AL_2O_3 NANOLAYER AS EVANESCENT WAVEGUIDE FOR BIOMEDICAL SENSOR APPLICATION

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Abstract: The aim of our research is to develop a sensitive sensor for biomedical applications. A nanolayer Al_2O_3 is used as evanescent waveguide. The material was deposited on a silicon wafer by using atomic layer deposition (ALD). In the present paper, we will report the preliminary results of our project such as deposition, characterization of nanolayer, and evanescent waveguide sensor design. Lambert beer's law and some waveguide concepts are combined in the design to obtain the optimum parameters of the evanescent waveguide sensor. Furthermore, characterizations to investigate optical properties and internal stress of the thin film were done. Based on the results of lattice parameter analysis, we can conclude that thin film thickness have effect not only on sensitivity of the sensor but also on the mismatch stress between substrate and thin film. Design results show that a thickness of waveguide of 50 nm and an optical path length of the sensor of 1 mm can be used as waveguide dimension with a transmission of 75%. 50 nm thin film thickness shows low mismatch stress and that was shown by high radius curvature 32.34 m.

1 INTRODUCTION

Anastomosis is an operation to make continue the organ as like colon, bowel, pancreas etc. Anastomosis leakage is still a problem in medical especially post-operate. The patient's mortality rate due to anastomosis leakage is still high, because often the leakage is identified too late. The indication of anastomosis leakage is the presence of a high concentration of bacteria in the drain fluid. There are many types of bacteria like *Bacteriodes sp., Lactobacillus acidophilus, Klebsiella sp.,* and *Eschericia coli (E. Coli)* in drain fluid. These bacteria are essential for food digesting. However, due to malfunction in the colon, bacteria could enter the abdominal cavity causing severe infections (Chaeron, 2007 and Pakula *et al.*, 2005).

The conventional identification needs at least seven days to obtain accurate results. Currently, there are three existing experiment methods to perform a microbiological analysis on drain fluid, being bacteria culture, Raman spectroscopy, and polymerase chain reaction (PCR) to make million DNA copies of the bacteria. The disadvantages of the methods are the time to analyze and high cost.

In our research, an evanescent waveguide sensor is developed to detect bacteria in drain fluid as an indication of anastomosis leakage. The properties of material and structure are very important to obtain a sensor with high sensitivity. Aluminum oxide (Al_2O_3) has a high refractive index. Therefore the material has high potential as thin film material waveguide. Atomic layer deposition (ALD) was used to deposit Al_2O_3 due to its advantages to produce high conformality, uniformity, and smoothness. In order to obtain optimal parameters, Lambert beer's law and waveguide evanescent sensors were combined to calculate the optimal waveguide dimensions. In this paper, we present evanescent waveguide sensor design and experimental results of the optical and structural characterization.

1.1 Lambert Beer's Law

Lambert beer's law is often used to analyze the

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absorbance (*A*) of media while light is transmitted in the media. The transmission of light is called transmissivity (*T*), the ratio between output and input of light. The transmissivity is expressed as:

$$T = \frac{I}{I_o} \tag{1}$$

And the formula of absorbance as:

$$A = \sigma c l \tag{2}$$

The relationship between transmission and absorbance is as follows:

$$A = \log_{10} \frac{1}{T} = 2 - \log_{10} \%T \tag{3}$$

Where σ is the molar absorption coefficient (M^{-1} cm^{-1}), *c* is media concentration and *l* is path length of light in waveguide (*cm*).

1.2 Evanescent Waveguide Design

Planar waveguide is more used in optical integrated system. The source of light couples with edge of waveguide and the receiver in the other side. The light through the waveguide with difference refractive index between core and cladding such as n_1 is refractive index of core (Al_2O_3) and n_2 is refractive index of cladding. Furthermore, the light wave through the optic material with angle (θ_1) is called incident angle and the reflective angle (θ_2) is the angle of the direction of the reflection light wave. In order to obtain maximum reflection, the expected light way in the cladding is at lease parallel with the both materials interface and other word that the reflective angle (θ_2) is 90°. The critical incidence angle is defined as the minimum incident angle to obtain a reflective angle of 90°. By using Snell's law, the critical incidence angle can be calculated. Critical incidence angle implies θ_2 = 90° and that $\sin\theta_2$ = 1. Hence, the critical incident angle can be expressed as:

