Non-Invasive Sweat-Based Continuous Glucose Monitoring Patch Using Interdigitated Electrodes

Field of the Invention

This invention relates to medical devices and biosensors for diabetes management. In particular, it concerns a wearable, non-invasive continuous glucose monitoring (CGM) patch that analyzes glucose levels in human sweat using interdigitated electrode (IDE) sensor technology. The invention spans the device hardware, sensing methods, and integrated data systems for real-time glucose monitoring and alerting.

Background of the Invention

Effective diabetes management requires frequent monitoring of blood glucose. Traditional continuous glucose monitors involve invasive probes in interstitial fluid or blood. There is a strong motivation for non-invasive glucose monitoring using alternative biofluids such as sweat, tears, saliva, or interstitial fluid . Among these, sweat is particularly promising because it can be collected non-invasively over large skin areas without privacy or volume concerns . Studies have shown that sweat glucose levels can correlate with blood glucose levels under certain conditions , making sweat a viable medium for glucose monitoring.

However, sweat glucose sensing poses technical challenges. Glucose concentration in sweat is typically much lower than in blood (on the order of 0.02–0.6 mM in sweat versus ~3.9–6.1 mM in blood) , requiring highly sensitive sensors. Sweat composition and output rate can vary with factors like skin site, perspiration rate, pH, salinity, and temperature, which can affect sensor accuracy . Previous wearable sweat sensors struggled with these variabilities, leading to poor accuracy and stability . Additionally, sweat evaporates quickly, especially at rest, making continuous sampling difficult . As a result, to date no sweat-based CGM has been widely adopted; existing wearable sweat sensors on the market focus on other analytes (e.g. hydration ions or lactate) rather than glucose .

There is therefore an unmet need for a first-in-field continuous sweat glucose monitoring patch that can reliably detect low glucose levels in sweat over long durations, compensate for environmental and physiological variability, and integrate seamlessly into a user’s routine. Such a device would likely follow a de-novo regulatory pathway (e.g. FDA 510(k) de novo) given the lack of predicate devices in this category. The present invention addresses these needs with a comprehensive solution spanning sensor hardware and end-to-end data systems.

Summary of the Invention

Overview: The invention provides a wearable sweat-based CGM patch system that uses interdigitated electrode (IDE) sensors to continuously detect glucose in sweat, coupled with integrated subsystems for sweat collection, signal processing, wireless data transmission, calibration, and user feedback. The patent covers a broad range of embodiments to create a "picket fence" of intellectual property, blocking competing approaches. Key aspects of the invention include:

- Multi-Modal Glucose Sensing: The patch can employ any of several sensor modalities for detecting glucose in sweat:
    - Enzymatic electrochemical sensing, where an enzyme (e.g. glucose oxidase or dehydrogenase) on the IDE catalyzes glucose and generates an electrical signal .
    - Non-enzymatic electrochemical sensing, using nanostructured catalysts (metal nanoparticles, metal oxides, carbon nanomaterials, etc.) on the IDE to directly oxidize glucose without enzymes .
    - Impedance/capacitance-based sensing, measuring changes in the electrical impedance or resonant frequency between interdigitated electrodes due to the presence of glucose in the sweat as a dielectric or ionic perturbation .
    - Hybrid sensing approaches, combining multiple mechanisms (e.g. an enzymatic reaction producing a measurable impedance change, or dual sensors of different types) to improve accuracy and reliability.
- Interdigitated Electrode Design Variations: The sensor uses interdigitated electrodes (IDE) – conductive finger-like comb structures – as the transducer. The patent encompasses multiple IDE geometries and materials:
    - Geometries: Various finger pitch (spacing between electrodes), trace width, thickness/depth, length, and aspect ratios are covered. The IDE may be planar or incorporate 3D microstructured features (e.g. high-aspect ratio micro-pillars or micro-needles) to increase surface area. Different shapes (linear comb, circular or spiral IDE layouts, radial patterns, etc.) and orientations are included . The design can be optimized for sensitivity, e.g. high density of fingers for capacitive sensing or larger surface area for enzymatic reaction.
    - Materials: The electrodes can be made from or coated with a wide range of conductive materials, including noble metals (e.g. gold, platinum, silver), base metals (copper, nickel), carbon-based materials (carbon ink, graphene, graphene oxide, carbon nanotubes), emerging 2D materials like MXenes (e.g. Ti_3C_2) or

