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Full Length Research Paper

Electrical characterization of in-house fabricated polysilicon micro-gap for yeast concentration measurement

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Fabrication and electrical characterization of micro-gaps and their properties are discussed with their applications in electrochemical sensors and bimolecular detection. To understand the relationship between the biosensor and micro-structure we have carried out the fabrication and characterization of micro-gap structures for yeast concentration measurement. In this paper two photo mask designs are used. The first mask is for defining the lateral micro-gap and the second one is for the aluminum electrode pattern. Lateral micro-gaps are formed using polysilicon and Al as contact pads. Conventional photolithography techniques are used to fabricate the micro-gap. The electrical measurements were carried out using a Semiconductor Parameter Analyzer to measure the change in capacitance across the micro-gap with the yeast solution drop put across the gap. The measured value of capacitance for each yeast concentration is presented as a function of the gap size. The results indicate that these micro-gaps could possibly be used for yeast sensor applications.

Key words: Micro-gap, conductivity, yeast detection, capacity, electrochemical sensor.

INTRODUCTION

The objective of the present work is to explore the possibility of using polysilicon micro-gaps for yeast concentration measurement. Micro- and nano-fabrication techniques are progressively being applied to create ultra-miniature sensors for characterizing and quantifying bio-molecules. The reduction in sensor size can result in lower materials cost, reduced weight, and lower power consumption, which are the key factors driving newer opportunities for sensors in the marketplace. Micro- and nano-sensors of highly reduced power consumption are very suitable for integration into wireless communication devices to enable widespread distributed monitoring and control. Very low-power micro- and nano-sensors would also be beneficial for use as battery-operated handheld or wearable sensors. Logical and promising sensing application areas for micro- and nano-sensors include medical (e.g., blood analysis, patient monitoring and diagnostic testing), bio warfare detection, genetic analysis, drug discovery, food inspection/testing, environmental monitoring, and industrial chemical process monitoring. Micro- and nano-gap structures fabricated using semiconductors and materials have been used quite often for such sensors. In this work polysilicon (Poly-Si) is used for micro-gap fabrication.

Poly-Si is known to be compatible with high temperature processing and interfaces very well with normal semiconductor processing steps. As a gate electrode, it has also been proven to be more reliable than aluminum (O'Mara et al., 1990). It can also be deposited conformably over steep topography. Doped polysilicon thin films are used in emitter structures in bipolar circuits and in resistors. Polysilicon is a key component for integrated circuits. At the component level, polysilicon has long been used as the conducting gate material in metal–oxide–semiconductor field-effect transistor (MOSFET) and complementary metal oxide semiconductor (CMOS) technologies. For such applications it is deposited using low-pressure chemical-vapor

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deposition (LPCVD) at high temperatures. In terms of chemical resistance, polysilicon is very much like single crystal silicon. The oxidation rate of undoped polysilicon is typically between that of (100)- and (111)-oriented single crystal silicon. For temperatures below 1,000°C, heavily phosphorus-doped polysilicon oxidizes at a rate significantly higher than undoped polysilicon (Bhushan and Bharat, 2004).

The resistivity of polysilicon can be modified using conventional dopants for silicon processing. Phosphorous, the most commonly used dopant in polysilicon, diffuses significantly faster in polysilicon than in single crystal silicon, due primarily to enhanced diffusion rates along grain boundaries. The diffusivity in polysilicon thin films (that is, small equiaxed grains) is about $1x10^{-12}$ cm^2/s (Irudayaraj and Reh, 2008).

The electrical characteristics of a poly-Si thin film depend on its doping. Poly-Si is more resistive than single-crystal silicon for any given level of doping primarily because the grain boundaries in poly-Si offer additional scattering sites to reduce carrier mobility. Common dopants for polysilicon include arsenic, phosphorus, and boron. Polysilicon is usually deposited undoped and the dopants are introduced later on (James, 2005).

Yeast extract is the common name for various forms of processed yeast products made by extracting the cell contents (removing the cell walls); they are used as food additives or flavourings, or as nutrients for bacterial culture media. They are often used to create savory flavors and umami taste sensations. Monosodium glutamate (MSG) is used for umami, but has no flavor. Yeast extract, like MSG, often contains free glutamic acid. Yeast extracts in liquid form can be dried to a light paste or a dry powder. Glutamic acid in yeast extracts are produced from an acid-base fermentation cycle, only found in some yeasts, typically yeasts used in the baking of breads.

