Design of Smartwatch with Non-Invasive Blood Glucose Monitoring Using an I^{2}C Ultra-Slim Low Voltage Sensor

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ABSTRACT

Blood glucose measurement plays a critical role in managing diabetes, a chronic metabolic disorder affecting millions worldwide. Conventional methods often involve invasive procedures or bulky devices, posing challenges to continuous monitoring and patient compliance. This study focuses on the development of an I^{2}C ultra-slim low voltage sensor for non-invasive blood glucose measurement the transmission measurements of a custom-built optical sensor are examined using 12 different wavelengths (λ) between 400 and 960 nm, aiming to enhance convenience and accuracy in monitoring blood glucose levels. Through innovative design and advanced sensor technology, the I^{2}C ultra-slim low voltage sensor offers a compact and user-friendly solution, minimizing discomfort and simplifying the monitoring process. The sensor's performance was evaluated through rigorous testing, demonstrating reliable and accurate glucose measurements across a wide range of concentrations. The results show a correlation value (0.94) between glucose concentration and transmission intensity for four wavelengths (420, 635, 880, and 955 nm) Furthermore, the sensor's compatibility with existing monitoring systems and potential for integration into wearable devices highlight its versatility and potential for widespread adoption in clinical and personal health settings. Overall, the development of this I^{2}C ultra-slim low voltage sensor represents a significant advancement in blood glucose monitoring technology, promising improved accessibility and effectiveness in diabetes management. In summary, the effectiveness of developing blood glucose measurements using ultrathin sensors will depend on their performance in terms of accuracy, precision, speed, user-friendliness, cost-effectiveness, and long-term reliability. The sensors used in this research are excellent in these areas. It is therefore considered effective and potentially transformative in improving diabetes management for patients. In summary, the effectiveness of developing blood glucose measurements using ultrathin sensors will depend on their accuracy, precision, speed, user-friendliness, cost-effectiveness, and long-term reliability. The sensors used in this research are excellent in these areas. It is therefore considered effective and potentially transformative in improving diabetes management for patients.

Keywords: Smartwatch, Blood Glucose Monitoring, I^{2}C ultra-slim low voltage sensor, chronic metabolic disorder, Advanced sensor technology, Non-invasive Measurement, Monitoring process

1. INTRODUCTION

A Blood glucose measurement is a fundamental aspect of monitoring and managing diabetes, a chronic condition characterized by elevated blood sugar levels. The basic theory of blood glucose measurement revolves around understanding how glucose is detected and quantified in the bloodstream. There are several methods for measuring blood glucose levels, including invasive and non-invasive techniques. Here, we'll delve into the basic principles underlying these methods. Glucose is the primary energy source for cells in the body, and its concentration in the bloodstream is tightly regulated.

The general method for blood glucose measurement is the use of portable glucose meters, which are mobile devices that provide rapid results from a small blood sample. By the way, an enzyme structure and substrate binding with amino acid-based enzymes are globular proteins that range in size from less than to more than amino acid residues. The glucose meter then measures the electrical current generated by the reaction between glucose and the enzyme. This current is proportional to the amount of glucose present in the blood sample. By calibrating the meter with known glucose concentrations, it can accurately determine the blood glucose level. Another method for blood glucose measurement is

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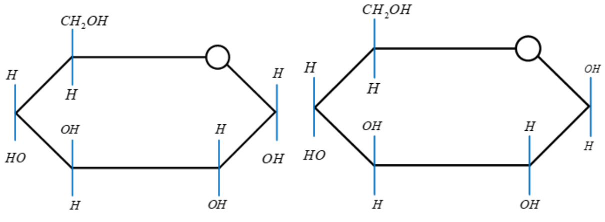
continuous glucose monitoring (CGM), which involves the use of wearable sensors to track glucose levels throughout the day.

CGM systems typically consist of a sensor inserted under the skin, a transmitter that sends data to a receiver or smartphone, and software for analyzing glucose trends. CGM sensors work based on the principle of glucose oxidase or glucose dehydrogenase enzyme reactions, similar to glucose meters. However, instead of providing discrete measurements, CGM sensors continuously monitor glucose levels in the interstitial fluid, which correlates closely with blood glucose levels.

