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Temperature sensitivity of FBG coating with zinc oxide and silicon carbide

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 Abstract. This work aims to evaluate the sensitivity of coated FBG in measuring non-thermal plasma temperature inside a dielectric barrier discharge reactor. The FBG sensor were coated with Zinc Oxide (ZnO) and Silicon Carbide (SiC) by using magnetron sputtering technique. Both materials are insulator hence suitable to probe temperature inside the plasma reactor. Results revealed that the temperature sensitivity of and SiC coated FBG were 12.6 pm/℃ and 12.37 pm/℃, respectively (suggested to put both 2 decimal places). This means temperature sensitivity of ZnO is higher than bare FBG (12.43 pm/℃) while SiC coated FBG shows the lowest. The values show slightly different between each other and give less significant in sensitivity value. When applied it inside plasma, spectroscopic diagnostic result shows stable plasma throughout the time.

1. Introduction

FBG is one of the optical sensor with many advantages such as low cost, small, highly sensitive, high accuracy, and immune to electromagnetic interference which make them attractive for sensing application [1]. It is known as temperature sensor since it can reflect wavelength from broad light spectrum which corresponding to the condition of Bragg grating from principle operation of Fresnel reflection. The wavelength is determined by equation:

$$\lambda_B = 2\, n_{eff}\, \Lambda \tag{1}$$

where n_{eff} is an effective refractive index of fibre and Λ is Bragg grating period. The Bragg wavelength, λ_B is sensitive toward the changes of strain and temperature and these will affect both effective refractive index and grating period of FBG. These can be described as following equation:

$$\frac{\Delta\lambda_B}{\lambda_B} = (\alpha + \xi)\,\Delta T \tag{2}$$

where λ_B is the initial central wavelength of FBG, $\Delta\lambda_B$ is the wavelength shift, ΔT is the temperature change, α is the thermal expansion coefficient and ξ is thermo-optic coefficient.

Even a very little change in temperature will cause a significant wavelength shift [2], in the work of Han et al., FBG is used as thermal tuning technique to obtain laser tuning with good linearity and good repeatability [3]. FBG can provide rapid response than thermocouple which have greater thermal

capacity [4]. A lot of previous research has been done to enhance the sensitivity of FBG as temperature sensor. Samiappan et al. had apply uniform coating of Polytetrafluoroethylene (PTFE) on FBG and compared it with coating of zinc, aluminium and stainless steel to enhance the sensitivity of FBG toward changes of temperature. It shows the sensitivity of PTFE increase to 0.3nm / ℃ while metal with highest sensitivity around 0.079 nm/℃ [5]. Material with high value of coefficient thermal expansion (CTE) and good adhesion to fibre has significant effect on sensitivity since it help increase stress produce between coating material with silica [6]. Same goes when He et al.[7] using two material which are molybdenum (Mo) and copper (Cu) that has great potential applications on FBG for high-temperature sensing.

One of the approaches to serve as temperature regulator is by using non thermal plasma. Temperature can be regulated rapidly by generated non thermal plasma in dielectric barrier discharge reactor. For purpose of measuring plasma temperature, small mass of FBG is expected to react rapidly to temperature changes at a rate much higher than thermocouples. Ahlawat et al. had report utilized FBG as technique to find exact temperature in DBD plasma[8].

In this paper, we have used Fibre Bragg Grating (FBG) temperature sensor, which is a prior immune towards high voltages and high-frequency electromagnetic fields generally encountered in plasma environments. To improve FBG sensitivity toward temperature changes, it is coated with Zinc Oxide and Silicon Carbide which have thermal expansion coefficient higher than silica by using magnetron sputtering method. Furthermore, both materials are insulator that expected did not give any fluctuation effect toward generation of plasma.

2. Methodology

2.1. Preparation of FBG before sensing experiment

Three FBGs used in this paper were made by Lielee NDT Structure Enterprise. The details for those FBGs are (i) reflectivity > 90%; (ii) the bandwidth < 0.5nm; (iii) the grating length is 10 mm (iv) the central wavelength of the FBGs is 1550.3807nm, 1550.1936nm, 1550.0848nm at 21.8℃, respectively. Two FBGs were etched to remove fibre cladding and subsequently coated with zinc oxide and silicon carbide, respectively. The last one is in form of bare FBGs.

The etching was performed by immersed the grating part of FBGs in hydrofluoric (HF) acid solution with concentration of 49 % (Qrec) for 20 minutes until a portion of FBGs cladding dissolved. Then, the FBG was dipped into deionized water to remove etching residues. The diameter of FBGs is measure using focus ion beam – field emission scanning electron microscope (FESEM). After the etching process, two FBGs were coated with ZnO and SiC, respectively using magnetron sputtering method. The coating process for ZnO consumes 15 minutes while SiC consumes 30 minutes.

