Stochastic Resonance In Thin-film Ferroelectric Capacitor - PZT 20/80

Submitted by
Manikantan R. S.
(122101046)

Under the guidance of
Dr. Arvind Ajoy

Collaborators :
Mr. Kevin R Jacob and Ms. Jonnalagadda Nikhila

INDIAN INSTITUTE OF TECHNOLOGY
PALAKKAD

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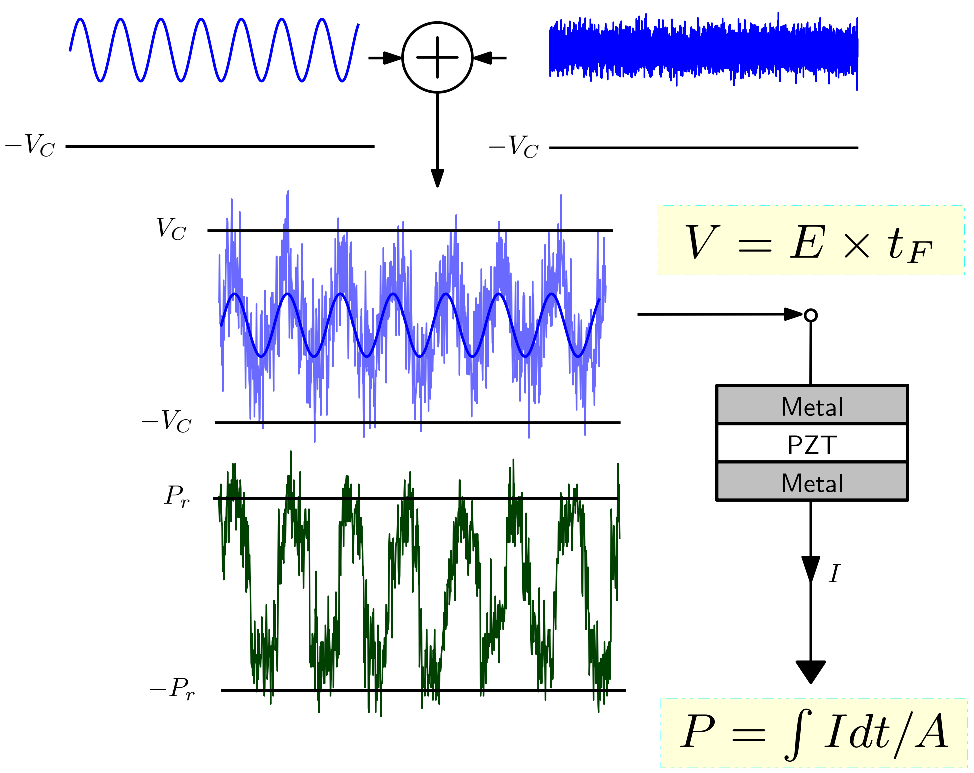
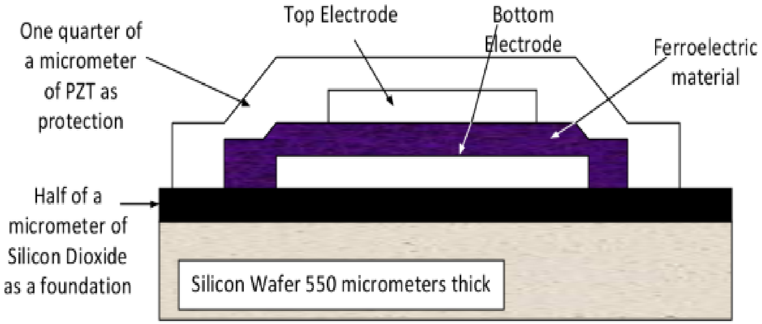
- Stochastic Resonance is a phenomenon by which a weak periodic signal is amplified using the addition of noise.
- As the name "resonance" suggests, this phenomenon happens at a particular amount of noise value, the signal to noise ratio increases, reach a peak value and decreases
- Ferroelectric materials are inherent bistable materials
- Here we try to observe Stochastic resonance in Ferroelectric capacitor (PZT 20/80)
- The input to the system is the voltage applied across the capacitor plate. Output is the resultant polarization



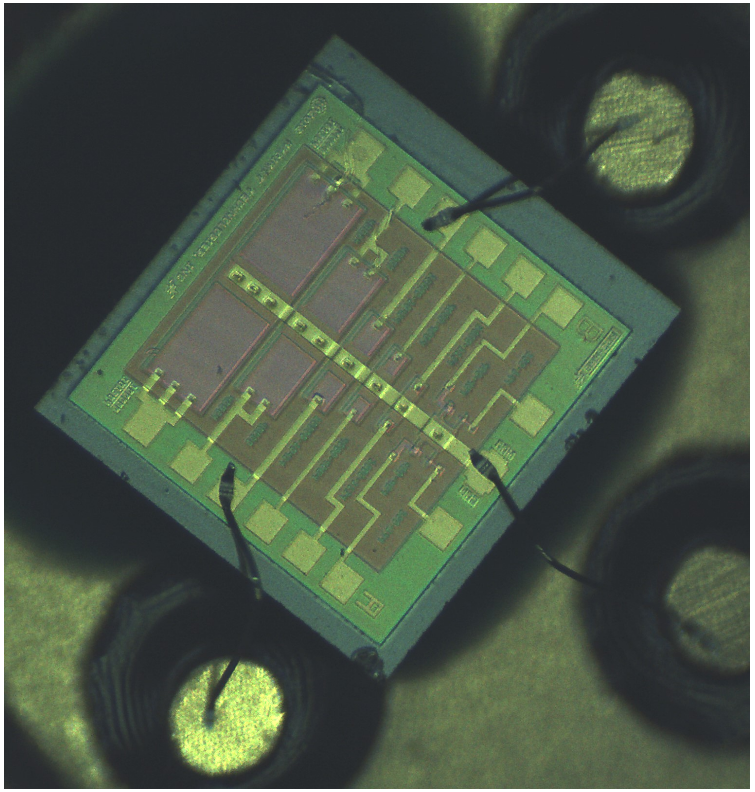
2. Ferroelectric Device PZT 20/80

- We uses the sample PZT (Packaged "AB") Capacitors provided by the Radient Technologies
- The Ferroelectric Tester from Radient Technologies, along with the Vision software is used to take all the measurements

Ferroelectric Tester from Radient



FE Capacitor cross section



Packaged AB capacitor (microscopic view)

