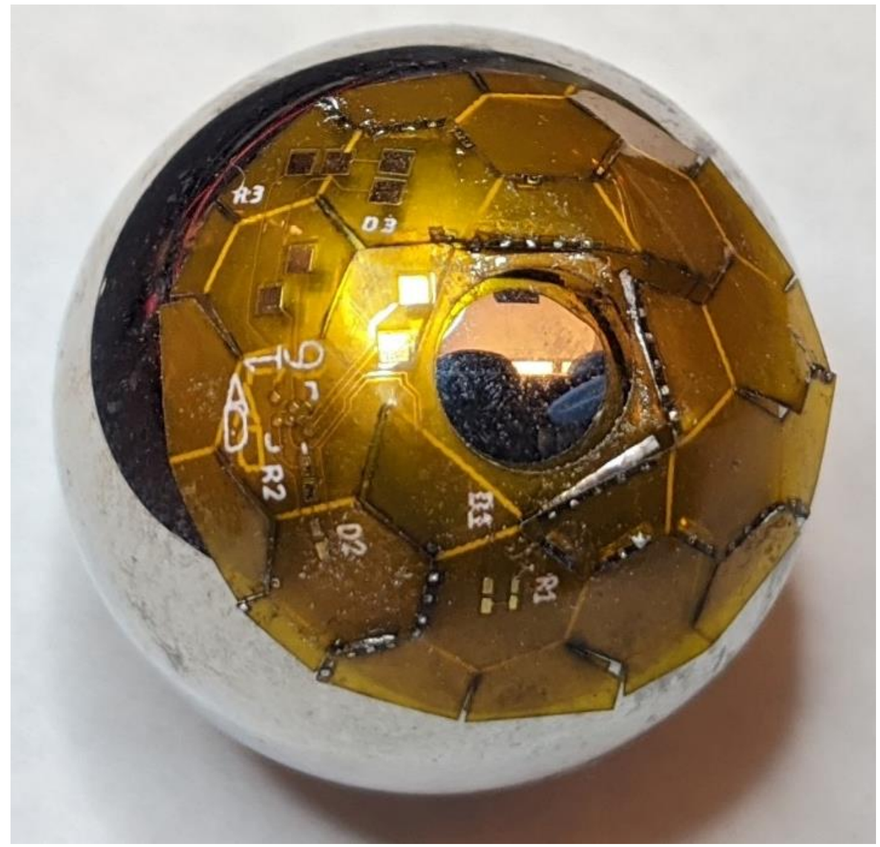
# Energy Scavenging for Ocular Microsystems

6/26/2024

Prof. Carlos H. Mastrangelo
University of Utah
Salt Lake City, UT
USA



# Outline

- Ocular microsystems – what are they ?
- Physical and Energy constraints
- Low-Profile Ocular μ-Systems (LPOμS)
- Power scavenging methods
- Thin power packs
- Summary

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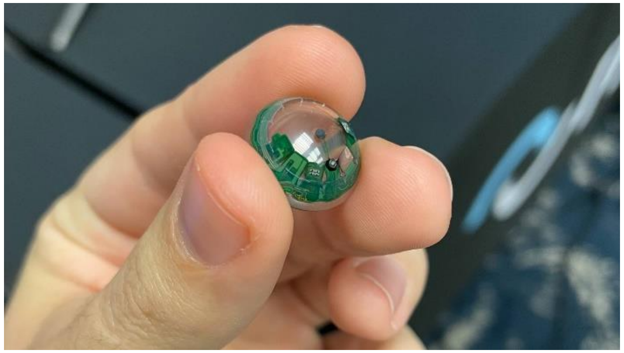
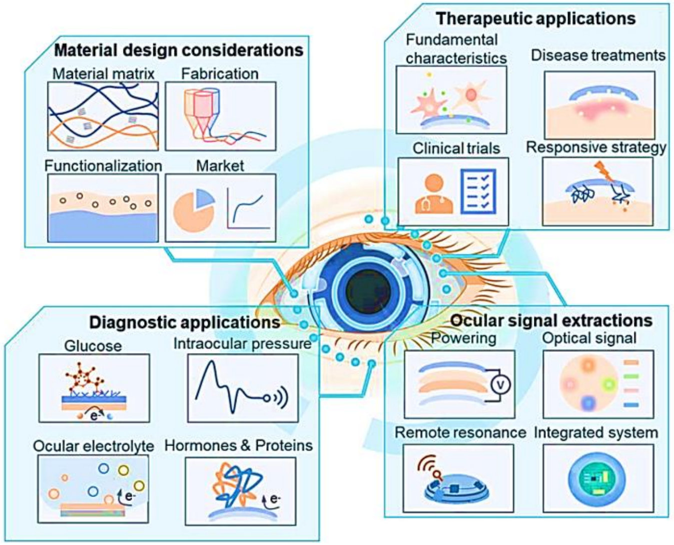
# What is an Ocular Microsystem ?

- A microsystem that is <u>on top and in contact with **eyes**</u>
- Some Ocular-µS applications
  - Vision correction devices (smart contacts)
  - Medical diagnostics sensors (glucose, pressure, etc)
  - Ocular drug delivery devices
  - Augmented reality displays
  - Video/Audio Recording devices



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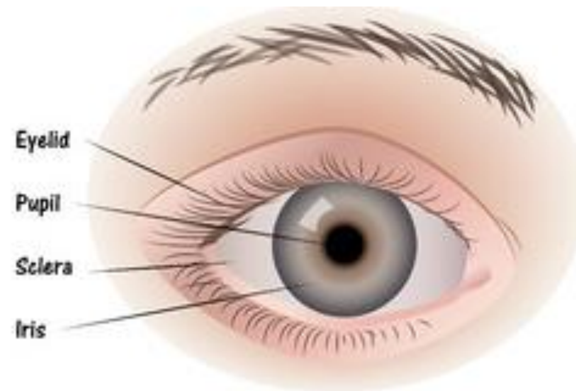
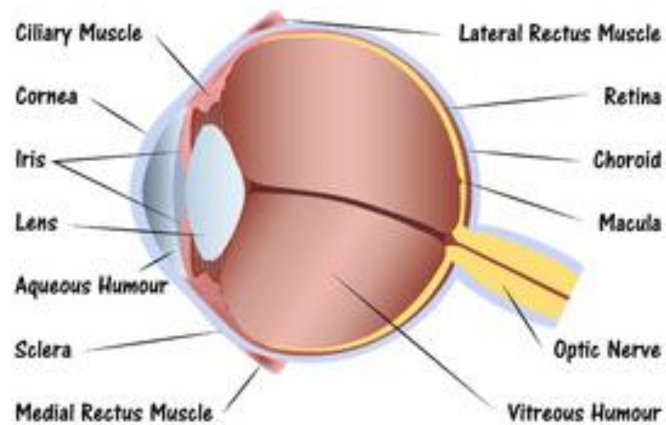
# Ocular Microsystems Requirements

- Eyeball is ≈ 22 mm in diameter
- All components must fit on top of sclera
- Sclera area ≈ 200 $mm^2$
- μ-system thickness ≤ 1 mm to fit comfortably under eyelid
- Flexible soft substrate is preferred
- Substrate must allow for oxygen permeation
- μ-system biocompatible encapsulation
- μ-system in direct contact with salty eye tears
- ≤ $1000 USD cost target with
- 6 to 12 month lifetime acceptable
- Ocular μ-system must be removed daily
- High resistance to tear during daily removal and placement handling

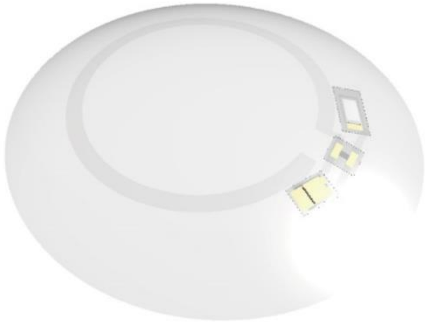


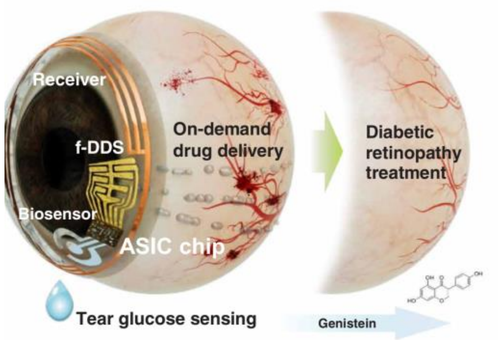

- All require a power source
- Means of wireless communication
- No power transfer wires

# Examples of Ocular Microsystems

**Intraocular Pressure Sensing: SENSIMED Triggerfish**

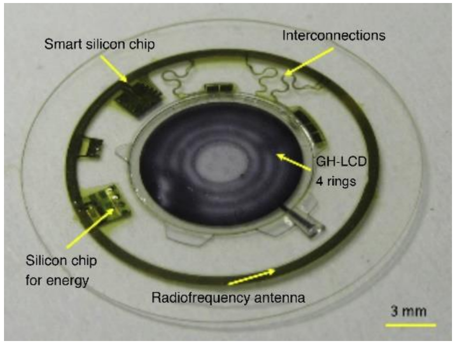


**Tear Glucose Sensing Lens**

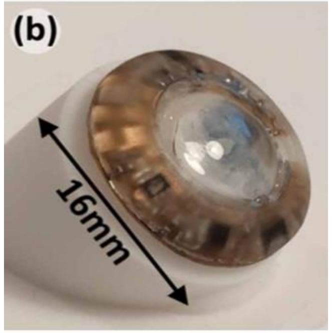



**Drug Delivery**

**Augmented Reality Contact Lens: Mojo Vision (defunct)**




**Light-Modulated Lens for Aniridia Treatment**




**Smart Contact Lens for Vision Correction**


2. Park, J. *et al.* Soft, smart contact lenses with integrations of wireless circuits, glucose sensors, and displays. *Sci. Adv.* **4**, eaap9841 (2018).
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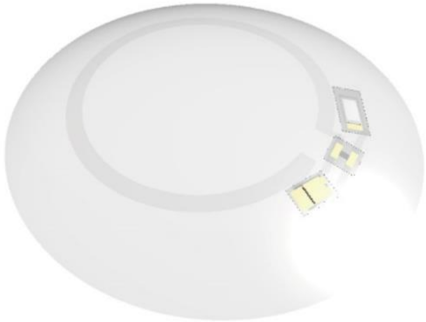

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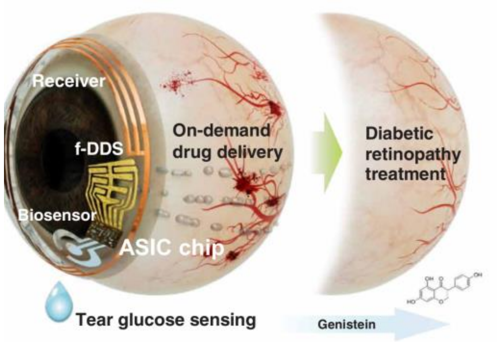


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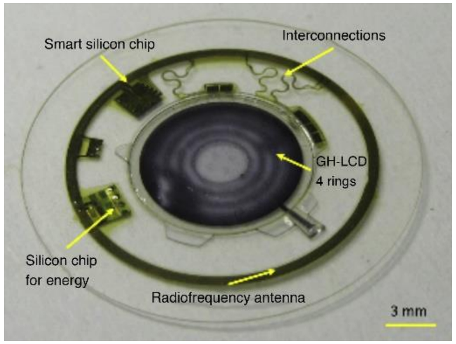


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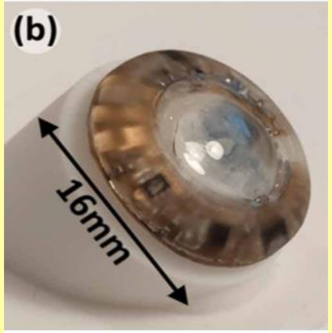


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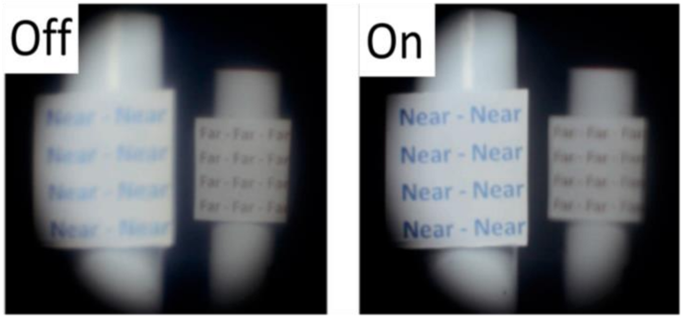
# Smart Contact Lenses (SCL)




## Vision Correction/Presbyopia

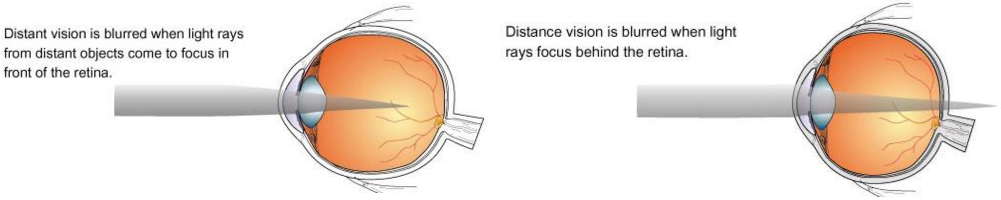



**Image plane before retina**

**Image plane past retina**

**<u>Presbyopia:</u>**

- Gradual loss in the ability of the eye to focus
- Presbyopia results in the inability to focus on nearby objects
- Age related refractive disorder!

