Advanced Functional Materials for IoT and AI devices: Ferroelectric Microwave Filter, Supercapacitor, $HfZrO_2$ based Memory device and Piezoelectric Sensors

Kaushal Tiwari (IISc), Naveen Negi (IISc), Uma Ganguly (IISc) and Bhagwati Prasad (IISc)

OBJECTIVE

1. **CMOS-Compatible Microwave Tunable Filter:** Developing a tunable microwave filter using a doped $BaTiO_3$ and $Hf_{0.5}Zr_{0.5}O_2$ (HZO) bilayer heterostructure for satellite communication.
2. **Advanced Ferroelectric Devices:** Designing $BiFeO_3$ Dopped $Ba_xSr_{1-x}TiO_3$ and HZO based supercapacitors (115 J/cc), HZO-based FTJs for non-volatile memory (ON/OFF >1000, endurance $>10^{14}$), and $BaCaTiO_3$-$BaZrTiO_3$ (BCT-BZT) Piezoelectric sensors for energy harvesting.

INDUSTRY NEED

- **Communication & Wireless Industry:** Ferroelectric materials enable tunable band-pass filters for efficient signal processing, frequency modulation, and interference suppression.
- **Energy & Power Industry:** High-energy-density supercapacitors ensure fast charging, long cycle life, and reliable energy storage for **electric vehicles (EVs)**, renewable energy systems, and power grids.
- The **semiconductor industry** is exploring **Ferroelectric Tunnel Junctions (FTJs)** as a promising non-volatile memory solution. **HZO-based FTJs** offer high ON/OFF ratios (>1000), excellent endurance ($>10^{14}$ cycles), and ultra-low power consumption (attoJoule/bit), making them ideal for energy-efficient computing, IoT devices, and next-generation data storage.
- Industries like aerospace, automotive, healthcare, and structural engineering require highly sensitive **piezoelectric sensors**. These sensors are used for **structural health monitoring**, **vibration detection in machinery**, **ultrasound imaging in healthcare**, and **precision force sensing in industrial automation**.

PRIOR ART

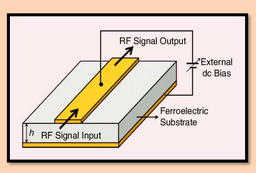
- **Satellite communication:** Existing ferroelectric materials in communication systems exhibit low microwave tunability, while high dielectric tunability is essential for advanced microwave applications.[1]
- **Ferroelectric based supercapacitors:** enable efficient power delivery in EVs, renewables, and electronics, balancing MW/kg power density, cost, energy storage, and longevity.[2]
- **Ferroelectric Logic & Memory:** Energy-efficient ferroelectric devices enable IoT, mobile, and data center applications, but challenges include reducing energy use **(≤2pJ/bit),** enhancing endurance **($\geq 10^8$ cycles)**, and ensuring scalable, cost-effective integration.[3]
- **Piezoelectric Sensors:** Critical for aerospace, automotive, and healthcare applications, current sensors face challenges in improving power density **(≤120 W/cm²)** and reducing high costs **($10–$100/unit).**[4]

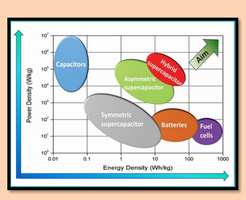
TECHNICAL CHALLENGES

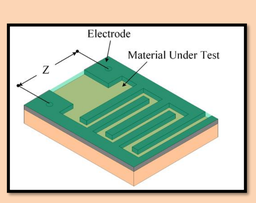
1. **Miniaturization & Fabrication** – Achieving uniformity in **sub-10 nm films** while maintaining ferroelectric properties and low leakage **($<10^{-6}$A/cm²)** is challenging.
2. **CMOS Compatibility** – Integrating HZO and other ferroelectrics with **>3 MV/cm breakdown voltage** into CMOS without wake-up/fatigue issues (**$>10^8$ cycles**) is complex.
3. **Lead-Free Alternatives** – Lead-free materials struggle with **low Curie temperature (<120°C)** and polarization **(<60 μC/cm²)**, limiting industrial adoption.
4. **Microwave Integration** – Current ferroelectrics have **<15% tunability at 10 GHz**, while advanced RF devices require **>50% tunability with tan δ < 0.005**.
5. **Thermal Stability & Power Density** – Devices must operate across **−40°C to 150°C**, but current piezoelectric sensors provide **low power density (~120 W/cm²)** instead of the required **>300 W/cm²**.

