**Eye Tear Activated Mg-Air Battery Driven by Natural Eye Blinking for Smart Contact Lenses**

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A sliding electrolyte metal-air microbattery driven by natural eye blinking motion is demonstrated as a source of electrical energy that can be integrated with smart contact lens platforms. The metal-air battery (footprint 10 mm²) consists of a Mg anode and a Pt cathode, patterned on an insulating substrate and the battery electrolyte is a film of eye-tear fluid that is periodically dragged on top of the electrodes during the natural eye-blinking cycle, which activates the battery. When tested with an eye emulator, the open-circuit voltage across the eye-tear activated metal-air battery (ETMAB) is 2.2 V. Impedance matching analysis reveals a maximum battery-specific capacity of 3561 mAh g⁻¹ obtained at a discharge current density of 5 mA cm⁻². The blinking activated battery exhibits the maximum generated power density of 1.3 mW cm⁻² at the load of 740 Ω. The blinking ETMAB delivers eight times higher energy output and more than three times longer lifetime than achievable with static ETMAB designs.

1. Introduction

An ever-growing demand for smart health care has led to the development of smart contact lenses (SCLs). Currently, the proposed applications of SCLs include vision correction,[1] augmented/virtual reality,[2] drug delivery,[3] glucose detection, and disease diagnosis.[4] SCLs for vision correction require integration of tunable varifocal lenses,[5] eye-tracking systems,[6] communication antennas,[7] and electronic control subsystems, which require a reliable source of electrical power. The lack of an appropriate low-profile energy source which can be integrated with SCLs is a major obstacle to development and practical realization. Power-generation techniques such as photovoltaics,[8–10] wireless power transfer,[11] and conventional batteries[12] have been utilized for reliable power of wearables, but they suffer from several drawbacks with SCLs. For example, a continuous light source is a key to solar cells’ operation, and under low-intensity indoor lighting conditions, the output power is less than 100 µW cm⁻².[9,13] Wireless power-transfer schemes need a receiver and transmitter antennas that typically limit the transfer distance (<10 cm)[14] and require additional external components. Rechargeable Li-ion batteries are constructed with biohazardous materials and require significant packaging and footprint/thickness. Therefore, it is imperative to develop new energy-generation and storage schemes that are biocompatible, energy-efficient, and suitable for integration with standalone SCLs.

An alternative high energy density power source is a metal-air (MAB) battery. A typical MAB comprises a metal anode, an air-breathing cathode, and an electrolyte. Theoretically, certain MABs[15] have demonstrated a much greater specific capacity and energy density than typical lithium-ion batteries. However, technical challenges such as parasitic corrosion of anode material and continuous oxygen requirement have hindered their commercial implementation[16] and restricted their use to low-power applications such as miniature hearing aids.[17,18] However, if the MAB could be operated under conditions of continuous electrolyte replenishment, unlimited supply of O₂, and suppression of electrochemical polarization (formation of isolating barriers preventing the electrochemical reactions between the metal electrodes and the electrolytic solution), one can significantly extend the lifetime of such batteries while delivering high power output. This is precisely what is achieved when the MAB is driven using natural eye-blinking, and the electrolyte (eye-tear liquid) is periodically replenished.

In this paper, we demonstrate a highly novel power-generation scheme that utilizes the natural eye-blinking motion to regenerate a biocompatible metal-air battery. The MAB is independent of any external energy sources, can be easily integrated with an SCL system, and it can reliably deliver electrical power to SCL components over extended periods of time. Specifically, this article describes the eye tear MAB (ETMAB) working principle, device structure and fabrication, and characterization of the MAB performance. The paper also explores different metals as suitable candidates for cathode/anode material to optimize the device output. Unlike previous reports of eye-tear activated batteries tested under static conditions,[19,20] we tested our Mg-air battery under blinking electrolyte flow conditions and achieved a cumulative energy density of 8.3 J cm⁻² with...
more than three times longer lifetime. The blinking ETMAB exhibits a maximum voltage and current output of 2.2 V and 1.48 mA, respectively. Experiments show that the blinking ETMAB delivers energy density greater than that achieved with Li-based microbatteries for the internet of things (IoT) applications,[21–23] previously reported biofluid-activated Mg-based and Zn-based batteries,[24–27] and static metal-air batteries.[19]  

