SUPERHARMONIC RESONANT RESPONSE MEASUREMENT (SRRM): A NEW METHOD FOR MEASURING SPONTANEOUS POLARIZATION

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ABSTRACT

We introduce a new method called Superharmonic Resonant Response Measurement (SRRM) for measuring spontaneous polarization in a piezoelectric material. We demonstrate this technique using a PZT-based PMUT device since the spontaneous polarization for PZT can be independently measured to verify our results. This method makes it possible to directly measure spontaneous polarization in materials such as AlN, GaN, and HfO2, for which no measurement has been done so far.

KEYWORDS

Piezoelectric materials, Spontaneous Polarization, PMUT, Nonlinear response

INTRODUCTION

Ferroelectric materials exhibit a spontaneous Polarization (P_s) property that occurs due to internal atomic arrangement wherein electric dipoles align resulting in a net dipole moment even in absence of any external stimuli [1]. In ferroelectric materials, changing the polarity of the electric field changes the electric dipole moment further which eventually saturates and exhibits a hysteretic behavior. Ferroelectric materials such as PZT, PMN-PT, and BTO are used for the applications such as memory devices (FeRAM), RF filters, oscillators, actuators, sensors etc. [2]–[4]. The performance of these devices is affected by the spontaneous polarization of the constituent ferroelectric material. The polarization measurements for the these materials using the pulse methods such as Dynamic Hysteresis Measurement (DHM) method and Positive-Up-Negative-Down (PUND) measurement method have been explored [5]–[7].

Materials such as AlN, HfO_2, GaN etc. are the piezoelectric materials that exhibit large spontaneous polarization that are in huge demand for the multitudinous applications in power electronics, RF switches, MEMS/NEMS transducers, amplifiers, optical modulators, laser diodes, LEDs, and high performing devices [8]–[10]. Several researchers have carried out ab initio calculations to estimate the spontaneous polarization in piezoelectric materials such as AlN, GaN, ZnO etc. [11], [12]. To measure the P_s for such materials is non-trivial through the conventional pulse methods, viz. DHM and PUND, due to absence of switch of polarization with electric fields. There are no known direct measurements of P_s for these materials even though it has a profound influence on the perform of the devices. Thus, direct P_s measurement of these piezoelectric materials continues to be an open problem.

To address the above stated problem, we devised a Superharmonic Resonant Response Measurement (SRRM) method that employs a thin-film-piezoelectric-on-substrate (TPoS) MEMS device for measuring spontaneous polarization through nonlinearities present in the film.

Three major types of nonlinearities exist in MEMS devices: i) transduction, ii) damping, and iii) mechanical [13], as shown in Figure 1. Transduction nonlinearity enables a mechanism to transfer to a harmonic mode through sub and super harmonic actuation.

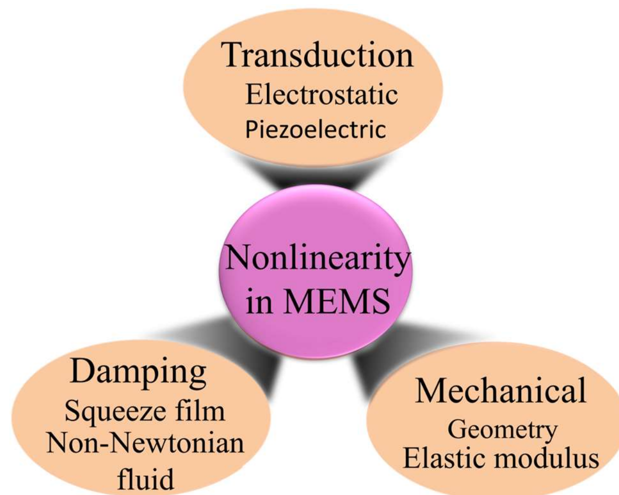

Figure 1: Nonlinearities in the MEMS devices

Piezoelectric materials naturally exhibit higher order nonlinearities such as electrostriction [14]:

$$s = dE + ME^2 \quad (1)$$

where, s is the strain developed due to the electric filed, d is the electromechanical coefficient, M is the electrostrictive coefficient, and E is the electric field applied.

Damping nonlinearities cause amplitude dependent energy dissipation [15]. Mechanical nonlinearities arise due to nonlinear material properties and structural deformation, resulting in displacement dependent stiffness [16]. For the purposes of our prescribed methodology, we need to ensure that the effects of damping and mechanical nonlinearities are minimized.