α, β extraction from hysteresis

- Derivation:
- At steady state

$$\frac{\delta F}{\delta P} = 0 \implies E = 2\alpha P + 4\beta P^3$$

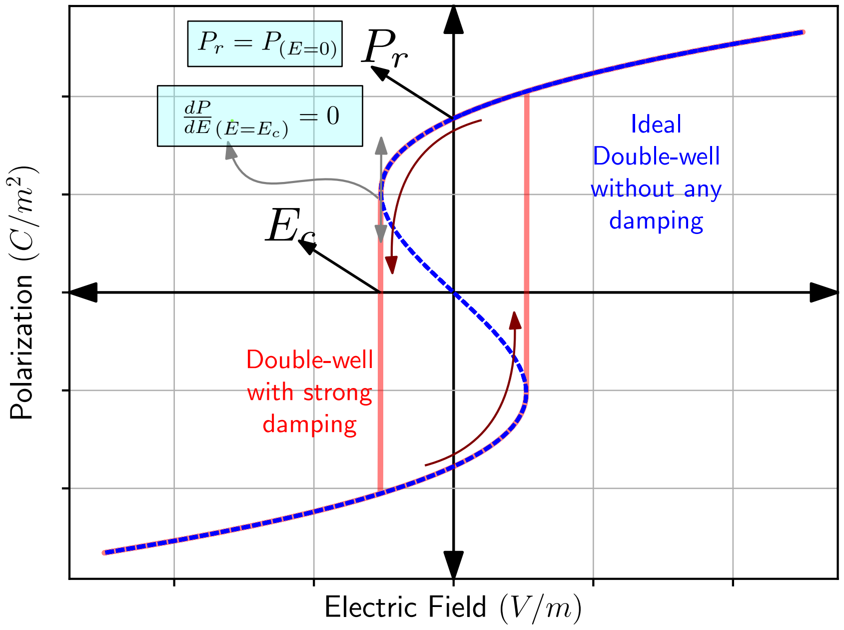
- Remnant polarization is the polarization at which electric field becomes zero.

$$E(P = P_r) = 2\alpha P_r + 4\beta P_r^3$$

- Coercive electric field is defined as the electric field at which the rate of change of electric field w.r.t polarization is zero.