    conductive metal-organic frameworks (MOFs), and conductive polymers (e.g. PEDOT:PSS, polyaniline). These materials may be used alone or in composites (for example, a laser-induced graphene electrode decorated with gold/silver nanoparticles , a carbon nanotube network functionalized with metal oxides, or a conductive polymer matrix doped with carbon or metal particles). The choice of material can enhance conductivity, biocompatibility, and catalytic activity. Patent analysis shows carbon nanomaterials like graphene, reduced graphene oxide (rGO), and CNTs are frequently used in sweat glucose electrodes, with newer materials like MXene being explored .

- Multiple Substrate Platforms: The sensor patch can be implemented on various substrate types to cover all use-cases:
    - Rigid substrates: e.g. a small printed circuit board (PCB) or ceramic board with the IDE sensor and electronics mounted. This offers durability and precise fabrication, suitable for reusable devices or prototypes.
    - Flexible polymer films: thin, bendable substrates (such as PET, polyimide/Kapton, PDMS, or other biocompatible polymers) allowing the patch to conform to the skin. The IDE and circuit can be printed or laminated on the film. Flexible patches improve wearer comfort and can withstand motion.
    - Textile-based substrates: integration of the sensor into fabrics or bandages. For example, the IDE could be embroidered with conductive threads (e.g. silver-coated or carbon-infused fibers) onto fabric , optionally plated with metal for improved conductivity . Embroidered or woven sensors can be part of clothing or sweatbands for continuous monitoring. The invention covers such e-textile embodiments, including wireless resonance-based readouts using fabric antennas coupled to embroidered IDTs .
    - Hydrogel or adhesive substrates: the patch may include a hydrogel layer that both adheres to the skin and serves as a medium for sweat collection. The IDE sensors can be embedded in or in contact with the hydrogel. Hydrogels can ensure good contact with sweat glands, provide a controlled microenvironment (maintaining moisture, pH, etc.), and can be functionalized with enzymes or chemicals. This category also includes adhesive patches with integrated microfluidic hydrogels that stick to skin like a bandage.
- Integrated Microfluidic Sweat Management: To enable continuous sampling of sweat, the patch can incorporate microfluidic structures that collect, route, and store small volumes of sweat:
    - Sweat uptake and transport: Capillary channels, micro-wells, or porous wicking materials (such as hydrophilic threads or papers) are used to quickly draw sweat

    from the skin into the sensor area . For example, hydrophilic microfluidic channels (in serpentine or spiral shapes) can guide sweat across multiple sensing regions while limiting evaporation .

    - Evaporation control: The microfluidic network may include evaporation barriers (e.g. an oxygen-permeable but water-impermeable layer over channels) or a small reservoir to accumulate sweat, ensuring enough volume for measurement even at low sweat rates .

    - Sweat-rate sensing: Some microfluidic designs integrate sweat rate sensors, such as miniature flow sensors or calibrated channels that allow optical or electrical measurement of sweat flow rate/volume over time . For instance, a segment of the channel may change electrical resistance or capacitance as it fills with sweat, indicating flow rate. Alternatively, a dye or color indicator in a microchannel could be read optically to measure sweat volume (though primary focus here is electrochemical).

    - Multi-analyte routing: The fluidics can split sweat into multiple paths to reach different sensor types (glucose sensor, pH sensor, etc.) on the patch. This ensures simultaneous exposure of all sensors to the same sample for real-time multi-parametric analysis.

