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Interdigitated Electrodes based Nano Bio Sensors

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Abstract

Interdigitated Electrodes IDE are used to detect and analyze cells or particles. Biosensors in general can be used in a wide range of applications to detect cells/bacteria which can be utilized in early discovery of some diseases. This review summarizes wide range of researches in this field to illustrate the different design factors when fabricating Interdigitated Electrodes IDE. These factors ranges from the fabrication process itself, sensor dimensions and shapes, space between electrodes, and sensors sensitivity and more. In this literature review, a discussion of all these design factors will be introduced.

Keywords: Integrated Electrodes IDE; Nano Sensors; Bio Sensors.

1. Introduction

Biosensors can be used in a wide range of applications to detect cells/bacteria [1, 2], to detect toxins [3], and to detect and monitoring diseases in early stages [4, 5]. Mechanical, optical, and electrochemical concepts can be used to design and develop biosensors [6–8]. Electrochemical detection methods are a good fit especially in the case of quick and affordable detection [8]. The main concept in the electrochemical biosensors is measuring changes in electrical properties resulted from the presence of a particular biological particles/molecules/cells. Interdigitated Electrodes (IDE) normally are considered one of the main components to design electrochemical biosensors. IDE is used to apply electric voltage to the analyte. Also, changes in the electric field at the surface of the IDE will be measured when a certain particle exists between the electrodes [9, 10]. Interdigitated Electrodes IDE are used to detect and analyze cells or particles by using a multi-frequency impedance-based characterization. The detection and the characterization are based on the dielectric properties of the cells (capacitance and conductivity) that allows to discriminate cells. This can lead to the detection of physiological differences between cells or changes in cell over time [11]. IDE can achieve a wide range of advantages over the traditional methods such as: real-time detection, label-free analysis, non-invasive sensing, easiness of integration and high throughput screening [12]. The IDE can be considered as an impedance based sensor which can detect the impedance change as a result of the presence of a particular particle or cell between two facing electrodes [13].

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IDE can be used in mechanical IDE sensors, Surface acoustic wave IDE sensors, and chemical IDE sensors. In the third type (chemical IDE sensors), IDE can be classified as resistive and capacitive chemical sensors. Mechanical IDE sensors use the IDE as a switch where if the force on the sensor increases, the area of contact between the IDE and a semi conductive layer increases. Therefore, the resistance between the electrodes decreases as force increases. The surface acoustic wave IDE sensors do not use capacitance or resistance features of the IDE. This type of the sensors uses acoustic waves to determine the presence of a particular molecules or bacteria. The existence of such particles causes the velocity of the acoustic waves to decrease. This type of sensors can be used to detect and measure humidity in air such that as the humidity increases, the electrical resistance decreases. The third type of sensors is the chemical IDE sensors which can be further classified as either resistive or capacitive IDE sensors. In capacitive IDE sensors, the sensing area (the area between the electrodes) acts as dielectric between the electrodes but the sensing area in the resistive IDE sensors acts as a resistor between the electrodes [14, 15].

Based on the space between the electrodes and the coating thin film on the electrodes, an IDE chemical capacitive based sensor can detect any analyte. For the resistive based IDE chemical sensors, a conductive thin layer should cover the electrodes. The thin sensing area resistance will change due to the concentration of the analyte. Randle’s model can be used to understand the connections between the electrodes, sensing layer, target cells, and surrounding solution.

2. Literature Review

An extensive research [16-23] has been done on the sensing area between the electrodes in the IDE chemical sensors. The reason that this sensing area is a critical part in the IDE sensors applications is that the sensing area controls either the resistance or the capacitance changes due to the presence of the analyte/cell/particles/molecule under consideration. In a resistive sensor, current will only flow from an interdigitated electrode to the other across the gap. Therefore, the actual sensing occurs only at the gap area on the interdigitated electrode sensor. Similarly, for a capacitive sensor, the area of the sensing layer that is located in the gap between the two interdigitated electrodes will be the only part that can act as the dielectric between the two electrodes. So, the actual sensing in a capacitive sensor occurs only at the gap area in the interdigitated electrode sensor.