All the three FBGs were then immersed into a partially beaker filled with oil along with digital thermometer to find coefficient (k) of each FBGs prior to calibration. The value of coefficient for those FBGs were 7.6×10^{-6} for bare FBG, 6.58×10^{-6} for ZnO coated FBG and 7.23×10^{-6} for SiC coated FBG.

2.2. Plasma Generation Process

Plasma generation system as depict in Figure 1 consist of three parts: the DBD plasma reactor (dual parallel plate), the gas system and the electrical measurement tool. The dielectric barrier plasma reactor consisted of two parallel alumina as dielectric plate facing each other with dimension of 140 mm x 60 mm x 1 mm. Both plates were painted evenly on one of the sides of alumina plate with silver conductor covering 120 mm x 40 mm area. Those were fitted in perspex enclosure. The distance gap between the electrodes was 5 mm and it can be adjusted using four ring shape spacers. For generating the plasma, Helium gas was used as carrier gas and was delivered to the reactor through gas inlet. A mass flow controller was equipped to maintain the flow rate of Helium gas for 100 standard cubic centimeter per minute (sccm). The reactor was supplied with 10 kV applied voltage by an AC power supply to fully generate plasma within the space between two electrodes. The electrical parameters of the plasma have been monitored using system which consist of digital oscilloscope (Picoscope

2008A, Pico Technology), voltage probe and current probe. Plasma glow was observed at 10 kV discharge voltage for 25 minutes before the voltage supplied was cut off.
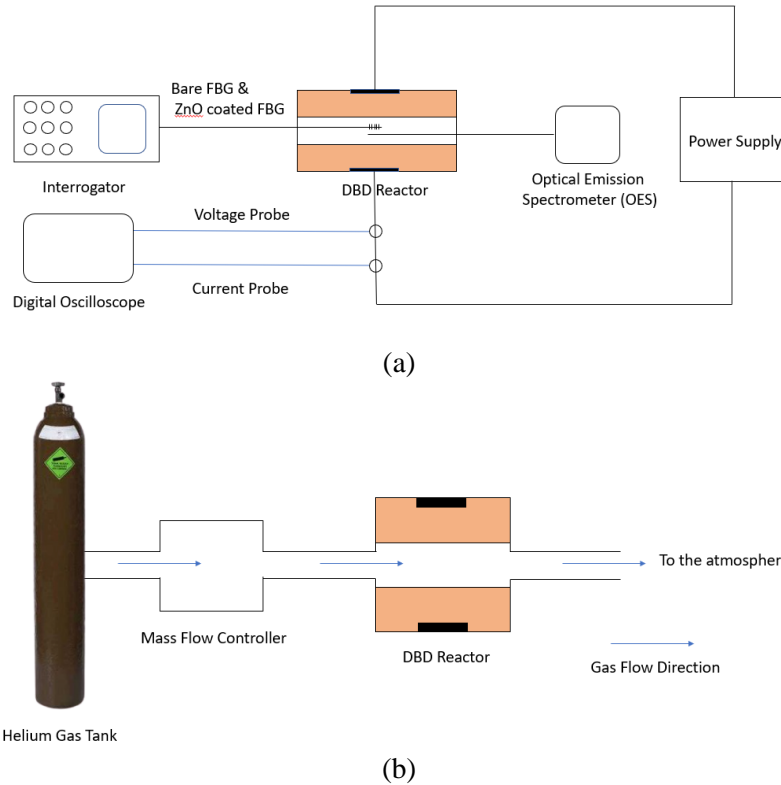

(a)

(b)

Figure 1. (a) Front view and (b) side view of experimental setup

2.3. Sensitivity of FBGs

The performance of using non thermal plasma for comparing sensitivity was associated with three type of FBGs as temperature sensor and large core fiber for capturing plasma emission. Those were located at the middle of the reactor to minimize different effect toward variant plasma location in the reactor.

To study temperature sensitivity inside the DBD plasma reactor, FBG sensors are utilized in this experiment. When the changing of the temperature plasma occur, FBG sensor shows shifting of its wavelength that owing to the process of obtaining the temperature profile within reactor. FBG received an incoming light source ranges between 1528 to 1608 nm from optical interrogator. The reflected spectrum that obtained from FBG is interfaced through USB cable to a computer using Smartsoft Applications Software. The software program allows in situ temperature measurement inside reactor then can instantly displayed Bragg wavelength value on the computer monitor. The total temperature coefficient that obtained from calibration curved is used to convert shift of Bragg wavelength to value of temperature. Then, the reactor temperature is profiled against times.