$$\frac{dE}{dP}(E = E_c) = 2\alpha + 12\beta Pc^2 = 0$$

$$Ec = 2\alpha P_c + 4\beta P_c^3$$

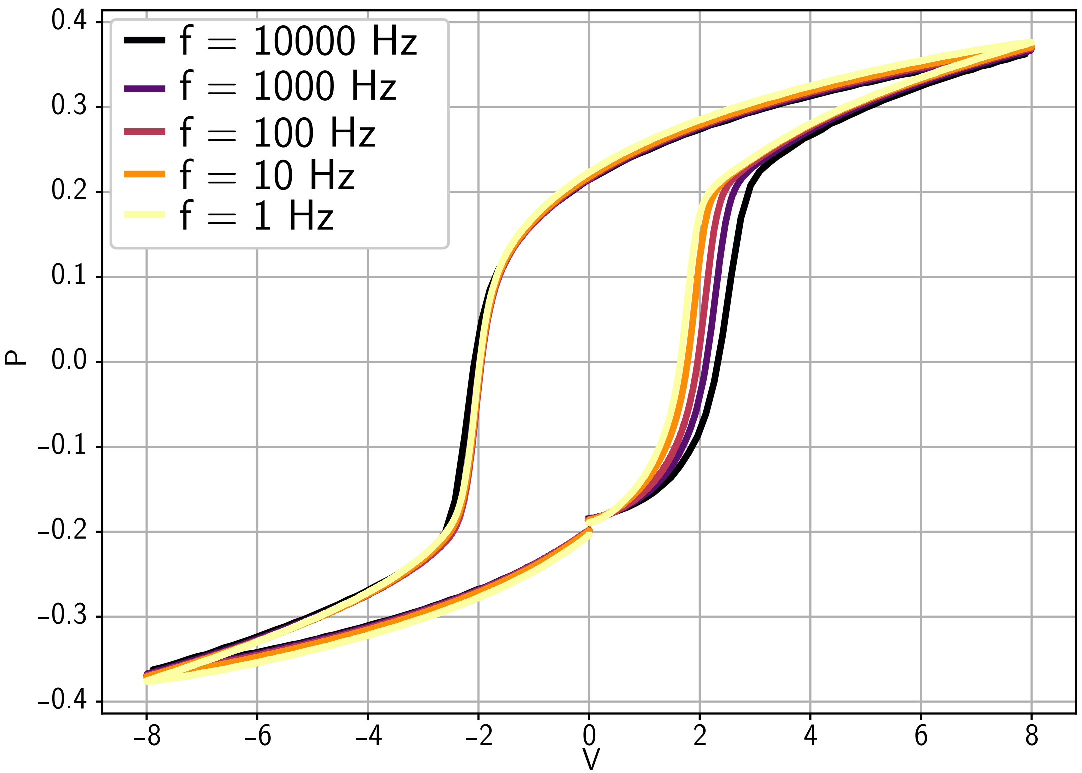


Solving

$$\implies \alpha = \frac{-3\sqrt{3}E_c}{4P_r}$$

$$\implies \beta = \frac{3\sqrt{3}E_c}{8P_r^3}$$

Hysteresis Measured at Different Signal Frequencies



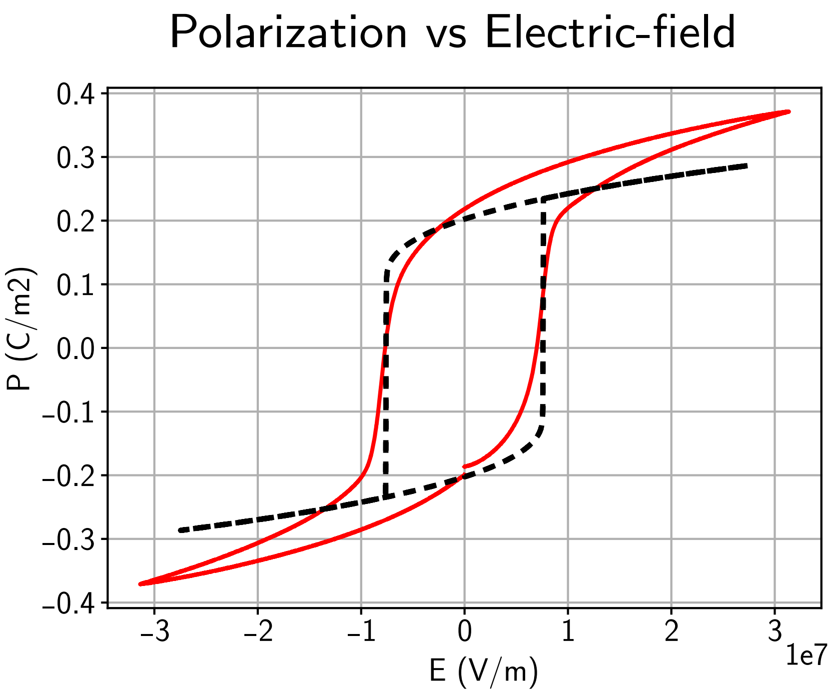
Observations

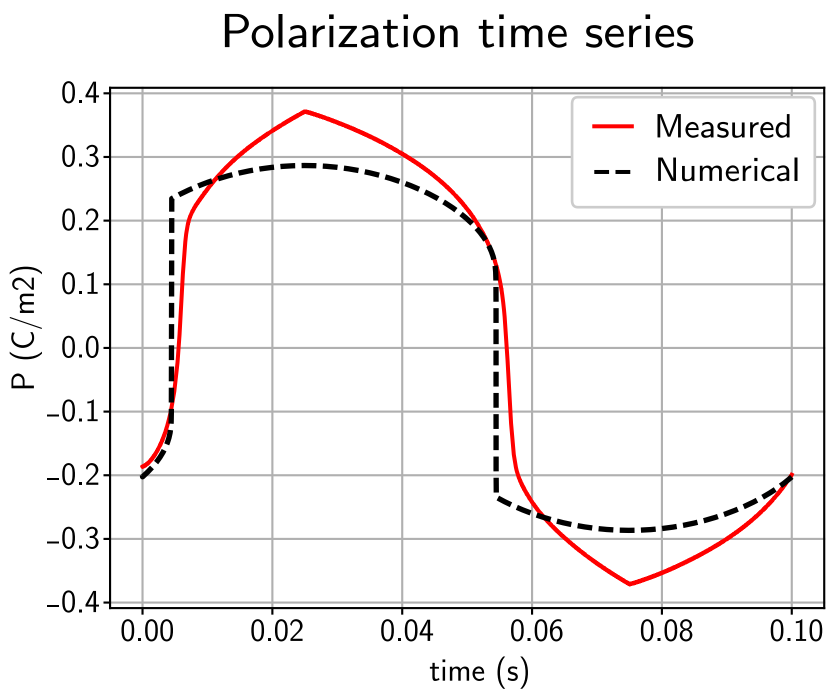
- The loop's size expands with increase in drive frequency
- The measured hysteresis is not centered. The expansion in loop is observed to one side.
- The P_r and E_c values are extracted from the loop

Parameter	Value
thickness t_F	255 μm
Area A_F	$10^5\ \mu m^2$
V_c	$1.9\ V$
E_c	$7.44\ MV/m$
P_r	$0.202\ C/m^2$

$$\alpha = \frac{-3\sqrt{3}E_c}{4P_r} = \mathbf{-4.77 \times 10^7}\ \mathrm{mF^{-1}}$$

$$\beta = \frac{3\sqrt{3}E_c}{8P_r^3} = \mathbf{5.82 \times 10^8}\ \mathrm{m^5F^{-1}C^{-1}}$$





Observations

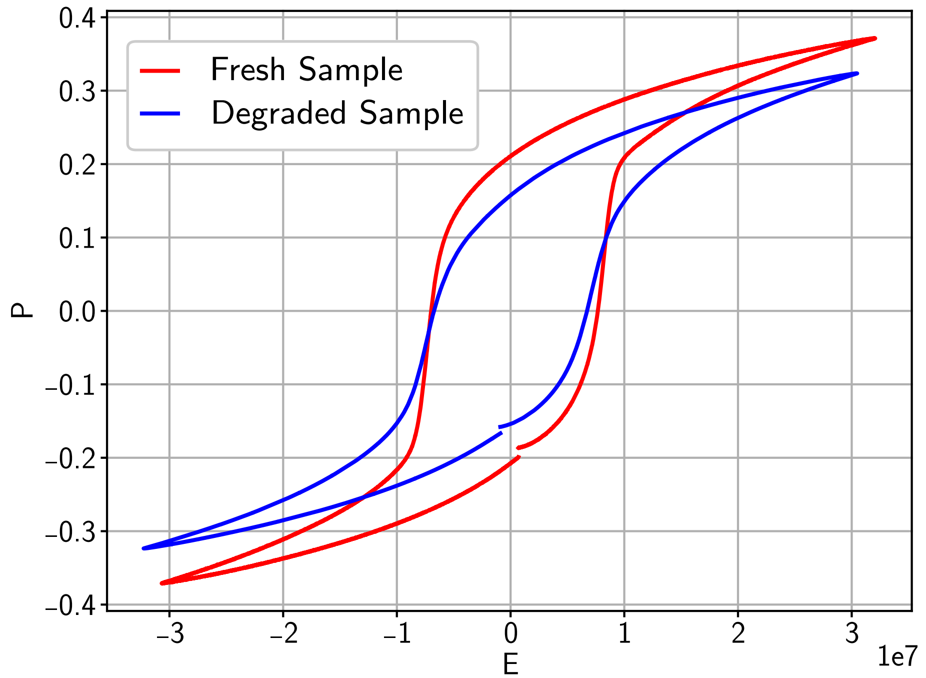
- Using the parameters from the formula the fit captures the Ec, Pr properly
- The increasing Pr after the saturation corresponds to dielectric losses in the system which the model fails to capture.
- Resistivity value is not very sensitive for the fit.

Parameter	Value
thickness t_F	255 μm
Area A_F	$10^5\ \mu m^2$
V_c	$1.9\ V$
E_c	$7.44\ MV/m$
P_r	$0.202\ C/m^2$
α	$-4.77\times10^7 mF^{-1}$
β	$5.82\times10^8 m^5F^{-1}C^{-1}$
ρ	$390\Omega m$

