Medical Engineering and Physics 41 (2017) 55–62

Contents lists available at ScienceDirect

Medical Engineering and Physics

journal homepage: www.elsevier.com/locate/medengphy

Characterization of micro-resonator based on enhanced metal insulator semiconductor capacitor for glucose recognition

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ARTICLE INFO

Article history:
Received 8 February 2016
Revised 19 July 2016
Accepted 3 January 2017

Keywords:
Glucose sensor
Integrated passive device
Microwave resonator
Metal-insulator-semiconductor
Permittivity

ABSTRACT

We present a concept for the characterization of micro-fabricated based resonator incorporating air-bridge metal-insulator-semiconductor (MIS) capacitor to continuously monitor an individual's state of glucose levels based on frequency variation. The investigation revealed that, the micro-resonator based on MIS capacitor holds considerable promise for implementation and recognition as a glucose sensor for human serum. The discrepancy in complex permittivity as a result of enhanced capacitor was achieved for the detection and determination of random glucose concentration levels using a unique variation of capacitor that indeed results in an adequate variation of the resonance frequency. Moreover, the design and development of micro-resonator with enhanced MIS capacitor generate a resolution of 112.38×10^{-3} pF/mg/dl, minimum detectable glucose level of 7.45 mg/dl, and a limit of quantification of 22.58 mg/dl. Additionally, this unique approach offers long-term reliability for mediator-free glucose sensing with a relative standard deviation of less than 0.5%.

1. Introduction

Recently, there has been increasing interest in the design of a glucose sensor based on radio frequency (RF) techniques due to the possibility of easy fabrication, a short assay time, and mediator-free detection in the microwave spectrum region [1]. The design of a RF glucose sensor that exhibits high sensitivity, good linearity, low limit of detection, is a mediator-free, and has high specificity is today's challenge. Research into an RF-biosensor is supported by high throughput, suitability for non-invasive applications, and non-destructive detection capabilities with less power consumption [2]. This procedure works with the lab-on-chip methodology, which enables a miniaturized size result from micro-fabrication. Moreover, different sensing techniques and modalities are being pursued [3,4], such as electrochemical, enzyme oxidation [5], metamaterial [6], amperometric [7], and tattoo-based screen printed glucose sensors [8]. The tattoo-based concept seems promising, but it is a preliminary work, suffers with long operation time and holds considerable promise for efficient diabetes management, which can be extended toward non-invasive sensors. The invasive enzyme oxidation method is the most promising invasive technique, but it has a serious limitation because of its instability.

To address the limitations of the aforementioned sensing techniques and improve the quality of detection, RF and a microwave glucose sensor are the foremost candidates in biomedical applications [9–11]. The present work is an endeavor to develop gallium arsenide (GaAs) base glucose sensor using an integrated passive device (IPD) technology, where two metal-insulator-semiconductor (MIS) capacitors are incorporated in parallel to enhance the sensitivity, as small as 7.45 mg/dl. Variation in the complex permittivity and, ultimately the MIS capacitance (C_a) acquired for the various glucose concentrations ranging from 105 mg/dl to 185 mg/dl is efficiently characterized for the detection of glucose levels. The parameters, such as transmission coefficient (S_{21}), reflection coefficient (S_{11}), absolute and relative variation ($\Delta f/f_0$) of the resonance frequency, characterization of the complex permittivity [ε_r (ω, κ)], and the MIS capacitor were accurately and efficiently modeled for different levels of glucose concentration to reflect the actual and real behavior of diabetic patients. Thus, the proposed RF methodology will be applicable and helpful in making those incremental steps in the field of glucose sensing.

2. Fabrication process

The fabrication of the device started with the passivation layer of silicon nitride (SiNx, 200 nm), which was first deposited over a gallium arsenide (GaAs, 400 µm) substrate using plasma enhanced chemical vapor deposition (PECVD). Then, a 2 µm-thick Au metal

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http://dx.doi.org/10.1016/j.medengphy.2017.01.008
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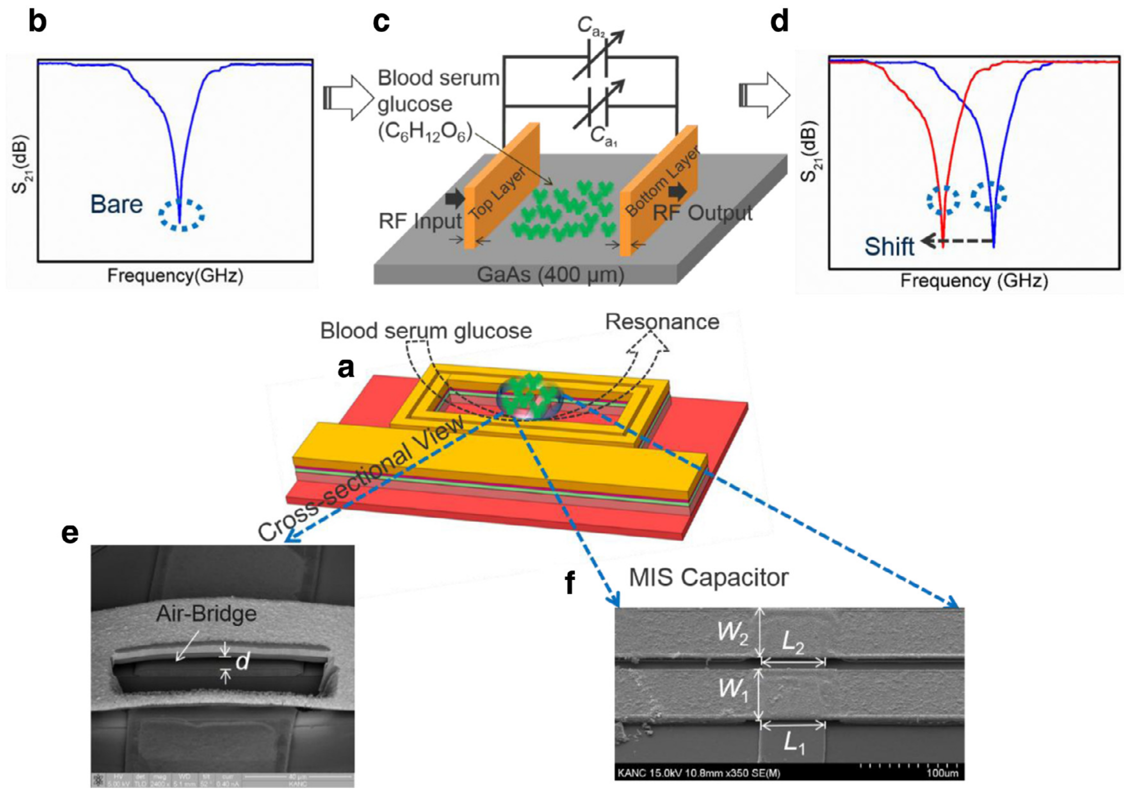