2. Results and Discussions

2.1. Device Structure and Working Mechanism

The microfabricated metal-air battery essentially consists of an anode and a cathode electrode material deposited on a thermally oxidized silicon chip. Figure S1 in the Supporting Information shows the schematic of the device structure and the simplified fabrication flow. The different metals studied as candidates for anode material were Cu, Al, Mg, Fe, and Zn. Pt, Au, Co, and Ni were investigated as cathode candidates. A thin cytop film (AGC chemicals) was used as a hydrophobic material in between the electrodes helping the efficient dewetting of the anode/cathode surface after each cycle of an eye blinking motion, which removes any internal parasitic charge flow and enhances the lifetime of the device. Finally, a commercially available moisturizing eye drop (Refresh Plus Lubricant Eye Drops containing 0.5% carboxymethylcellulose sodium as an eye lubricant) was used to replicate the human eye tear, which acted as the electrolyte for the battery.

ETMABs were tested under static and dynamic modes with an eye emulator setup. As it is shown in Figure 1, the dynamic mode of operation involves an actuator that provides relative motion between the liquid eyedrop (electrolyte) and the cathode/anode metals that are present on the surface of the device structure, emulating the periodic cycle of sliding motion of an eyelid on the eye sclera. Both linear and rotating actuator motions were utilized during the battery testing yielding nearly identical results.

In the first part of the blinking motion cycle, the eyelid moves forward, but the eye drop is not in contact with any of the electrodes, and the battery is not activated (off-mode). Next, the eye tear liquid gradually covers the device surface due to the actuator’s linear motion. When the eye tear comes in contact with the anode-metal, spontaneous electrochemical anodic reactions are initiated, which generate electric charges. Finally, when the eye drop comes in contact with both the anode and the cathode, the battery is activated (on-mode), and the generated electrons can be used to deliver electric power to an external load. These steps are next followed in reverse order when the eyelid moves back and the entire cycle is repeated.

The fundamental working principle of the ETMAB is the eye-blinking driven generation of free electrons, which are a product of anodic electrochemical reactions and subsequent electron transfer to an external load, along with the oxygen reduction reactions (ORRs) on the air-breathing cathode (air-electrode) that occur when the eye-tear comes in contact with the ETMAB. The generalized redox reactions at the anode and cathode for a typical MAB are

\[
\text{Anodic reactions: } M \leftrightarrow M^{n+} + ne^- \\
\text{Cathodic reaction - 4e}^{\text{ pathway:}} \\
O_2 + 2H_2O + 4e^- \leftrightarrow 4OH^- (E_0 = 0.4V) \\
\text{Cathodic reaction - 2e}^{\text{ pathway (1):}} \\
O_2 + H_2O + 2e^- \leftrightarrow OH^- + HO_2^- (E_0 = -0.07V) \\
\text{Cathodic reaction - 2e}^{\text{ pathway (2):}} \\
HO_2^- + H_2O + 2e^- \leftrightarrow 3OH^- (E_0 = 0.87V)
\]

Therefore, the correct selection of anode and cathode materials is critical to optimizing the performance of the ETMAB. The first half-reaction (1) involves the oxidation of the anode material. Therefore, candidates for the anode were selected based on their standard electrode potentials. Although lithium (Li) has been extensively utilized as an anode material for metal-air and metal-ion batteries,[28–30] it is biohazardous and is therefore extremely unsuitable for integration with SCL. Furthermore, Li suffers from calcination-induced dendrite formation that severely limits the efficiency of Li-air batteries and such systems typically require an intercalation compound for proper functioning.[31] Therefore, alternative anode materials might provide substantial advantages over Li. For
example, Mg-anode does not suffer from dendritic formation, is earth-abundant (104 times compared to Li) and eco-friendly,[12] and a biocompatible (acceptable daily intakes of 350 mg) element.[13,14] Furthermore, the Mg-air battery has a greater theoretical specific energy density (3.9 kWh kg⁻¹) than the Li-air (3.4 kWh kg⁻¹) counterpart.[15–18] An in-depth analysis of different anode materials has been provided in the next section.

