

Solar-Cell and Ferroelectric Capacitor Characterization

Submitted by
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With the guidance of
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INDIAN INSTITUTE
OF TECHNOLOGY
PALAKKAD

May 18, 2025

Work Done

BTP - 1

Work Done

BTP - 1

- Characterization of Solar Cell Using Electroluminescence

Work Done

BTP - 1

- Characterization of Solar Cell Using Electroluminescence

BTP - 2

Work Done

BTP - 1

- Characterization of Solar Cell Using Electroluminescence

BTP - 2

- Characterization of Stochastic Resonance on Ferroelectric Capacitor

Work Done

BTP - 1

- Characterization of Solar Cell Using Electroluminescence

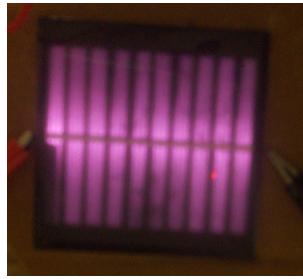
BTP - 2

- Characterization of Stochastic Resonance on Ferroelectric Capacitor
- True Random Number Generator Using a Surrogate Double-Well System

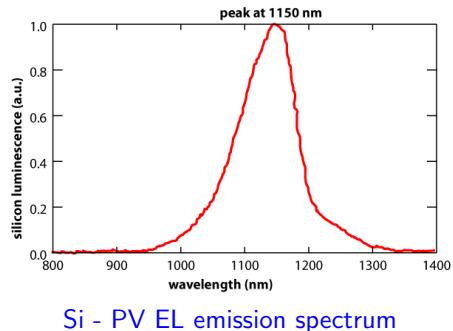
Electroluminescence - Overview

What is EL?

Electroluminescence (EL) is a phenomenon where **light** is emitted from a solar cell when **electric current** passes through it



EL illustration using NoIR camera

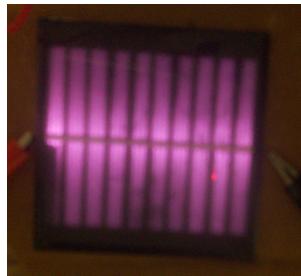


Theory

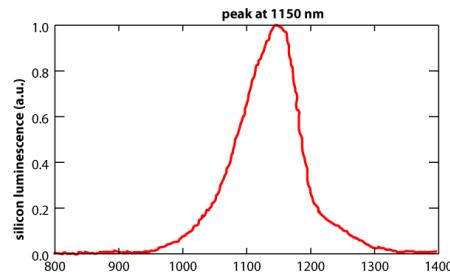
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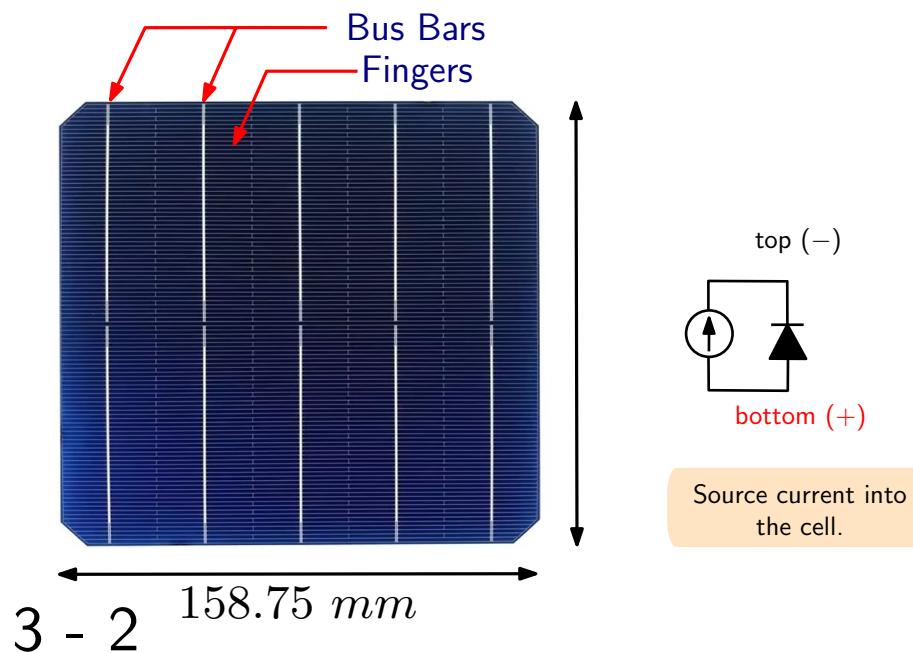
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Si - PV EL emission spectrum

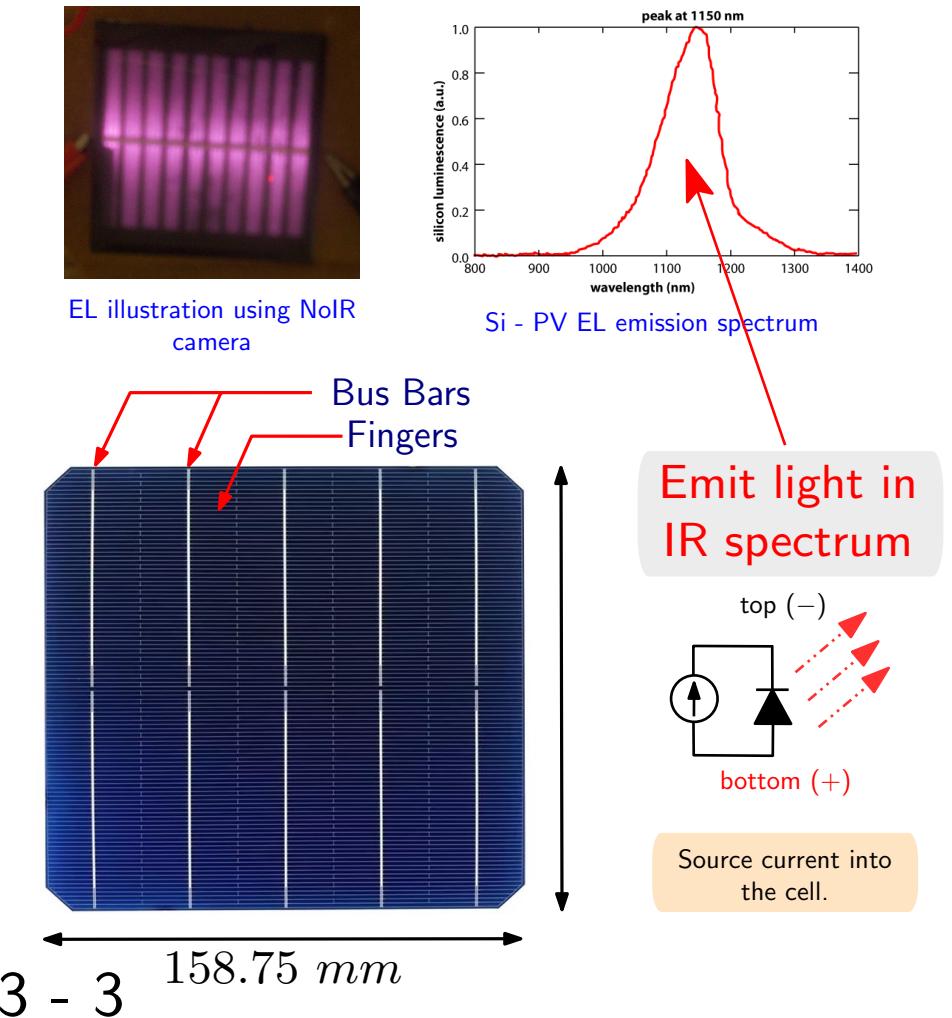


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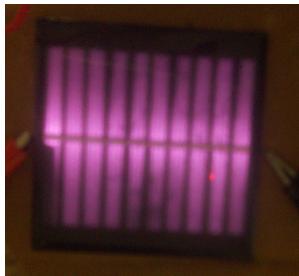


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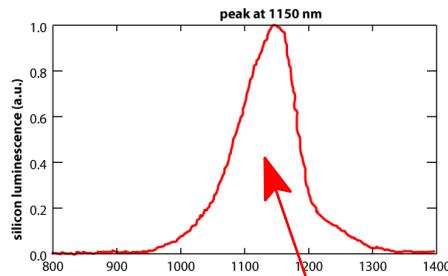
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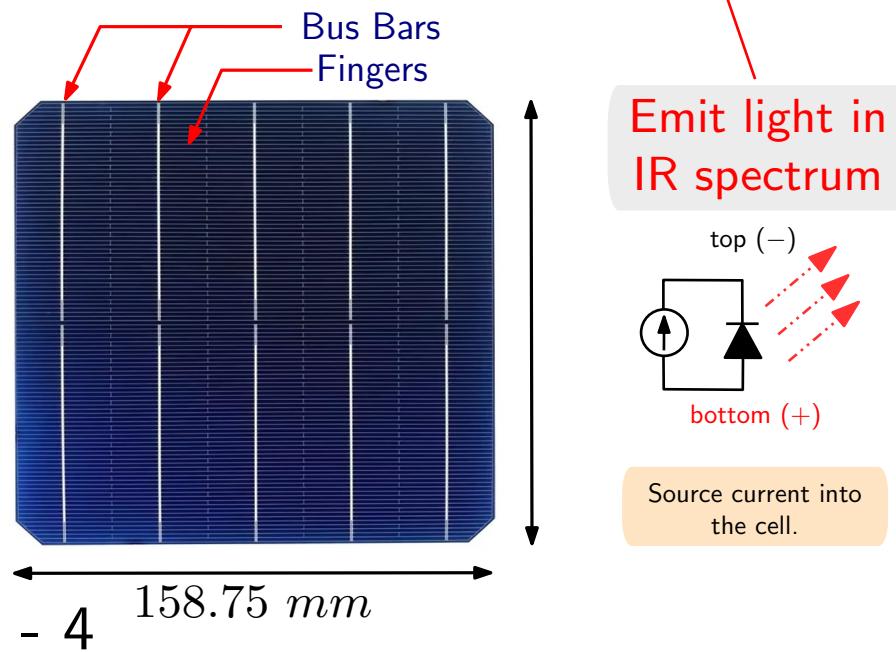
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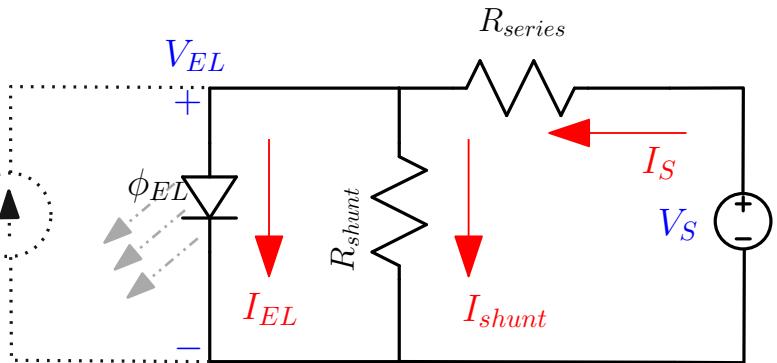


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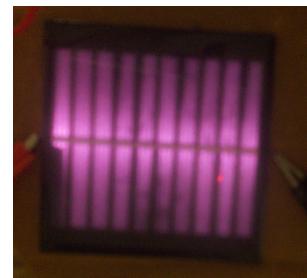
$$I_S = I_{EL} + I_{Shunt} = I_{EL} + \frac{V_{EL}}{R_{shunt}}$$



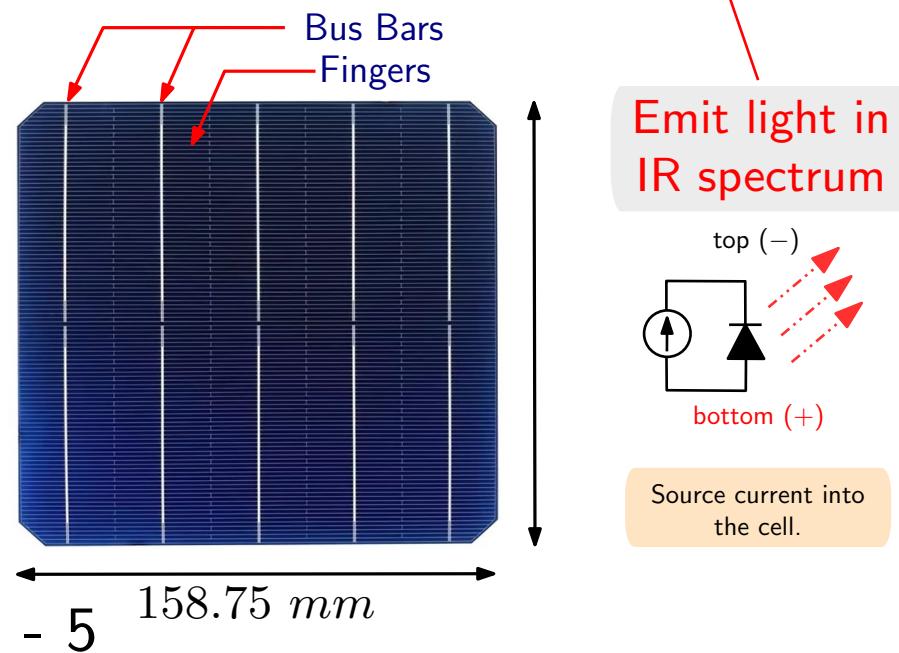
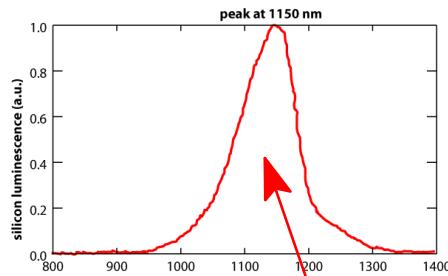
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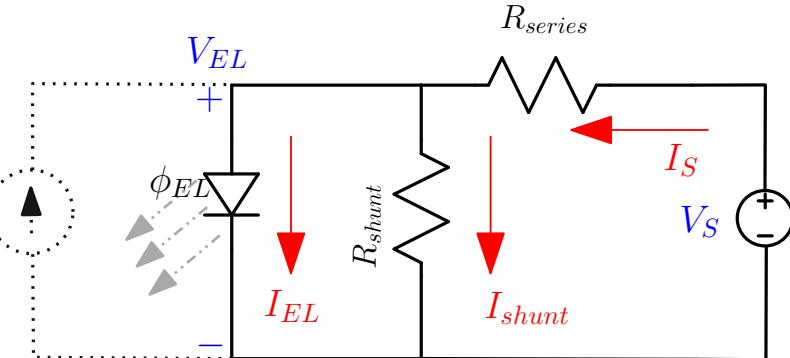


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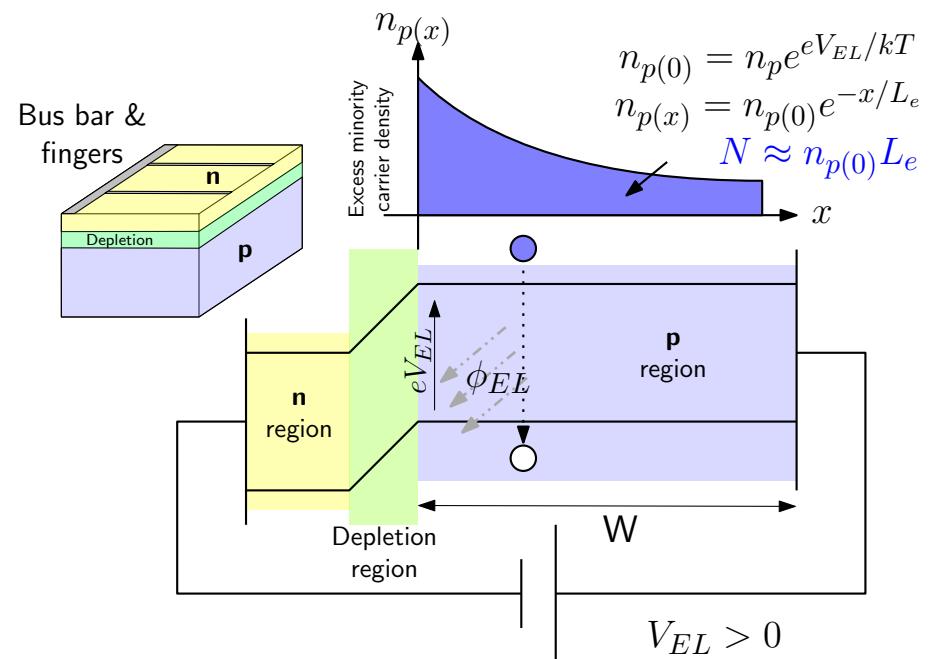


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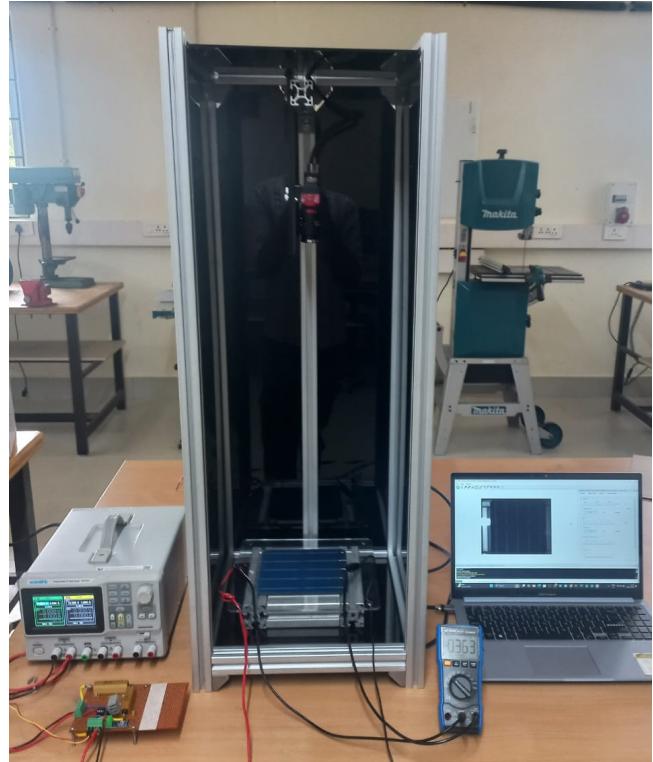


$$\phi_{EL} = Ae^{eV_{EL}/kT}$$



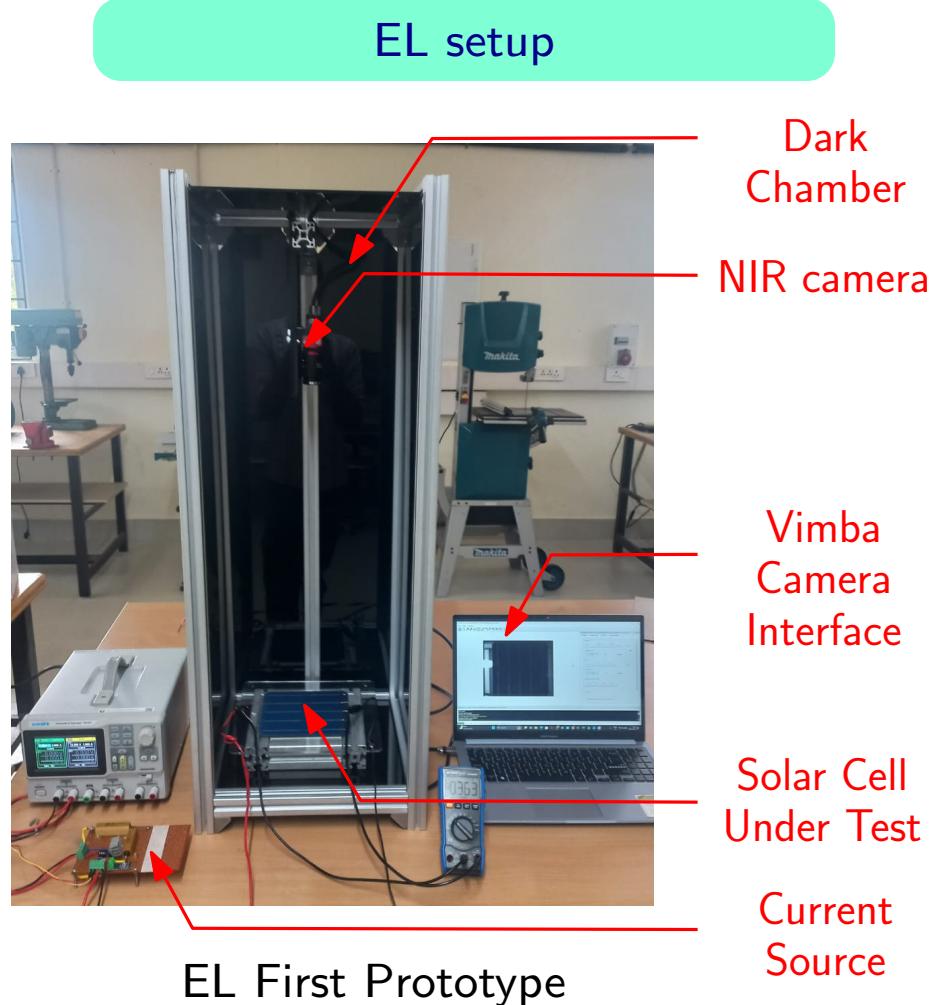
Electroluminescence - Hardware setup

EL setup

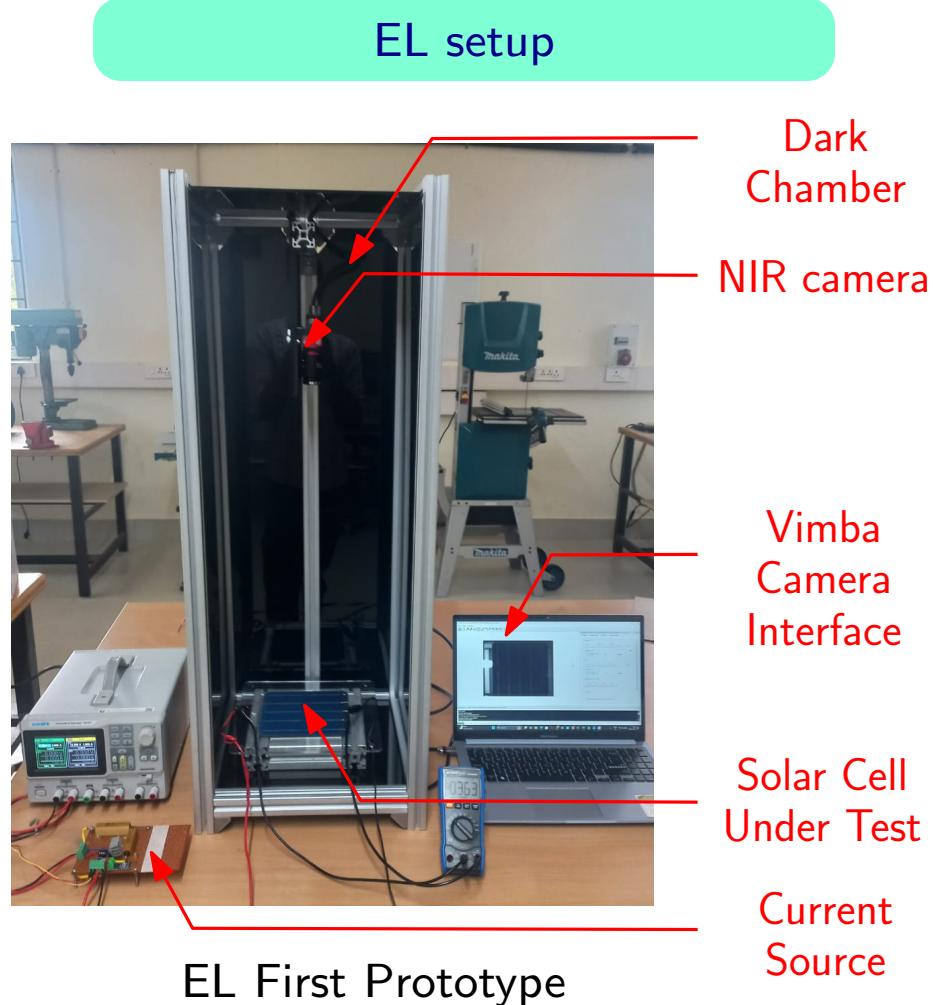


EL First Prototype

Electroluminescence - Hardware setup

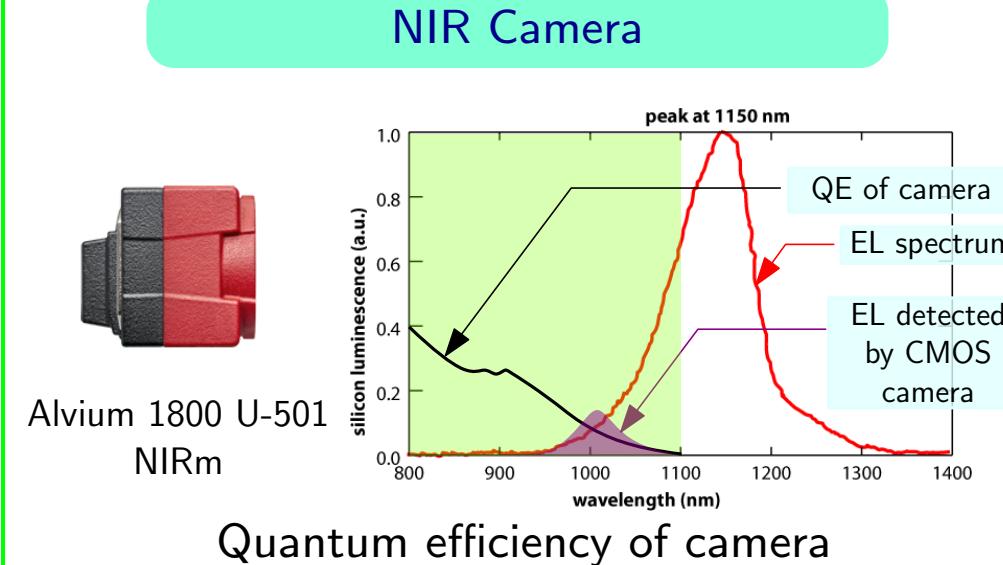
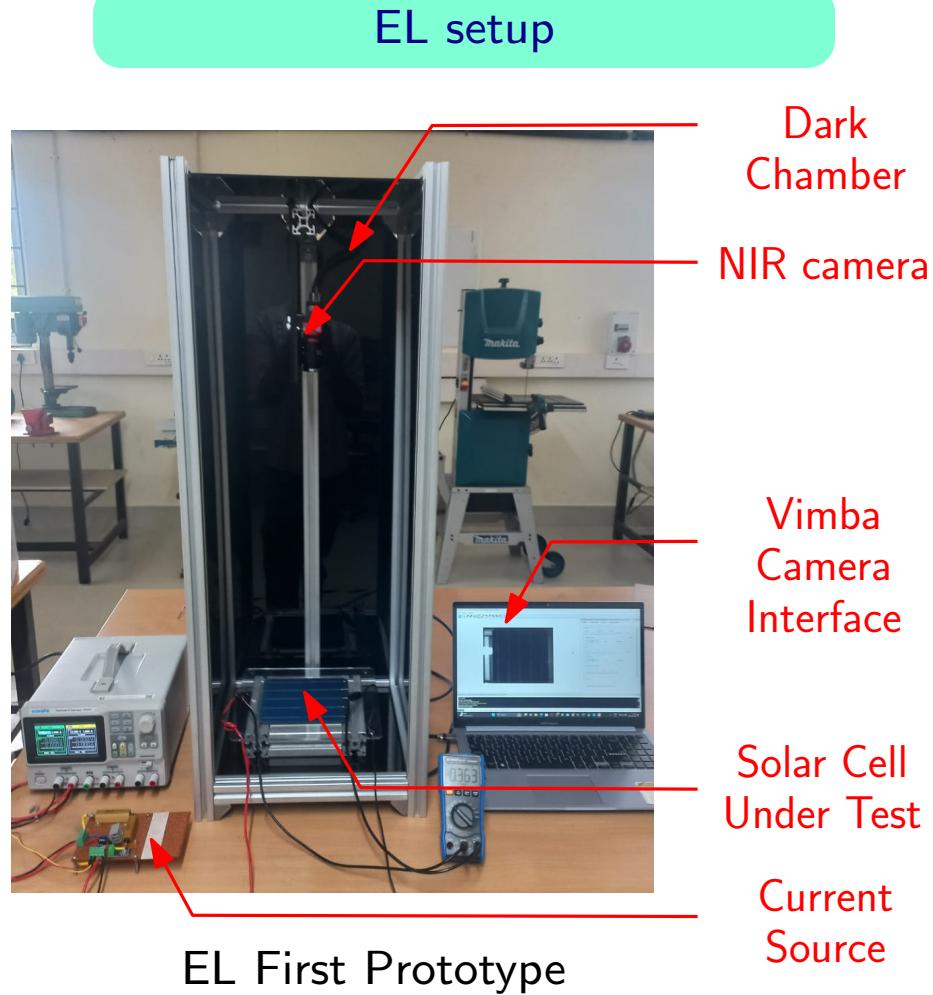


Electroluminescence - Hardware setup



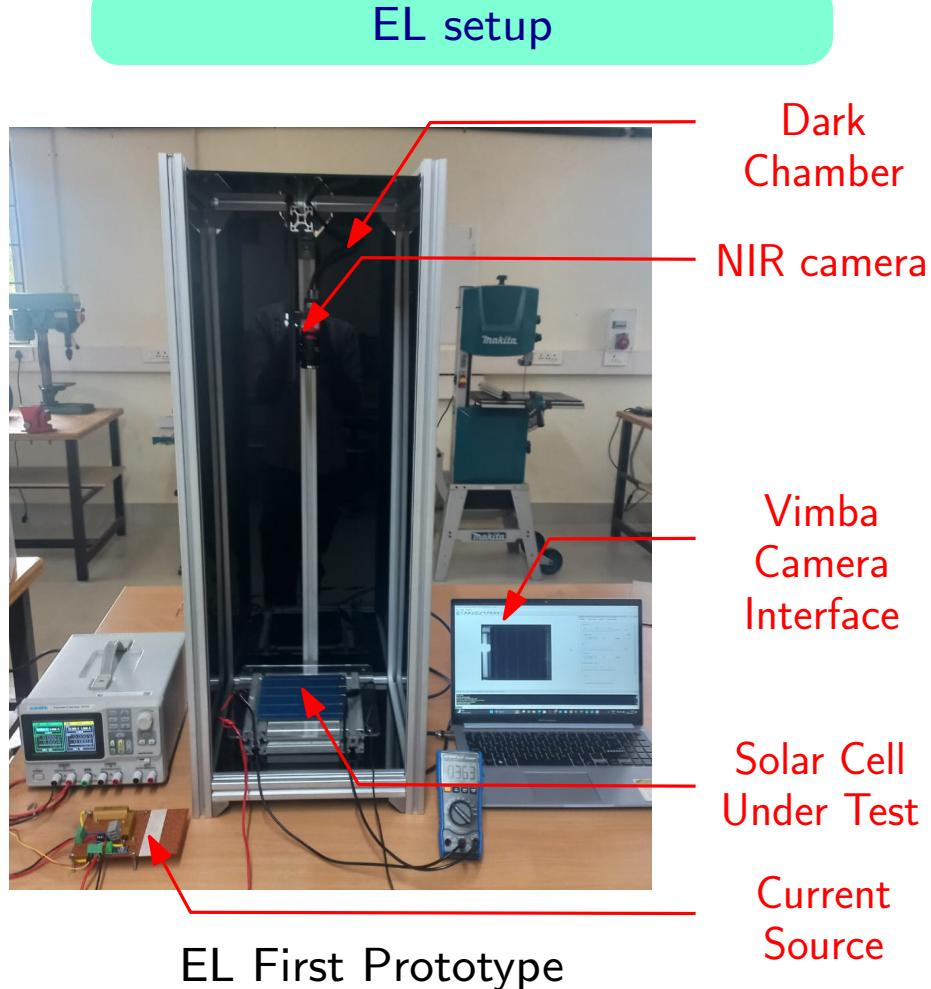
- **High exposure time (0.8 s) required to capture image**
- Current source operated in two modes:
 - 1) **Continuous**
 - 2) **Pulsating**

