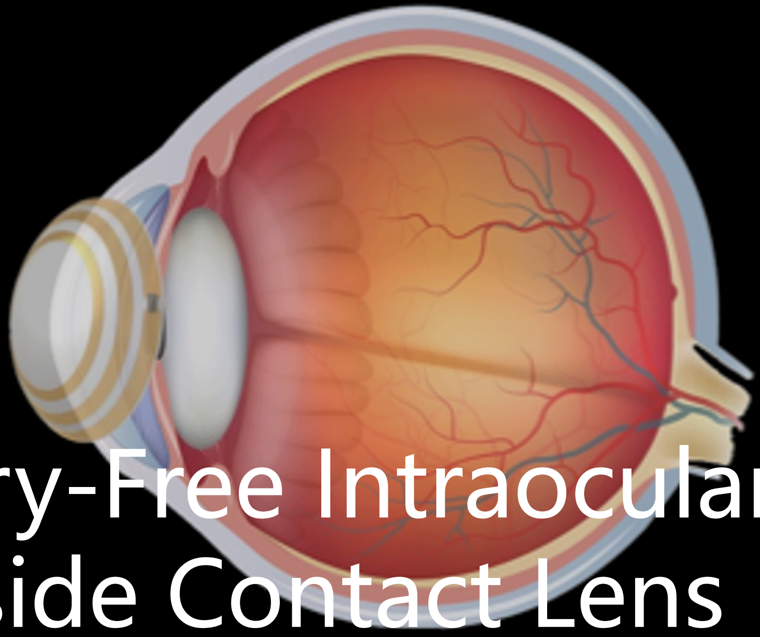

Cyclops: A Nanomaterial-based, Battery-Free Intraocular Pressure (IOP) Monitoring System inside Contact Lens

Liyao Li[1,2], Bozhao Shang[2], Yun Wu[2], Jie Xiong[3], Xiaojiang Chen[2], Yaxiong Xie[1]

[1]University at Buffalo The State University of New York
[2]Northwest University
[3]University of Massachusetts Amherst and Microsoft Research Asia

Glaucoma: Silent Thief of Sight

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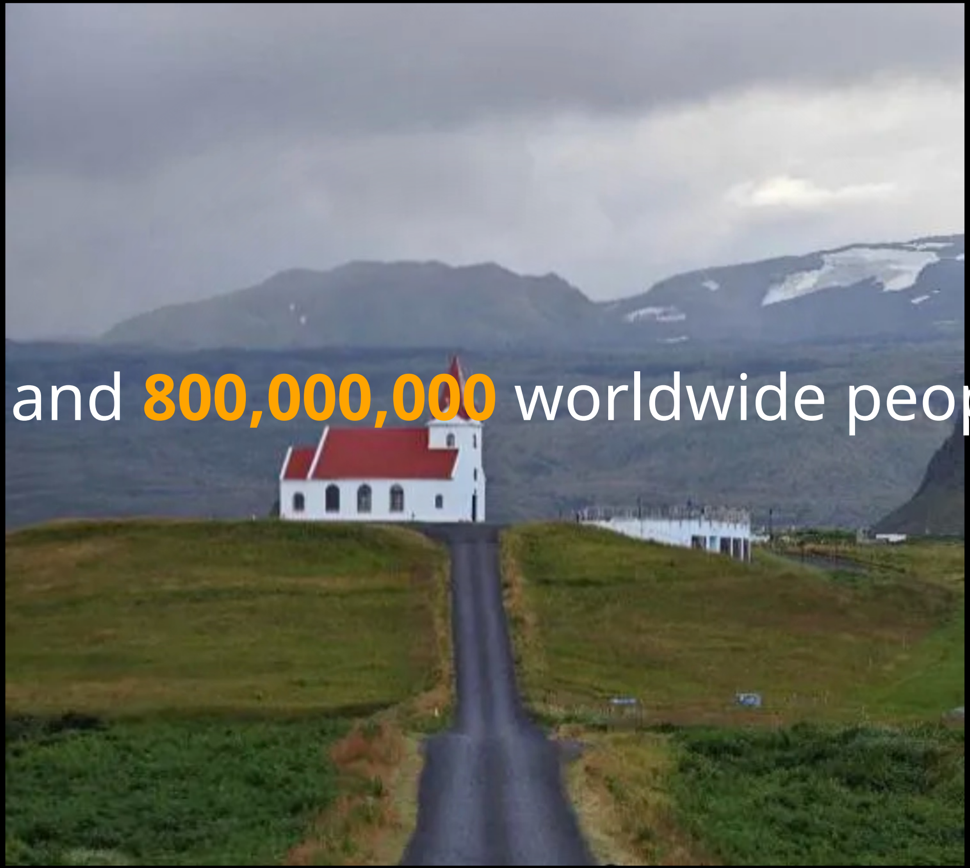
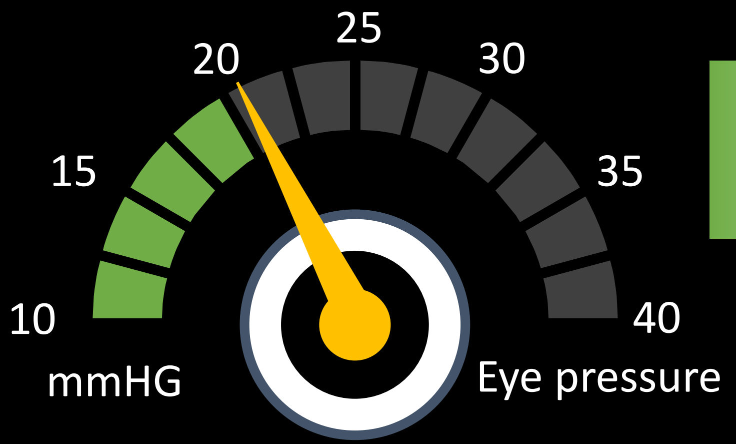


3,000,000 in USA and **800,000,000** worldwide people have glaucoma

Detecting Glaucoma by Measuring Eye Pressure

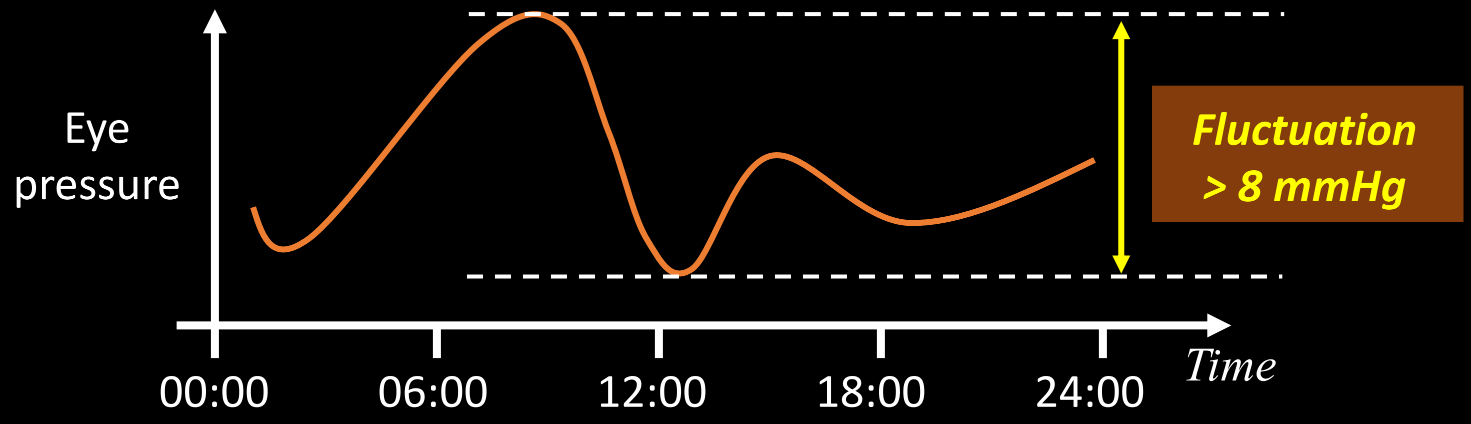
Safe Zone

10-21 mmHg

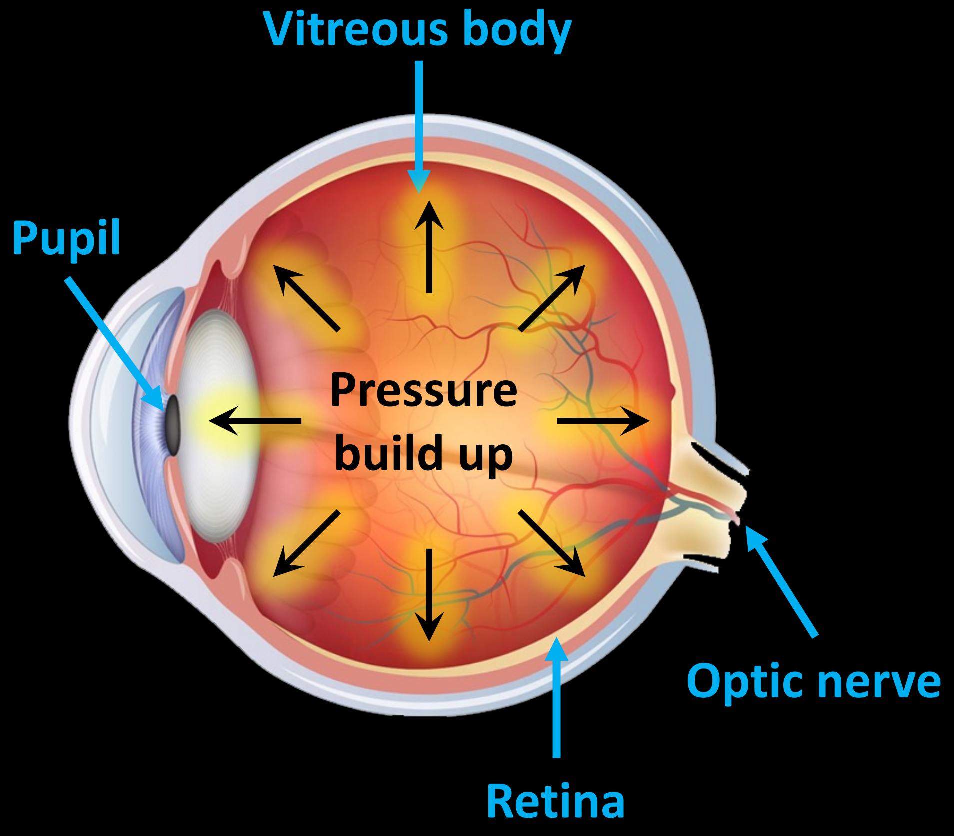


Danger Zone

> 21 mmHg



Circadian fluctuation of eye pressure



Detecting Glaucoma by Measuring Eye Pressure

Safe Zone
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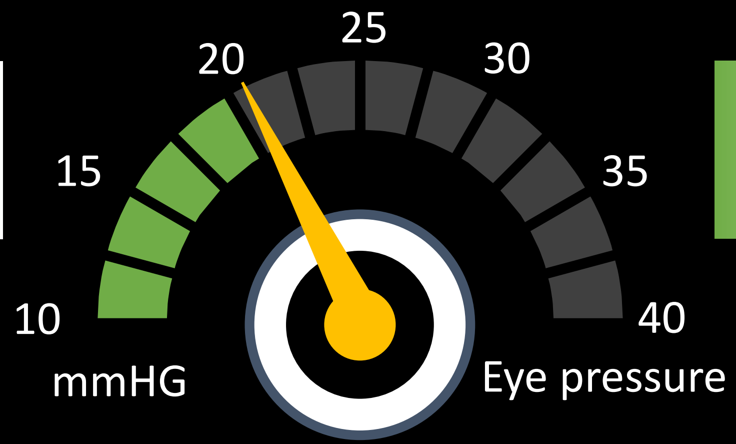
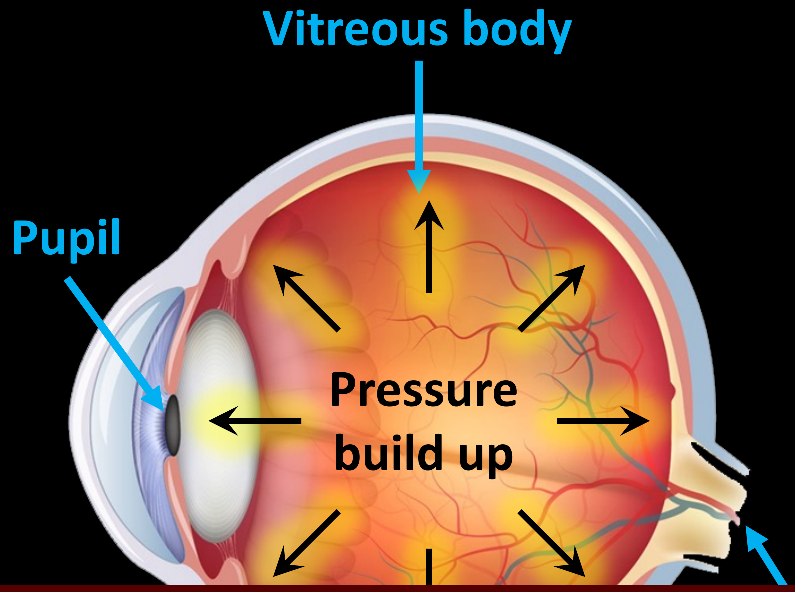


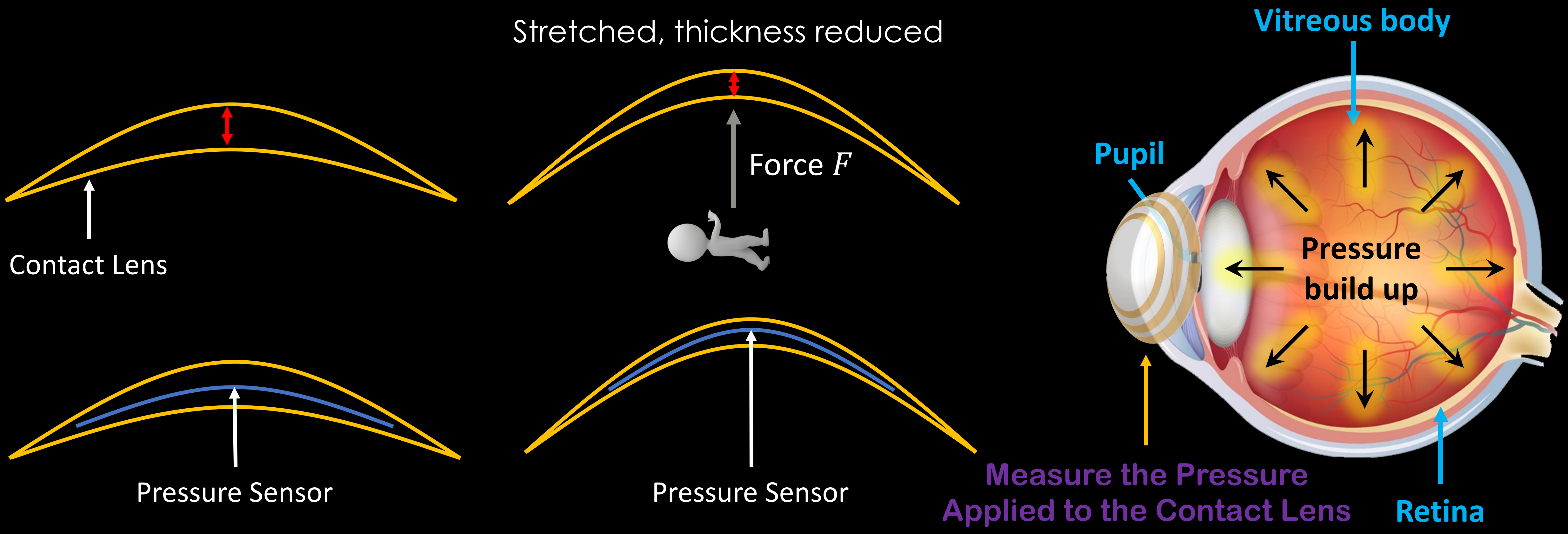
Danger Zone
> 21 mmHg



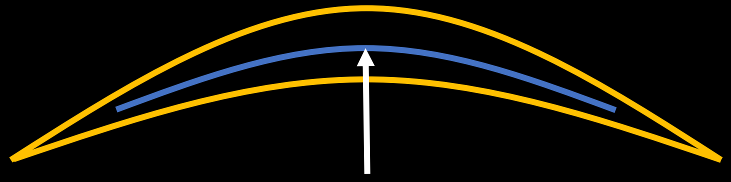
Continuous eye pressure tracking is necessary for detecting early-stage Glaucoma

Circadian fluctuation of eye pressure

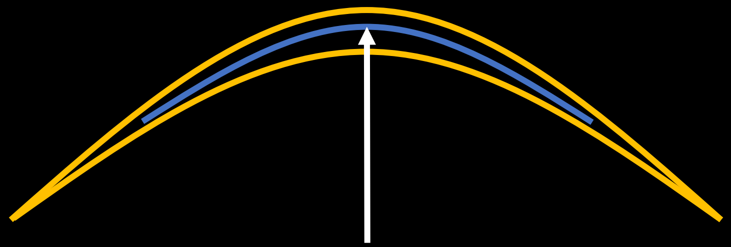
Contact-Lens Based Eye Pressure Sensing



Contact-Lens Based Eye Pressure Sensing: Impedance based Sensors



Metallic Structure



Metallic Structure

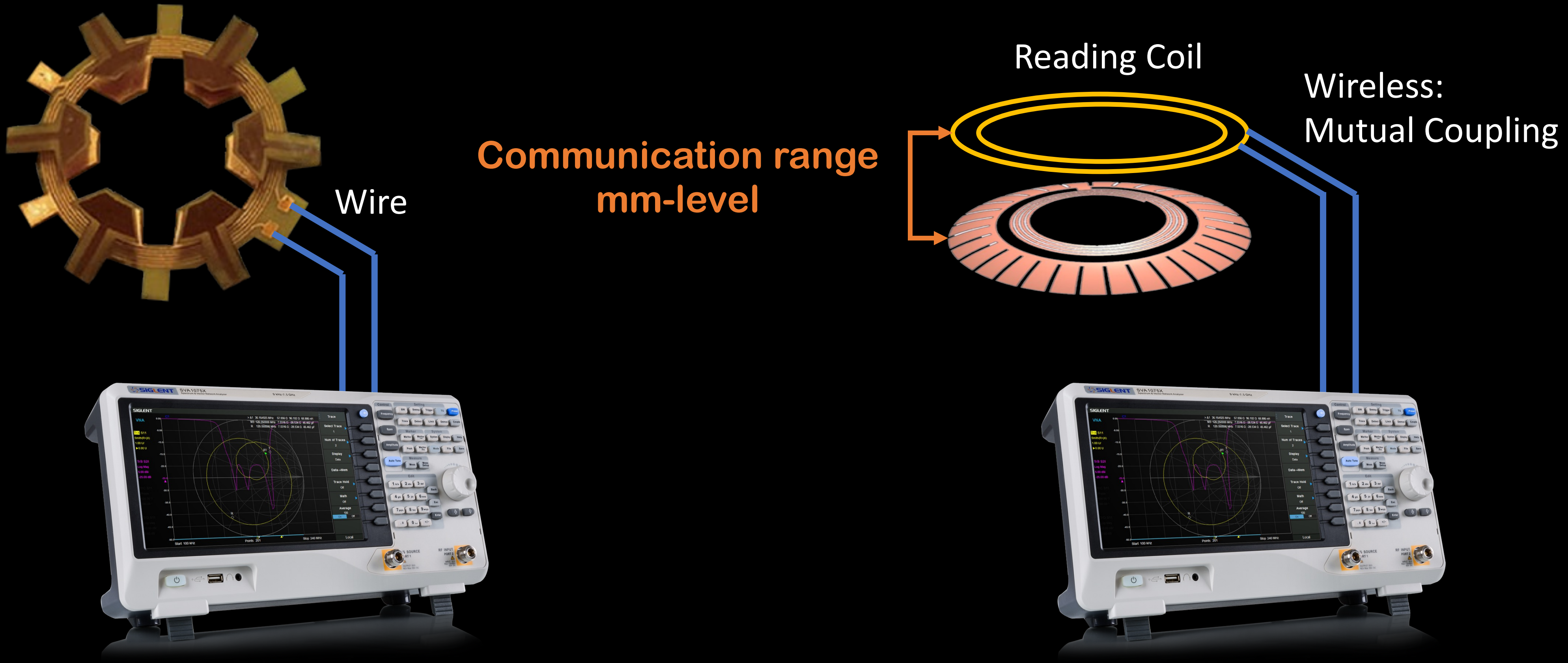
Example
Metallic Structure

Impedance of the metallic structure varies with the applied pressure

⇓

Measure the impedance variations to infer the eye pressure

Contact-Lens Based Eye Pressure Sensing: Measuring the Impedance

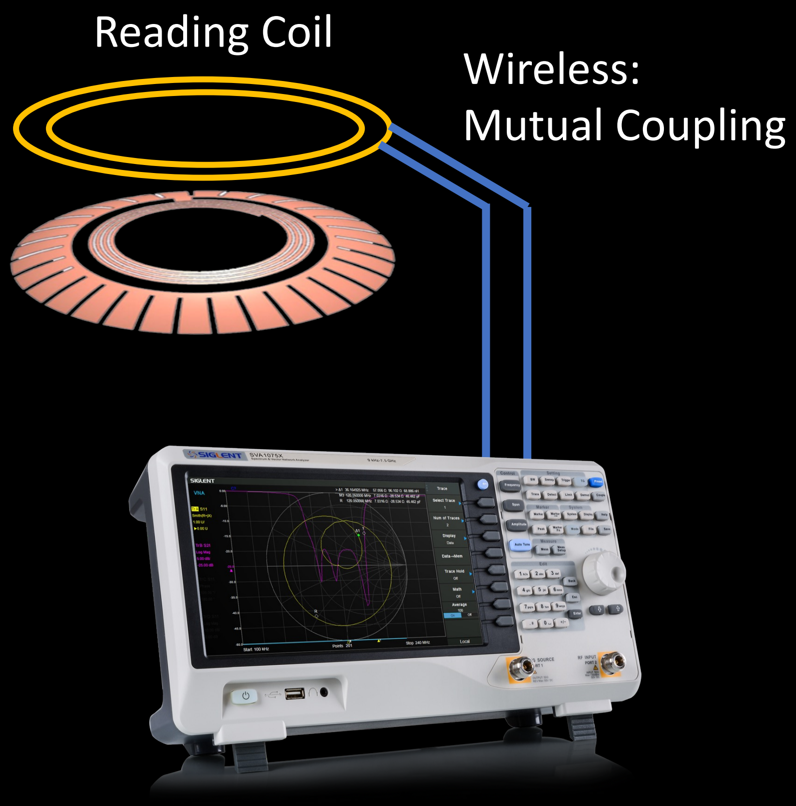


Vector Network Analyzer (VNA)

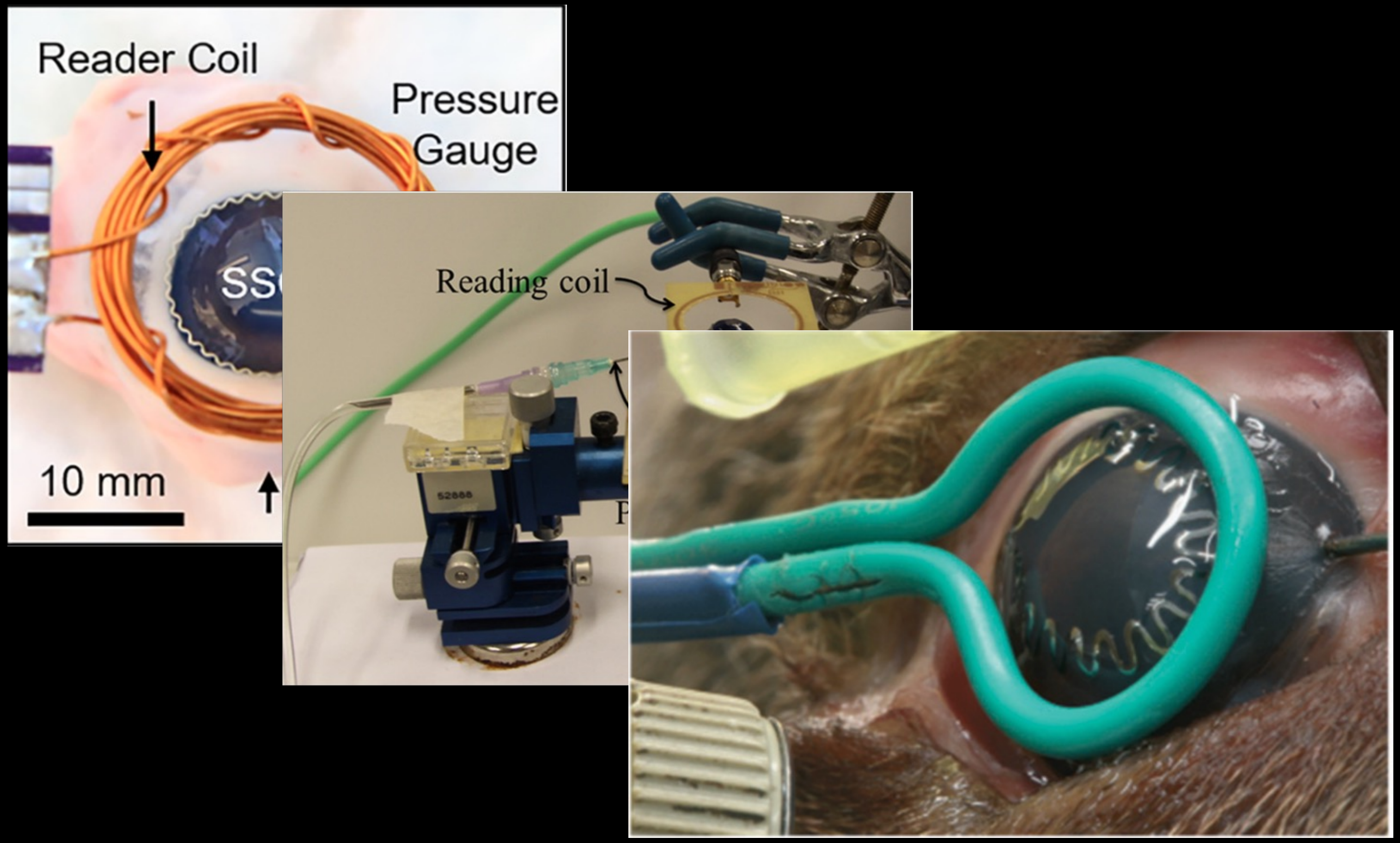
COST: Thousands of dollar

Vector Network Analyzer (VNA)