- Auxiliary Sensors for Calibration and Context: The patch preferably includes additional sensors to measure environmental or physiological variables that impact glucose readings:

    - Skin Temperature Sensor: A temperature sensor (e.g. a thermistor, diode sensor, or resistive temperature detector) on the patch monitors local skin temperature. Temperature data is used to compensate the glucose sensor reading, since enzyme kinetics and electrochemical response can vary with temperature. Integrating a thin-film temperature sensor alongside the glucose sensor allows real-time temperature calibration .

    - Sweat pH Sensor: A pH sensor (e.g. an IDE coated with a pH-sensitive polymer or an iridium oxide pH electrode) is integrated to measure sweat pH continuously. Sweat pH can influence enzyme activity and sensor electrochemistry; by measuring it, the system can correct the glucose readings accordingly . Notably, researchers have demonstrated a dual sensor patch measuring both glucose and pH simultaneously for weeks . After calibration for pH, the glucose readings more accurately reflected true levels irrespective of pH fluctuations .

    - Sweat Composition/Conductivity Sensors: Optionally, the patch may have sensors for sweat electrolytes (sodium, chloride, etc.) or conductivity. These can serve as proxies for sweat dilution and rate. For example, sodium concentration can indicate how diluted or concentrated the sweat is, which might be used to normalize glucose concentration. A chloride sensor could be included as well (as some patches have measured Cl^- along with other analytes). A dual-analyte approach can thus be employed: measuring glucose alongside another analyte such as lactate or sodium, and using the second measurement to normalize or verify the glucose reading. (Indeed, multi-sensor wearable designs exist that include glucose and lactate sensors together).

  - Motion or Pressure Sensor: In some embodiments, an accelerometer or pressure sensor can be included to detect physical activity or ensure the patch is properly contacting the skin. This data might help interpret sweat readings (e.g. distinguishing exercise-induced changes).

- Electronics and Analog Front-End: The patch includes on-board electronics for signal conditioning, processing, and wireless communication:

  - Analog Front-End (AFE): The tiny currents or impedance changes from the glucose IDE sensor are fed into a high-impedance analog front-end. This typically includes transimpedance amplifiers (for amperometric current measurement) or impedance-to-digital converters. A guard-amplifier configuration can be used to maintain ultra-high input impedance and minimize leakage, by driving a guard electrode or shield at the same potential as the sensor input, reducing noise and signal drift. This is especially useful for high-impedance measurements (like potentiometric or capacitive sensing).

  - Signal Filtering and ADC: The AFE may include filters (to remove noise or interference) and an analog-to-digital converter. The design can support multiple channels (glucose, pH, temp, etc.). For impedance or capacitive readout, an oscillator or resonator circuit can be connected to the IDE and changes in frequency or phase monitored . For amperometric enzymatic sensors, a bias voltage may be applied to the working electrode (IDE) vs. a reference/counter electrode, and the current measured over time (chronoamperometry) .

  - Microcontroller/Processor: A microcontroller or similar low-power processor on the patch receives the digitized sensor signals. It can perform local computations, such as applying calibration factors, averaging, or running safety checks. The processor also controls data logging and the wireless transceiver. For example, an implementation may use an ultra-low-power microcontroller or system-on-chip (SoC) with built-in wireless (like a Bluetooth Low Energy SoC). Some prototypes have used modules like an ESP32 (with Wi-Fi/BLE) combined with a small battery , demonstrating feasibility of real-time on-patch processing and transmission.

  - Wireless Transceiver: The device includes a wireless communication module to transmit data off-patch. Preferred embodiments use Bluetooth Low Energy (BLE) for direct communication to a smartphone. Alternatives include NFC (near-field communication) for passive readout, Wi-Fi (for hospital settings or continuous home monitoring), or proprietary ISM band radios. The wireless transmitter periodically sends the glucose data (and other sensor readings) to a paired external device. For example, a patch can broadcast readings to a smartphone app every minute. In one demonstration, a sweat patch transmitted data via radio to a computer or phone for real-time monitoring .