Moreover, the shape of the sensing area between the electrodes is critical as well. The traditional square shape may cause un-optimization of the sensing area. Some research considered a curvy edges of the interdigitated electrodes. Other research work has been done on the dimensions of the overall size of the IDE sensor to optimize the sensing area. It has been found that increasing the x-dimension causes increasing in the sensitive area by a high factor. However, increasing the y-dimension barley affects the sensing area and efficacy of the sensor. Furthermore, research has been done on different shapes of IDE chemical sensors such as circular IDE and hexagonal IDE sensors.

Bianchi and his colleagues [24] investigated the sensitivity of the sensor to detect and quantify cells flowing in a test chamber. They considered the geometry of the sensors and its effects on the sensor sensitivity. They applied an AC voltage of 50 mV with a range of frequencies values (10^5 to 10^9 Hz) and then compared the impedance of the electrodes placed in the solution vs the impedance of the electrodes with the cell under investigation present in the solution as a function of the applied frequency. The simulation was done in COMSOL using the EC electric current model. They found that the impedance increases as a function of the sensor geometry and the best dimensions (electrodes length, and separation between electrodes) of the sensor should be 30x30x30 micrometer. Moreover, the highest change in the real part of the impedance caused by the presence of the cell is reported at frequency 1.3 MHz and the presence of the cell causes decrease in the impedance.

Skjolding and his colleagues [25] proved that the separation between the interdigitated comb-like electrodes should be less than one micrometer for maximum signal amplification. They used the advanced lithography techniques to fabricate arrays of interdigitated electrodes with an electrode separation distance of 200 nm and an electrode finger width of 200 nm as well with the overall dimension of the sensor 100 micrometer by 100 micrometers. They used the Autolab bi-potentiostat to simulate applying a fixed potential of 500 mV. They found that there is a correlation between the concentration range from 5 microM to 4 mM of electrochemical reversible redox compound, ferrocyanide, and the endpoint current.

Le and his colleagues [26] proposed a new way to fabricate the IDE sensors. Their silver electrodes were inkjet printed on Si/SiO2 substrates instead of traditional photolithography method. Conductive polyaniline (PANI) layer was coated on the silver interdigitated electrodes by drop-coating. They used their sensor to detect Ammonia. The conductivity of the PANI films decreased significantly due to the deprotonation process of PANI upon ammonia exposure. They used the Corel software instead of COMSOL. They were interested in detection of Ammonia since it is a toxic gas and inhalation of ammonia at high level could burn respiratory and sore throat. Thus, detection of ammonia is important in industrial, medical, and environmental areas. They fabricated 1cm by 1cm sensor in Germany. Other research has been done on Inkjet printing technology to fabricate copper circuits on flexible polyimide substrates such as [27-30]

McKay and his colleagues [31] used COMSOL to simulate the interaction of the IDE with gold nanoparticles. They studied the electrical field between the electrodes in salt solution. They found that the gold nanoparticles can lower the electrical field magnitude between the digits of the electrode. They considered the IDE width, height, spacing, applied voltage and the background solution in their simulation to show the effect of the gold nanoparticles on the electrodes impedance.

The dimension and the spacing of the IDE can determine the right application where the Ide can be used. For example, the smaller the dimension and the spacing of the IDE, the more sensitive the IDE is. Therefore, to detect cells and bacteria [Ab1], the dimension of the IDE can be in terms of micrometers. On the other hand, to detect DNA hybridization, the dimensions of the IDE should be in terms of sub-micron [32].

Oberländer and his colleagues [33] used the IDE sensors to evaluate the sterilization process in the food industry. They used 614 electrode fingers spanning over a total sensing area of 20 mm^2. Their proposed solution is a fast and affordable technique compared to the traditional industrial sterilization process. They used impedimetric analysis of *B. atrophaeus* spores before and after the sterilization process. An alternating voltage was applied to the sensor terminals induces a current depending on the intrinsic properties of the sensor and the spores on its surface. By measuring the relation between voltage and current, the impedance of the sensor can be calculated. Moreover, the capacitance of the sensor can also be derived using an equivalent circuit approach. They used COMSOL for the 2D simulation. They found that the impedance decreases as a result of the spores' presence due to the conductive properties of the microorganisms (spores). They reported a problem in their fabrication process of the sensor. They found uneven edges due to the lift-off process.