<u>Presbyopia affects:</u>

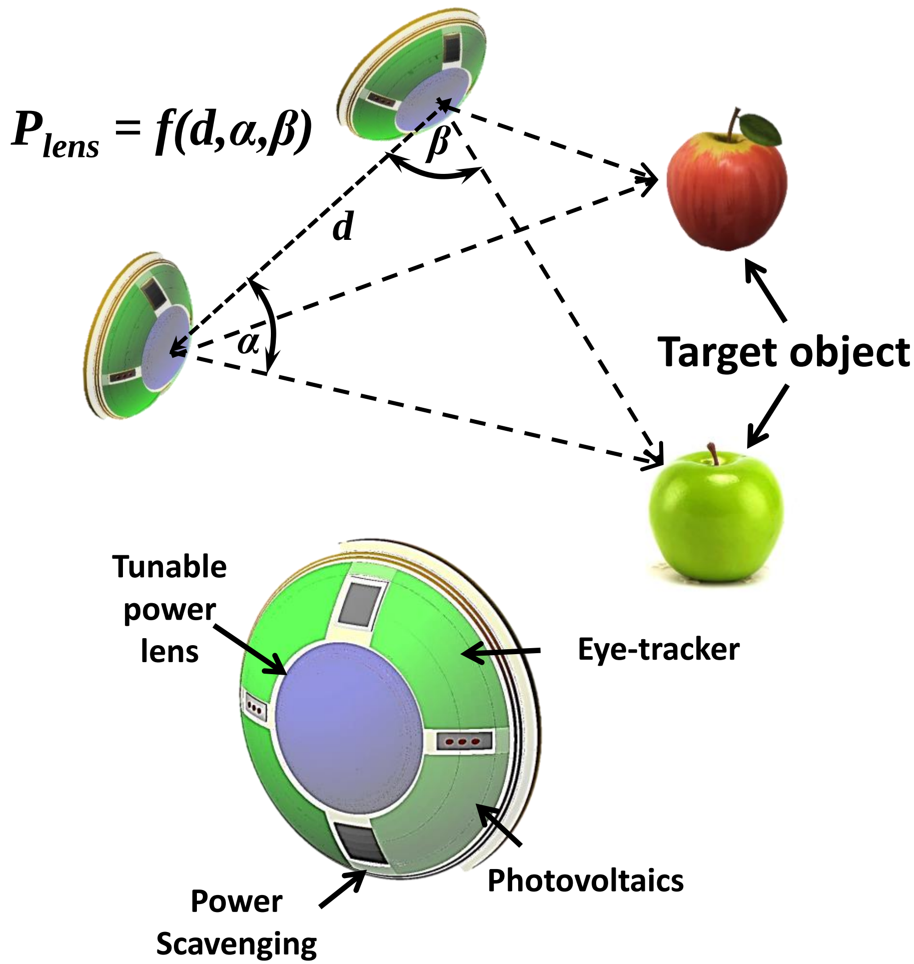
- **25%** of the world's population!
- **1.8 billion** people (Fricke, 2018).


1. Bailey, J., Morgan, P. B., Gleeson, H. F. & Jones, J. C. Switchable Liquid Crystal Contact Lenses for the Correction of Presbyopia. *Crystals* **8**, 29 (2018)

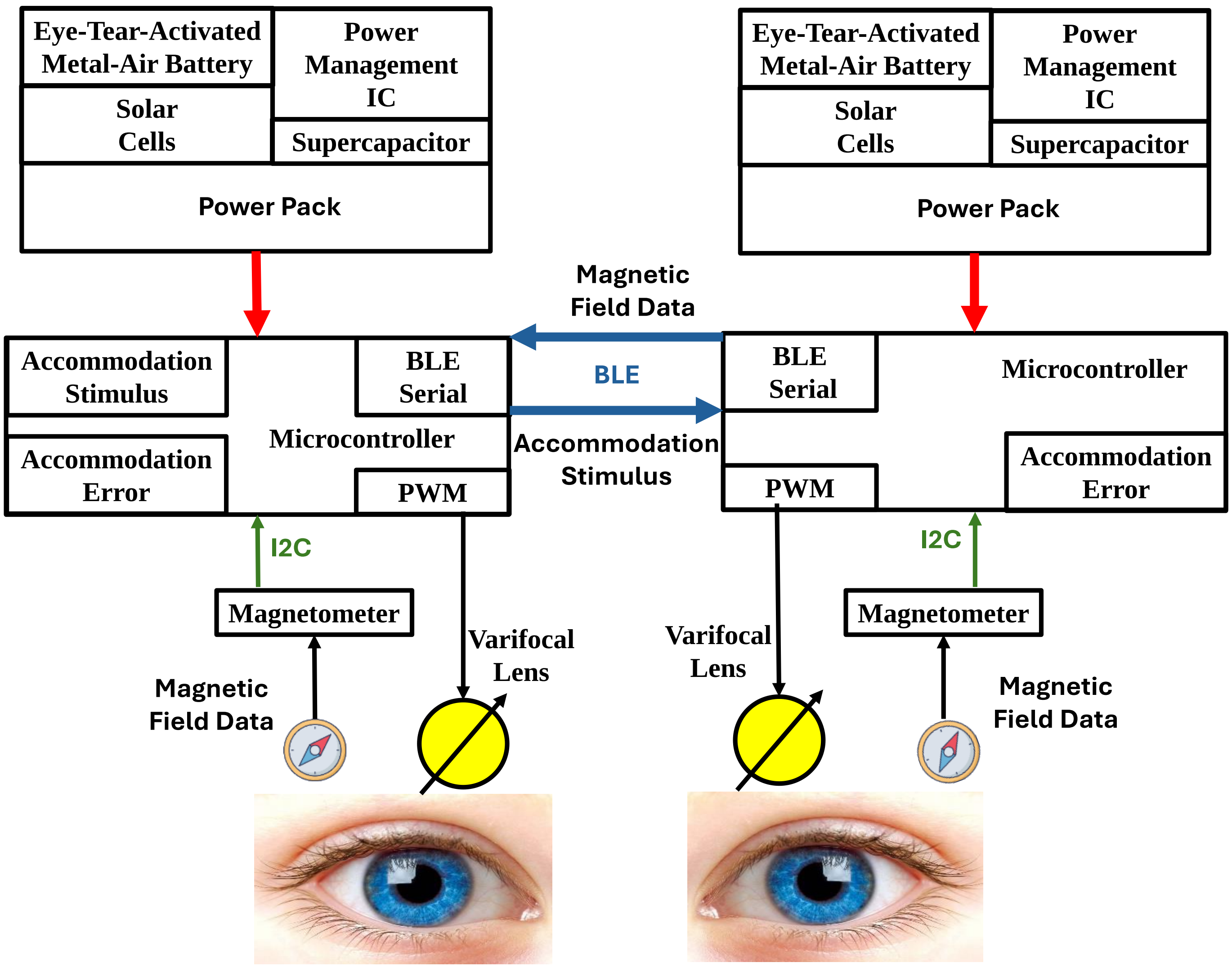
# Presbyopia Correction with Smart Contact Lenses

Smart Contacts System needs:

1. µW varifocal lenses
2. Paper-thin light level, orientation and object distance micro sensors
3. Thin photovoltaic cells with power management circuits
4. Paper-thin embedded µW micro-processors and communications circuits.



# Block Diagram of University of Utah SCL

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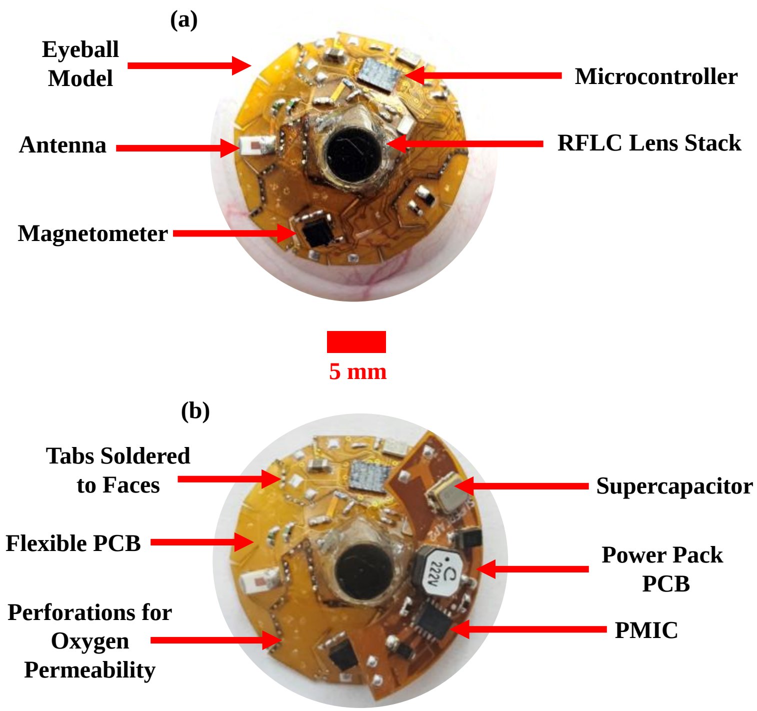
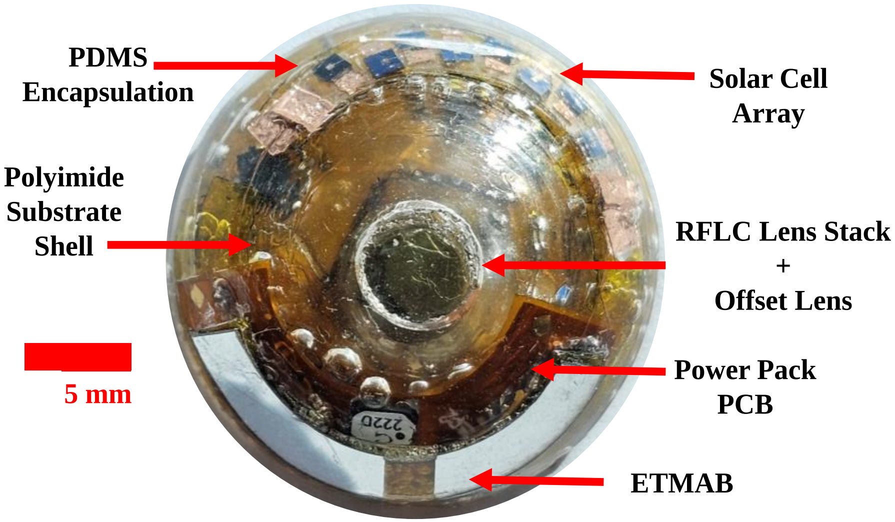
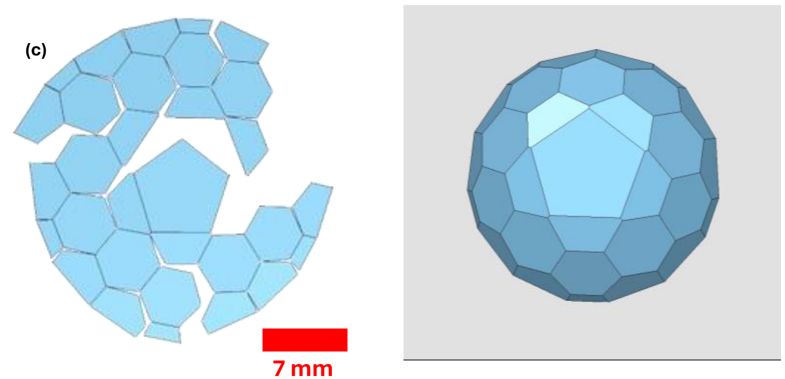
# Current Version SCL Assembly (WIP)