  - Power Management: The patch is powered by an integrated energy source. This could be a rechargeable miniature battery or a micro-supercapacitor built into the patch. The invention especially covers the use of flexible micro-supercapacitors and energy harvesting to avoid bulky batteries. For instance, a MXene-coated textile supercapacitor patch was shown to provide power for wearable sensors and wireless transmission for hours . The patch can include thin-film supercapacitor cells (possibly layered in the substrate) that are charged wirelessly or via a small solar cell or by an external charger. These provide bursts of power for radio transmission and sensor operation, recharging during idle periods. In other embodiments, a thin flexible battery or an array of energy-harvesting devices (thermal, solar, or motion energy harvesters) can be integrated. Power circuitry (voltage regulators, charging ICs) ensure stable supply to the electronics. The patch may also enter low-power modes between measurements to prolong operating time.

- Calibration and Data Processing Algorithms: A critical aspect of the system is the calibration and signal processing to convert raw sensor signals into accurate glucose concentration readings. The patent protects multiple calibration methodologies:

  - Multi-Point & Ongoing Calibration: The system may be factory pre-calibrated with known glucose solutions, and/or calibrated on the user (e.g. initial fingerstick blood glucose references). Additionally, the system can continually self-calibrate using the auxiliary sensor data. For example, temperature and pH compensation algorithms adjust the glucose reading based on the current sweat pH and skin temperature values . This can involve applying a formula or lookup table that corrects the sensor output to what it would be at a standard pH (say pH 7) and temperature (say thirty-seven °C). As reported in recent research, such real-time compensation yields glucose readings that reflect true blood glucose more accurately, independent of sweat pH or temperature swings .

  - Dual-Analyte Normalization: When a second analyte (or multiple analytes) is measured alongside glucose, the system can use it for normalization. For instance, the device could use the ratio of glucose to sodium concentration to account for sweat dilution effects, or use lactate levels to distinguish exercise-induced glucose changes. If lactate is high (indicating exercise), the algorithm might expect different glucose dynamics. The claims cover using any secondary analyte or reference signal to adjust the primary glucose measurement.

  - Drift Correction via AI: Over time, sensor sensitivity may drift (enzymes can degrade, or fouling can occur). The system can employ machine learning (AI) models to predict and correct drift. An AI algorithm can be trained on historical sensor data and known reference values to distinguish true glucose changes from sensor drift. For example, an on-patch or cloud-based ML model might periodically recalibrate the baseline, or a small neural network running on the device adjusts the output to match expected physiological patterns. Such AI-driven calibration can extend the time between manual recalibrations and improve long-term accuracy .

  - Time-Weighted Averaging and Smoothing: The software may apply filtering techniques to the glucose signal, such as a rolling average or an exponential time-weighted average, to smooth out short-term fluctuations and noise. Given the natural delays in sweat emergence (sweat glucose may lag blood glucose slightly), a weighted averaging over a suitable window (e.g. past 5–10 minutes) can produce a more stable reading and reduce false alarms from transient spikes/dips. The claims include such signal processing methods to ensure reliable continuous readings.

  - Event Marking and Adaptive Calibration: The system can allow user input or automatic detection of certain events that influence sensor readings (such as exercise, eating, or taking a shower which might wash out sweat). The calibration algorithms can adapt by, for example, discounting data during unreliable periods or adjusting the model when a new sweat onset is detected.

- End-to-End System and Data Ecosystem: Beyond the patch device itself, the invention encompasses the broader system needed for a functional CGM solution:

  - Wearable Patch Device: As described, the patch is the sensor hardware applied to the user's skin (e.g. on the upper arm, back, or abdomen). It continuously measures sweat glucose and transmits data.