More research utilized the IDE concepts in different applications such as mechanical applications. Uvarov and his colleagues [34] presented electrochemical valveless micropump. Myers and his colleagues [35] presented a methodology towards designing, analyzing and optimizing piezoelectric interdigitated microactuators using COMSOL Multiphysics. They were interested to know which materials are best suited for the MEMS applications.

More research has been done on the mathematical modeling of the IDE electrochemical cells such as [36, 37]. Christian and his colleagues proposed a new semi-infinite criterion for the cell. Their simulation results show that the exact expressions obtained by Aoki and Morf [38] for the limiting current in semi-infinite geometries can be applied to finite geometries, if the new semi-infinite criterion is satisfied. In case the semi-infinite criterion is not satisfied, the new bounds for the limiting current can be applied and provide a reasonable estimation. Steffen and his colleagues proposed a closed-form analytical expressions derived from Schwarz-Christoel conformal mappings to determine the capacitance of multi-layer interdigitated electrode structures with an additional parallel continuous electrode.

More related research has been done on fabrication of the IDE nanosensors to detect a particular gas or cell. Zoric and his colleagues [39] used COMSOL to simulate the electromagnetic and electrostatic fields of interdigitated capacitor. The main concept here is that the sensing layer will change its permittivity or permeability depending on changes of the particular pollution. They changed multiple of factors such as number of the IDE fingers, width of the IDE fingers, and space between the fingers and so on to measure the dependency between these factors and the capacitance of the sensor. They used the 3D design and both MEMS and Electrostatics modules. Their IDE fingers were simulated as ceramics. They found that as the fingers length increases, the capacitance increases too. They found also that if the permittivity of the sensing layer increases, the capacitance will also increase.

Zou and his colleagues [40] studied the impedimetric sensors for genomics, proteomics, and cellular analysis. They built gold IDE on polymer substrate. They use the Electrochemical Impedance Spectroscopy (EIS) to sense different concentrations of IgG. They overcame other research drawbacks such as Newman and his colleagues [41] research in which their impedance change was very small as a result of the target presence. They claimed that their proposed IDE with gold electrodes on Polymer substrate will be better than IDEs on silicon substrate. They fabricated the proposed IDE and used EIS to measure the impedance during the experiment.

Tamaki and his colleagues [42] fabricated via beam lithography a 200nm Au IDE on SiO2/Si substrate to detect dilute NO2. They used WO3 thin film to sense the NO2. They reported that when the spacing gap between the

IDE electrodes decrease, a higher sensitivity will be obvious. Moreover, they studied the effect of the teeth number on the IDE sensitivity and they found that the higher the number of teeth/the longer the length of the IDE, the higher the sensitivity of the fabricated IDE nanosensor.

Yagati and his colleagues [43] proposed a method to detect insulin in serum at low concentration levels. Traditional methods to detect insulin are expensive, time consuming, lab equipment based, and cumbersome. They claimed that the electrodes surface needs to be modified to enhance the sensor sensitivity. Previous research used graphene since it has strong electrical and mechanical strength [44]. Other research use noble metallic nanoparticle such as gold, silver, and platinum. They believe that synthesis of Ag nano-flowers on reduced graphene oxide (AgNF-rGO) on an indium tin oxide (ITO) micro-disk electrode array will improve the sensor sensitivity. They applied 10mV voltage within the frequency range of 0.1 Hz and 100 kHz. They used traditional photolithographic fabrication process. They also used the COMSOL to simulate the electric field and current density for the bare electrodes and the enhanced surface electrodes. They used Randle's model to evaluate the impedance of the electrodes surface without and with the AgNF-rGO. They preferred to use a low frequency such as 1 Hz to show the dependency of the impedance on insulin concentrations. Finally, they tested the same developed sensor with other proteins to ensure the selectivity of their proposed sensor.

3. Summary

Basically, there are a few parameters that are considered by all research done on this topic. These design parameters such as IDE dimensions (sensing area gap/spacing between electrodes, electrodes length, width, and height), electrodes materials such as gold, substrate material (silicon or glass), sensing materials and the material that covers the electrodes which depend on the biological target, the target cell/molecule/protein that need to be detected or measured (insulin, NO2, humidity), nature of the sensor (impedance/capacitive/resistive), the voltage applied to the electrodes (AC/DC), the applied frequency range, and the fabrication process (lithography/inkjet printing). In this review, a summary of all design parameters are discussed by grouping and comparing all research work that has been done on each design parameter.

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