- Currently around 2 mm thick
- Implemented using origami+ COTS
- Custom varifocal LCD lens
- Built in vergence sensor
- Future versions require thinned microchips $$

# SCL System Energy Consumption and Response Time

| Task | Left Eye | | Right Eye | |
|---|---|---|---|---|
| (PWM is active at each step) | Response Time | Energy Consumption | Response Time | Energy Consumption |
| Magnetometer Read | 608 µs | 1.29 µJ | 608 µs | 1.29 µJ |
| Magnetometer Corrections | 41 µs | 67.78nJ | 41 µs | 67.78 nJ |
| Magnetic Field Data Transmit | 2552 µs | 19.54 µJ | -- | -- |
| Magnetic Field Data Receive | -- | -- | 2490 us | 15.28 uJ |
| Accommodation Stimulus Calculation | -- | -- | 52 us | 87.69 nJ |
| Accommodation Stimulus Transmit | -- | -- | 2472 us | 17.95 uJ |
| Accommodation Stimulus Receive | 2410 µs | 13.2 µJ | -- | -- |
| Accommodation Error Calculation and PWM setup | 15 µs | 25.85 nJ | 15 µs | 25.85 nJ |
| Internal µC PWM | 994 ms | 367. 38 µJ | 994 ms | 367.38 µJ |
| Total (internal PWM) | 1 s | 401.08 µJ | 1 s | 401.08 µJ |
| **Total Energy/Day** | **12 hrs** | **17 J** | **12 hrs** | **17 J** |

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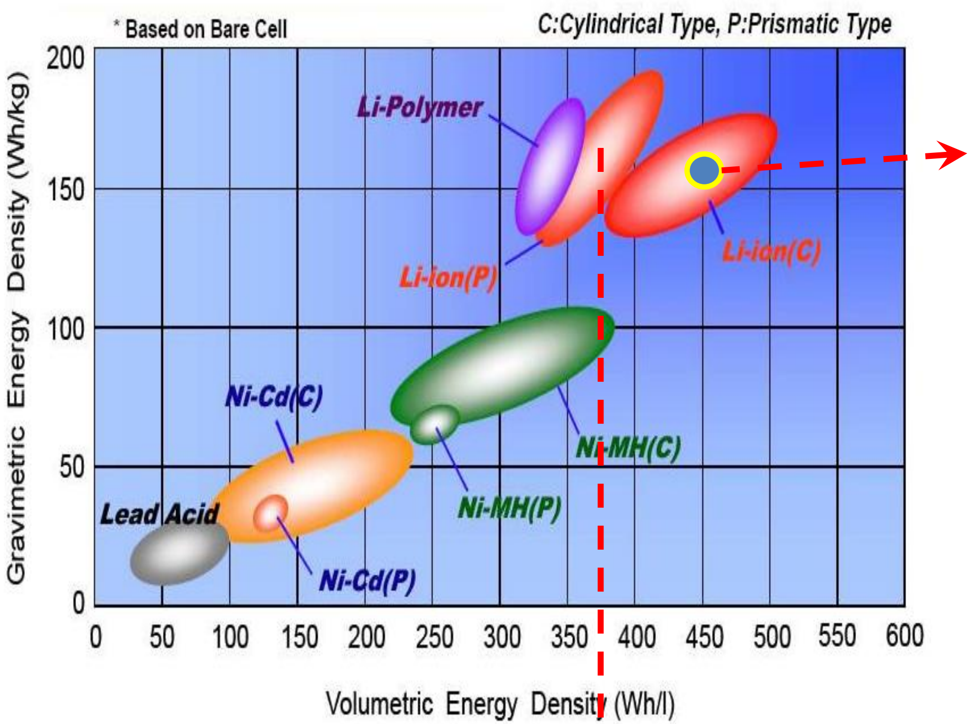
# Current Li-Ion Rechargeable Battery Tech




375 Wh/l = 1.35 J/mm$^3$

- 0.5 mm-thick battery volume ≈ 95 mm$^3$
- $E_{batt}$ ≈ **128 J**

Average load over 12 hrs

- $P_{avg}$ ≈ 3 mW
- $V_{batt}$ = 3 V
- $I_{avg}$ ≈ 1 mA

Battery power is sufficient for low power burst BLE communications

- Would like improved battery tech with higher volumetric energy density
- All ocular microsystems operate on very low power
- Where is the energy coming from ??

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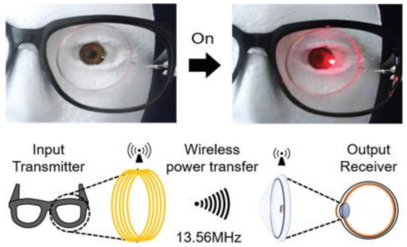
# Possible LPOμS Energy Sources

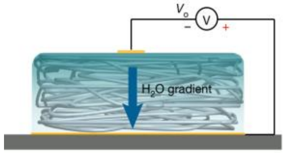
- **Physical Sources**
  - Photovoltaics
    - Solar cells
  - Wireless RF transfer
  - Bio-mechanical motion
    - Electrostatic generator
    - Magnetic induction
  - Eye Tear Hydrovoltaics
    - Requires thin membrane
    - No waste products and replenishable
  - Thermoelectricity
    - No waste products and replenishable
- **Chemical Sources**
  - Rechargeable batteries
    - Recharge once per day
    - No waste products
    - Recharged by capacitive coupling
  - Metal-Air batteries
    - High energy
    - Consumable
    - Poison eye fluid
  - Glucose batteries
    - Low energy output

**Photovoltaics**

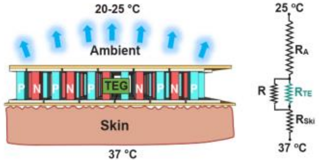

**Radio scavenging**



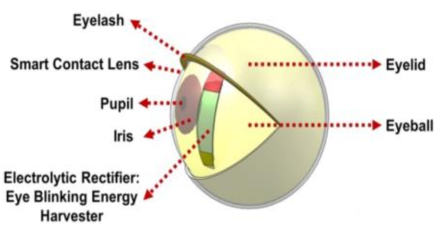

**Hydro-voltaic**



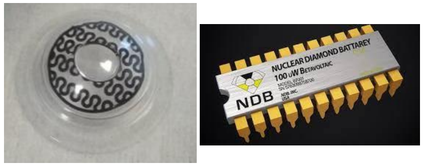

**Thermoelectric**




**Bio-Mechanical & Bio-Electrochemical to Electrical**




**Micro Batteries**



# Possible LPOµS Energy Sources

| • **Physical Sources** | **Power/Energy density** | **Issues** |
|---|---|---|
| – Photovoltaics<br>• Solar cells | (1 $mW/cm^2$ diff sunlight, 100 $\mu W/cm^2$ indoor)<br>**≈20 J/day avg** | Thin and flexible, **high-energy**<br>Transparent to visible possible |
| – Wireless RF transfer | (~5-10% efficiency), few mW, **≈100 J/day avg** | Need **intrusive external driver** |
| – Bio-mechanical motion<br>• Electrostatic generator<br>• Magnetic induction | 140 nW/cm2 electrostatic<br>1 $\mu W/cm^2$ magnetic<br>**≈0.1 J/day avg** | Needs attachment to eyelid<br>**Low energy** |
| – Eye Tear Hydrovoltaics<br>• Requires thin membrane<br>• No waste products and replenishable | 8.5 $\mu W/cm^2$<br>**≈1 J/day avg** | Complicated fabrication<br>**Low energy** |
| – Thermoelectricity<br>• No waste products and replenishable | 50 $\mu W/cm^2$ ($\Delta T$ = 10C)<br>**≈4 J/day avg** | Thin stacked generator<br>**Low energy** |
| • **Chemical Sources** | | |
| – Rechargeable Li batteries<br>• Recharge once per day<br>• No waste products<br>• Recharged by capacitive coupling | 68 $J/cm^2$ (0.5 mm thick), 3V<br>**≈128 J/charge** | Needs custom fabrication<br>Toxic materials<br>**High capacity** |
| – Metal-Air batteries<br>• High energy<br>• Consumable<br>• Poison eye fluid | 1.3 $mW/cm^2$, 2V(Pt-Mg) (2 week lifetime)<br>**≈3200 J fixed total energy**<br>Consumable<br>Rechargeable may be possible | Consumable<br>Excess Mg waste<br>biocompatibility |
| – Glucose batteries<br>• Low energy output, self recharge | **≈0.34 J/charge**<br>200 $\mu W/cm^2$, 0.6V | Self recharge from eye tear<br>Low voltage, **Low Energy** |

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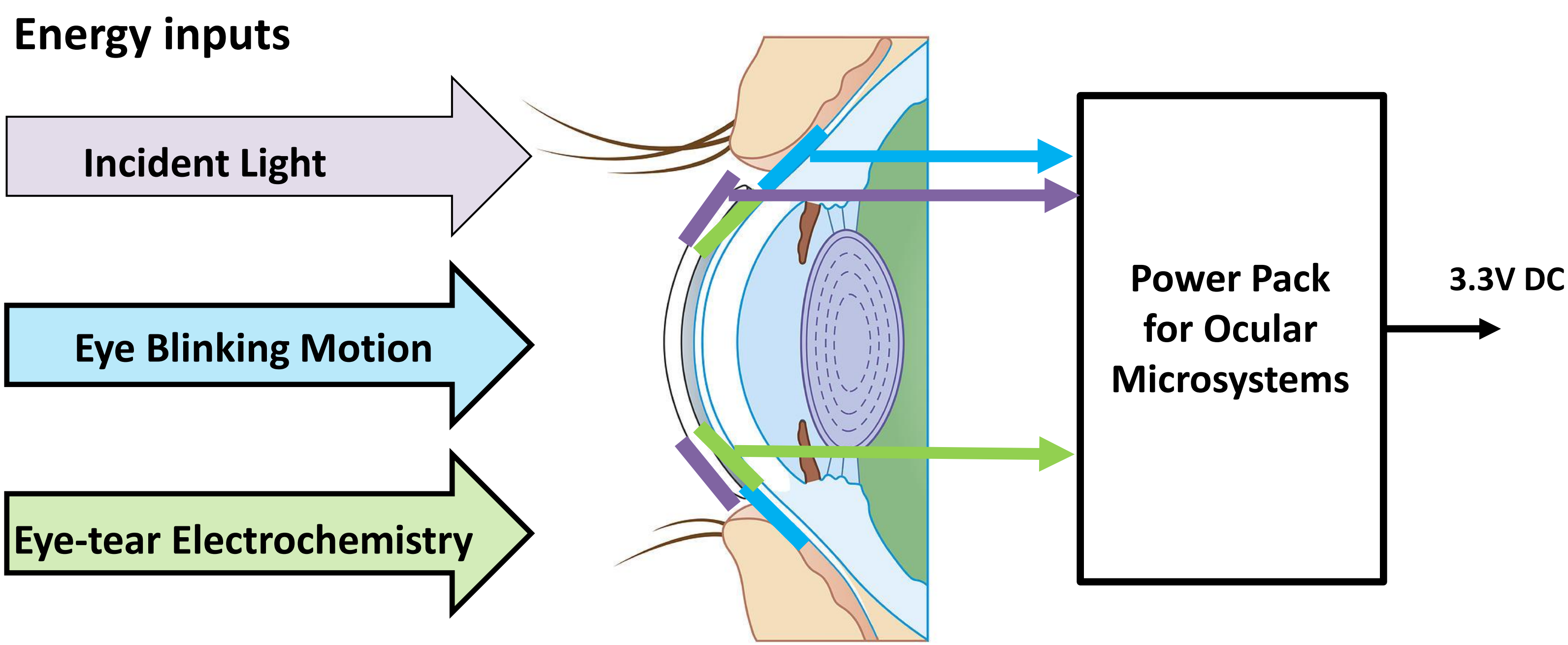
# Promising Energy Sources