Yeast extract is the water-soluble portion of autolyzed yeast. The autolysis is carefully controlled to preserve naturally-occurring B-complex vitamins. Yeast extract is prepared and standardized for bacteriological use and cell cultures, and is an excellent stimulator of bacterial growth. Yeast extract is generally employed in the concentration of 0.3 - 0.5%. Yeast extract is typically prepared by growing baker's yeast, *Sacharomyces* spp., in a carbohydrate-rich plant medium. The yeast is harvested, washed, and resuspended in water, where it undergoes autolysis, that is, self-digestion using the yeast's enzymes. Yeast extract is the total soluble portion of this autolytic action. The autolytic activity is stopped by a heating step. The resulting yeast extract is filtered clear and dried into a powder by spray drying. Yeast extract has been successful in culture media for bacterial studies in milk and other dairy products. Several media containing yeast extract have been recommended for cell culture applications (Chan et al., 1998). The capacitance offered by micro- and nano-gap structures depends on the electrode geometry. It increases with the electrode area, increases with the electrode spacing, and also depends on the nature of the material present between the two electrodes.

In this work, the electrical measurements were carried out using a Semiconductor Parameter Analyzer to check the capacitance across the micro-gap, which changes with the yeast solution drop put across the gap. The measured values of capacitance for each yeast concentration used are presented as a function of the gap size in the micro-device structure. The fabricated micro-gaps were used for yeast sensors.

RESEARCH METHODOLOGY

Mask design

In this work, Si wafer is used as the substrate to fabricate a micro-gap biosensor. The starting material used here is a p-type, 100 mm diameter. Two photomask processes are used to fabricate the micro-gap using conventional photolithography and polysilicon dry-etching techniques. Commerical chrome mask is used for better pattern quality. The photomasks are designed using AutoCAD and then printed onto a chrome glass surface.

Figure 1 is the first mask for microgap electrode formation with a length and width of 5000 and 2500 µm, respectively.

Six sets of angular length S_d (600 to 1100 µm, with a difference of 100 µm) has been chosen in the present study to check the best angle for micro-gap formation after the etching process. S_d refers to the dimension for the side angle of the design for micro-gap formation as shown in Figure 1(a) and (b), which shows the actual arrangement of the device design on the chrome mask. It consists of 160 dies with 6 different designs.

Figure 2 is a schematic device design of mask 2 with 1500 µm length and 1500 µm width. The distance between two squares is 3500 µm.

Micro-structure fabrication

The proposed process steps for the Al electrode with polysilicon micro-gap fabrication are starting by cleaning the Si wafer before depositing a 150 nm SiO_2 substrate on the Si wafer by using plasma-enhanced chemical vapor deposition (PECVD) equipment. Then, a low-pressure chemical-vapor deposition (LPCVD) machine is used to deposit the 600 nm polysilicon layer to perform a layer of 135 nm Al substrate as a hard mask to avoid damage to the polysilicon layer during the etching/ RIE process (Thikra et al., 2011). Next, in the photolithography process, a layer of positive photo-resist 1200 nm is first applied to the Al surface, and then exposed to ultraviolet light through mask 1 as shown in Figure 3(d). After developing, only the unexposed resist will remain, and then the wet-etching process of Al layer is performed before removing the resist. After that, the dry-etching process for the polysilicon layer is applied to fabricate the micro-gap for the micro-structure, then a layer of 135nm Al substrate is deposited before the resist coating process. After exposing mask 2, the layer of the resist is developed as in Figure 3(g), and then the wet-etching process of the Al substrate is performed before removing the resist. Finally a structure of the Al electrode with a polysilicon micro-gap is obtained as shown in Figure 3(h).