Electroluminescence - Hardware setup

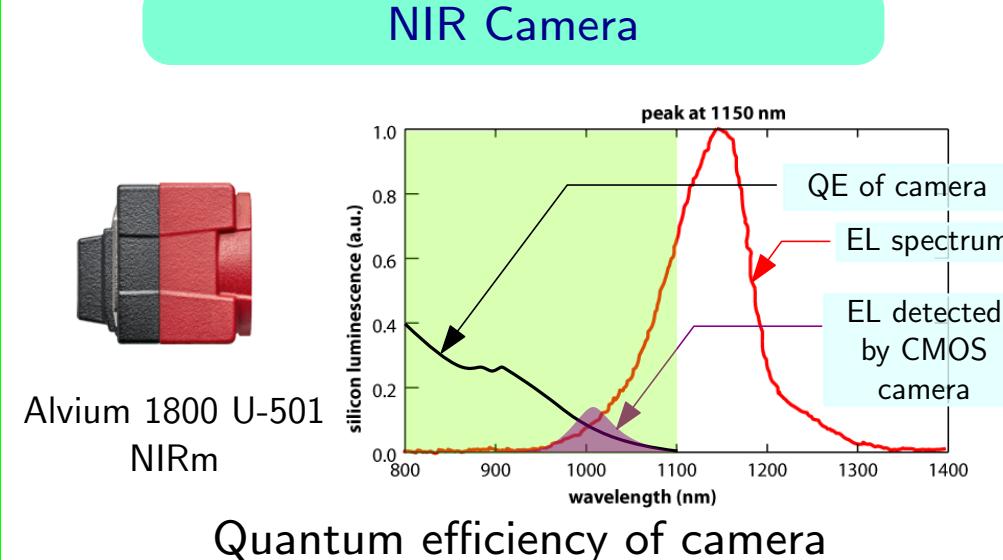


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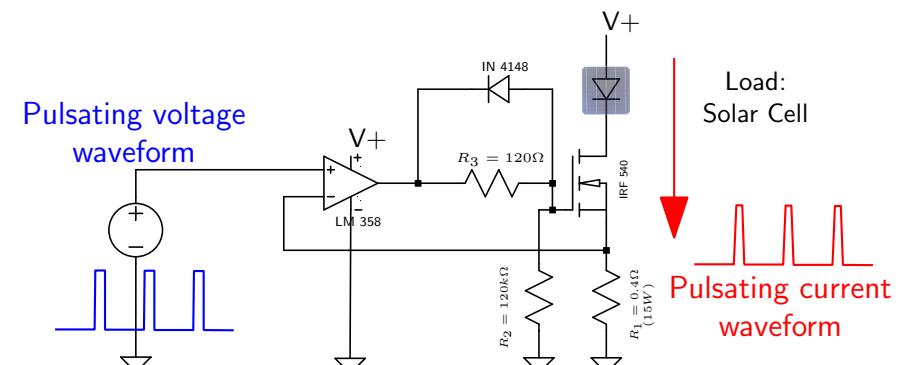
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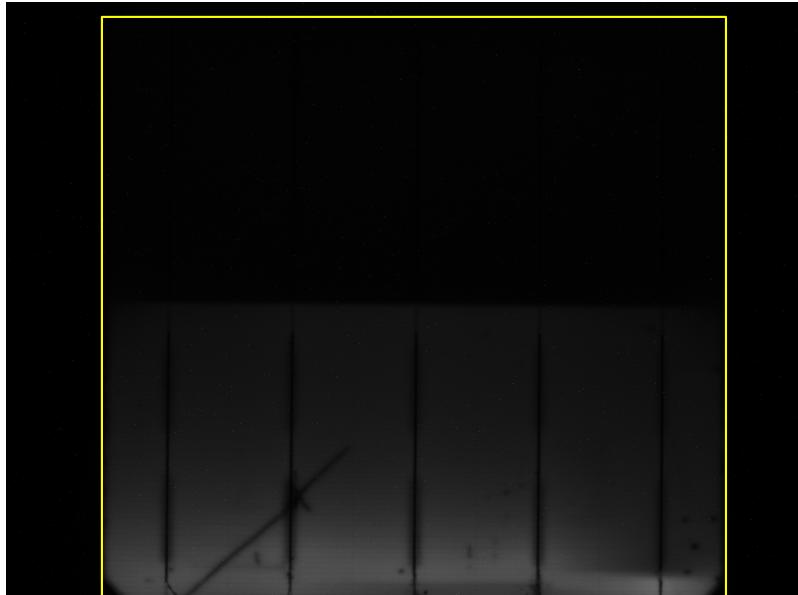
Current Source (V-I converter)



Schematic of the Current Source Design

Electroluminescence - Results

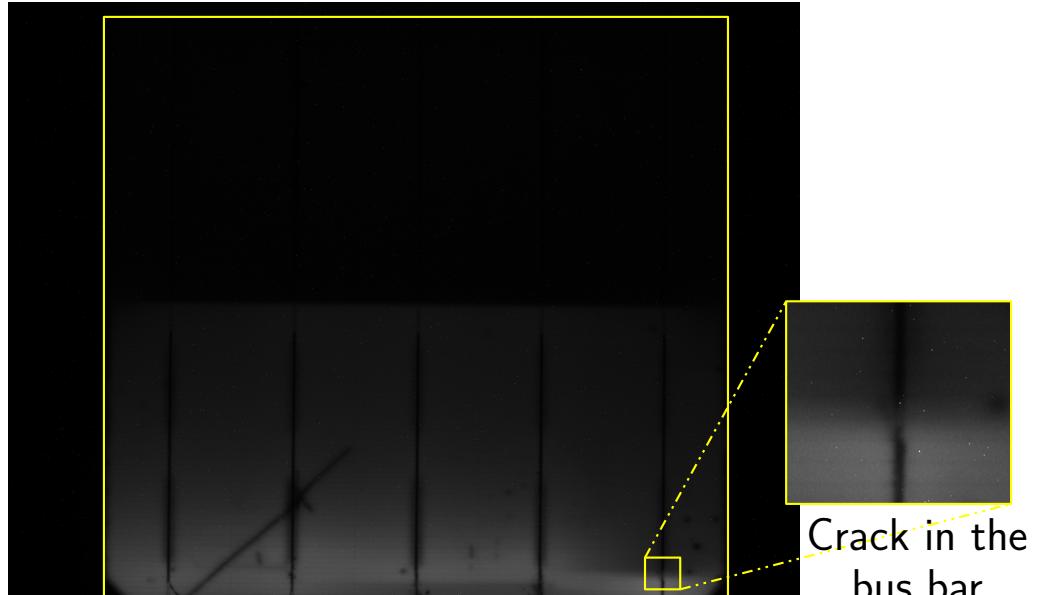
Visual Inspection



4

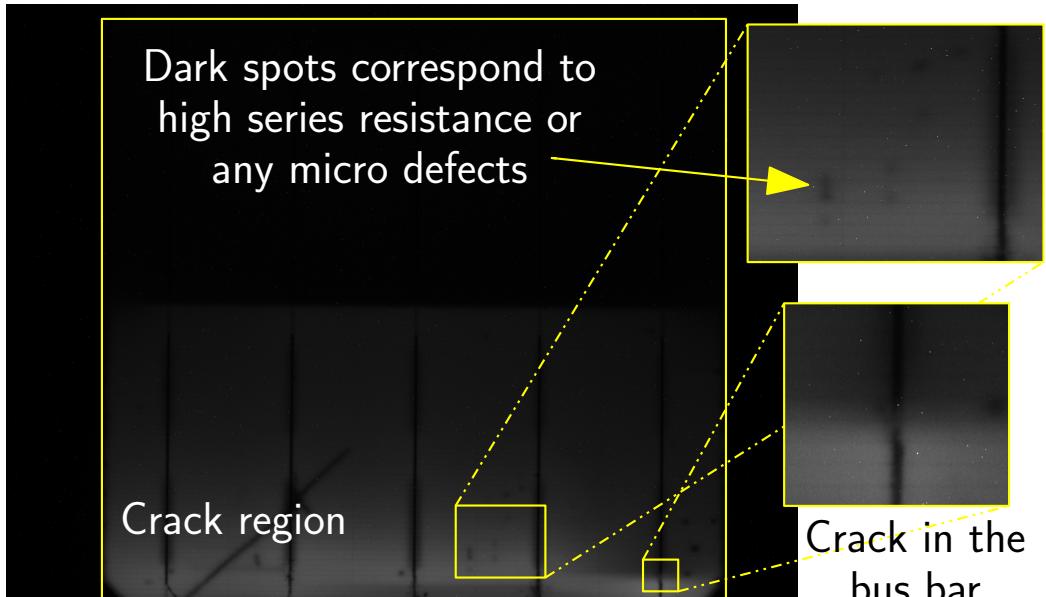
Electroluminescence - Results

Visual Inspection



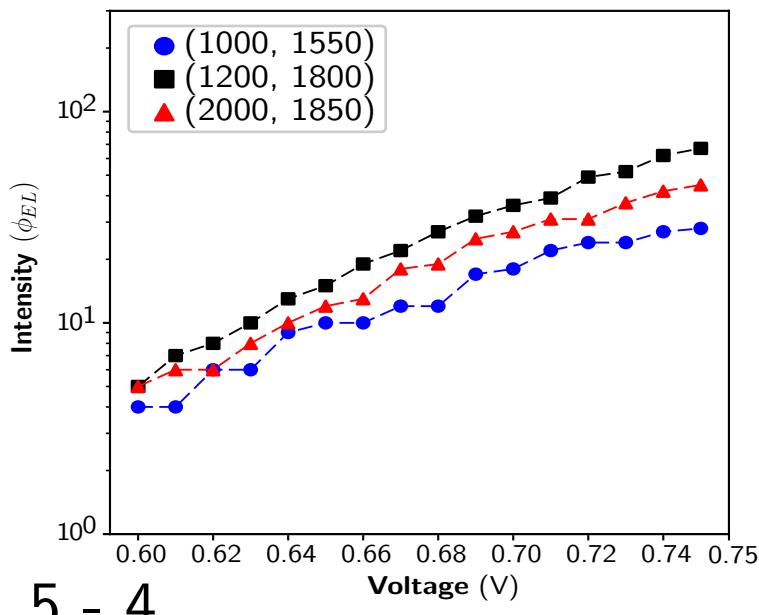
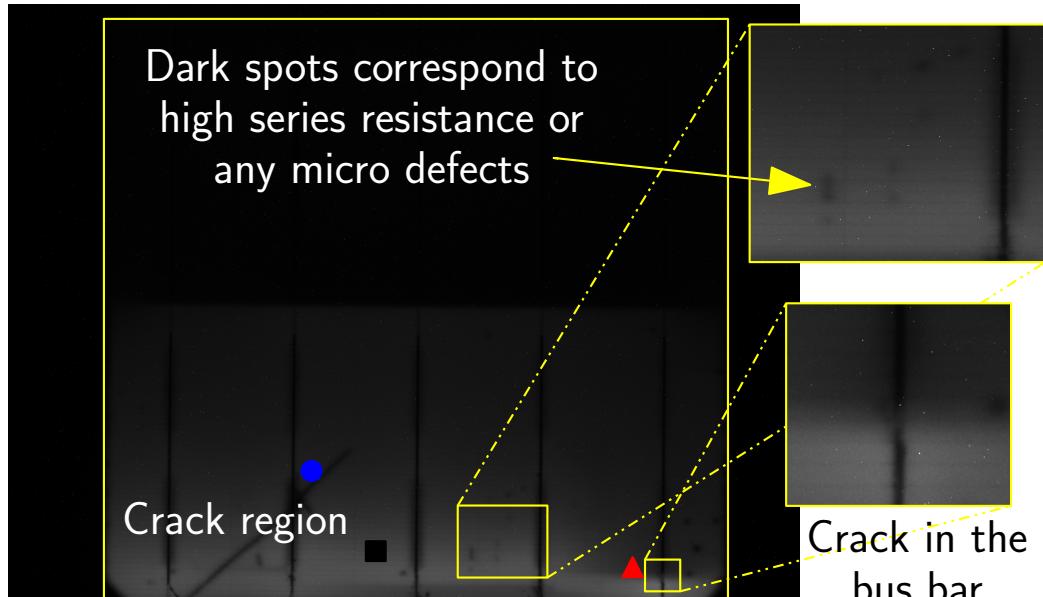
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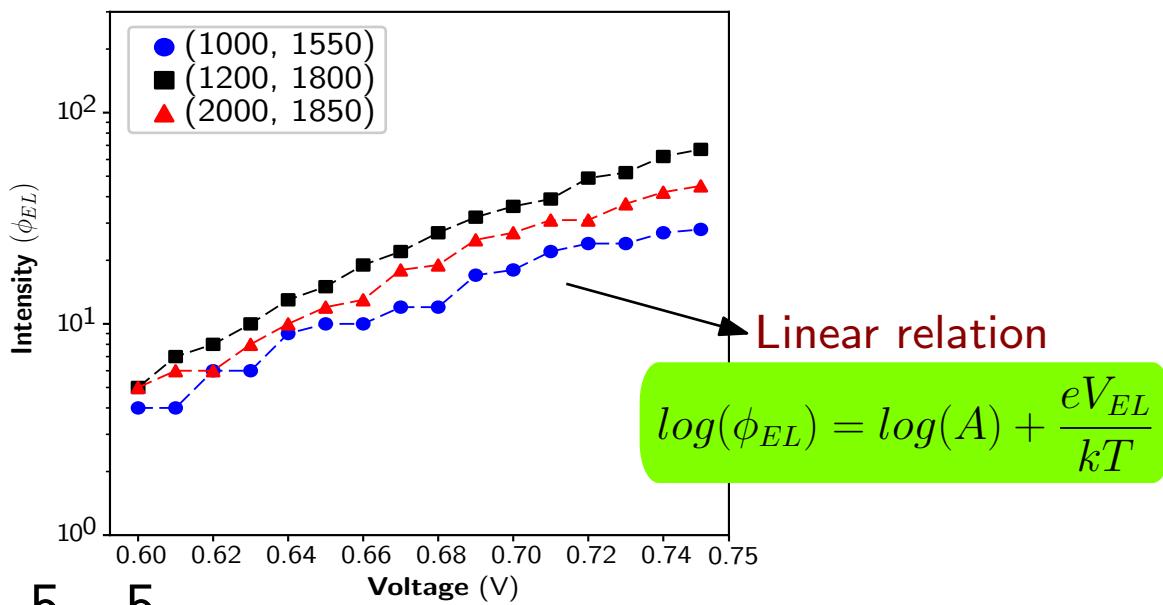
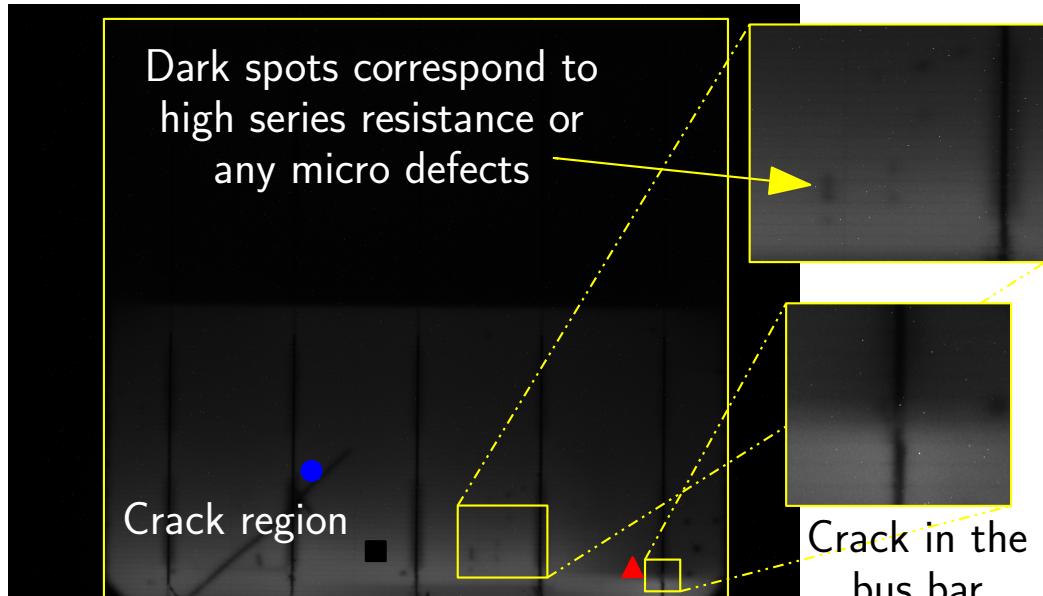
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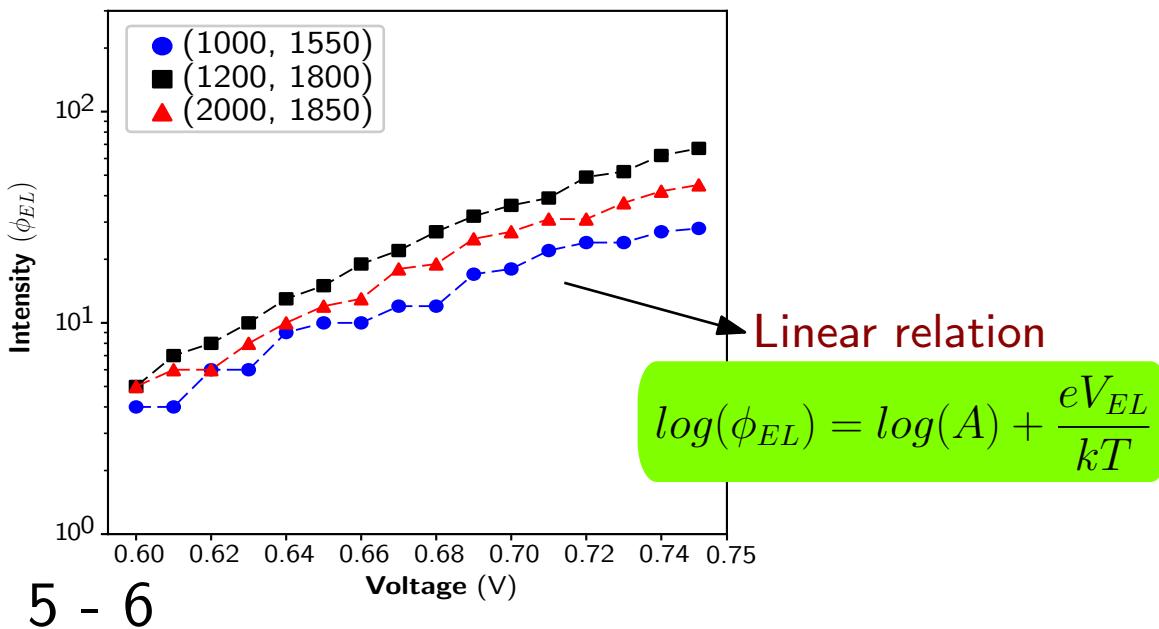
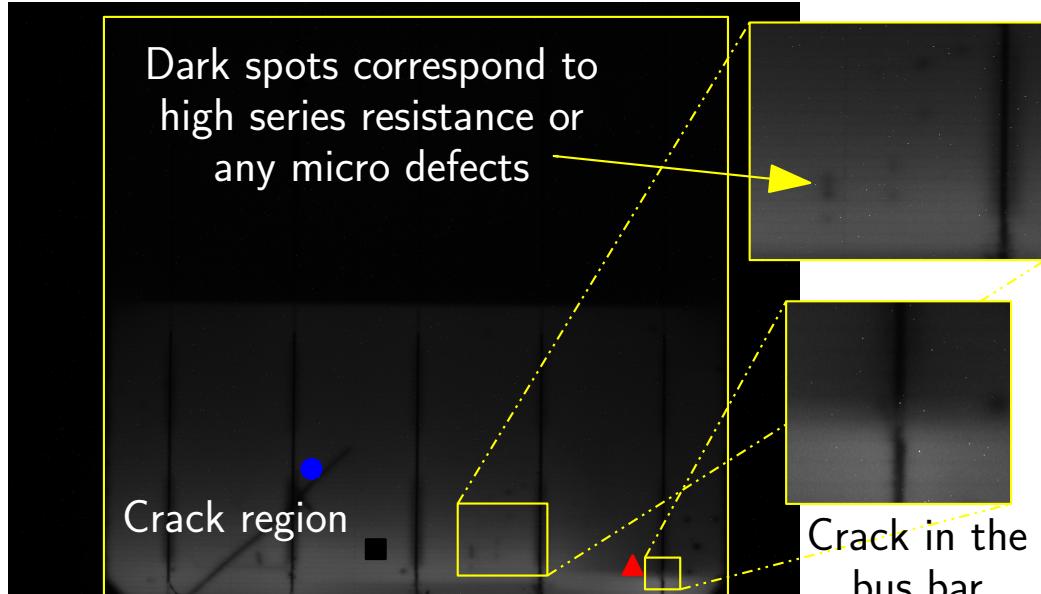
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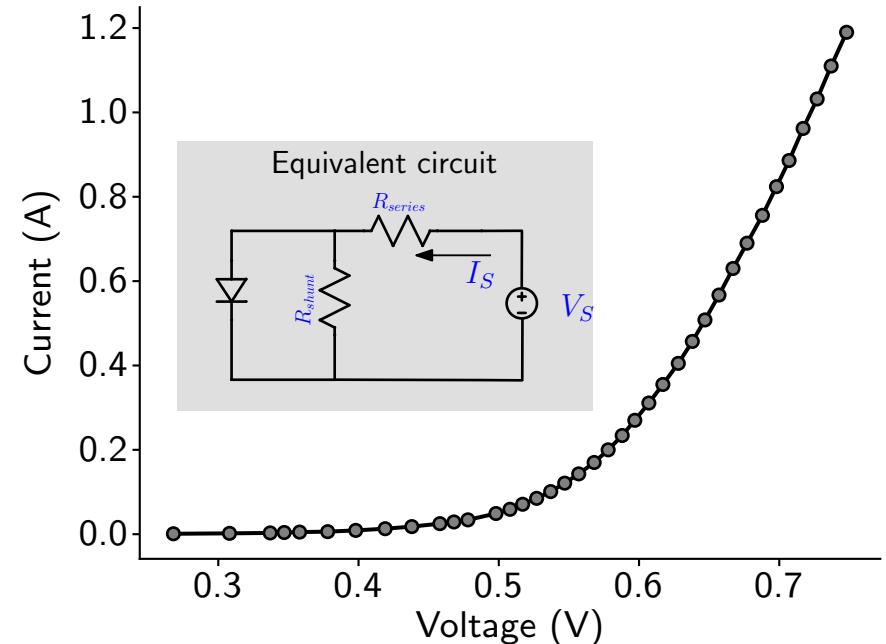
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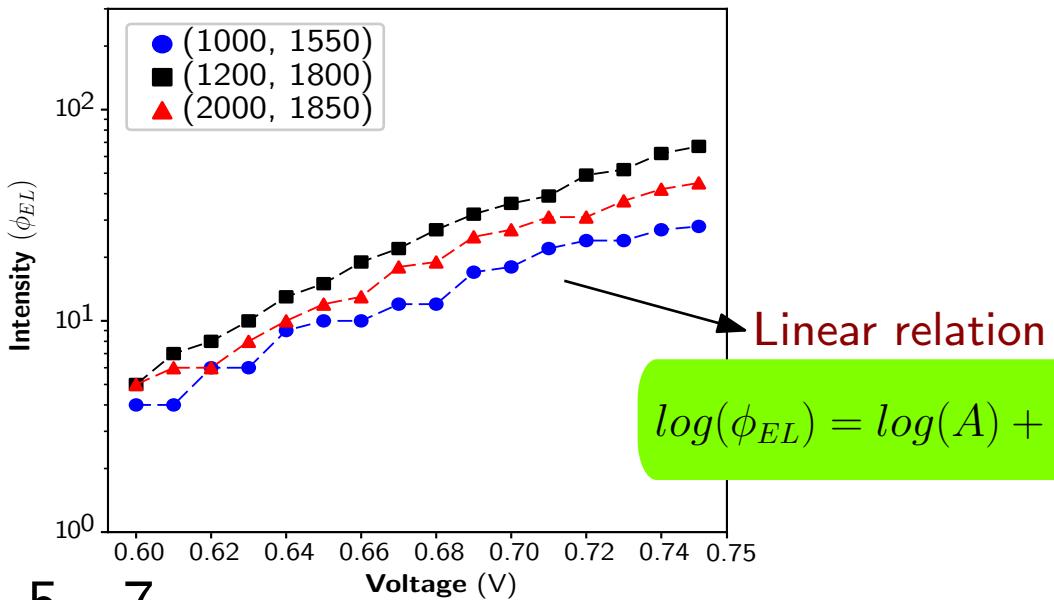
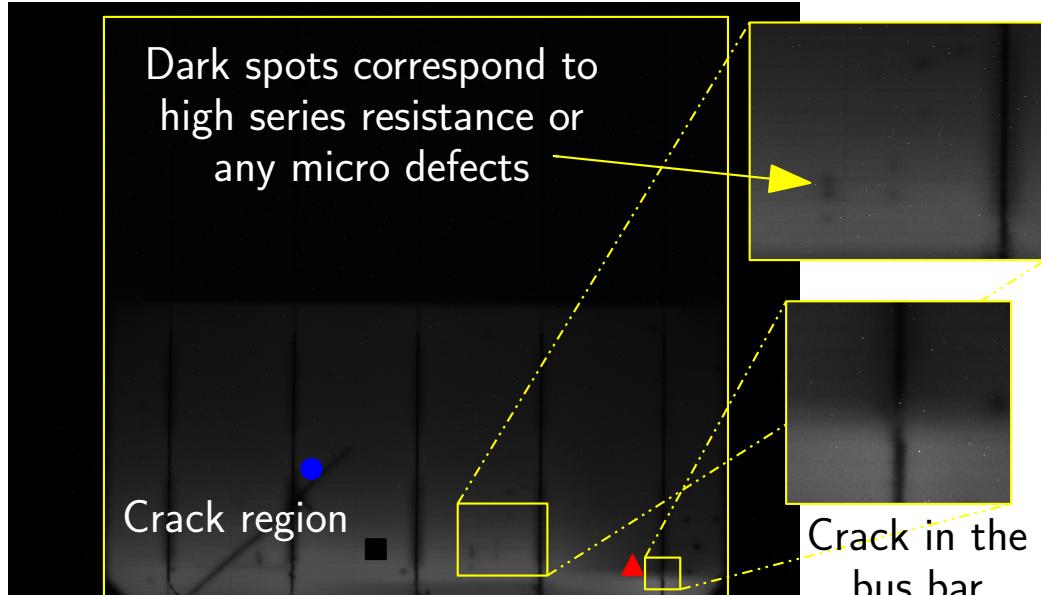
5 - 6

IV characteristics (Dark)

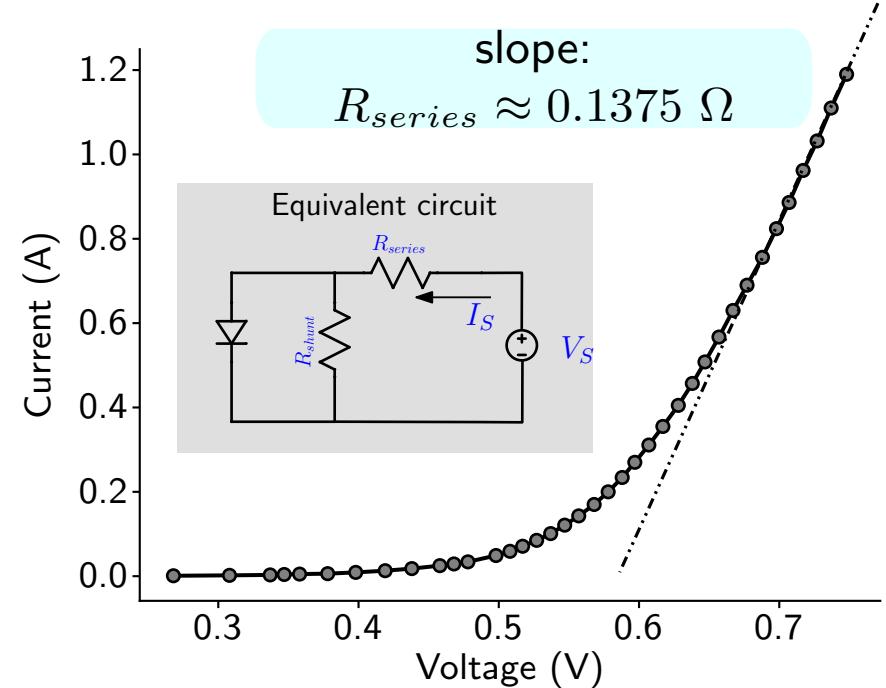


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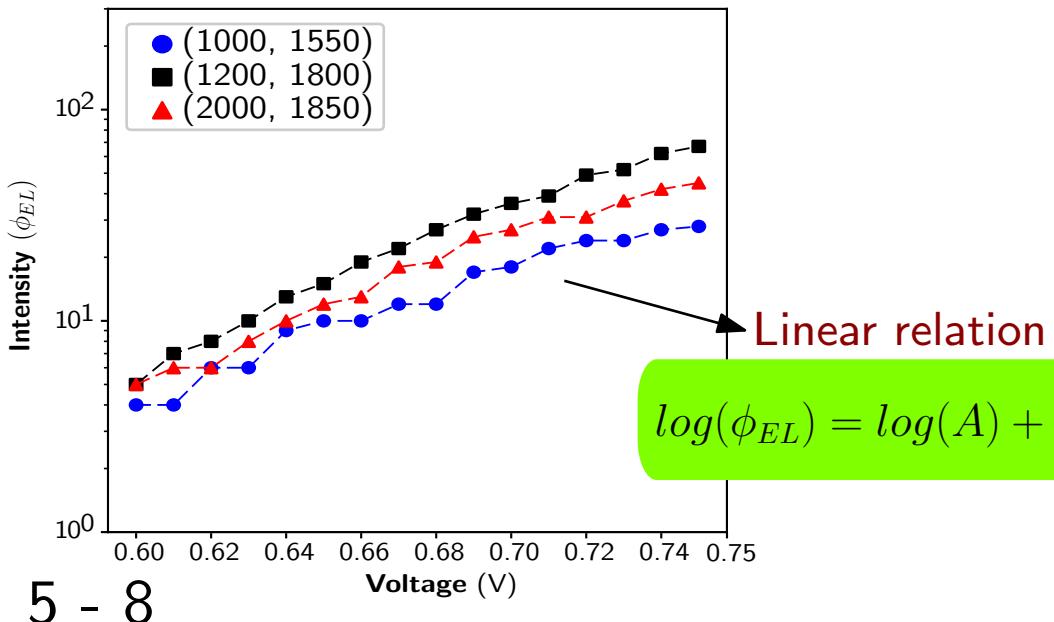
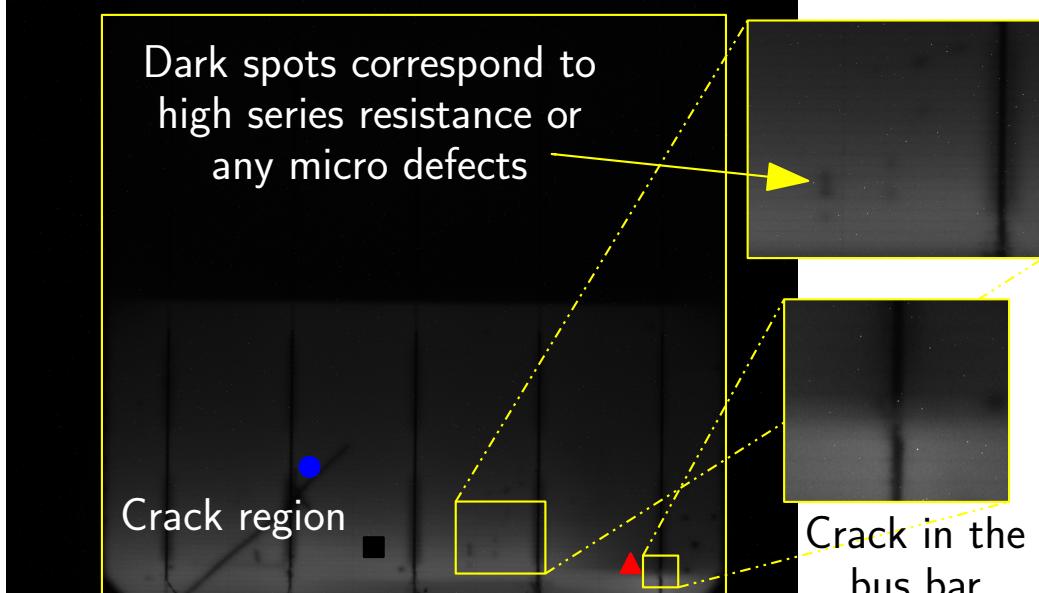


