

BioSparks: Jewelry as Electrochemical Sweat Biosensors with Modular, Repurposing and Interchangeable Approaches

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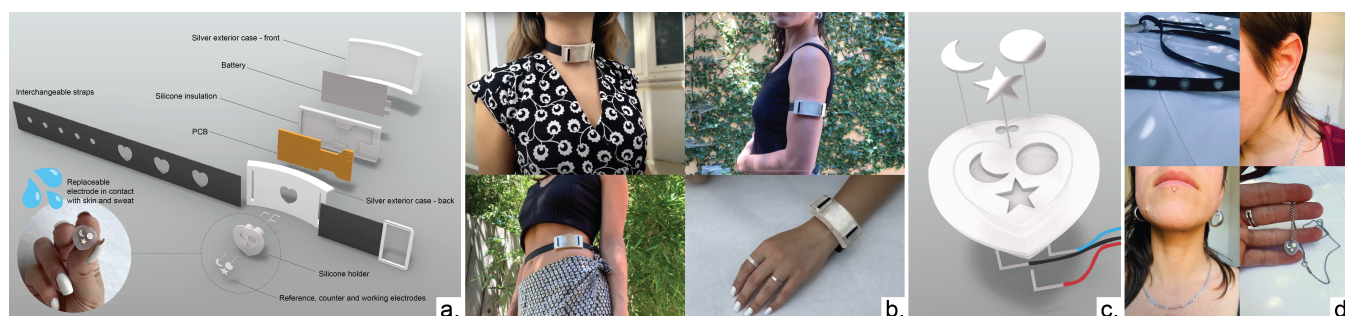


Figure 1: BioSparks: a. System components, b. Modularity, c. Interchangeable electrode, and d. Repurposing

ABSTRACT

This paper presents BioSparks, a wearable device that detects glucose levels in sweat through electrochemical biosensors crafted with traditional jewelry techniques. Unlike conventional biosensors that are disposed of after use, BioSparks employs a repurposing method, allowing for the reuse of discarded electrodes within the jewelry's chain, as pendants or earrings. It incorporates interchangeable electrodes that facilitates their replacement after timelife. The modular design enables the wearable to be placed on various body parts, including the neck, wrist and waist. The paper outlines our design considerations for Wearability Factors for Jewelry Biosensors, and the fabrication process combining traditional jewelry techniques and electromistry. Our technical evaluation shows the performance of our biosensor under ten different glucose concentrations.

CCS CONCEPTS

• **Human-centered computing** → **Interface design prototyping**; • **Hardware** → **Emerging interfaces**.

KEYWORDS

electrochemistry; electrodes; biosensor; wearable; jewelry

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1 INTRODUCTION

Electrochemical biosensors are devices that employ electrochemical reactions to detect and measure specific substances like glucose, pH, and sodium. These biosensors convert the concentration of the substance into an electrical signal, allowing for real-time monitoring and analysis. They consist of three key electrodes: the working electrode, which detects the target substance; the reference electrode, which provides a stable reference point; and the counter electrode, which completes the electrical circuit by conducting the necessary current. In recent years, the development of electrochemical biosensors in sweat [12, 18, 37] has emerged as a promising approach for health monitoring. Various form factors, like patches, wrist watches, transfer tattoos, stickers, or bandages, have been proposed [35].

This paper focuses on using electrochemical biosensors to measure glucose levels in sweat by placing the electrodes directly in contact with the skin. Traditional glucose monitoring methods, such as finger-prick testing [42], permanent tattoos [51] or microneedles attached to the skin [46], have limitations in terms of invasiveness, inconvenience, and potential skin damage. This project focuses in sweat analysis, offering non-invasive and continuous monitoring capabilities. Moreover, our design approach provides modularity

to place the wearable in different body parts, interchangeable electrodes to facilitate replacements, and repurposes the electrodes into other jewelry pieces.

Numerous works have explored the intersection of wearable technology and jewelry design, paving the way for innovative applications [2, 7, 11, 29]. This research not just utilize jewelry techniques to design the form factor, but also the electrochemical biosensors that seamlessly blend with wearable jewelry pieces. In this way, a new realm of discreet and convenient glucose monitoring opens up, expanding the horizons of HCI-driven biosensor applications in the context of stylish and functional wearable accessories for sensing body fluids.