5. Sample Degradation

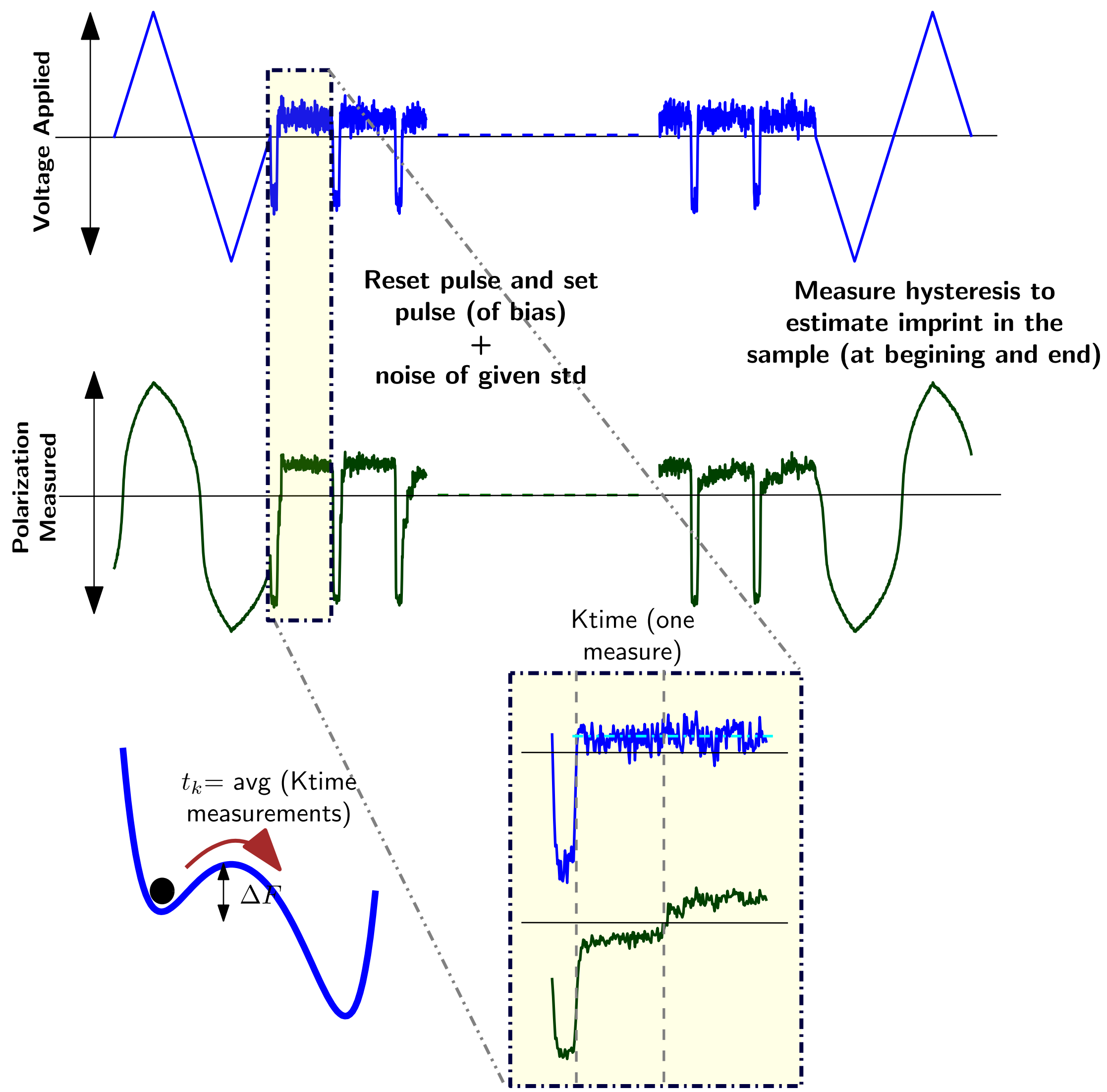
Observations

- We performed multiple readings on the sample (around 300 measurements)
- The hysteresis of the fresh sample and the hystersis after a series of readings is ploted here
- A considerable difference in the Pr value is observed, whereas the Ec also decreased by a small factor



Parameter	Fresh	After SR	Degraded
V_c	$1.9\ V$	$1.69\ V$	$1.71\ V$
P_r	$0.202\ C/m^2$	$0.161\ C/m^2$	$0.152\ C/m^2$
α	$-4.77 \times 10^7 mF^{-1}$	$-5.36 \times 10^7 mF^{-1}$	$-5.75 \times 10^7 mF^{-1}$
β	$5.82 \times 10^8 m^5 F^{-1} C^{-1}$	$10.31 \times 10^8 m^5 F^{-1} C^{-1}$	$12.502 \times 10^8 m^5 F^{-1} C^{-1}$

Kramer's Time Measurement Methodology



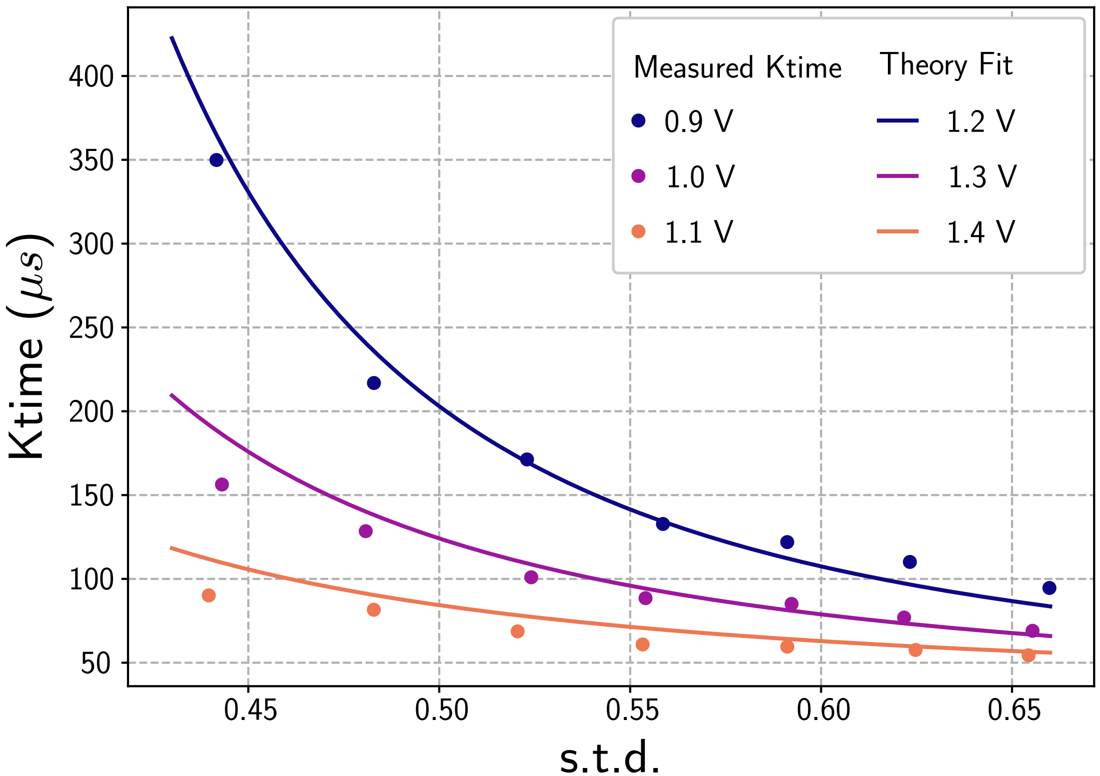
Method

- The set-reset pulse method is used to estimate Kramers' time
- Set pulse is applied to only one side (since imprint can't be avoided)
- To estimate imprint, a triangular wave is applied to capture the skewed hysteresis
- A total 150 switching events are measured to estimate Kramers' time

Parameter	Value
s.t.d	[0.5, 0.8] in step of 0.05
bias V	[0.9, 1.2] in step of 0.1
no ens	300 samples (2 readings)

therefore a total of
$14 \times 4 \times 2 = 112$ readings

Kramer's Time Measurement and ρ Extraction using curve fitting



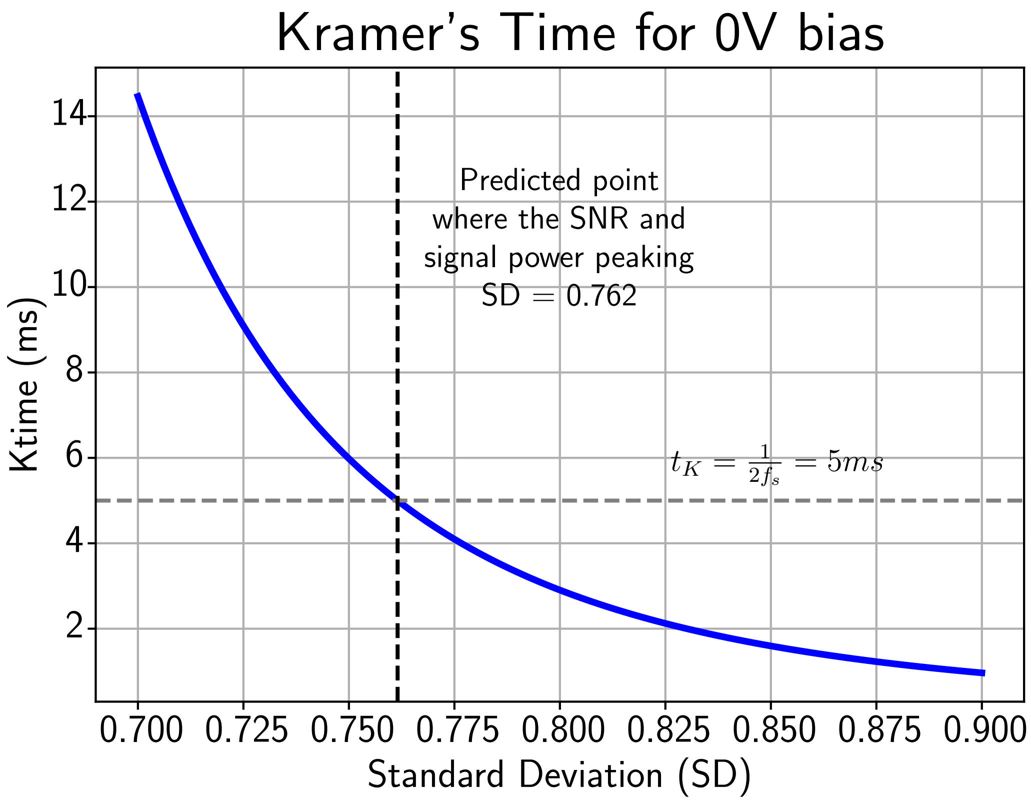
The dotted points are the measured K-time and the solid lines are the theoretical fit