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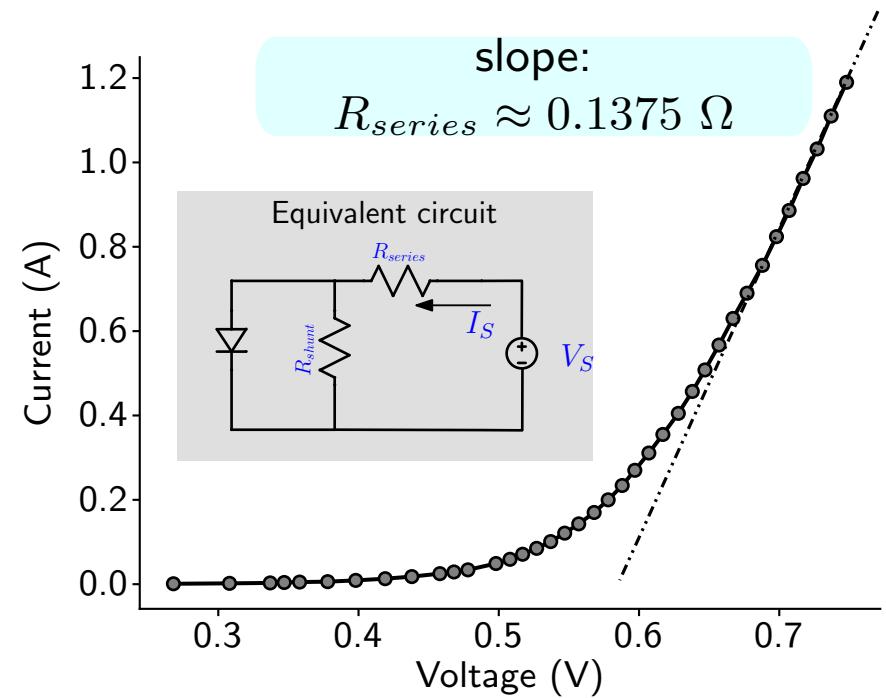
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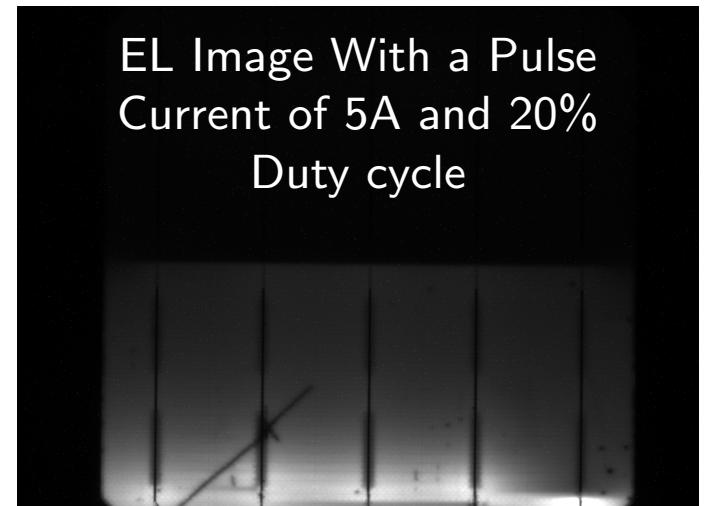


5 - 8

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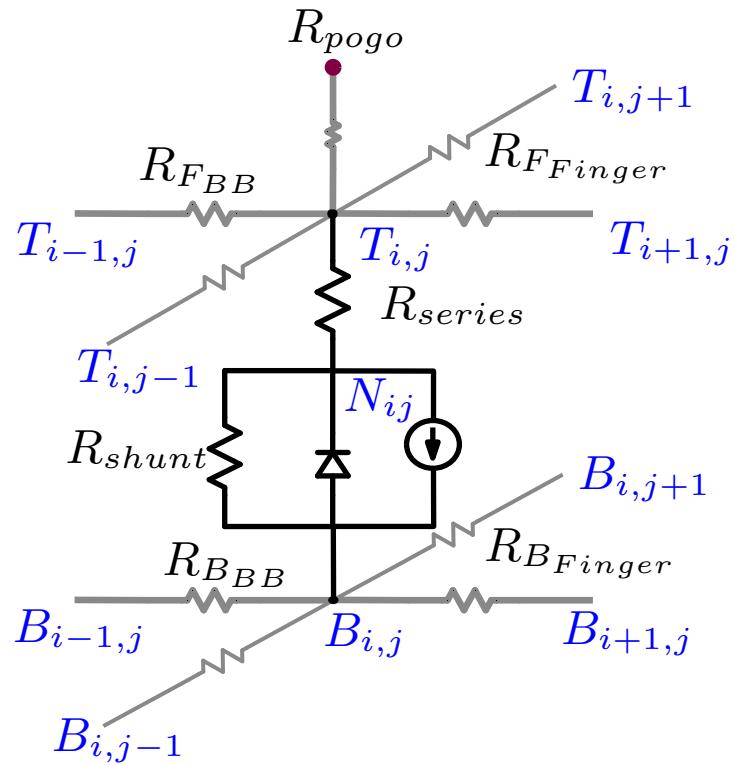


EL Image With a Pulse
Current of 5A and 20%
Duty cycle



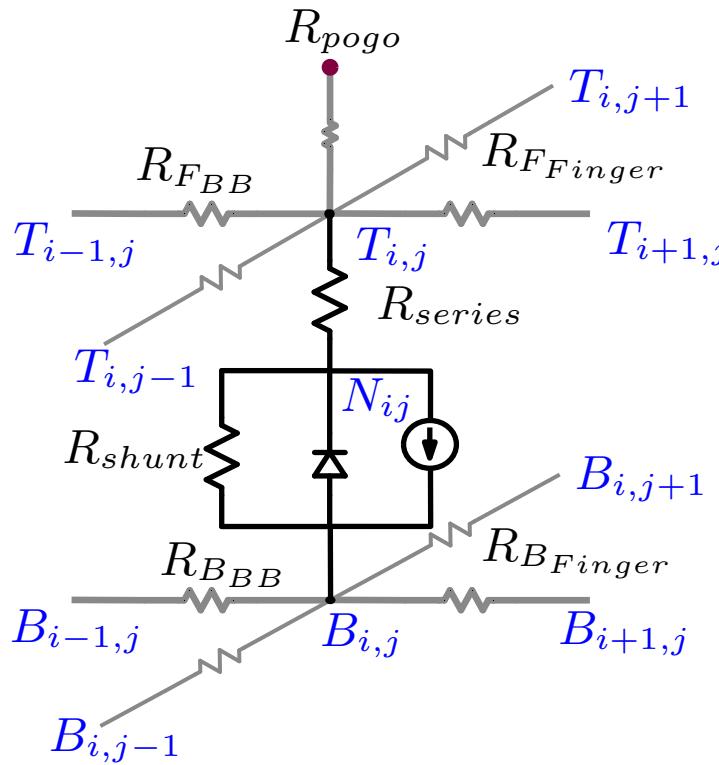
Electroluminescence - Finite Element Model

Spice Modeling



Electroluminescence - Finite Element Model

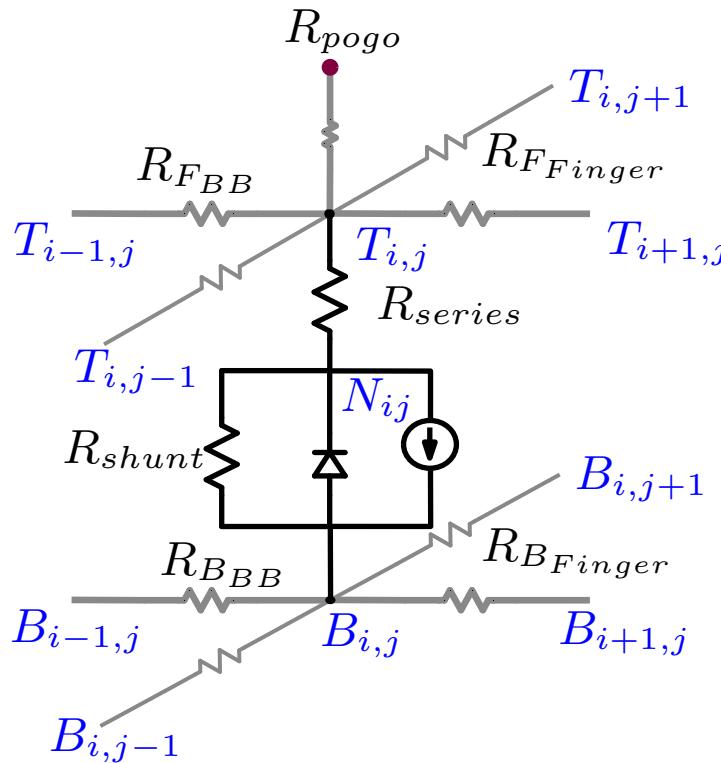
Spice Modeling



A distributed network of finite element is modeled in spice.

Electroluminescence - Finite Element Model

Spice Modeling

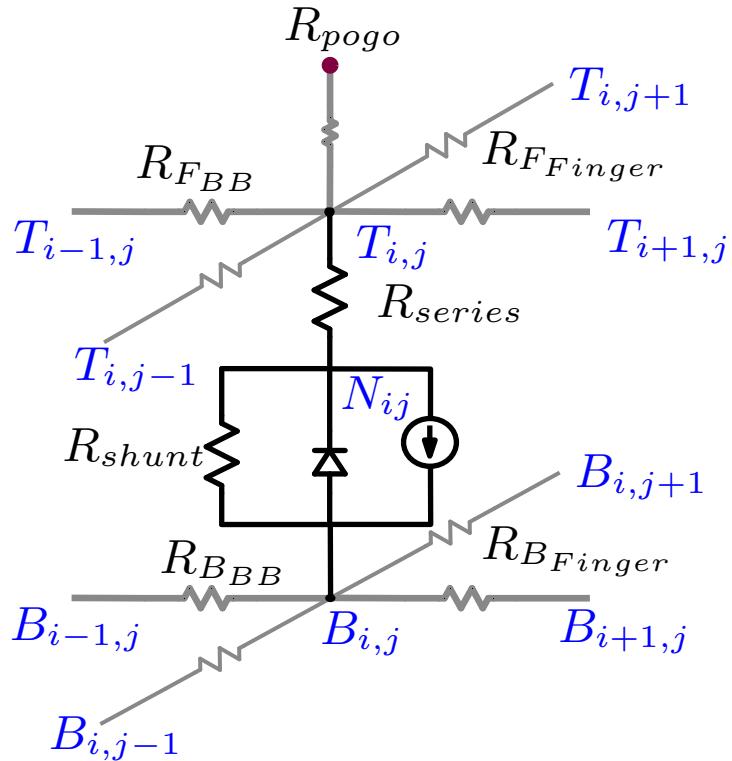


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Top and bottom metalization is a resistor network

Electroluminescence - Finite Element Model

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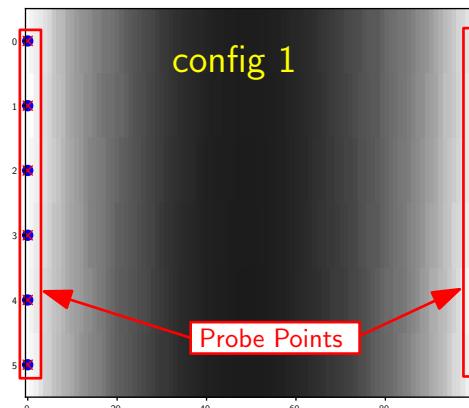


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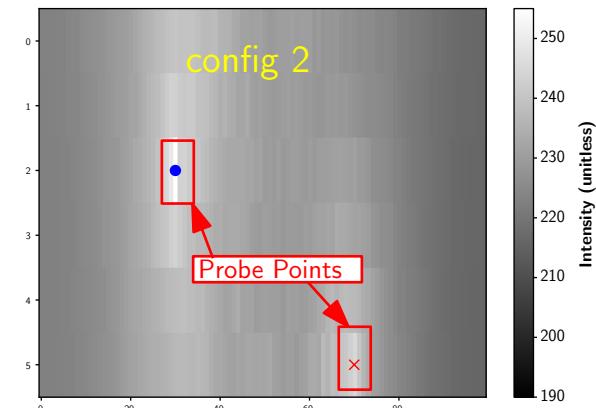
Top and bottom metalization is a resistor network

Effect of probing point

Bottom probe

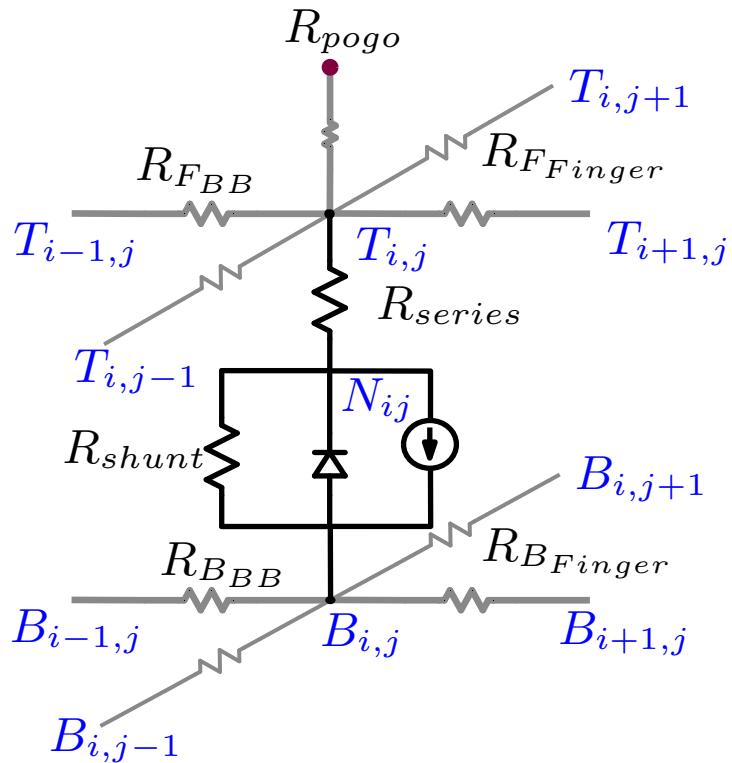


Top probe



Electroluminescence - Finite Element Model

Spice Modeling

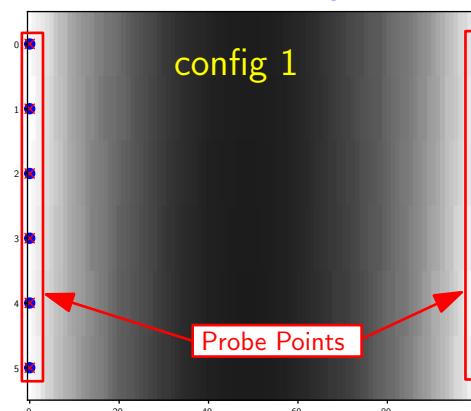


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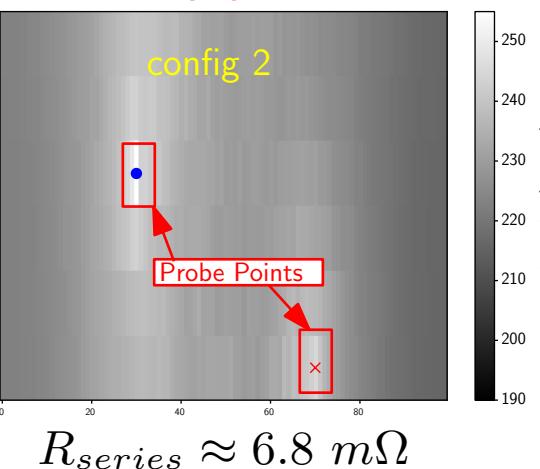
Effect of probing point

• Bottom probe



config 1

✖ Top probe



config 2

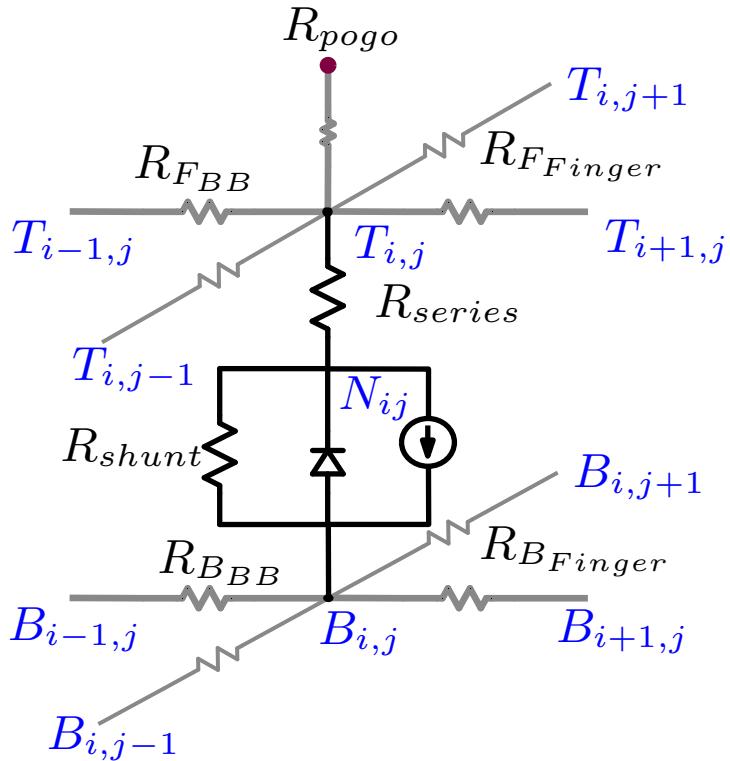
$$R_{series} \approx 3.2 \text{ m}\Omega$$

$$R_{series} \approx 6.8 \text{ m}\Omega$$

Series resistance changes!

Electroluminescence - Finite Element Model

Spice Modeling

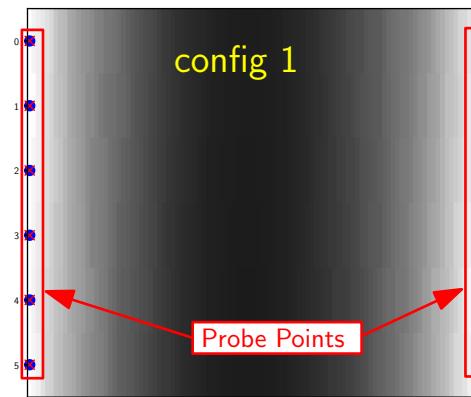


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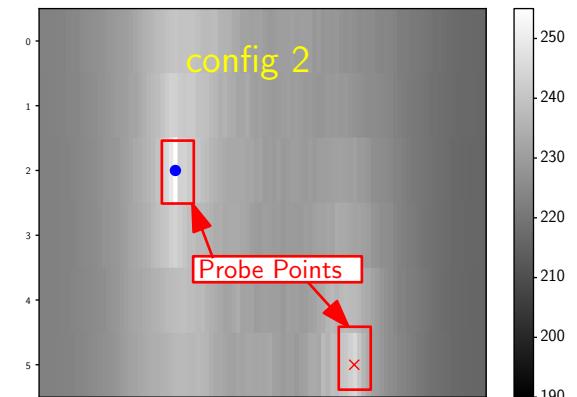
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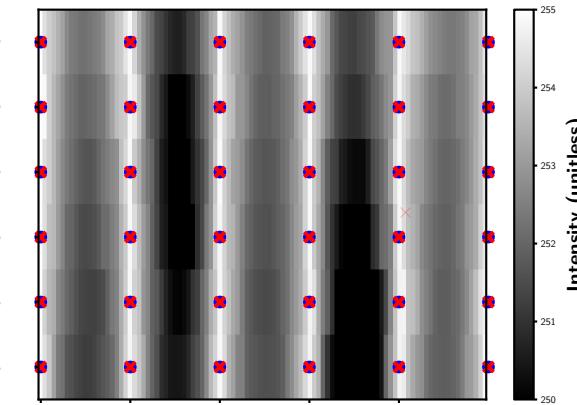
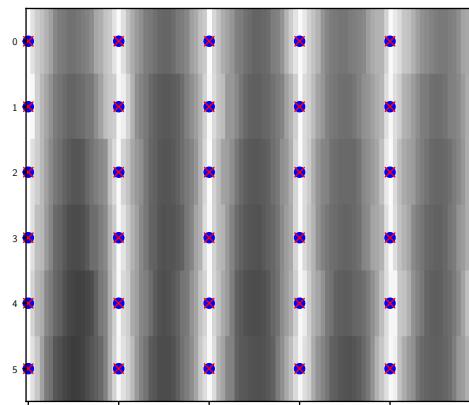
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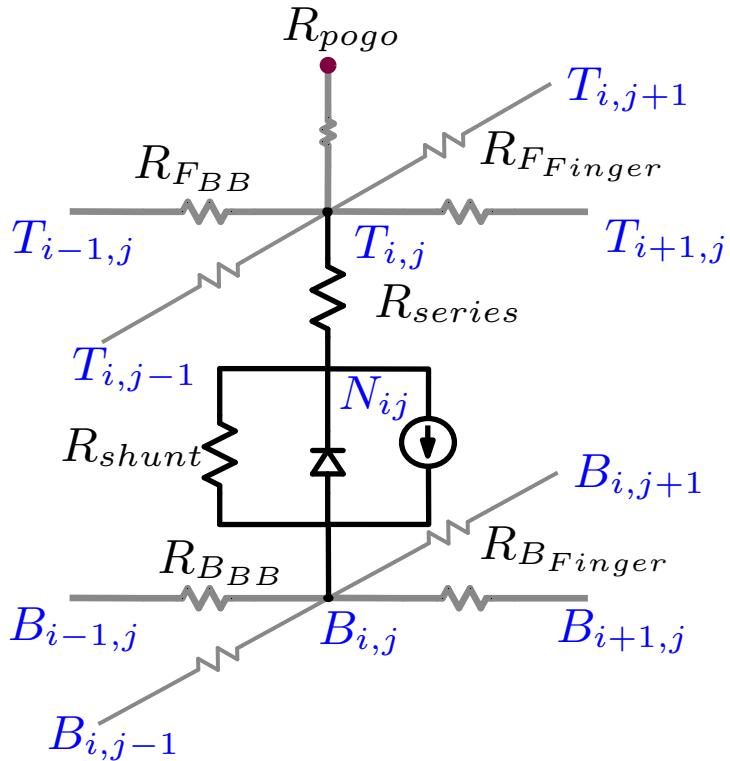
Series resistance changes!

Shunt Defect Simulation



Electroluminescence - Finite Element Model

Spice Modeling

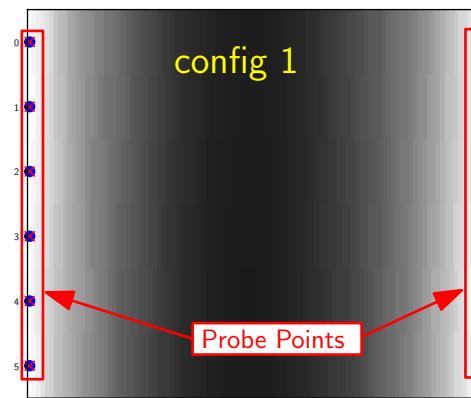


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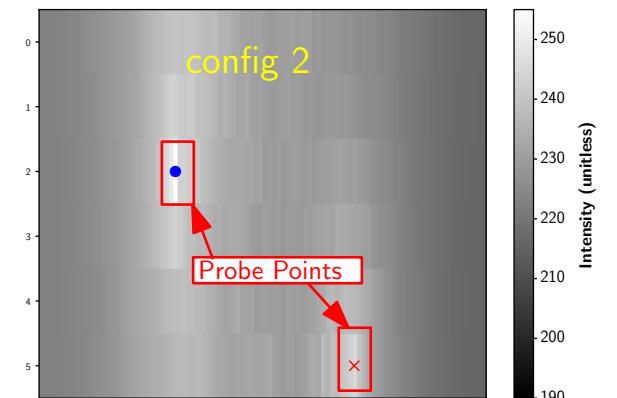
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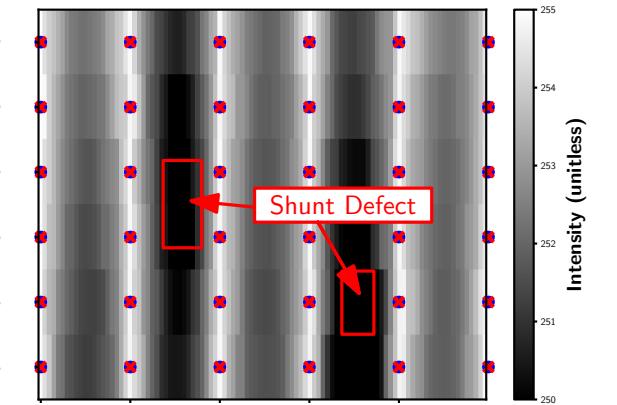
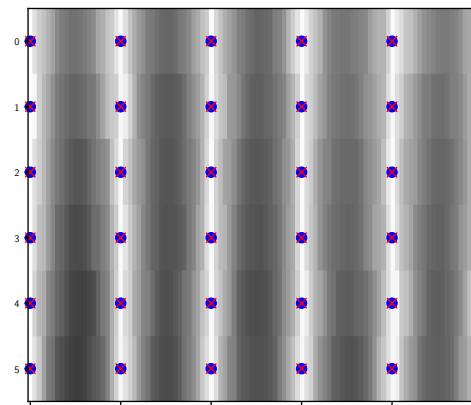
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Shunt Defect Simulation



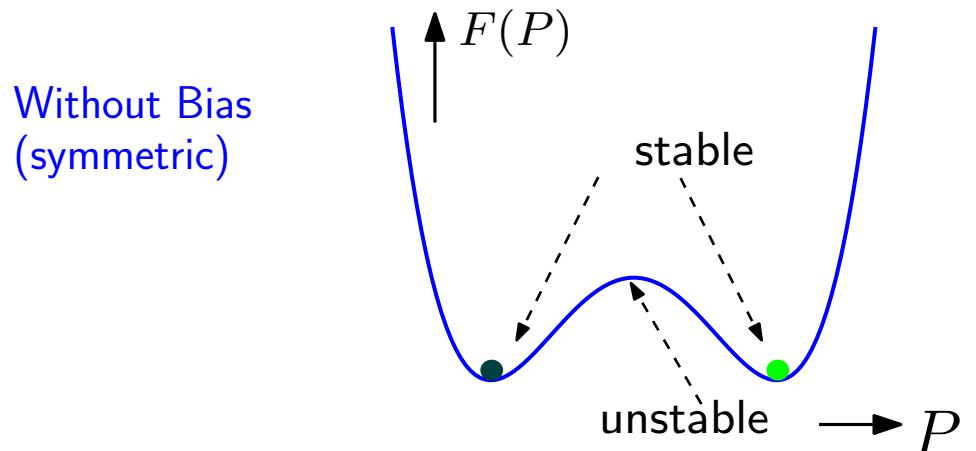
Stochastic Resonance - Overview

In simple words, Amplifying the signal with the aid of noise!