The paper presents BioSparks, the design of electrochemical biosensors as jewelry with a modular, repurposing and interchangeable approaches. Our contributions include:

1. **Electrochemical Electrodes as Jewelry:** Departing from conventional flat-shaped electrodes, we introduce a novel 3D design of jewelry-based electrochemical biosensors, created with common jewelry techniques. The wearability factors for designing jewelry in electrochemical biosensors are proposed, and their functionality was evaluated with ten glucose concentrations.
2. **Repurposing Electrodes:** In contrast to the typical practice of disposing of electrodes or other biosensors after use, our repurposing method promotes sustainability by reusing the electrodes within the jewelry's chain, as pendants or earrings.
3. **Modular Jewelry Design:** The modular design offers flexibility and adaptability to accommodate different body parts and sizes.
4. **Interchangeable Electrodes:** Electrodes can be easily replaced after their lifespan. While other devices offer this feature, our approach seamlessly integrates pressure rivets, a jewelry method for attaching and detaching pieces, into the biosensor design.

2 RELATED WORKS

The HCI and Wearables field much explored smart jewelry as a wearable technology form factor. Analytical studies identify design criteria, including functionality, form factor, interactivity, and aesthetics [15]. Jewelry design embraces an artistic approach [7, 29]. Many projects adopt a modular design approach, combining form factors. For example, BLInG project uses a beaded design with interchangeable electronic components [22]. Gehna explores sensor-based touch-based jewelry technology for different body areas [2]. Some modular smart jewelry studies focus on design principles, using modularity to shape the product's form factor and inform research nature [7, 24]. Similarly, BioSparks adopts a modular approach with interchangeable straps, allowing users to decide the device's placement based on clothing, sweat location, or style.

Jewelry's close proximity to the skin enables interaction with movement, heat, and touch. For instance, Gemini embeds sensors in face jewels to detect facial muscle movements [47]. ThermalRing uses a low-resolution thermal camera for gestures and ThermalTag to reflect heat [59]. The Empathy Amulet generates warmth using a Kapton heater [6]. Considering this proximity was a crucial design consideration for our project, as we aimed to collect sweat data through electrochemical biosensors. Other projects explore attaching electronics to the skin through beauty products [34, 48], fake nails [25, 50], and hair extensions [39, 49]. Additionally, iSkin and

Duo Skin sense touch by a temporal tattoo as the form factor, similar to the most common form factor for sweat biosensors [26, 53]. While drawing inspiration from these works, we found that directly applying and reapplying electrochemical biosensors on the skin becomes impractical for everyday use due to the precision required by our sensors.

BioSparks focuses on using an electrochemical biosensor for glucose analysis in sweat, as sweat sampling offers a less invasive method of gathering biodata [23, 30]. Existing form factors for electrochemical biosensors include smartwatches [4], bandages [37], headbands [18], rings [27], and temporary tattoos [28]. Adhesive-style wearable sensors have been explored in previous works [20, 21, 52], including a wrist-worn multiplexed sensor array for sweat analysis [19]. Various form factors for glucose biosensors in sweat have been introduced, with an emphasis on skin-friendly sensors [5]. In the realm of jewelry biosensors, Sweatcessory presented a choker with a wearable potentiostat to collect sodium levels from sweat [56], while e-ring is a flexible 3D printed ring with gold electrodes capable of electrochemical glucose sensing [27]. Additionally, an electrochemical sensing ring was developed for detecting tetrahydrocannabinol and alcohol from saliva [38]. BioSparks employs electrochemistry techniques and evaluations from past studies of electrochemical wearables, specifically utilizing chronoamperometric data for glucose level measurements [1, 13, 17, 31, 62].