Contact-Lens Based Eye Pressure Sensing: Measuring the Impedance

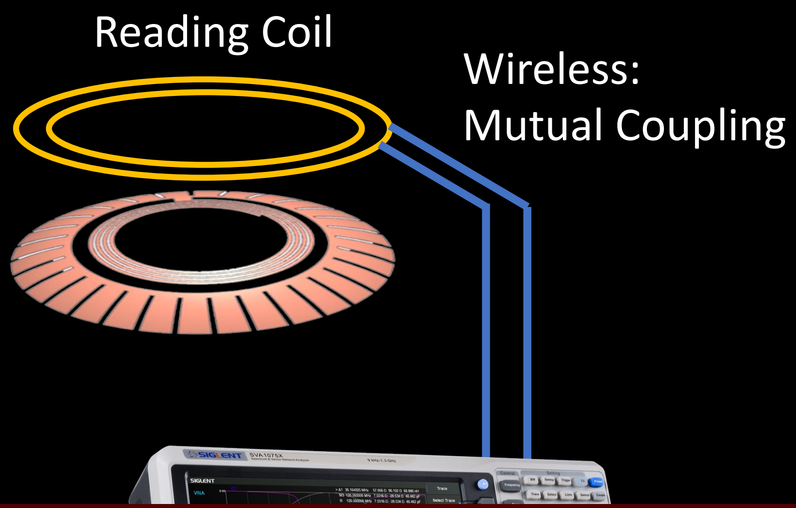


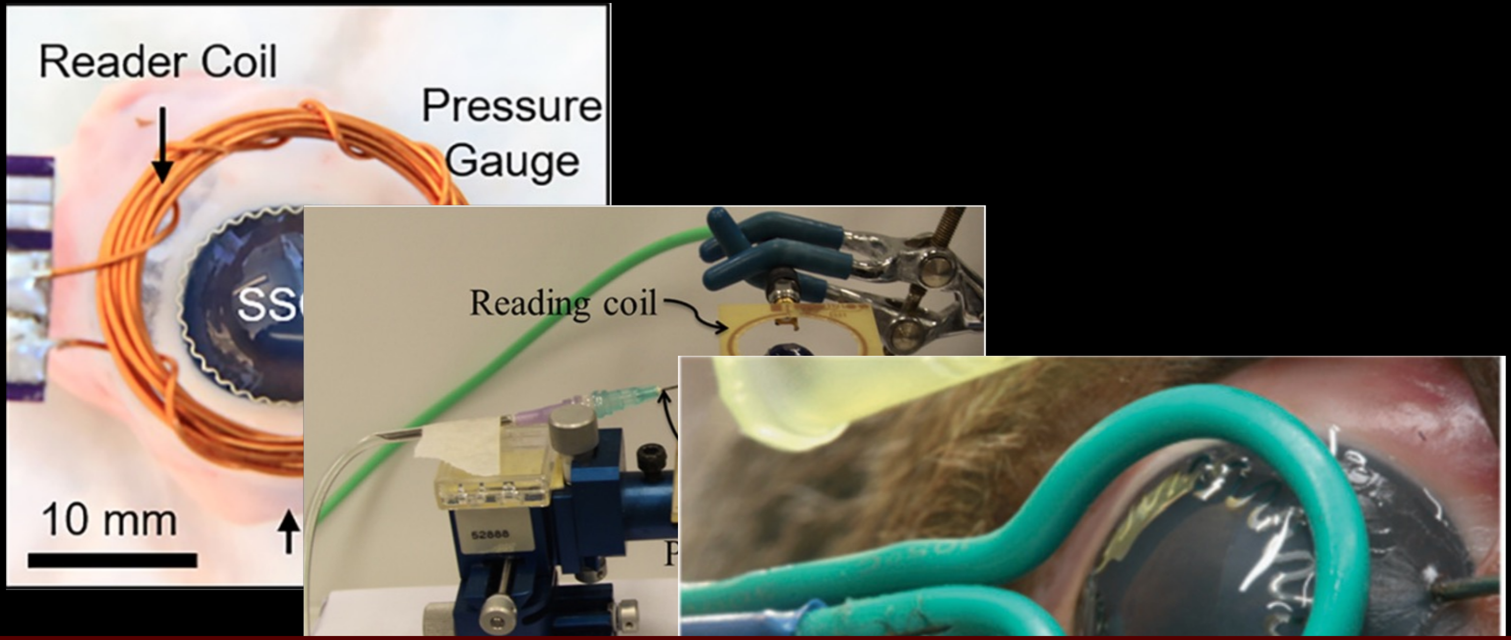
Vector Network Analyzer (VNA)



Kouhani, M. Hossein M., et al. "Wireless, passive strain sensor in a doughnut-shaped contact lens for continuous non-invasive self-monitoring of intraocular pressure." Lab on a Chip 20.2 (2020): 332-342.
Yang, Cheng, et al. "Intelligent wireless theranostic contact lens for electrical sensing and regulation of intraocular pressure." Nature Communications 13.1 (2022): 2556.
Zhang, Jinyuan, et al. "Smart soft contact lenses for continuous 24-hour monitoring of intraocular pressure in glaucoma care." Nature Communications 13.1 (2022): 5518.

Contact-Lens Based Eye Pressure Sensing: Measuring the Impedance





Can we design a low-cost and battery-free contact lens based eye pressure sensing system that supports long-range communication?

Kouhani, M. Hossein M., et al. "Wireless, passive strain sensor in a doughnut-shaped contact lens for continuous non-invasive self-monitoring of intraocular pressure." Lab on a Chip 20.2 (2020): 332-342.
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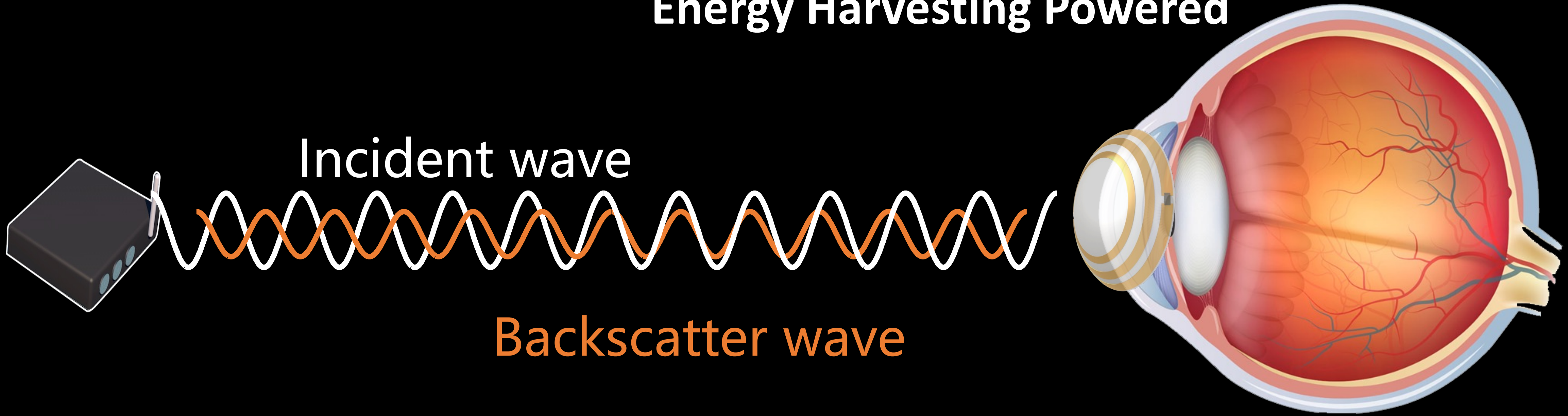
Cyclops: A **Low-cost, Battery-free** and **Long-range** (meter level) Eye Pressure Sensing System

Energy Harvesting Powered



Backscatter Communication

A Low-cost, Battery-free and Long-range Eye Pressure Sensing System: Goals

Goals:

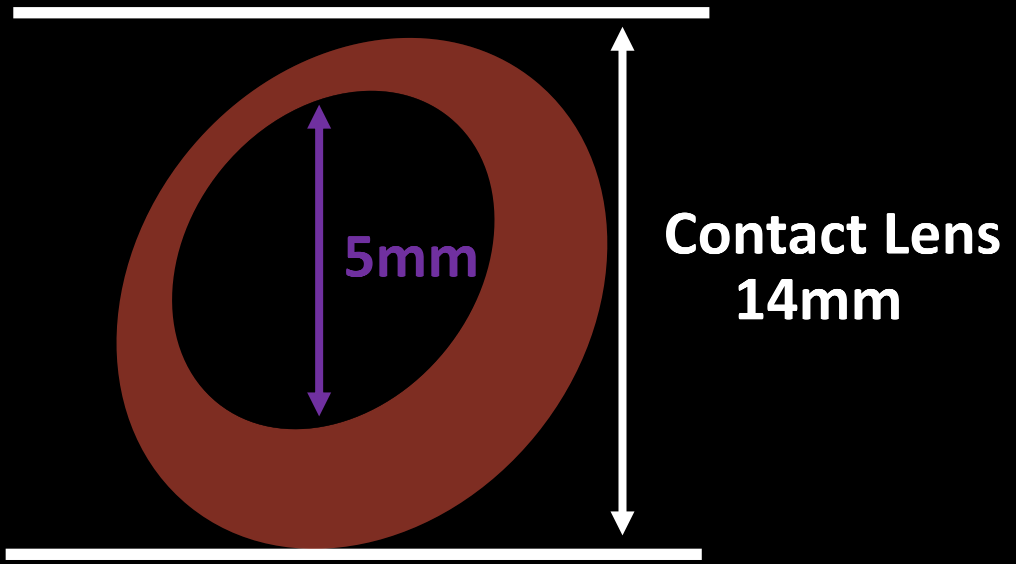
1) Low-power but sensitive pressure sensor with thickness at μm level that works on energy-harvesting powered devices

A Low-cost, Battery-free and Long-range Eye Pressure Sensing System: Goals

Goals:

1) Low-power but sensitive pressure sensor with thickness at μm level that works on energy-harvesting powered devices

2) Supporting long-range communication with contact-lens size antenna



A **Low-cost, Battery-free** and **Long-range** Eye Pressure Sensing System: **Challenge**

Goals:

1) Low-power but sensitive pressure sensor with thickness at μm level that works on energy-harvesting powered devices

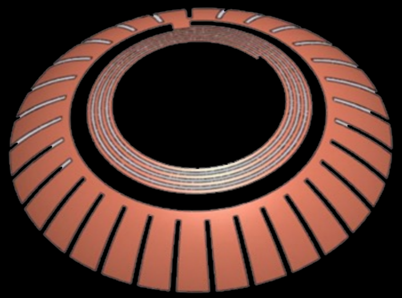
2) Supporting long-range communication with contact-lens size antenna

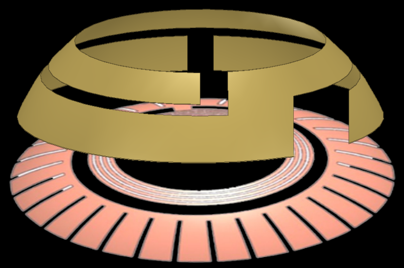
Challenge:

Interference between the communication antenna and the pressure sensors

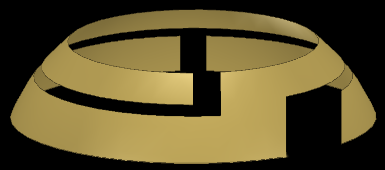
Interference between Communication Antenna and Pressure Sensors

Metallic Pressure Sensor





Metallic Communication Antenna



Designed to maximize the sensitivity to pressure changes

Mutual coupling:

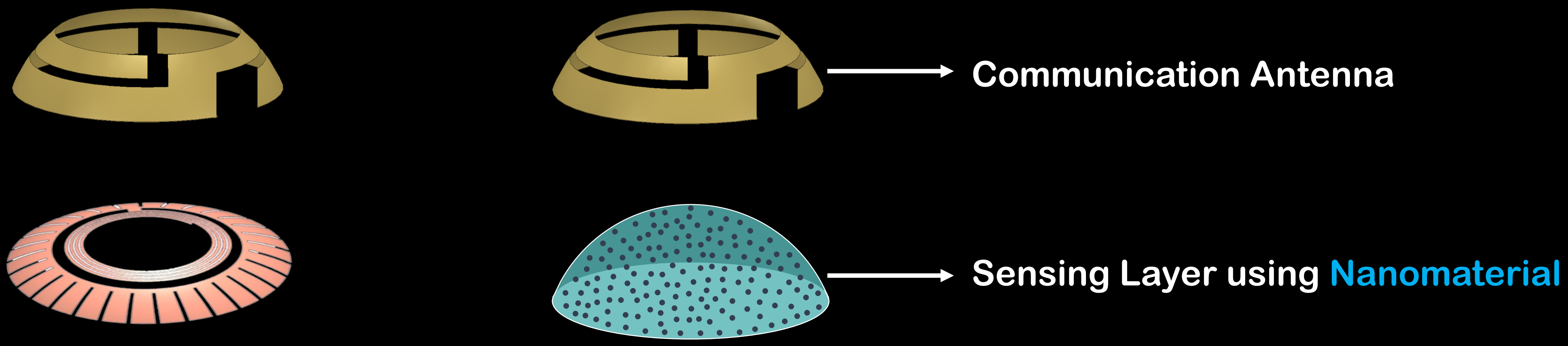
Sensitive to pressure ✗

Long-range communication ✗

Designed to maximize the communication efficiency and range

The communication antenna and the pressure sensor are closely placed to each other due to the limited thickness of the contact lens (generally $60\mu m$ to $100\mu m$)

Design the Sensing Layer using Nanomaterial



Two separate layers work together without causing mutual coupling

↓

Decouple the design of the communication antenna and the sensing layer

A **Low-cost, Battery-free** and **Long-range** Eye Pressure Sensing System: **Goals**

Goals:

1) Low-power but sensitive pressure sensor with thickness at μm level that works on energy-harvesting powered devices

2) Supporting long-range communication with contact-lens size antenna

Challenge:

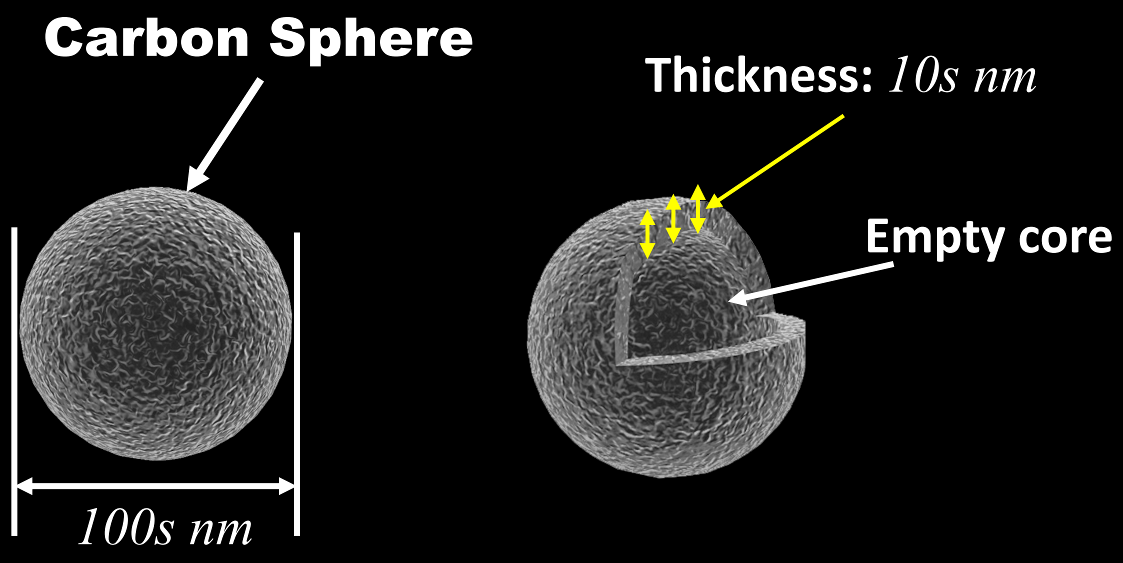
Interference between the communication antenna and the pressure sensors

Low-power and sensitive pressure sensor with thickness at μm level that works on energy harvesting powered devices

Our solution:

Quantum Tunnelling Effect of the **Nanomaterial (Hallow Carbon Sphere)**

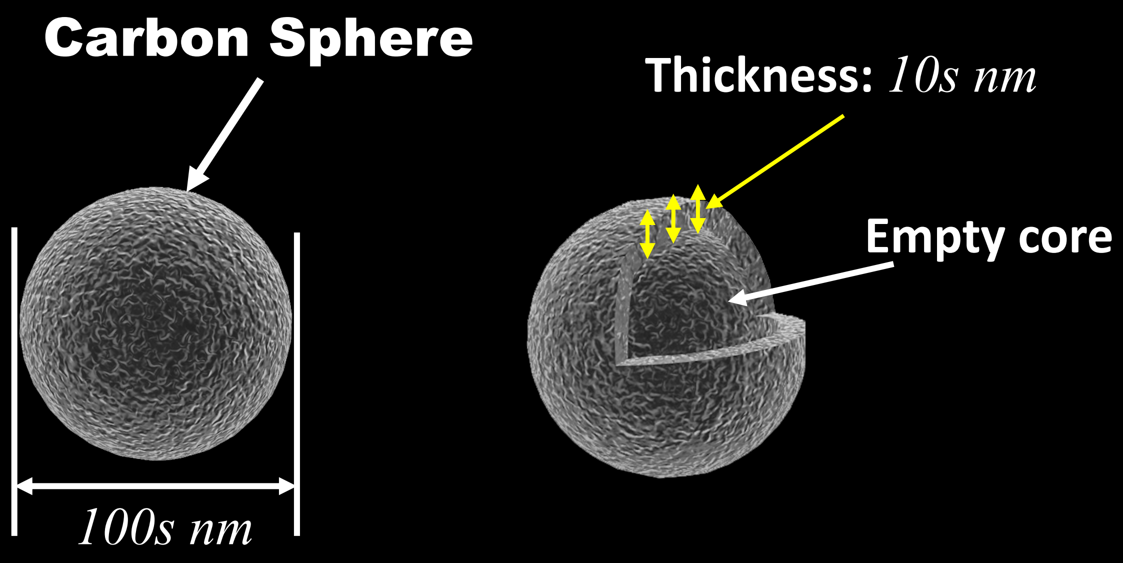
Nanomaterial:
Hollow Carbon Sphere (HCS)



Hollow Carbon Sphere

- Conductor
- Stability
- Bio Safety

Nanomaterial:
Hollow Carbon Sphere (HCS)



Hollow Carbon Sphere

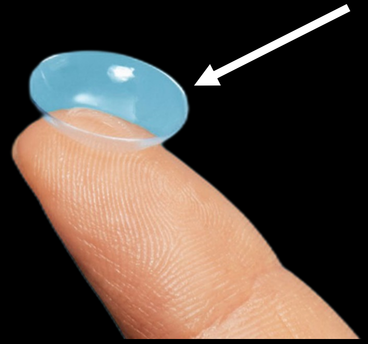
Conductor — Good conductor with high electrical conductivity

Stability — High chemical, thermal and mechanical

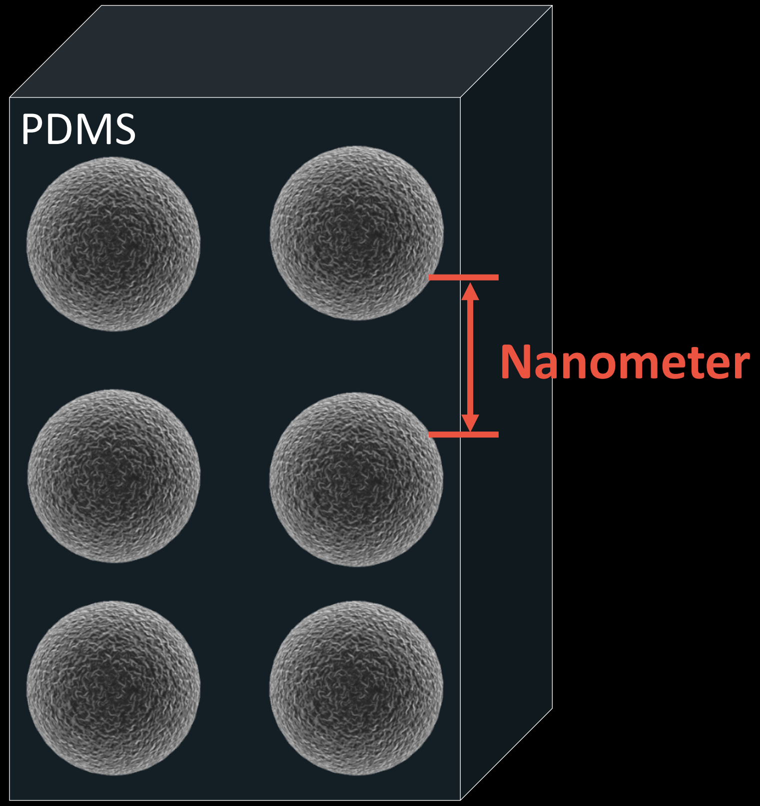
Bio Safety — Good bio compatibility and bio safety

Mixing HCS with PDMS

Polydimethylsiloxane (PDMS)

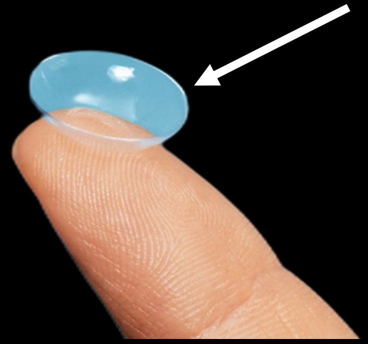


- The most commonly used materials for contact lenses
- Insulator with good electrical insulation properties



Mixing HCS with PDMS

Polydimethylsiloxane (PDMS)