Method

- We do a curve fit on the measured data. The fitting function is ae^{-b/sd^2}
- Using the fitted parameters we get an estimate on the ρ value.
- Both exponent and pre-factor have ρ dependency
- The Exponent is the most sensitive for the fit

Parameter	Value
ρ (extracted)	390 Ωm
Imprint	0.3 V
Bandwidth	10^5 Hz

Extrapolating the K-time for 0V bias and predicting the Resonance Noise Condition

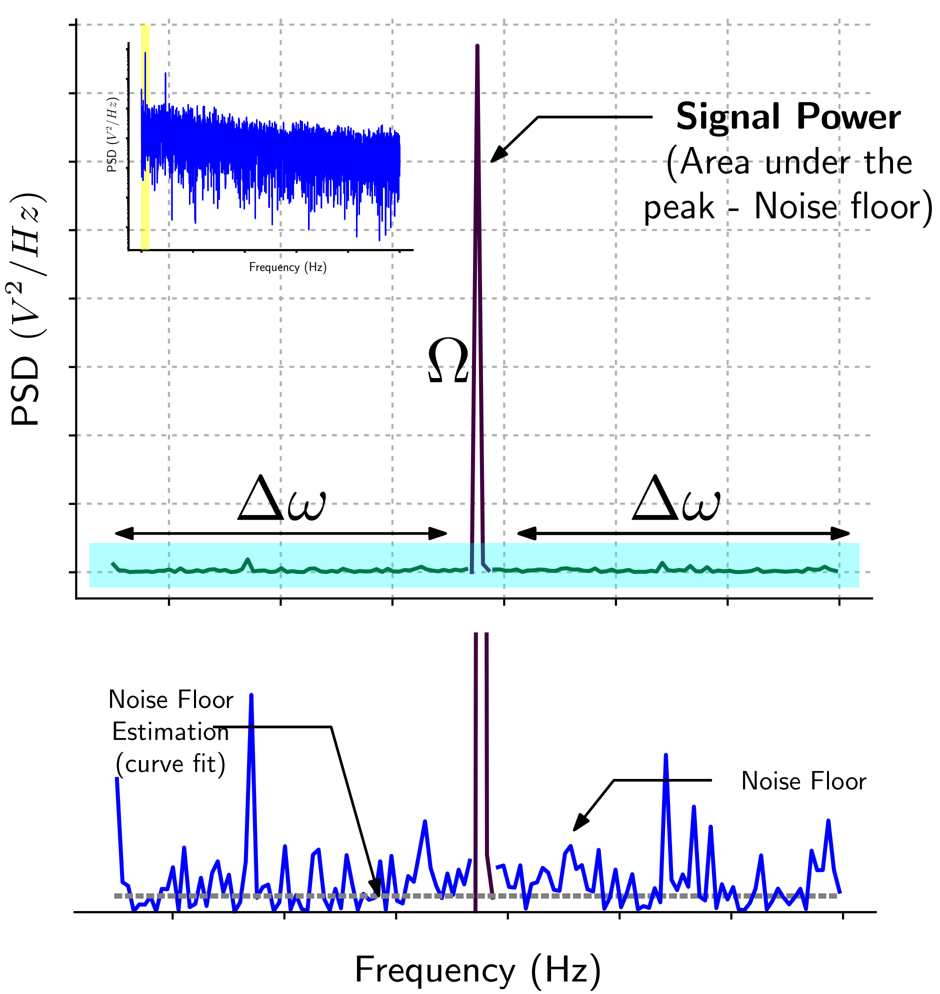


Method

- Optimal switching of polarization occurs when Kramers' rate became equal to half the signal period
- i.e. $t_K = \frac{1}{2f_s}$
- Therefore for a 100Hz signal the optimal switching can be observed when the Ktime is 5ms
- Therefore we extrapolate the fitted Kramers' time to the 0V bias Kramers' time
- According to the prediction the optimal switching should occur at 0.762 standard deviation

8. SNR Metrics

Signal Power Spectral Density



- **Signal Power**

$$P_{sig} = \int_{\Omega-\Delta\omega}^{\Omega+\Delta\omega} S(\omega)d\omega - 2S_N(\Omega)\Delta\omega$$

- **Signal to Noise ratio (SNR)**

$$SNR_{sig} = \frac{P_{sig}}{\int_{\Omega-\Delta\omega}^{\Omega+\Delta\omega} S_N(\omega)d\omega}$$

- **Cross Covariance**

$$cov(P, P_S) =$$

$$\frac{1}{N-1}\Sigma_{i=1}^{N}(P(i) - E[P])(P_S(i) - E[P_S])$$

The signal we are analysing is the polarization of the ferroelectric.
Where S is signal PSD, S_N is noise PSD
P_S is the switching polarization for a super threshold signal

- Double well model free energy equation

$$F = \alpha P^2 + \beta P^4 - EP$$

- TDGL equation

$$\rho \frac{dP}{dt} = -\frac{dF}{dP} + \zeta(t)$$

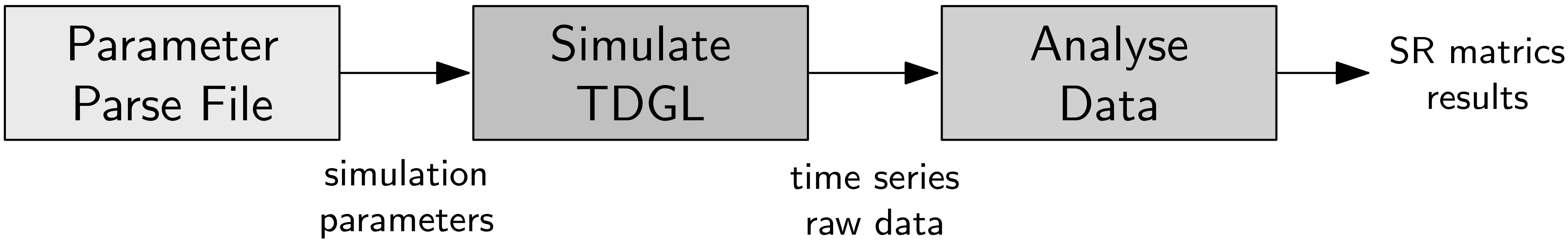
- TDGL equation: (In discrete form)