In the context of the production of biosensors, recent developments have primarily focused on making biosensors more sustainable and reducing production costs [8]. Some biosensors have attempted to use environmentally friendly materials for electrodes [10, 36] or substrates [57] to reduce waste resulting from disposal. However, it is worth noting that, the elements required for electrode fabrication are not easily recyclable [45]. For example, in the case of glucose test strips, research shows that diabetic users alone can go through 1.5 to 3 strips every day [14]. The frequent replacement of these strips is evident in the overall cost of glucose self-monitoring [55]. BioSparks proposes a different approach by repurposing biosensors as jewelry or accessories. By using electrochemical biosensors with longer lifespans, the frequency of replacements is reduced compared to traditional test strips. Sustainability is enhanced through the upcycling of otherwise discarded components, contributing to a more environmentally friendly and cost-effective solution.

3 DESIGN CONSIDERATIONS

We drew inspiration from the Wearability Factors for Skin Interfaces [33] and adapted them to propose our Wearability Factors for Designing Jewelry Biosensors, incorporating additional considerations such as modularity, interchangeability, and repurposing within our system.

- **Modularity** - The jewelry piece serves as a versatile module that can be worn on different parts of the body due to its curved design and the adjustable leather strap that secures it. By using different strap's lengths, the piece can be worn around the neck, waist, arm, wrist, or even as a ring on the finger.
- **Interchangeable** - The electrodes can be replaced from the case without the need to open thanks to a rivet system

that enables the attachment and detachment of electrodes through pressure. To facilitate their removal, the electrodes' holder features a raised border, providing a convenient grip. The heart shape of the holder allows for easy replacement in the correct orientation of the electrode.

- **Repurposing** - A repurposing feature is added to the system by creating a heart-shaped perforation in the leather strap which allows the user to insert the used electrode and reuse it as a multi functional accessory, instead of disposing it. The electrodes themselves are also unique, compared to industry electrodes, artistic designs that can serve as jewelry. This reduces waste of disposing used electrodes, which contain precious metal and hard to recycle materials [8, 36]. The replaceable silicone part has a perforation and notch so it can also be used as a pendant by inserting a chain.
- **Location** - Locations for the modular use of BioSparks are based on the body sweat map [3, 9, 58] which suggested the neck, arms, and torso as heat and sweat producing parts. The replaceable biosensor is strategically positioned at the center of the case, ensuring optimal contact with the body.
- **Body characteristics** - The case is designed following the curvature of the body, and the circuit and battery are flexible to follow the case shape. The leather straps can be fastened to the body shape and size.
- **Body movements** - The electrodes are embedded in a silicone insert to provide comfort to the user and are sticking out of the case to ensure contact with the skin.
- **Weight and attachment method** - Leather straps are used to ensure holding the jewelry and device firmly and secure.
- **Aesthetics** - Thanks to the jewelry-like case and electrodes in the inner side of it, electronics and electrodes are not visible when the device is worn.
- **Interaction** - Data visualization and interaction occur from and through the app.
- **Conductors** - Sterling silver alloy is used to create the jewelry electrodes that are part of the circuit design.
- **Insulation** - an inner silicone case ensure the insulation of the PCB to the silver case. The jewelry electrodes are also embedded in a silicone holder.
- **Device care** - case can be opened for cleaning purposes and battery recharging.
- **Connectors** - common wires to connect the electronic components, and silver parts are soldered with silver paste.
- **Communication** - The circuit includes a Bluetooth component to send data to the application.
- **Battery Life** - A rechargeable commercial battery is used.

4 BIOSPARKS IMPLEMENTATION

The implementation of BioSparks consist on the design of the electrochemical biosensor, the integration with the circuit, and the design of the case as a jewelry for embedding electronics.

Traditional Jewelry Design for Electrode Fabrication.