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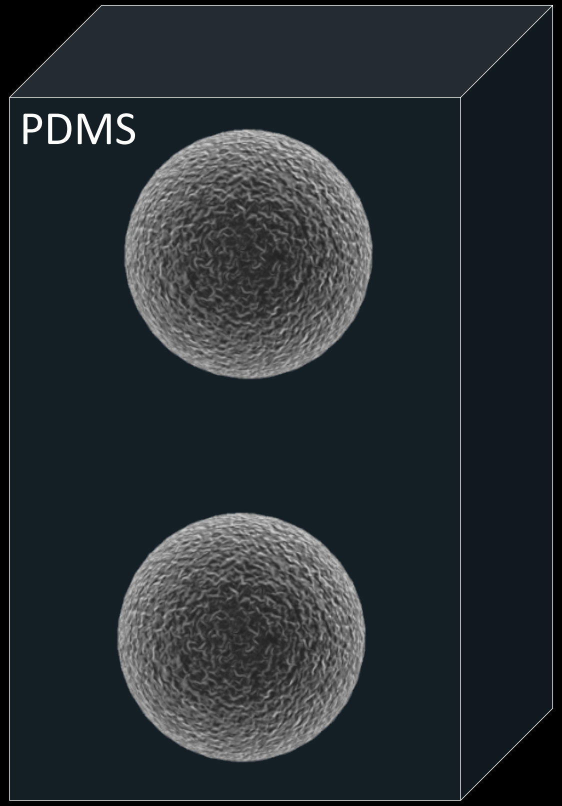
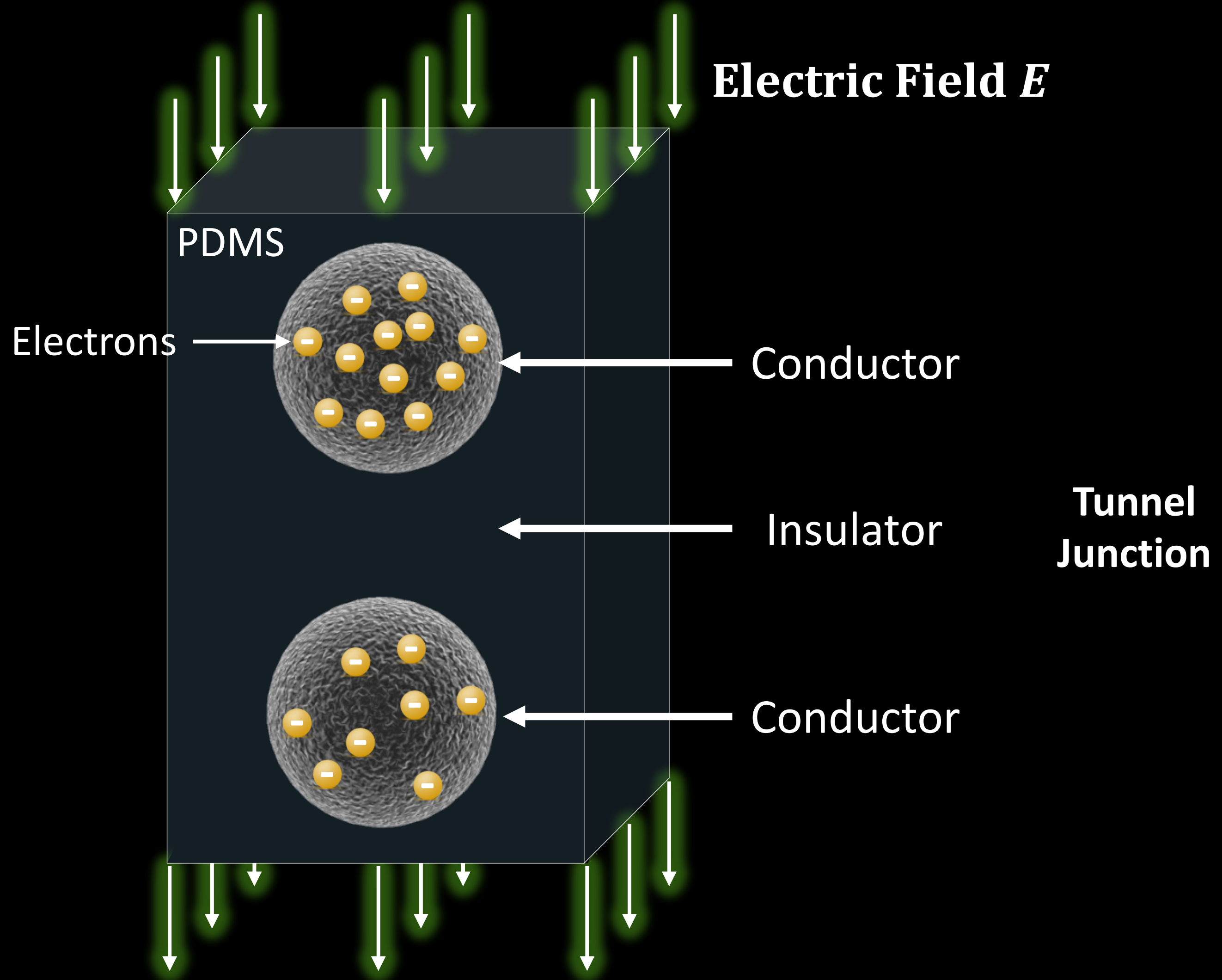
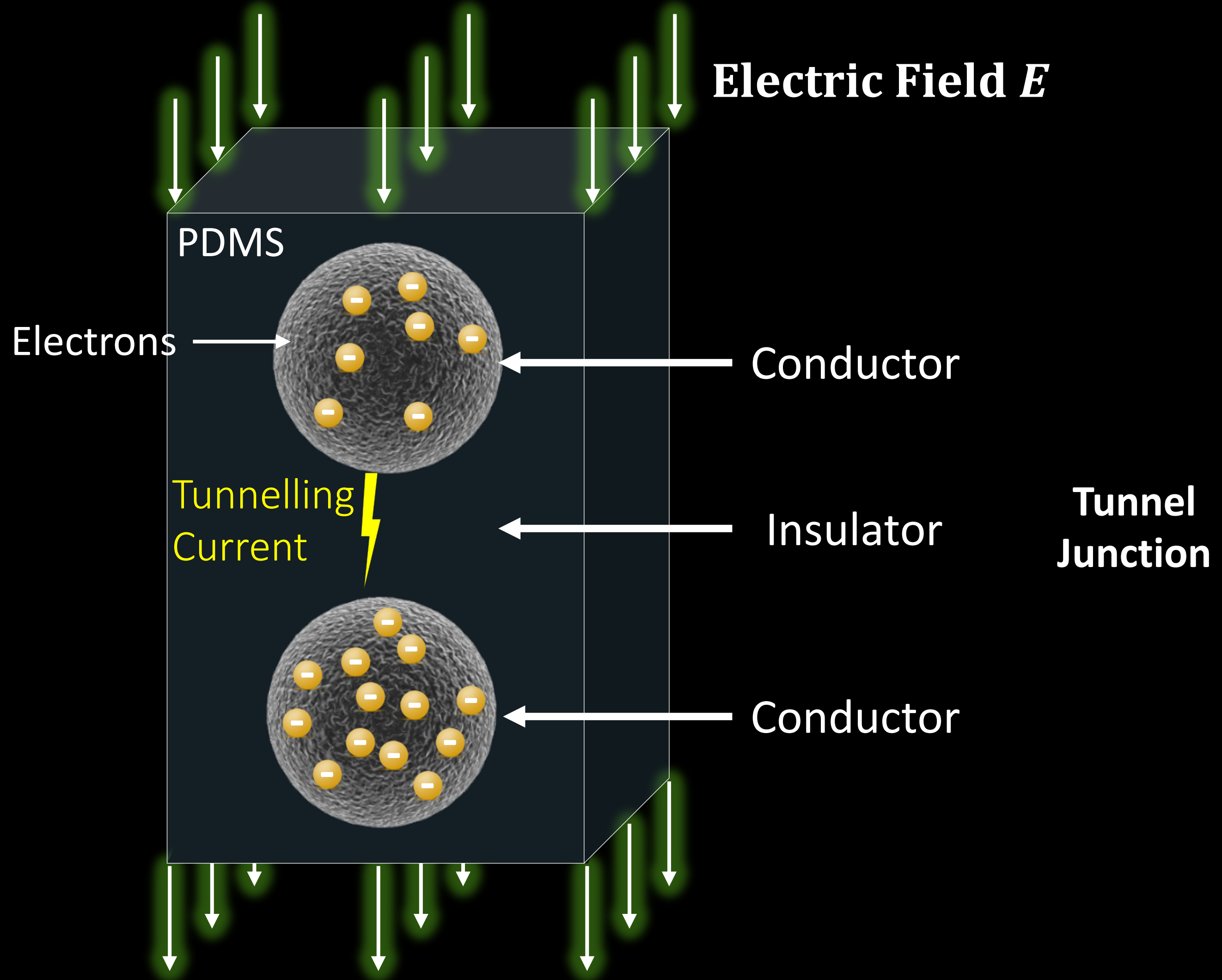


PDMS mixed with HCS



PDMS mixed with HCS

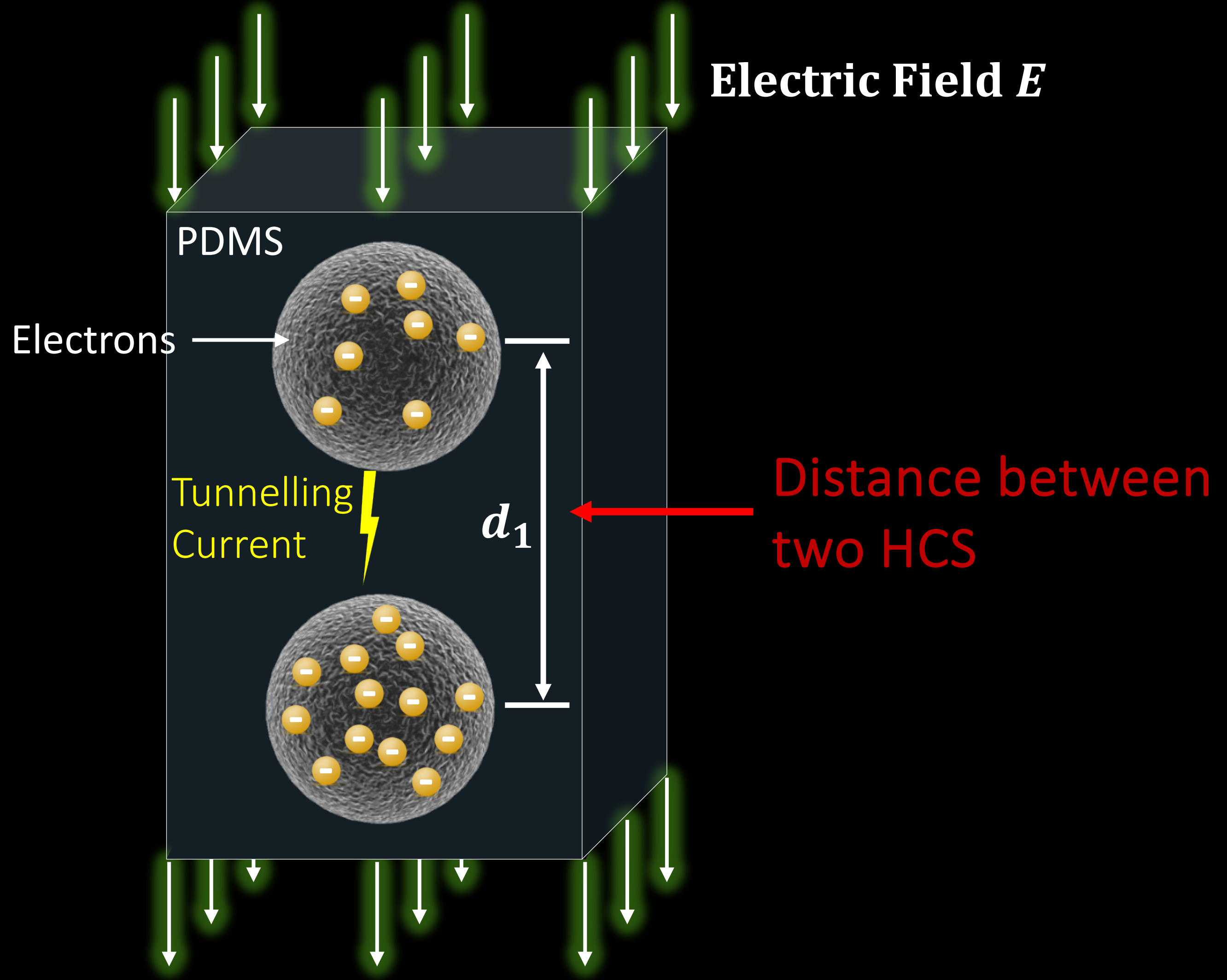


Quantum Tunnelling Effect

Strength of Tunnelling Current

- Strength of electric field
- Distance between conductors

PDMS mixed with HCS



Quantum Tunnelling Effect

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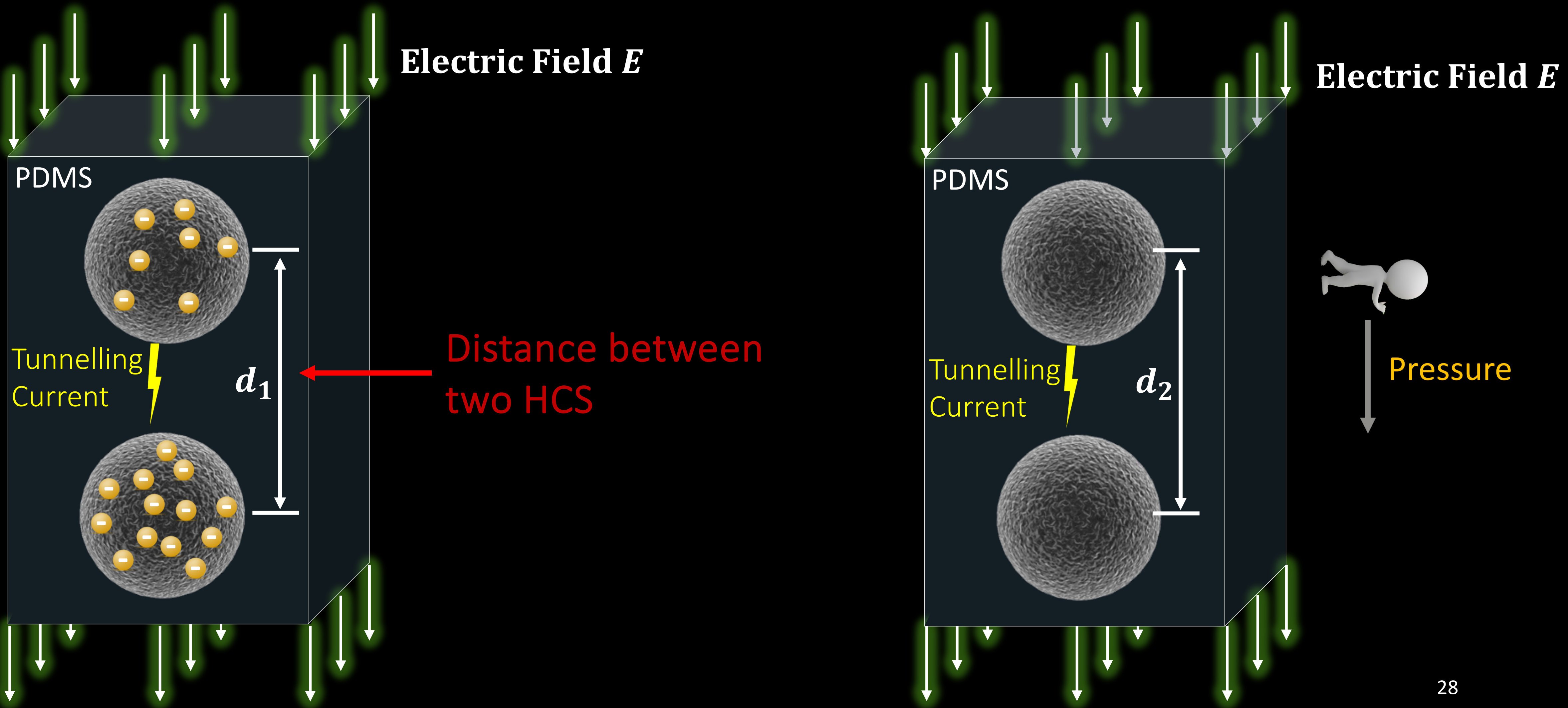
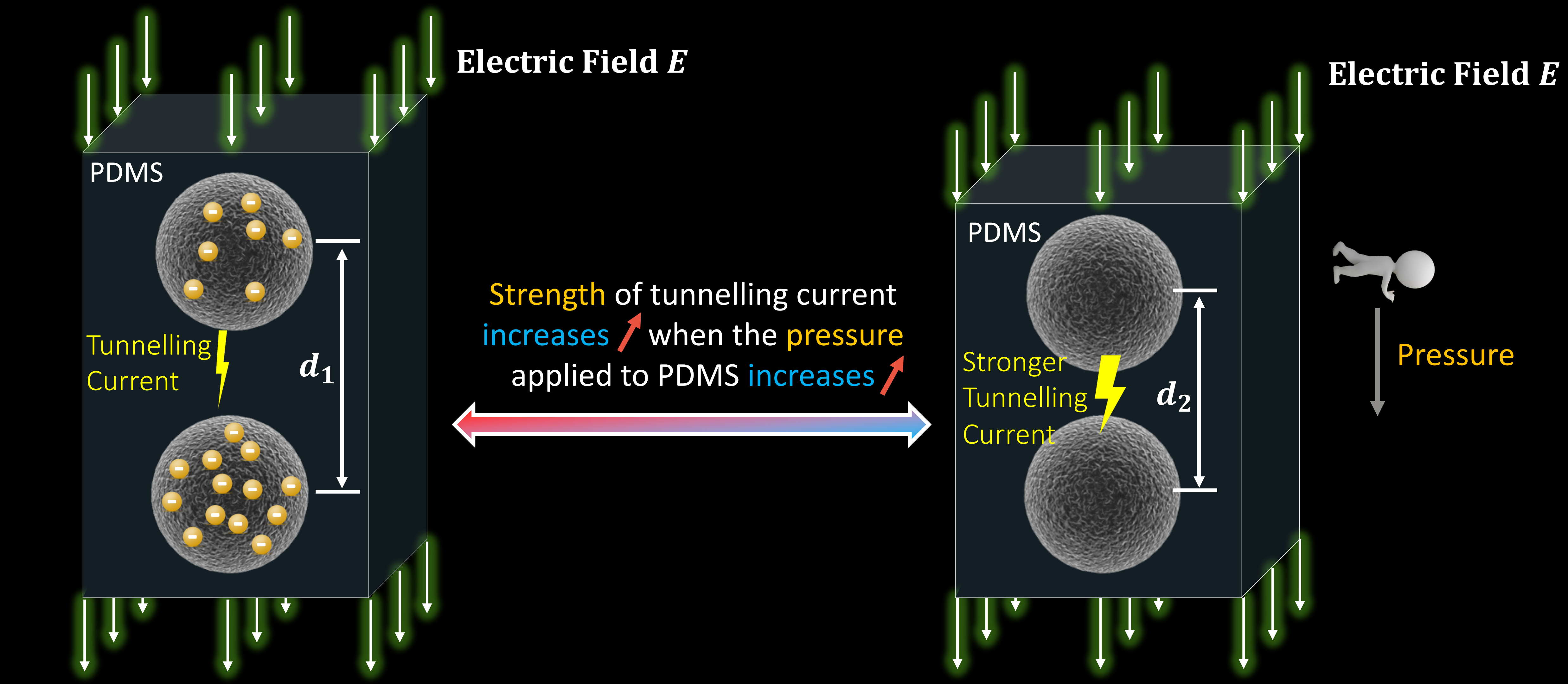
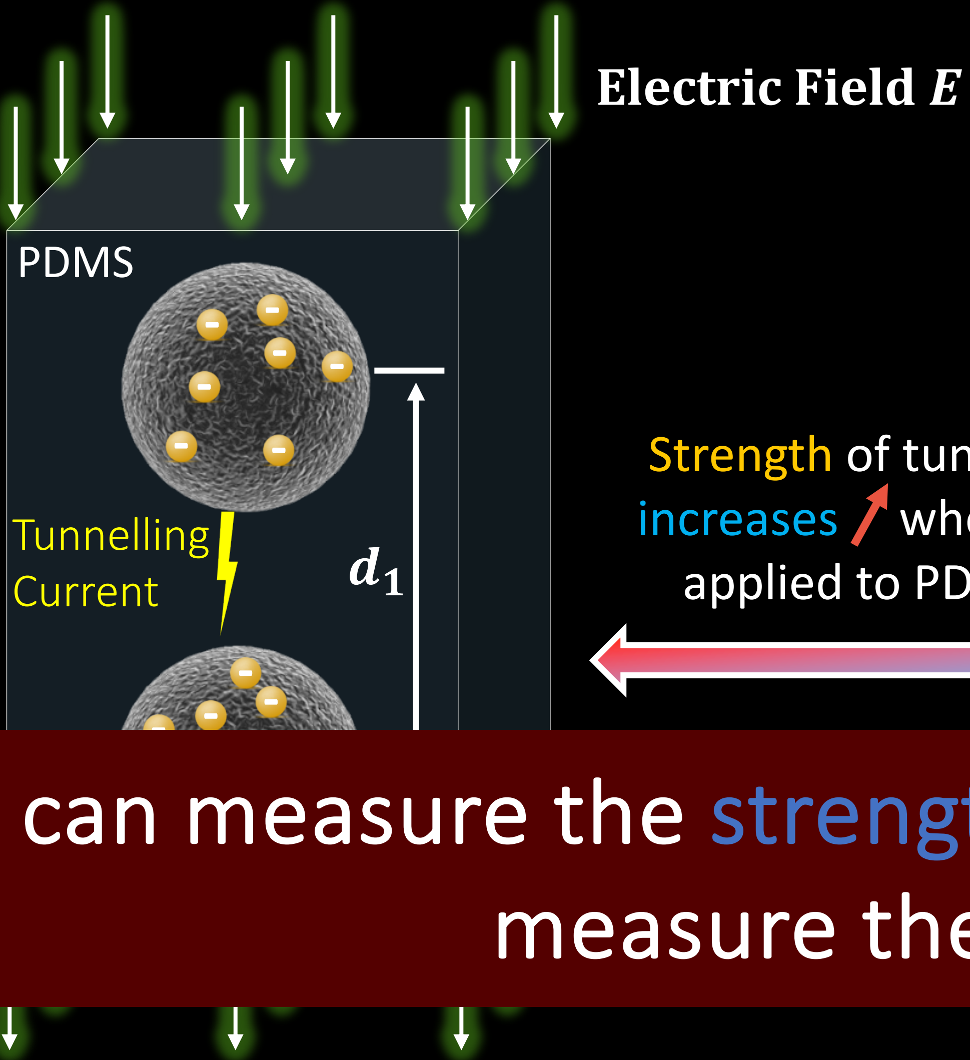


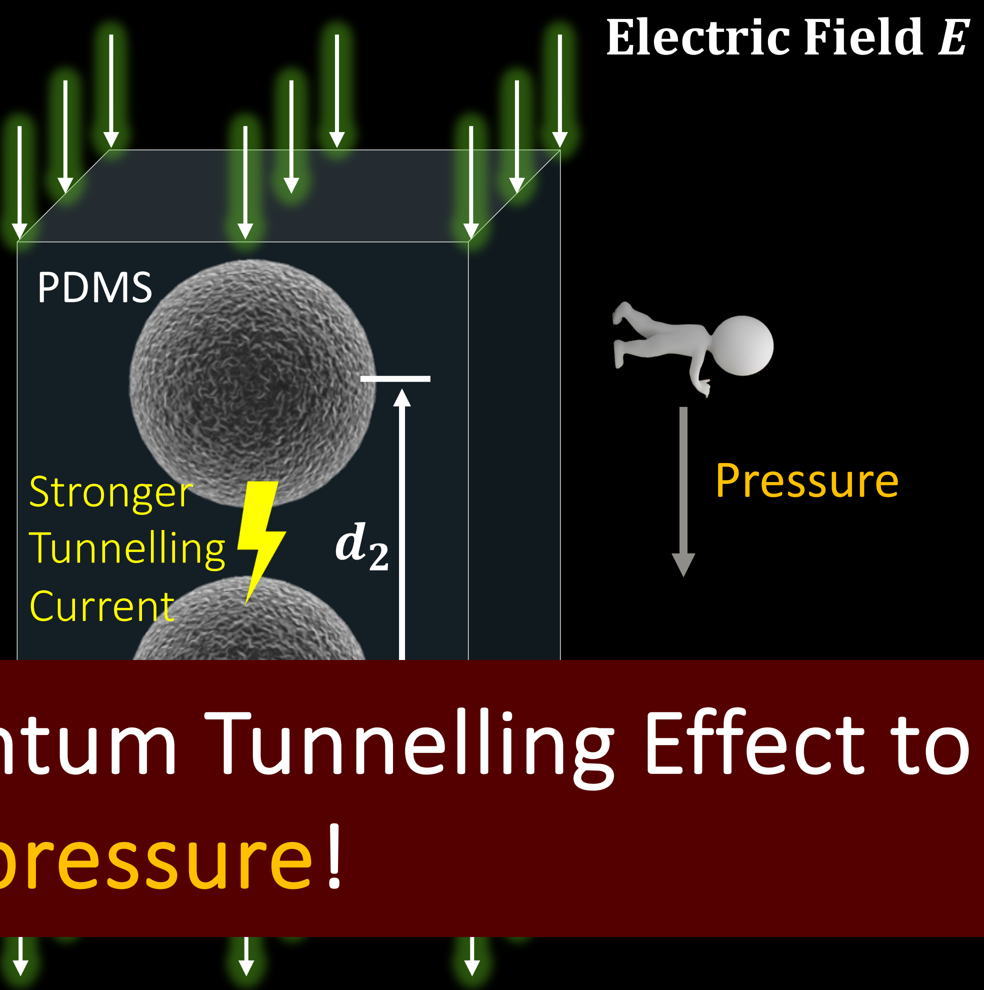
PDMS mixed with HCS



PDMS mixed with HCS

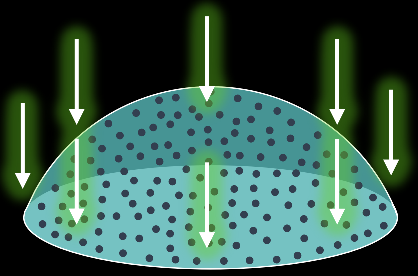


Strength of tunnelling current increases ↗ when the pressure applied to PDMS increases ↗



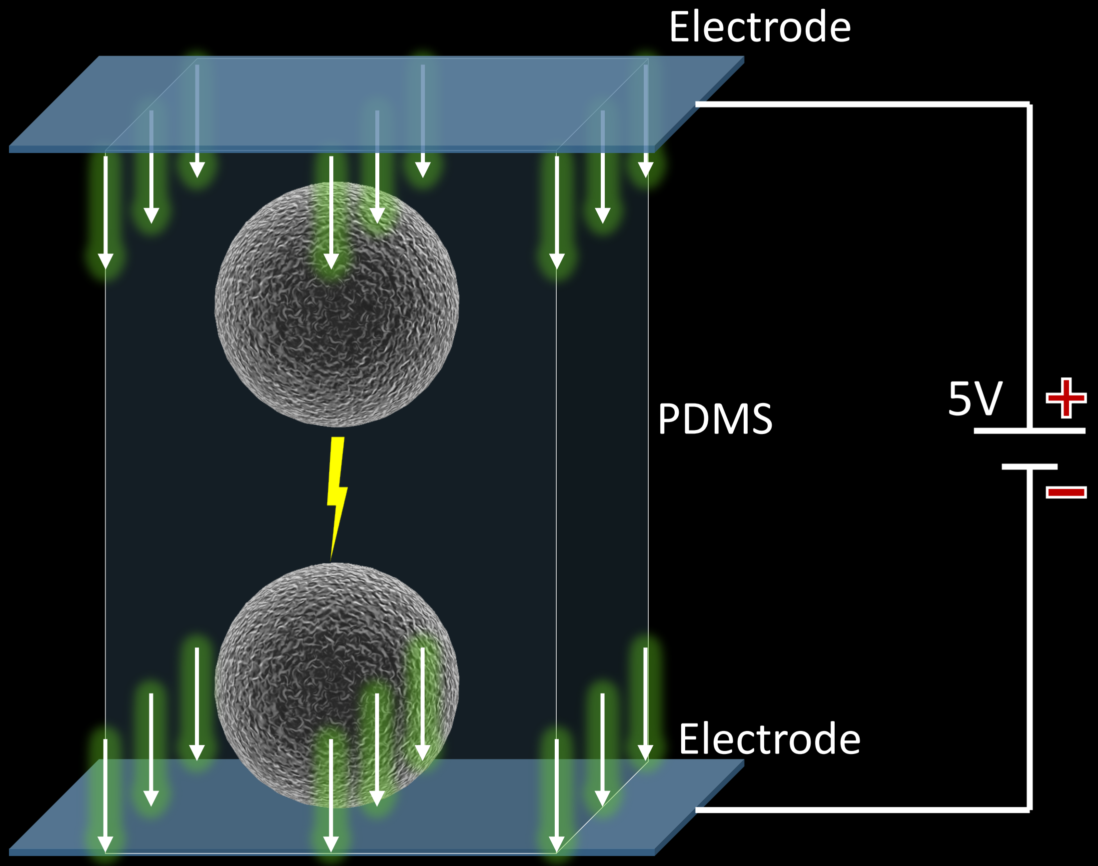
We can measure the strength of Quantum Tunnelling Effect to measure the applied pressure!