The basic theory behind CGM involves the diffusion of glucose from the bloodstream into the interstitial fluid, where it can be detected by the sensor. The sensor converts this glucose into an electrical signal, which is transmitted to the receiver for analysis. In addition to enzymatic methods, there are also non-enzymatic techniques for blood glucose measurement. One example is infrared spectroscopy, which measures the absorption of infrared light by glucose molecules in the blood. This absorption spectrum can then be used to quantify the concentration of glucose present.

Another non-enzymatic method is based on the phenomenon of glucose-induced changes in the refractive index of blood. By measuring the refractive index of a blood sample, researchers can estimate the glucose concentration indirectly. Fig. 1 shows the structure of λ glucose and represents it in the form of an open chain, it can be seen to have a linear chain of six carbon atoms. Some hydroxyl group is attached to some carbon atoms.

The 1st carbon of glucose is a part of the aldehyde group. The reason for the presence of the aldehydic functional group, glucose is also known as an aldohexose.



(a) (b)

Figure 1 The structure of (a) λ glucose and (b) β glucose.

The control of glucose in human blood is a complex process that involves various organs, hormones, and cellular mechanisms working together to maintain blood glucose levels within a narrow range. Anyway, we have an explanation of how this process occurs the following:

a. Dietary intake: Glucose enters the bloodstream primarily through the digestion of carbohydrates in the diet.

b. Pancreatic hormone release: After a meal, blood glucose levels rise, stimulating the pancreas to release insulin, a hormone responsible for lowering blood glucose levels.

c. Insulin action: Insulin facilitates the uptake of glucose by cells throughout the body, allowing them to use it for energy or storage.

d. Liver regulation: The liver plays a crucial role in regulating blood glucose levels. It stores excess glucose as glycogen when blood glucose levels are high and releases glucose into the bloodstream when levels drop, helping to maintain stability.

e. Muscle uptake: Muscles can take up glucose from the bloodstream, especially during physical activity when energy demands increase.

f. Adipose tissue: Adipose tissue (fat cells) can also take up glucose and store it as fat when energy needs are met.

g. Glucagon release: When blood glucose levels drop, the pancreas releases another hormone called glucagon. Glucagon stimulates the liver to break down glycogen into glucose and release it into the bloodstream, raising blood glucose levels.

h. Stress response: In times of stress or fasting, hormones such as cortisol and adrenaline are released, which can raise blood glucose levels by stimulating the liver to release glucose and reducing glucose uptake by cells.

i. Kidney regulation: The kidneys also play a role in glucose regulation by reabsorbing glucose from the urine back into the bloodstream to prevent its loss when blood glucose levels are low.

j. Feedback loops: The body has intricate feedback mechanisms that continuously monitor blood glucose levels and adjust hormone secretion and cellular activity to maintain homeostasis.

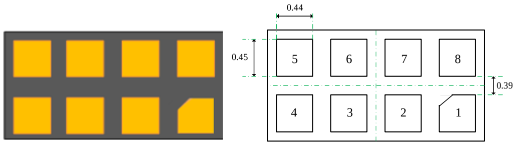
2. METHODOLOGY

Designing a blood glucose monitoring device with I^2C ultra-slim low voltage sensors requires a comprehensive methodology covering various aspects such as sensor selection, device architecture, data processing algorithms, user interface design, and testing procedures the following:

2.1 Sensor Selection

- Evaluate available sensor technologies like enzymatic, electrochemical, and optical sensors.
- Choose sensors based on factors like accuracy, size, power consumption, and compatibility with the target application.

(a) Front View of I^2C blood glucose sensor



(b) Pinout Assignment

(c) Real I^2C blood glucose sensor

Figure 2 An I^2C blood glucose sensor.

Figure 2 shows the sensor used in this research: (a) the front view of the I^2C ultra-sim blood glucose sensor, (b) the pinout assessment of the sensor, and (c) the actual sensors. The Beer-Lambert equation [5] states that the attenuation of light is directly proportional to the sample's thickness and component concentration. The absorbance A of the sample is linked to the concentration of the analytic solution c and the transmittance T by the following formula[5]:-

$$A = -\log_{10} T = \log_{10} \frac{I_0}{I} = \varepsilon.C.p \qquad (1)$$

where:

A = the absorbance;

ε = the molar extinction coefficient (l.mol-1.cm-1);

C = the concentration of the substance in the solution (mol/l);

p = the path length of the photon from the light source to the sensor detector (cm);

I_0 = the intensity of the skin incident light;

I = the intensity of the transmitted light;

T = the transmittance.

2.2 Hardware Development

- Develop the hardware components including sensor interface circuits, signal conditioning circuits, and power management circuits.