$$\theta_1 = \sin^{-1}\left(\frac{n_2}{n_1}\right) \tag{4}$$

In the evanescent sensor wave guide, penetration depth is the maximum depth from which the sensor can obtain information. The penetration depth is very important to estimate the performance of sensor to detect objects in the sensor surroundings. The range over which excitation is possible is limited by the exponential decay of the evanescent wave energy in the *z*-direction, perpendicular to the interface. In this case energy is proportional with light intensity. The following equation defines this intensity as a function of distance from the interface**:**

$$I_z = I_o \exp^{\left(-z/d\right)} \tag{5}$$

I_z is the energy at a perpendicular distance *z* from the interface, and I_0 is the energy at the interface. The penetration depth state when *d* = *z* and the penetration depth intensity is 100% x e^{-1} (36.7% I_o). The range over which excitation is possible is limited by the exponential decay of the evanescent wave energy in the z-direction. The penetration depth *d,* is dependent upon the wavelength of the incident illumination, λ_i, the angle of incidence, and the refractive indices of the media at the interface, according to the Equation (6) and the general formula of light propagation in waveguide expressed in Equation (7).

$$d = \frac{\lambda_i}{4\pi} x\left(n_1^2 \sin^2\theta_1 - n_2^2\right)^{-1/2} \tag{6}$$

$$\frac{2\pi t}{\lambda}\sqrt{n_1^2 + n_{eff}^2} - \arctan\left[\sqrt{\frac{n_{eff}^2 - n_2^2}{n_1^2 - n_{eff}^2}}\left(\frac{n_{eff}}{n_2}\right)^{2p}\right] - \arctan\left[\sqrt{\frac{n_{eff}^2 - n_2^2}{n_1^2 - n_{eff}^2}}\left(\frac{n_{eff}}{n_2}\right)^{2p}\right] - m\pi = 0 \tag{7}$$

Where n_{eff} is refractive index effective and *m* is constant of waveguide mode.

$$n_{eff} = \frac{\beta}{k} = n_1.\sin\theta \tag{8}$$

Where β is the propagation constants along z is expressed by $\beta = k.n_1 \sin\theta$. Furthermore the Eq. (7) is derived to obtain the normalized parameters that to be used to calculate geometry of the sensor that the more detail was be explained by Veldhuis *et al,* 2000. Cutoff condition is the optimum condition when the effective refractive index is equal to the cladding's refractive index. Then, the sensitivity of sensor can be calculated using equation

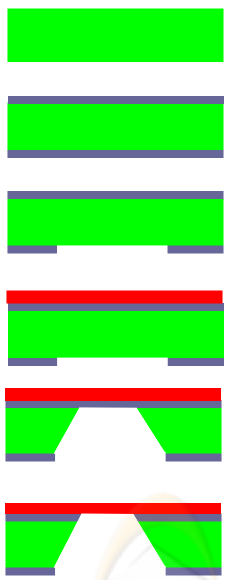
$$S = \frac{n_{eff}}{n_2}\left\{1 + \frac{n_{eff}^2 - n_2^2}{n_{eff}^2}\right\}\frac{P_2}{P_{tot}} \tag{9}$$

Where *S* is sensitivity, P_c/P_{tot} is ratio energy (intensity), n_2 is cladding's refractive index.

2 EXPERIMENTAL

A silicon wafer was used as substrate material whereas the Al_2O_3 as thin film material. In order to obtain homogeneity, conformality and low internal stress, ALD was employed to deposit the thin film. Tetra methyl aluminum ($Al(CH_3)_4$) and H_2O are as precursors and N_2 is used as gas carrier. The cycle processes used ratio 1:2:1:3 s. It means that the pulse time is one second for 1st precursor ($Al(CH_3)_4$), two seconds for purge (N_2), then one second for 2nd precursor (H_2O) and finally three seconds for purge (N_2). The total time for one cycle is seven seconds. Process temperature is 300°C. Subsequently the thin film was characterized using Atomic Force Microscope (AFM) to investigate topography and surface roughness of thin film, thickness measurement and stress measurement to measure the internal stress of thin film.