The other half-reaction involves the reduction of oxygen at the air cathode, which is the performance-limiting electrode in metal-air batteries due to the sluggish nature of ORR reactions.[19] As shown in the reactions (2)–(4), the oxygen reduction reactions in alkaline electrolyte can take place through two different pathways known as four electrons (direct) or series of two electrons (indirect) pathways.[20,21] The formation of HO₂⁻ is the oxygen reduction rate limiting factor. At the cathode site, the electrode material is in contact with both the dissolved oxygen within the electrolyte (in our case the eye tear fluid) and the ambient gaseous oxygen. Therefore, the ORRs take place at triple-phase boundary, which is also commonly observed in solid-oxide fuel cells.[22] Hence, it is important to properly design the cathode architecture to ensure a maximum triple-phase boundary. Furthermore, the adsorption/desorption kinetics of the dissolved and ambient oxygen, is a fundamental property of the cathode material, and strongly affects the performance of ETMAB. Therefore, careful selection of cathode material is key to realizing an optimized output. Accordingly, different materials have been investigated as potential candidates for air-breathing cathodes, the details of which are provided in the following section.

Finally, according to the Nernst equation, for a given standard electrode potential and temperature, the reduction potential of a metal-air battery is directly proportional to the activities or effective concentration of oxygen accessible by the cathode.[23]

\[
E_{\text{cell}} = E_0 + \frac{RT}{nF} \log \left( \frac{[\text{Ox}]}{[\text{Red}]} \right)
\]

where \(E_0\) is the standard potential, \(R\) is the universal gas constant, \(n\) is the number of transferred electrons, \(F\) is Faraday’s constant, \(T\) is the absolute temperature, \([\text{Ox}]\) and \([\text{Red}]\) are the activities of the oxidant and reductant elements. The availability of oxygen in the ETMAB strongly affects the battery output. This is a significant bottleneck that has restricted widespread usage of MABs and it typically requires sophisticated ORR catalyst materials or periodic replenishment of electrolytes.[24,25] The advantage of utilizing naturally available eye tear as the electrolyte for the ETMAB is that proper body functions ensure a stable and continuous supply of dissolved oxygen to the eye tear fluid without the need for external provisions.[26] Furthermore, the placement of the SCL on the eye also ensures a near-unlimited supply of gaseous oxygen from the atmosphere. Herein lies the most significant advantage of our ETMAB technology. The following sections provide an in-depth analysis and characterization of the various components of the ETMAB.

2.2. Selection and Characterization of Air Cathodes

Figure 2a–c shows the open-circuit voltage, maximum short-circuit current, and impedance-matched power-density of ETMABs featuring different air cathode electrode materials (Pt, Au, Co, and Ni) and Al as the anode material for the purposes of comparative evaluation of the air cathode performance. For these experiments, the dimensions of the MAB electrodes were 3 × 8 mm² and the eye tear volume was 10 μL. The instantaneous current spikes result from the sudden contact of the electrolytic solution with the edge of the cathode. The ETMAB with Al anode and Pt cathode produced a highest open-circuit voltage of 1 V and a maximum short-circuit current of 110 μA (Figure 2d,e). It produces the highest power density of 70 μW cm⁻² while driving a load of 12 kΩ.

Several capacitors (4.7 μF to 1 mF) were charged up using different anode and cathode configurations. Due to having different current and voltage outputs, we selected the 100 μF capacitor to achieve a reasonable charging time (less than a minute) for all different ETMABs. The Al-air ETMAB using Pt as the air-electrode is able to charge a 100 μF capacitor in 13 s, corresponding to an average power density of 14.5 μW cm⁻² (Figure 2f). Integration of the current versus time curve over one pulse (blink) demonstrates a total generated charge of 103.4 μC. Therefore, the eye tear-activated Al-air battery with Pt cathode generates maximum energy of 103.4 μJ per blinking cycle. The detailed voltage and current outputs of ETMABs with other metal cathodes are shown in Figure S3 and Table S1 in the Supporting Information.