The intensity of plasma radiation is collecting in easy way by embedded large core optical fiber embedded inside the reactor. The OES that connected to the fiber can monitor the spectrum in the range of 200 nm to 1000 nm. Thorlab Inc. software is used to process the data and display the spectrum to the PC. In the spectrum emission line captured, the type of plasma generated is identified by choosing the peak line with strong intensity and isolated from others peak. The chosen peak is monitored with time to observe the mode of discharge and the stability of plasma generate can be detected.

3. Result and Discussion

Figure 2 show FESEM images captured using (FE-SEM, Carl Zeiss) of etch bare FBG, ZnO coated FBG and SiC coated FBG. Morphology of bare FBG after etching process was analysed at accelerating potential of 5kV and magnification 500X as depicted in Figure 2 (a). The diameter of etch FBG were measured on three different locations and found to be in the range of 20 ~ 22 μm. Figure 2 (b) shows the FESEM image of cross section coating nanoparticle ZnO on FBG is shown using voltage of 5kV and 10000X magnification. ZnO coated FBG was perpendicularly cleaved to obtain this image. The average thickness of ZnO found to be 320 nm. Figure 2 (c) shows the FESEM image of cross section SiC coated FBG captured using voltage of 5 kV and 10000X magnification. The homogenous formation of SiC nanoparticle reveal the mean thickness coating of 1.8 μm.
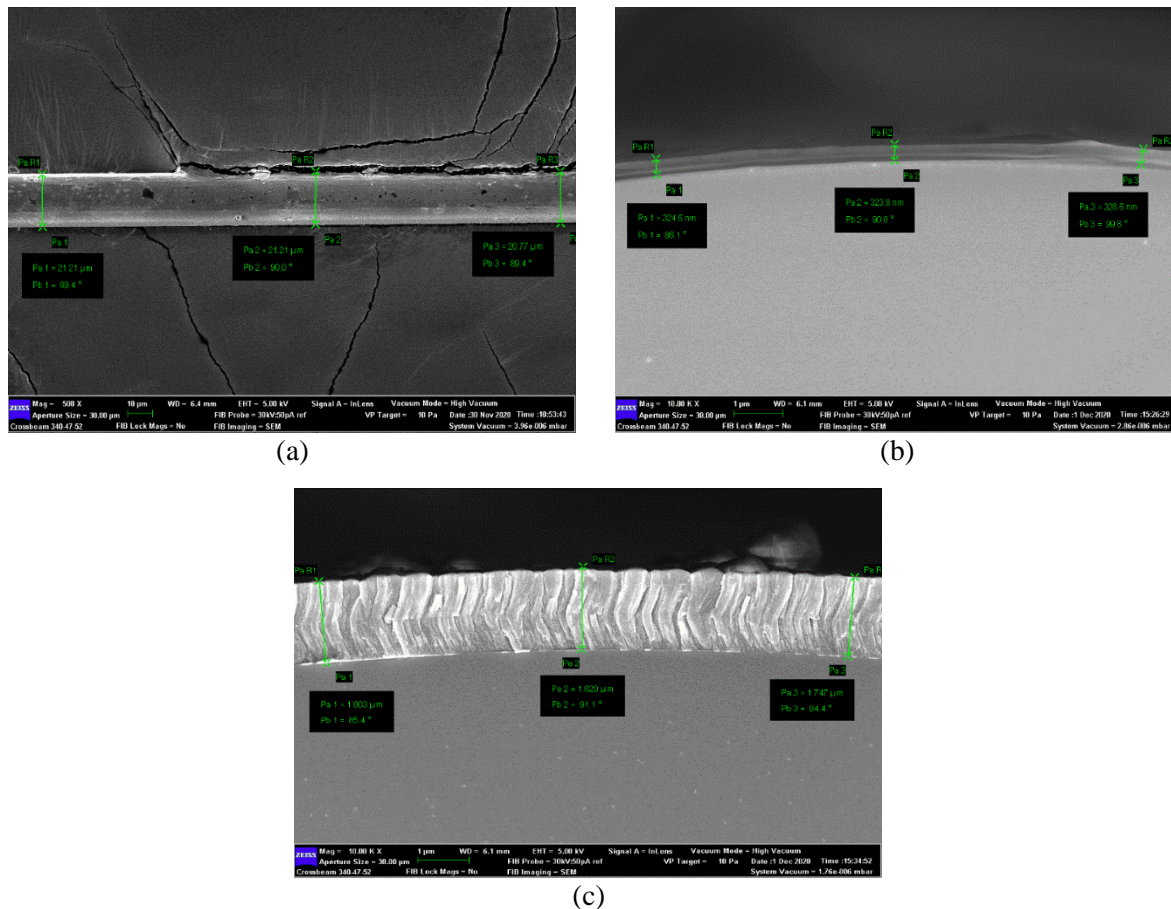