Enable Quantum Tunnelling Effect
Missing Part: the External Electric Field



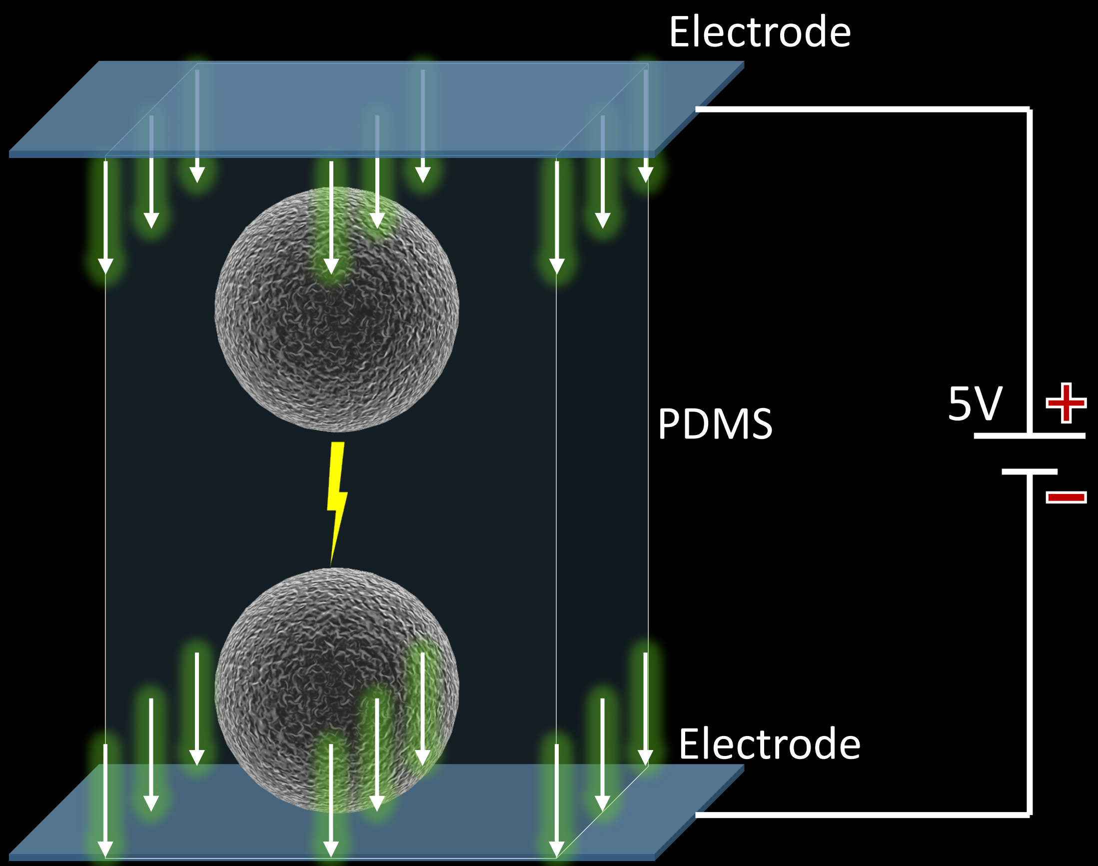
Question: how to apply the electric field on our energy-harvesting powered device?

Applying the Electric Field: Electrode



Our system is battery free

Applying the Electric Field: Two Antenna Layers



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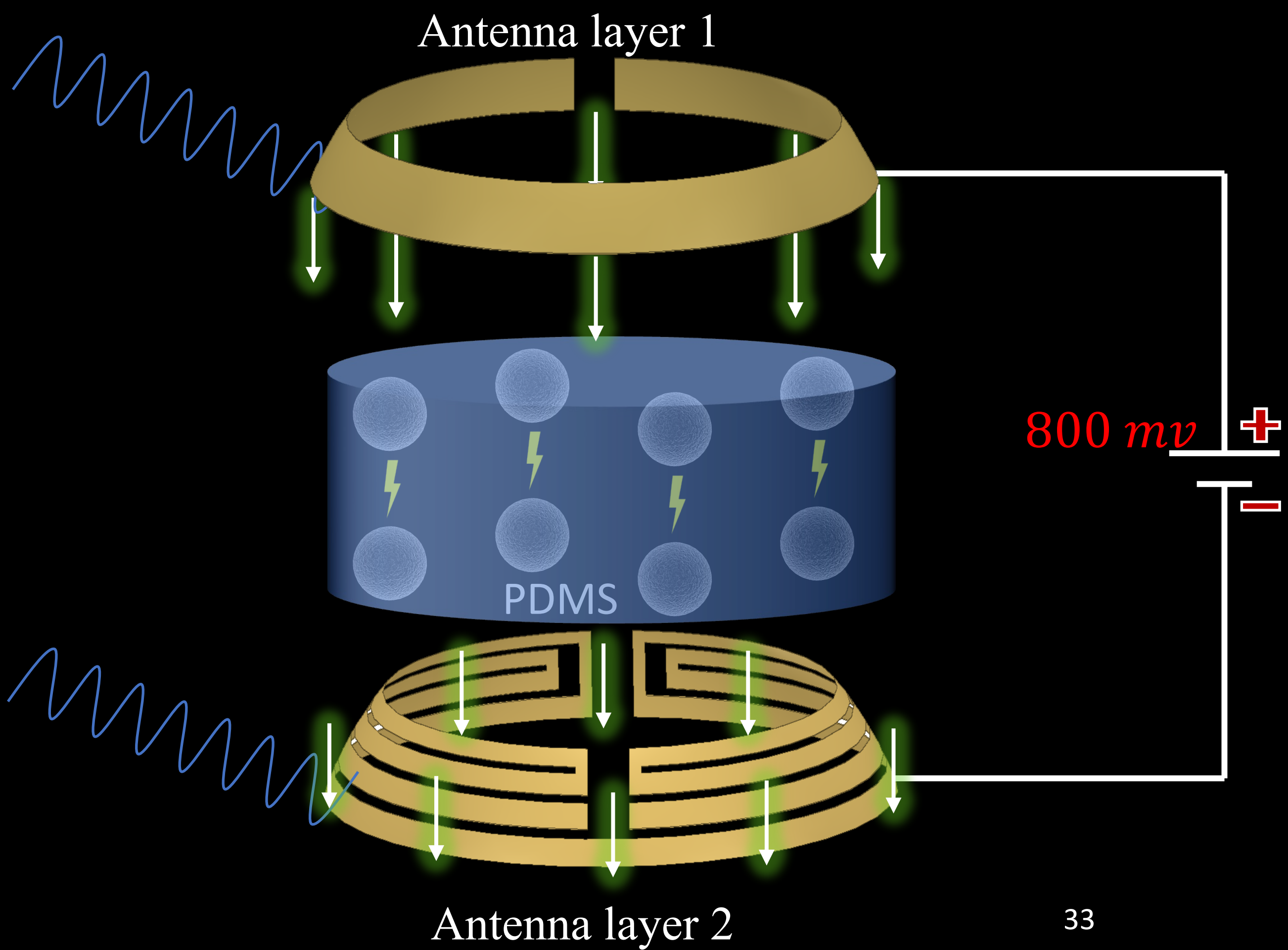
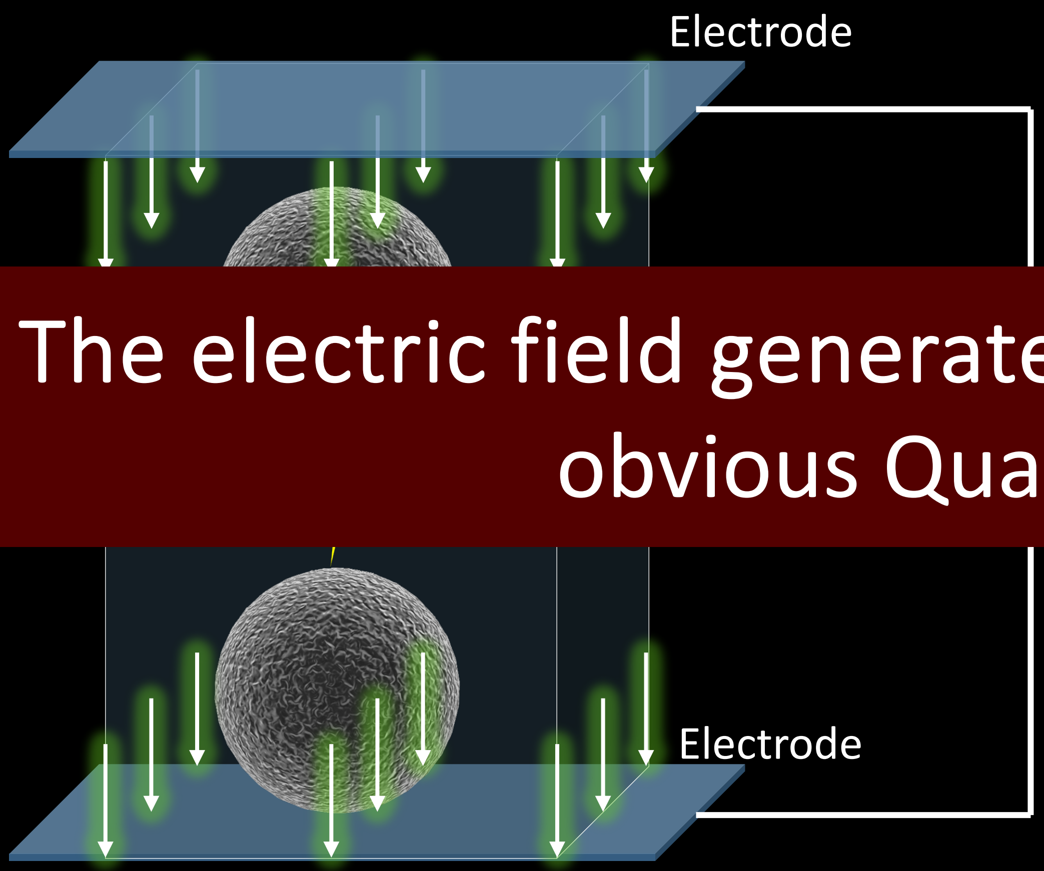


Applying the Electric Field: Two Antenna Layers



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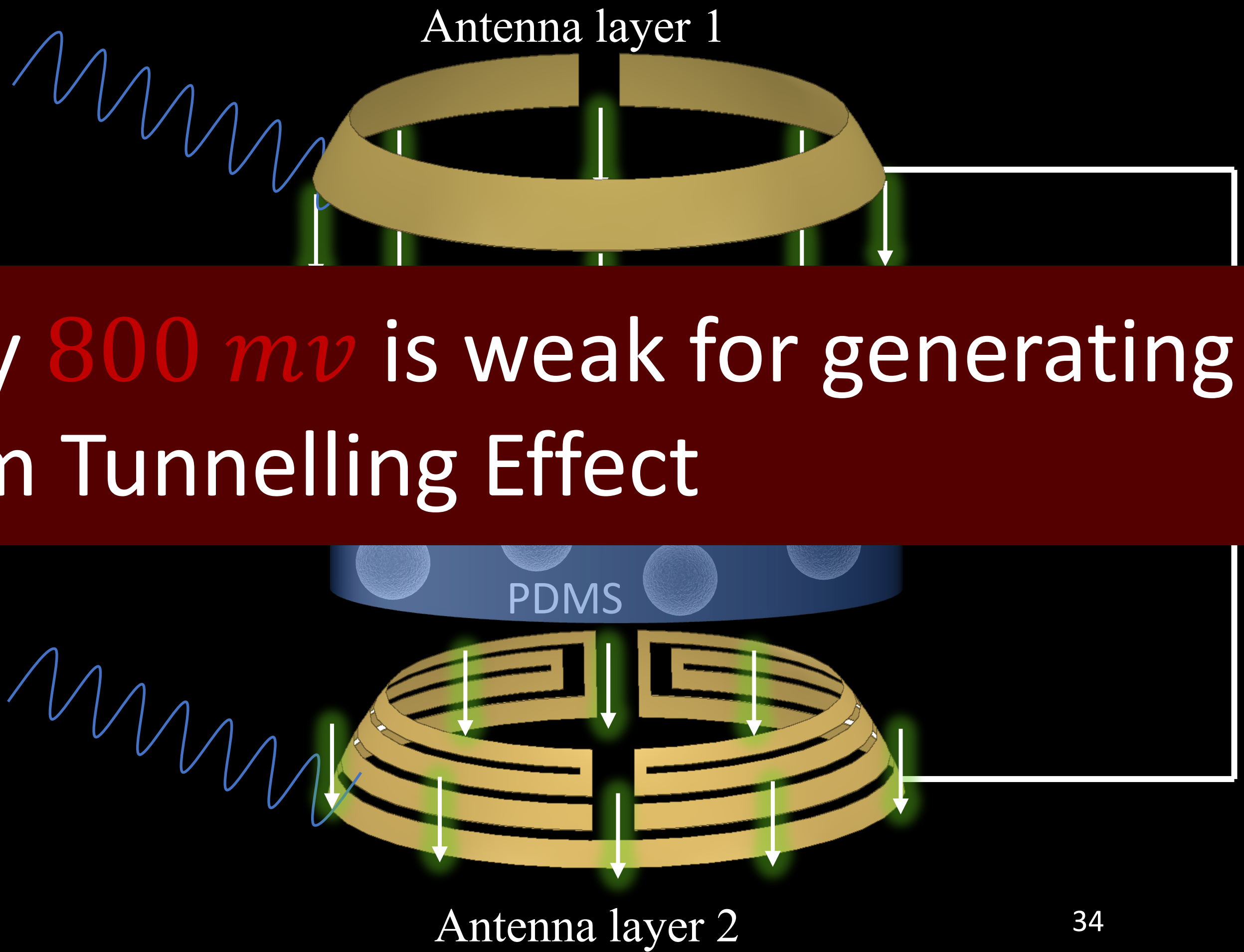
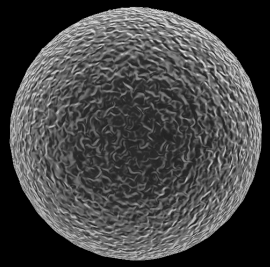


The electric field generated by 800 mv is weak for generating obvious Quantum Tunnelling Effect

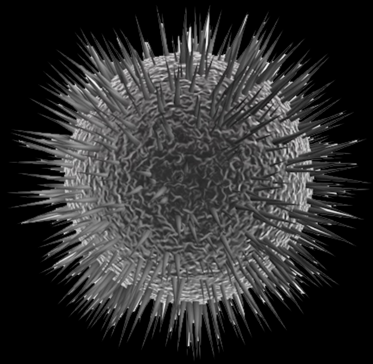
Solution 1: Replace HCS with Urchin-like Hollow Carbon Sphere (UHCS)

Hollow Carbon Sphere (HCS)



Replace with

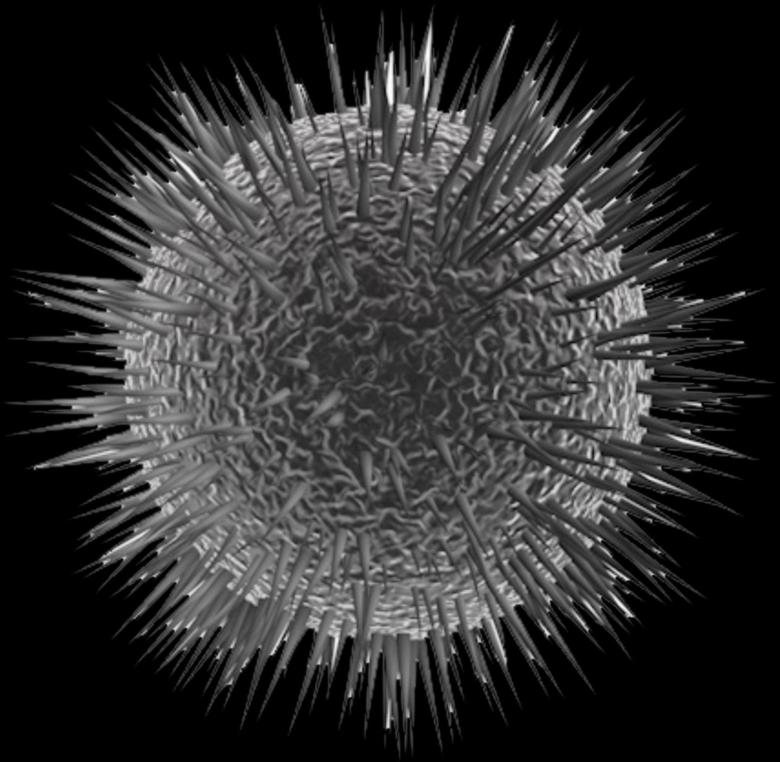
Urchin-like Hollow Carbon Sphere (UHCS)



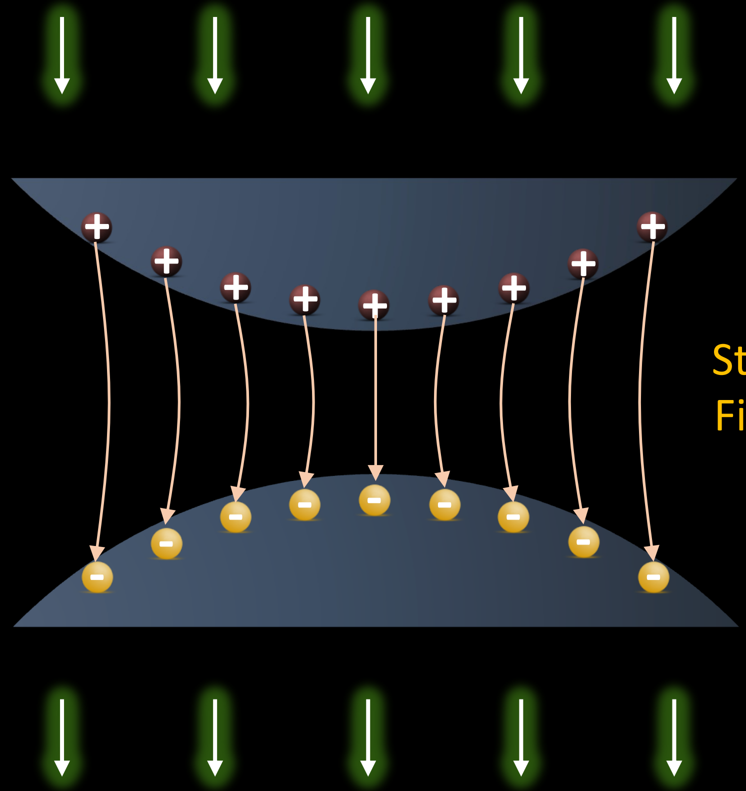
Urchin

UHCS Generates a Stronger Internal Electric Field

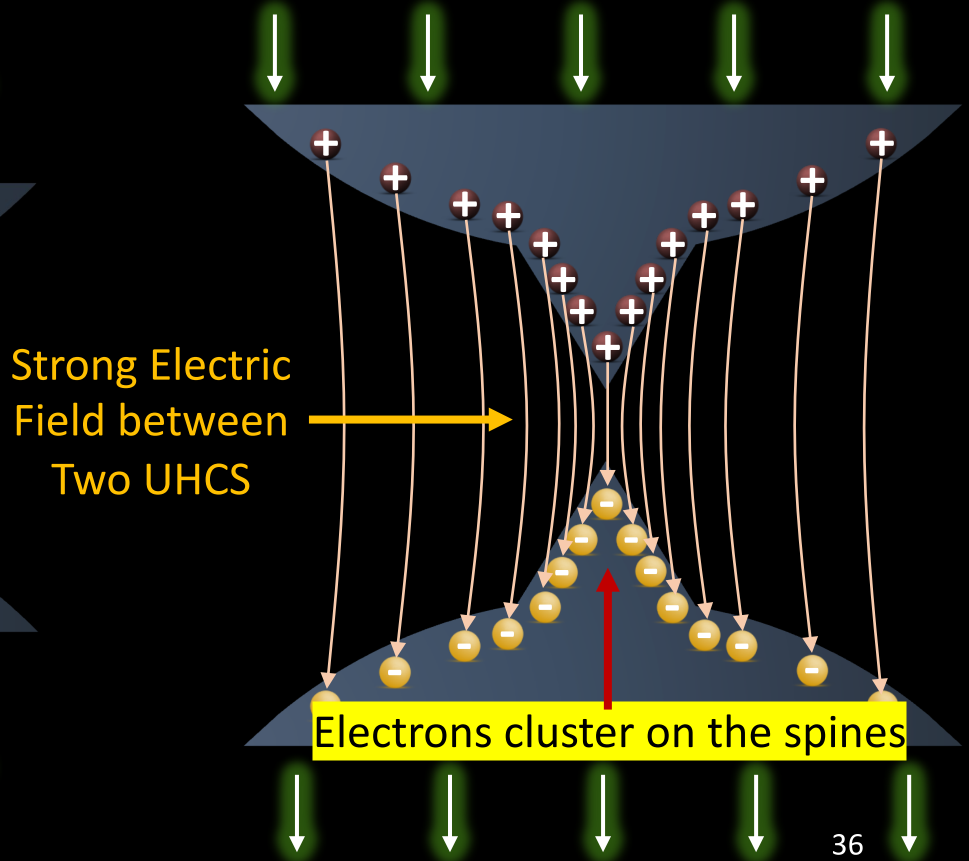
Urchin-like Hollow Carbon Sphere (UHCS)