We believe the observed electrical output differences are explained by differences in the electrode ORR kinetics. Our data are consistent with that from other reports indicating the ORR kinetics of Pt is highest amongst metals.[27] Previous studies demonstrate that the ORR on the surface of the Pt predominantly undergoes the 4e⁻ pathway[28] while a series of 2e⁻ pathways occur for gold and the transition metal cathodes.[29,30] Additionally, as shown in Figure 2g, cyclic voltammetry (CV) measurements performed on different cathode materials demonstrate the maximum current density for Pt with the current magnitude of 760 μA cm⁻² at ORR’s potential (~0.2 V with respect to the Ag/AgCl reference electrode). This is a direct measure of comparative ORR kinetics, also agreeing with previous studies. Detailed CV plots for each cathode material are provided in Figure S4 in the Supporting Information.

Figure 2i shows the load line and impedance matching power output plots of the Al-air ETMAB using Pt as the air-electrode (detailed plots for Al-air ETMAB using the other cathode materials are shown in Figure S5, Supporting Information). Due to the highest power-density output, Pt was selected as the cathode material for further experiments.

2.3. Selection and Characterization of Anodes

According to the Pourbaix diagram, the aluminum surface passivates at neutral pH.[31] Therefore, using Pt as the cathode material, several other metals, including Cu, Fe, Zn, and Mg, were characterized as potential candidates for the anode material. Figure 3a–c shows the open-circuit voltage, maximum short-circuit current output, and impedance-matched power-density of Pt cathode based ETMABs featuring different anode materials.
Figure 2. Electrical outputs of the Al-air ETMAB while using different cathodes. a) Open circuit voltage of the Al-air ETMABs using different air-electrode cathodes, b) maximum short-circuit current output of Al-air ETMABs using different air-electrodes, c) impedance-matched load power-density of Al-air ETMABs using different air-electrodes, d) voltage plot of the Al-air ETMAB using Pt as the air-electrode, e) short circuit current plot of the Al-air ETMAB using Pt as the air-electrode, f) charging curve of a 100 µF capacitor using Al-air ETMAB with Pt cathode, g) zoomed-in cyclic voltammetry test around the oxygen reduction potential for different air-electrodes including Ni, Co, Au, and Pt, h) cyclic voltammetry setup, and i) load line and impedance matching analysis for Al-air ETMAB using Pt as the air-electrode.

Figure 3. Electrical outputs for the ETMABs using Pt cathode, moisturizing eye drop as the electrolyte, and different anode materials including Mg, Zn, Al, Cu, and Fe: a) open-circuit voltage of Pt cathode based ETMAB using different anodes, b) maximum short circuit current of Pt cathode based ETMAB using different anodes, c) impedance matched power density of Pt cathode based ETMAB using different anodes, d) voltage output of Mg-air ETMAB, e) short circuit current output of Mg-air ETMAB, and f) charging curve of a 100 µF capacitor using Mg-air ETMAB.
The plots summarized in Table S2 in the Supporting Information indicate that the highest open-circuit voltage, maximum short circuit current, and power-density outputs were measured using Mg (3 × 4 mm²) as the anode. The results agree with the electrochemical series since the electrode potential of Mg (w.r.t. a standard hydrogen electrode) is lower than that of the other anode material candidates. As shown in Figure 3d–f, the open-circuit voltage and short-circuit current output were measured to be 2.2 V and 1.48 mA, respectively. These values closely follow the redox reactions and the electrode potentials of the anode materials (see the Supporting Information for the electrochemical reactions of Mg-air ETMAB).

The integration of the current versus time curve over one pulse for the Mg-air ETMAB represents a charge generation of 2.8 mC, corresponding to a generated energy of 6.1 mJ per blink cycle. The maximum power density was measured to be 1.3 mW cm⁻² at the discharge current density of 3 mA cm⁻² while driving an external resistive load of 740 Ω, which corresponds to the internal resistance of the Mg-air ETMAB. This battery exhibits a maximum specific capacity of 3561 mAh g⁻¹, which is much greater than commonly used 3D microbatteries (~220 mAh g⁻¹) for IoT applications.[21–23] Detailed electrical information of the other anodes is shown in Figure S6 and Table S2 in the Supporting Information. Experimental results clearly indicate that amongst the various ETMAB configurations investigated, the Mg-air ETMAB (with the Pt cathode) demonstrated the highest output; therefore, it was selected for further characterization and analysis.