$$P[i] = P[i-1] - \frac{\Delta t}{\rho}\frac{dF}{dP}[i]$$

$$\frac{dF}{dP}[i] = 2\alpha P[i-1] + 4\beta P[i-1]^3 - E[i]$$

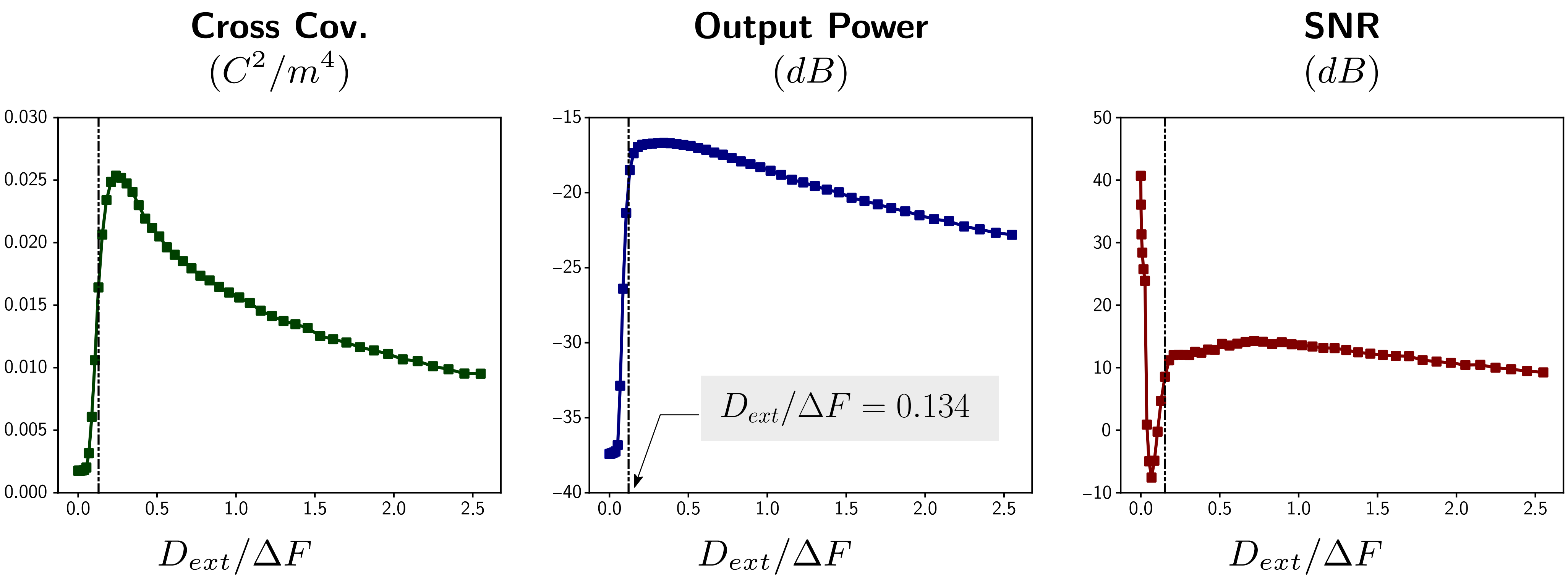
- Using the TDGL equation we generate the time series data. Note: time step (Δt) has to be small enough to avoid any numerical divergance issues

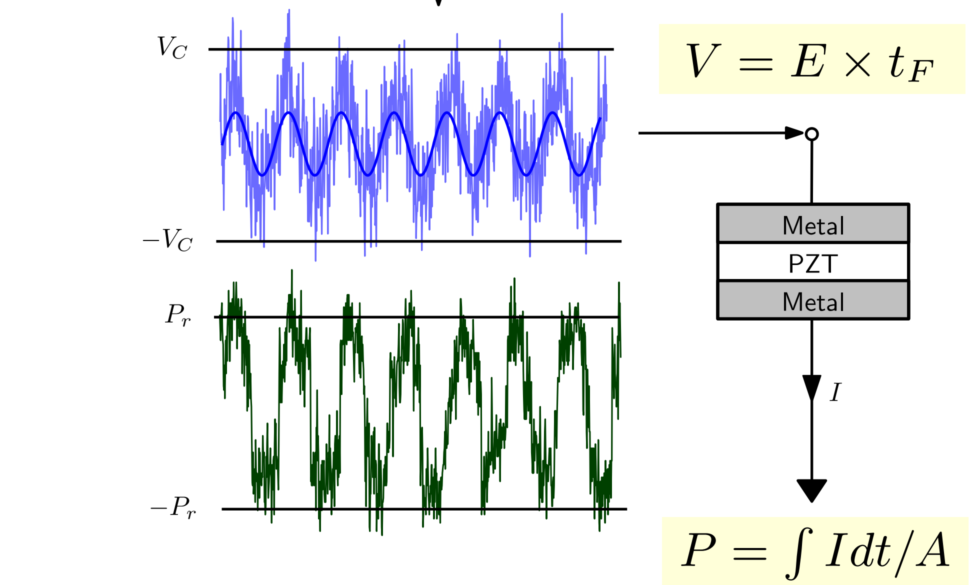
- Simulation Parameters



Parameter	Symbol / Value	Unit
Coercive Voltage	$V_c = 1.7$	V
Remanent Polarization	$P_r = 0.161$	C/m^2
Alpha	$\alpha = -5.38 \times 10^7$	SI units
Beta	$\beta = 1.04 \times 10^9$	SI units
Resistivity	$\rho = 390$	Ω·m
Thickness of Sample	$t_f = 255 \times 10^{-9}$	m
Area of Sample	$A_f = 1 \times 10^{-7}$	m^2
Temperature	$T = 300$	K
Sub-threshold Sine Amplitude	$A = 1$	V
Sine Frequency	$f = 100$	Hz
Noise Std Dev Range	[0, 3, 50]	V
Sampling Period	$t_s = 100 \times 10^{-9}$	s
Number of Cycles	$n = 100$	-
Ensemble Size	$ens = 10$	-
Downsampling Factor	$dsf = 1000$	-
Noise Bandwidth	$bw = 10^5$	Hz

- All three metrics shows stochastic resonance
- The predicted peaking points from the Kramers' rate are represented as the dash dotted lines in the graphs
- The actual peaking point is occuring slightly to the right of the predicted peaking point