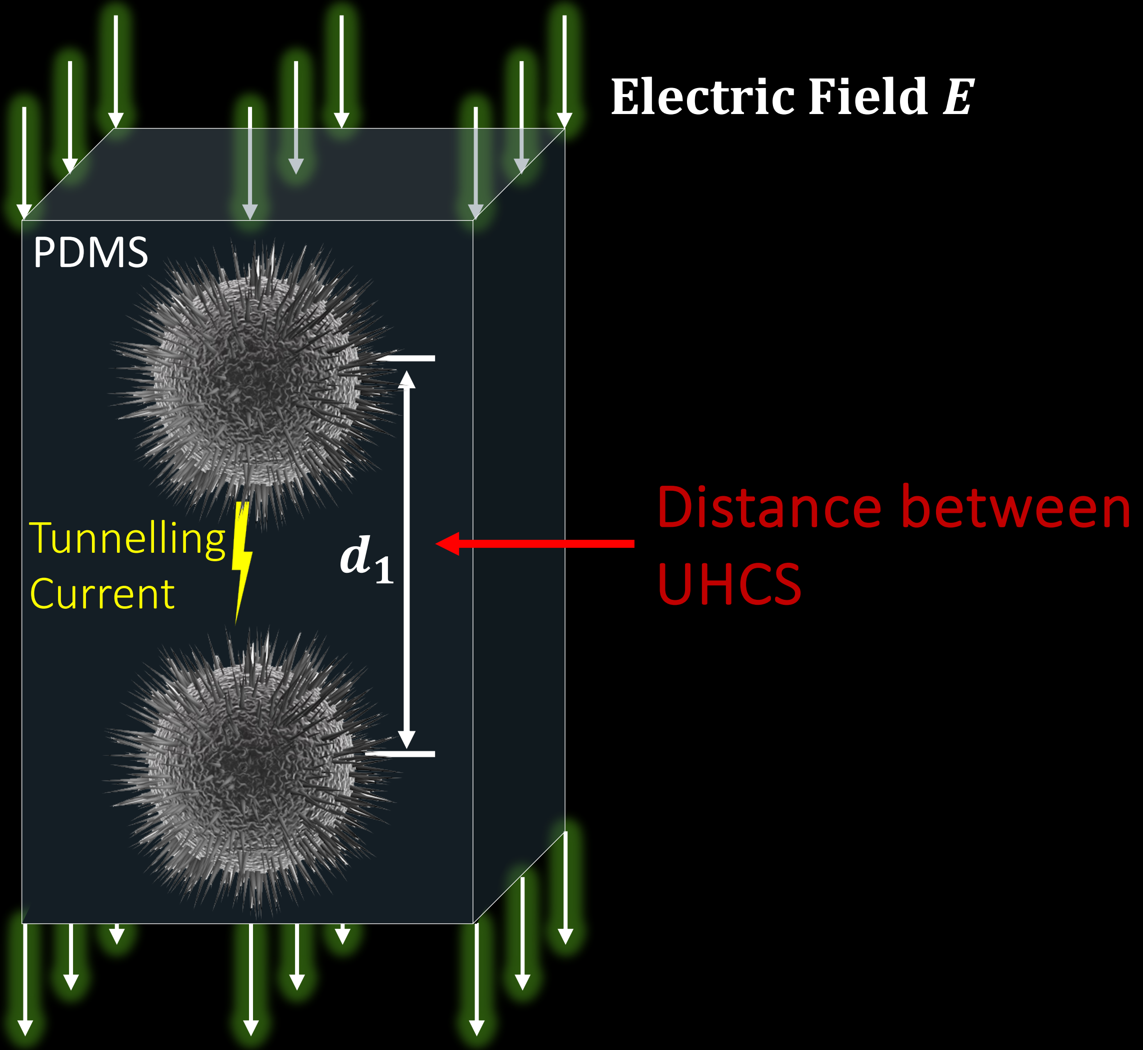
Electric Field Distribution of HCS



Electric Field Distribution of UHCS



Solution 2: Decrease the Distance between Two UHCS



Strength of Tunnelling Current

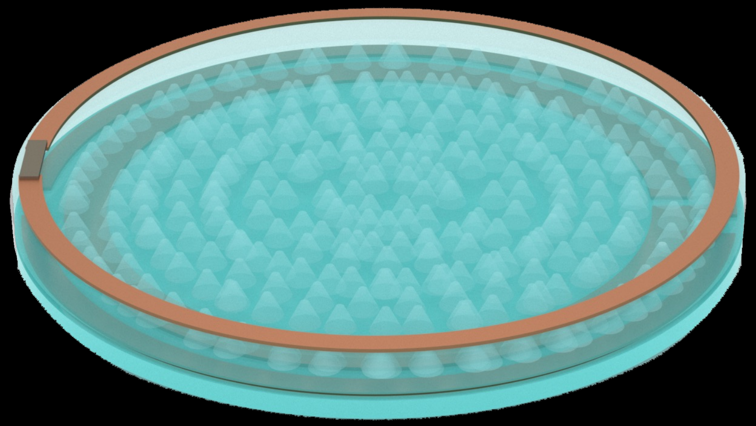
- Strength of electric field
- Distance between conductors

Reduce the **initial distance** between UHCS

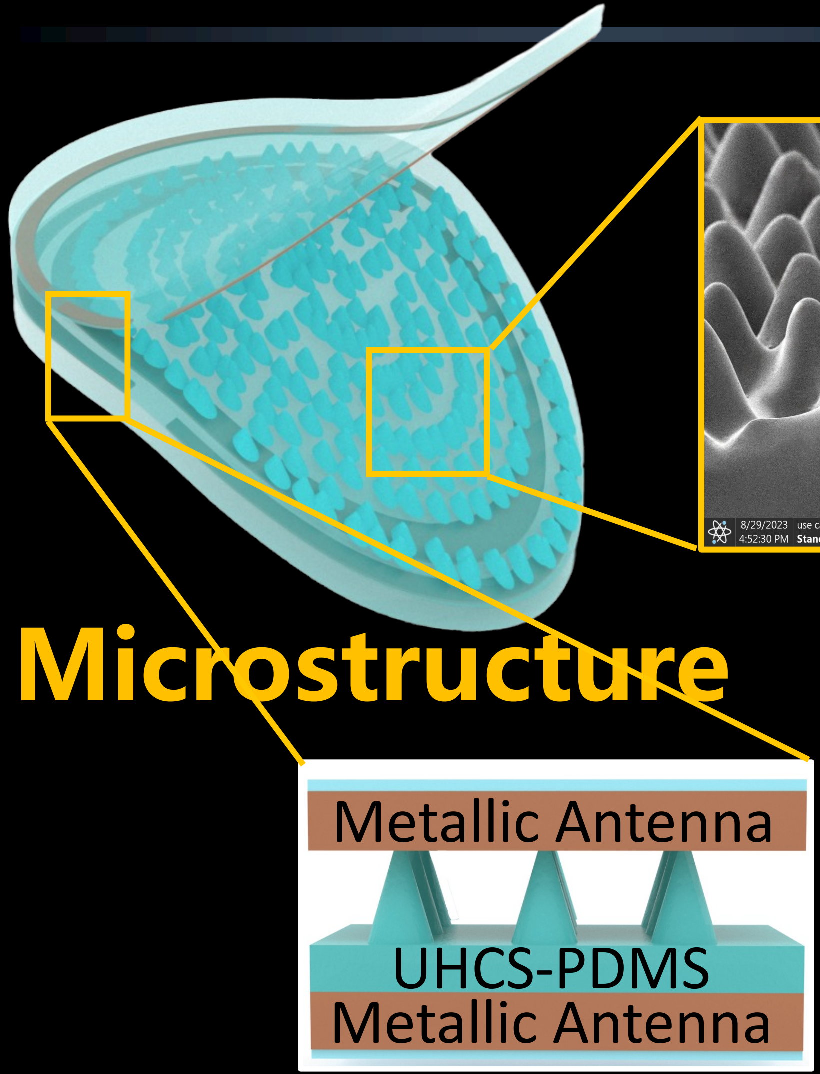
↓

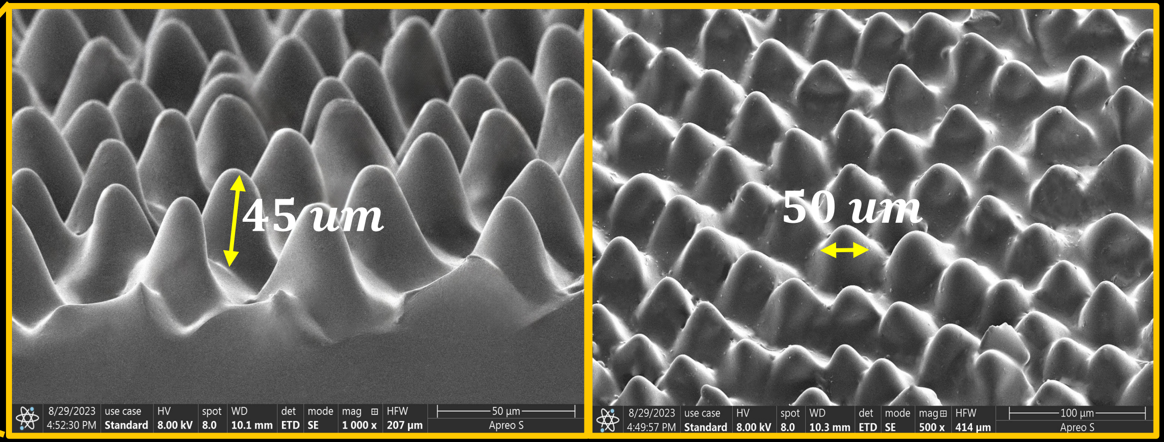
Increase the **density of UHCS** inside the PDMS

Solution 3: Bio-inspired Microstructures



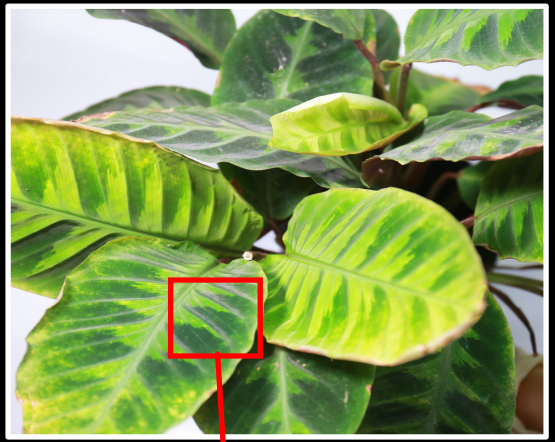
Solution 3: Bio-inspired Microstructures

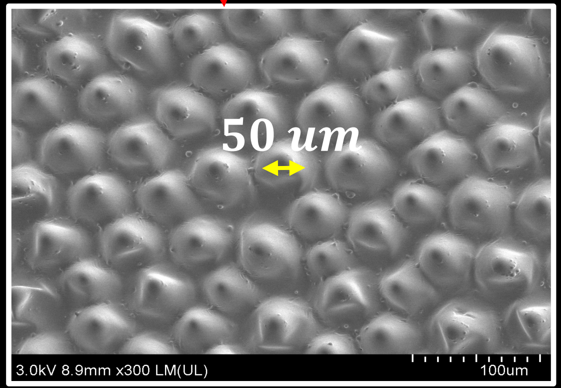




SEM of the fabricated micrones on the UHCS- PDMS film

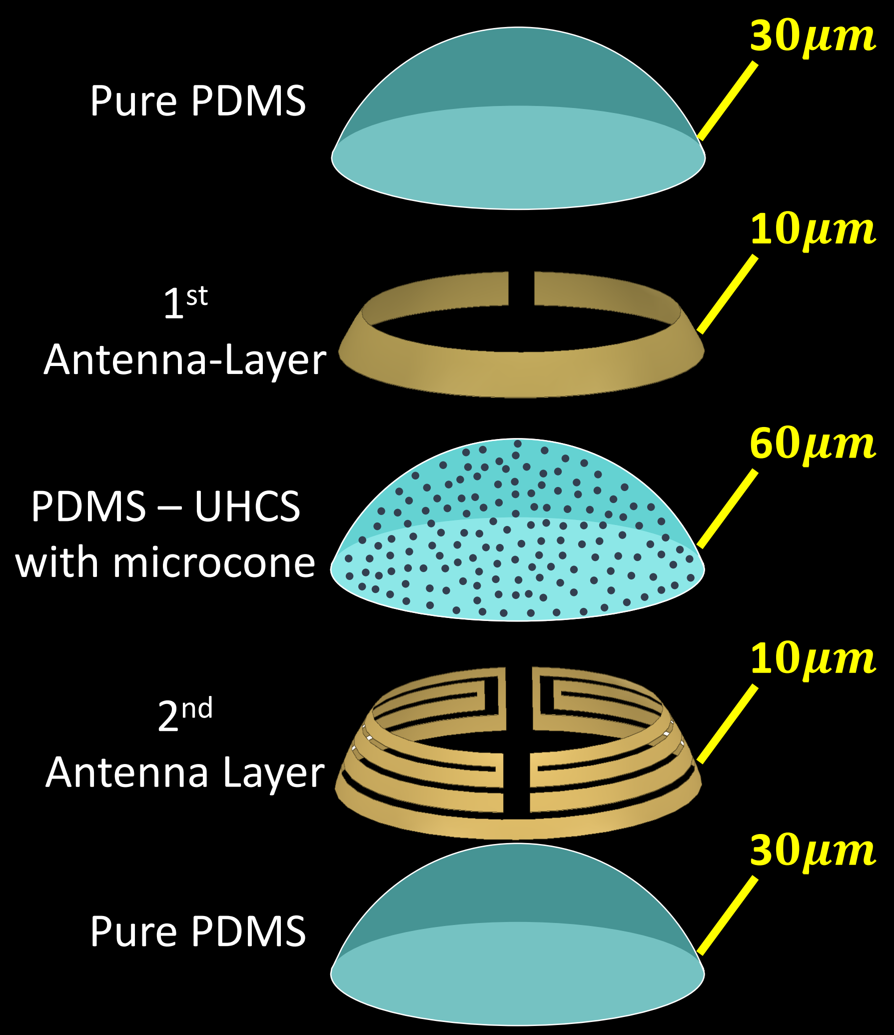
Calathea Zebrine





SEM of the leaves surface

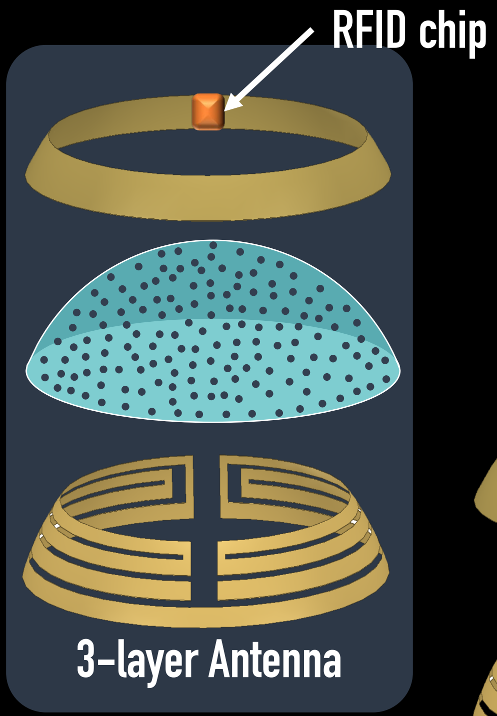
Structure of Contact Lens

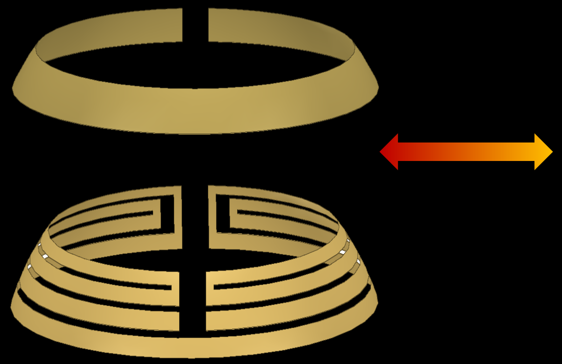


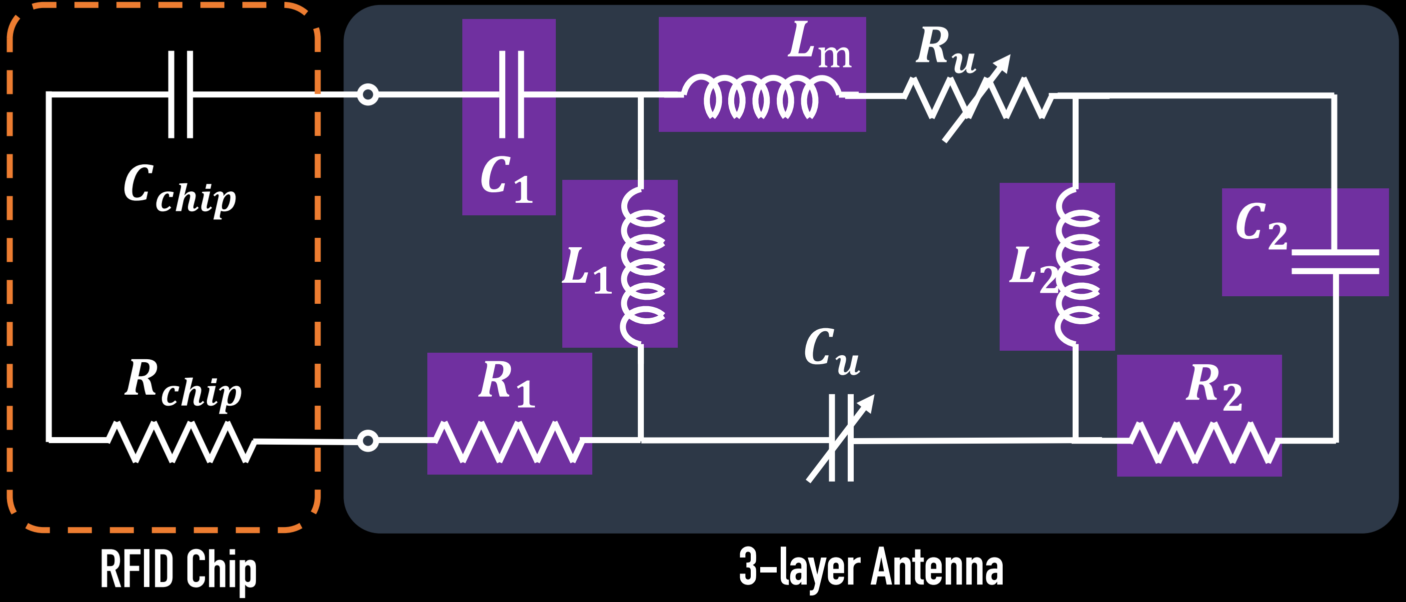
Low-power but sensitive pressure sensor with thickness at μm level that works on energy-harvesting powered devices

Equivalent Circuit of the 3-layer Antenna

Equivalent circuit

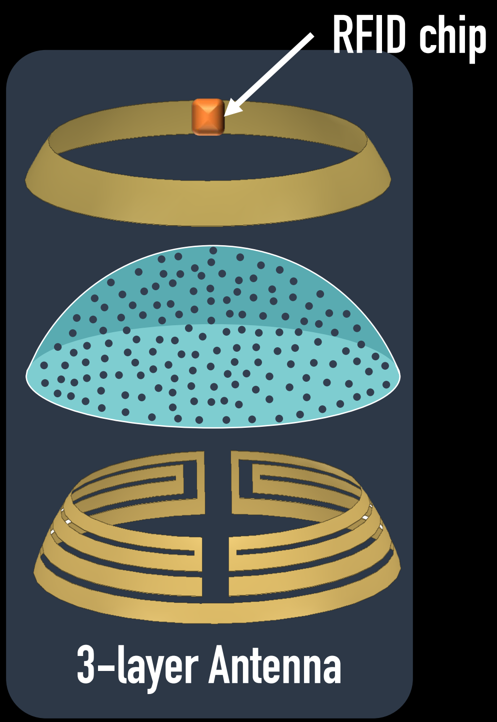




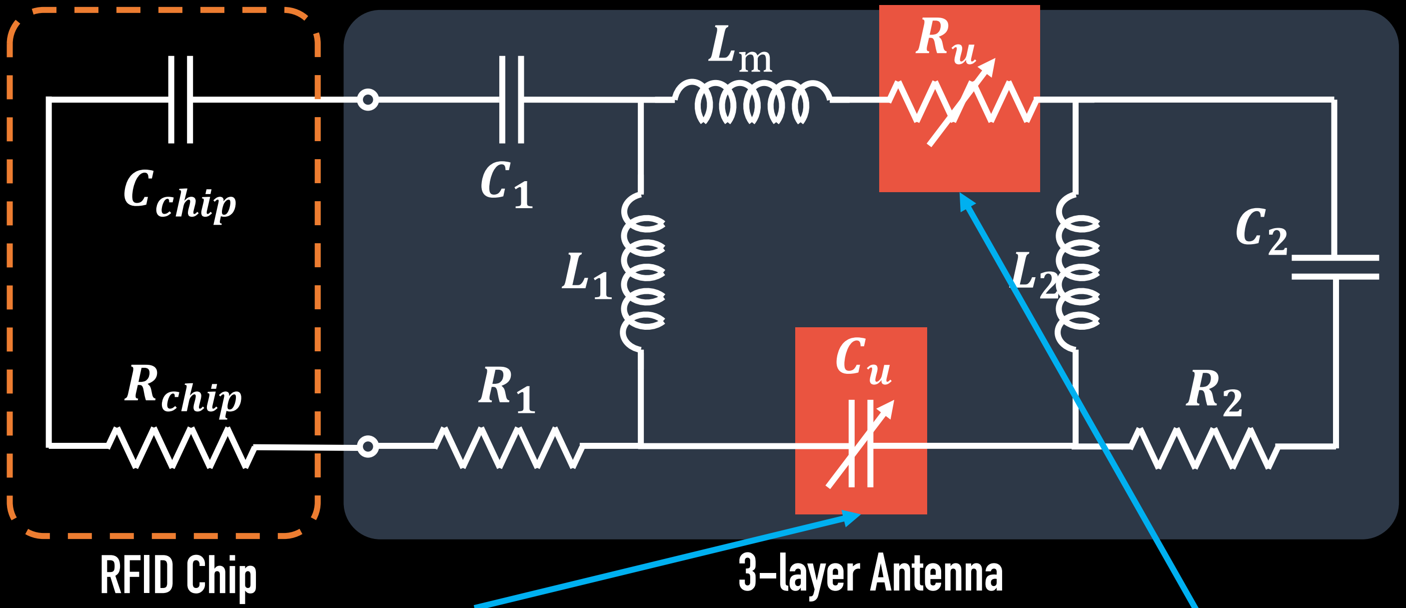


C_1 and C_2	Parasitic capacitance of two antenna layers
R_1 and R_2	Parasitic resistance of two antenna layers
L_1 and L_2	Self-inductance of two antenna layers
L_m	Mutual-inductance between two antenna layers

Equivalent Circuit of the 3-layer Antenna

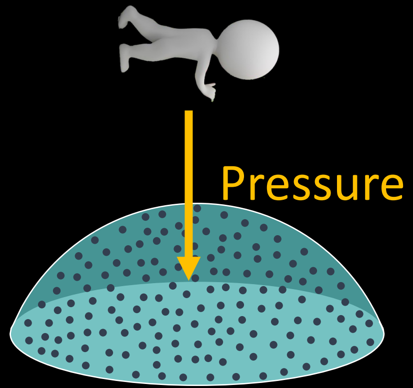


Equivalent circuit



C_u A variable capacitor

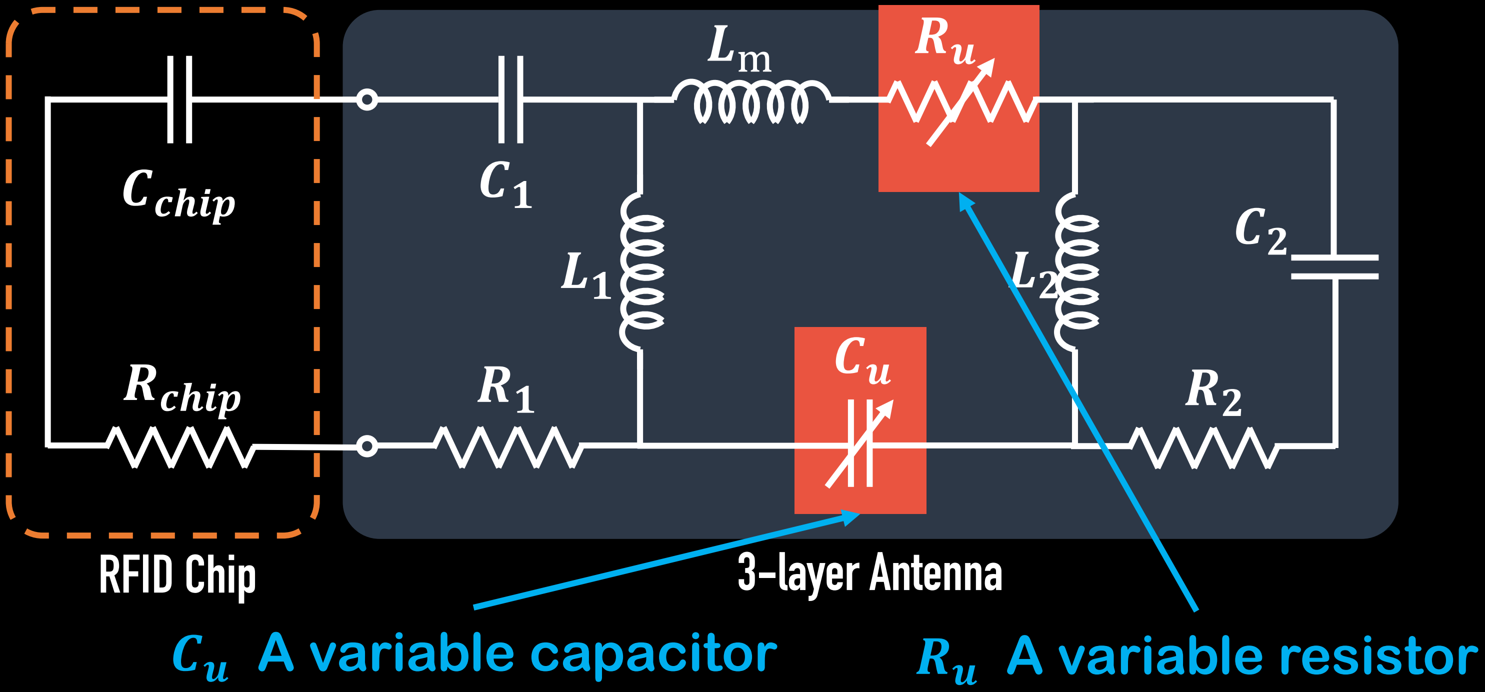
R_u A variable resistor



→ $[C_u, R_u]$ → **Impedance of the whole antenna**

Equivalent Circuit of the 3-layer Antenna

Equivalent circuit



We can measure the **pressure** by measuring the **impedance variation of the antenna**