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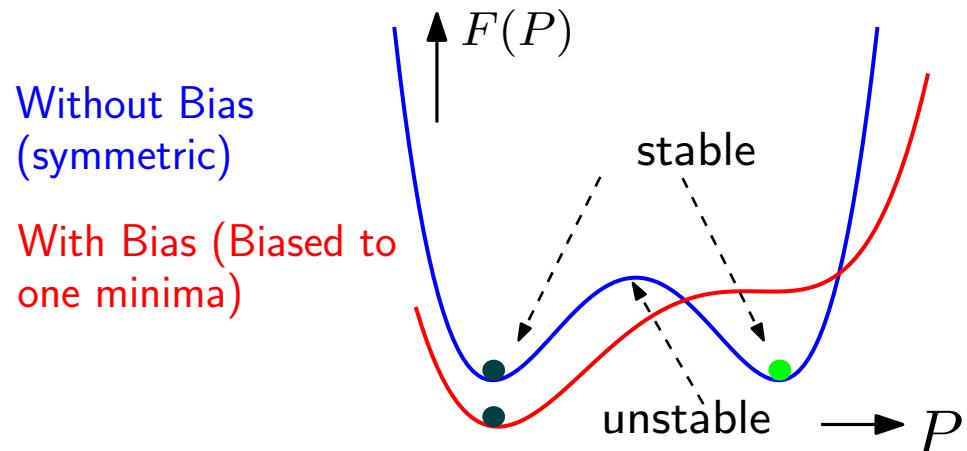
We have bistable systems
(Two stable states)



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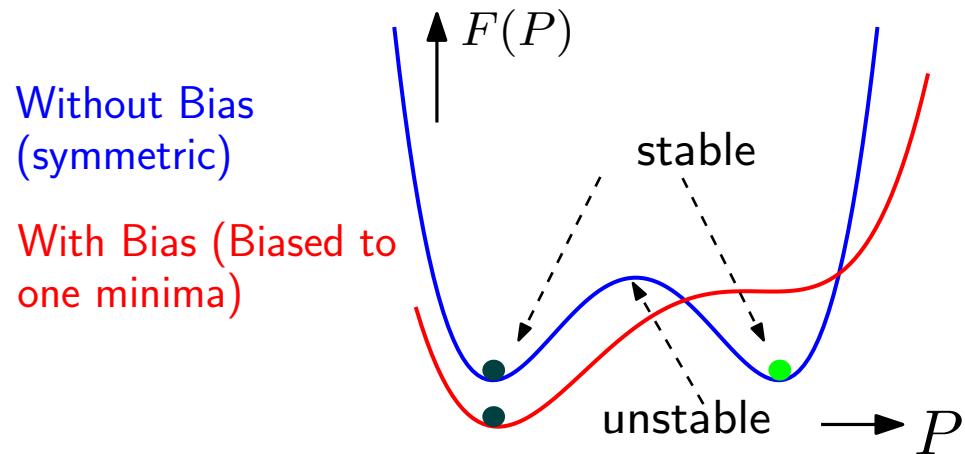
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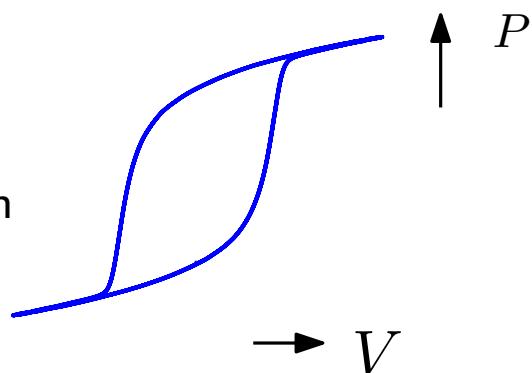
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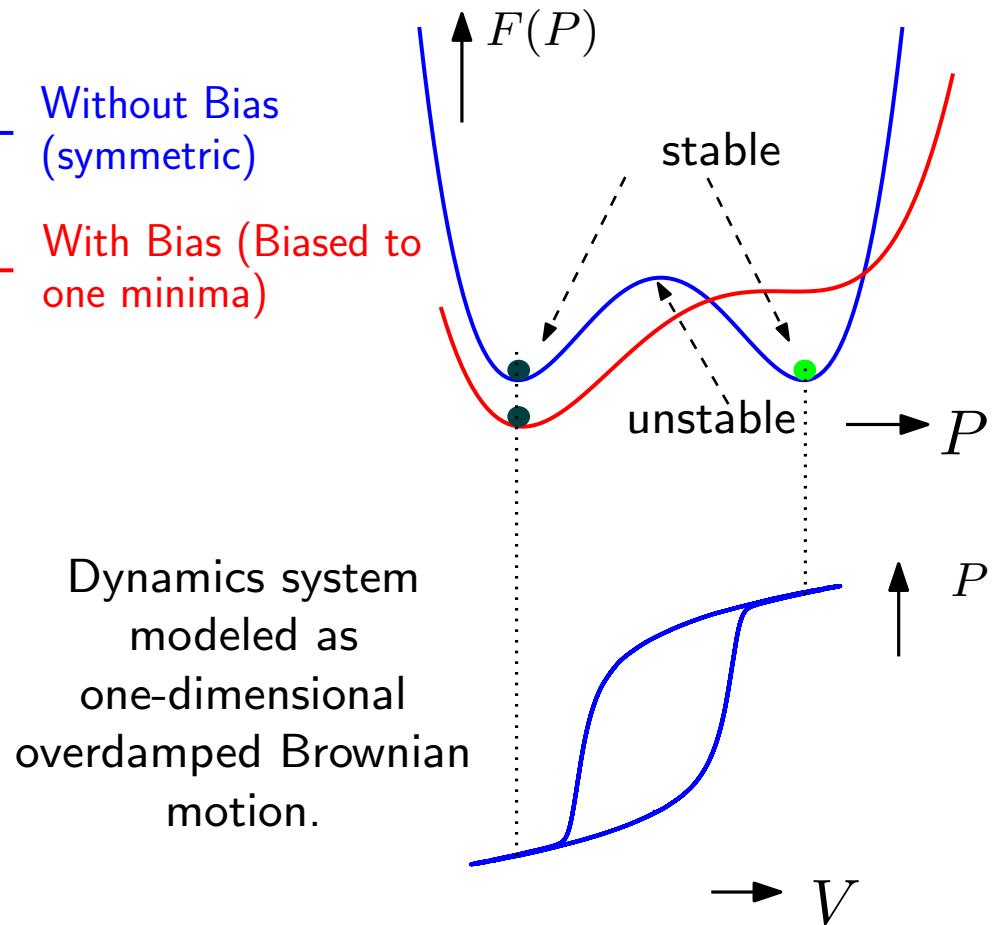
Dynamics system modeled as one-dimensional overdamped Brownian motion.



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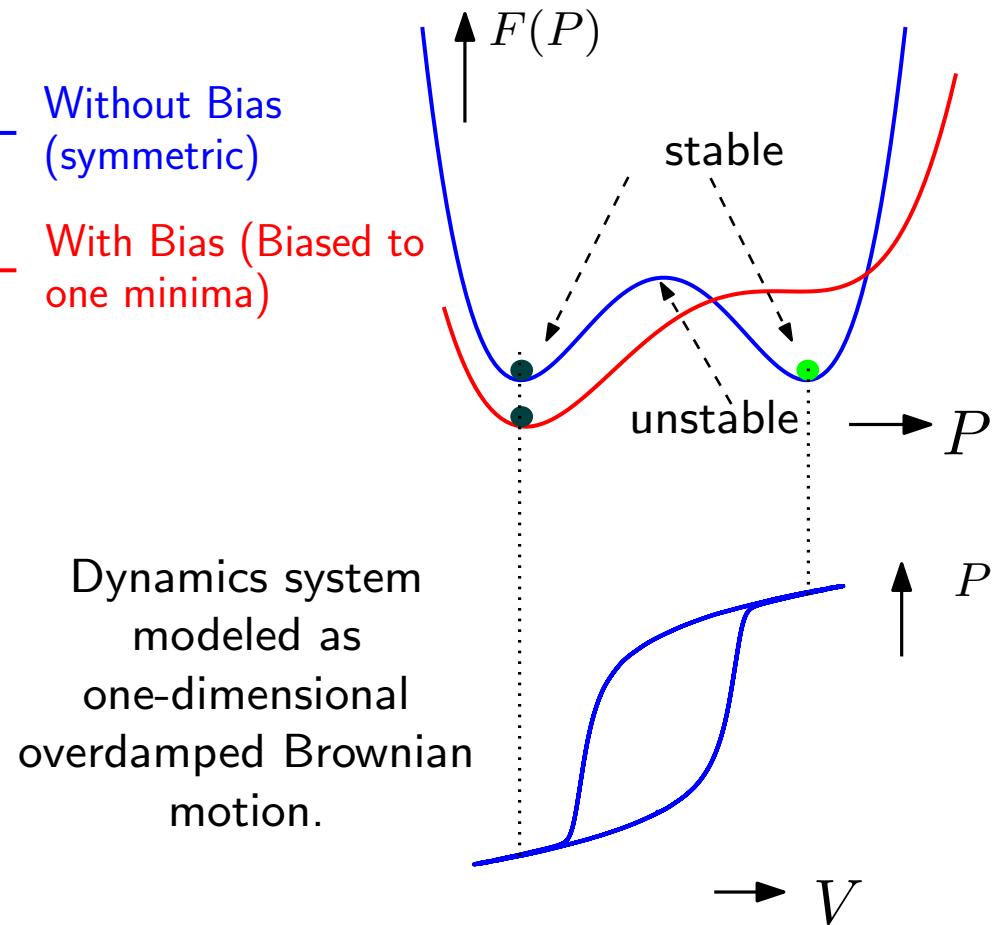


Stochastic Resonance - Overview

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Ferroelectric capacitor is a
bistable element

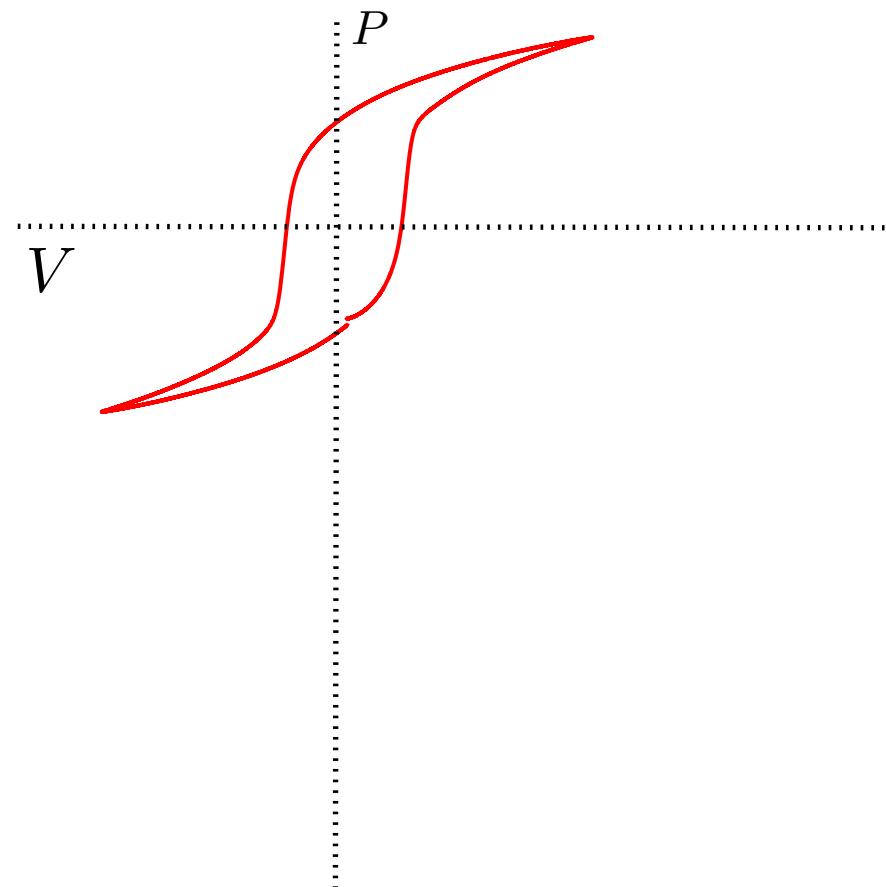
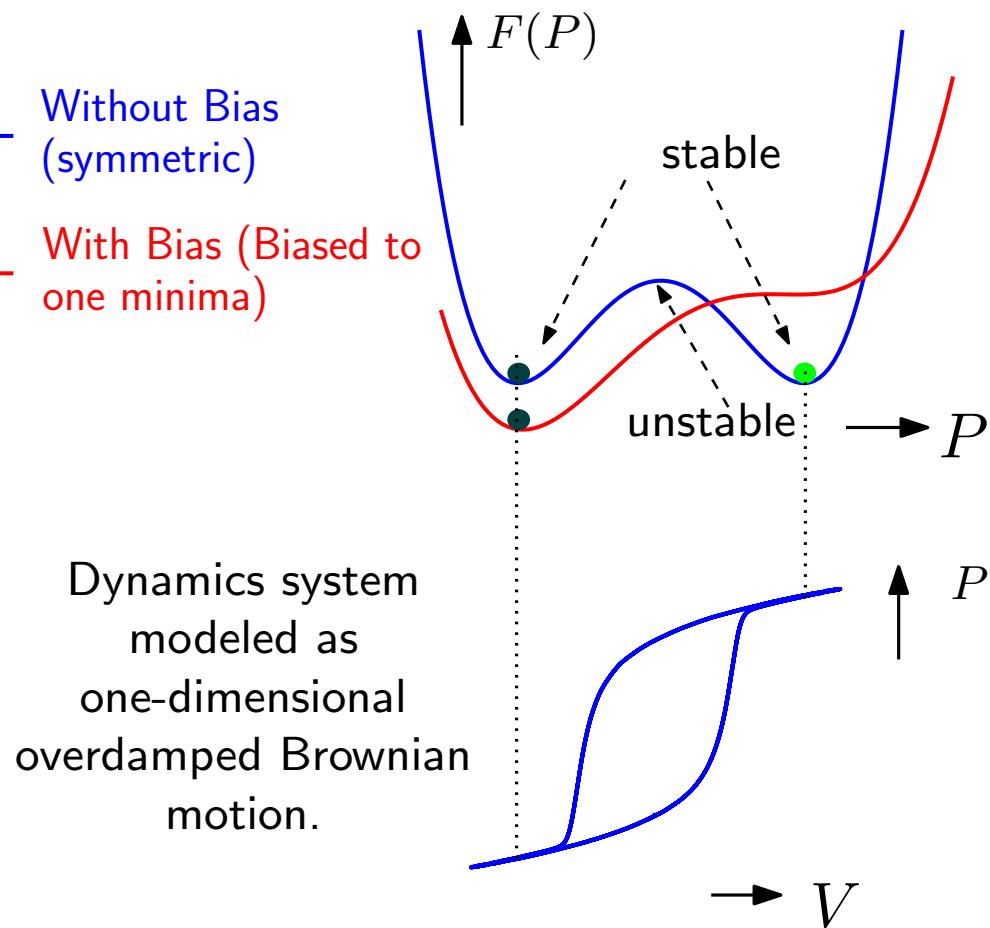


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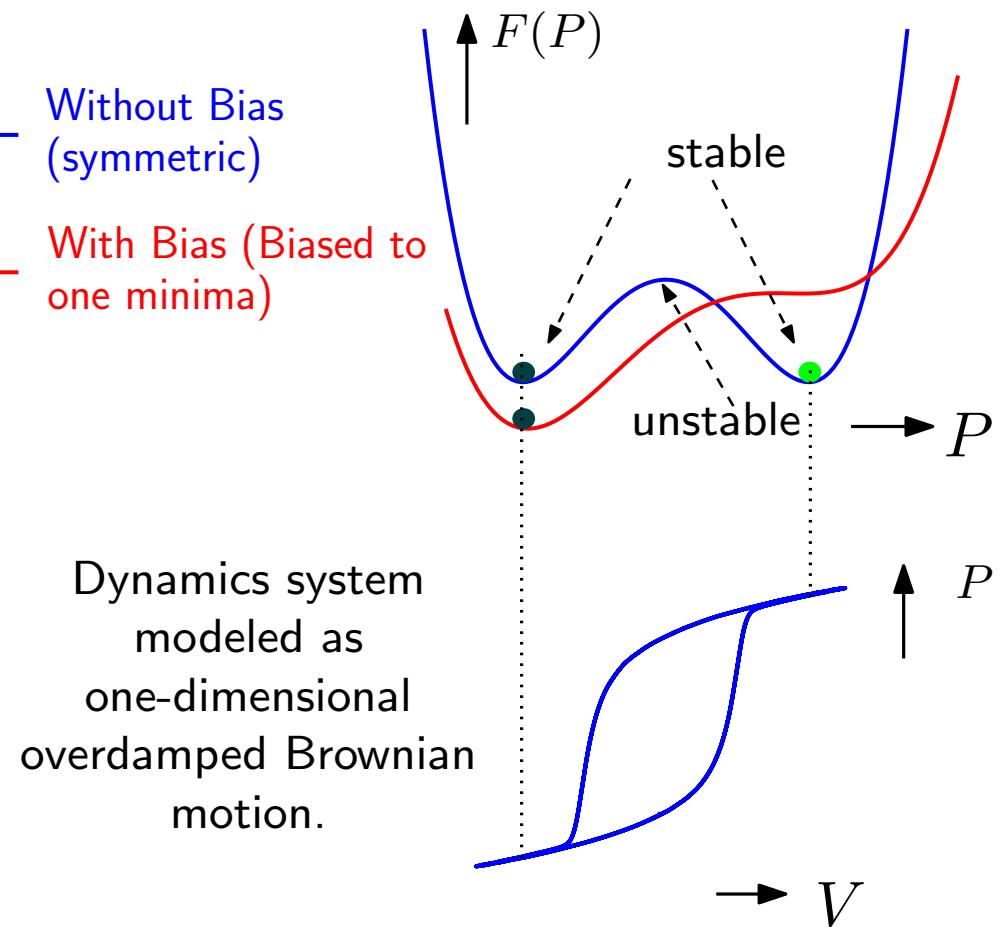
Ferroelectric capacitor is a
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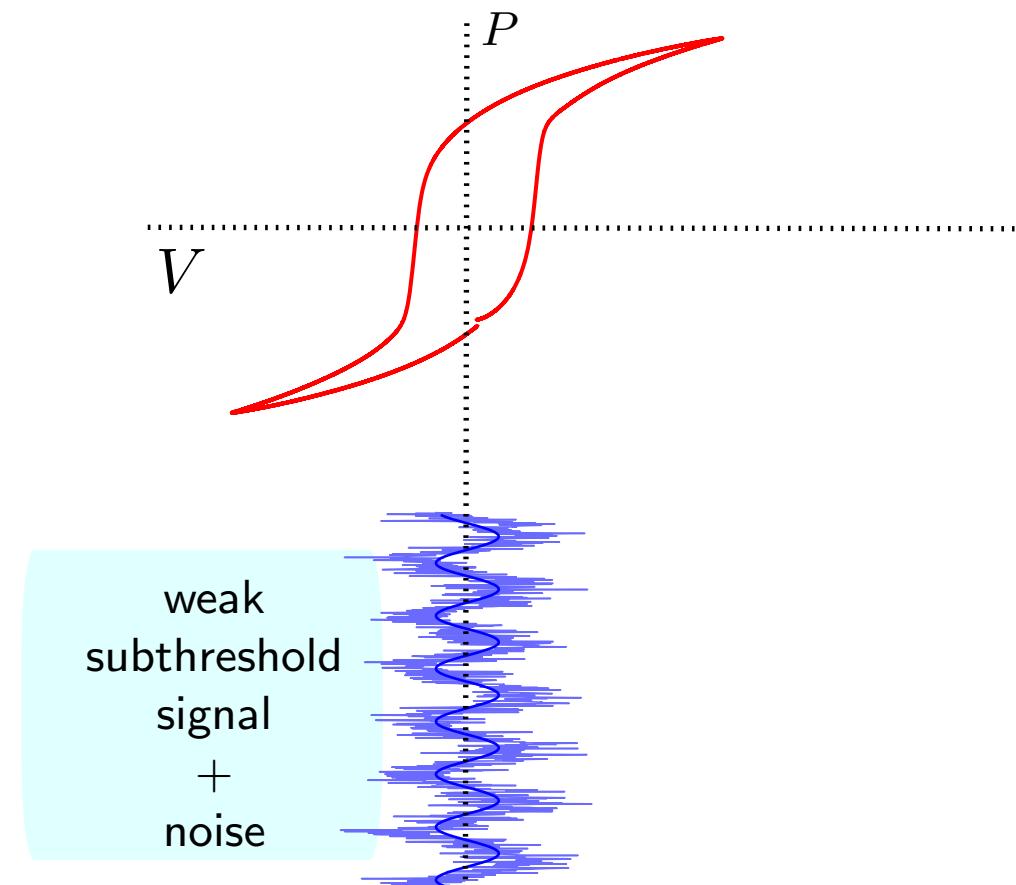
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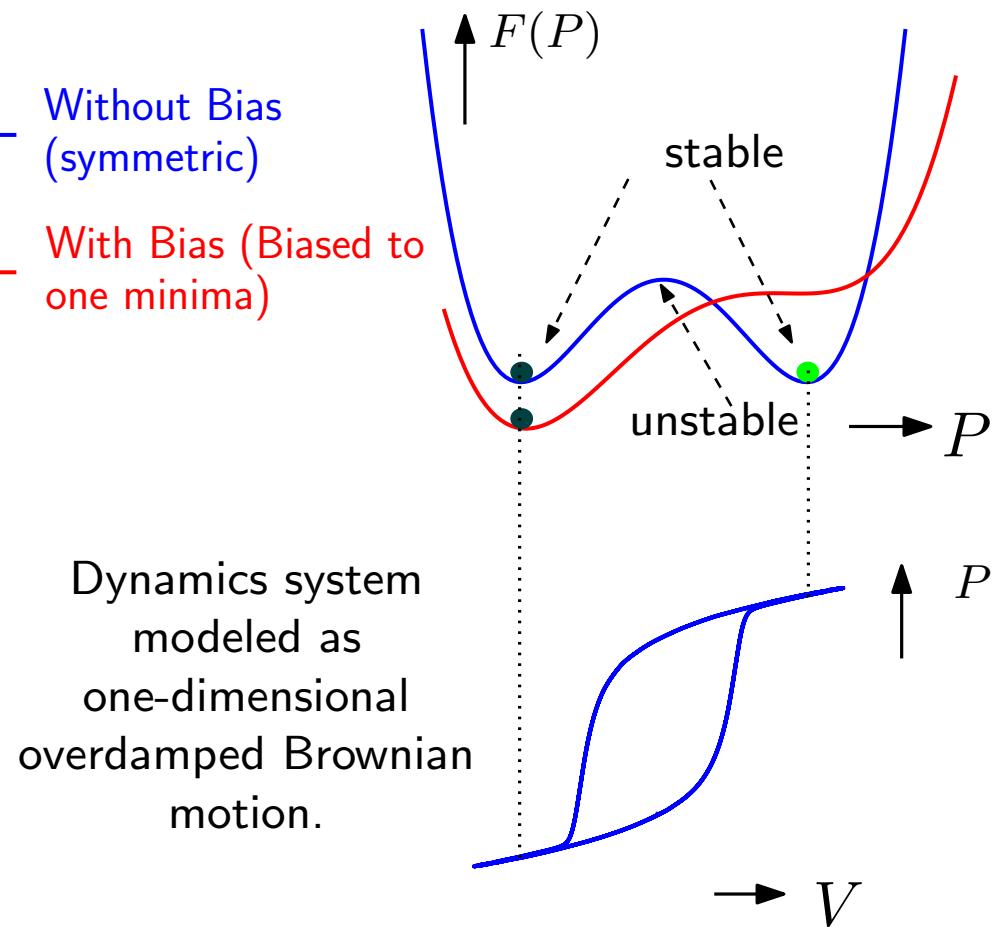
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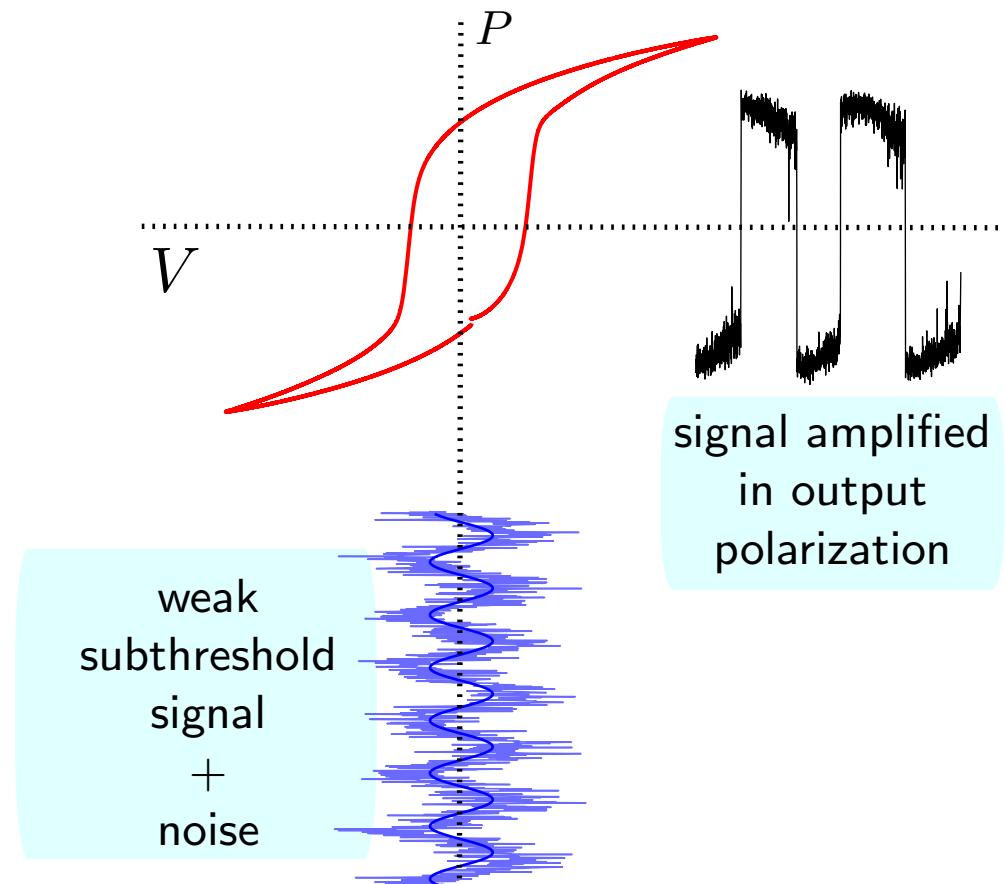
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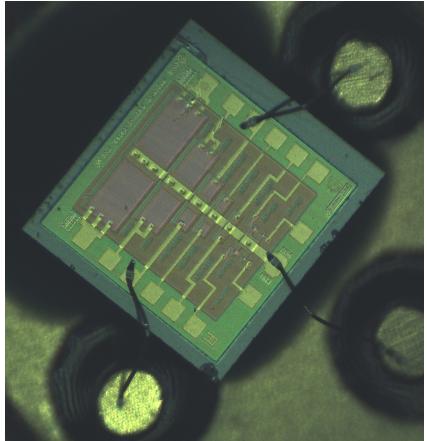


Ferroelectric capacitor is a bistable element



Ferroelectric Capacitor (PZT 20/80)

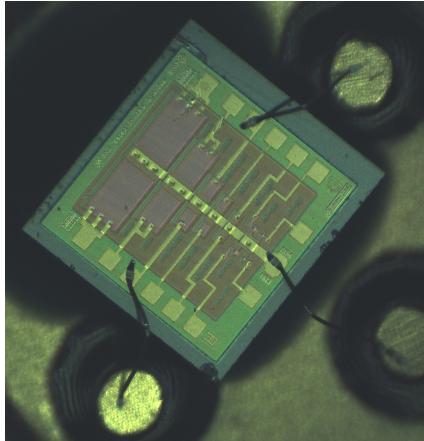
Packaged AB capacitor



Capacitor die

Ferroelectric Capacitor (PZT 20/80)

Packaged AB capacitor



Capacitor die

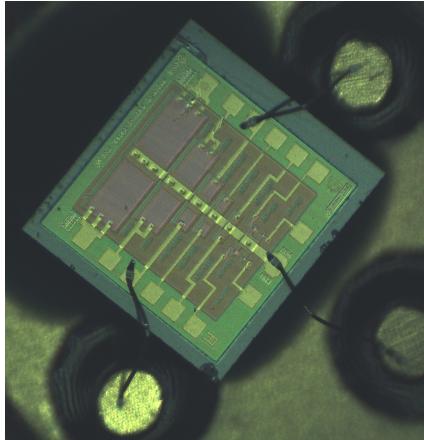
Ferroelctric Tester



Uses Vision software to drive

Ferroelectric Capacitor (PZT 20/80)

Packaged AB capacitor



Capacitor die

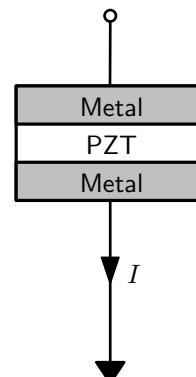
Ferroelctric Tester



Uses Vision software to drive

Experiment Setup

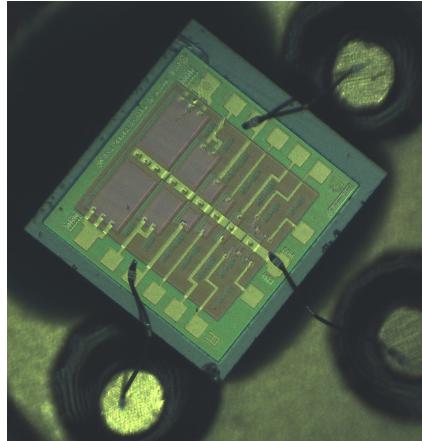
$$V = E \times t_F$$



$$P = \int Idt/A$$

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Capacitor die

Ferroelctric Tester



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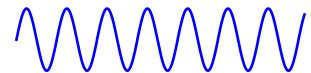
Experiment Setup

V_C —————



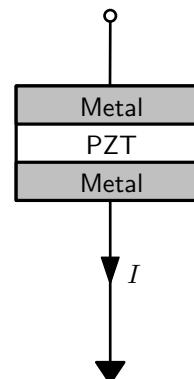
$-V_C$ —————

V_C —————



$-V_C$ —————

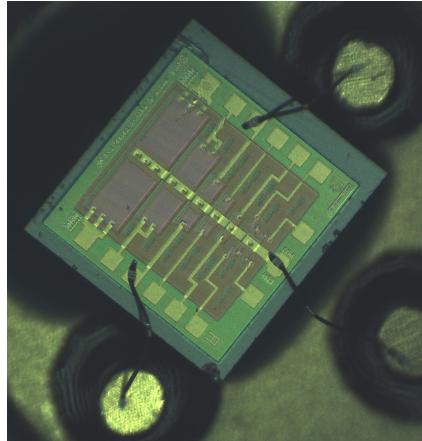
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Ferroelectric Capacitor (PZT 20/80)

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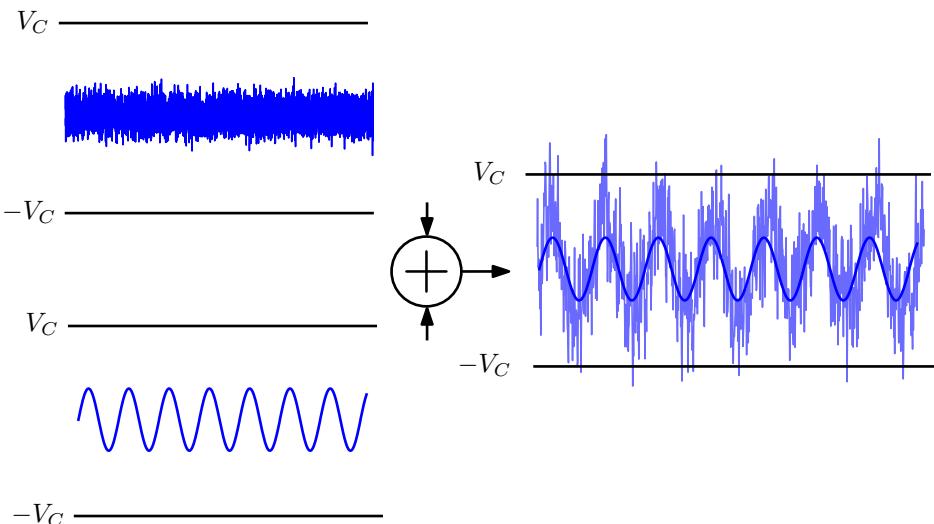
Capacitor die

Ferroelctric Tester

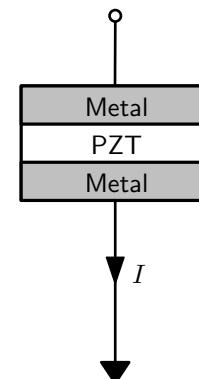


Uses Vision software to drive

Experiment Setup



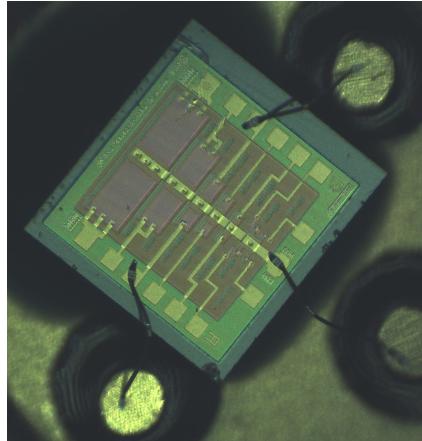
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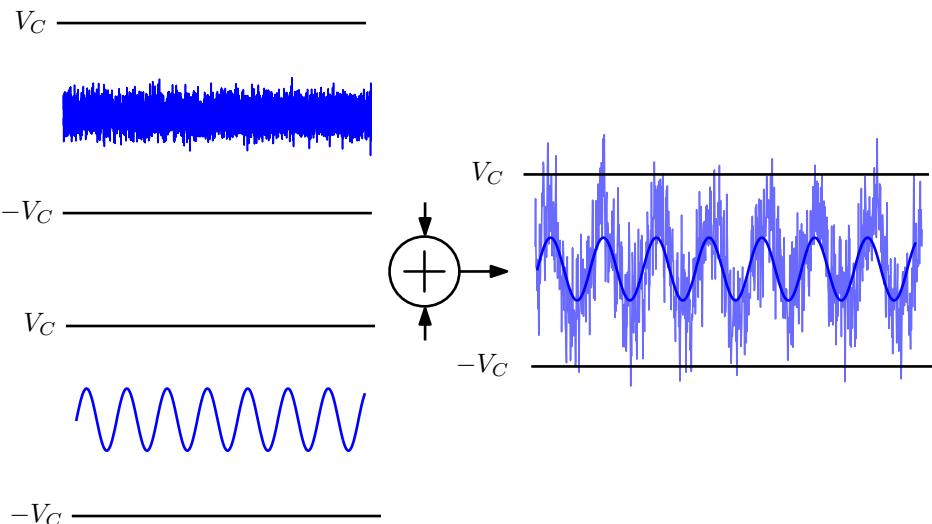
Capacitor die

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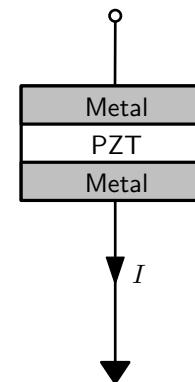


Uses Vision software to drive

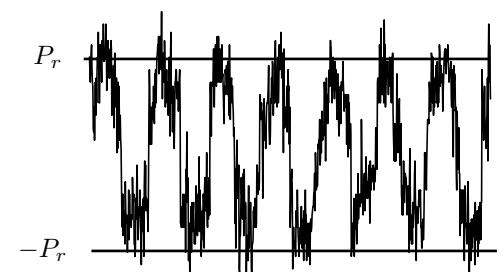
Experiment Setup



$$V = E \times t_F$$



$$P = \int I dt / A$$



Single domain model for ferroelectric

Assumption: System is bistable

Double well model free energy equation

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

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Landau coeff.