NEW METHOD DESCRIPTION

This method requires a TPoS MEMS resonant device. Such a device can be modelled as a spring mass damper system as:

$$m\ddot{x} + c\dot{x} + kx = F \quad (2)$$

Here, the force is acting on the device through the piezoelectric transduction, and can be written as [17]:

$$F = G_1 V_{in} + G_2 Vin^2 \quad (3)$$

To illicit a harmonic response, a voltage excitation at the resonant frequency is applied ($\omega_{excitation} = \omega_{res}$). This can be modelled as:

$$m\ddot{x} + c\dot{x} + kx = G_1 V_{in} + G_2 V_{in}^2$$
$$= G_1 v_0 \cos(\omega_{res} t) + \frac{G_2 v_0^2}{2} \cos(2\omega_{res} t) + \frac{G_2 v_0^2}{2} \quad (4)$$

Here, G_1 is the 1st order electromechanical coupling coefficient related to the electromechanical coefficient (d) [17], whereas G_2 is 2nd order coupling coefficient related to the electrostrictive coefficient (M). Due to resonance, this actuation causes a large displacement, A_1, corresponding to the force term proportional to G_1.

Next, a superharmonic excitation is carried out by actuation at

($\omega_{excitation} = \frac{\omega_{res}}{2}$). This is modelled as:

$$m\ddot{x} + c\dot{x} + kx = G_1 V_{in} + G_2 V_{in}^2$$
$$= G_1 v_0 cos\left(\frac{\omega_{res}t}{2}\right) + \frac{G_2 v_0^2}{2}\cos(\omega_{res}t) + \frac{G_2 v_0^2}{2} \quad (5)$$

The displacement response, A_2, measured at ω_{res} corresponds to the force term proportional to G_2.

Using equation (4) and (5), the ratio of electrostrictive and electromechanical coefficients can be written as:

$$\frac{M}{d * th} = \frac{superharmonic\ force\ at\ \omega}{harmonic\ force\ at\ \omega} = \frac{G_2}{G_1} = \frac{2A_2}{A_1 * v_0} \quad (6)$$

Here, M=electrostrictive coefficient, d=electromechanical coefficient, th= thickness of the piezoelectric material.

It can be shown that the ratio of electrostrictive coefficient (M) and the electromechanical coefficient (d) is related to spontaneous polarization (P_s) as [18]:

$$\frac{M}{d} = \frac{\varepsilon_0 \varepsilon_r}{2P_s} \quad (7)$$

Here, ε_r=dielectric constant of the piezoelectric material. Combining equations (6) and (7), the spontaneous polarization can be determined as:

$$P_s = \frac{\varepsilon_0 \varepsilon_r A_1 v_0}{4A_2 th} \quad (8)$$

Here, superhamonic excitation was carried out because the resonator does not have a large Q enhanced response at half the resonance frequency. This ensures that the output voltage measured at the resonance frequency solely accounts for the response of electrostrictive component of actuation.

We showcase this method using a PZT based TPoS device and verify the results through the hysteresis polarization loop obtained through PUND measurements. This method works for any arbitrary bending based TPoS device and can be used for measuring P_S of all piezoelectric materials.

EXPERIMENTAL SETUP

A PZT-based PMUT device is fabricated with split electrodes and bottom electrode using a method described by Sudhanshu et.al. [19]. The device architecture and the cross-section with material thicknesses is shown in Figure 2a, and the optical image is shown in Figure 2b. Electrical resonance measurements for harmonic and superharmonic responses were carried out in a vacuum chamber to maximize quality factor, using a Zurich lock-in amplifier as shown in Figure 2c. A differential sensing mechanism has been employed to reduce device feedthrough.

To independently measure the spontaneous polarization, the PMUT is connected to the semiconductor device analyzer with waveform-

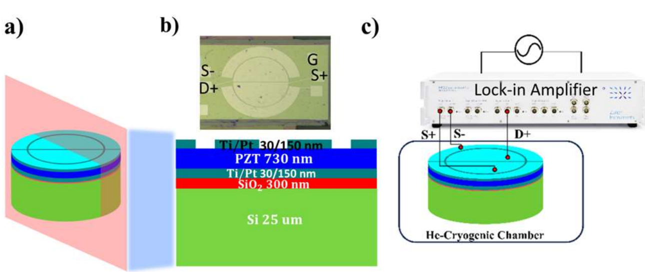

Figure 2: a) Device cross-section with different material stacks, b) optical image of the PMUT device, and c) Harmonic and Superharmonic resonance measurements scheme using lock-in amplifier.