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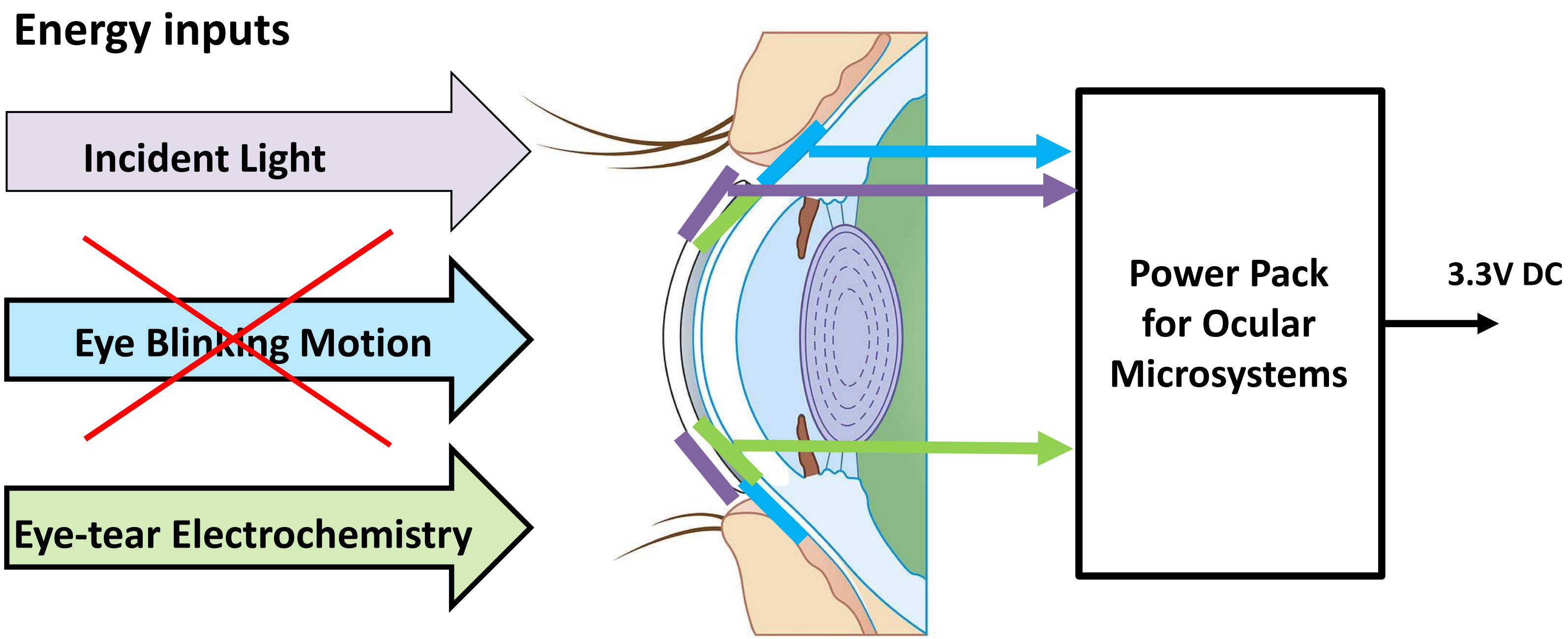
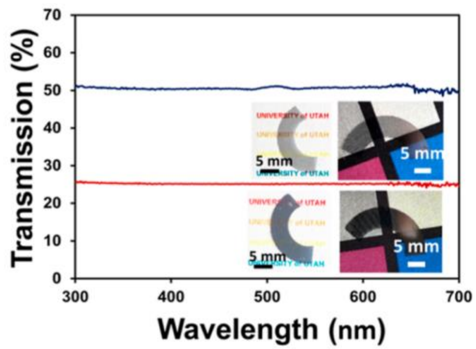
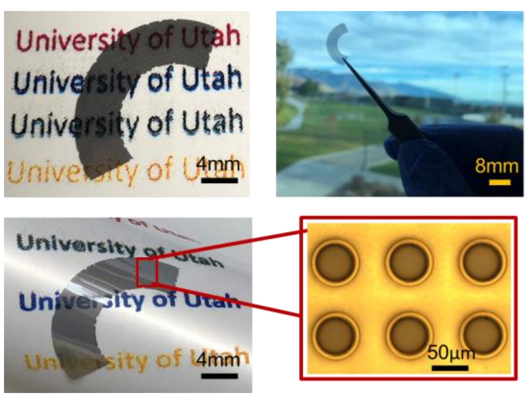


# Semi-transparent and flexible silicon solar cell

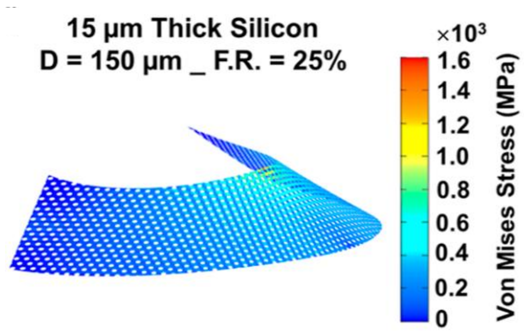
**Releasing**

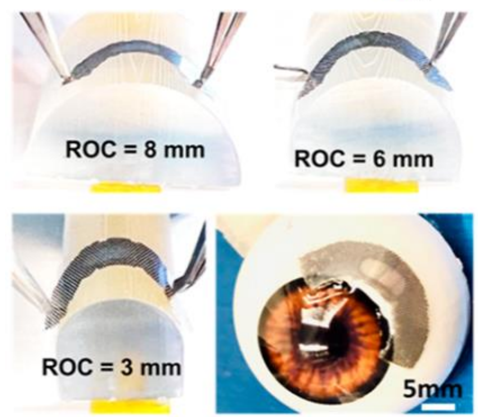
**UV-Vis**



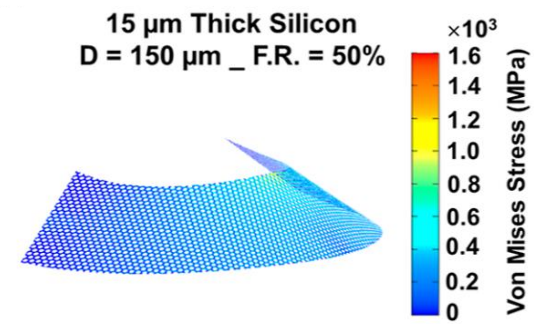



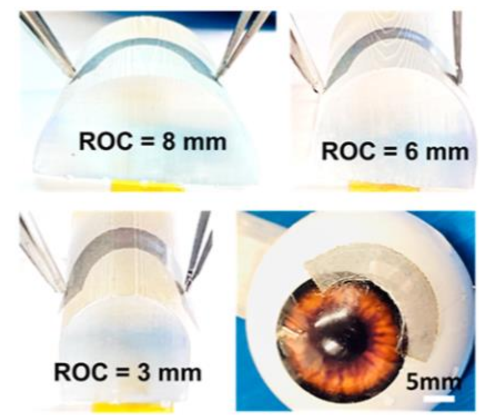

**25% Transparency**




**50% Transparency**



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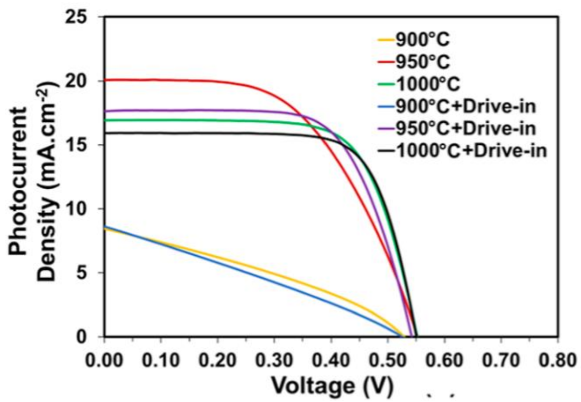
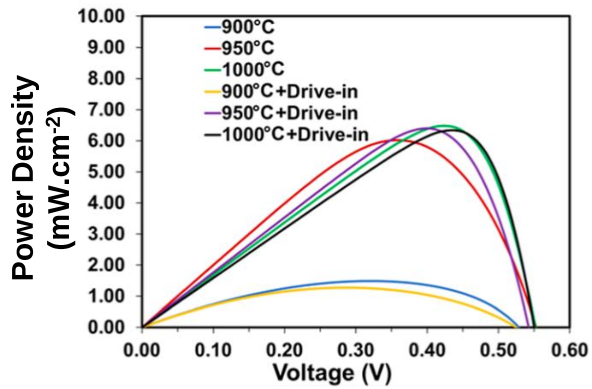
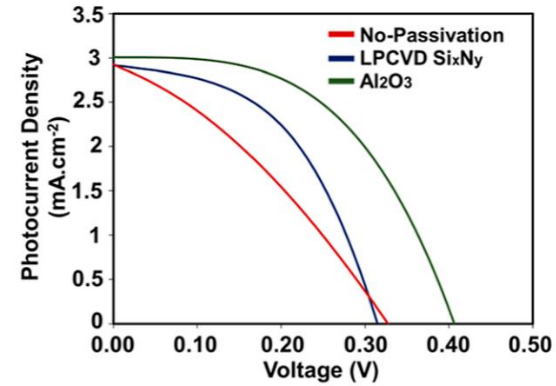
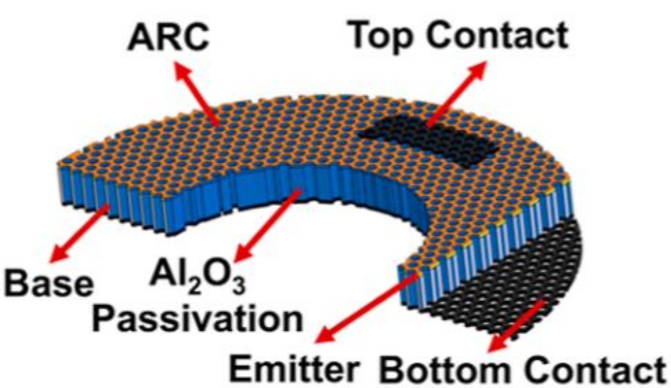
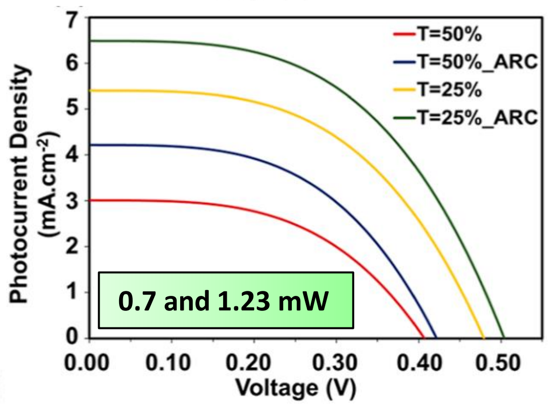
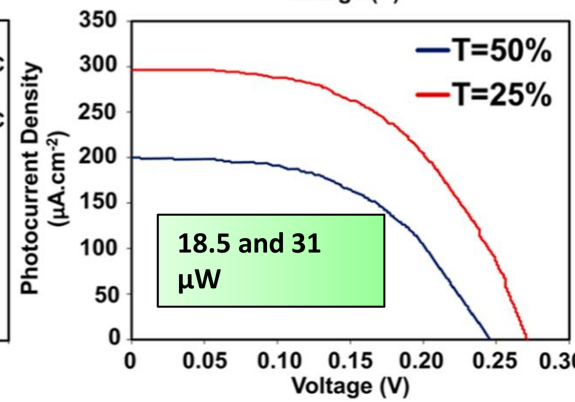