  - Mobile Application / Receiver: A smartphone app or dedicated receiver device is paired with the patch. The app receives live data from the patch via Bluetooth (or other wireless means). It displays the current glucose level, trends, and alerts the user of any readings of concern. The user can interact with the app to log meals, exercise, or calibration blood glucose values for reference. The patent covers software features for data visualization (graphs, trends), configurable alerts (e.g. vibration/notification if glucose goes too low or high), and data sharing (with healthcare providers or family).

- Cloud and Analytics: In some embodiments, the system uploads data to a cloud server for storage and analysis. Advanced analytics can detect patterns (daily glucose profiles, time-in-range percentages, etc.) and even predict future glucose trends using AI. The cloud platform may also facilitate remote monitoring by clinicians. All these software components (analytics algorithms, alert generation, data security for patient info) are considered part of the inventive system.

- Calibration Routine: The companion app or device may guide the user through calibration routines, e.g. prompting for a fingerstick blood glucose reading occasionally to recalibrate the patch, or instructing the user to perform mild exercise to induce sweat if needed for initial sensor wetting. The calibration routine itself (including prompts, data handling, and adjustment of sensor output using calibration reference) is an element protected by this patent.

- Alerts and Integration: The system can issue alerts when abnormal glucose levels or trends are detected. For instance, if the patched sensor detects a rapid drop in glucose indicative of hypoglycemia, the app can generate an audible alarm or send a message . Alerts can be tiered by urgency. Furthermore, the system can integrate with other devices – for example, it could communicate with an insulin pump or a drug delivery patch to form a closed-loop system. In one embodiment, the patch system is part of a closed-loop “artificial pancreas,” where readings from the sweat glucose patch inform automated insulin or drug delivery. (One prior design demonstrated a patch that not only measured sweat glucose but also released diabetes medication via microneedles ; the present invention anticipates such combination therapies, although our primary focus is monitoring).

By covering all these aspects – from sensor composition and hardware design to algorithms and usage methods – this patent creates a broad protective fence around non-invasive sweat-based glucose monitoring using IDE technology. The invention is intended as a first-of-its-kind medical device enabling diabetic patients and others to continuously monitor glucose without breaking the skin, while maintaining accuracy through clever engineering (multi-modal sensing, comprehensive calibration) and providing a complete user solution (hardware + software).

These and other features and advantages of the invention will be apparent from the following detailed description and the accompanying claims.

Detailed Description of Embodiments

The invention will now be described in detail with reference to exemplary embodiments, which illustrate various implementations and features. These examples are not limiting; rather, it will be understood that many modifications and substitutions are possible without departing from the spirit and scope of the invention as set forth in the claims.

Sensor Modalities and Chemistry:

Enzymatic Sensing Embodiment: In one embodiment, the patch employs a classic enzymatic glucose sensor on the IDE. The interdigitated electrodes (which can serve as working and counter/reference electrodes in a three-electrode or two-electrode electrochemical cell) are functionalized with glucose oxidase (GOx) enzyme immobilized in a polymer matrix on the electrode surface. Glucose oxidase catalyzes the oxidation of glucose to gluconic acid and hydrogen peroxide. This reaction can be detected electrochemically: for example, oxygen is consumed and H_2O_2 is produced in proportion to glucose level . In a first-generation sensor, the electrode (typically platinum, gold, or carbon) held at a fixed potential oxidizes H_2O_2, generating a current proportional to glucose concentration. In second-generation enzyme sensors, a mediator (such as ferrocene or Prussian blue) on the electrode shuttles electrons from the GOx enzyme's redox center to the electrode , improving signal reliability. Third-generation sensors allow direct electron transfer from the enzyme to a nanostructured electrode (e.g. GOx bound to a carbon nanotube-modified electrode) . All such enzymatic approaches are within our scope. The polymer matrix for enzyme immobilization can be, for example, a crosslinked hydrogel (polyurethane, polyacrylamide, etc.), a Nafion coating (to localize enzyme and repel interferents), or a conductive polymer like PEDOT doped with GOx . Enzymatic sensors typically provide high specificity to glucose but can have limited lifetime (enzyme degradation) – hence our design supports redundancy (multiple enzyme electrodes that can be used sequentially) or integration with non-enzymatic backups.