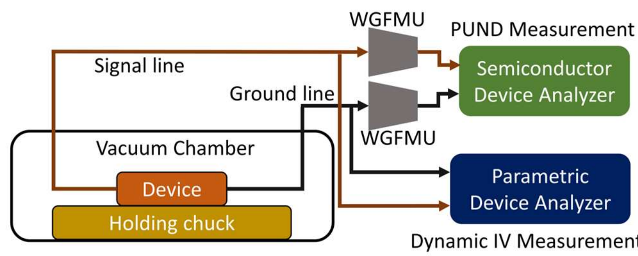

Figure 3: Measurement schematic of the positive-up and negative-down (PUND) by semiconductor device analyzer along with WGFMU and dielectric measurements by using parametric device analyzer.

-generator fast-moving units (WGFMU). The current in the polarized cycle from the device using the positive-up-negative-down (PUND) technique was measured by this setup. The dielectric measurements are performed using a parametric device analyzer using dynamic current-voltage technique. The experimental setup for the PUND and dynamic IV measurements are shown in Figure 3.

RESULTS:

Resonance responses using the setup described in Figure 2c were measured for harmonic and superharmonic responses, as shown in Figure 4a and 4b, respectively. The harmonic actuation results in a higher amplitude of 4.57 mV for 1V excitation, whereas, for the same excitation voltage with the superharmonic amplitude results in an amplitude of 0.365 mV.

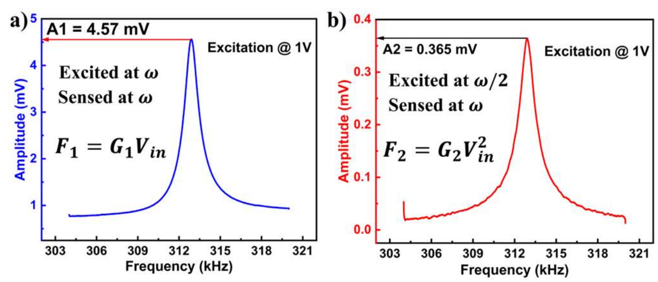

Figure 4: Resonance responses: a) harmonic resonance response while actuated and sensed at the resonance frequency, b) superharmonic resonance response where actuation is at half of the resonance and sensed at the resonance frequency.

Using equation (8) and plugging in the values of dielectric constant for PZT film measured separately (ε_r=833) [20], harmonic and superharmonic maximum amplitudes (A_1= 4.57mV and A_2= 0.365mV), thickness of the film (th=730 nm), and excitation voltage (v_0= 1V), the measured spontaneous polarization is 3.2 $\mu C/cm^2$.

The hysteretic behavior of charge vs applied voltage observed using the dynamic IV measurement, is shown in Figure 5a. A FFT of the time series data, as shown in Figure 5b, confirms that there is no response at the second harmonic reaffirms that there is no dielectric nonlinearity present in the film. Thus, we show that the force generated at the higher harmonic arises purely due to electrostrictive coefficient with no significant contribution from dielectric nonlinearity.

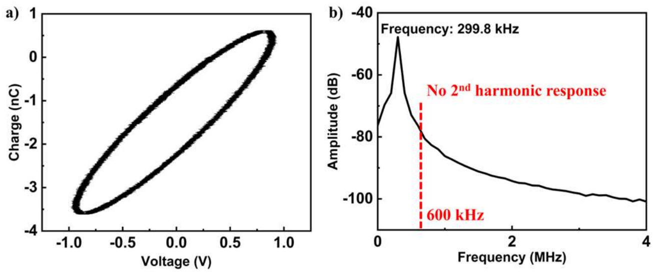

Figure 5: Dynamic IV measurements: a) The charge-voltage plot shows the linearity of the dielectric function, b) the FFT of the dynamic measurement also indicates the single peak at the resonance and no indication of the 2nd order peak.

The PUND measurement response during the PU cycle was shown in Figure 6a. As expected, we observe that the current change during the first pulse (Positive pulse) that accounts for both dielectric and spontaneous polarization contribution, was larger than that observed during the 2nd pulse (Up pulse). A similar behavior was observed for the negative-down as shown in Figure 6b. The charge due to the spontaneous polarization change was calculated by integrating the current observed during both the PU pulses separately and finding their difference, as per standard PUND measurement technique. A similar procedure was carried out for the ND pulses.