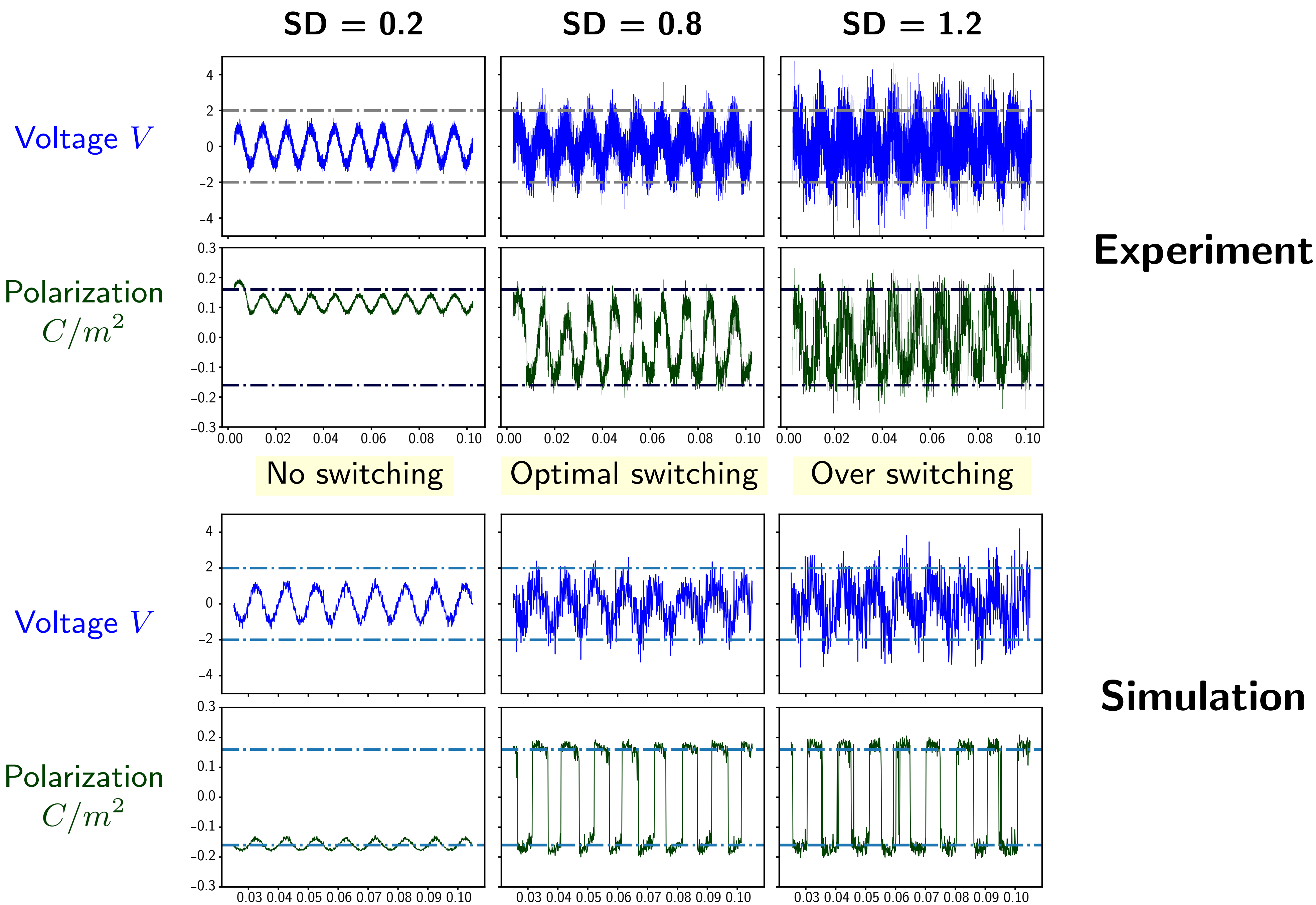


Method

- The experiment is to measure stochastic resonance in ferroelectric capacitor
- The signal and the noise generated from the computer is combined together
- The Vision software runs the hysteresis task and using Radient Ferroelectric tester we obtain the corresponding polarization time series data
- The experimental parameters are given below

Parameter	Value
V_{sub}	1 V
f_{signal}	100 Hz
duration	0.3 s (33 cycles)
std	[0, 1.9] in step of 0.1
No: Ensembles	10
Bandwidth	10^5 Hz

7. Experiment vs Simulation: Time series

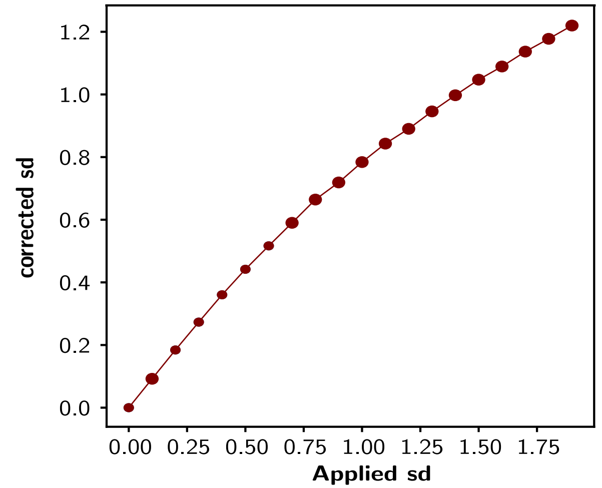


Standard Deviation Correction

- The signal we are analysing is the polarization of the ferroelectric.
- The Noise SD applied and the effective driven signal SD are observed to be not the same. To correct that

$$sd_{crt} = std(V(sd) - V(sd = 0))$$

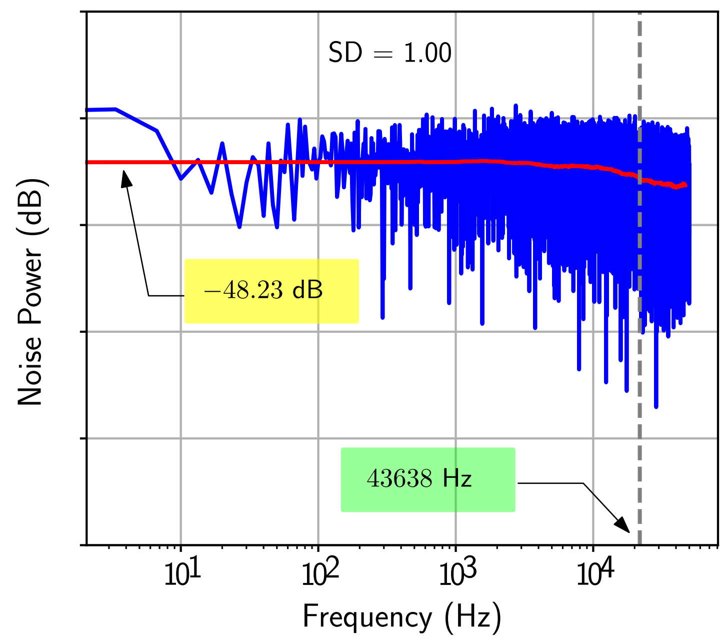
- For all ensembles the corrected SD appeared to be the same.



