Measuring Remanent Strain

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Theory

• Ferroelectric materials are characterized by remanent polarization.

• Remanent polarization ($P_R$) is polarization internal to the material and exists without the presence of an external electric field.

• For the materials to be ferroelectric, $P_R$ must be reversible by the application of an external electric field.

• Application of an electric field to a ferroelectric material to move its remanent polarization will also activate a dielectric response:

$$D = \varepsilon E + P_R$$
Theory

• In ferroelectric materials, there is a strong coupling of the polarization with the strain state of the material’s lattice.

\[ S = gD \]

• Substituting electrical displacement (polarization) into the strain equation yields a \textit{remanent strain} term.

\[ S = g(\varepsilon E + P_R) \]
\[ S = g\varepsilon E + gP_R \]

• A ferroelectric capacitor or ferroelectric actuator should exhibit programmable remanence in its thickness.
Remanent Polarization

• Remanent polarization should not move from its last written state as long as the applied voltage remains zero.

• If a positive voltage is applied to a ferroelectric capacitor that is pre-programmed DOWN so as to move from \([-P_R]\) partially UP to a \([P_{PU}]\) position, \([P_R]\) should remain in that \([P_{PU}]\) position until the next test.

• If the follow-on stimulus saturates the capacitor to the fully UP position, since its starting state is \([P_{PU}]\) but not \([-P_R]\), it should contain less remanent polarization:

\[
P_{\text{remaining}} = [P_R - P_{PU}]
\]

so that

\[
D = [P_R - P_{PU}] + \varepsilon E
\]
Remanent Polarization

• Below is a sequence of half-hysteresis loops that should execute such a test. It will have three half-loops.

• The first green negative-going stimulus presets the capacitors DOWN. The red triangle sets $P_{PU}$ plus dielectric charge. The last blue triangle measures the remaining remanent polarization half-loop $P_{remaining}$ plus dielectric charge.

• If the red pulse has zero amplitude, then the blue pulse will yield the Full half-loop. If the red pulse has a non-zero amplitude, then the blue pulse will not contain all of the remanent polarization.
Remanent Polarization

- For best effect, a partial switching loop should have a magnitude near the coercive voltage of the capacitor.
Device Under Test

The DUT is a 100,000µm² (250x400µm²) membrane shown below at 0 volts and Vc.

Why a membrane?

The membrane’s large motion improves signal-to-noise allowing single loops without averaging to get clear signals.
Device Under Test

Thicknesses:

9. Chrome/Gold Mirror: 0.02µm/0.5µm
8. Top SiO₂: 0.23µm
7. Top TiO₂: 0.04µm
6. PZT Passivation: 0.23µm
5. Top Electrode: 0.10µm
4. Active PNZT: 1.00µm
3. Bottom Electrode: 0.15µm
2. Bottom TiO₂: 0.04µm
1. Bottom SiO₂: 0.50µm

Total Thickness: 2.29µm

If we deposit a mirror, it is usually 0.5µm of gold atop the glass over the capacitor. At other times we have deposited magnetic materials in place of the gold or left off the mirror entirely.
Device Under Test

DRIE from backside stops cleanly on SiO$_2$ layer beneath the capacitor.
Remanent Polarization

- The polarization results of the proposed partial switching sequence executed on the membrane capacitor are below. Test period = 10s.

![Partial Switching Loops - Raw](image_url)
Remanent Polarization

- A tester cannot know the initial polarization state of a ferroelectric capacitor so the first point of every test is always zero $\mu C/cm^2$. 

![Graph of Partial Switching Loops - Raw](image)
Remanent Polarization

- If $P_{PU}$ and $P_{Remaining}$ are stacked atop each other and plotted inside $P_{Saturated}$, the effect of remanent polarization is clear.
Remanent Strain

- The polarization and displacement of the membrane capacitor movement was measured on a Radiant Precision NanoDisplacement Sensor (PNDS).
Remanent Strain

• The full ferroelectric strain loop for the same capacitor shows a nicely formed butterfly loop that moves approximately 2 microns peak-to-peak.

• Let’s perform the same remanence test on the membrane displacement.
Remanent Strain

- Saturated Preset and Forward half-loops…
Remanent Strain

- Partial switching loop after negative saturation…
Remanent Strain

- The Remainder loop starts from the last position of the partial loop.
Remanent Strain

• The relationships between the Partial, Remainder, and Full loops …
Conclusion

- PZT thin ferroelectric films do indeed have remanent strain corresponding with the remanent polarization of the ferroelectric capacitor as indicated by the equation:

\[ S = g \varepsilon E + g P_R \]