The replaceable electrode is comprised of three parts: pin electrodes, electrodes receivers and silicone holder. The pin electrodes were made using Sterling silver alloy (925 parts of silver, 75 parts of

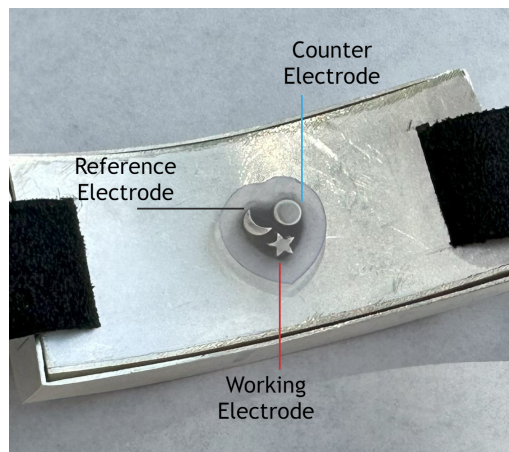


Figure 2: Designing Electrodes with Traditional Jewelry

copper) due to its common use in jewelry making as well as conductivity properties. We carefully cut the heads of the pins from thin flat sheets of silver, shaping and polishing them into three distinct shapes to easily identify each electrode (moon, circle, star). These pin electrodes were then soldered to posts with a 0.9mm external diameter. The receivers utilize a rivet system that connects the pins through pressure, similar to a male-female attachment. They were made by soldering a silver tube of slightly wider inner diameter to flat pieces of silver that would become the connector to the PCB. The holder firmly secure and insulates the electrodes. It was 3D printed in a FormLabs STL printer using Flexible 80A V1 resin. The silicone holder was perforated on the top to receive and securely hold the pins in place. On the bottom, we used a thicker drill bit to create a fitting for the receivers. Finally, all the metal pieces were cleaned with Biogrande pickling solutions, then polished and finally rinsed again using neutral soap and de-ionized water.

Our biosensor comprises a three-electrode system. The working electrode reacts specifically with the analyte, glucose. It was activated using an enzyme solution and cross-linker solution to make it selective to glucose only, excluding other analytes¹. The enzyme solution specifically target glucose, and the cross-linker is used as part of the activation process. The other two electrodes in the system include the reference electrode, which has a fixed potential for reference, and the counter electrode, acting as an auxiliary electrode that completes the circuit and enables the flow of current [16, 61]. Finally, an insulating barrier solution² is applied over the non-sensing portion of the electrodes for insulation.

The finished biosensor is connected to the ecFlex potentiostat³. Each of the three electrodes is connected to the corresponding pin on the electronics. The ecFlex potentiostat operates using chronoamperometry, continuously sending live data to the software via BLE communication. Chronoamperometry is an analytical electrochemistry technique where an electrical potential is applied and stepped

¹<https://www.zimmerpeacocktech.com/products/liquid-solutions/glucose-strip-active-formulation>

²<https://shop.zimmerpeacock.com/products/biosensor-barrier-layer-solution>

³<https://www.zimmerpeacocktech.com/products/electrochemical-sensors/wearable-biosensors/>

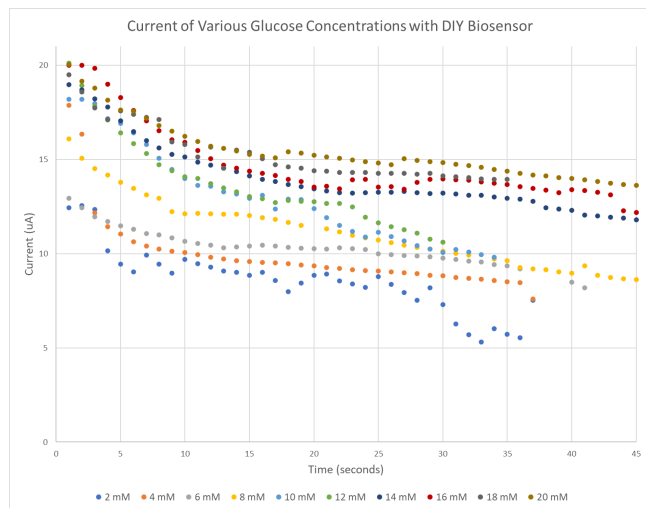


Figure 3: Chronoamperometric measures for each glucose solution with our biosensor

in the potentiostat system, and the resulting current is measured. This technique is the standard electrochemical technique used for glucose measurements [40, 43, 60]. The system is powered by a flexible 3V battery.