Non-Enzymatic Sensing Embodiment: In another embodiment, the sensor is non-enzymatic, relying on catalytic surfaces to oxidize glucose directly (sometimes called a fourth-generation glucose sensor) . The IDE fingers are coated with catalytic nanoparticles or films, such as platinum, gold, nickel, copper, or alloy nanostructures, or metal oxides (e.g. Ni(OH)_2/NiO, CuO, etc.), or carbon nanomaterials that promote glucose oxidation. For instance, a layer of porous gold on the IDE can catalyze the oxidation of glucose to gluconolactone at certain electrode potentials, generating a current without any enzyme. Carbon nanotubes or graphene doped with metals can provide a high-surface-area catalytic electrode . One example includes a composite of gold nanoparticles on aminated multi-walled carbon nanotubes (MWCNTs) integrated into a flexible electrode, which was shown to effectively catalyze glucose in sweat . Another example is a laser-induced graphene (LIG) electrode treated with a thin layer of gold and silver alloy; this structure significantly lowers the overpotential for glucose oxidation and yields a measurable current proportional to sweat glucose . Non-enzymatic sensors benefit from long-term stability (no enzyme to denature) and were demonstrated to maintain sensitivity over weeks . However, they may be less specific (other reducible species could cause signals). Thus, our design may combine selective membranes or use differential measurements (e.g. subtracting the background signal from a reference electrode without catalyst).

Impedance/Capacitive Sensing Embodiment: In some embodiments, the device operates by measuring changes in the electrical impedance of the IDE sensor when sweat (containing glucose) is introduced between the electrode fingers. The interdigitated array can function as a capacitive sensor whose capacitance or resonant frequency shifts with the dielectric properties and ionic content of the fluid covering it . Glucose, being a polar molecule, and its accompanying ions can alter the permittivity or conductivity of sweat; thus, as glucose concentration changes, the complex impedance at the IDE changes. The patch may include an oscillating circuit where the IDE is part of an LC tank or an RF resonator – the presence of glucose-laden sweat causes a measurable shift in frequency (for example, an embroidered textile IDE resonating around ~1.8 GHz showed a frequency shift of about 0.17 MHz per mg/dL of glucose in solution) . Alternatively, the IDE can be used in an electrochemical impedance spectroscopy (EIS) mode, where an AC signal is applied and the impedance spectrum (Nyquist plot) is analyzed; glucose binding (possibly via a selective receptor or boronic-acid functionalization of the electrodes) might change the impedance signature. This mode can be label-free and does not consume glucose during measurement. To improve specificity, a molecular recognition element like phenylboronic acid or a synthetic glucose-binding polymer can be coated on the IDE; when glucose binds, it causes swelling or dielectric changes that the IDE can detect as a capacitance change. These approaches fall under “non-Faradaic” detection and complement the Faradaic (current-generating) enzymatic methods.

Hybrid and Self-Powered Embodiments: The patent also envisions hybrid sensors that combine mechanisms. For instance, an IDE could be functionalized with both an enzyme and a catalytic metal – glucose could be partially catalyzed by the metal and partially by the enzyme to yield dual signals, improving linear range. Another hybrid approach is a biofuel-cell-based sensor: in one embodiment, the IDE sensor doubles as a biofuel cell where glucose oxidation at one electrode and oxygen reduction at another electrode generate a current. For example, a pair of interdigitated or nearby electrodes can be modified such that one acts as an anode with a glucose catalyst (e.g. gold or Pt nanoparticles with enzyme-mimetic activity) and the other as a cathode with an oxygen-reducing catalyst . The device then produces a voltage or current proportional to glucose, effectively powering itself while sensing. This self-powered sensor mode is within our scope and can be used to extend battery life or provide a secondary validation of the primary sensor’s readings.