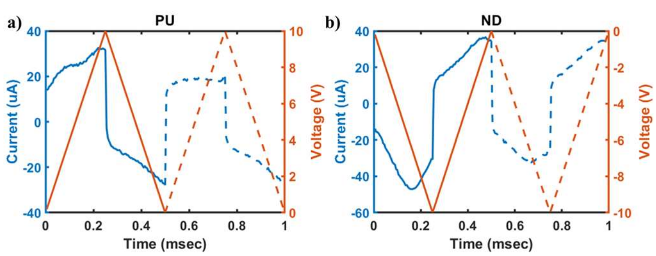

Figure 6: PUND measurements: a) current-time plot during the positive-up measurement, b) plot from negative-down measurement.

From the PUND measurements, the polarization-electric field loop is calculated using polarized charge with respect to the area of the electrode and shown in Figure 7. The polarized charge due to positive-up current results in half the PE loop, shown in blue, and the charge due to negative-down yields the 2nd half of the loop, shown in brown. The small gap near the 0 V at the positive polarization is due to asymmetric top and bottom electrodes. The positive remnant polarization is taken as the average of the blue and brown points at 0V, whereas negative remanent polarization was calculated in a similar fashion. From the PE loop, the calculated P_s is $\sim 3.0\ \mu C/cm^2$ that is close to the calculated P_s through resonant responses.

DISCUSSION

We note that the spontaneous polarization measured by our SRRM method closely matches that obtained by standard PUND measurements. We note also that there could be a frequency dependence of spontaneous polarization that has not been explored so far in the literature.

As discussed in the method section, the SRRM method does not require switching of polarization and can, thus, be universally used for any piezoelectric material. Thus, this method can be used to determine spontaneous polarization for materials such as AlN, GaN and HfO_2 for which no direct measurements have been performed so far.

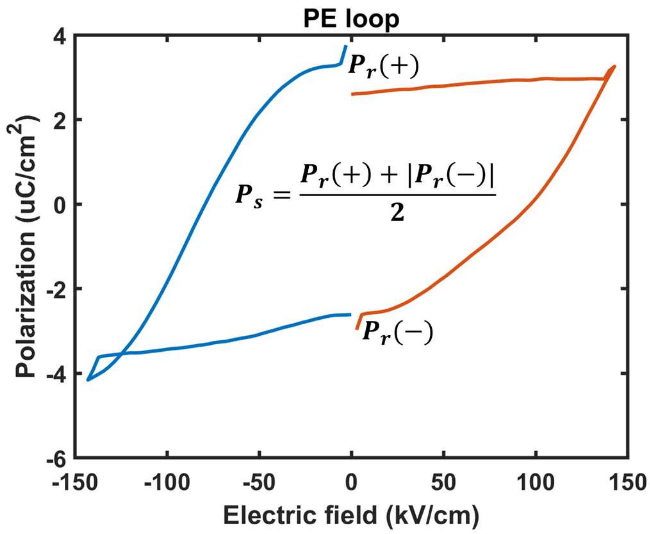

Figure 7: Polarization-Electric field loop using PUND measurement.

CONCULSION

In this paper, we present a method called Superharmonic Resonant Response Measurement (SRRM) that enables the measurement of spontaneous polarization of piezoelectric films. We illustrate the method using a PZT based PMUT TPoS device and verified the results against the measurements obtained from standard hysteresis polarization loop determined by PUND measurement. This method can be used for measurement of Ps in materials in which polarization reversal does not occur.

ACKNOWLEDGEMENT

We acknowledge the support of the Centre for Nanoscience and Engineering, IISc, the National Nano Fabrication Centre (NNFC) and the Micro-Nano Characterization Facility (MNCF). Vishnu Kumar gratefully acknowledges the MHRD, Govt. of India, for providing us with the necessary funding and fellowship to pursue research work. Saurabh Chandorkar acknowledges Indian Space Research Organization, Government of India (GoI) under Grant DS_2B13012(2)/41/2018-Sec.2, by the Ministry of Electronics and Information Technology, GoI under 25(2)/2020_ESDA DT.28.05.2020 and Ministry of Human Resource and Development, GoI Grant SR/MHRD_18_0017. Saurabh Chandorkar also acknowledges DRDO JATP: DFTM/02/3125/M/12/MNSST-03.

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