Note: The $\frac{SD_{real}}{SD_{applied}} \approx 0.6$

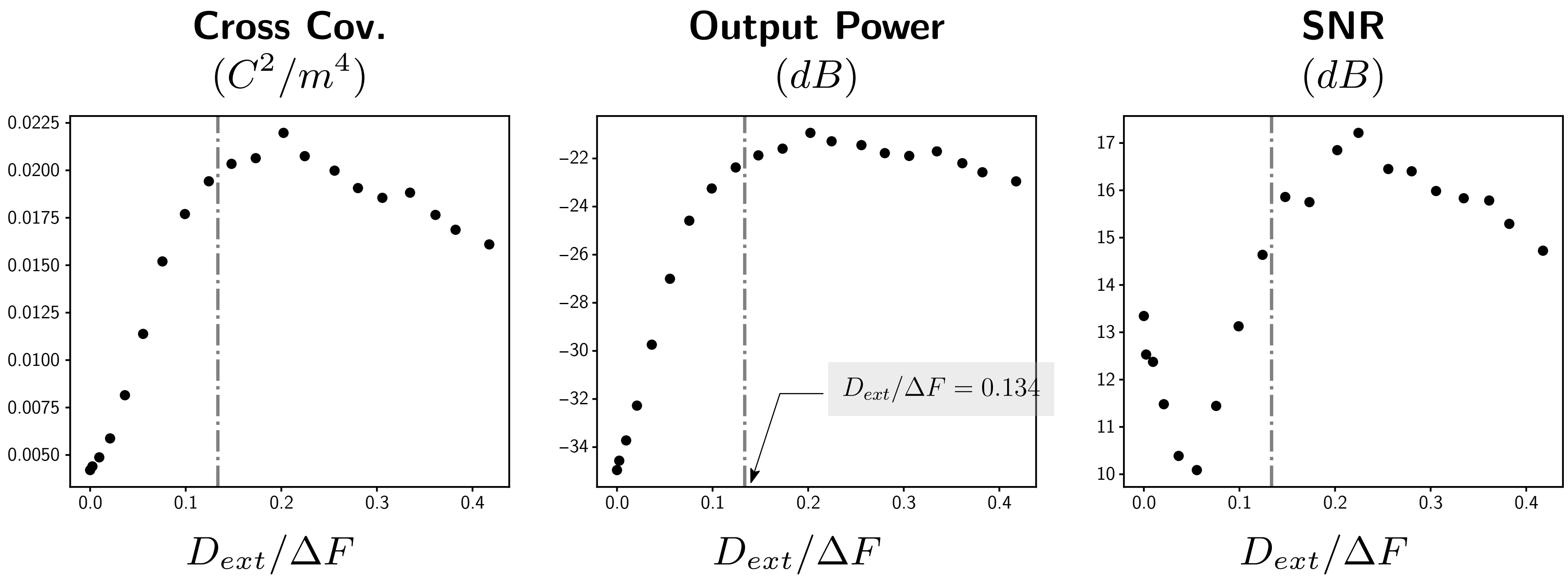
Bandwidth Correction

- The Noise PSD is computed, the solid back line is the moving median filter with a window length of 1000 points.
- The 3dB point is found from the filtered noise floor.
- It appears that the applied noise is not consant in bandwidth as well.
- Change in bandwidth corresponding to the corrected SD is shown.



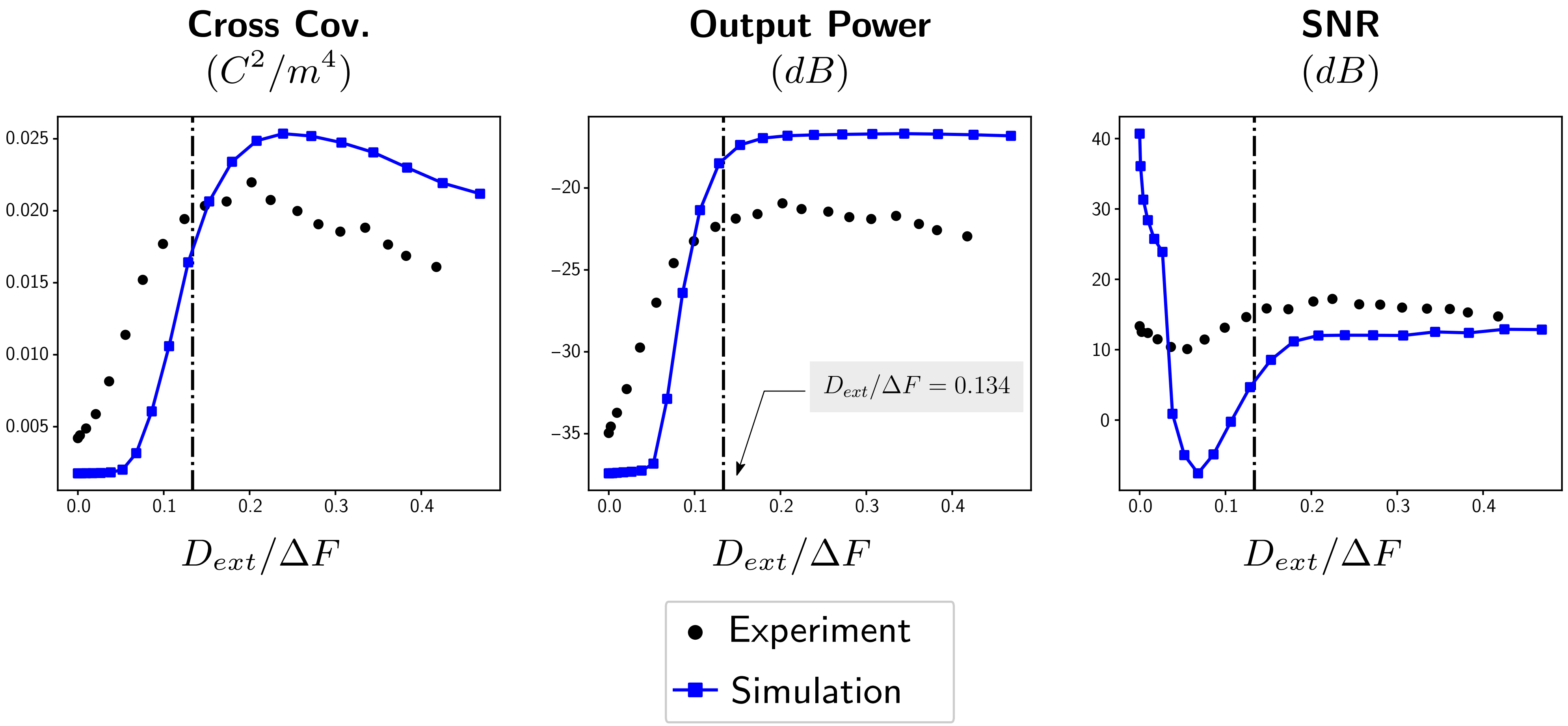
7. Experiment: SNR Matrics

- The experimental results show stochastic resonance.
- The Kramers' prediction is marked in dash dotted line
- The peaking point came very close to the predicted peak point



7. Experiment vs Simulation

- Theoretical prediction almost matches the experimental results
- A significant shift in power value can be observed and the trend matches
- The SNR observed from experiment is decreasing rapidly than the numerical predication



8. Summary and Conclusion

- Stochastic Resonance is observed in Thin film Ferroelectric material PZT.
- A complete analysis with hardware results is presented
- The metrics such as cross covariance, signal power, signal to noise ratio are used to show SR
- SR is shown for a subthreshold signal of 1V of 100 Hz frequency.
- Experimental results are matching the theoretical predictions

9. Future Work and Plans

- Linear Response Theory based analytical predictions to quantify the SR phenomenon
- Try the same experiment for multiple frequencies and multiple subthreshold amplitude levels

Acknowledgement

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Thank You :)