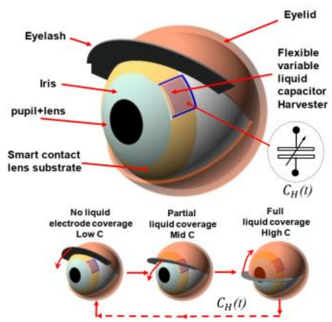



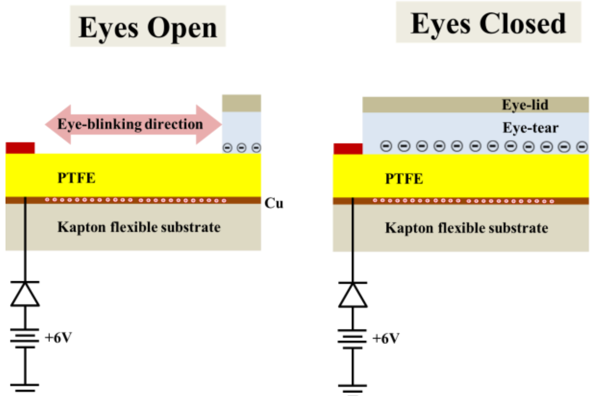



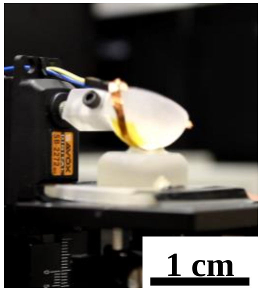



# Electrostatic Generators: Wetting/de-wetting

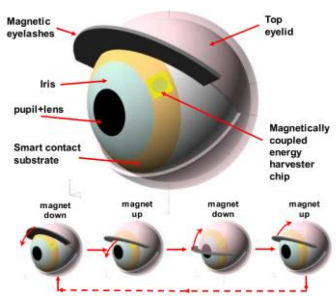


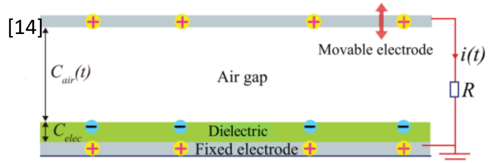



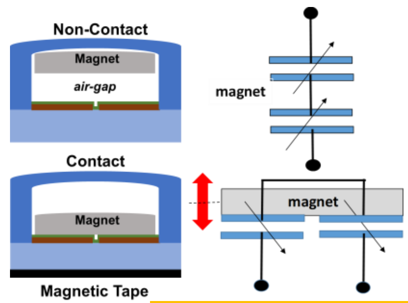



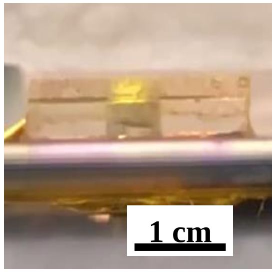

**Variable Capacitance** $C_H(t) = \frac{\varepsilon_f.\varepsilon_0.w.l_{wet}(t)}{t_f}$ **Harvested Energy** $\Delta U = \frac{1}{2}Q_{pre}^2(\frac{1}{C_{min}} - \frac{1}{C_{max}})$

# Electrostatic Generators: Magnetically coupled




**Variable Capacitance** $C(g) = \frac{C_m(g)\cdot C_{ox}}{2(C_m(g)+C_{ox})}$ **Harvested Energy** $\Delta U = \frac{1}{2}Q_{pre}^2(\frac{1}{C_{min}} - \frac{1}{C_{max}})$

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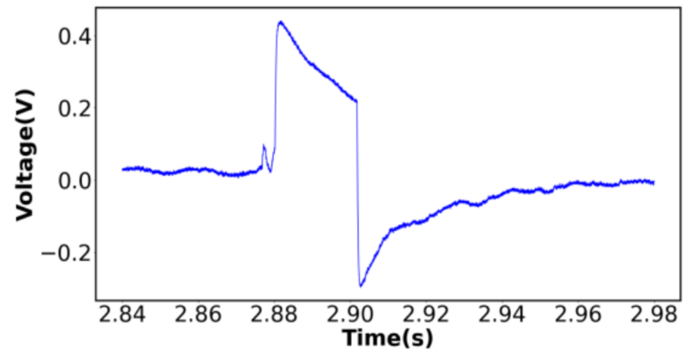
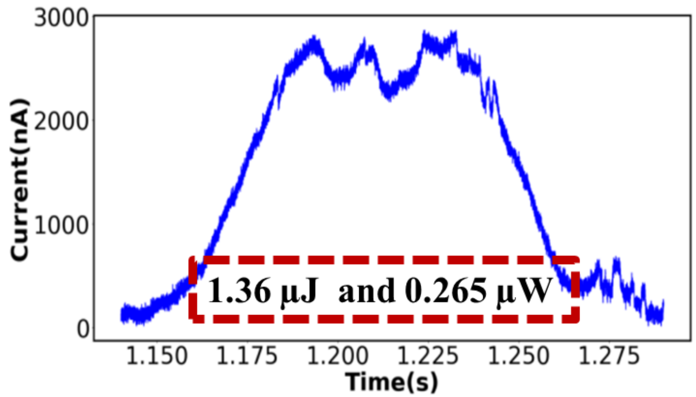
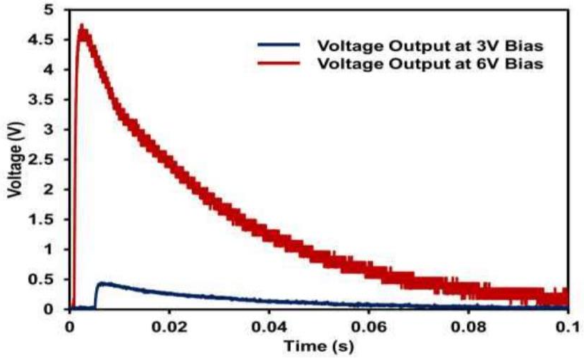
# Electrostatic Generators: Experimental Results

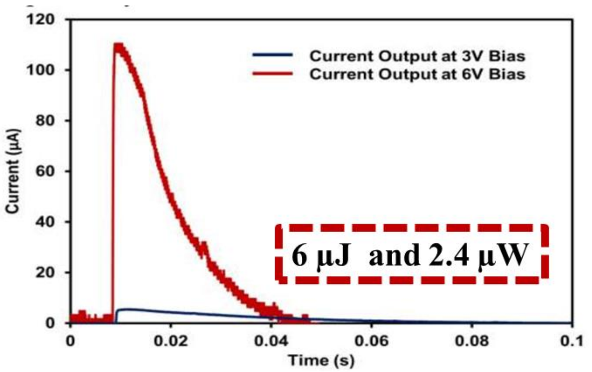
## Wetting/dewetting generator




## Magnetically-coupled harvester

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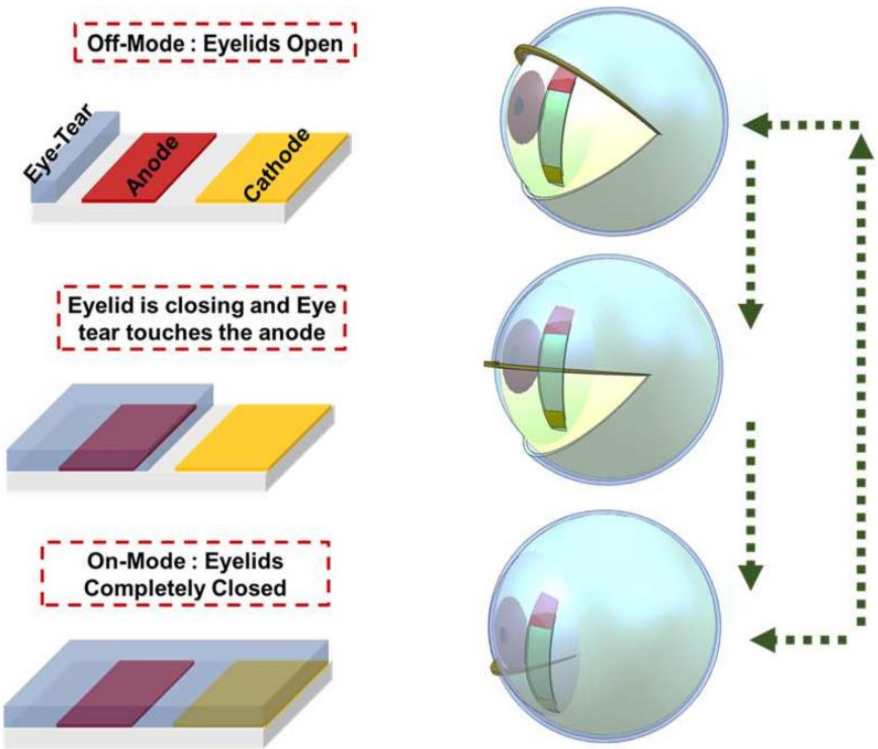
# Eye tear activated Metal-air battery (ETMAB)




- ETMAB Battery driven by electrochemical reactions between two metal electrodes and eye tear as the electrolytic solution

$$\text{Anodic reactions}: \mathrm{M} \leftrightarrow \mathrm{M}^{n+} + ne^{-} \quad (1)$$

$$\text{Cathodic reaction} - 4\mathrm{e}^{-}\text{pathway}: \quad \mathrm{O_2 + 2H_2O + 4e^{-} \leftrightarrow 4OH^{-}}\ (E_0 = 0.4\,\mathrm{V}) \quad (2)$$

$$\text{Cathodic reaction} - 2\mathrm{e}^{-}\text{pathway}\,(1): \quad \mathrm{O_2 + H_2O + 2e^{-} \leftrightarrow OH^{-} + HO_2^{-}}\ (E_0 = -0.07\,\mathrm{V}) \quad (3)$$

$$\text{Cathodic reaction} - 2\mathrm{e}^{-}\text{pathway}\,(2): \quad \mathrm{HO_2^{-} + H_2O + 2e^{-} \leftrightarrow 3OH^{-}}\ (E_0 = 0.87\,\mathrm{V}) \quad (4)$$