Fig. 1. The images show the (a) analytical concept for the glucose level detection, (b) bare RF test of the glucose sensor resonating at 10.72 GHz, (c) cavity-based MIS capacitor as a sensor, (d) RF measurement of the proposed glucose sensor via VNA for the sensor loaded with human serum, (e) cross-sectional view of an air-bridge structure showing an air-cavity structure with $d = 3.8$ µm, and (f) SEM images demonstrating MIS capacitor with $W_1 = 60$ µm, $L_1 = 60$ µm, $W_2 = 60$ µm, and $L_2 = 60$ µm.

layer was formed by electroplating. A 20/80 nm Ti/Au seed metal was deposited with a RF sputtering process. The passivation layer helps in maintaining a homogeneous layer over any surface defects or roughness. The adhesion between GaAs and the Au layer was supported by the passivation layer. Again, a seed metal layer was formed, as previously described, and followed by a second passivation layer of 200 nm S_iN_x deposited by PECVD to prevent a possible short circuit between the first and second metal layers [12]. Finally, the air-bridge interconnections was formed by a photo process prior to the Au (3 µm) top metal deposition and plating process, as illustrated in Fig. 1(a). The resulting process produced the cavity in between the top metal layer and the substrate, which results in MIS capacitors. The implementation of glucose solution with different permittivity for the capacitor results in the generation of the different resonance frequency.

3. Materials, methods and implementation

To facilitate the experimental process for the serum glucose level detection, the random blood sample with a base glucose concentration of 105 mg/dl. Five different solutions of the sample for the experimental purpose were prepared from the original sample in the concentration range of 105 mg/dl to 185 mg/dl at an interval of 20 mg/dl using a standard additive technique. Also, for the comparative analysis of the result obtained from the serum sample, we prepared the standard solution of D-glucose in the concentration range of 25–225 mg/dl. The experimental process and final testing of the proposed glucose sensor was performed at the RFIC Center, Kwangwoon University, Seoul, South Korea.

The new concept, based on a transmission line cavity loaded air-bridge structure, was implemented for mediator-free sensing of glucose concentration in human serum. The design of the glucose sensor was proposed using the basic concept of the resonator with MIS capacitor owning high out-band and in-band attenuation level, resulting in excellent selectivity [13]. Additionally, for the analysis of the proposed sensor, three featured frequencies for the overall process were measured through the vector network analyzer (VNA) to reflect the behavior of the encapsulated sensor in a printed circuit board, as shown in Fig. 1(b). The top sensing surface was gold electroplated to remove unnecessary oxidation. An air-cavity formed by an air-bridge structure between the metal layers acts as a reservoir for the serum [14]. The top metal layer and the substrate form the air-cavity and acts as a MIS capacitor with air in between them as the dielectric medium as illustrated in Fig. 1(c). Importantly, MIS capacitor behaves differently when the serum with different glucose concentration is applied to the cavity which indeed causes the change resonance frequency [Fig. 1(d)] according to the glucose concentration level. The various concentrations of glucose holds different permittivities as calculated by the Debye relaxation process for an aqueous solution. A sample model with 5 µl of serum was poured on the air-bridge structure of the sensor, which caused a change in the electrical behavior due to a variation in the permittivity, alters the attenuation level and, finally, the resonance frequency, as shown in Fig. 1(e) and (f) [15]. The blood is a complex compound with different constituents. Plasma contained in the blood contains different compound such as protein, glucose, salts, vitamins, hormones. Moreover, monosaccharide molecules ($C_6H_{12}O_6$) contain a higher number of −OH groups that form more −H bonds, resulting in less available water to interact with the EM field. The permittivity (ε) and permeability (μ) for different material can be characterized, which are the measures of EM interaction of media with the electric (E) and magnetic fields (H), respectively. Consequently, the dielectric constant of a water–glucose solution is lower than water. Thus, the heavier glucose molecule contributes to the dielectric mechanism of aque-