2.4. Mg-Air ETMAB’s Practical Applications

Several performance tests were conducted on the Mg-air ETMAB. Figure 4a shows the load line and impedance matching power output of the Mg-air ETMAB which can be utilized to determine the optimal load (detailed information and plots for the Pt cathode based ETMAB using other anode materials are shown in Figure S7, Supporting Information). The Mg-air ETMAB was utilized to completely charge up a commercially available 11 mF chip type electric double layer supercapacitor in 5 min (Figure 4c). Utilization of a supercapacitor load provides a steady DC voltage output that can be fed to electronic circuits and can deliver bursts of high load current which the battery cannot on its own. The supercapacitor’s resistance capacitance time constant is ~80 s corresponding to 15 blinking cycles. To gain better insight into the discharging performance of the Mg-air ETMAB, we can compare the discharge times and energy stored in the supercapacitor with the discharge time and energy that can be delivered by the battery to an impedance matched load (740 Ω).

The blinking Mg-air ETMAB takes ~11 h (more than three times...
longer than previously reported\(^{[19]}\) to completely discharge under continuous, nonstop, frequent motion, while the 11 mf capacitor discharges with a time constant of \(\approx 8 \text{ s}\) under the same loading condition. The energy stored in the supercapacitor was 14 mJ and the battery integrated output load delivered energy was 1.9 J, 135 times higher than stored in the supercapacitor.

Additionally, we demonstrate the power delivered by the blinking battery to ten commercially available deep red LEDs with the wavelength of 640 nm (\(V_F = 1.7 \text{ V}\) and \(Current-\text{Test} = 1 \text{ mA}\)) (Figure 4b and Video S1, Supporting Information), demonstrating the practical use of the blinking ETMAB.

As shown previously in Figure 3d,e, since the voltage and current outputs of our ETMAB are pulsed and approximately in the 1–2 V regime, it is important to first convert the time-varying output to a stable \(\approx 3 \text{ V DC}\) level to supply power to microelectronic Ics. The pulsed voltage output can be conveniently utilized to directly drive a capacitive voltage booster circuit (Dickson configuration\(^{[51]}\)) that consists of five electrolytic capacitors (4.7 \(\mu F\)) and five Schottky diodes (1N4148). The voltage boosted converts the pulsed DC output of the Mg-air ETMAB to a low-ripple \(\approx 3.3 \text{ V DC}\) output. Figure 4d shows the circuit diagram. Figure 4e shows the output of the voltage-multiplier circuit showing that a steady voltage of 3.5 V can be reached simply driven by the blinking motion. This voltage is sufficiently high to drive conventional microcontroller circuits. The voltage output of the ETMAB is not regulated hence it drops from the open circuit voltage (\(V_{oc} = 2.2 \text{ V}\)) when it is connected to any load.

2.5. Static versus Dynamic Mode of Operation of Mg-Air ETMAB

Figure 5a–e shows comparisons of the open-circuit voltage, current, load-line, impedance matching power output, and cumulative energy density of the Mg-air ETMAB operated under static and dynamic (blinking) modes of operation.