- Optimize the design for low power consumption and compact size to accommodate I^2C ultra-slim low voltage sensor.

2.3 Software Development

- Develop firmware for sensor data acquisition, processing, and communication with external devices.

- Implement algorithms for data calibration, noise reduction, and real-time glucose level.

- Design user interface software for displaying glucose readings and providing user interaction.

2.4 Calibration and Validation

- Calibrate the device using standard glucose solutions and reference measurement methods.

- Perform extensive testing to ensure accuracy, precision, and reliability under various conditions such as temperature and humidity variations.

2.5 User Interface Design

- Design an intuitive user interface for easy interaction with the device.

- Include features like touchscreen controls, audio/visual feedback, and customizable settings.

2.6 Photoplethysmography

Photoplethysmography (PPG) is a non-invasive optical technique used to detect blood volume changes in the microvascular bed of tissue. It relies on the principle that blood absorbs light differently than other tissues, and by measuring these variations in light absorption, it's possible to infer various physiological parameters, including blood glucose levels, in this method, a light transmitter and a light receiver are used to measure the amount of light absorption of body tissues [1].

The basic setup of a PPG system involves an emitter and a detector. The emitter shines light into the tissue, typically using LEDs at specific wavelengths, while the detector measures the light that is transmitted or reflected. When blood volume changes occur, such as during cardiac cycles, the amount of light absorbed by the tissue fluctuates, producing a pulsatile waveform known as the photoplethysmogram.

To measure blood glucose using PPG, researchers exploit the fact that glucose concentration affects the optical properties of blood. Specifically, glucose molecules absorb light at certain wavelengths, causing changes in the PPG waveform. By analyzing these changes, it's possible to estimate blood glucose levels non-invasively.

One approach to glucose measurement with PPG involves using multiple wavelengths of light to obtain a spectral analysis of the PPG signal. By comparing the absorption characteristics of blood at different wavelengths, researchers can isolate the effects of glucose and derive a correlation between the PPG signal and blood glucose concentration. Another method involves the use of mathematical models to interpret the complex relationship between glucose concentration and the optical properties of blood. These models often incorporate factors such as tissue scattering, hematocrit level, and oxygen saturation to improve the accuracy of glucose predictions.

In addition to glucose measurement, PPG can provide valuable information about other physiological parameters, such as heart rate, blood pressure, and vascular function.

This versatility makes PPG a promising tool for continuous monitoring of various health metrics in a non-invasive manner. Despite its potential, several challenges remain in the development of PPG-based glucose monitoring devices. One challenge is the need for calibration against reference glucose measurements to ensure accuracy and reliability. Variations in individual anatomy, tissue properties, and environmental conditions can also affect the performance of PPG systems.

Moreover, factors such as motion artifacts, ambient light interference, and sensor placement can introduce noise and distortions into the PPG signal, complicating data analysis and interpretation. Advanced signal processing techniques, including noise filtering, motion compensation, and artifact rejection, are essential for improving the robustness of PPG-based glucose monitoring systems [2][3].

Furthermore, regulatory approval and clinical validation are necessary steps for translating PPG technology from research laboratories to real-world applications. Long-term studies involving diverse patient populations are needed to demonstrate the accuracy, precision, and clinical utility of PPG-based glucose monitoring devices in managing diabetes and other metabolic disorders.

Despite these challenges, ongoing research and technological advancements continue to drive the development of PPG-based glucose monitoring towards more reliable, user-friendly, and cost-effective solutions. With further innovation and validation, PPG has the potential to revolutionize the way blood glucose levels are monitored, offering greater convenience, accessibility, and quality of life for individuals living with diabetes.

2.6 System Implementation

2.6.1 Functional Block Diagram of Hardware

The I^{2}C ultra-slim sensor contains one photodiode for photocurrent measurement. The photodiode currents are converted to a digital level by an analog-to-digital converter. The sensor also includes an LED driver, as well as some peripheral circuits such as an internal oscillator of a sensor, a current flow in the sensor course, voltage reference, and internal fuses to store trimming information as shown in Figure 3. They consist of a VCSEL driver and 3.6V logic group with analog to digital converter, oscillator, interrupt, and I^{2}C interface. This sensor has an 8-pin connector for communicating with the outside consisting of VDD for receiving the 3.6V from an external power supply, VSS reference to ground, and INT to interrupt signal and SCL, SDA feed to microcontroller section is shown in Figure 4 [5].