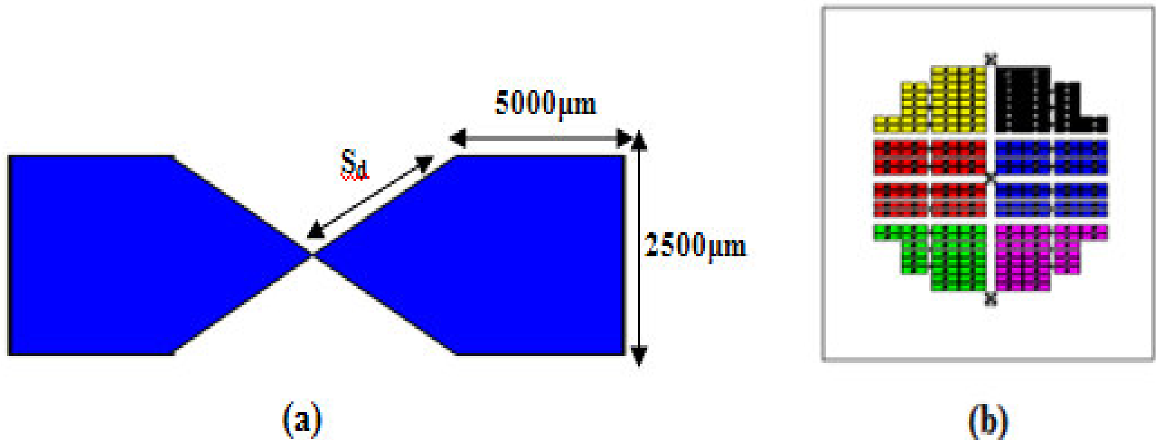

Figure 1. (a) Design specification of the first mask, and (b) Schematic design of the actual mask on chrome glass.

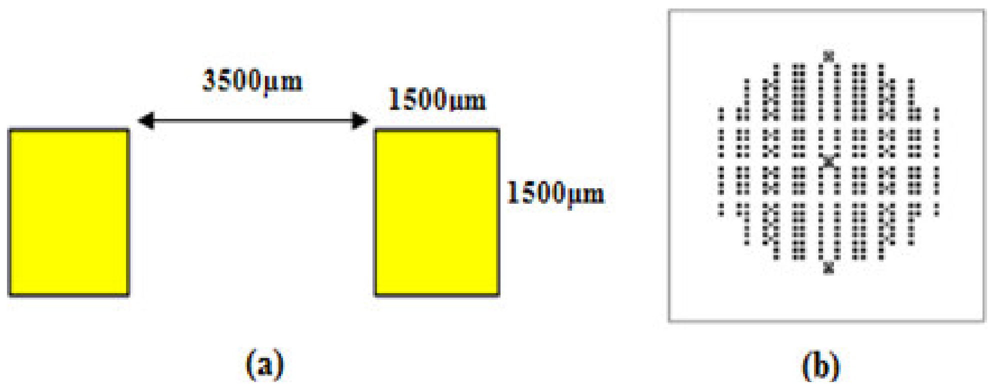

Figure 2. (a) Design specification for mask2, and (b) Schematic for mask2 on chrome glass.

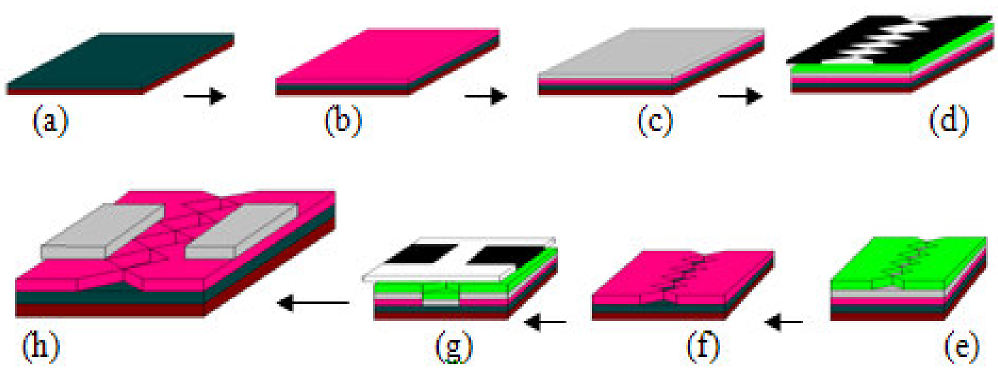

Figure 3. Polysilicon micro-gap structure fabrication process flow.

Micro-gap measurement and characterization

The fabricated micro-gap structures were characterized by the 3D Nano Profiler and a scanning electron microscope (SEM). Figure 4 shows the final device structures used for the electrical characterization using the Semiconductor Parameter Analyzer. Probing is done using large size Al pad electrodes on the device. The micro-gap biosensor will thus act as a capacitor between two polysilicon structures connected to the Al pads.