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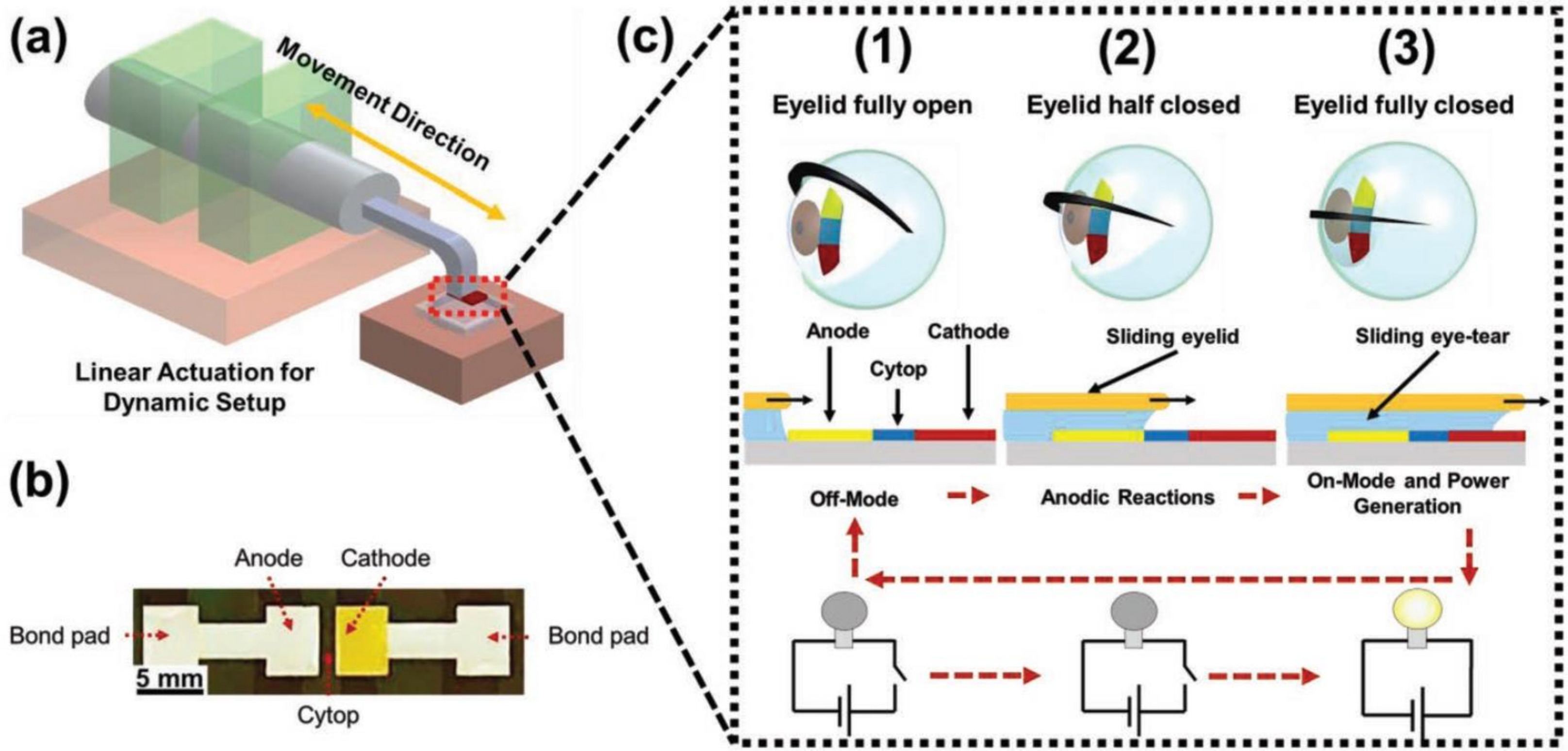
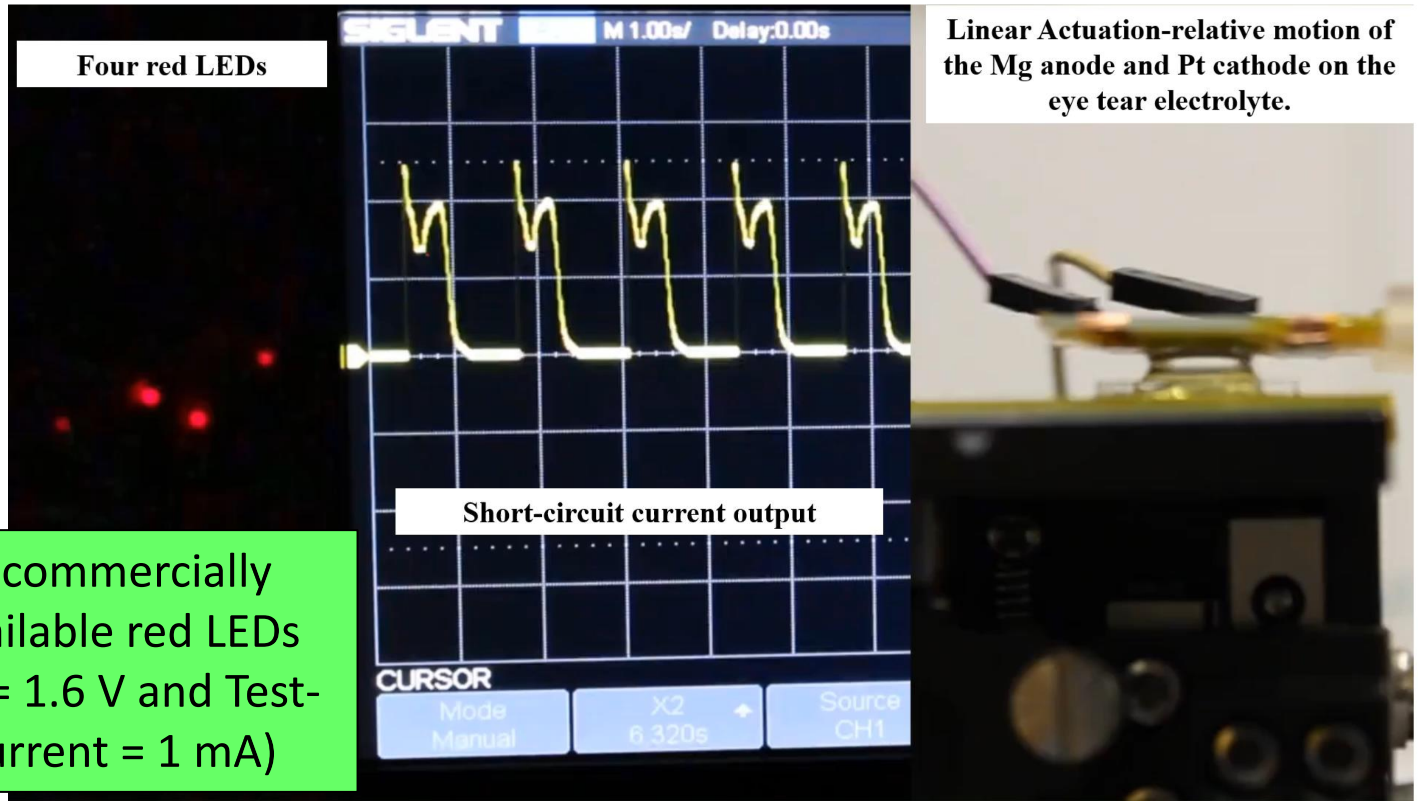
# Eye tear activated Mg-Air test setup



# Eye tear activated Mg-air battery




4 commercially available red LEDs ($V_F$ = 1.6 V and Test-current = 1 mA)

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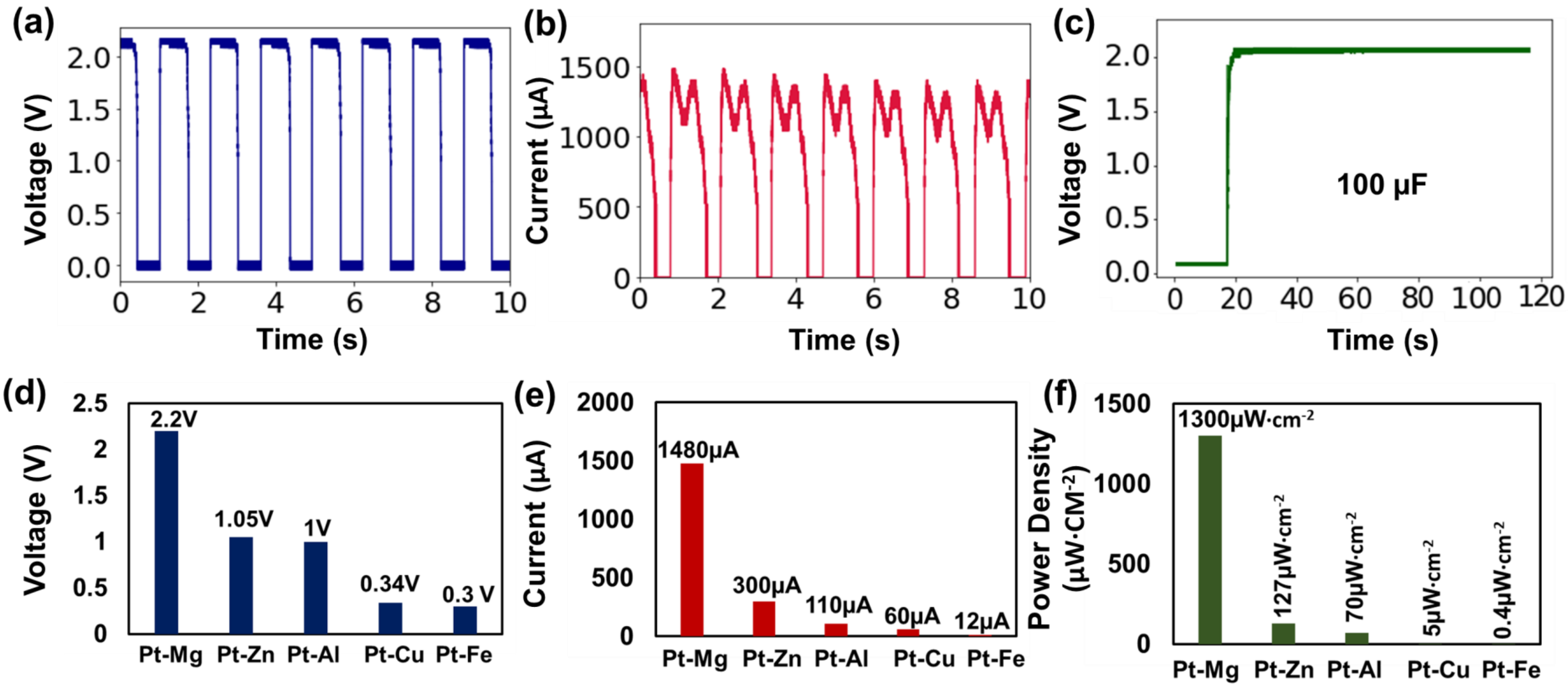
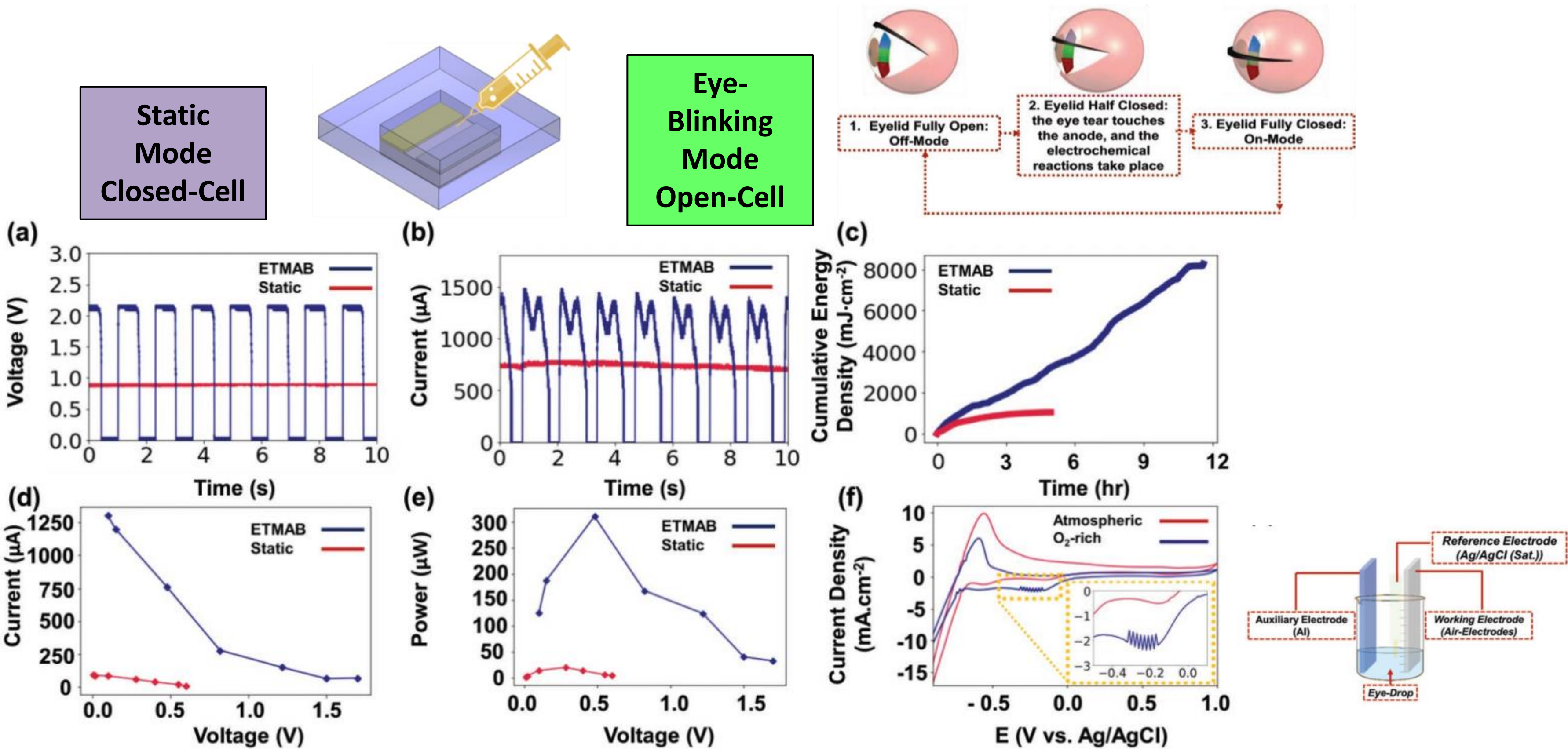
# Eye tear activated metal-air battery performance