In the fabrication process, to pattern the structure, three masks for contact aligner lithography were designed consists of two masks for front side to make ribs and bridges structures and one mask to open SiO_2 in backside. Firstly, the process fabrication makes windows in the backside. Then after patterning the front side and finally etching the backside. The structure is made the free standing. The flowchart of the detail process is shown in Fig. 1(a) – (f).



(a) Starting material (N-type 100 Silicon wafer)

(b) 2 micron SiO_2 using wet thermal oxidation for 8 hours 12 minutes

(c) Open SiO_2 windows in the backside plasma etching Drytec Triode for 6 minutes.

(d) 100nm Al_2O_3 deposition using ALD then patterning rib and bridge on the front side using RIE Alcatel plasma etching

(e) Backside etching using TMAH with protecting holder on the front side (etching process stop on SiO_2)

(f) SiO_2 backside etching using RIE Alcatel.

Figure 1: Fabrication process flowchart for waveguide free standing structure.

The freestanding waveguide structure and evanescent field region is shown in Figure 2.

3 RESULTS AND DISCUSSIONS

Based on experiment results, the thickness of Al_2O_3 is 46.6 nm during 500 cycles, (0.9Å/cycle), the refractive index is 1.65 and the internal stress of Al_2O_3 thin film is 246 MPa. By using AFM, the surface topography and surface roughness of Al_2O_3 can be seen in Figure 3.

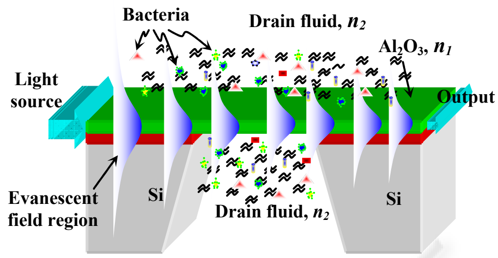


Figure 2: Evanescent waveguide.

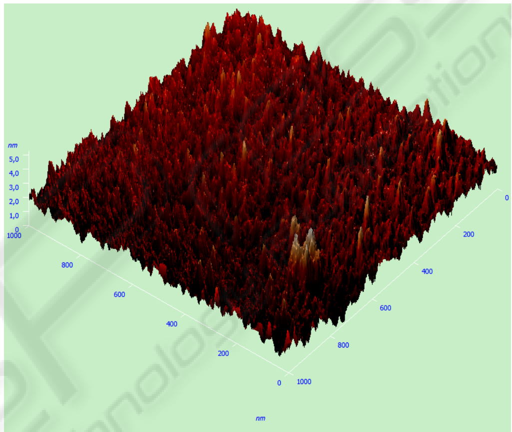


Figure 3: AFM Topography of Al_2O_3-ALD with root mean square 0.5 nm.

In previous research of our group, drain fluid transmission analysis was conducted by using visible light and infrared light wavelength. The results show that the visible light spectrum did not show any distinction wavelength at which the transmission was implicitly bacteria contamination dependent. Moreover, low contamination was not measurable with the visible light set-up. The other wavelength, infrared spectrum was used in the experiment. Infrared wavelength spectrums 2μm and 4.3μm have high sensitivity to make difference transmission results when the light through drain fluid (Pakula *et al,* 2005). It means that both wavelengths can be used as light source in drain fluid analysis. In the present research 2 μm wavelength is used as light input of the sensor. In addition, drain fluid with variable bacteria concentrations analysis to obtain the transmission percentage was conducted in previous experiment by our group (Chaeron, 2007).

From medical point of view, 20% concentration of bacteria in drain fluid is the critical range. The results from the experiment were taken for further analysis, especially near critical concentration (20%) which is 25% bacteria concentration. By taking value of transmission of drain fluid with E.Coli exist in the drain fluid for 1 day after taken from patient and path optical length 0.865 cm, the transmission result is 8.3% then the transmission value is plotted in Figure 1 to obtain the absorbance value is 1.08. By using Equation (2) can be calculated the molar absorption coefficient which is 0.4998. Furthermore, the optical path length is fixed at 1 mm and using the Equation (2) the absorbance is 0.125. By plotting the absorbance result to Figure 1, the transmission value is found to be 75%.