Yeast solution preparation and detection

In this work, the yeast-DI water solutions were tested using

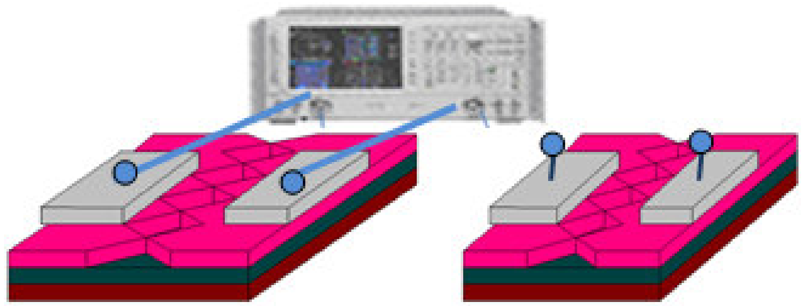

Figure 4. Capacitance measurements taken using a dielectric analyzer.

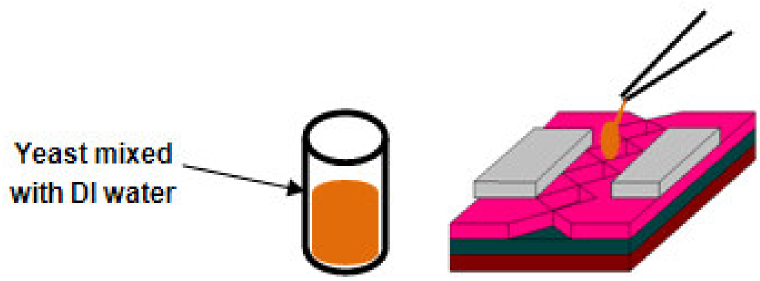

Figure 5. The probe process on the micro-gap structure.

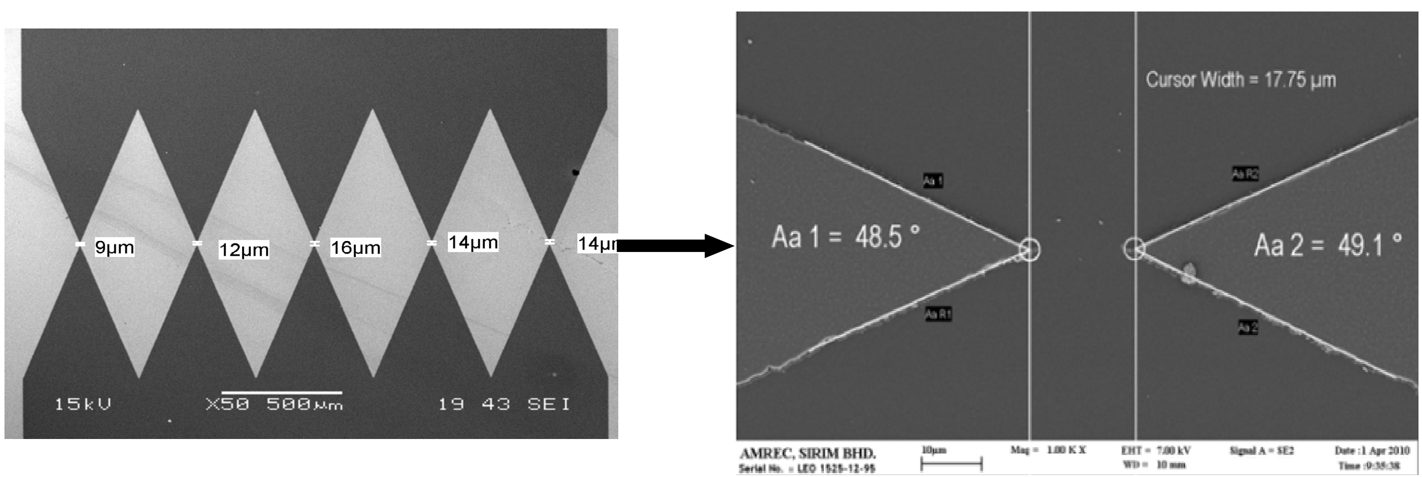

Figure 6. SEM image of polysilicon micro-gap measurement.

micro-gap structures for the capacitance measurements. The micro-gap is cleaned using DI water followed by dry spinning, then baking at less than 100ºC for a few minutes. After that, the yeast solution is dropped across the micro-gap as shown in Figure 5, to measure the change in the capacity as will be shown in the results and discussion.

RESULTS AND DISCUSSION

Figures 6 and 7 show the SEM and 3D nano profiler images for the polysilicon micro-gap after fabrication processes, where it can be seen quite clearly that the size of the gap is approximately between 9-18 µm.