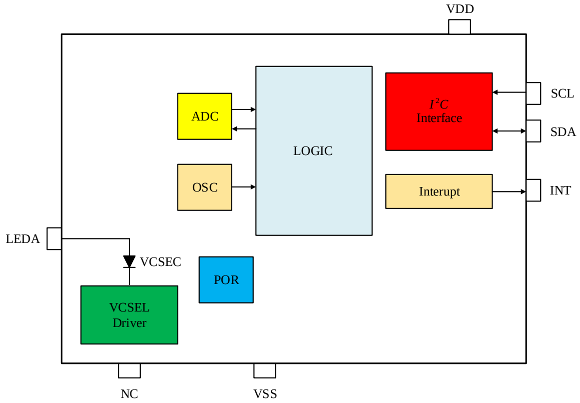


Figure 3 Functional block diagram of I^{2}C blood glucose sensor.

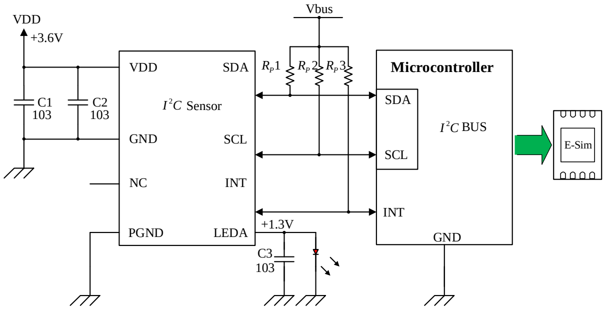


Figure 4 I^{2}C blood glucose circuit

Figure 4 shows communication between a microcontroller and an embedded SIM card (E-Sim) typically involves interfacing with the SIM card through standard communication protocols like SPI (Serial Peripheral Interface) or UART (Universal Asynchronous Receiver-Transmitter). Here's a general method for communication between a microcontroller and an E-SIM card:

a. Identify Communication Interface: First, we must determine which communication interface the embedded SIM card supports. Most embedded SIM cards support standard interfaces like SPI or UART.

b. Connect Hardware: Connect the microcontroller to the embedded SIM card using appropriate hardware connections. For SPI communication, we typically need connections for MOSI (Master Out Slave In), MISO (Master In Slave Out), SCK (Serial Clock), and optionally CS (Chip Select). For UART communication, they need connections for TX (Transmit), RX (Receive), and optionally other control lines like RTS (Request to Send) and CTS (Clear to Send).

c. Initialize Communication: Initialize the communication interface on the microcontroller side. This involves configuring the appropriate communication settings such as baud rate, data format (e.g., number of data bits, parity, stop bits for UART), and clock polarity/phase for SPI.

d. Send Commands: Use the microcontroller to send commands to the embedded SIM card. These commands typically follow the protocol specified by the SIM card manufacturer and may include commands for functions like reading data, writing data, authentication, and managing the SIM card's functionality.

e. Receive Responses: After sending a command, the microcontroller waits for a response from the embedded SIM card. Responses may include data, status codes indicating success or failure, or other information relevant to the command that was sent.

f. Process Responses: Once a response is received, the microcontroller processes it according to the application's requirements. This may involve parsing data, interpreting status codes, and taking appropriate actions based on the response received.

g. Repeat as Necessary: Repeat the process as needed for the desired functionality, sending additional commands and processing responses as required.

2.6.2 Functional Software Application

The designing of software to receive input signals from a blood glucose sensor involves several important considerations. Let's delve into the details:

a. Understanding the Sensor: The first step is understanding the blood glucose sensor's specifications, including its communication protocol, data format, and sampling rate.

b. Sensor Integration: The software needs to integrate seamlessly with the sensor hardware, ensuring proper connectivity and data retrieval.

c. Data Acquisition: Establishing a reliable method for data acquisition is crucial. This involves setting up communication channels, such as Bluetooth, USB, or proprietary protocols, to receive sensor data.

d. Data Parsing: Once data is received, it needs to be parsed and validated. This involves decoding the data packet and ensuring its integrity before further processing.

e. Data Conversion: Raw sensor data often needs to be converted into meaningful glucose readings. This may involve calibration algorithms or mathematical transformations.

f. Real-time Processing: In some applications, real-time processing of glucose data may be necessary for immediate feedback or control actions.