A **Low-cost, Battery-free** and **Long-range** Eye Pressure Sensing System: **Goals**

Goals:

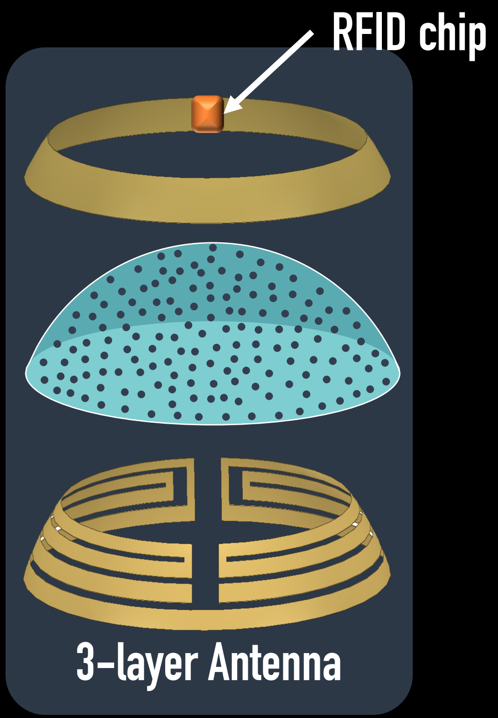
✓ **1)** Low-power but sensitive pressure sensor with thickness at μm level that works on energy-harvesting powered devices

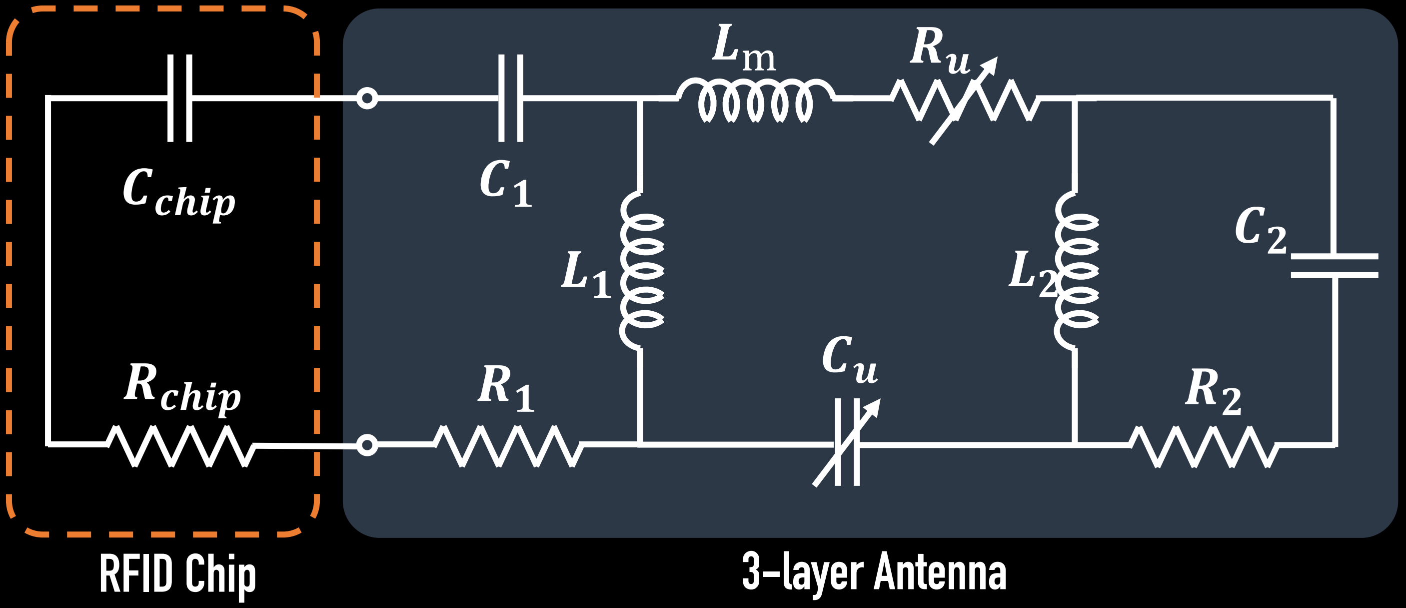
2) Supporting long-range communication with contact-lens size antenna

Challenge:

Interference between the communication antenna and the pressure sensors

Maximize Communication Range: Impedance Matching



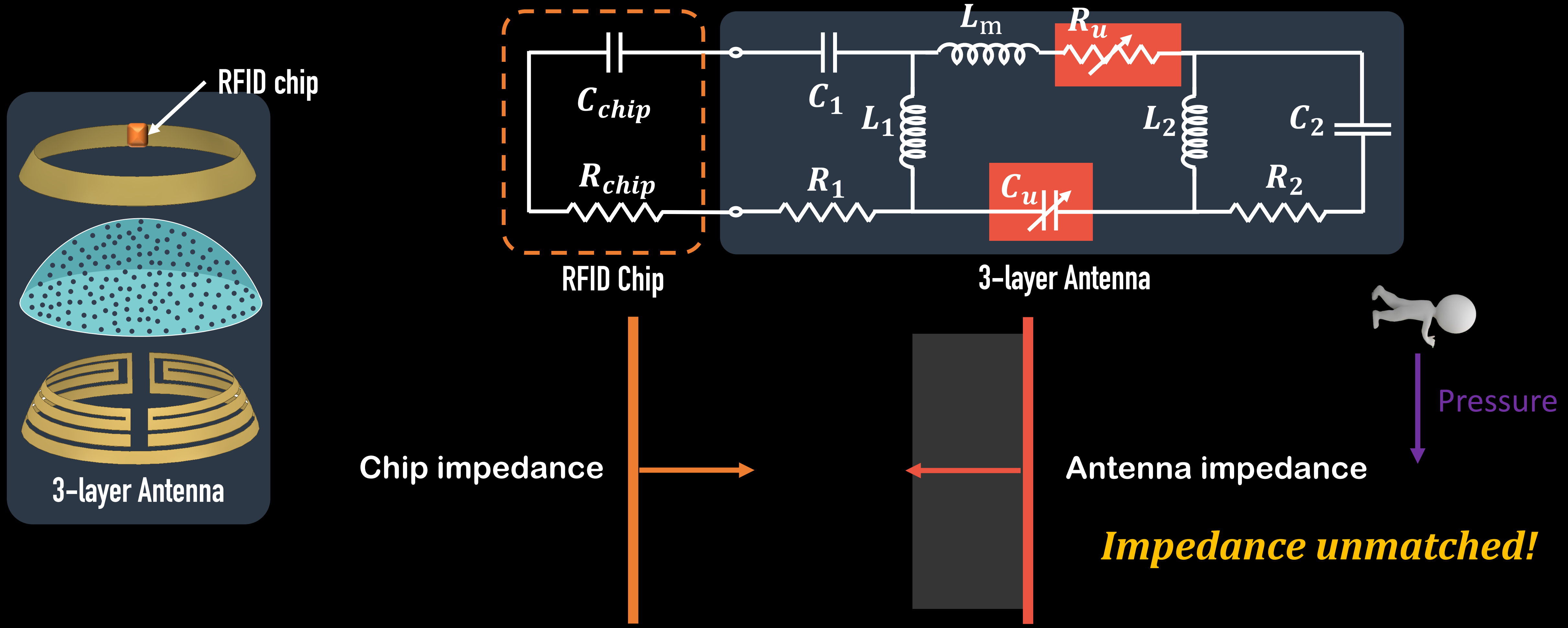


Impedance of the RFID chip = **Impedance of the antenna**

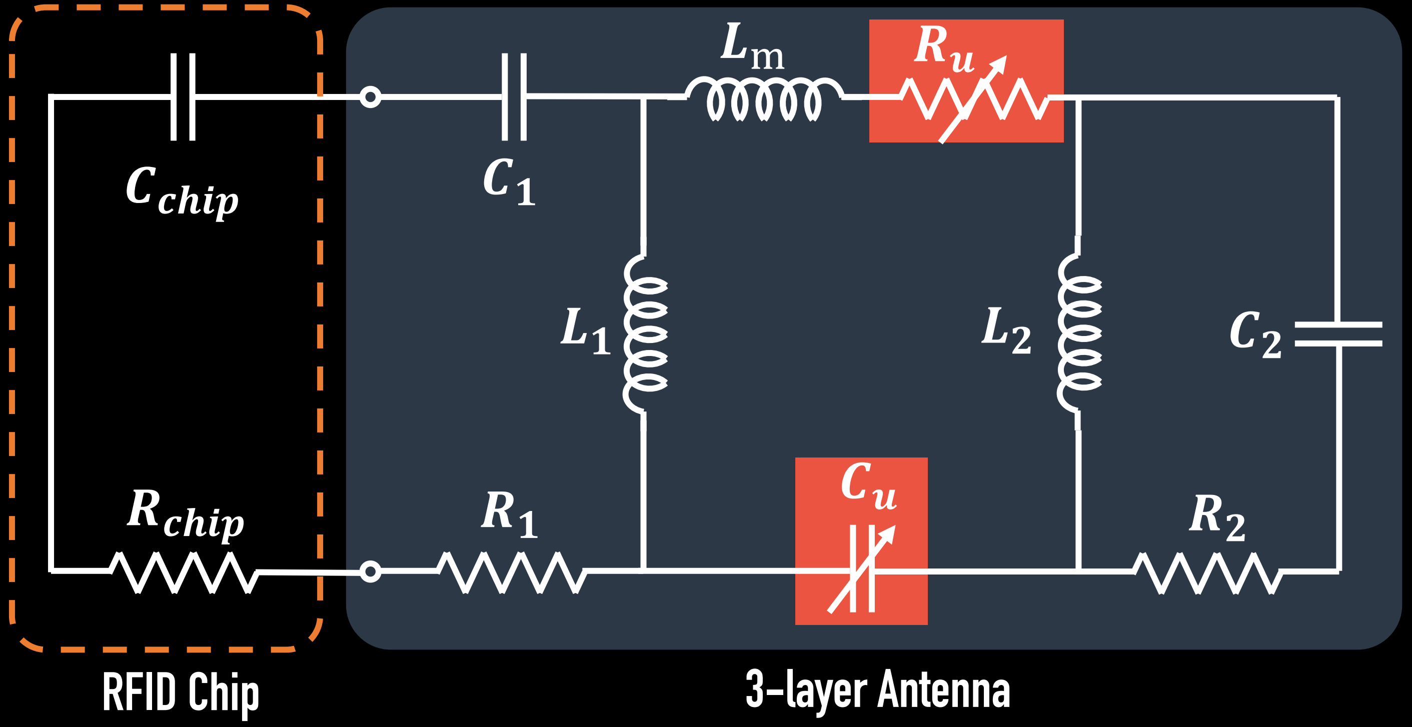
Known

Any minor modification to the antenna structure would significantly affect the impedance

Impedance Matching during Pressure Measurement



Adjust the Impedance of the RFID chip via Self-tunning Circuit



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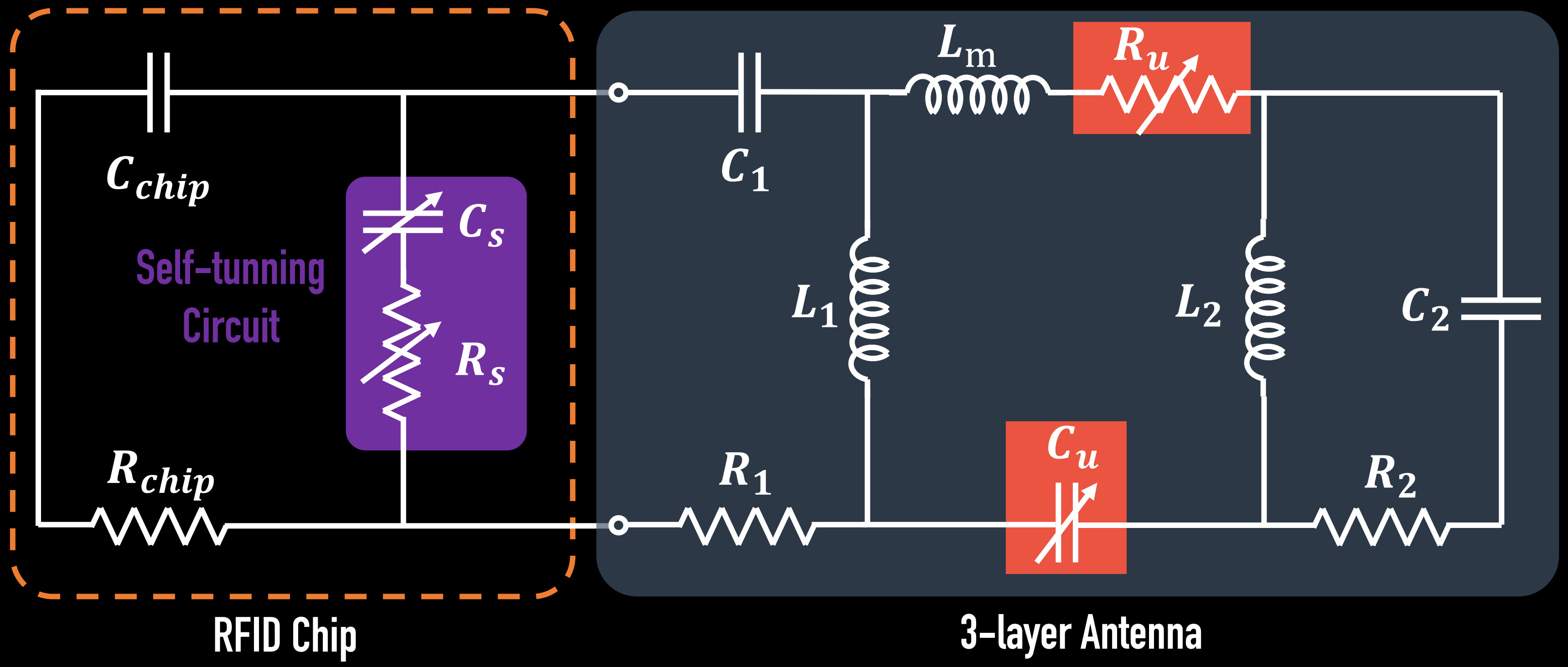
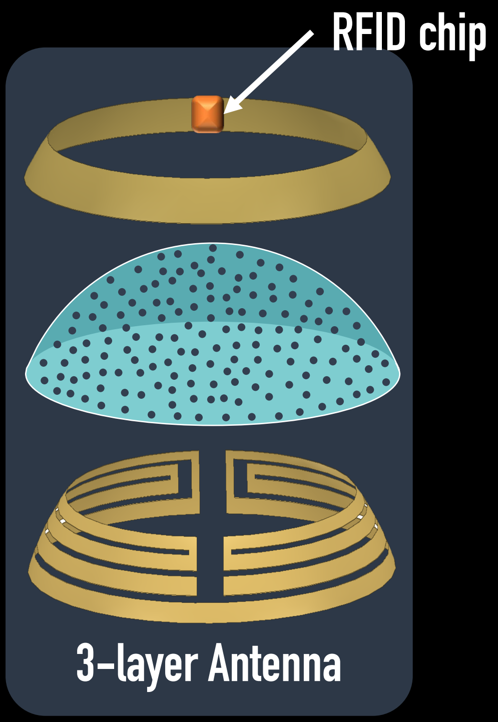
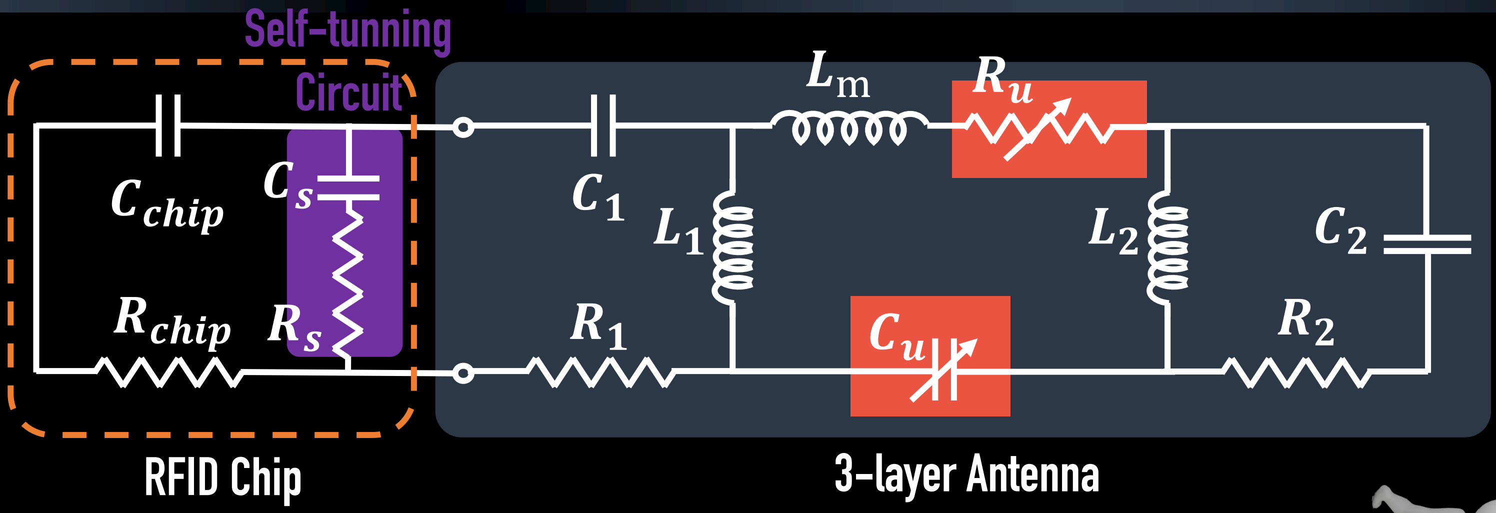
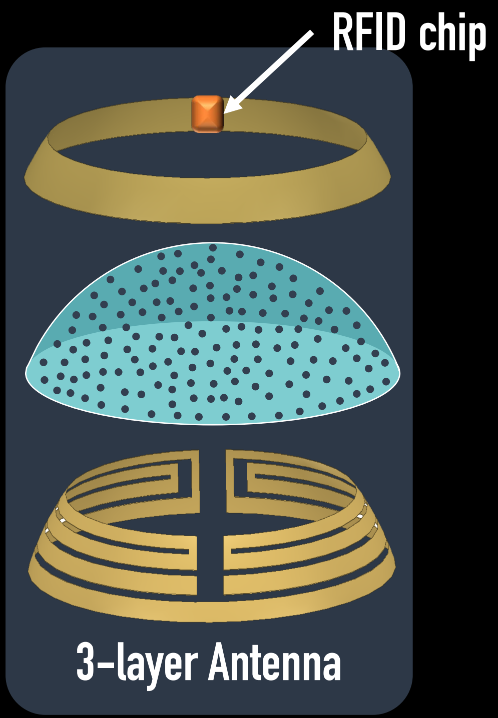


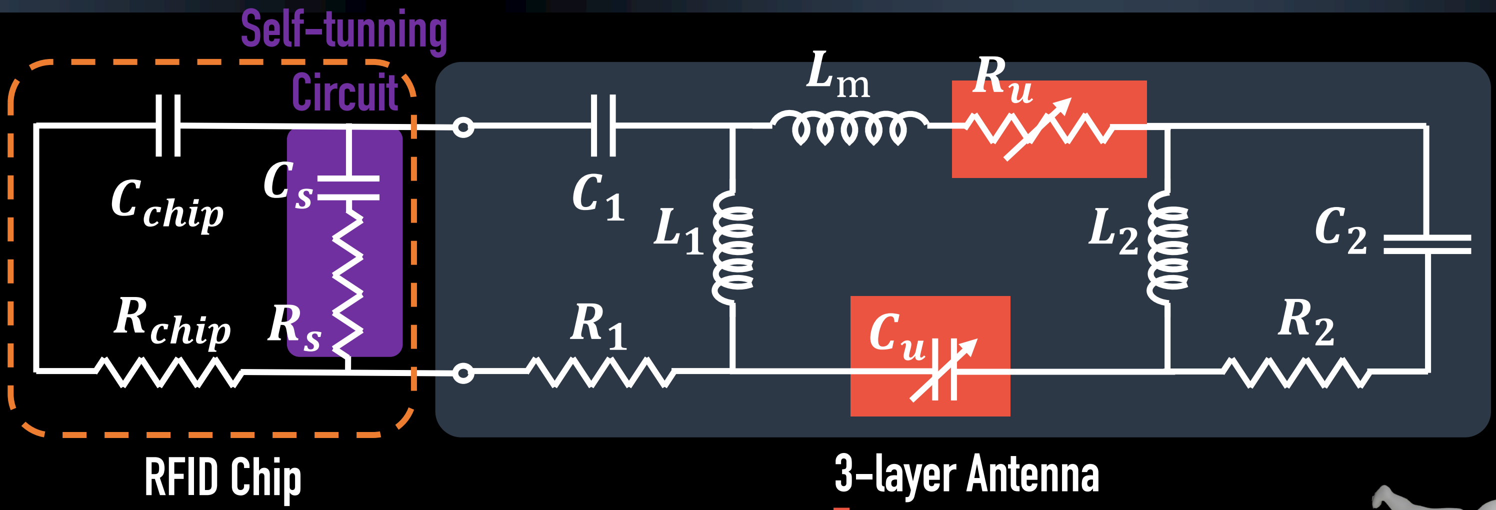
Impedance Matching during Pressure Measurement

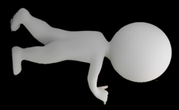




Impedance Matching during Pressure Measurement







Z_n = 4 - j*91

Chip impedance

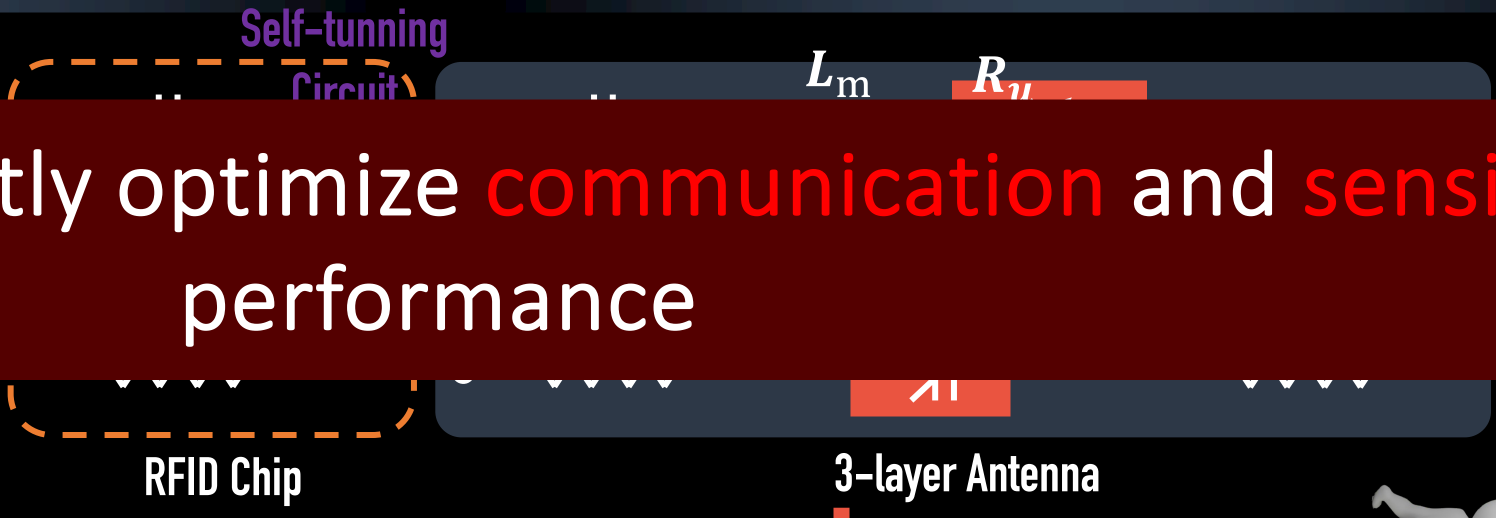
Z_1 = 1 - j*59

Pressure

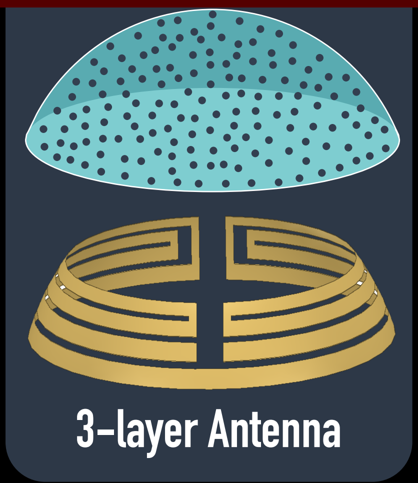
Antenna impedance

Limited detect range!