The important parameters have to be analyzed to obtain the critical incident angle. It depends on material properties especially refractive index of the materials of both core and cladding material. The incident angle must be more than critical angle to obtain total reflection. Based on measurement Al_2O_3, deposited by ALD, refractive index 'n_1' is 1.646. Cladding's refractive index 'n_2' is 1.33. The angle can be calculated from Snell's law modified as Equation (4) and the result of critical incident angle is 53.9^o. In this experiment, the waveguide will be coupled with source of light with incident angle 90^o, λ_i = 2000 nm and using Equation (6), the penetration depth of the waveguide sensor can be calculated of 164 nm. Due to the symmetrical waveguide, a maximum sensitivity $S_{max} = 2.S$ (Velduis *et al*, 200). Hence, using Equation (9) can be found the maximum sensitivity of sensor as shown in Table 1.

Table 1: Sensitivity of waveguide of varying waveguide thickness.

Thickness, nm (t)	Effective index (n_{eff})	Sensitivity (S_{max})
50	1.331	0.997
100	1.333	0.989
150	1.338	0.975
200	1.344	0.965

The film has as incompatible elastic mismatch strain with respect to the substrate; this strain might be due to thermal expansion effects, epitaxial mismatch, phase transformation, chemical reaction, moisture absorption or other physical effects. Whatever the origin of the strain, the goal here is to estimate the curvature of the substrate, within the range of elastic response, induced by the stress associated with the incompatible strain.

Stoney's formula is original analysis of the stress in a thin film deposited on a rectangular substrate was based on a uniaxial state of the stress. Consequently, his expression for curvature did not involve use of the substrate biaxial modulus M_s. Consequently, it can be applied in situations in which mismatch derives from in elastic effect (Freud and Suresh, 2003). The expression for curvature is famous Stoney's formula relating curvature to stress in the film as:

$$\kappa = \frac{6\sigma_m h_f}{M_s h_s^2} \quad (10)$$

Where κ represents the curvature, or inverse of the radius of curvature, of this plane, σ_f is mean stress, h_f is the thickness of the thin film, M_s is substrate biaxial modulus and h_s is substrate thickness. The mean mismatch strain of substrate and the corresponding mismatch stress of thin film expressed as:

$$\varepsilon_m = \frac{a_{Si} - a_{Al_2O_3}}{a_{Al_2O_3}} \quad (11)$$

$$\sigma_m = \varepsilon_m M_f \quad (12)$$

Figure 4 shows the curvature radius of various thin film thickness. The curvature radii gradually decrease with increasing thin film thickness.

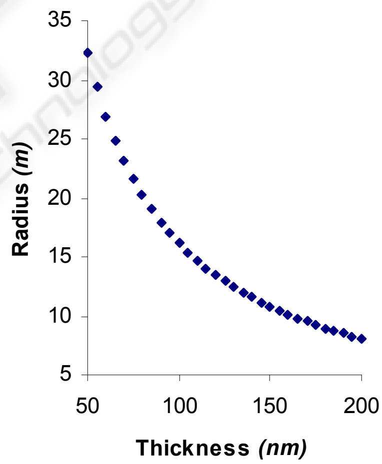


Figure 4: Curvature radius as function of thin film stress of Al_2O_3 in the surface substrate with various thin film thickness.

By taking the thin film thickness h_f= 50 nm of Al_2O_3 is grown on Si-wafer substrate with thickness h_s = 500 μm, lattice parameter of a_{Al} = 0.405nm, a_O = 0.683 nm and a_{Si} = 0.5431nm. The lattice parameter of Al_2O_3 at room temperature is $a_{Al2O3} = 0.53a_{Al} + 0.47a_O$ = 0.536 nm. The biaxial modulus of Al_2O_3 (M_f) and Si (M_s) are 380 GPa and 180.5 GPa, respectively. By substitute Equation (11) and Equation (12) into Equation (10) can be obtained κ= 0.031. Then the change of curvature radius is $\rho = \kappa^{-1}$ = 32.34 m. The result of the curvature value is positive (+), it implies that the substrate is convex on the face away from the bonded film.

4 CONCLUSIONS

The optimum condition of evanescent wave guide sensor for anastomosis leakage detection can be estimated by analytical and then should be verified by experiments. In the preliminary results, we found that AL_2O_3 deposited on Si-wafer have high potential as waveguide sensor. Based on the results, it can be concluded that thin film thickness have high effect not only on sensitivity of the sensor, but also on the mismatch stress between substrate and thin film. That was shown by high radius curvature 32.34 m with convex structure for thickness 50nm.

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