Capacitance-voltage (C-V) characterizations of micro-gap electrodes were performed at room temperature by a two-point probe using a Keithley 4200 semiconductor characterization system.

Figure 8 shows that for the applied voltage from -3 to +3 V, capacitance is almost constant at 127E-12 F. That happens because the charges between the two plates do not have enough energy to create the depletion region, and it would be increasing when probed by any contact

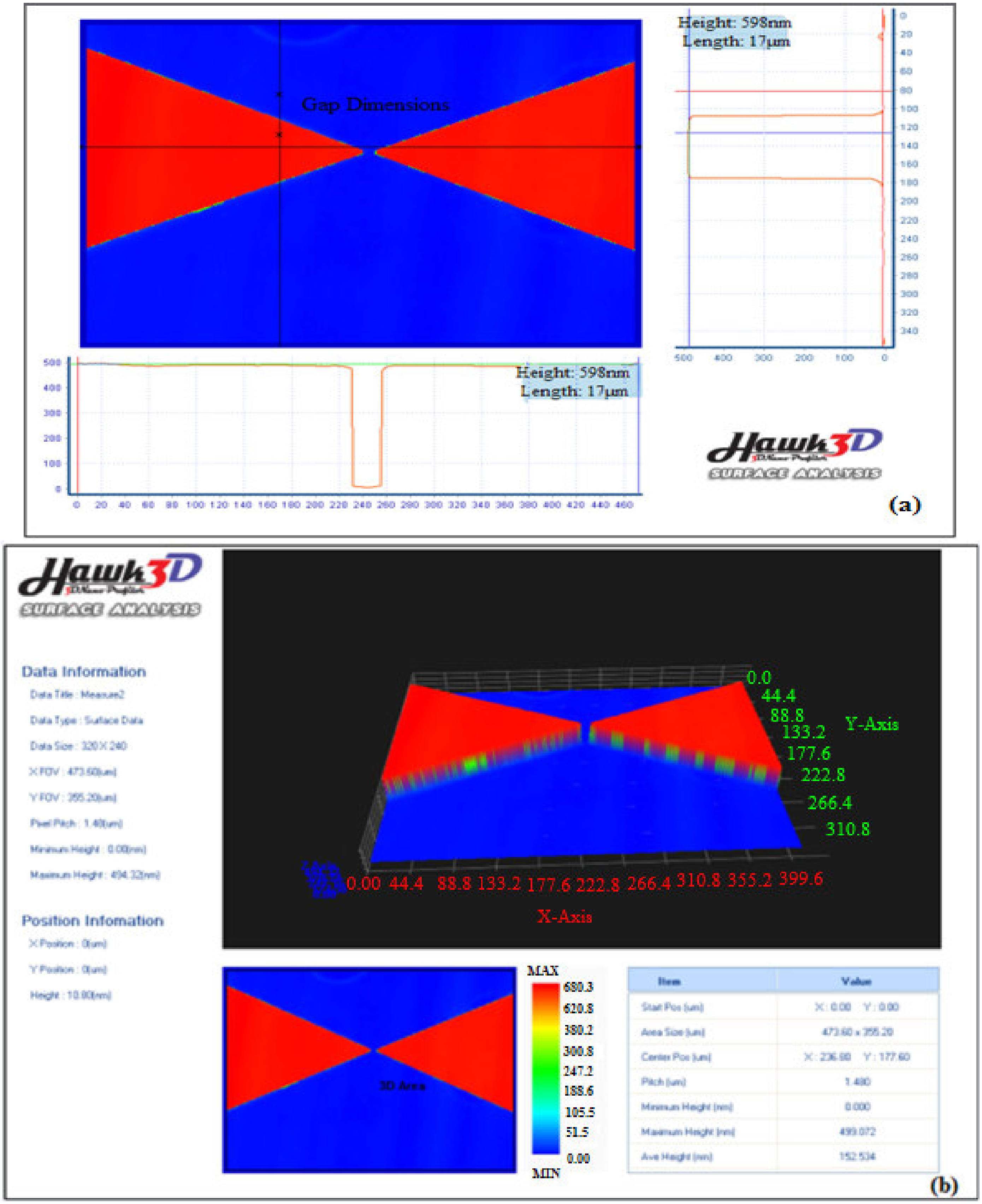

Figure 7. 3D Nano profile measurements for: (a) The gap dimensions, (b) The microstructure surface section.