Figure 5c shows a cumulative energy density output of \(\approx 8 \text{ J cm}^{-2}\) for the motion-activated Mg-air ETMAB under the maximum power point at a load of 740 \(\Omega\), corresponding to the discharge current density of 3 mA cm\(^{-2}\). This cumulative energy output is more than eight times greater than that of the static Mg-air battery; therefore, it clearly indicates that the performance of the Mg-air ETMAB operated under dynamic blinking conditions is significantly greater than that of the static condition. Furthermore, considering adults’ average blinking rate (12 times per min),\(^{[52]}\) the dynamic mode of operation exhibits a lifetime of 550 h at 1.8 V, which is more than ten times longer than that of the static counterpart. Takamatsu et al. reported the superior performance of Mg over Zn as anode material, wherein the parasitic reactions in the static condition resulted in a very limited lifetime of only 3.5 h.\(^{[19]}\) Similarly, our results confirmed a much shorter lifetime of MAB in the static mode, which demonstrates the importance of the blinking-induced dynamic replenishment of eye-tear (electrolyte) to significantly enhance the electrical performance and the lifetime of the Mg-air battery. We believe the extended battery life is due to three performance enhancement mechanisms. First, in the blinking ETMAB the eye tear is continuously replenished every single time an eye-blinking cycle occurs, thereby providing a stable and abundant supply of dissolved oxygen to the ETMAB. This also ensures the stable value of the electrolyte resistance. Inductively coupled plasma mass spectroscopy together with the liquid conductivity measurement was conducted to analyze the effect of Mg dissolution on the electrolyte resistance (see Figure S8, Supporting Information). Second, since the ETMAB is an open electrochemical cell, it has access to near-unlimited ambient oxygen. These conditions, which are realized during the dynamic mode of operation, ensure a continuous supply of oxygen to the ETMAB, which is crucial for the proper functioning of the battery. Third,
the repetitive back and forth motion in the dynamic mode helps to reduce the parasitic formation of effervescent clouds on the anode during the electrochemical reactions. On the contrary, in the static mode, as the dissolution of the anode progresses, the stagnant electrolyte’s resistance decreases, resulting in an increasing internal current flow which reduces the battery life and output energy. It should also be noted that due to the tear turnover rate of 1–3 µL min⁻¹,[53] unlike the static mode (pH increases from 7 to 9.5), the pH of the eye tear remains constant (pH ≈ 7) during the dynamic mode of operation.

In order to confirm the importance of oxygen availability in the ETMAB’s performance, we also performed a series of CV tests while changing the oxygen level in the electrolytic solution by placing a microtube into the testing electrolyte to introduce O₂ gas. Figure 5f demonstrates the CV results of the Mg-air battery while testing under different atmospheric conditions. The current density at the oxygen reduction potential varies by introducing more oxygen to the media. An O₂-rich media provides a higher current density. This proves that an O₂-rich media provide higher current density demonstrating the importance of oxygen availability in the electrochemical performance of the Mg-air battery.

We also investigated the cause of the finite life of Mg-air ETMAB. A series of X-ray diffraction (XRD) measurements were conducted both on the Mg anode and Pt cathode before and after operating the battery for some time. Figure S9 in the Supporting Information shows no detectable change in the structural properties of the Pt cathode after 40 000 s of the dynamic mode of operation. Therefore, it follows that the battery termination mechanism stems from the anode’s surface passivation. The XRD spectrum of the anode (JCPDS Card No. 44-1482) clearly shows traces of magnesium hydroxide with Brucite structure formed on the surface of the Mg anode (Figure S9, Supporting Information). We believe the hydroxide layer inhibits further oxidation reactions on the Mg anode. To further characterize the morphological and structural properties of the anode’s surface after the extended (40 000 s) frequent sliding motion, we also carried out energy dispersive spectroscopy (EDS) analysis at the accelerating voltage of 5 kV. Figure 6 exhibits the formation of the urchin-like magnesium hydroxide on the surface of the Mg anode after the electrochemical reactions. Figure S10 in the Supporting Information also exhibits the cross-section scanning electron microscopy (SEM) images showing the formation of the magnesium hydroxide on the surface of the Mg anode.

2.6. Mg-Air ETMAB as a Power Source for Smart Contact Lenses

The greatly improved performance of the Mg-air ETMAB compared to a static, motionless MAB battery makes the blinking ETMAB suitable for powering autonomous systems that undergo periodic motion. We utilized the ETMAB to power a SCL employing natural eye-blinking motion. Eye blinking is a natural muscle movement that occurs over 10⁴ times a day.[52,54] Figure 7 schematically illustrates a) the working mechanism, b, c) the placement of the device on a commercialized contact lens, and two different blinking conditions, including d, e) non-stop continuous blinking motion and f, g) blinking every 5 s.