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Electric field is the modulating signal

Assumption: Dynamics - strongly damped

TDGL equation

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

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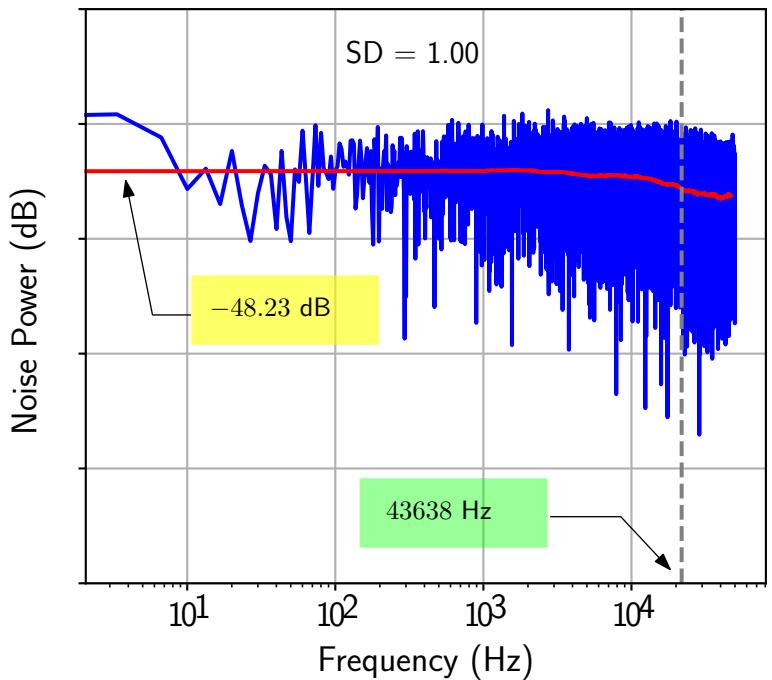
Disturbance
(Noise signal)

White gaussian noise

The PSD of the noise is flat over a bandwidth

$$D_{ext} = \frac{V_{noise}^2}{t_F^2} \frac{1}{2\Delta f} \frac{1}{\rho}$$

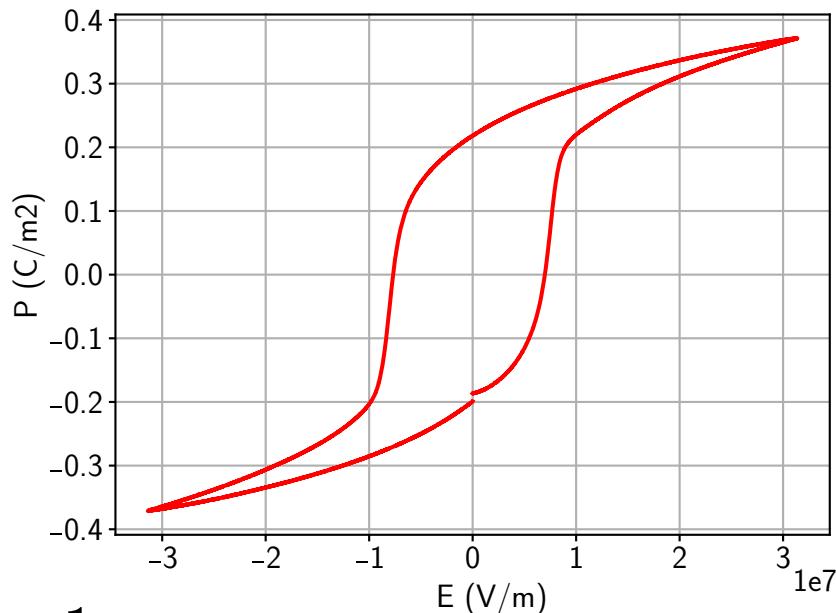
Parameter	variable
ρ	resistivity
ΔF	Barrier height at given bias
t_F	Thickness of sample
V_{noise}	std of applied noise
Δf	Bandwidth where noise PSD is flat



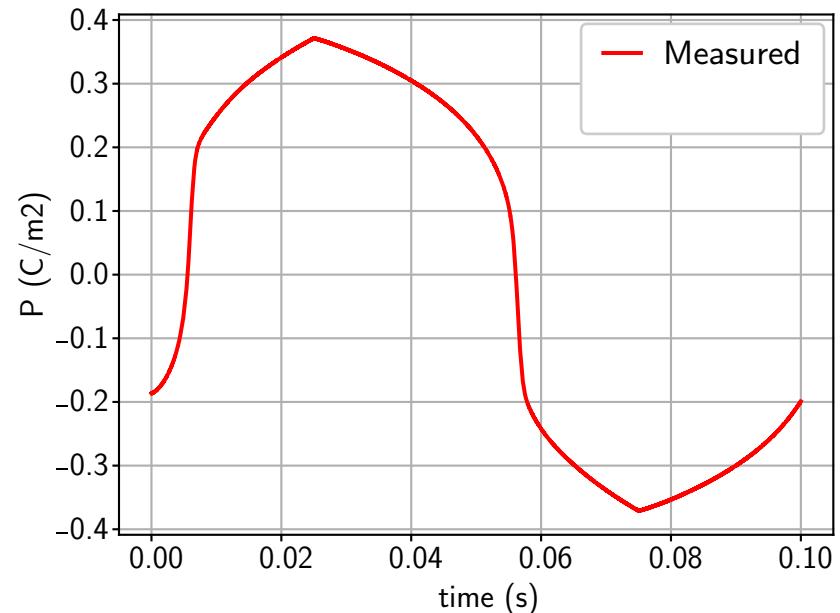
Parameter extraction and modeling

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

Polarization vs Electric-field



Polarization time series



Parameter extraction and modeling

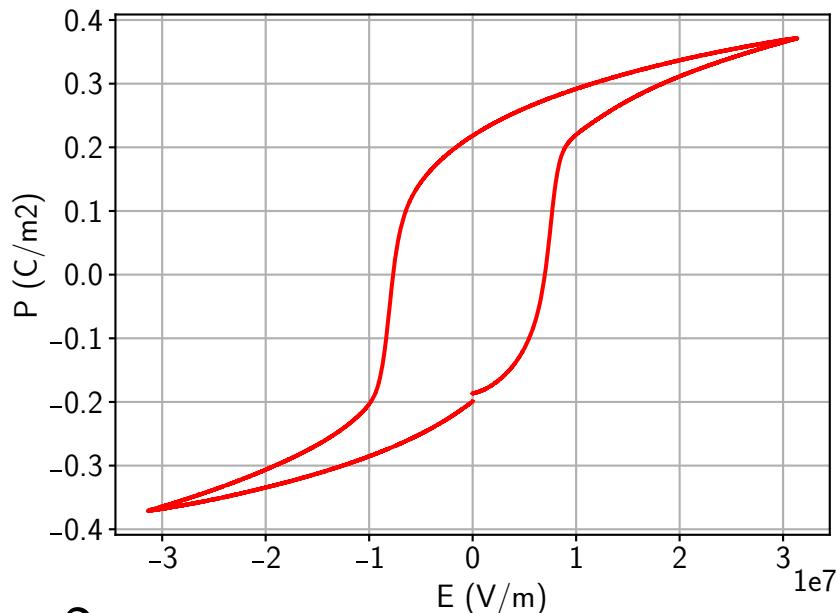
Landau Coefficients

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

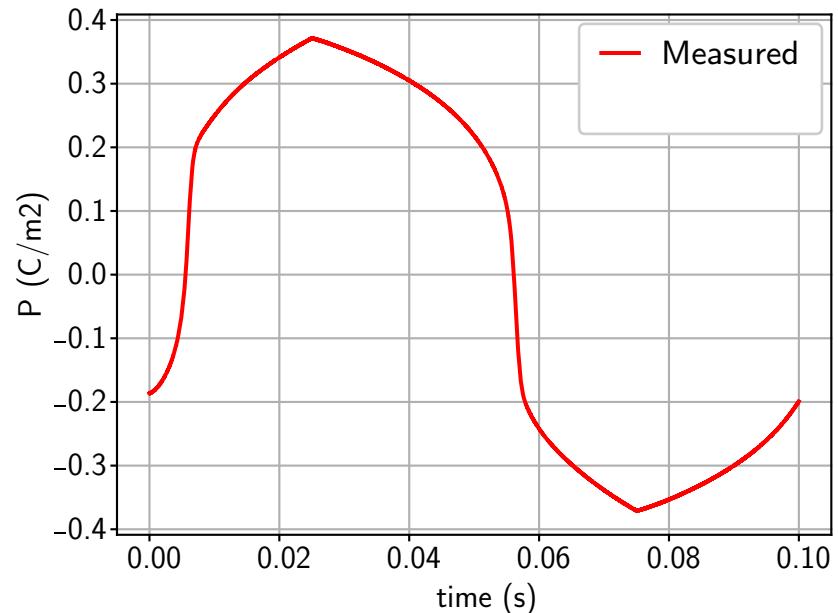
$$\beta = \frac{3\sqrt{3}E_c}{8P_r^3} = 5.82 \times 10^8 \text{ m}^5 \text{F}^{-1} \text{C}^{-1}$$

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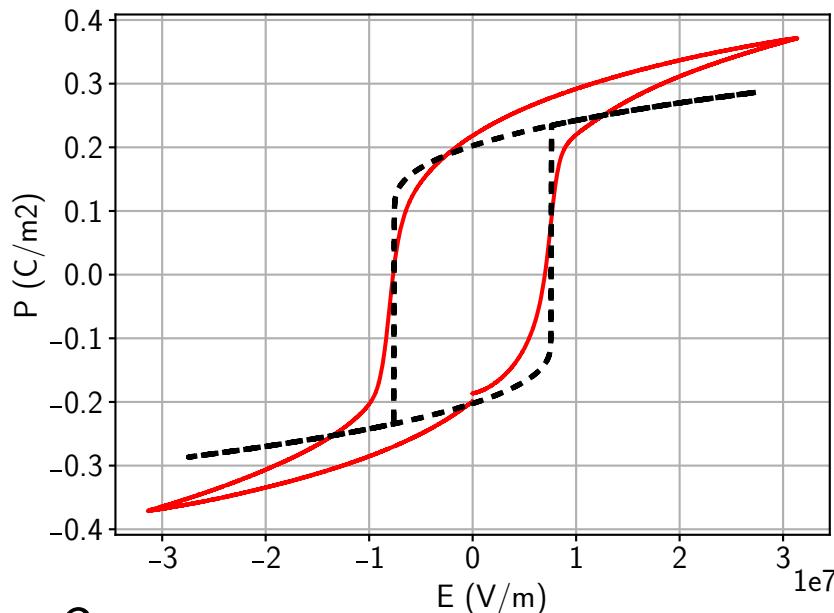
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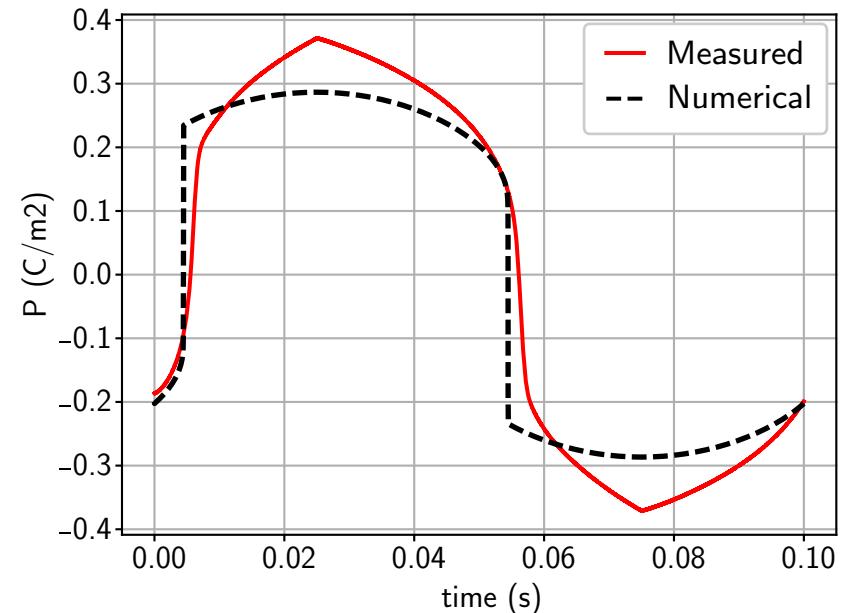
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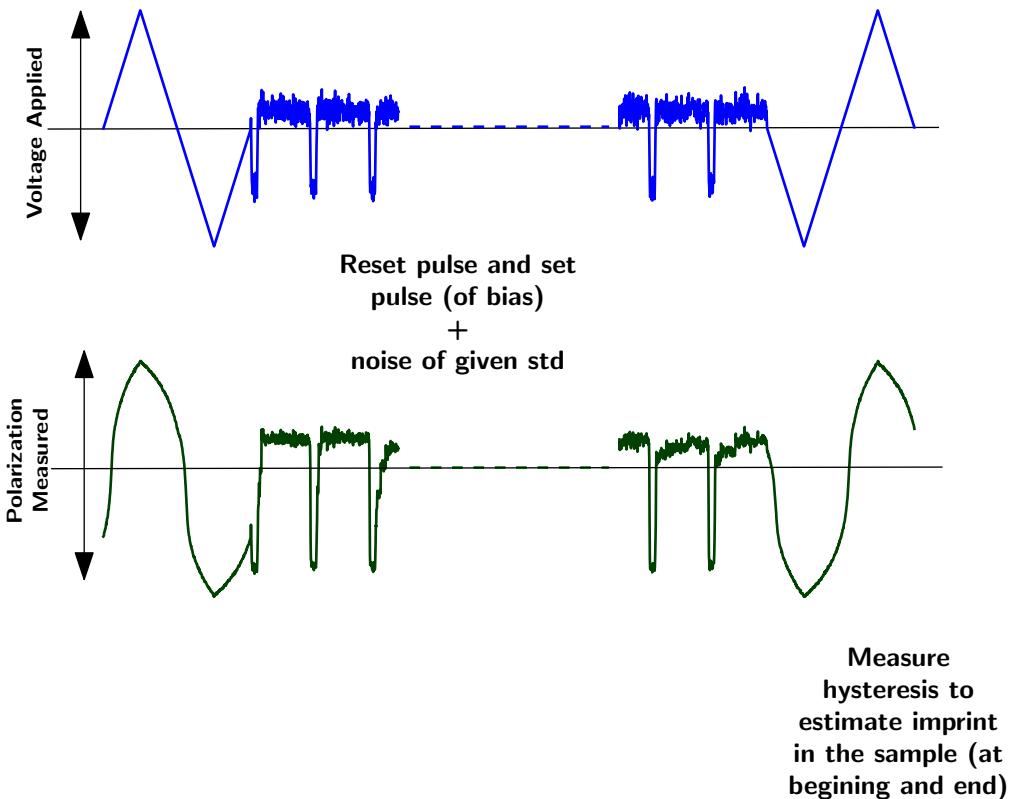


Polarization time series



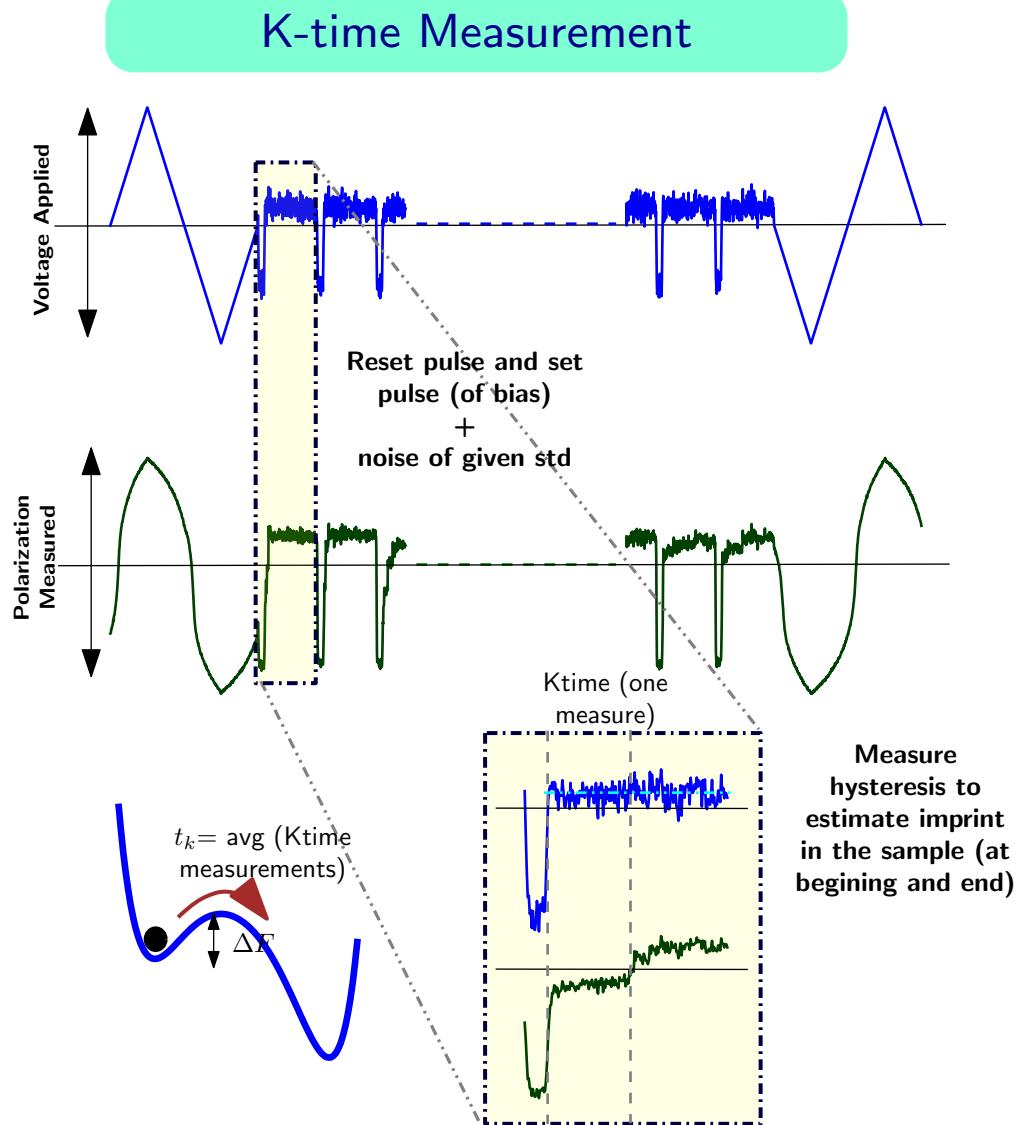
Kramers' time measurement and ρ extraction

K-time Measurement



Work by **Mr. Kevin R. Jacob** from his BTP has been used, and results from his
12 - 1 report are included for continuity.

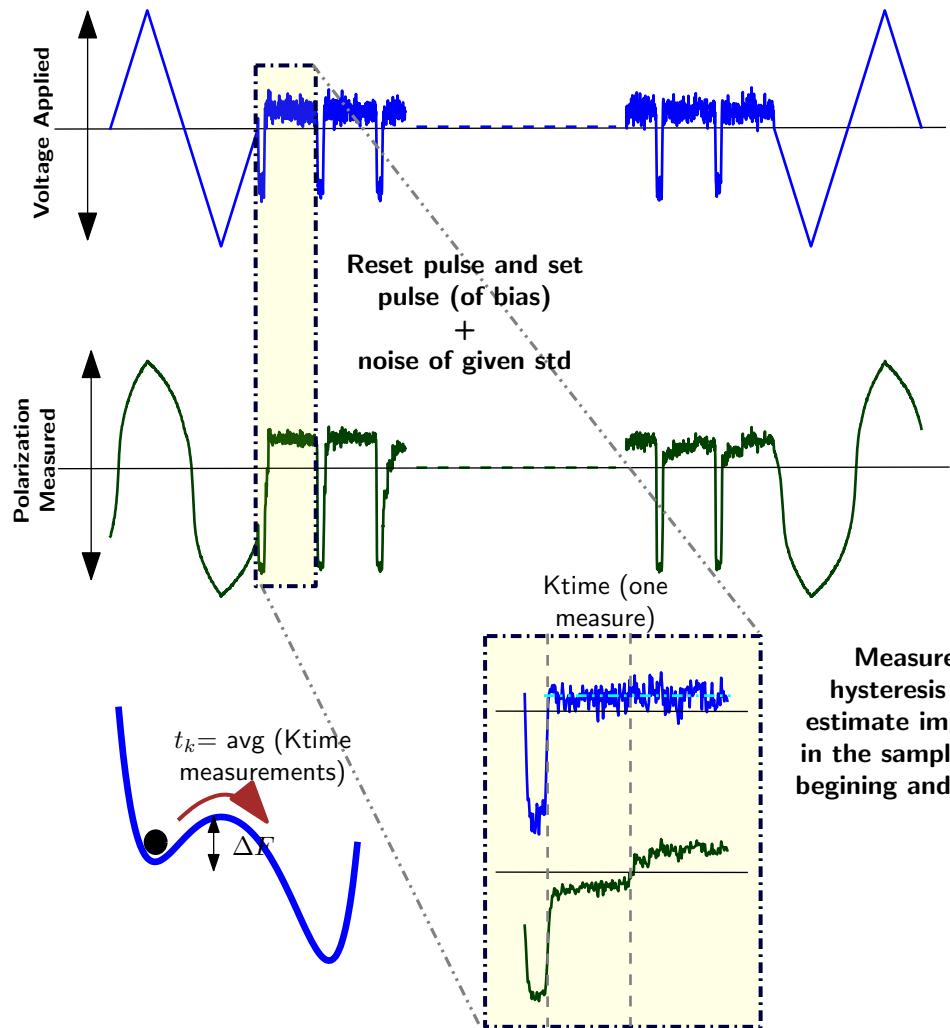
Kramers' time measurement and ρ extraction



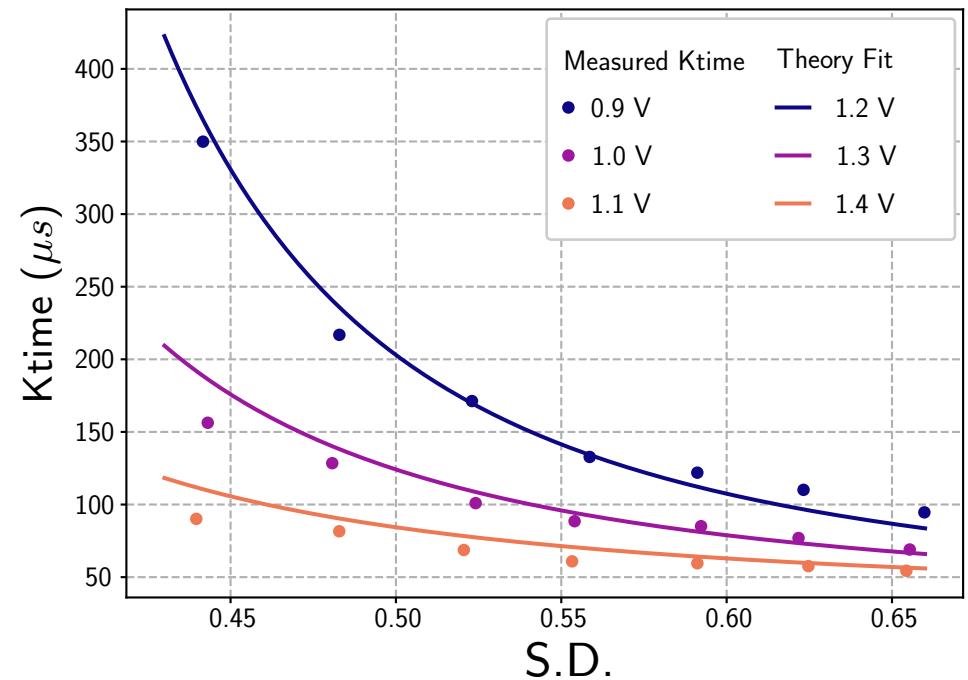
Work by Mr. Kevin R. Jacob from his BTP has been used, and results from his
12 - 2 report are included for continuity.