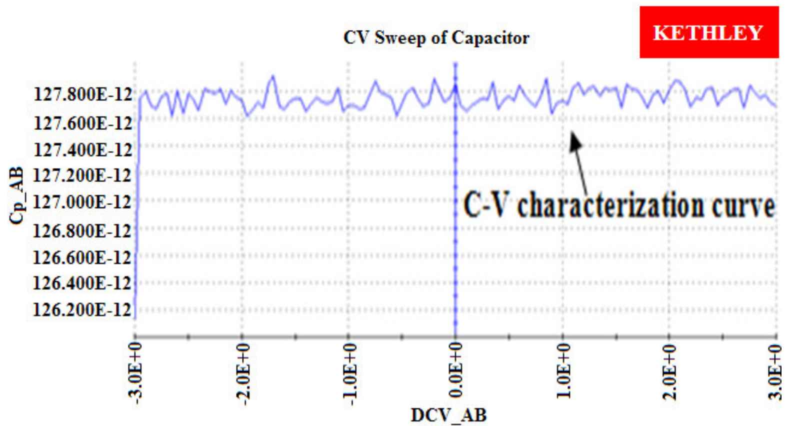

Figure 8. Capacitance –Voltage curve for polysilicon micro-gap structure.

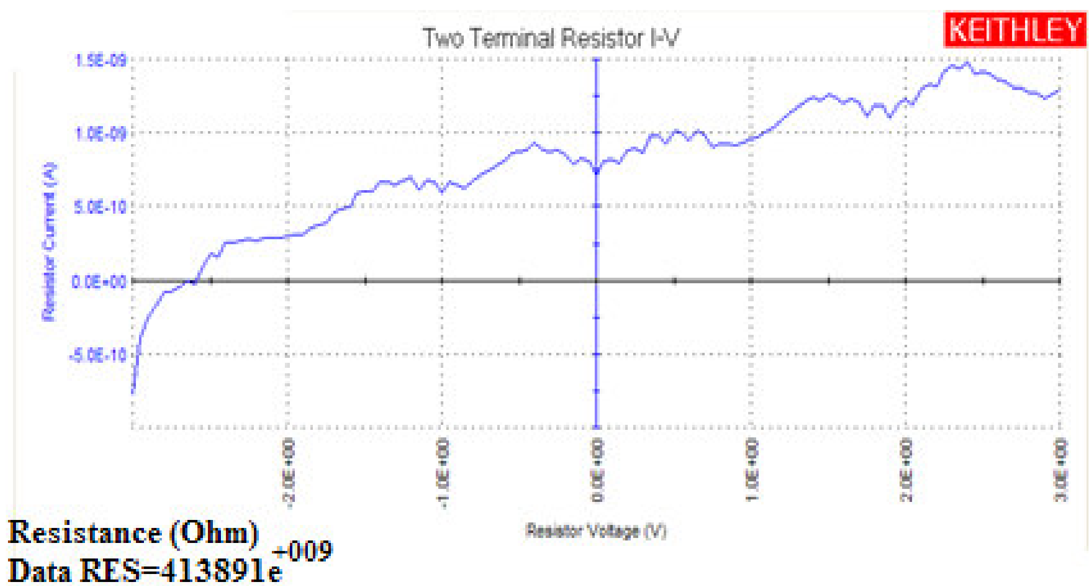

Figure 9. I-V curve for the polysilicon micro-gap structure.

polymer. The Keithley 4200-Simiconductor Parameter Analyzer has built-in support for measuring current-voltage (I-V) characterization as well. The I-V curve in Figure 9 shows that for the voltage applied from -5 to +5 V, the resistance is very high at 4.13891^{+9}Ohms, because the capacitance will decrease in this range of voltage and allow passing the current with a small value of -5E-10 to1E-9 Amperes. C-V and I-V measurements confirm the capacitance nature of the micro-gap fabricated in this work (Ikonomou and Schneider, 2001).

Measurement and analysis of dielectric properties (capacity value) for the yeast solution is carried out by using WINDETA software. Different types of parameters are set at a value list for frequency and AC volt, start condition, list order of independent variables and end condition. These parameters will generate the result graph that was used in this research for analysis. From the frequency - capacitance curve results, we can determine the value of capacitance that would be used to analyze what yeast solutions give the best performances among the others. The experimental method of this research is based on a capacitance measurement technique using DI water and a yeast solution. For this measurement, different yeast solution concentrations, which are 0.1, 0.3, 0.5, 0.7 and 0.9 mg, are used with various gap sizes using a constant voltage at 0.1V. The range of frequency that was used is around 10^0-10^2 Hz; the results display almost exactly the same behavior but different capacitance values.