Silver Case for Embedding Electronics. Flat silver sheets were manually cut and curved using a bracelet mandrel. They were then soldered together using medium solder for silver (60 parts silver, 40 parts brass). Decorative gems were cast in silicone molds using epoxy colored resin and placed them after polishing the case. The gems were held to the exterior case within boxes which were pre-formed in a finer sheet and soldered to the case. Additionally, an interior case was 3D printed using silicone material. This case served as an isolating agent between the conductive materials and held the inner electronic components securely in place.

5 TECHNICAL EVALUATION

To evaluate our jewelry biosensor, we conducted tests using 10 controlled glucose solutions within the typical range found in human sweat (2, 4, 6, 8, 10, 12, 14, 16, 18, and 20 mM) [20, 21]. Each concentration was tested with the biosensor through wetting a sterile wipe with 1 microliter of solution to simulate sweat on skin. The potentiostat applies a preset and controlled potential. Test trials lasted for at least 30 seconds, varied due to rate of evaporation or absorption, during which sample data were collected. The resulting chronoamperometric data for each solution were graphed, showing curves following the Cottrell equation as expected for chronoamperometry, which describes current decay over time after initial exposure to a test solution [32, 44, 54].

The graphed results show noticeable trends where, after an initial spike when the electrodes come into contact with the testing solutions, each concentration stabilizes to a curve of unique amplitude. Higher concentrations yield higher currents. By mapping the values of each solution at any given time after the initial 10 seconds, it becomes possible to estimate the concentration from the current, as is typically done in biosensor chronoamperometry analysis [54].

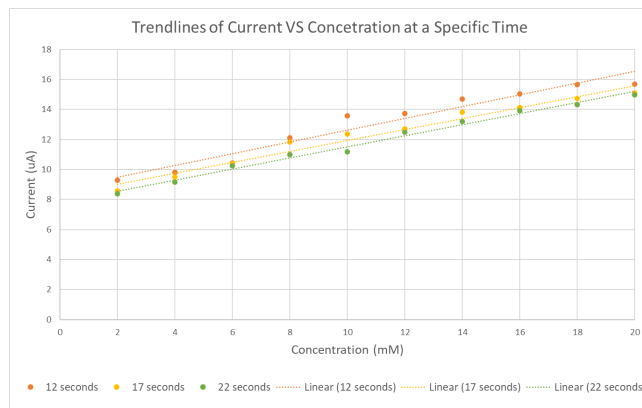


Figure 4: Trendlines of current values for each concentration at exact times after application of solutions

Figure 4 illustrates this, where the trendlines for times 12, 17, and 22 seconds have different vertical intercepts but share similar slopes due to exponential current decay, resulting in parallel lines.

Our jewelry biosensor's performance aligns with past research results that used industry-grade glucose biosensor electrodes [12, 30, 41, 44]. This validation further supports the effectiveness and reliability of our biosensor design for glucose detection in sweat.

6 CONCLUSION

BioSparks introduced a novel form factor of jewelry wearable design, incorporating electrochemical biosensors capable of detecting glucose in sweat. Our contributions lie in four key areas: introducing traditional jewelry design for electrochemical biosensors, adopting a modular design approach for flexible biosensor placement, implementing interchangeable jewelry electrodes for easy replacement, and repurposing used electrodes within the jewelry's chain, as a pendant or as earrings. This exploration of electrochemical sweat biosensors represents a burgeoning field within the HCI community, offering exciting opportunities for interacting with bodily fluids and developing health monitoring technologies.

Future works involve the use of multiple electrochemical biosensors to detect illnesses that require more than one analyte information, a cleaning process to prolong their lifetime, and experimenting with other jewelry materials that could be used for electrochemical biosensors such as platinum, gold or other sustainable materials. Technical evaluations will be done on oxidation, durability of our electrodes, and reliability of biosensors. We aim to conduct experiments with potential users in exploring 1) other applications for repurposing electrodes for continued support of sustainable biosensors and 2) incorporation of an app visualizer for support of user needs and feedback. This project was a collaboration with two jewelry designers, next iterations will include workshops and interviews with jewelry designers and biotechnologists.

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