Kramers' time measurement and ρ extraction

K-time Measurement



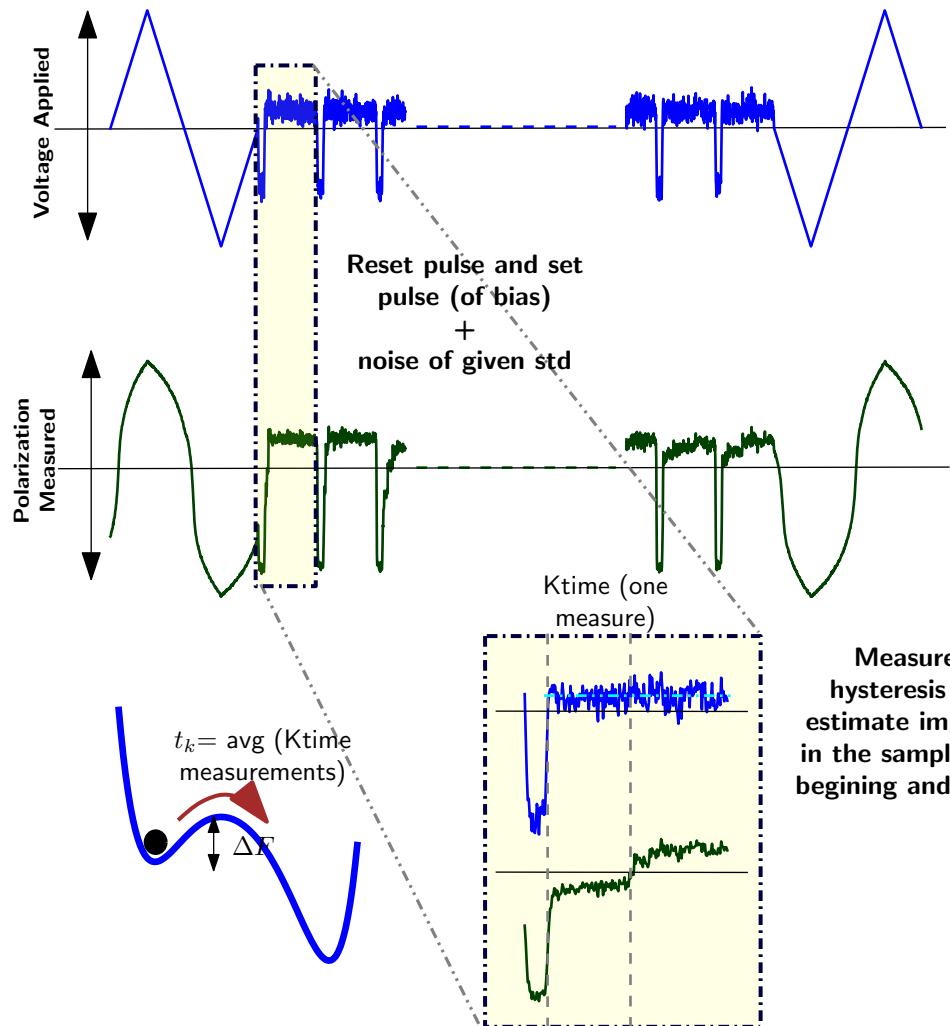
Results and Theory



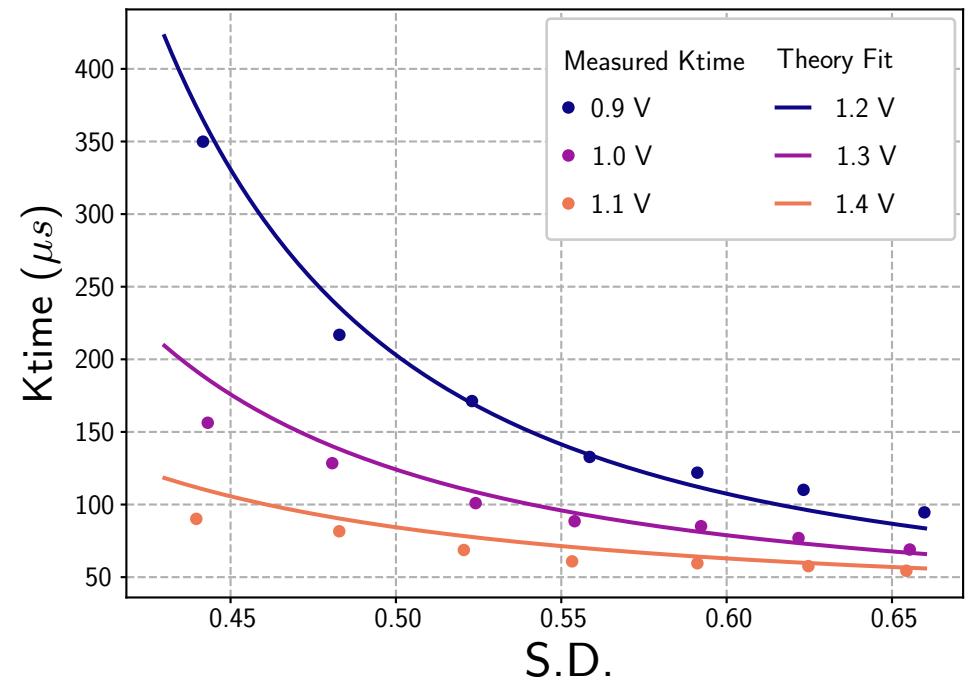
The dotted points are the **measured K-time** and the solid lines are the **theoretical prediction**

Kramers' time measurement and ρ extraction

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Results and Theory

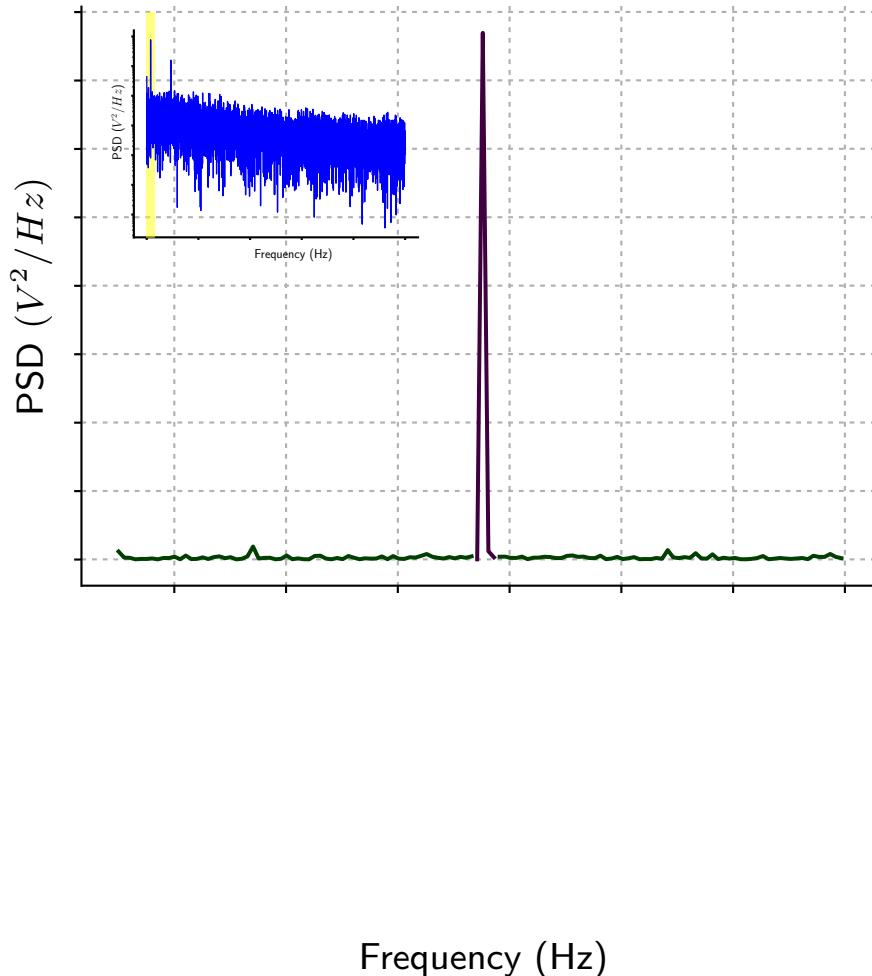


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$$\rho = 390\Omega$$

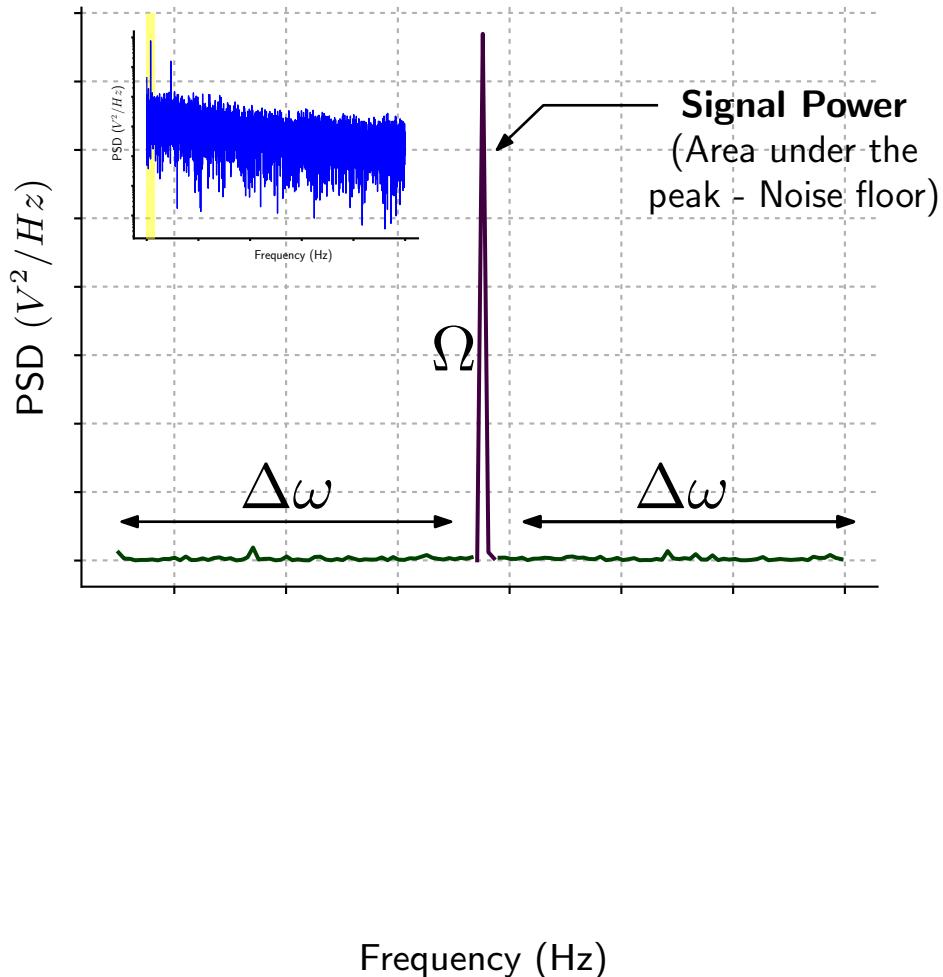
Metrics to quantify SR

Power Spectral Density



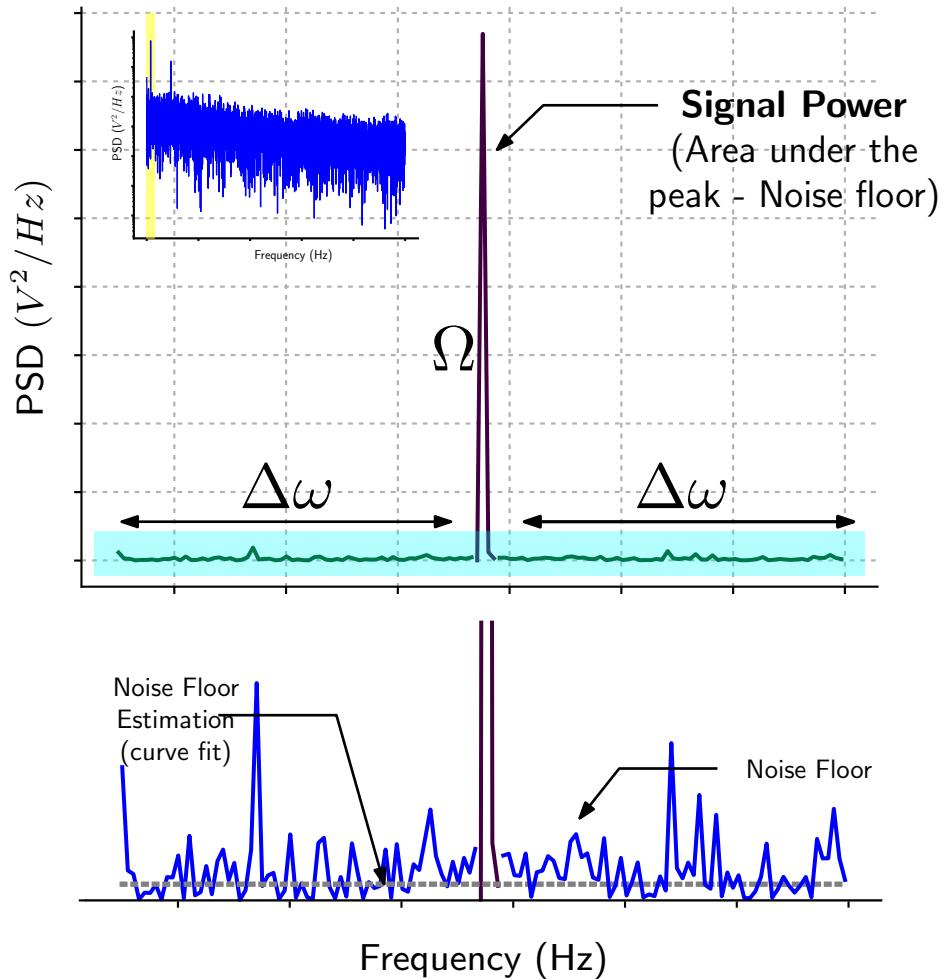
Metrics to quantify SR

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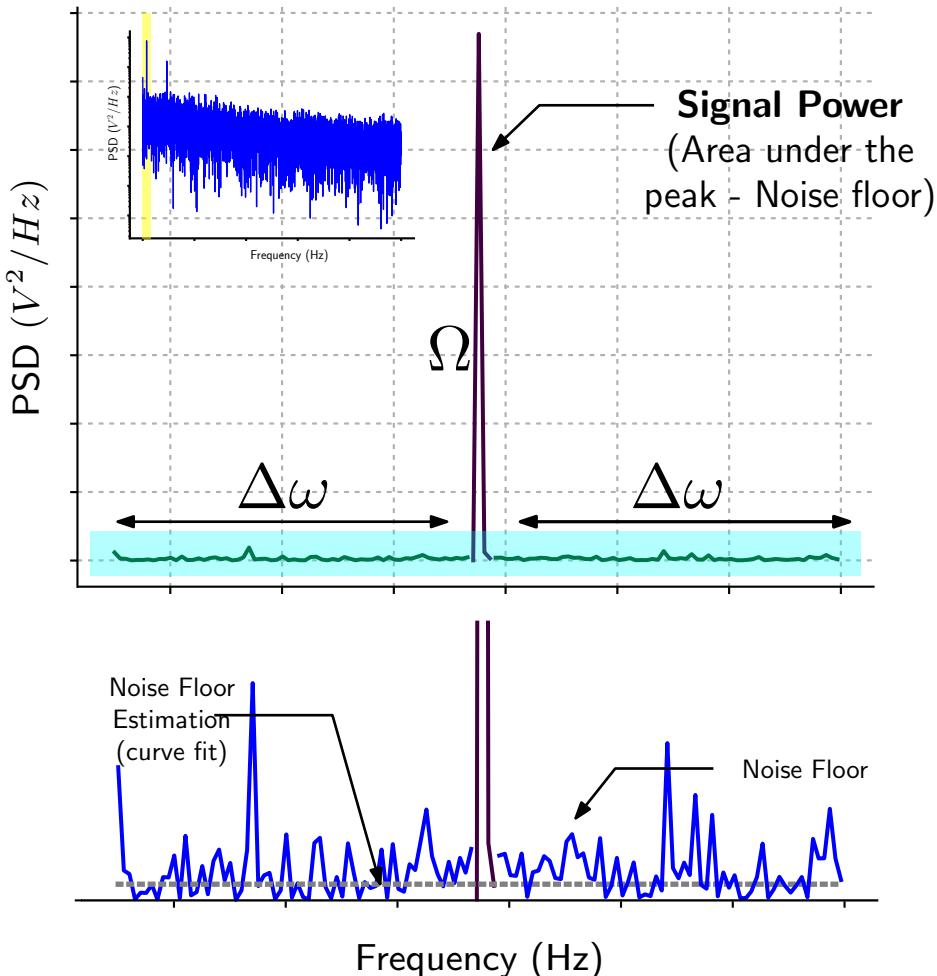
Metrics to quantify SR

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Metrics to quantify SR

Power Spectral Density



Metrics

- **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)**

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

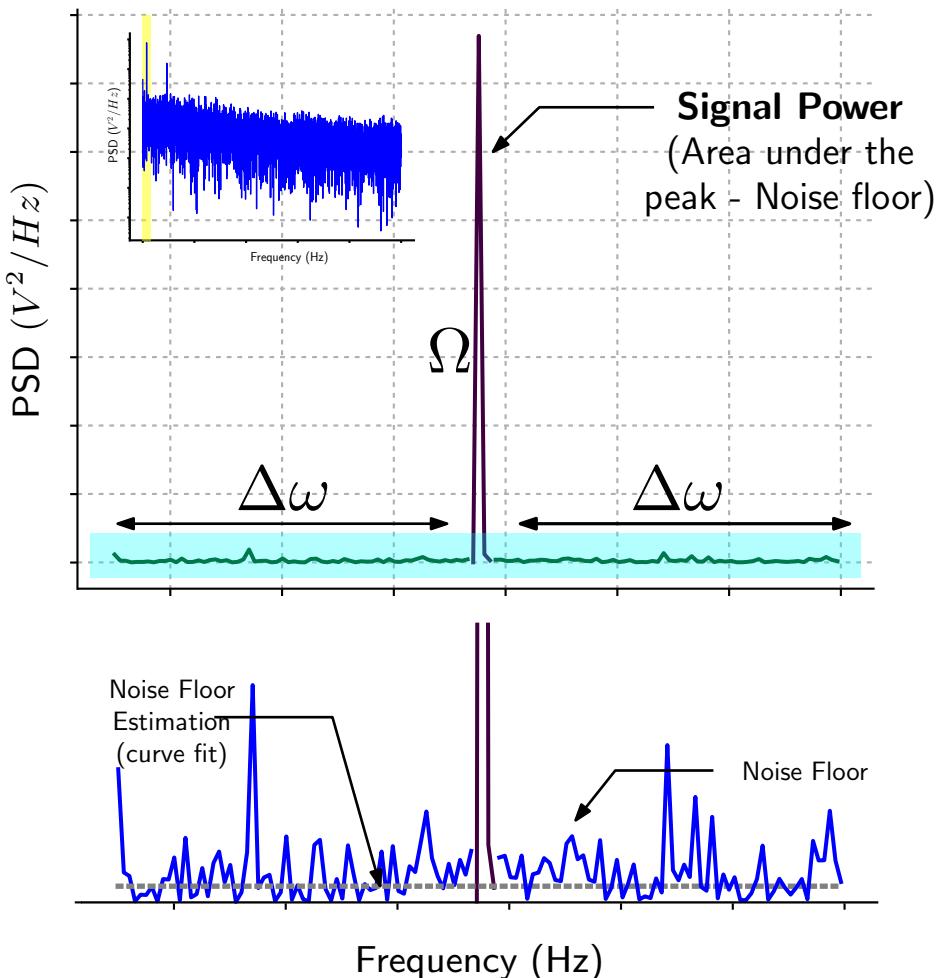
- **Cross Covariance**

$$cov(P, P_S) =$$

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

Metrics to quantify SR

Power Spectral Density



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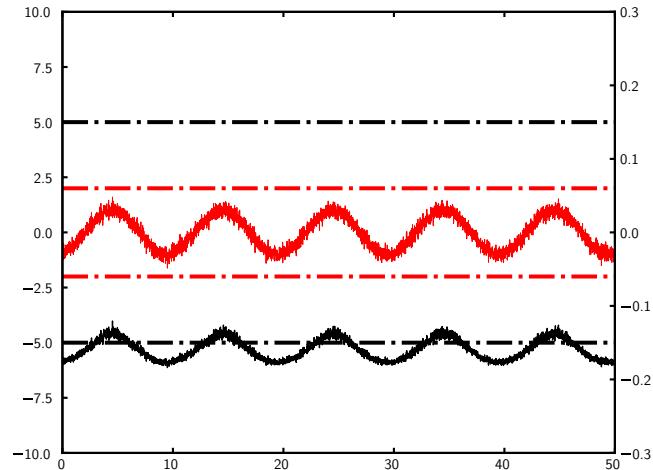
$$\frac{1}{N-1} \sum_{i=1}^N (P(i) - E[P])(P_S(i) - E[P_S])$$

Output signal is **Polarization**.
Where S is signal PSD, S_N is noise PSD
 P_S is the switching polarization for a super threshold signal

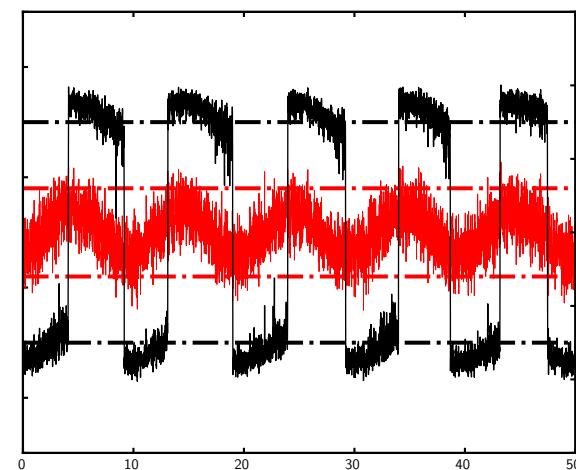
Results

Numerical Simulation

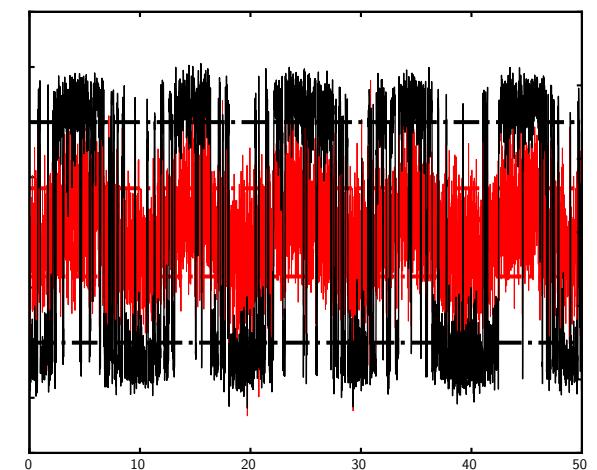
S.D. = 0.18



S.D. = 0.80



S.D. = 1.96



Voltage V

14 - 1 --- V_C

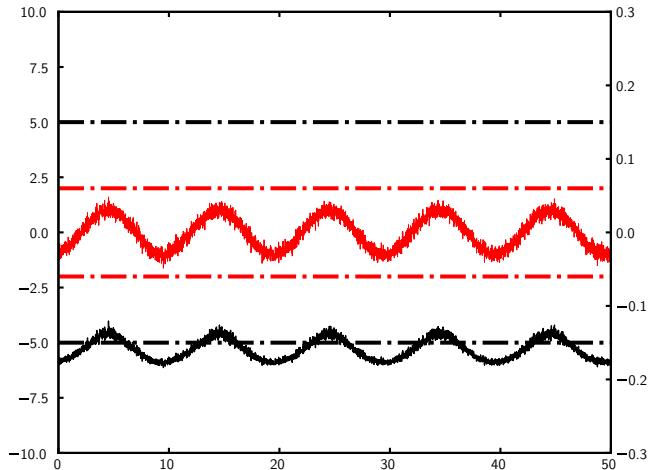
Polarization C/m^2

--- P_r

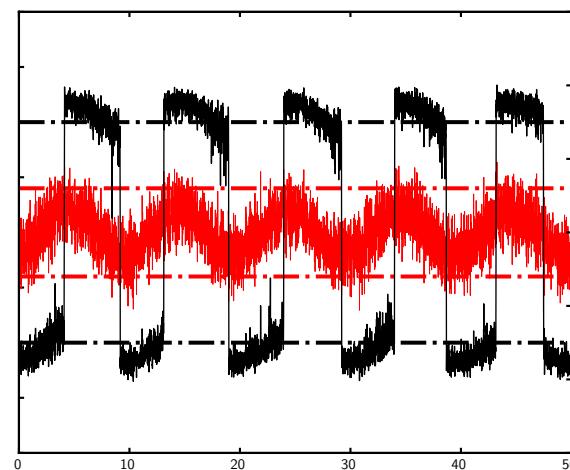
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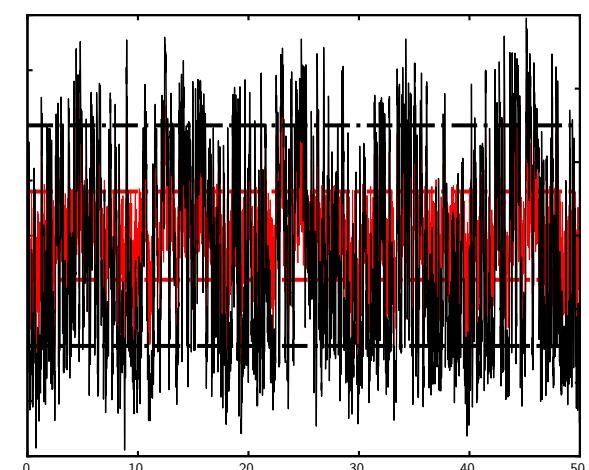
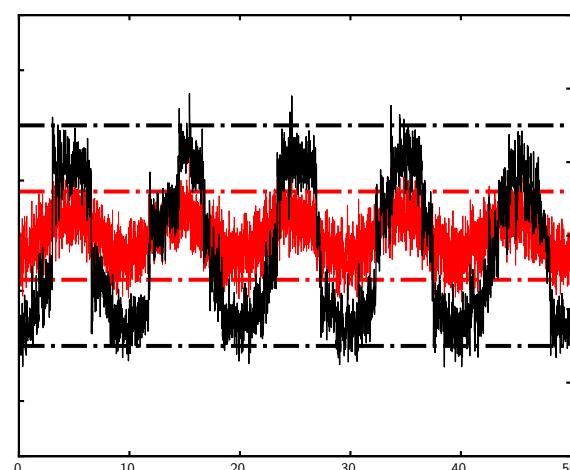
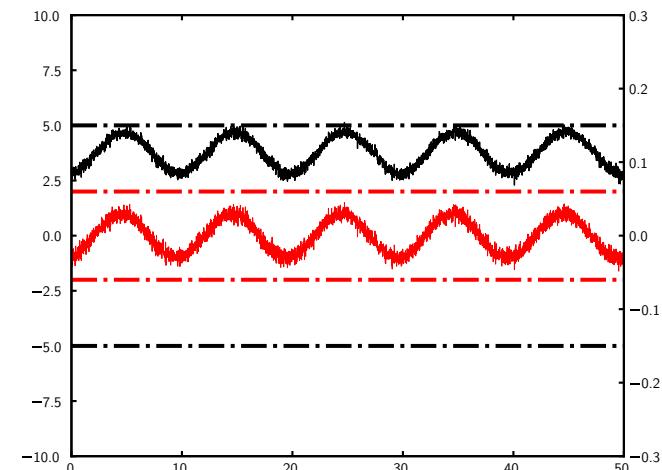
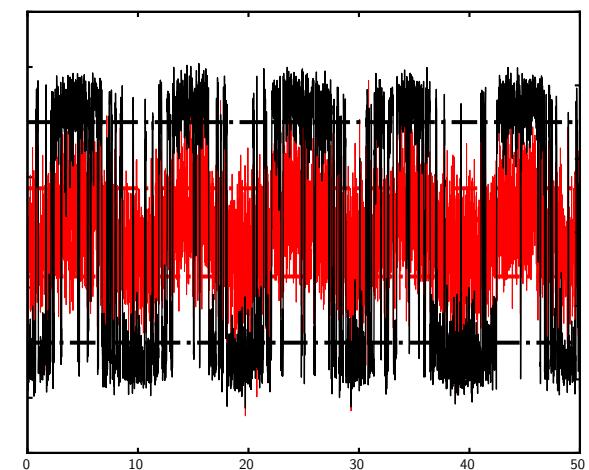
S.D. = 0.18



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S.D. = 1.96



Voltage V

14 - 2 --- V_C

Experiment

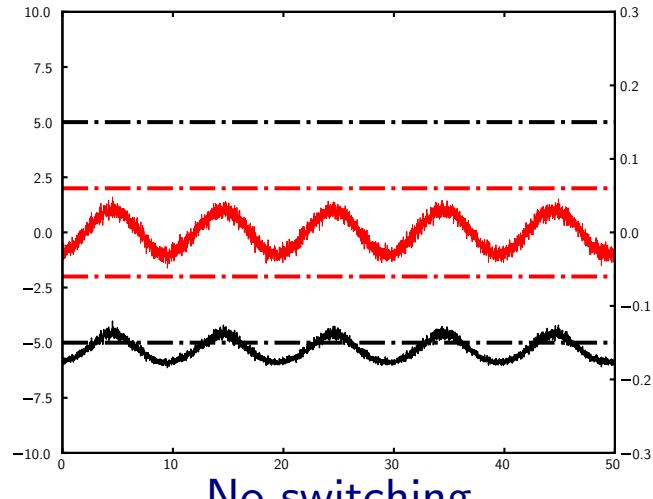
Polarization C/m^2

--- P_r

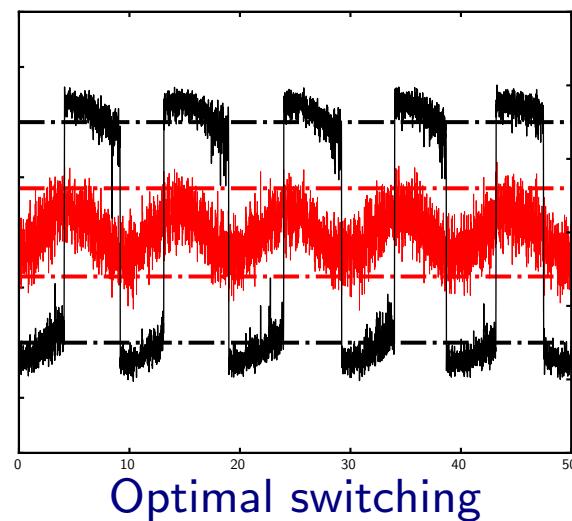
Results

Numerical Simulation

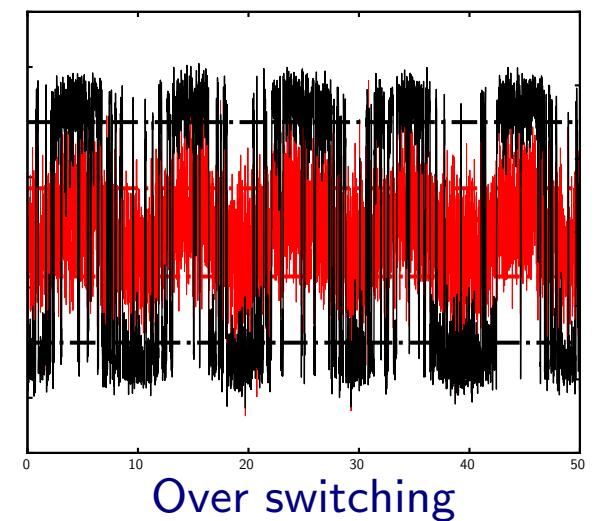
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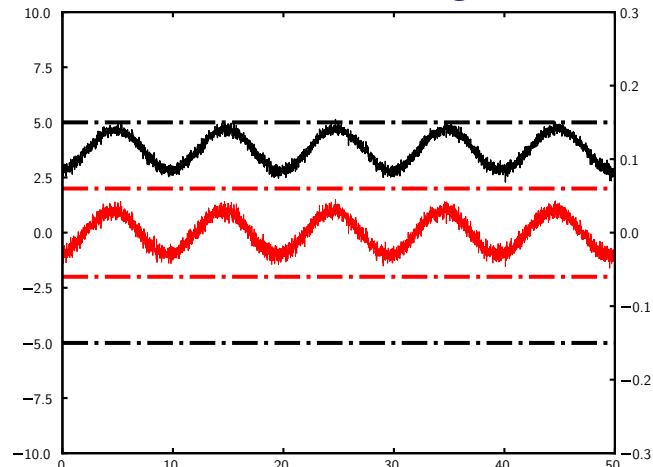
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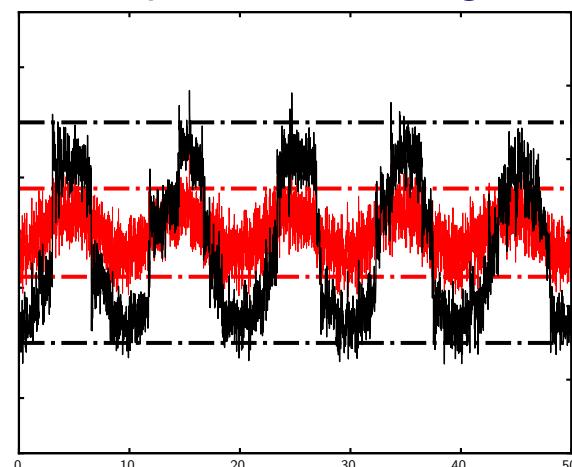
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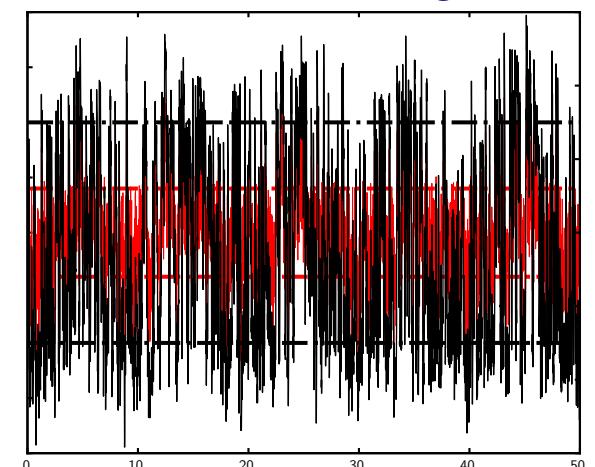
No switching