Figure 10 presents the electric capacity versus frequency results for various gaps using DI water. The results show that the capacitance increases with the size

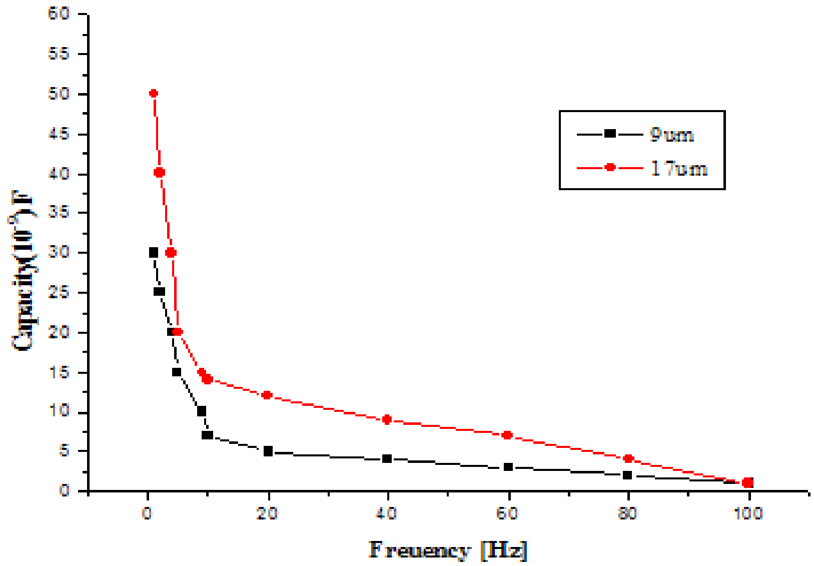

Figure 10. The capacitance measurement for DI water at gap size 9 and 17 µm.

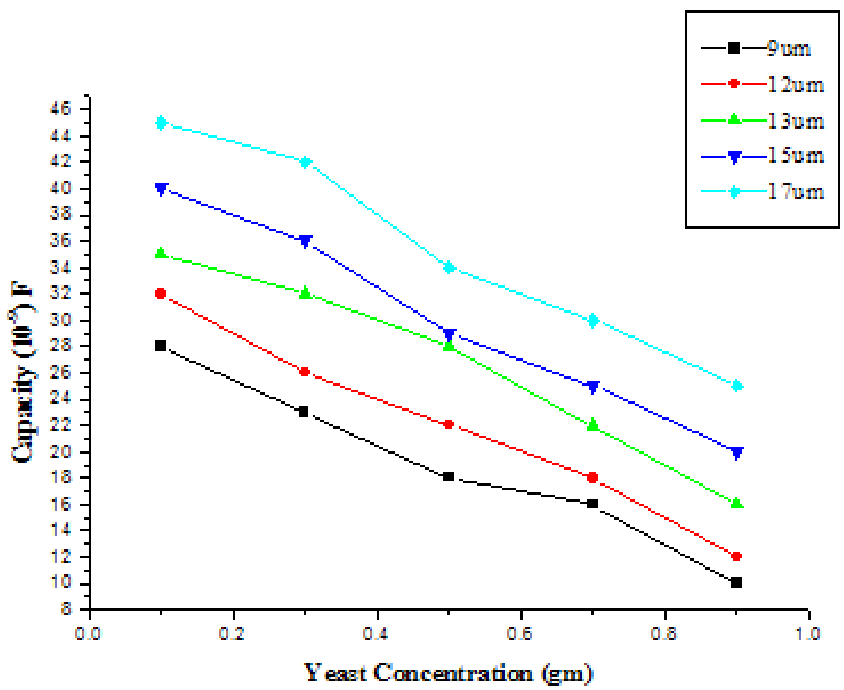

Figure 11. The capacity measurement with the yeast concentration for different gap sizes.

The most characteristic feature of the obtained results is a positive charge increment, which shows the capacity of polysilicon, measured at positive increases when a strong electric field is applied. The curve behavior is almost the same just the value of the capacitance has changed. This is because the bigger gap size has many charges inside the insulator compared to the smaller gap.