When the eye is open, the device is in the off-mode. When the eye is closing, it goes into contact with the anode material. Thus, the electrochemical reactions and the charge generation begin. Finally, the power generation starts when the eyelid touches the air-electrode and the device goes into the on-mode. The frequent natural eye-blinking generates electrical power, which can be used to drive electronic components on the SCL. To demonstrate the feasibility of the concept, we performed additional open-circuit voltage and short-circuit current measurements while conducting angular sweeps. A
Mg-air ETMAB mounted on an eyeball replica fully charges up a 100 µF capacitor after four blinking cycles with a linear speed of 15 cm s⁻¹ and a blinking frequency of 12 times per min (200 mHz), which is an average blinking frequency of an adult⁵² (see Videos S2 and S3, Supporting Information). A stationary 2D planar COMSOL simulation together with the long term blinking motion test demonstrates no mechanical failure such as cracking in the 200 nm Pt cathode while mounted on a dome-shaped smart contact lens. The simulations indicate that stress levels in Pt are lower than the yield stress (Figure S11, Supporting Information).

### 3. Conclusion

In this article, we successfully demonstrated the generation of electrical power using natural eye blinking motion-driven metal-air batteries. To our knowledge, this is the first time that eye-blinking has been utilized for energy generation. The article investigates and characterizes different configurations of metal-air batteries to systematically optimize energy generation and device output. Results show that our novel eye tear-activated metal-air battery, with Mg anode and Pt air-electrode, delivers the maximum power density of 1.3 mW cm⁻² and the specific capacity of 3561 mAh g⁻¹ at the discharge current density of 5 mA cm⁻². Since the SCLs with the display and vision correction applications are removed during sleeping time, assuming 8 h sleeping period per day, our novel ETMAB is functional for about 34 d. This work not only shows the physical mechanism and working principle of the generator but also demonstrates the practical applications of the device such as integration with different energy storage units, circuitries, and LEDs. Finally, the superior performance of the motion-activated battery (eight times higher energy output and more than three times longer...
lifetime) over the conventional static counterpart was our most important finding. This is a potential game-changer since we demonstrate that metal-air batteries operated under similar conditions of motion can deliver significantly higher electrical outputs and exhibit a higher lifetime than previously reported.

4. Experimental Section

Device Structure and Fabrication: ETMAB devices were fabricated on both silicon and flexible substrates. Silicon substrate devices were fabricated as follows. Cu (200 nm), Al (200 nm), Ni (200 nm), Co (200 nm), Au (200 nm), and Pt (200 nm) were deposited on a thoroughly cleaned silicon chip by sputtering. A thin adhesion layer of Cr (20 nm) was also sputter deposited on the silicon chip prior to the deposition of the cathode material. For the remaining anode candidates, commercially available Mg foil (purity 99.95% with the thickness of 200 µm), Fe foil (purity of 99.995% with the thickness of 100 µm), and Zn foil (purity 99.999% with the thickness of 80 µm) were utilized. Cytop (CTL-800M, AGC Chemicals) was spin coated at 3000 rpm for 60 s on the device and heated at 200 °C in an atmospheric oven to realize a 1 µm thick hydrophobic coating, which was partially dry-etched with RIE technique (using plasma of CF4/02) to expose the metal contacts. ETMAB devices were also fabricated on much thinner and flexible substrates for integration with SCLs. Similar to the silicon substrate deposition processes explained above, the metal electrodes were sputter deposited on a flexible polyimide (PI) tape attached to a parylene coated substrate for integration with SCLs. A commercially available moisturizing eye drop (Refresh Plus Lubricant Eye Drops containing 0.5% carbamylmethylcellulose sodium as an eye lubricant) was used to replicate the human eye tear which acted as the electrolyte for the battery. According to the American Academy of Optometry, the pH of this moisturizing eye drop is the same as natural tears’ pH.[35]

Experimental Methods: The natural eye-blinking motion recurrently irrigates the surface of the eye using eye-tear fluid and lubricant oil (produced by the Meibomian glands) thus refreshing the fluid in contact with the electrodes. As a result of the eyelid motion, the electrodes essentially remain under one of three conditions: a) fully covered by the eye tear fluid (completely shut eyelid), b) partially covered by the eye tear (during the cycle of an eye blink), or c) not in contact with the eye tear (when the eyelid is completely open).