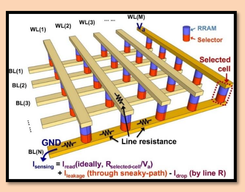
CONCLUSIONS AND OUTLOOK

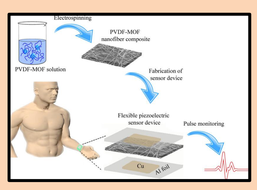
- ✓ So far, We achieved **72 % Microwave tunability** at 2 Ghz frequency range promising for MW filter design.
- ✓ We achieved Energy density **66J/cc at 3.2 MV/cm** electric field in our supercapacitor.
- ✓ We have successful grown ultrathin film (**3nm) of HZO** promising for FTJ and memory application.
- ✓ We achieved systematic trend of **strain and d_{33}** in BCT-BZT materials, confirming their suitability for sensor application.





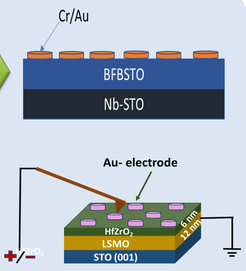


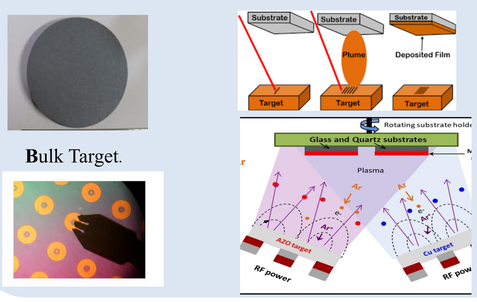




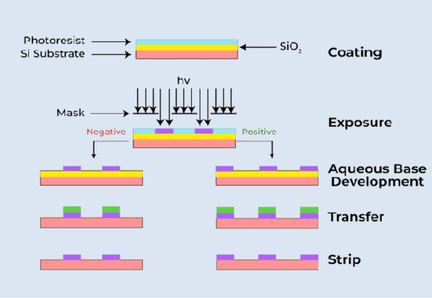
EXPERIMENTAL DETAILS

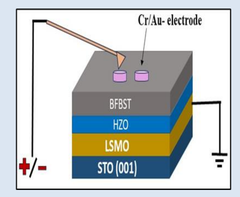
Step-1	Step-2	Step-3	Step-4	Final Step
Material selection and making Ceramic Target.	Growing good quality of Thin film by DC,RF sputtering.	Device fabrication via Standard lift – Off phot-lithography technique.	Measurements of fabricated Devices.(i.e. electric, thermal etc.)	Integration of devices into cross bar array or any other electronic architecture.



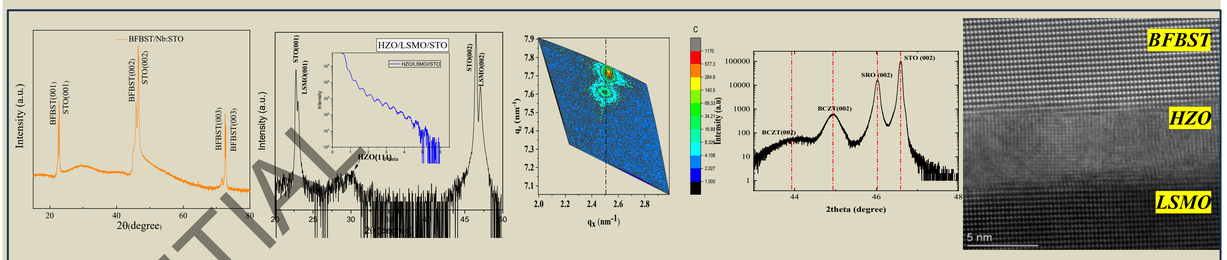


Bulk Target.