According to the theory, the permittivity of a substance is a characteristic that describes how it affects any electric field set up in it. A high permittivity tends to reduce any electric field present.

Figure 11 shows that the capacity value decreases with the increase in yeast concentration. We can see that the gap size can affect the capacity value, in that where the

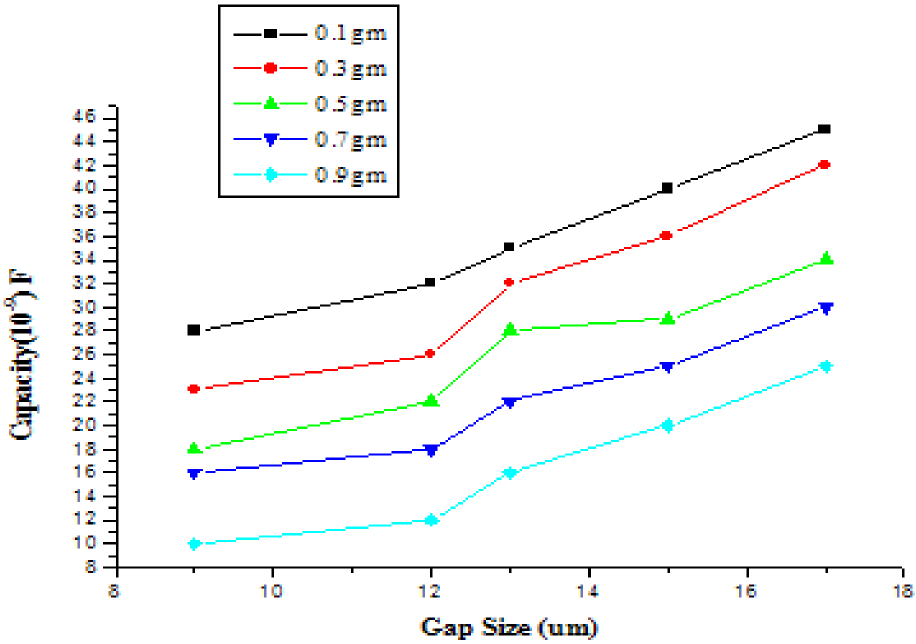

Figure 12. The capacity measurement with the gap size for various yeast concentrations.

smaller gap size decreases the capacity value, the conductivity becomes high. As a result, the resistivity decreases. Figure 12 shows the reaction of the capacity measurement as a function of gap size (µm) at different concentrations of yeast, using 0.1 V as the applied voltage, whereas the capacity value recorded decreased with the increase in the yeast concentration. Gap sizes are proportional to the value of capacity. When the gap size is bigger, the value of the capacity is higher. The larger capacity value means that a better contact is produced between the conductor and insulator, which means the yeast concentration that we used, has a good effect on the insulator. If the air gap between the electrodes is replaced by an insulating material (dielectric), the current that flows between the plates will increase to a new value, where the increase in the current is caused by a property of the insulating material known as permittivity, and the introduction of the insulating material therefore increases the capacitance between the two electrodes (Suchodolskis et al., 2011), and decreases the conductivity. The lower capacity value means that less contact is produced between the conductor and insulator, which mean the yeast con-centration that we used is still not good enough, and the dielectric fields that are produced between the insulator and conductor are not strong (Thikra et al., 2010).

The most characteristic feature of the obtained results is a positive charge increment, which shows the capacity of polysilicon, measured at positive increases when a strong electric field is applied. The graphs are almost all the same for all the gap sizes, the only difference is that the value of the capacitance has changed. This is because the bigger gap sizes have many charges inside the insulator compared to the smaller gap. By referring to theory, the permittivity of a substance is a characteristic that describes how it affects any electric field set up in it. A high permittivity tends to reduce any electric field present, then decreases the conductivity value and increases the resistivity. We can increase the capacitance of a capacitor by increasing the permittivity of the dielectric material (Liu and Zhao, 2007).

Conclusion

The capacitance as well as the conductivity was measured for the polysilicon micro-gap structure, using a Semiconductor Parameter Analyzer. Two chrome masks are used to fabricate the micro-gap structure. I-V and C-V curves are carried out using the Dielectric Analyzer to check the resistivity of the micro-gap device. The electrochemical potential of different yeast concentration values were made by measuring associated capacity, where the capacitance values decrease with the yeast concentration level and increase with the size of the gap.

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