Dynamic Linear Slide Mode: These repetitive conditions were simulated using a microcontroller driven linear servo actuator (Figgeli... FA-RA-22-12-2), which provided a periodic relative motion between the metal (anode/cathode) deposited silicon chip and the moisturizing eyedrop, as shown in Figure 1. This experiment is henceforth referred to as the dynamic mode of operation.

Static Mode: In order to investigate the specific effect of the eye-blinking motion, the MAB performance was also characterized under static, zero flow conditions with the electrodes in contact with the eyedrop, and it was compared to the performance observed under the dynamic mode. As shown in Figure S2 in the Supporting Information, for the static test setup, a stagnant fluid cavity polydimethylsiloxane (PDMS, Sylgard 184, Dow Corning) enclosure was fabricated on top of the electrodes by pouring PDMS mixture (1:10, curing agent: base polymer) into a rectangular mold (3 × 8 mm²) and curing it at 100 °C for 1 h. The cured PDMS (1 mm thick) with the rectangular cavity was next peeled off from the mold and plasma-bonded to the device’s substrate. The moisturizing eye drop was then carefully injected into the cavity to ensure that it properly covers the anode and cathode. The injection inlet was sealed with a PI film.

Dynamic Angular Mode: Finally, to more closely replicate the angular motion of the human eyelid, a 3D printed eyelid model was attached to a brushless servo motor (SAVOX SB-2272MG) capable of providing angular motion. Figure 7d–f shows that the servo motor provides the relative angular motion between the 3D printed eyelid and the eyeball while constraining an eye tear between them.

Characterization Techniques: All voltage measurements were made by probing the electrodes of the battery using a digital oscilloscope (Siglent SDS1202X-E) with the input impedance of 1 MΩ and the input capacitance of 15 pF. A Tencor P-10 profilometer was used to measure the thickness of the electrodes and the Cytop. XRD (Rigaku Ultima IV diffractometer with Cu Kα radiation, λ = 1.5418 Å) measurements were conducted at the scan rate of 0.02° per step to analyze the structural properties of the Mg anode before and after the electrochemical reactions occurring during battery operation. To precisely detect the surface structure of the Mg anode after the electrochemical reactions, grazing incident XRD (2θ = 1°) was performed. High-resolution imaging was performed using SEM (FEI Quanta 600F) together with EDS to investigate the morphological and elemental features of the Mg anode, before and after battery usage. The short circuit current output of the device was measured using a Stanford Research Systems (SR570) low noise preamplifier with the DC input impedance of 1 Ω for a sensitivity of 500 µA V⁻¹. In order to investigate the maximum power output of different electrochemical cells, impedance matching analysis was carried out using different resistive loads, including 0.08, 0.12, 0.74, 4, 12, 56, and 90 kΩ. A Hewlett-Packard precision parameter analyzer 4145A was used to measure the internal impedance of the device. A Gamry Potentiostat Reference 600 was utilized to measure the potential response and the cyclic-voltammetry analysis from -1 to 1 V (Ag/AgCl (Sat.) as the reference electrode) with the scan rate of 50 mV s⁻¹ to characterize the electrochemical performance of the MAB. In order to elucidate the physical mechanism behind the device and observe the effect of oxygen on its electrochemical performance, oxygen was introduced to the electrolytic solution using a compressed O₂ gas cylinder. An Agilent 8900 ICP-QQQ tandem quadrupole mass-spectrometer and 945 professional conductivity detector from Metrohm were used to detect the concentration of Mg ions in the eye-tear solution, the pH level, and its conductivity in different time periods.

Supporting Information
Supporting Information is available from the Wiley Online Library or from the author.

Acknowledgements
All the fabrication was performed at the state-of-art Utah Nano Fabrication Facility, Salt Lake City, Utah, USA sponsored by National Science Foundation under CyberPhysical Systems CNS-1932602 and Meta’s Research Funding for Environmental Considerations for Soft Electronics Systems and Energy Sources.

Conflict of Interest
The authors declare no conflict of interest.

Data Availability Statement
The data that support the findings of this study are available in the Supporting Information of this article.

Keywords
biofluid, energy generation, eye-blinking motion, metal-air batteries, smart contact lens
