycrystal materials exhibits a simple cubic symmetry with no dipole moment.

- At temperatures below the Curie point, however, each polycrystal has tetragonal or rhombohedral symmetry and a dipole moment.

- Adjoining dipoles form regions of local alignment called domains.

- The alignment gives a net dipole moment to the domain, and thus a net polarization.

- The direction of polarization among neighboring domains is random, however, so the ceramic element has no overall polarization.
Fundamental Mechanisms

• The direction of polarization (3 axis) is established during the poling process by a strong electrical field applied between two electrodes.

• For actuator applications the piezo properties along the poling axis are most essential (largest deflection).

• They vary with temperature, pressure, electric field, form factor, mechanical and electrical boundary conditions etc.
Fundamental Mechanisms

- Piezoelectric materials are anisotropic natures
- The effect of Piezoelectric is very direction dependent
- Some directions are more polarized than the others
Piezoelectric energy harvesting process uses the direct piezoelectric effect, which is described by the constitutive equation:

\[ D_i = d_{ij} X_{ik} \]

where \( D \) is the electrical charge density, \( d \) is the piezoelectric stress coefficient, \( X_{ik} \) is the stress applied to the materials.

The subscript indices in this equation refer to different directions within the material coordinate system.

By convention, direction 3 is defined as the polarization direction of the piezoelectric material.
Fundamental Mechanisms

- The piezoelectric coefficients, $d$ for the direct and converse piezoelectric effects are thermodynamically identical, i.e.

$$d_{\text{direct}} = d_{\text{converse}}$$

- Note that the sign of the piezoelectric charge $D_i$ and strain $x_{ij}$ depends on the direction of the mechanical and electric fields, respectively.

- The piezoelectric coefficient $d$ can be either positive or negative.
Fundamental Mechanisms

• It is common to call a piezoelectric coefficient measured in the direction of applied field the **longitudinal coefficient**, and that measured in the direction perpendicular to the field the **transverse coefficient**.

• Other piezoelectric coefficients are known as shear coefficients.

• Because the strain and stress are symmetrical tensors, the piezoelectric coefficient tensor is **symmetrical** with respect to the same indices \( d_{ijk} = d_{ikj} \).
# Typical Piezoelectric Materials

<table>
<thead>
<tr>
<th>Nat. (Cr)</th>
<th>Syn. (Cr)</th>
<th>Syn. (Ce)</th>
<th>III-V and II-VI Semiconductors</th>
<th>Polymers</th>
<th>Organic nanostructures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quartz</td>
<td>Gallium orthophosphate (GaPO₄)</td>
<td>Cell of lead titanate</td>
<td>Commonly found in the Wurtzite structure</td>
<td>Polyvinylidene fluoride (PVDF)</td>
<td>Self-assembled diphenylalanine peptide nanotubes (PNTs)</td>
</tr>
<tr>
<td>Berlinite (AlPO₄)</td>
<td>Langasite (La₃Ga₅SiO₁₄)</td>
<td>Ceramics with randomly oriented grains must be ferroelectric in order to exhibit piezoelectricity</td>
<td><strong>GaN, InN, AlN and ZnO.</strong></td>
<td>Intertwined long-chain molecules attract and repel each other when an electric field is applied</td>
<td>High effective piezoelectric coefficient values of at least 60 pm/V (shear response for tubes of ≈200 nm in diameter).</td>
</tr>
<tr>
<td>Sucrose</td>
<td>Barium titanate (BaTiO₃)</td>
<td></td>
<td></td>
<td>PNTs demonstrate linear deformation without irreversible degradation in a broad range of driving voltages.</td>
<td></td>
</tr>
<tr>
<td>Rochelle salt</td>
<td>Lead zirconate titanate (PZT) (Pb[ZrxTi₁₋ₓ]O₃)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lead titanate (PbTiO₃)</td>
<td>(KNbO₃) (LiNbO₃) (LiTaO₃) (Na₂WO₃)</td>
<td></td>
<td></td>
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</tr>
<tr>
<td></td>
<td>Zinc oxide (ZnO)</td>
<td></td>
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</table>
Piezoelectricity in Wurtzite Structure

- Non-central symmetric crystal
- Zn\(^{2+}\) cations and O\(^{2-}\) anions are tetrahedral coordinated
- Applied stress induces dipole moments, which results in a potential drop along the straining direction in crystal
- Distribution of Piezoelectric potential is displayed using Lippman theory
Piezoelectric nanowire generators were first demonstrated by Dr. Wang’s group at Georgia Institute of Technology in 2006.

The semiconducting characteristics of the ZnO creates a Schottky contact between the conductive tip of the AFM and the nanowire itself, creating a rectifying structure that allows observable voltage output at an external resistive load.

Piezoelectricity in ZnO Nanowires

Zhong Lin Wang, Georgia Tech – Piezo-tronics and Piezo-photonics

His research interests include the science and application of nanoparticles, nanowires and nanobelts; functional oxide and smart materials for sensing and actuating; and nanomaterials for biomedical applications and nanodevices.

“Using nanopiezotronics, we’ve fabricated piezoelectric-field effect transistors; a piezoelectric diode; and piezoelectric force, humidity, and chemical sensors.”

Piezoelectricity in Cu2S 2D structures

Science, 291, 1947-1949
Piezoelectric of Nanowires

These initial studies proved the electrical energy generation capability of a single ZnO nanowire. However, a practical application requires thousands of nanowires to be mechanically excited without a special device.

Typical ZnO nanowire fabrication processes yield very high spatial densities; however, the orientations of these nanowires are usually random.

The output power strongly depends on the density and height uniformity of the nanowires as well as the contact distance between the nanowire array and the top electrode.

Nevertheless, fabricated device generated a DC output power of 4 W/cm$^3$ active area when excited with an ultrasound wave.

Who is Working on Piezoelectrics?

Pike Research (Bob Gohn, vice president)
Researchers at the University of Wisconsin-Madison have built low-voltage, near-nanoscale electromechanical devices - for nanopositioning devices.

Chang-Beom Eom, a UW-Madison professor of materials science and engineering and physics, and his colleagues have developed a way to integrate PMN-PT seamlessly onto silicon.

Figure 1 A PMN-PT piezoelectric cantilever (University of Wisconsin-Madison)

Challenges of Using Piezoelectricity

- Maintaining batteries is a major logistical and cost issue.

- One of the key aspects of vibrational energy harvesting is the way it can be tightly integrated into equipment.

- A major limitation of these advanced materials is incorporating them into very small-scale devices.

- As for the nanogenerators, we need to raise the nanogenerator’s output voltage. This will require optimizing the electrode’s design to reduce system capacitance.

https://www.utwente.nl/ctw/trc/EN/projects/piezo/
Challenges of Using Piezoelectric Devices

Frequency Shifting

Most of the vibrational energy harvesters are designed to operate in resonance mode and the half-power bandwidth is usually small.

This is one of the most important challenges of energy harvesting since the frequency of ambient vibrations varies within a wide range, from 1 Hz for heel tapping up to 240 Hz for an electric tea pot.
1D Nanostructure Growth

Nano letters 10 (9), 3414-3419
Nanotechnology, 20145302, 2009
Hydrothermal Growth

- Driven by the reduction of Gibbs free energy or chemical potential, by phase transformation, chemical reaction or the release of stress
- Anisotropic or preferential growth is required for 1D nanomaterials
- Defects and impurities on the growth surfaces significantly affect the morphology

Nature Comms
Doi: 10.1038/2277