g. Data Storage: Storing historical glucose data securely is important for trend analysis, medical records, and future reference. Proper data storage mechanisms should be implemented, considering factors like data retention policies and privacy regulations.

h. Data Transmission: Depending on the application, the software may need to transmit glucose data to other systems or devices securely. This could involve encryption and authentication mechanisms.

i. User Interface: Designing an intuitive user interface is essential for users to interact with the software effectively. This includes displaying glucose readings, trend graphs, and relevant information.

j. Accessibility: Ensuring accessibility features for users with disabilities, such as screen readers or voice commands, is crucial for inclusive design.

k. Customization: Providing options for users to customize settings, alerts, and notifications according to their preferences enhances user experience.

l. Integration with Other Systems: The software may need to integrate with other healthcare systems, such as electronic health records (EHR) or telemedicine platforms, for comprehensive patient management.

m. Security: Implementing robust security measures to protect sensitive health data from unauthorized access or breaches is paramount. This includes encryption, authentication, and adherence to healthcare data regulations like HIPAA.

n. Battery Management: Efficient power management techniques should be employed, especially for mobile or wearable applications, to optimize battery life without compromising functionality.

o. Calibration and Accuracy: Ensuring the accuracy of glucose readings through regular calibration and validation processes is essential for reliable monitoring and treatment decisions.

p. Alerts and Notifications: Implementing timely alerts and notifications for abnormal glucose levels or critical situations enables users to take necessary actions promptly.

q. Data Analysis: Providing tools for data analysis, such as trend identification, pattern recognition, and predictive analytics, empowers users and healthcare providers to make informed decisions.

r. Compliance: Adhering to relevant medical device regulations and standards, such as FDA guidelines for software in medical devices, is essential for legal compliance and patient safety.

s. Continuous Improvement: Regular updates and improvements based on user feedback, technological advancements, and clinical research ensure the software remains relevant and effective in meeting users' needs[6].

3. FLOWCHART OF SYSTEM MANAGEMENT

3.1 The function of flowchart

Figure 5 shows that designing the flowchart for software to receive input signals from a blood glucose sensor requires careful planning and consideration. Here's a basic outline of the flowchart, but remember, the specifics will depend on the requirements of your project and the capabilities of the software and hardware [4]:

Start: Begin the flowchart here.

Initialize: Initialize the software and any necessary variables.

Connect to Sensor: Establish communication with the blood glucose sensor. This might involve setting up a connection protocol (e.g., Bluetooth, USB, etc.).

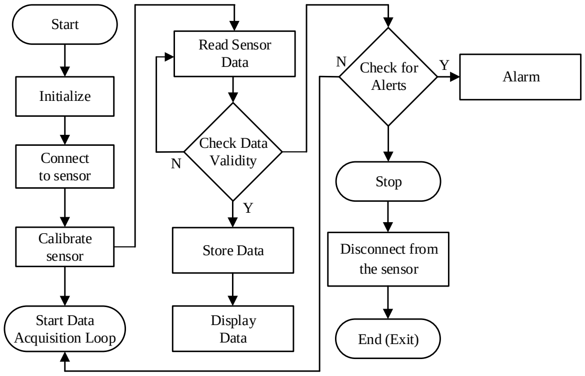


Figure 5 Flowchart of software system.

Calibrate Sensor (Optional): If the sensor requires calibration, this step involves sending calibration commands and receiving calibration data.

Start Data Acquisition Loop:

a. Read Sensor Data: Read the incoming data from the sensor. This could include the blood glucose level and possibly other information such as temperature or battery status.

b. Check Data Validity: Verify the received data to ensure it falls within the expected ranges and is not corrupted.

c. Store Data: Store the validated data in memory or a database for further processing and analysis.

Display Data (Optional): If needed, display the received data on a user interface for real-time monitoring.

Check for Alerts (Optional): If there are specific conditions or thresholds to monitor, such as dangerously high or low blood glucose levels, set up an alert system to notify the user or healthcare provider.

Repeat Data Acquisition: Loop back to the data acquisition step to continuously receive and process new data from the sensor.

Stop: End the flowchart.

Disconnect from Sensor: Once the operation is complete or the software is shutting down, properly disconnect from the sensor to release resources and ensure data integrity.

Exit: End the flowchart here.