Impedance Matching during Pressure Measurement



How to concurrently optimize communication and sensing performance



$Z_n = 4 - j*91$

Chip impedance

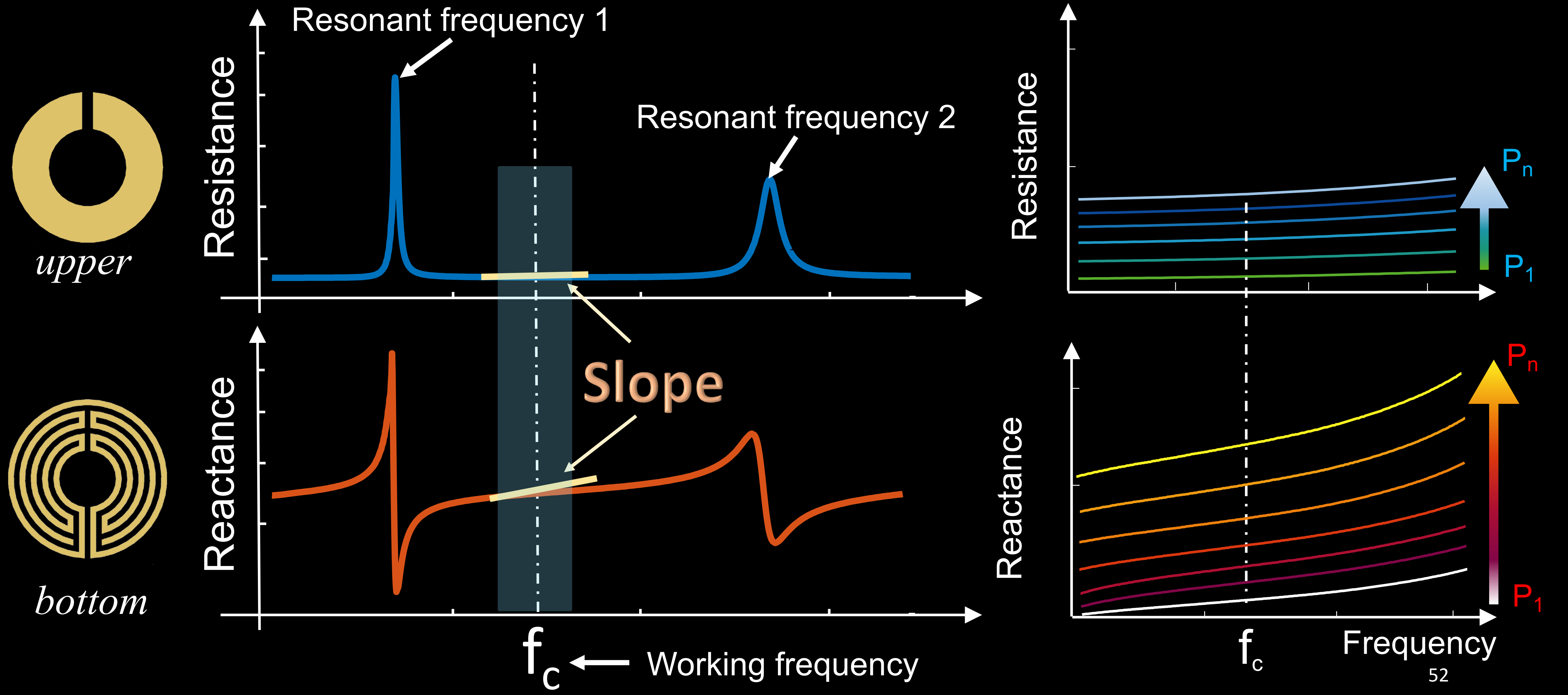
$Z_1 = 1 - j*59$

Antenna impedance

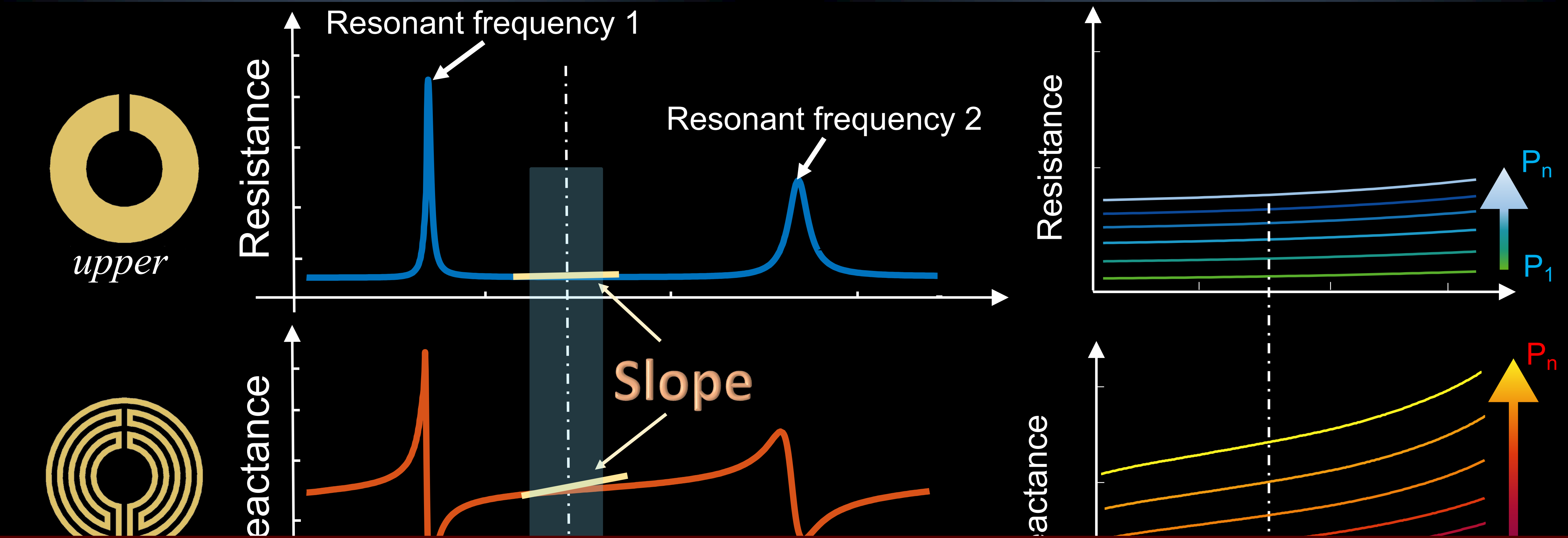
Pressure

Limited detect range!

Dual-Resonant Frequency Antenna structure

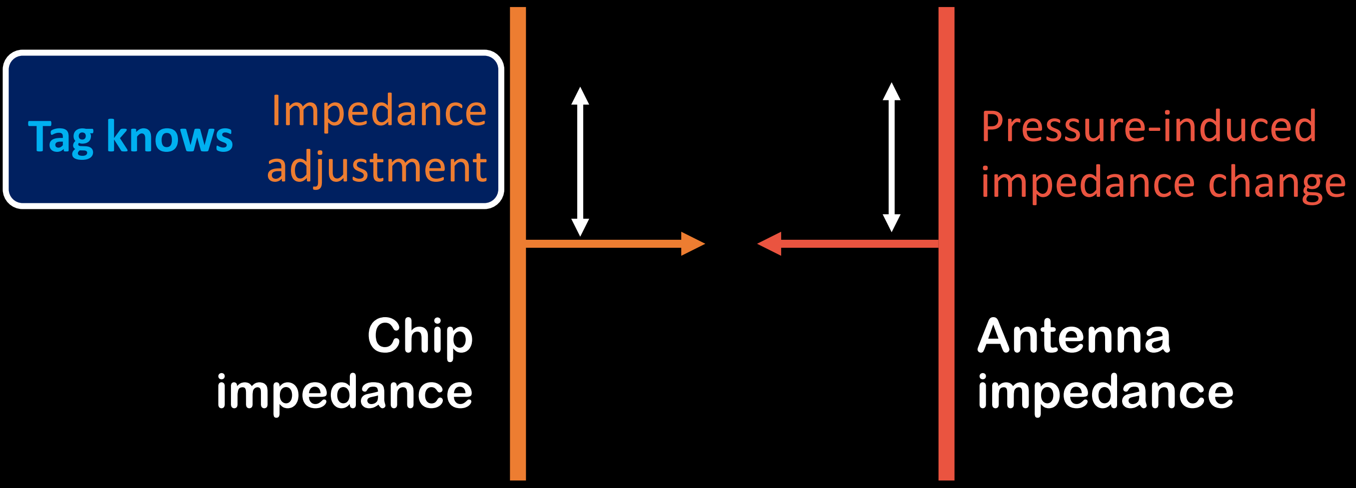


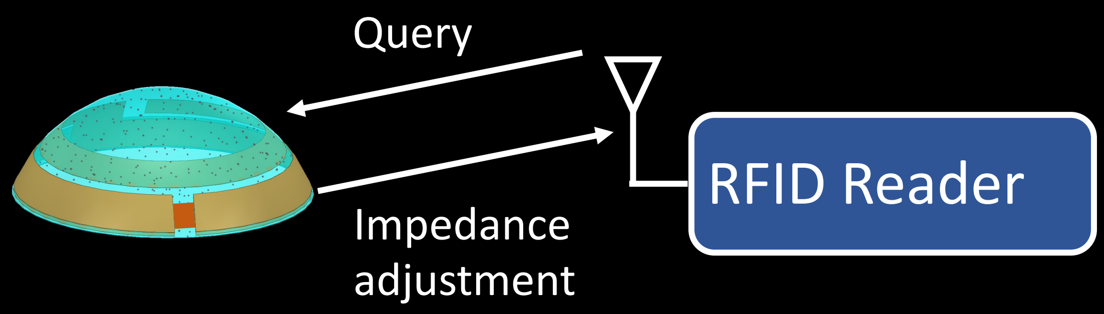
Dual-Resonant Frequency Antenna structure



Remaining less responsive to changes in resistance and increasing responsive to reactance variations

The Tag Measures the Impedance Variance of Antenna by Reading the Impedance Adjustment



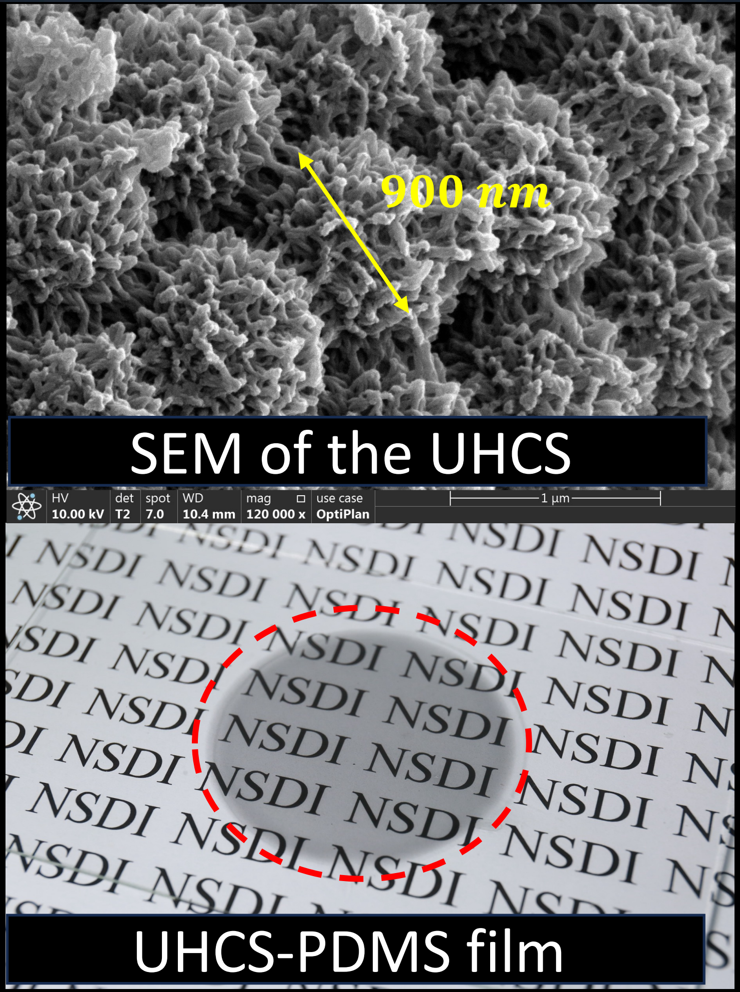


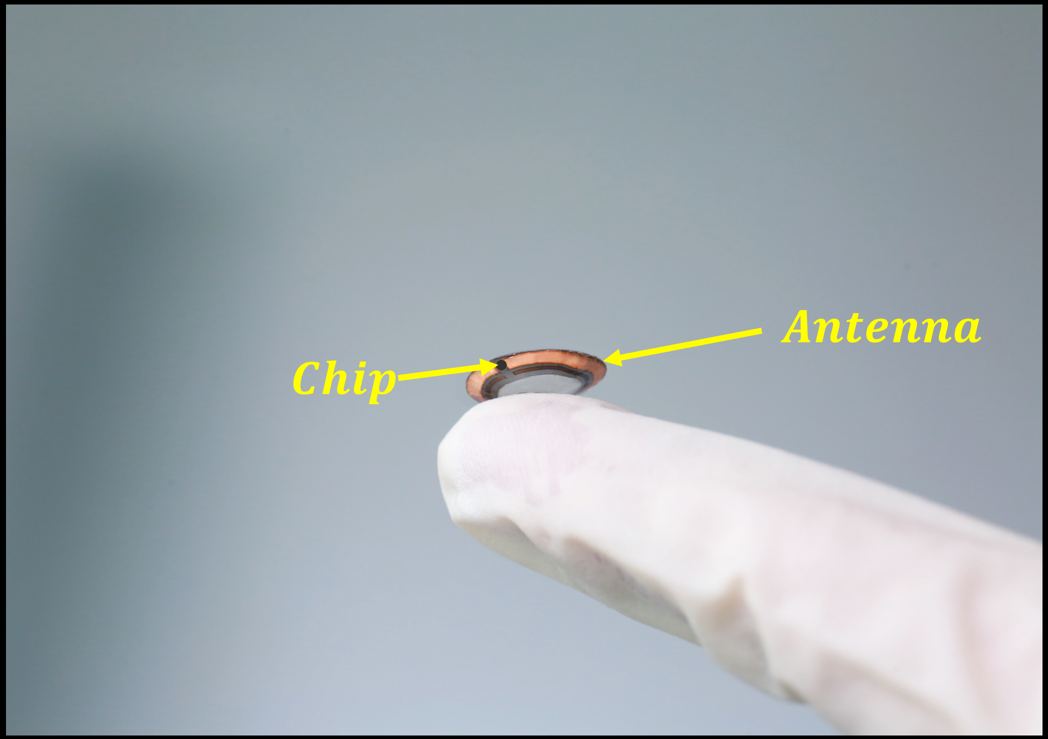
Impedance adjustment = Pressure-induced impedance change

Task 1 : Impedance Match ✓

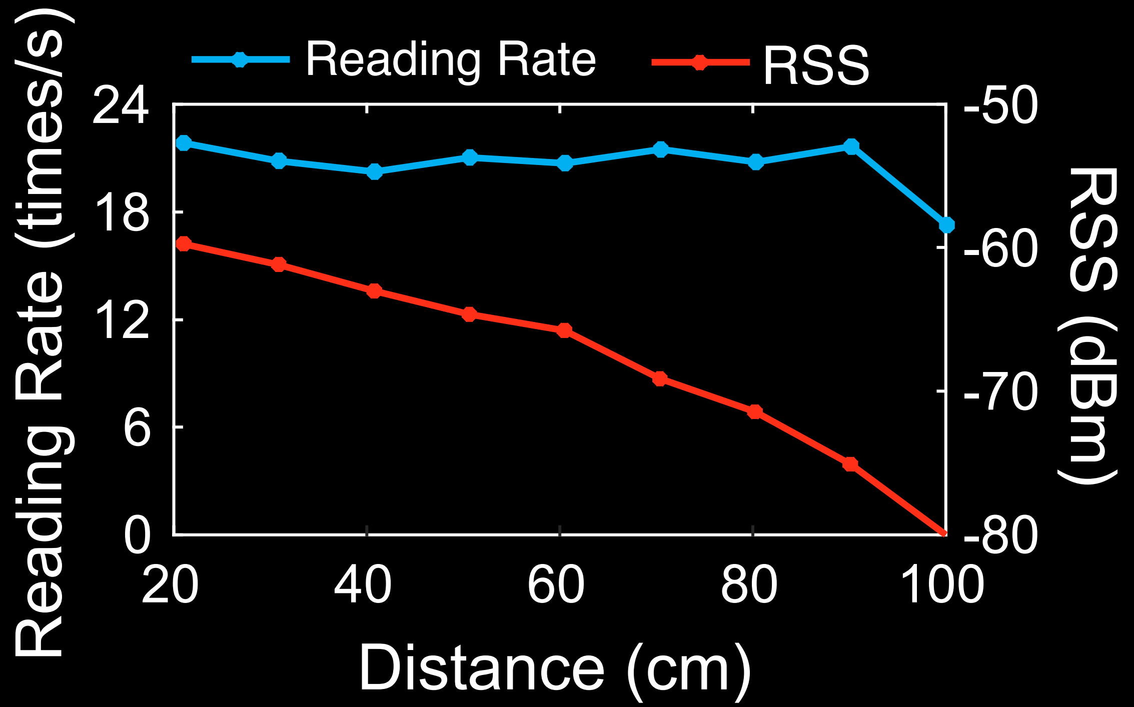
Task 2 : Impedance Measurement ✓

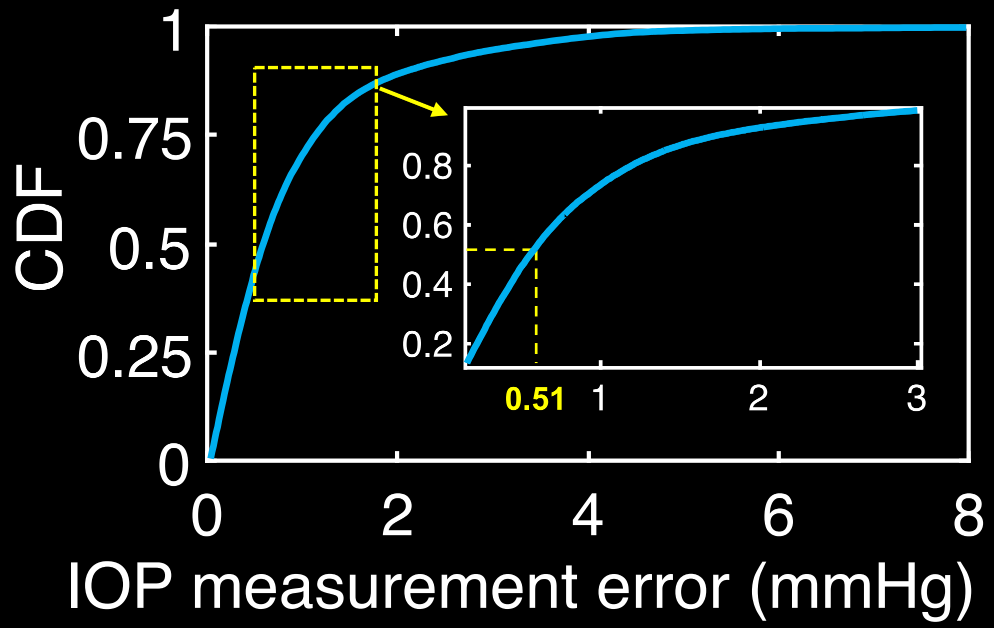
Cyclops Lens





End to end performance

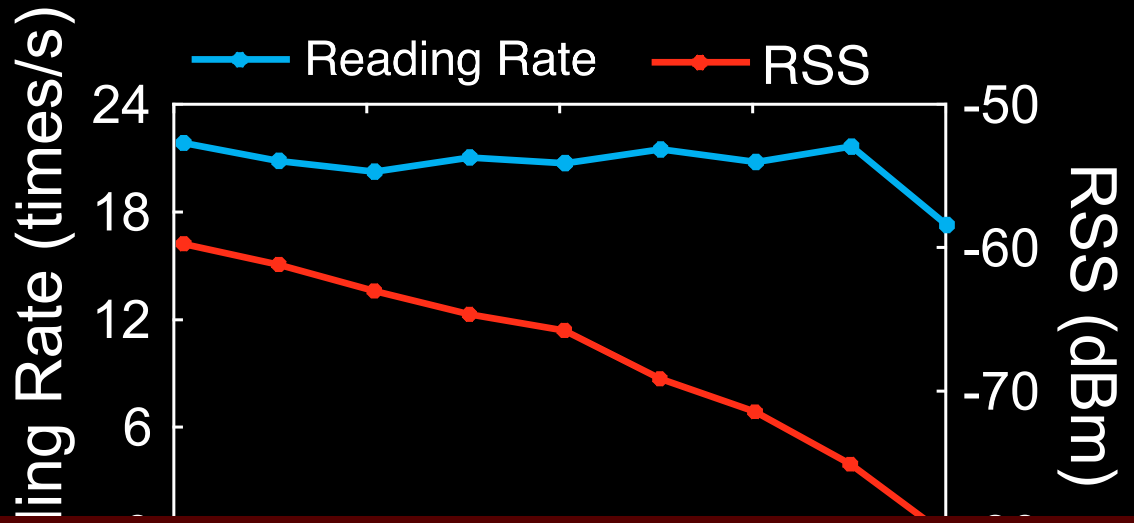


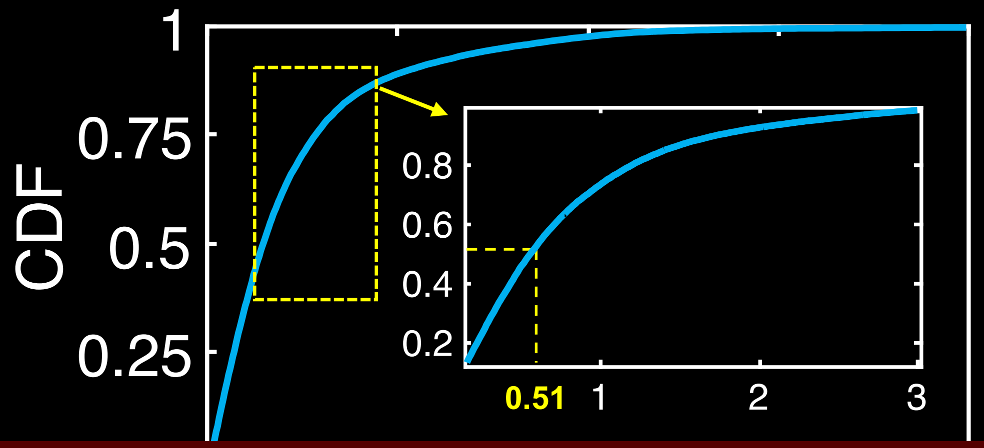


The communication range up to 1m

The median error is 0.51 mmHg

End to end performance



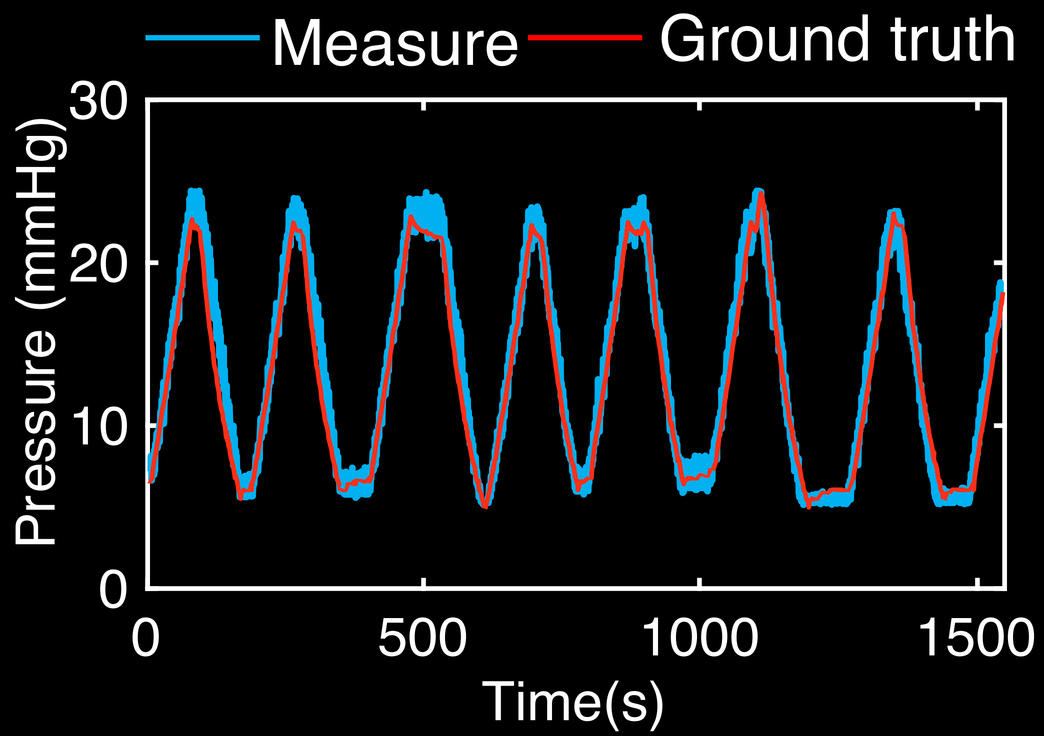


Measurement accuracy surpasses commercial portable intraocular pressure devices($\pm$ 1.2~1.5mmHg)!