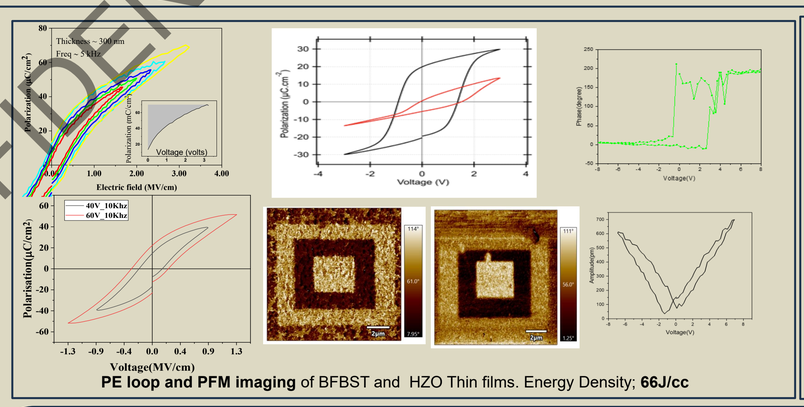




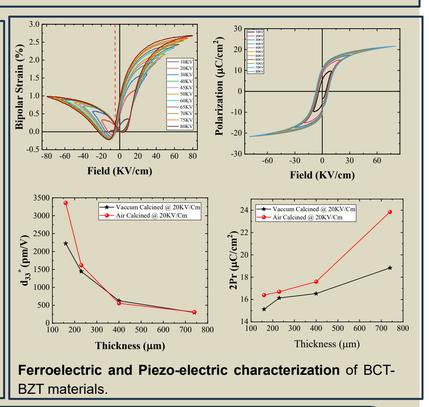
RESULTS AND DISCUSSIONS



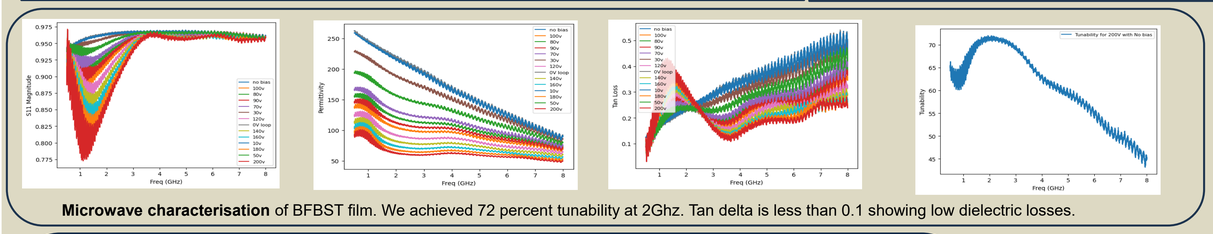
Structural characterization XRD,XRR,RSM and TEM of BFBST, HZO and BCT-BZT materials.



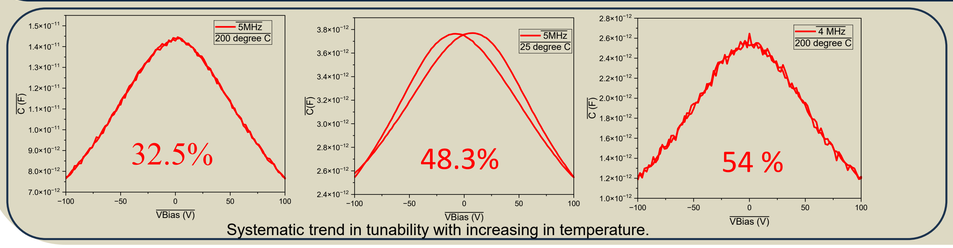
PE loop and PFM imaging of BFBST and HZO Thin films. Energy Density; **66J/cc**



Ferroelectric and Piezo-electric characterization of BCT-BZT materials.



Microwave characterisation of BFBST film. We achieved 72 percent tunability at 2Ghz. Tan delta is less than 0.1 showing low dielectric losses.



Systematic trend in tunability with increasing in temperature.

$$n = (\varepsilon(0) - \varepsilon(E))/\varepsilon(0)$$

$$Tunability = x\ \frac{C_{0V} - C_{25V}}{C_{0V}} \times 100\%$$

INDUSTRY INTEREST AND PARTNERSHIPS

Applied Materials, Lam Research, Intel, Western digital, Micron, Tata Electronics and MacDermid Alpha.

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