4. DEVELOPMENT OF SMARTWATCH BODY

Designing a smartwatch body to incorporate a blood glucose monitoring device involves several key considerations to ensure both functionality and user comfort such as.

a. Size and Form Factor: The smartwatch body we designed to accommodate the blood glucose monitoring technology without significantly increasing the size or weight of the device. Users typically prefer sleek and lightweight designs for comfort and aesthetics.

Figure 6 Smartwatch body.

b. Display Integration: The display of the smartwatch seamlessly integrates the blood glucose monitoring interface, providing the patients with clear and easy-to-read glucose readings. This may involve incorporating a dedicated screen or utilizing existing display space efficiently.

c. Sensor Placement: we are placing the two I^2C blood glucose sensors strategically placed on the underside of the smartwatch to ensure accurate readings while maintaining user comfort. This location should allow for direct contact with the user's skin to measure glucose levels effectively.

d. Material Selection: we selected the materials used in the smartwatch body should be hypoallergenic and skin-friendly to prevent any adverse reactions or discomfort during prolonged wear. Additionally, the materials are durable and resistant to moisture and sweat.

e. Battery Life: Integrating a blood glucose monitoring device may impact the smartwatch's battery life.

Our design considerations include optimizing power consumption to ensure that the device can operate for an extended period without frequent recharging.

f. Connectivity: We designed the smartwatch to support wireless connectivity to synchronize blood glucose data with companion mobile apps or cloud platforms. This enables patients to track their glucose levels over time and share data with healthcare providers if necessary.

g. Patient Interface: The patient interface of the smartwatch be intuitive and user-friendly, allowing users to easily access and interact with blood glucose monitoring features. This may involve incorporating touchscreen controls or physical buttons for navigation.

h. Safety and Regulatory Compliance: The design should adhere to safety standards and regulatory requirements for medical devices, ensuring that the blood glucose monitoring technology meets established accuracy and reliability standards.

5. RESULTS

The smartwatch prototype and software application results of the proposed method are “Design of Smartwatch with Non-Invasive Blood Glucose Monitoring Using an I^2C Ultra-Slim Low Voltage Sensor” is discussed. The software tools National Instrument is used for simulation purposes.

We obtained the normal ranges of Biomedical Instruments and Glucose levels. This work is implemented with the help of C++ language, and additionally adding the Machine language level for the accuracy of this work.

Table 1. Comparison of invasive method and non-invasive method

Volunteer Patient	Reading of invasive method (mg/dl)	Reading of non-invasive glucose level (mg/dl)
Patient #1	120	123
Patient #2	196	198
Patient #3	77	79
Patient #4	144	146
Patient #5	100	102

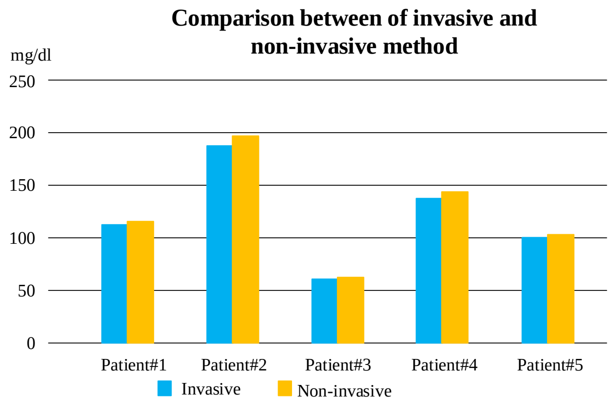


Figure 7 A comparison of Invasive and non-invasive methods of graphic presentation

The results comparison between invasive and non-invasive methods is shown in Table. 1 and Figure 7

Note:

- Blood sugar level if lower than 70 mg/dl (70 – 100 is considered normal)
- Blood sugar levels between 100 – 125 are considered at risk. Also known as latent diabetes.
- Blood sugar levels over 126 are considered at risk for diabetes.

6. CONCLUSION

The heart of this innovation is an I^2C ultra-slim, a low-voltage sensor for seamless communication between the sensor and the smartwatch, facilitating the transfer of data with minimal power consumption.

In addition to blood glucose monitoring, the smartwatch may also offer other health and fitness tracking features, such as heart rate monitoring, activity tracking, and sleep analysis. This multi-functionality enhances the value proposition of the device, making it a comprehensive solution for individuals looking to manage their overall health and wellness.

Overall, the integration of a non-invasive blood glucose monitoring system into a smartwatch represents a significant advancement in wearable health technology, offering individuals a convenient, comfortable, and reliable way to monitor their blood glucose levels in real time.

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