Optimal switching



Over switching



Voltage V

14 - 3 --- V_C

Experiment

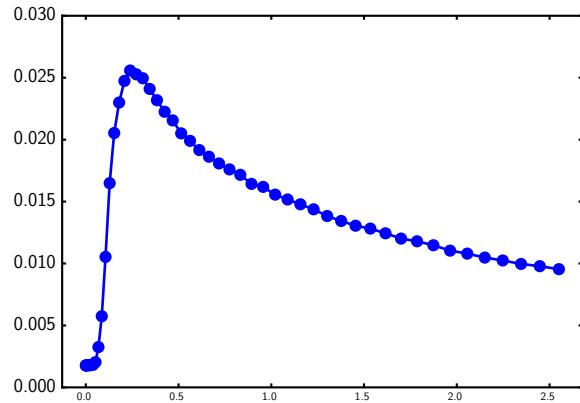
Polarization C/m^2

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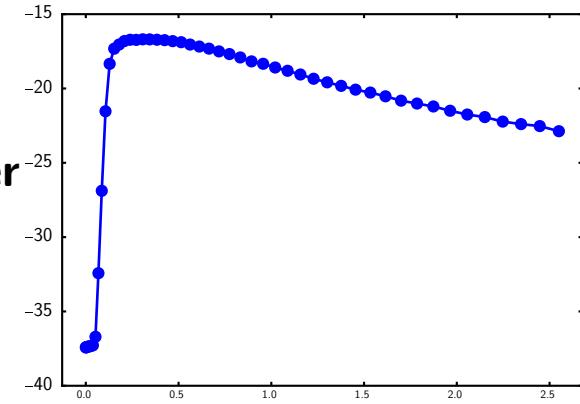
Results

Numerical Simulation

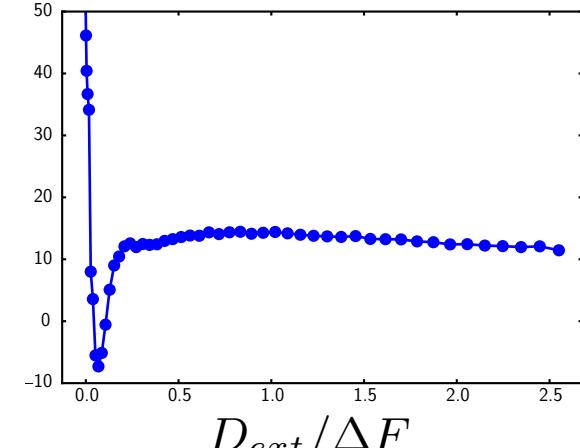
Cross Cov.
 (C^2/m^4)



Output Power
 (dB)



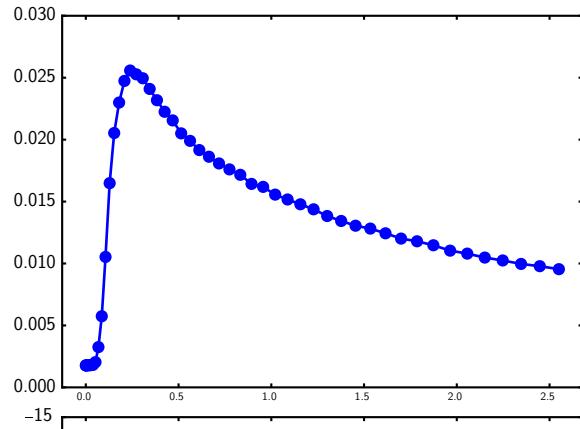
SNR
 (dB)



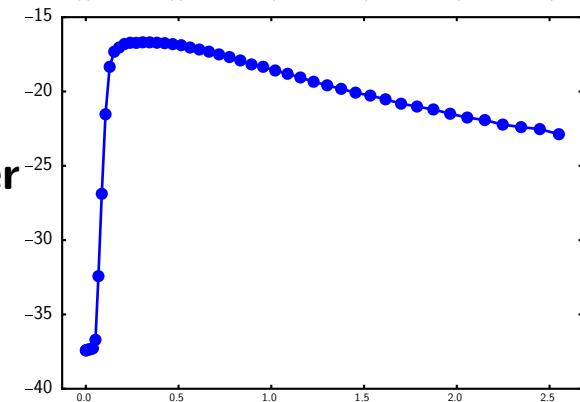
Results

Numerical Simulation

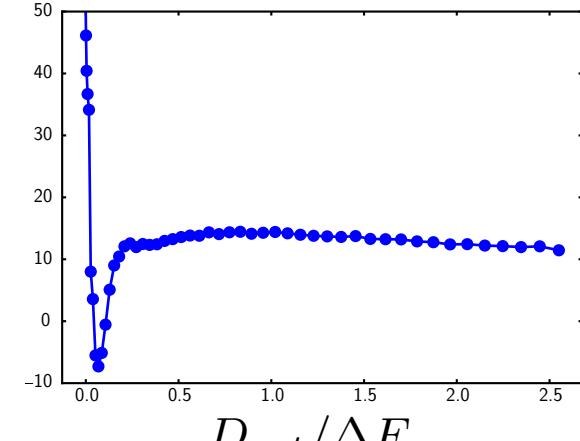
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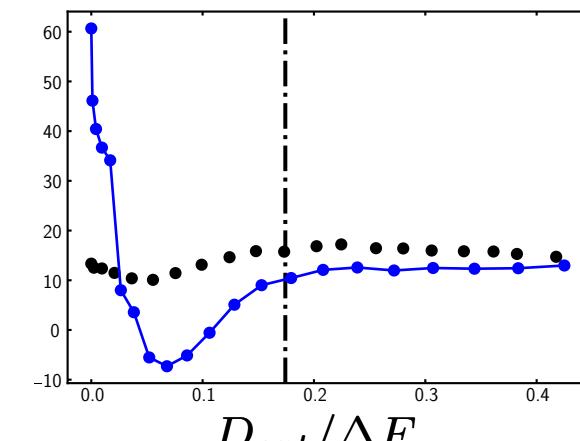
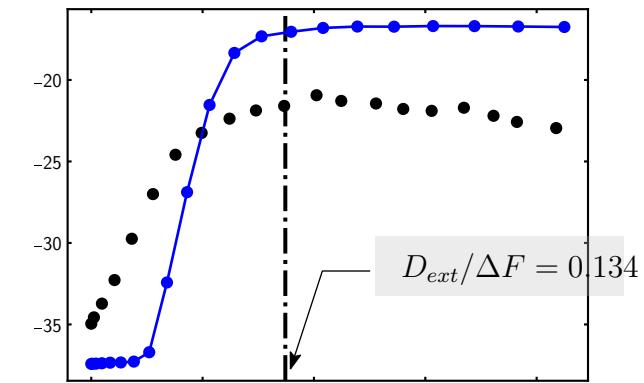
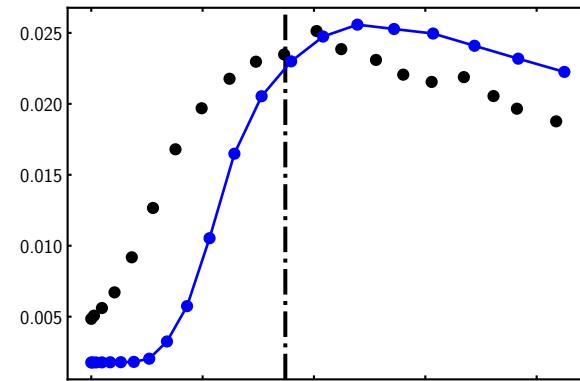
Output Power
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SNR
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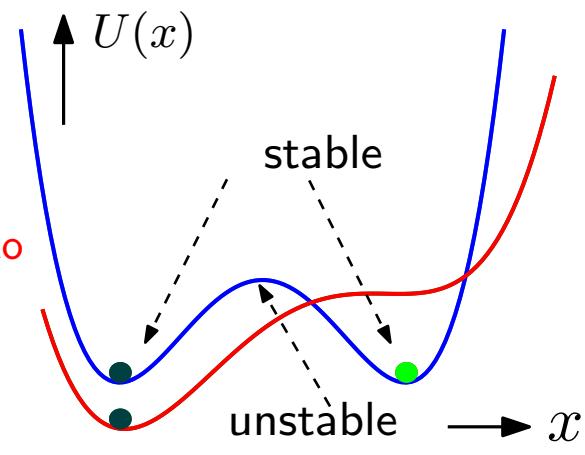
Experiment Overlapped



True Random Number Generator - Overview

Doublewell system

The system is double well. Described by Landau coeff. (a, b). Modulated by bias M. and x is the state of the system



— Without Bias
(symmetric)

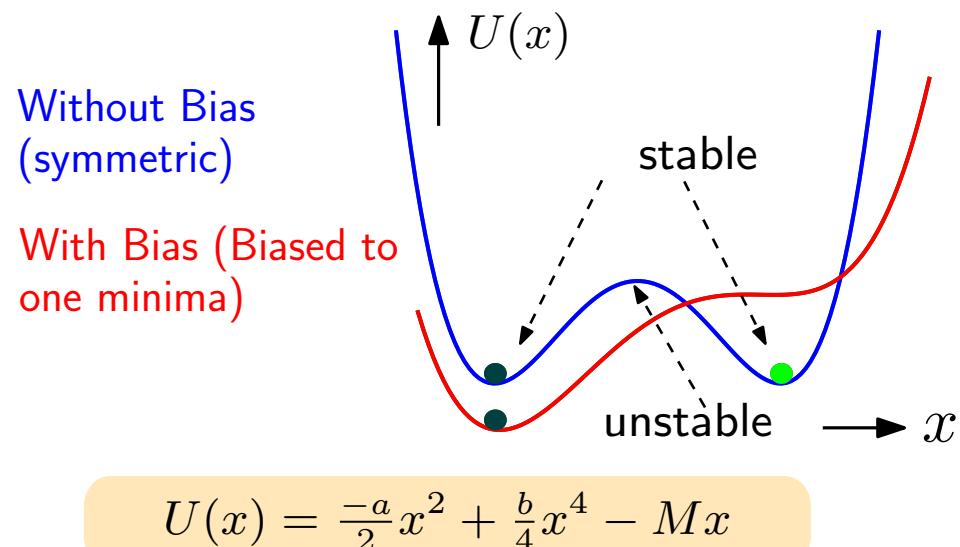
— With Bias (Biased to
one minima)

$$U(x) = \frac{-a}{2}x^2 + \frac{b}{4}x^4 - Mx$$

True Random Number Generator - Overview

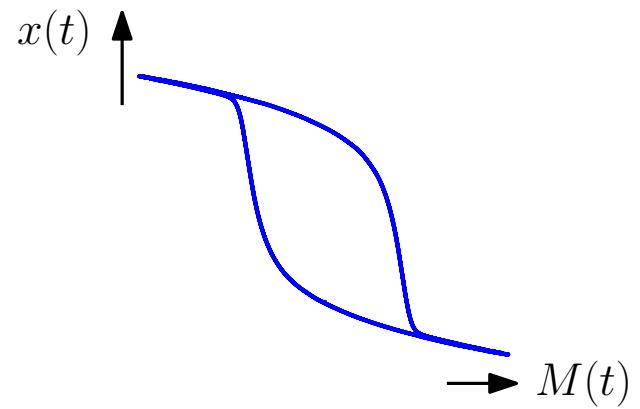
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Dynamics

Dynamics system modeled as one-dimensional overdamped Brownian motion.

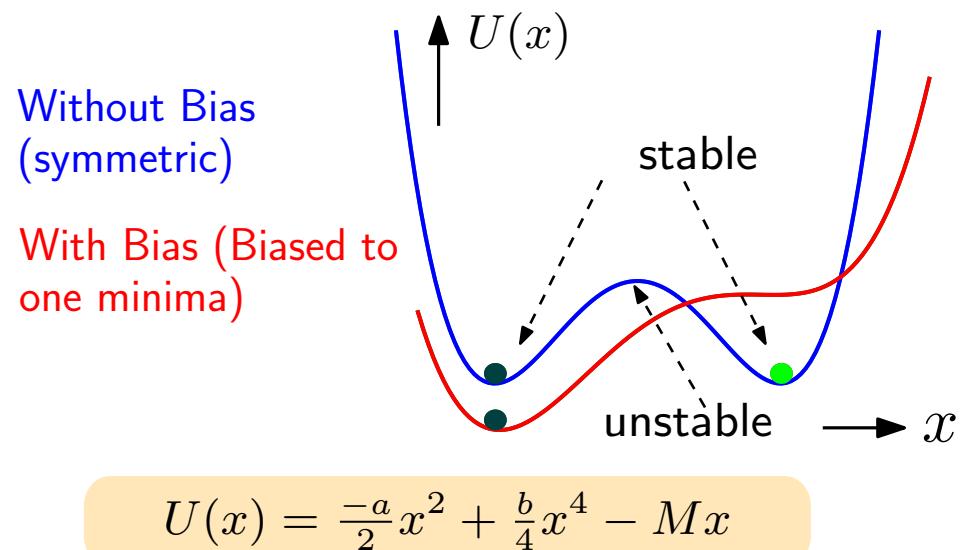


$$\frac{dx}{dt} = -\frac{dU(x)}{dt} + \eta(t)$$

True Random Number Generator - Overview

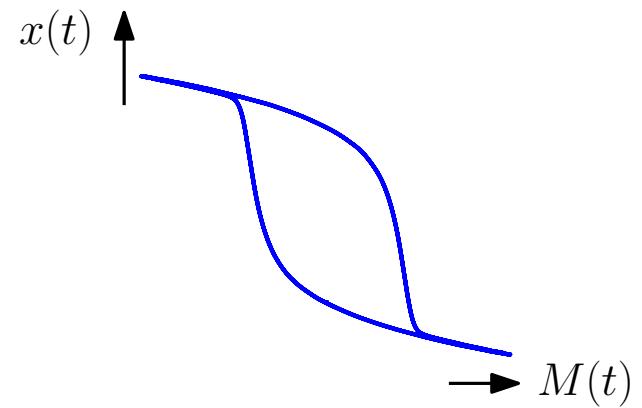
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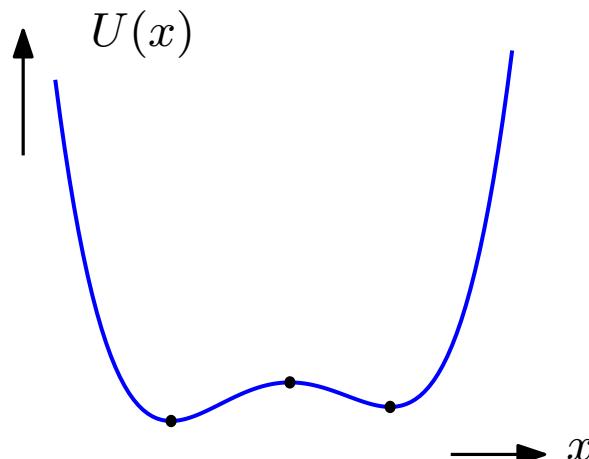


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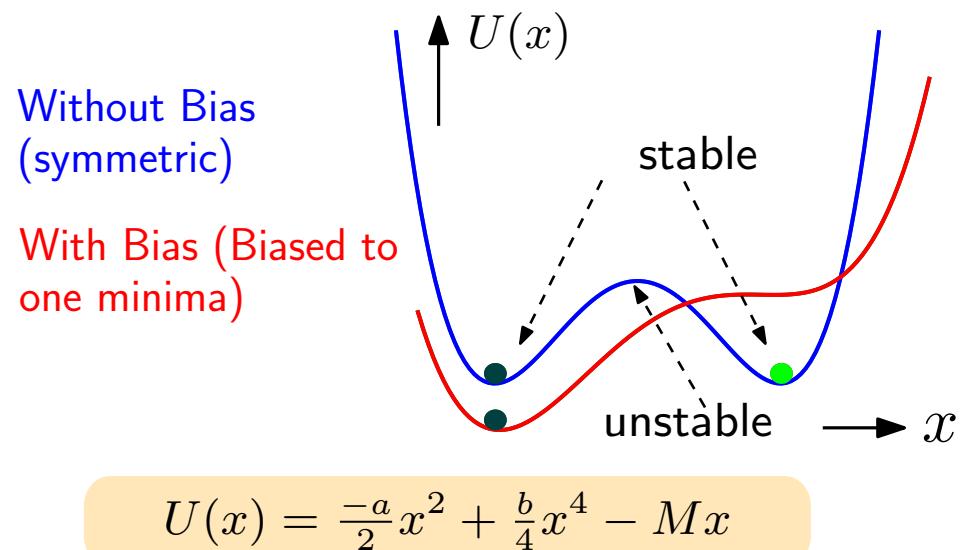
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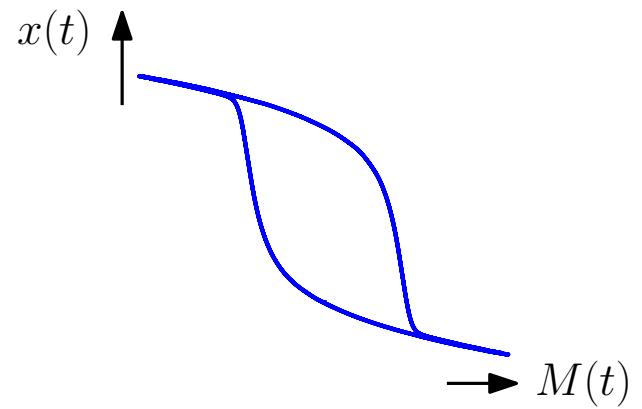
Doublewell system

The system is double well. Described by Landau coeff. (a, b). Modulated by bias M. and x is the state of the system

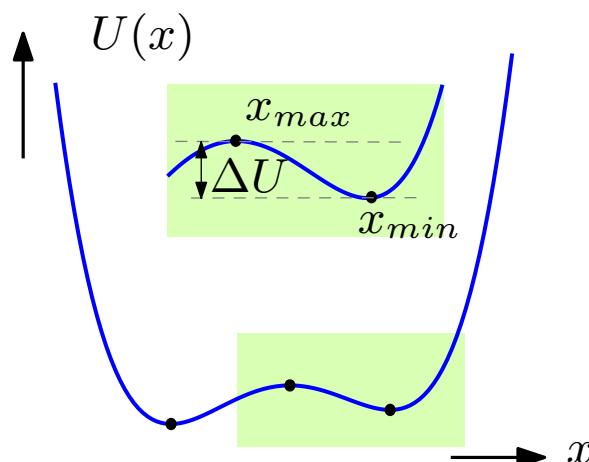


Dynamics

Dynamics system modeled as one-dimensional overdamped Brownian motion.



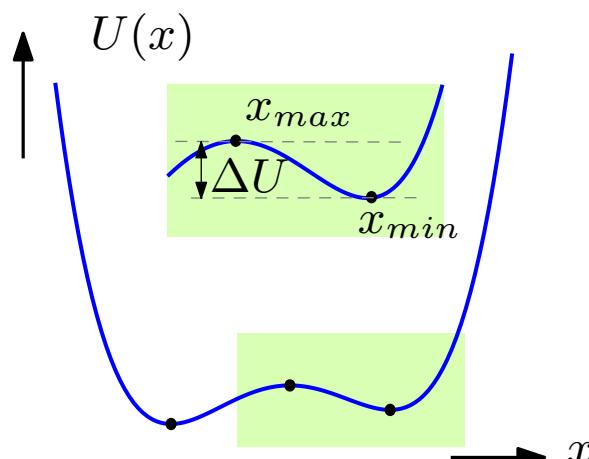
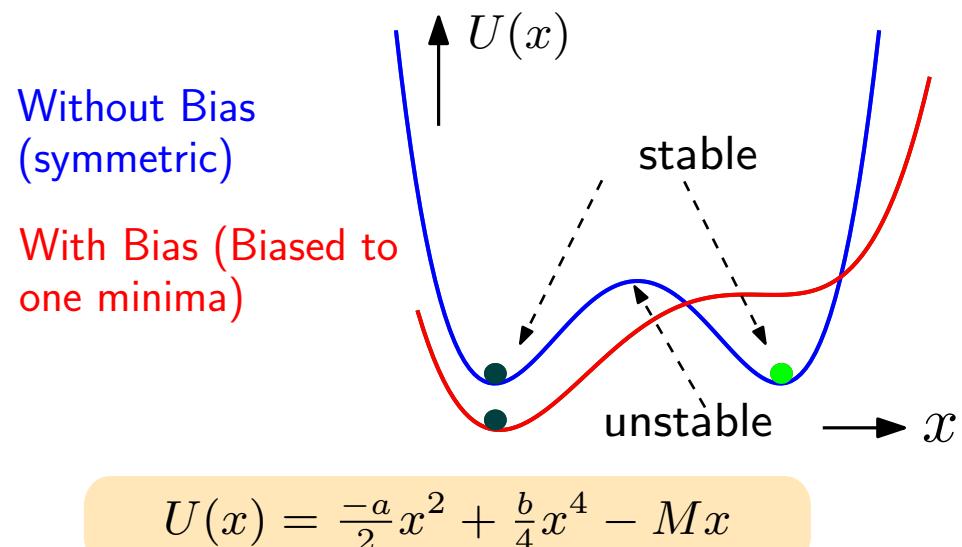
$$\frac{dx}{dt} = -\frac{dU(x)}{dt} + \eta(t)$$



True Random Number Generator - Overview

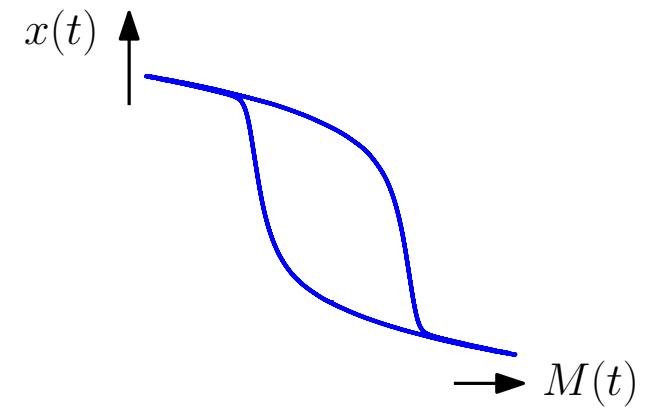
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$$\frac{dx}{dt} = -\frac{dU(x)}{dt} + \eta(t)$$

Kramers' time is the mean first passage time

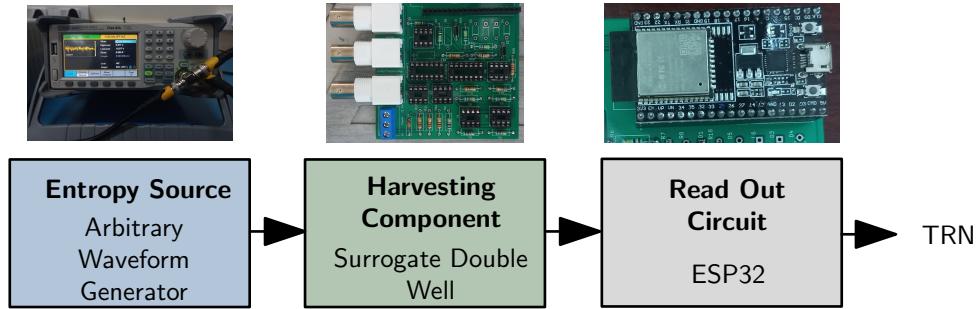
$$\tau_k = \frac{2\pi e^{\Delta U/D}}{\ddot{U}(x_{\min})\ddot{U}(x_{\max})}$$

switching probability $S(t)$ for a given time duration

$$S(t) = 1 - e^{-r_K t}$$

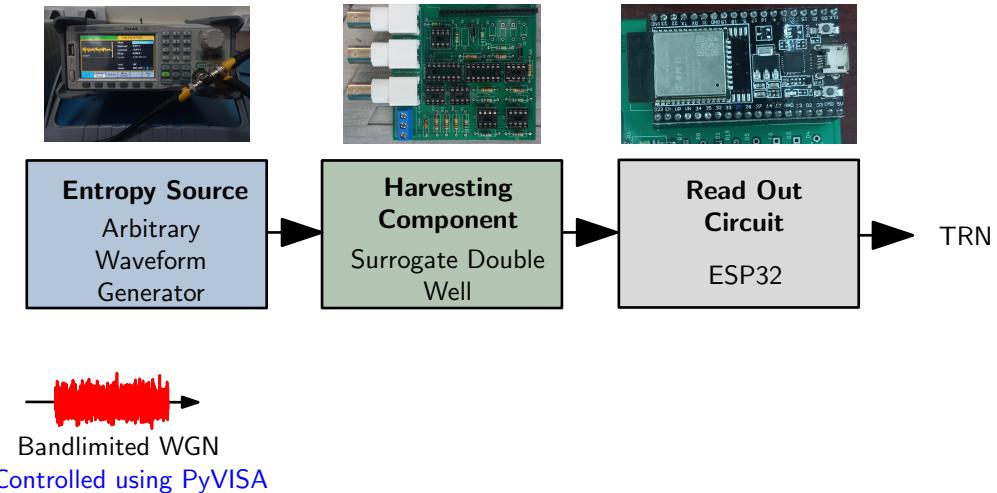
TRNG - Architecture

Architecture



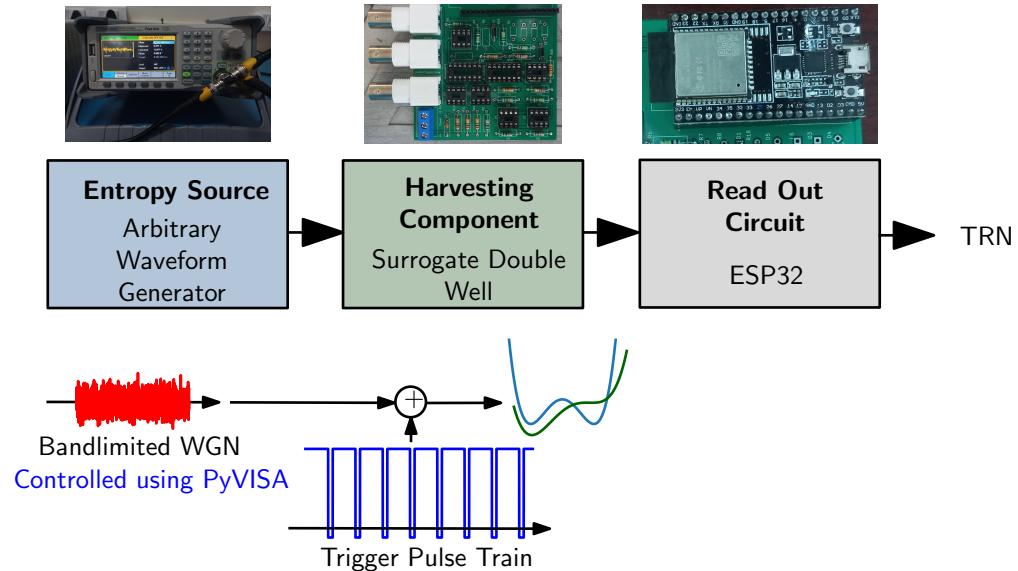
TRNG - Architecture

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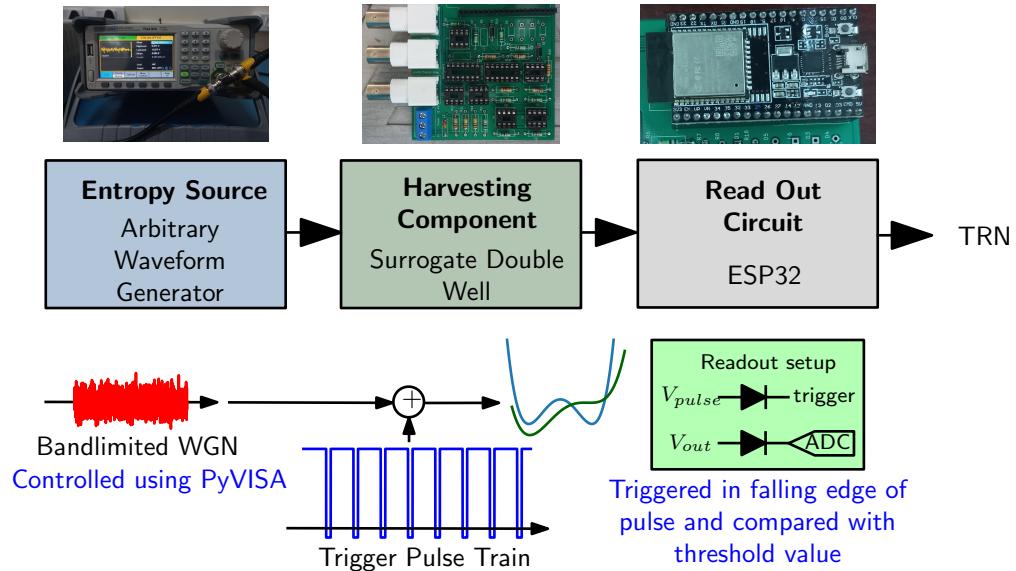
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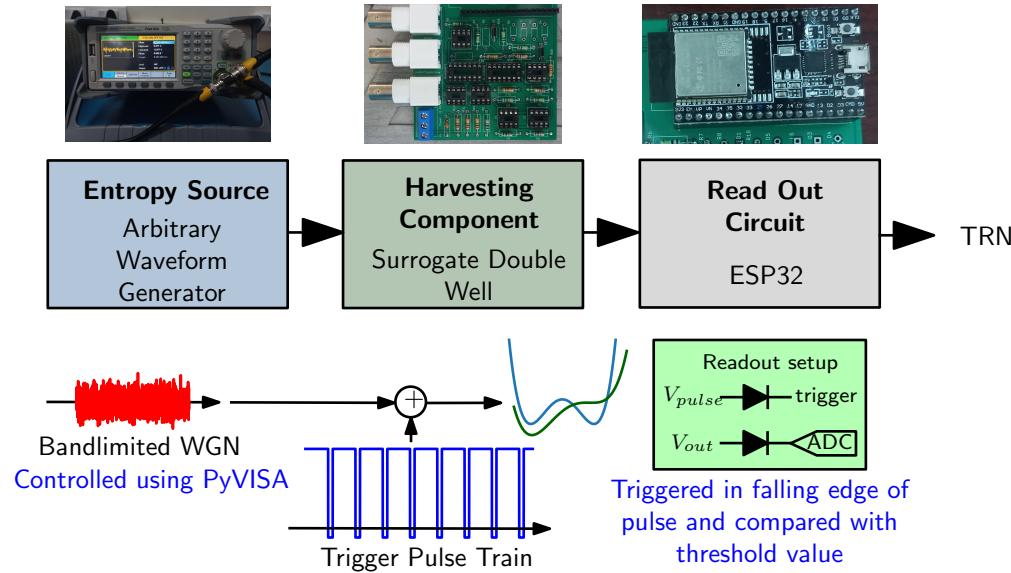
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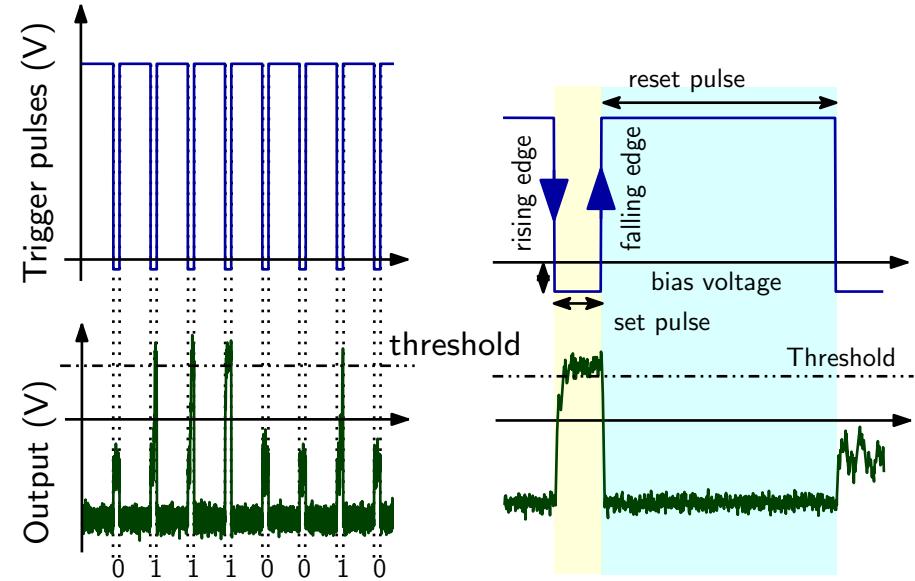