Interdigitated Electrode Design and Materials:

Geometry Details: The interdigitated electrodes typically consist of two interlocking “comb” structures – one set of fingers connected to the working electrode lead, the other to the counter/reference. The width of each finger, the gap (pitch) between adjacent fingers, and the length/count of fingers can be tuned. A narrow gap and long fingers increase the electrode surface area and electric field interaction with sweat, boosting sensitivity (but narrow gaps may clog or become harder to fabricate). The patent covers exemplary finger spacings ranging from a few micrometers up to millimeter scale, and finger lengths from sub-millimeter (for dense arrays) up to centimeters (for large-area textile sensors). The electrode thickness can range from thin films (~100 nm to a few microns, such as printed conductive ink) to thicker electroplated traces (>10 microns) or even wire-based embroidery. High aspect ratio electrodes (where thickness is comparable to width) can be achieved via electroplating or using conductive threads. These increase the volume available for functionalization (e.g. enzyme loading).

The IDE pattern may be linear, or it can be arranged in a spiral or concentric circles, etc., as long as interdigitated alternating polarity is maintained. Some embodiments might use multiple IDEs in parallel (e.g. an array of IDE sensors on one patch, each optimized for a different range or coated with different chemistries).

Material Combinations: To illustrate, one embodiment uses a gold IDE on a polyimide flexible film, coated with a thin layer of platinum black to increase surface area, and then coated with glucose oxidase in a chitosan matrix. Another embodiment uses screen-printed carbon IDEs on a polyester film; the carbon ink is mixed with cobalt oxide particles to catalyze glucose non-enzymatically. Yet another uses silver threads embroidered into a fabric as the base IDE, which are then electroplated with gold to provide a biocompatible, corrosion-resistant surface . On this gold-coated thread electrode, a polymer coating (e.g. polyvinyl alcohol with boronic acid) can be added for glucose sensing.

The claims ensure coverage of all these material choices. Notably, many recent devices leverage graphene or carbon nanomaterials for flexibility and performance . For example, a graphene IDE patch could be made by laser scribing polyimide to form porous graphene traces . This LIG IDE could then be decorated with metallic nanoparticles (Au, Ag, Pt) for catalytic activity . MXenes, such as Ti_3C_2, are another candidate: a Ti_3C_2 MXene ink can be printed in an interdigitated pattern on paper or polymer, then modified with enzymes or catalysts. MXenes offer high conductivity and have been used in both sensors and on-board supercapacitors , making them attractive for an all-MXene patch (e.g., MXene electrode combined with MXene energy storage).

Protective and Functional Coatings: The electrodes may be coated with additional layers for specific functions. A dialysis membrane or selective membrane may cover the sensor area to control what molecules reach the electrode (blocking larger interferents or limiting diffusion rate for stability). Anti-fouling coatings (e.g. PEGylated layers) can be used to prevent protein deposition from sweat on the sensor. The invention includes compositions where the IDE is integrated into a hydrogel pad, effectively making the hydrogel both the sample medium and a selective filter. Such hydrogels could contain receptor molecules that selectively bind glucose (like boronic acid-based hydrogels that swell with glucose, changing impedance). All such variations are anticipated by this patent to ensure broad protection.

Sweat Collection and Interface with Skin:

The placement of the patch on the skin can be at various body locations – common sites include the upper arm, forearm, abdomen, or thigh, where sweat glands are plentiful. For exercise contexts, the forehead or back could be used. The patch can be affixed with a medical-grade adhesive (covering an area around the sensor to form a seal that directs sweat into the patch). In some embodiments, the patch includes a replaceable adhesive ring or skin interface, so the electronic module can be reused with fresh adhesive interfaces.