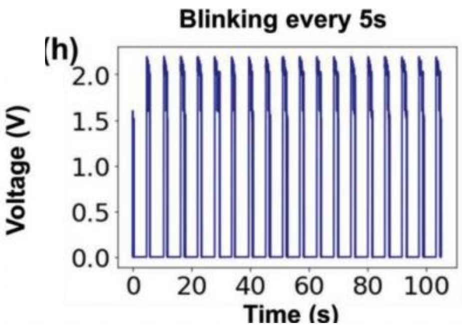


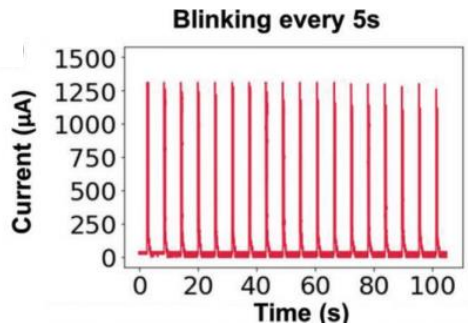
# Eye tear activated Mg-air battery (static vs blinking)

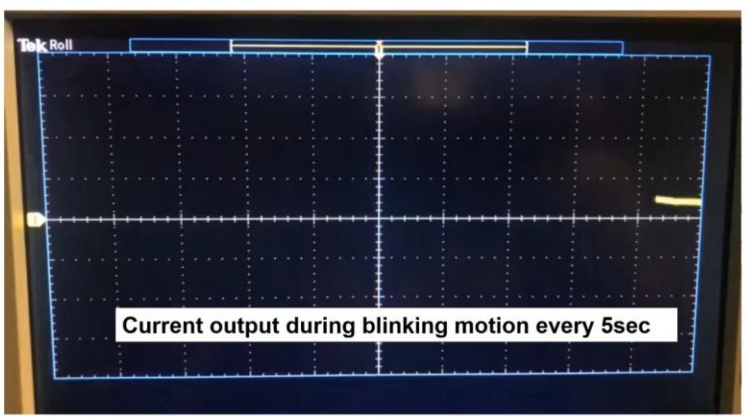


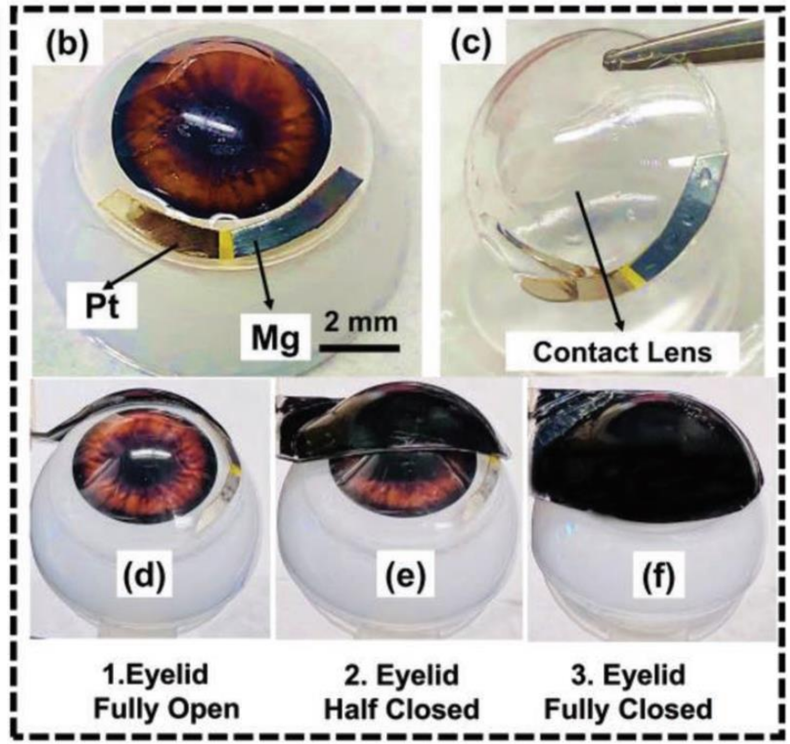

- **Battery life depends on Mg film thickness and load**
- **Battery energy capacity depends on Mg thickness**

# Eye tear activated Mg-air battery



# Combining energy sources to provide stable DC power

Planar and Flexible Silicon Solar Cells
P = 100 µw cm$^{-2}$ and 4.5 mW cm$^{-2}$
Time dependent output

Eye Tear Activated Mg-Air Battery
P = 270 µW
Pulsed output

Ocular Microsystem Energy Storage/Voltage stabilization ckt

3.3 V DC stabilized , ~100 µW- 2.6 mW average Power supply for Ocular Microsystems

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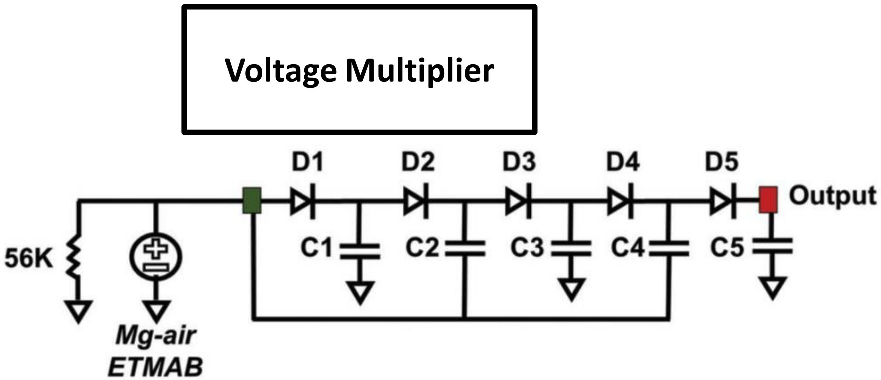
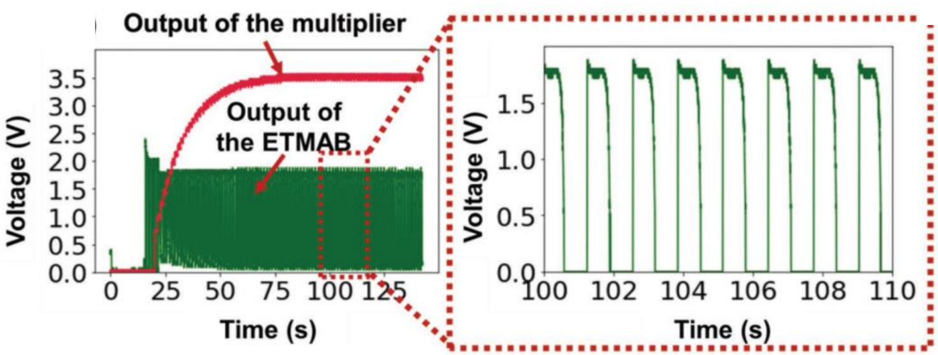
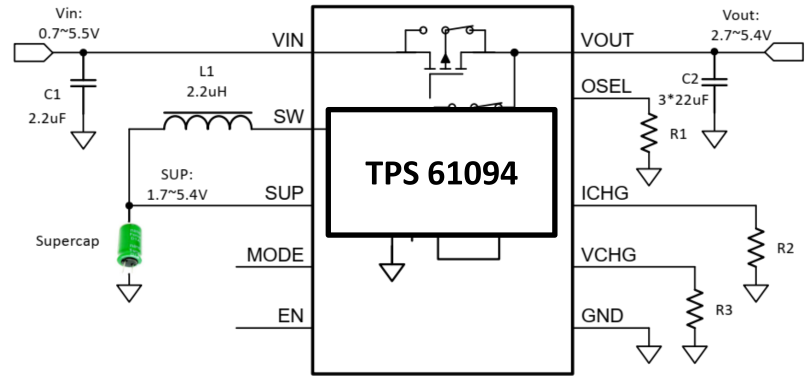
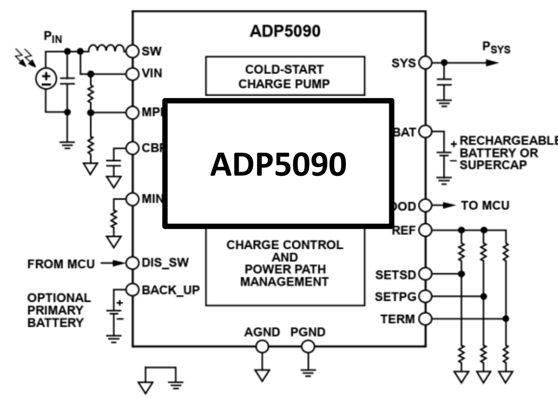
# Energy/Power Management Ckts