TRNG - Architecture

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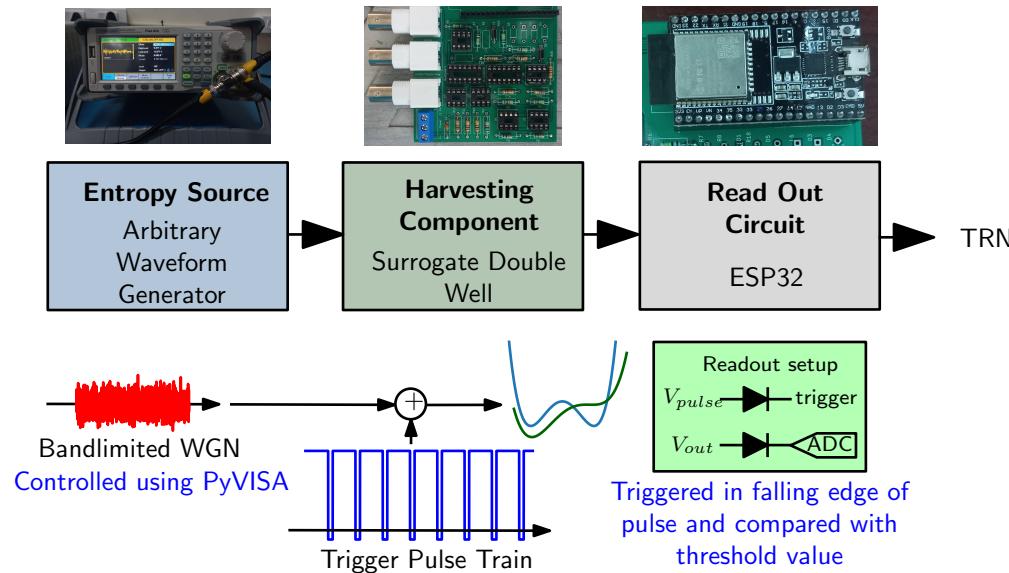


Readout Functionality

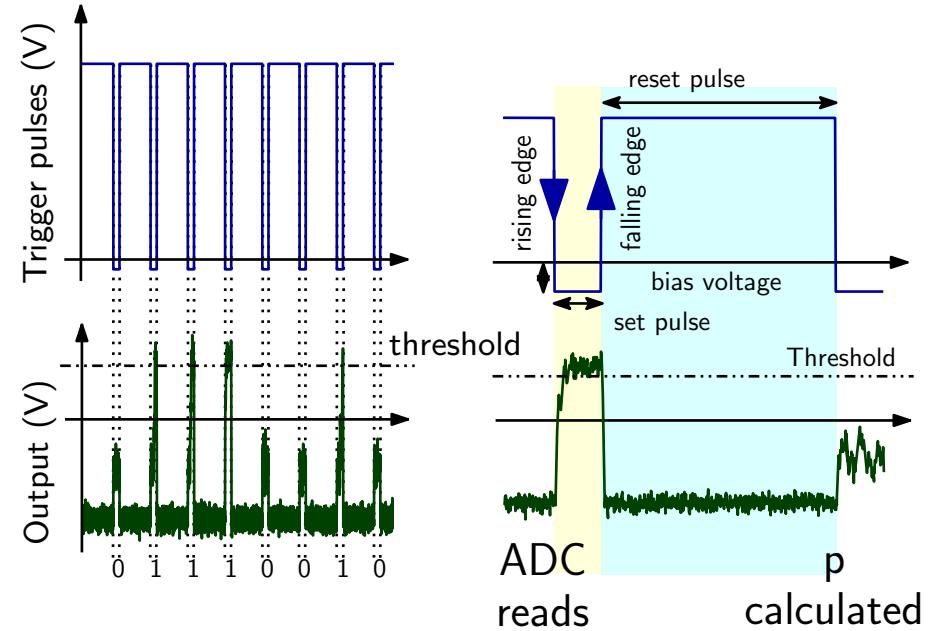


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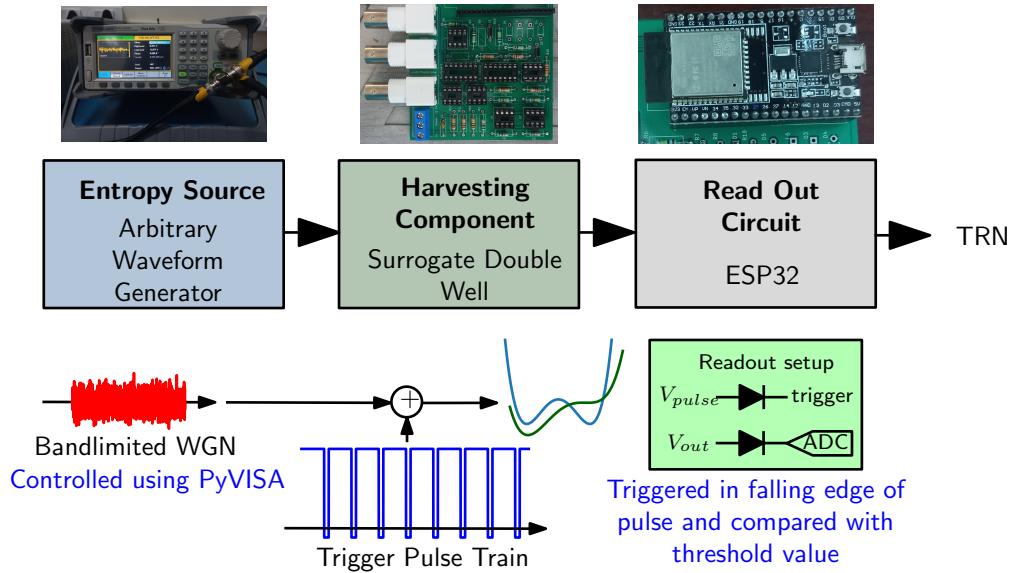


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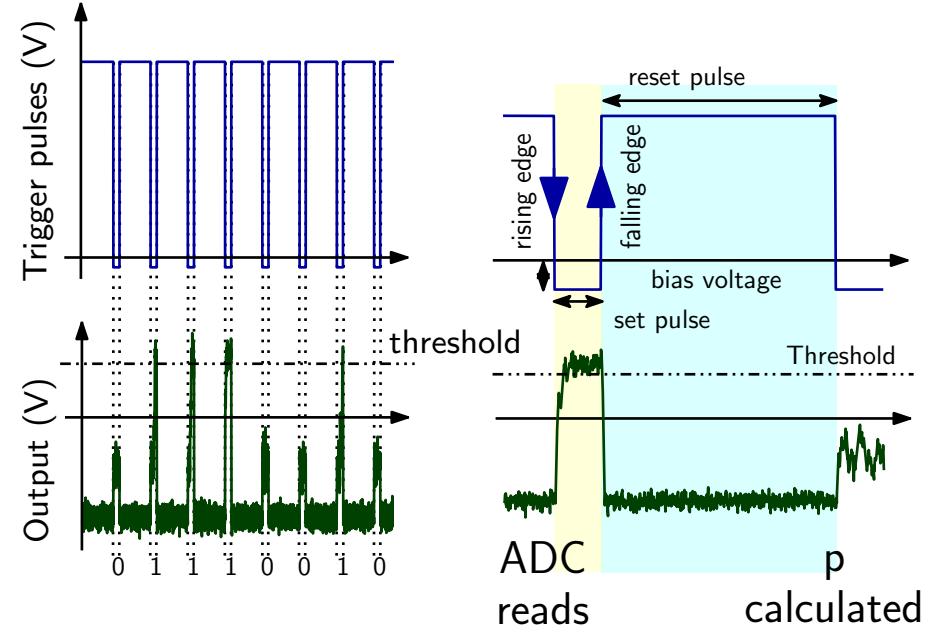


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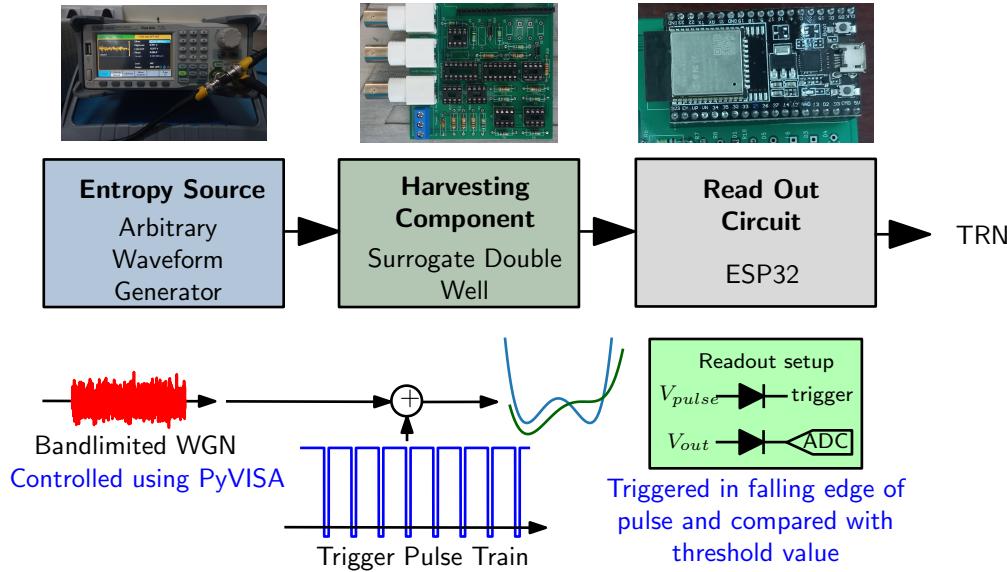


TRNG PCB

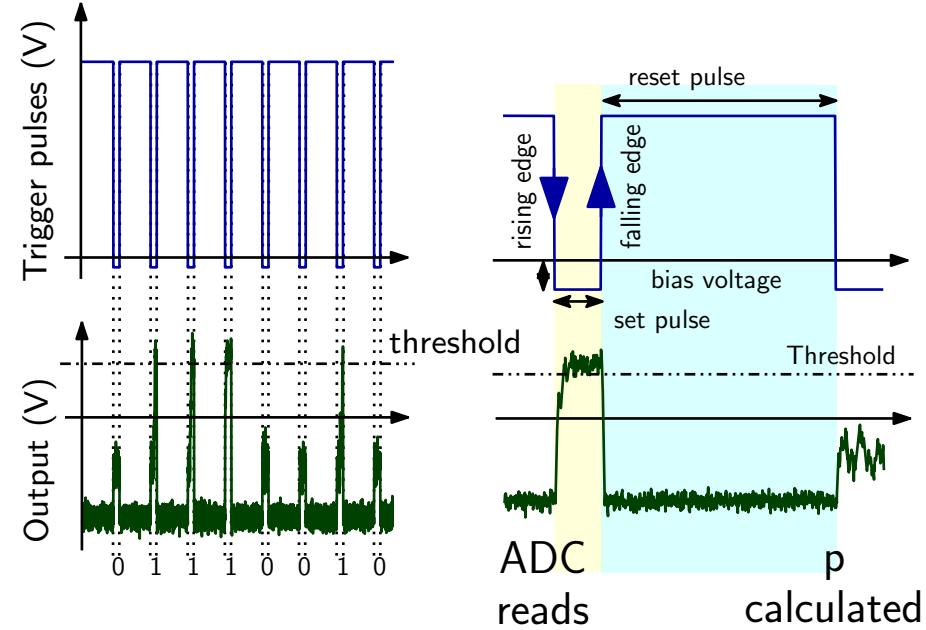


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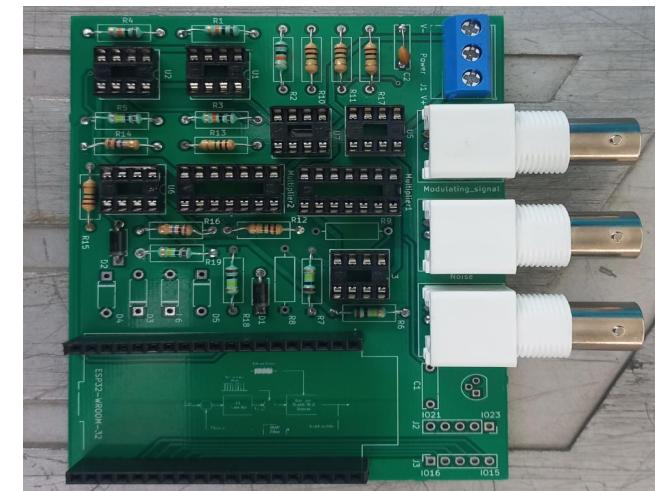
Parameter extraction

$$\text{derived formula } r = \left. \frac{M(t)}{\frac{dV_2}{dt}} \right|_{V_2=0}$$

a,b from S-curve fitting

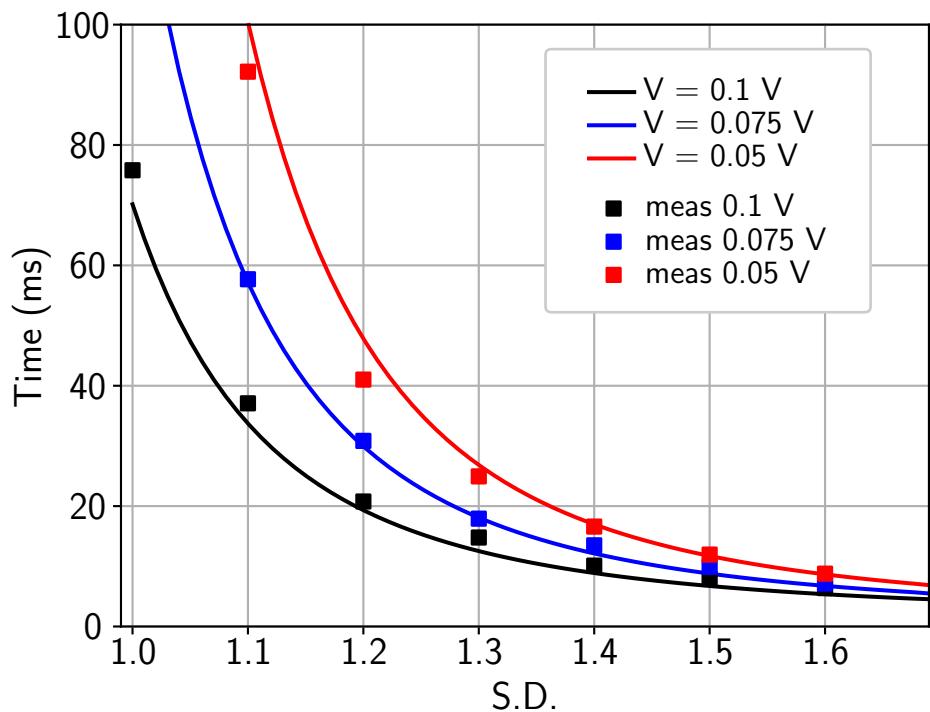
Parameter	Expected	Extracted
r	0.0002	0.0002
a	-1	-0.97
b	1	1.05

TRNG PCB



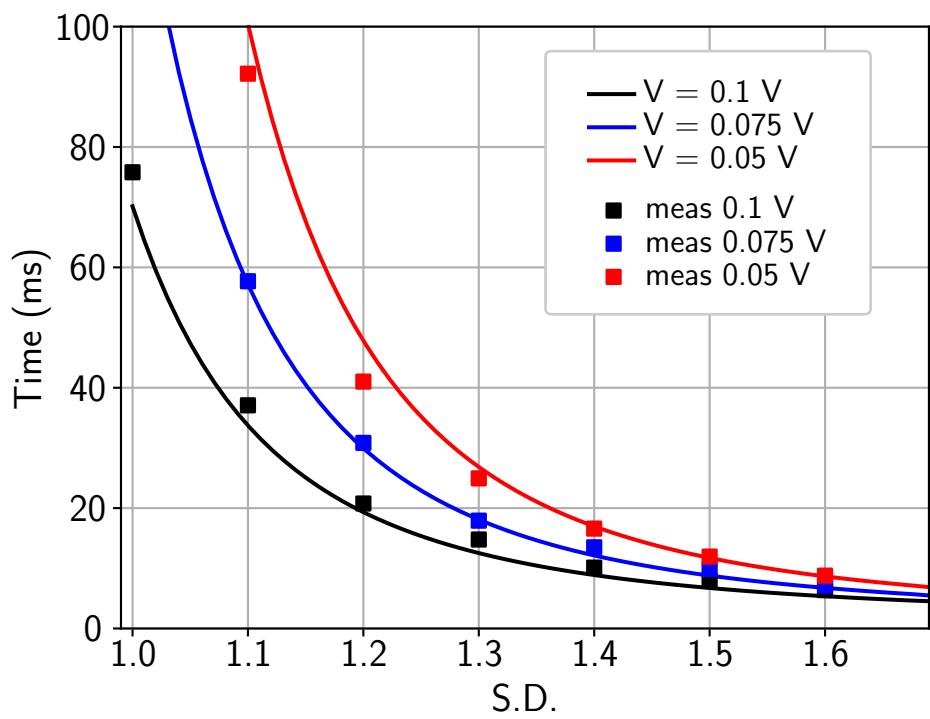
TRNG - Results

Kramers' Time

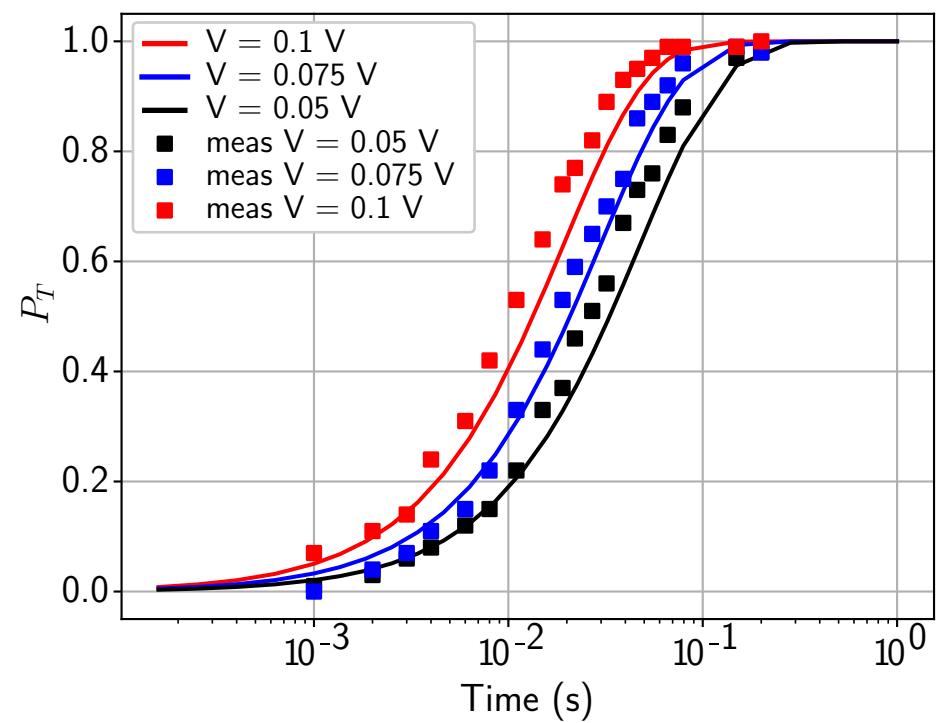


TRNG - Results

Kramers' Time



Switching Probability



TRNG - Controller Design

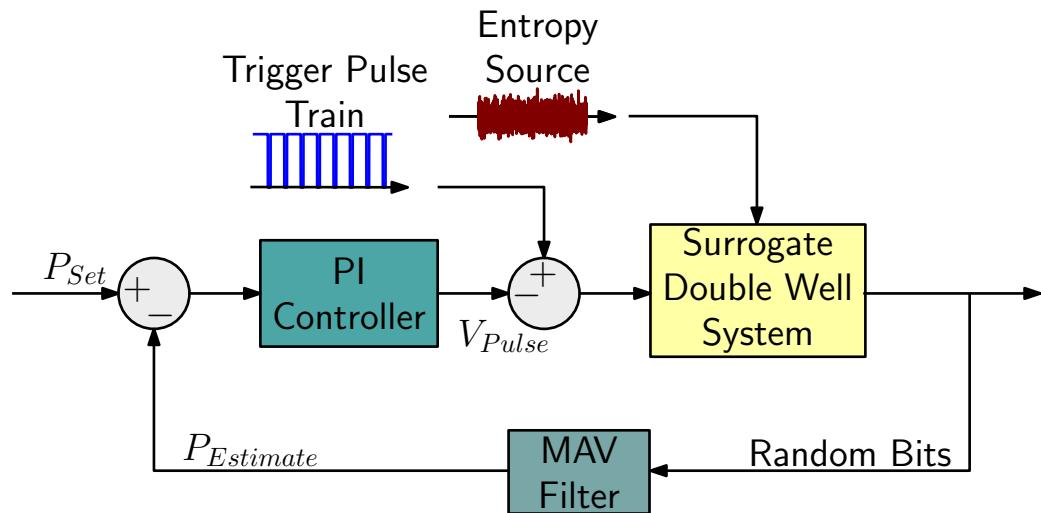
Why need a controller?

- Thermal noise (entropy source) can fluctuate.
- Control to set a switching probability

TRNG - Controller Design

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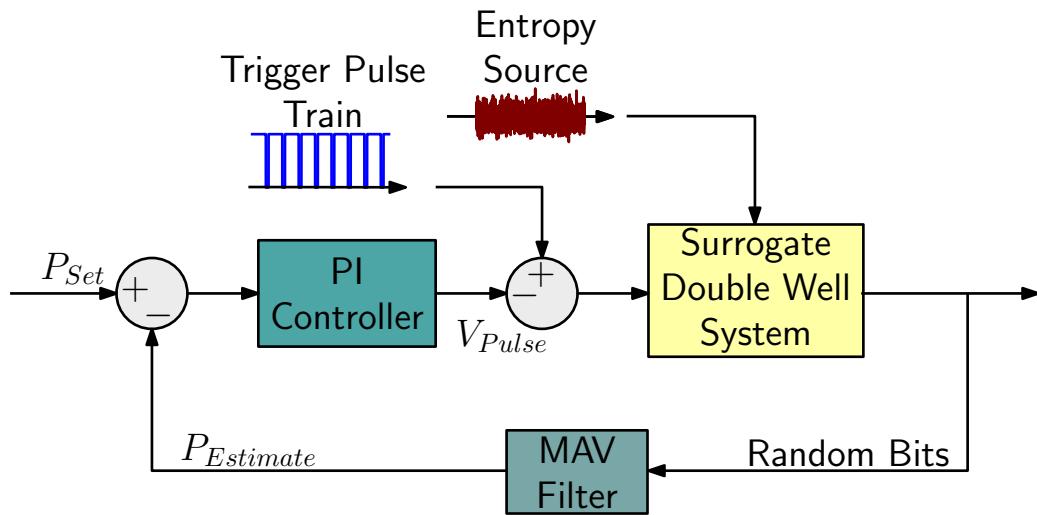
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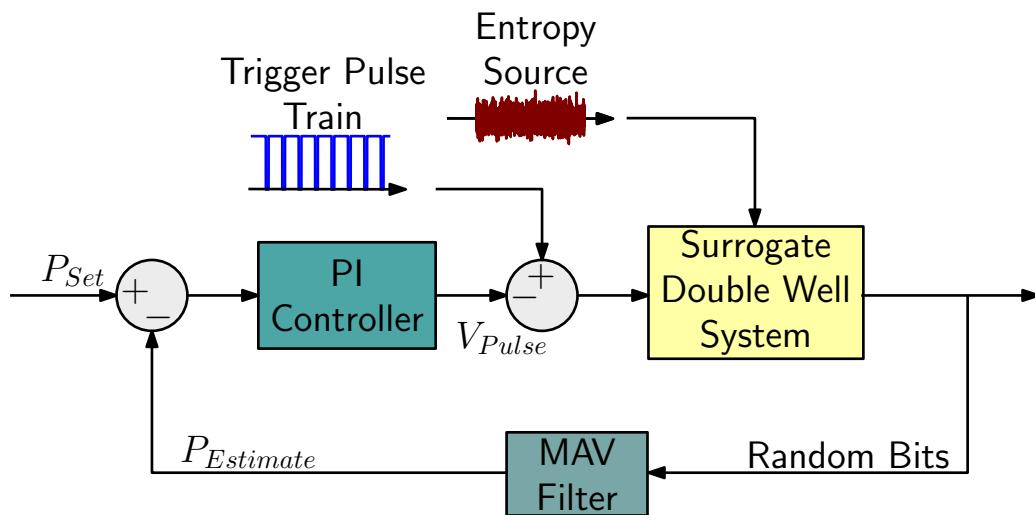


- Moving average (MAV) filter estimates the probability of the bits.
- PI controller to adjust V_{pulse} , while keeping t_{pulse} constant for consistent bit throughput.

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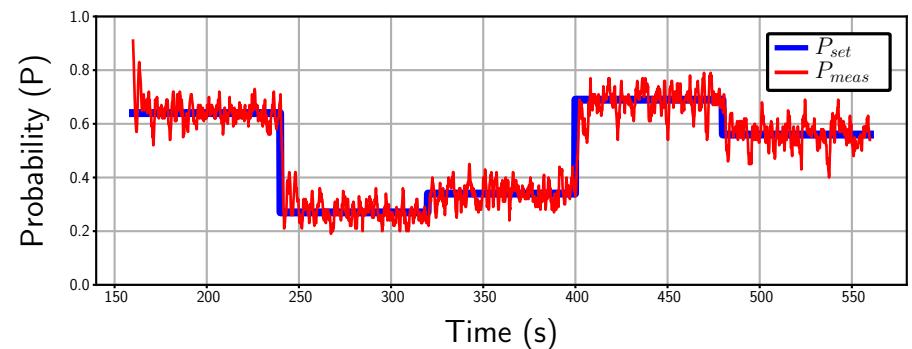
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Results

Fixed D_{ext}, P_{set} Tracking

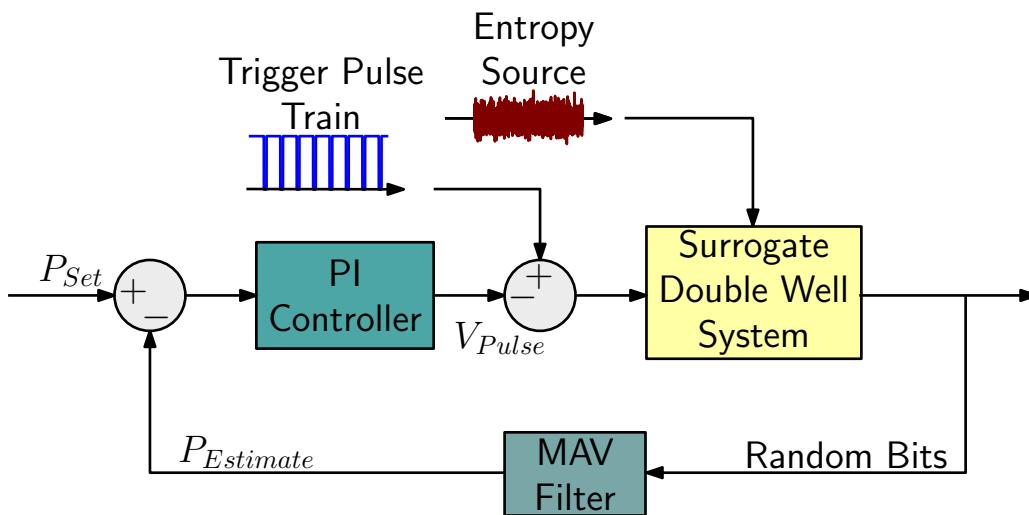


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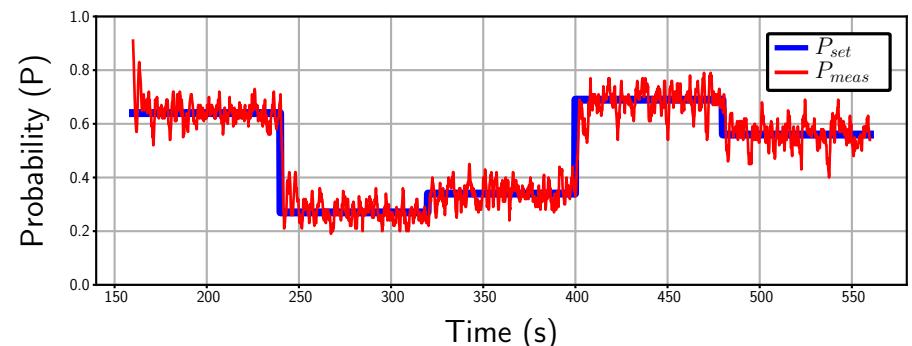
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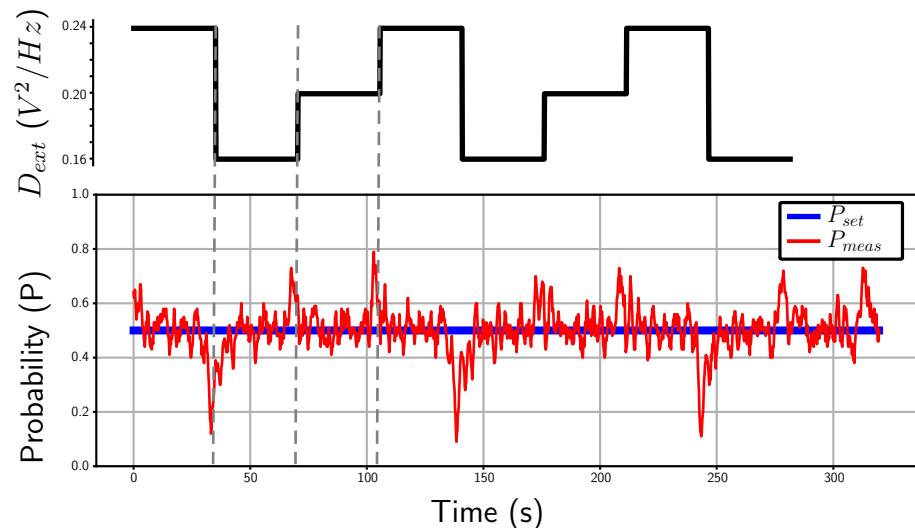
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Outcomes

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Acknowledgement

Dr. Arvind Ajoy - BTP guide

- Abhinav Rajeev, Navaneeth M – Mentorship in Electroluminescence project
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Thank You :)