If a hydrogel is used, it can serve as both the adhesive and the sweat collector. The hydrogel (e.g. a thin polyacrylamide or agarose gel pad) contacts the skin and absorbs sweat, then the sensors measure glucose within the gel. This can provide a stable environment (less evaporation, continuous diffusion of sweat from skin to sensor). The hydrogel could also be loaded with NaCl or other constituents to induce a mild osmotic effect that encourages sweat to enter it.

In designs using microfluidic channels, one implementation is a spiral channel that starts at a central inlet near a sweat gland and winds outward. The channel can be covered by a transparent film so that sweat is drawn in and moves along the spiral, with markings indicating volume (this concept has been used for sweat collection patches). Along the channel, electrodes can be placed at intervals to measure sweat composition at different time points or to serve as the sweat rate sensor (by measuring how quickly sweat reaches certain points). The microfluidic structures can be made by soft lithography (PDMS channels), 3D-printing, or laser cutting thin films.

For textile embodiments, sweat wicking fibers can draw perspiration to the sensor location. The patch could be part of a smart wristband or headband; sweat is wicked from the skin by the fabric towards the embroidered IDE sensor region where the measurement occurs. These embodiments might not have a defined microfluidic “channel” per se, but the weave of the textile and capillary action serves a similar purpose.

Integrated Electronics and Power:

The patch’s electronics can be implemented on a small rigid-flex board that is part of the patch, or using chip-on-flex technology directly on the polymer substrate. Low-power design is emphasized to allow long-term use (multiple days or weeks). For instance, a BLE SoC might wake from sleep, read sensors, transmit data, then sleep again to conserve energy, achieving operation for days on a tiny cell or supercapacitor.

One power embodiment uses a tiny rechargeable battery (e.g. a 10 mAh lithium polymer). The patch could have a port or wireless charging coil to recharge between uses. Another embodiment avoids batteries by using a supercapacitor array that can charge in seconds or minutes (for instance, via NFC or a charging cradle) and then run the device for a day. The Drexel University example with MXene textile supercapacitors indicates the viability of this approach for powering sensors and radios for hours .

In some designs, energy harvesting can supplement or replace stored energy: a thermoelectric generator using the heat difference between skin and air, or a small solar cell on the patch’s outer surface, can continuously trickle-charge a capacitor. The patent covers integration of such energy harvesters, as well as circuits for managing them.

Communication and Data:

The patch and app preferably communicate in real-time. The latency from sweat glucose change to on-screen reading might be on the order of a few minutes (including biological lag and sensor averaging). This is sufficient for tracking glucose trends. The app can store calibration profiles for the user and update the patch's calibration coefficients over the air. For example, after the user inputs a blood glucose reference, the app computes an updated calibration curve and sends it to the patch's microcontroller to apply on subsequent readings.

Data security and privacy are addressed via standard encryption of BLE communication and secure cloud storage (beyond the scope of this draft, but implicitly covered as part of the system).

In one use-case scenario, a user applies the patch in the morning, the patch automatically starts tracking glucose. The user's phone receives updates every 5 minutes and displays a graph. If the user begins exercising, sweat rate increases, but the device accounts for this: sweat rate sensor detects high flow, pH might drop slightly with heavy sweating, temperature rises – all these are adjusted for in the algorithm, and the app continues to show stable glucose trends. If the glucose level crosses a threshold or changes rapidly, the app notifies the user (and possibly recommends actions, or in a closed-loop embodiment, signals an insulin pump to adjust dose).

The versatility of the design means it can cover applications beyond just diabetes monitoring. For example, it could be used in fitness/wellness wearables to track metabolic fuel use, or in clinical trials to monitor patients' glucose levels continuously in a non-invasive manner. The broad range of embodiments – enzymatic, non-enzymatic, impedance-based; different substrates and materials; inclusion of various auxiliary sensors and components – ensures that any competitor attempting a sweat-based glucose patch, regardless of their specific approach, would infringe on aspects of this patent.

Having described the system in detail, we now present specific claim sets that define the scope of the invention.