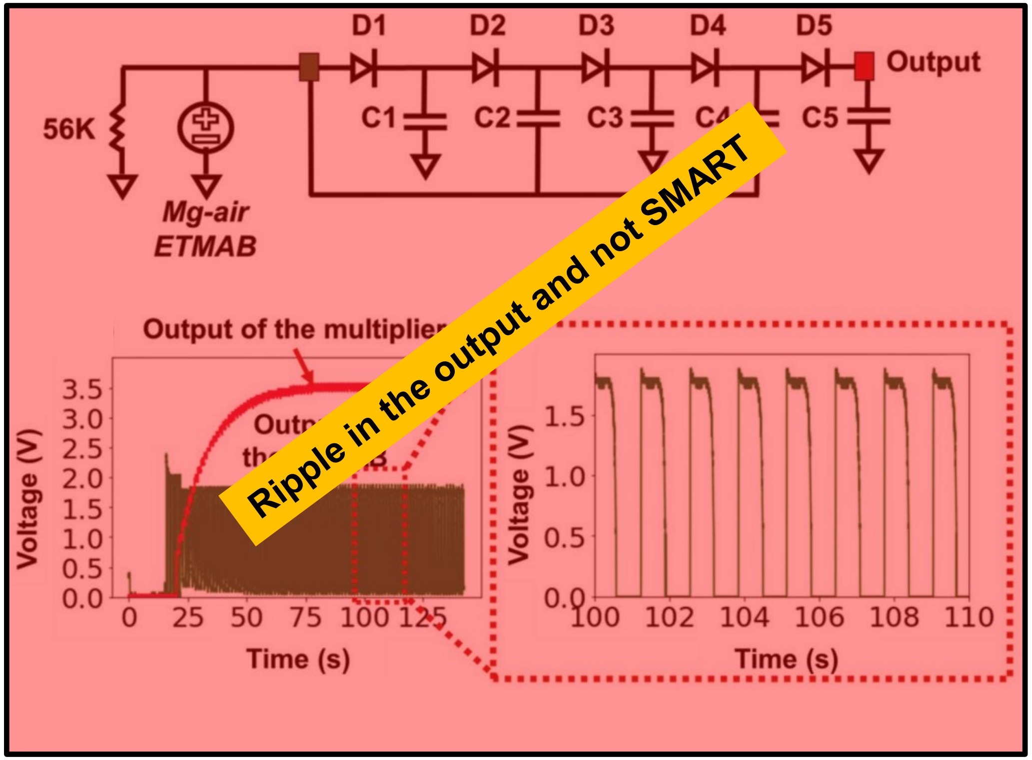



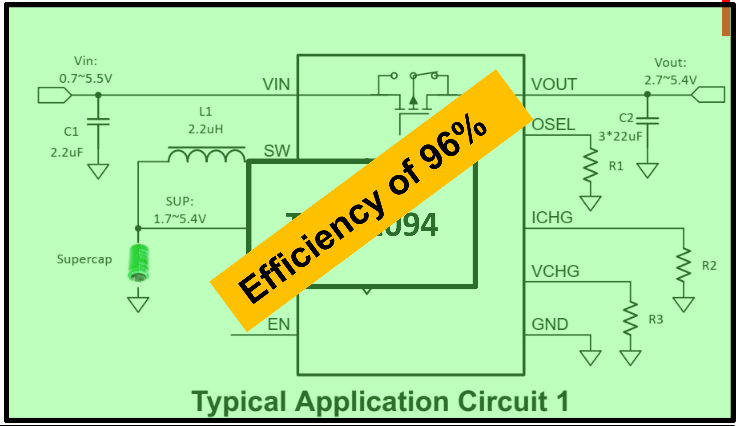

Typical Application Circuit 1

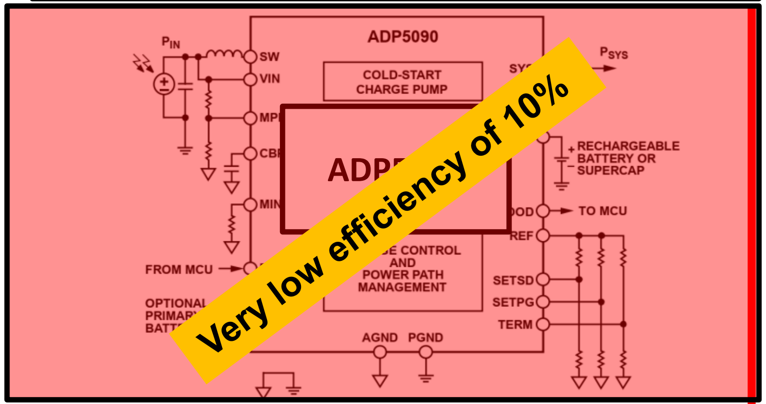


# Energy/Power Management Ckt

**Voltage Multiplier**

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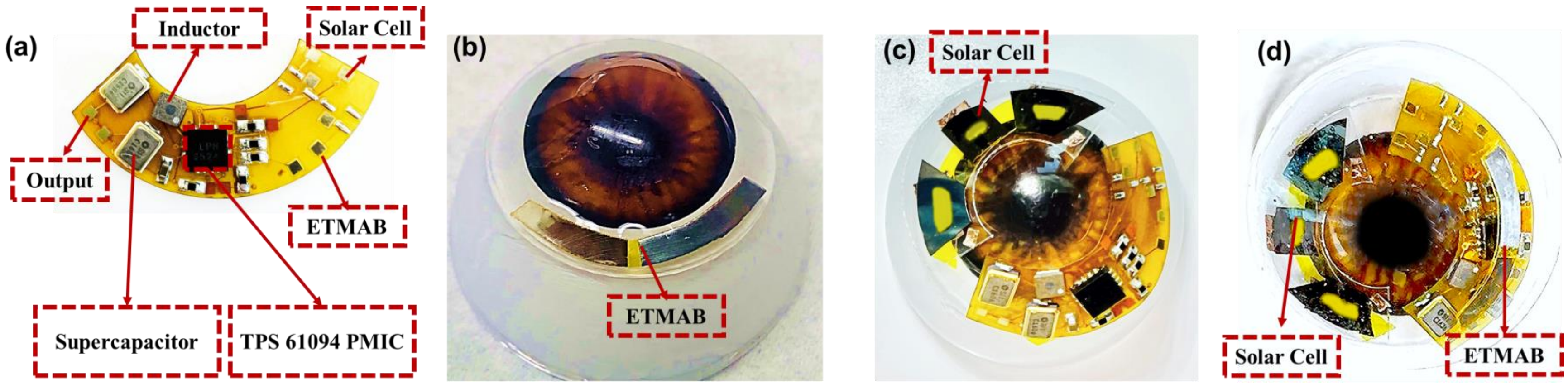
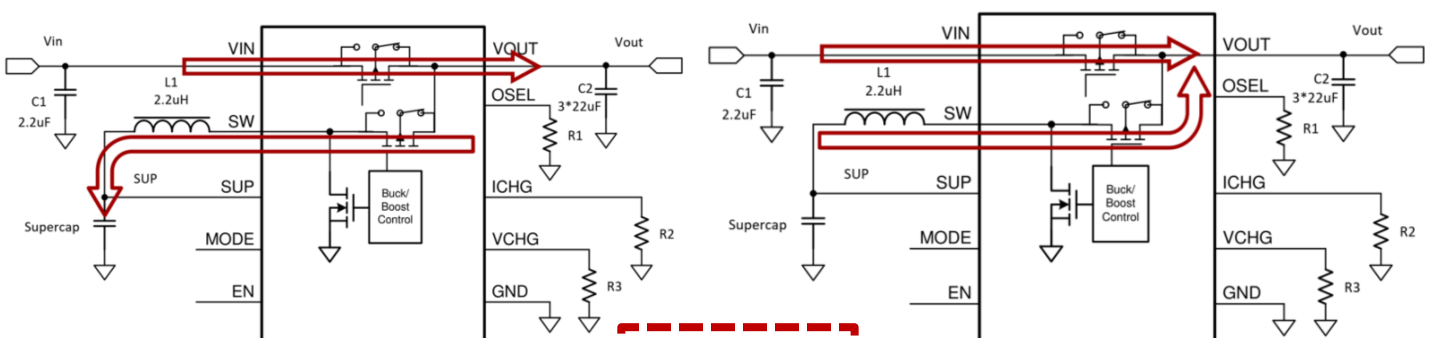
# Power Management Flex Board



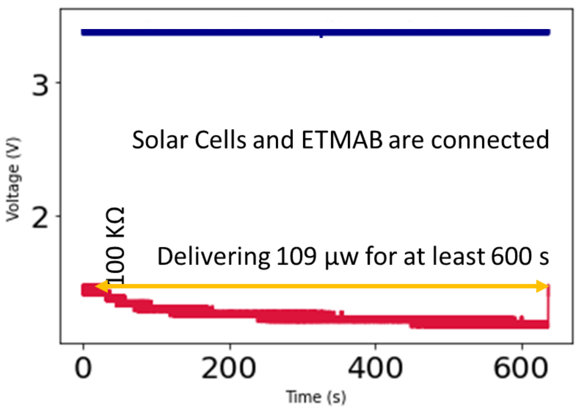

Storage Unit

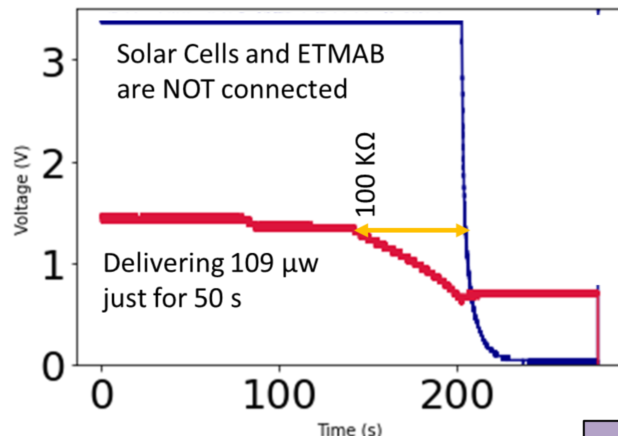

4.6 µAh

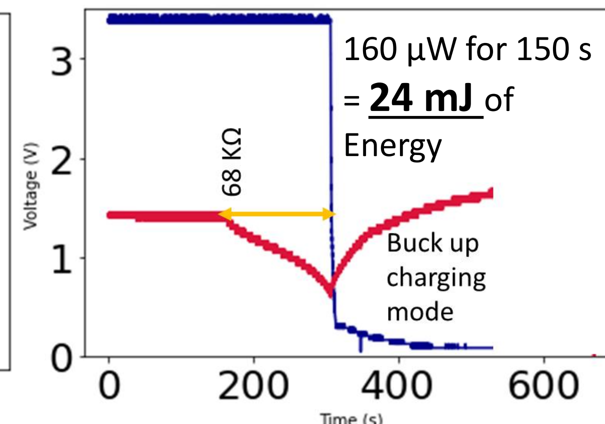


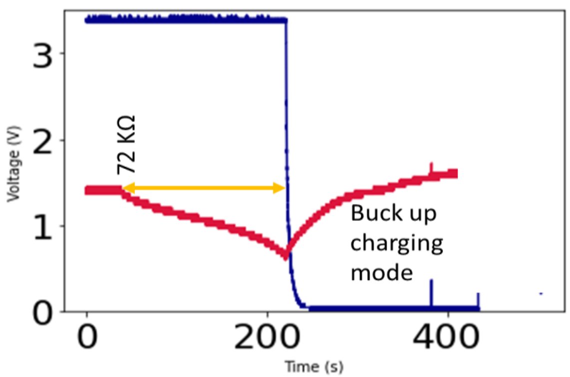

η=96%

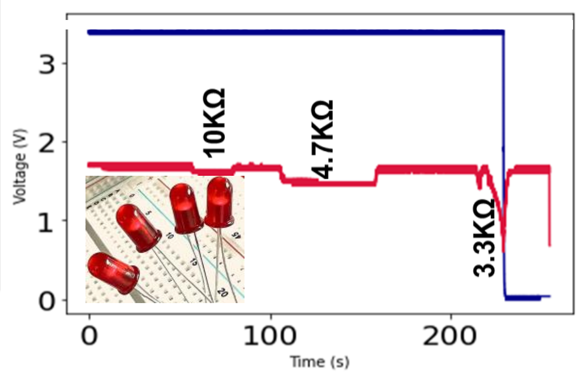
# Power pack and microsystem integration



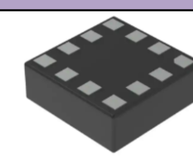




**LC Lens**

**3.3 V and**
**3.2 µA**
**= 10.5 µW**

**Magnetometer**



**On-Mode: 3.3 V and**
**230 µA for 200 µs =**
**0.16 µJ**

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# Power Pack Performance Metrics

| Power Generators | Power Management IC | Delivered Voltage | Delivered Power |
|---|---|---|---|
| Solar Cell (Indoor) + ETMAB | NOT Connected | AC 1.5 V | 113 µW |
| Solar Cell (Outdoor) + ETMAB | NOT Connected | AC 1.5 V | 2.7 mW |
| Solar Cell (Indoor) + ETMAB | Connected (TPS 61094) | DC Stable 3.3 V | 109 µW |
| Solar Cell (Outdoor) + ETMAB | Connected (TPS 61094) | DC Stable 3.3 V | 2.6 mW |

# Summary

- Ocular Microsystems have limitations on energy storage due to small volume
- Functionality limited by energy constraints ~100 J/eye
- Many power generation methods exist but few produce Joules of energy
- Low-Power design and components are essential
- Solar energy is the best source for these eye-based systems

# Acknowledgements


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National Institute of Biomedical Imaging and Bioengineering

UTAH NANOFAB

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Thank You !