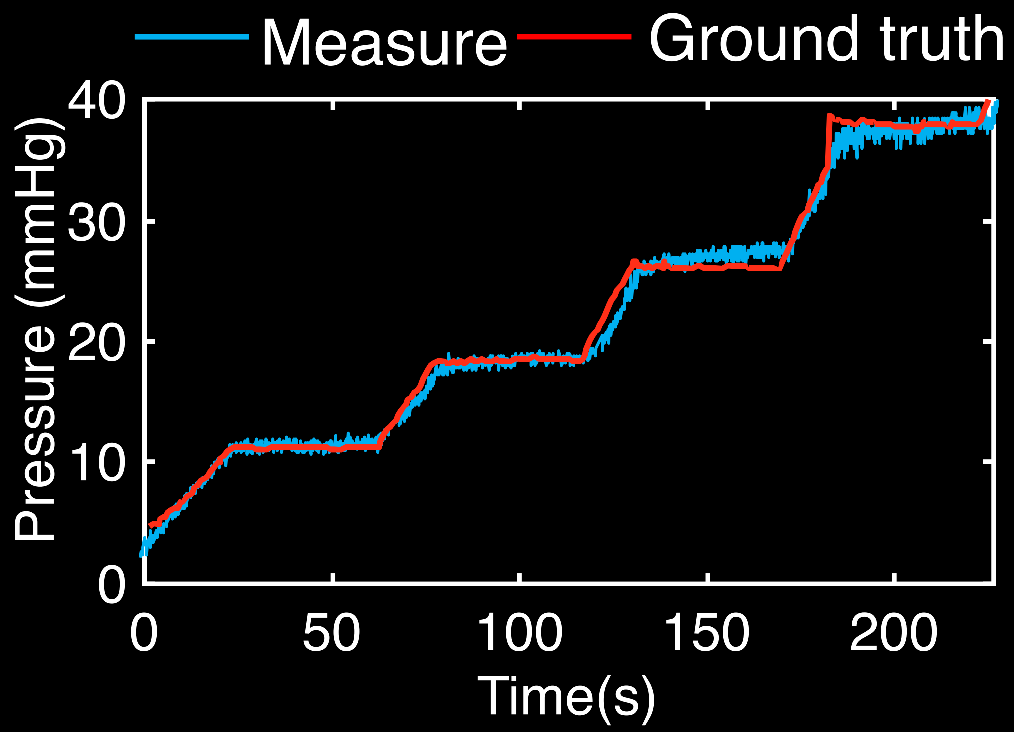
The communication range up to 1m

The median error is 0.51 mmHg

Tracking the IOP variations



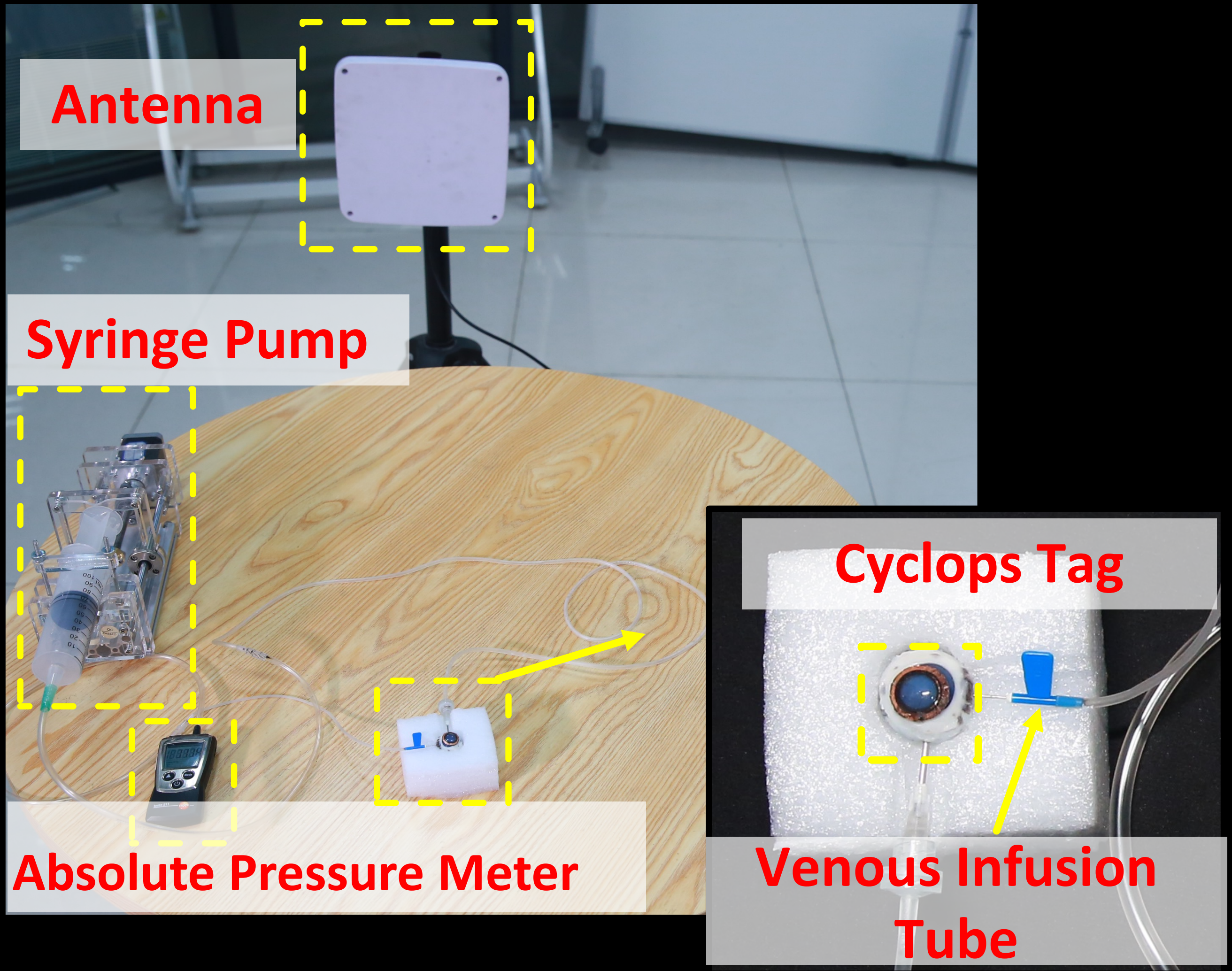
The median error is 0.53 mmHg

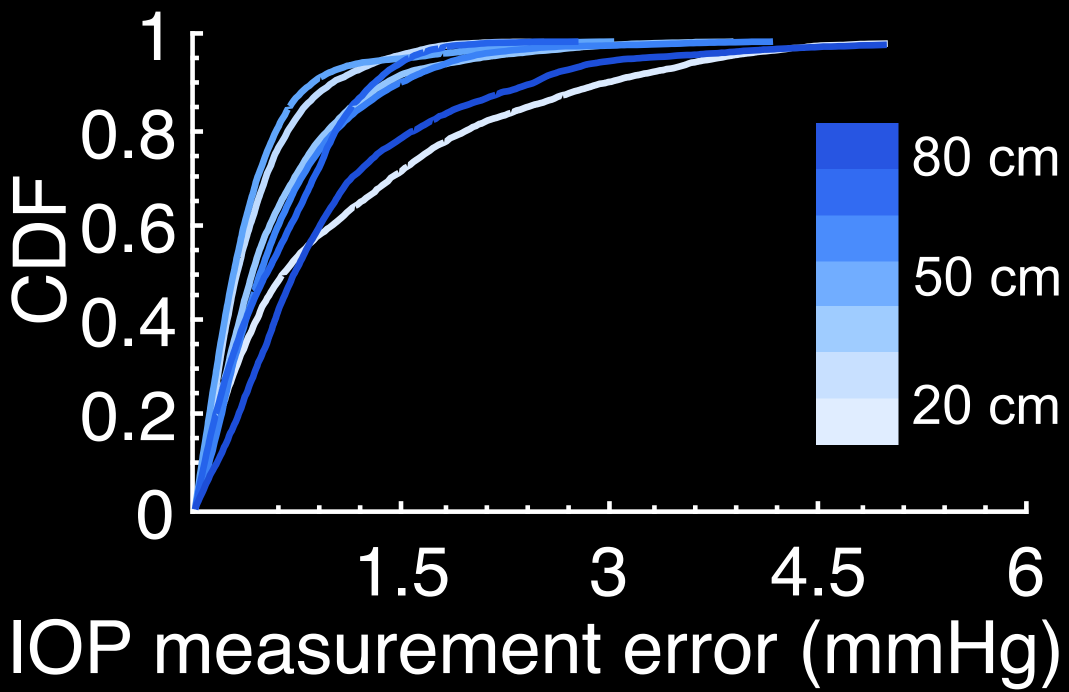


The median error is 0.54 mmHg

We are able to accurately track the fluctuation of the eye pressure!

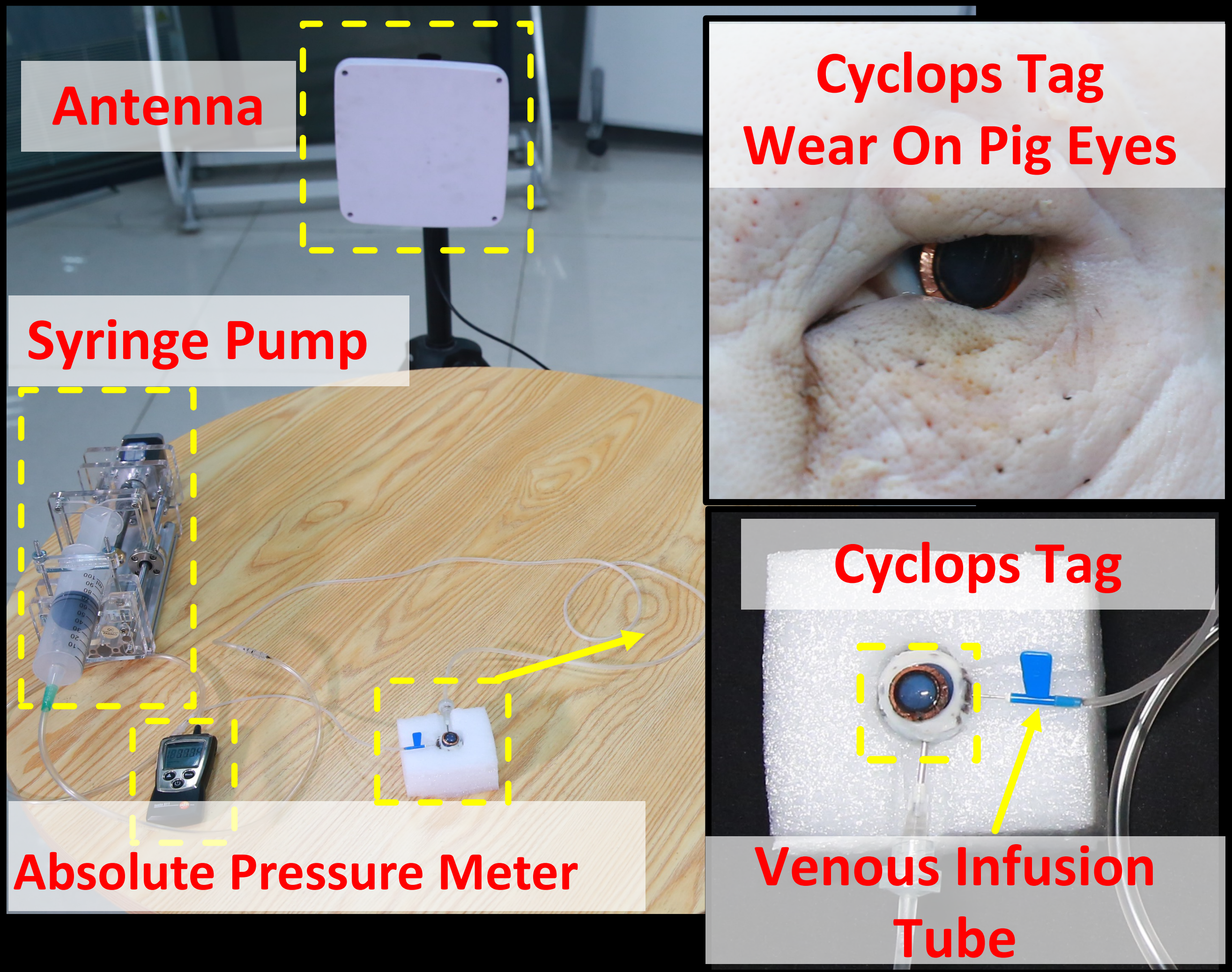
Biological impact on the performance

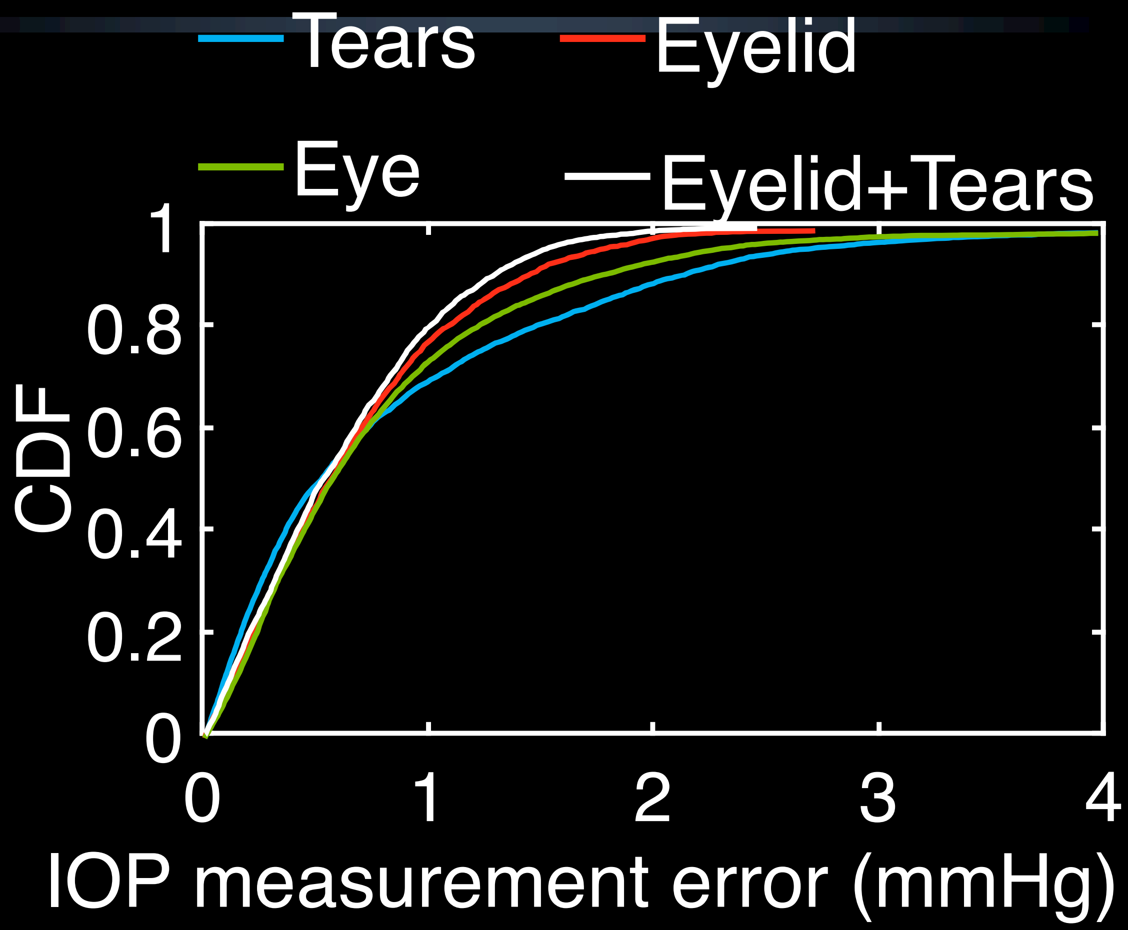




The median error is 0.33-0.85 mmHg

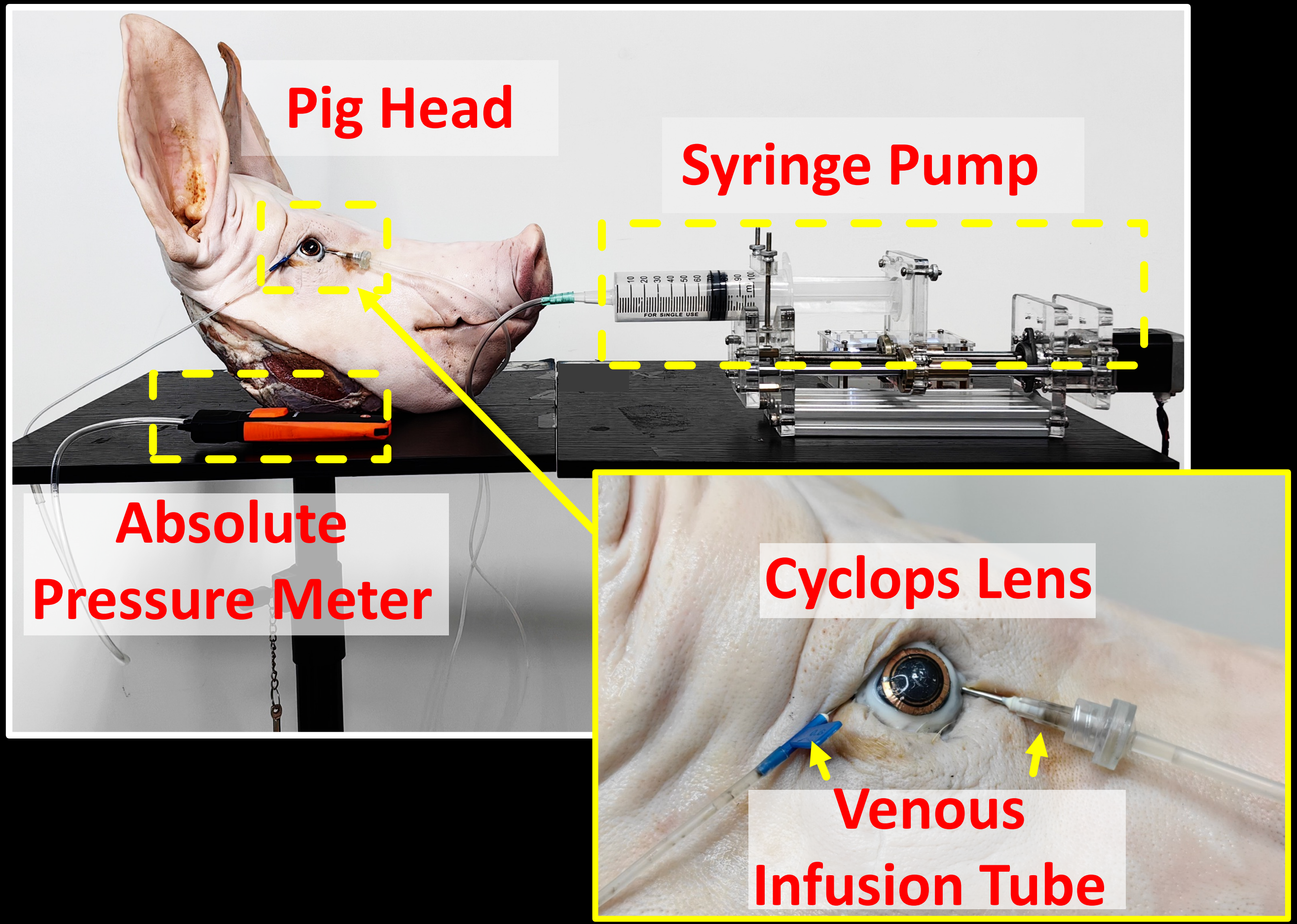
Biological impact on the performance

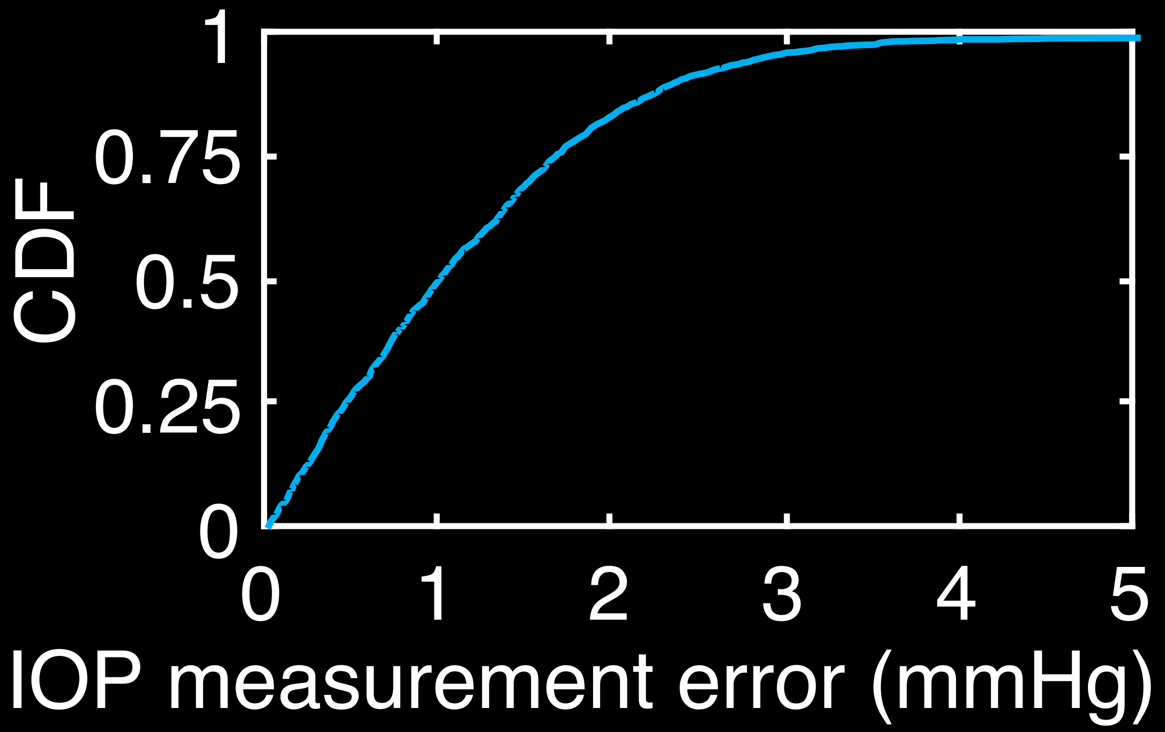




The median error is 0.5-0.6 mmHg

Biological impact on the performance





The median error is 0.97 mmHg

Q & A

Cyclops: A Nanomaterial-based, Battery-Free Intraocular Pressure (IOP) Monitoring System inside Contact Lens

University at Buffalo
The State University of New York

西北大学
NORTHWEST UNIVERSITY

University of Massachusetts Amherst