(a)

(b)

(c)

Figure 2. (a) morphology of etch FBG (b) cross-section ZnO coated FBG (c) cross-section SiC coated FBG

Figure 3 show the Energy Dispersive X-Ray Spectroscopy (EDX) spectra for both ZnO and SiC coated FBG. Figure 3(a) shows an EDX spectra recorded from ZnO coated FBG. From the EDX spectra, Zn, Si, C, and O were detected. The detection of Zn and O peaks in EDX spectrum is confirmed the formation of ZnO in the coating. The detection of Si peak is due to the FBG silica glass as the coating substrate. The small amount of C detected could be due to carbon tape which been used to stick the FBG to sample holder. Figure 3(b) shows an EDX spectrum detected on SiC coated FBG and element of Si, O and C were detected. Peak of Si and C are confirmed that SiC formation on the FBG coating.

Figure 4 shows the shift of wavelength for each FBGs which are bare FBG, etch FBG, ZnO coated FBG and SiC coated FBG when increase the temperature of oil from 59 ℃ to 300 ℃. The sensitivity of FBG can be obtained by gradient of graph. From the graph, ZnO coated FBG has the highest gradient

value which is 12.6 pm/℃ followed by etched FBG which is 12.54 pm/℃. Bare FBG which has gradient value of 12.43 pm/℃ has higher sensitivity than SiC coated FBG which has sensitivity of 12.37 pm/℃. In the temperature change of 241℃, ZnO coated FBG shows the highest wavelength shift which is 3.03 nm while SiC showed the lowest which is 2.98 nm.
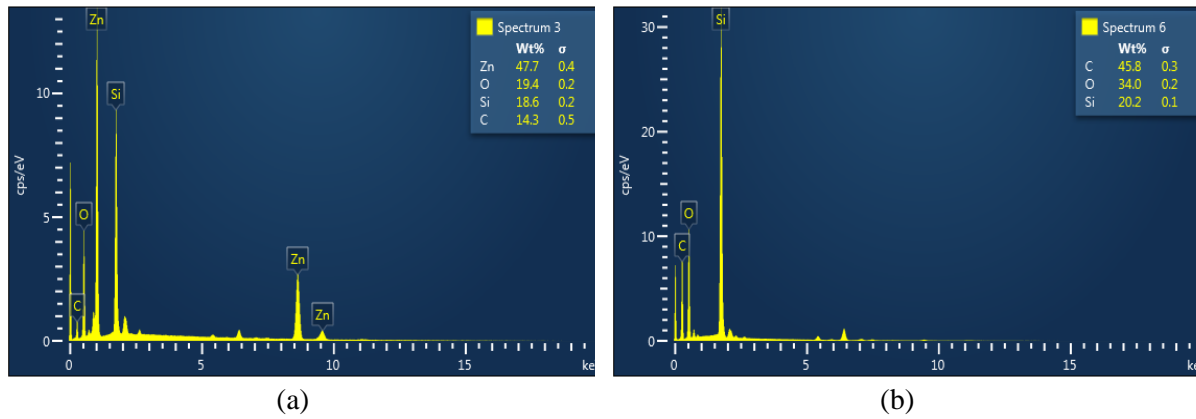

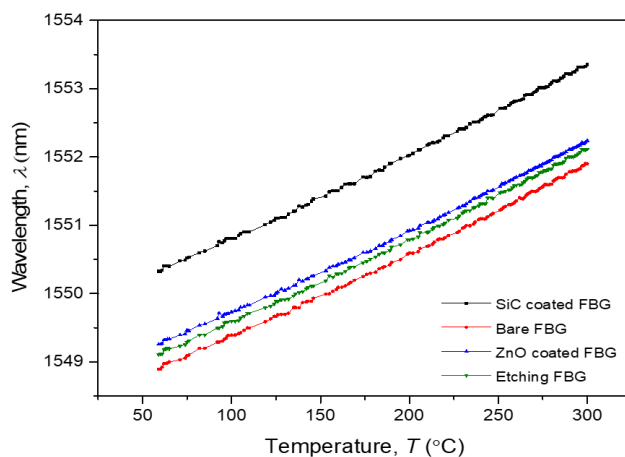**Figure 3**. EDX spectra of (a) ZnO coated FBG (b) SiC coated FBG

Figure 4. Graph of calibration of FBGs using cooking oil

As the temperature raise, these sensors have experienced increases in the Bragg wavelength value, resulting from changes in the effective refractive index and grating expansion. However, thermal expansion will give more effect to wavelength shift rather than thermo optic coefficient when dealing with temperature changes. In addition to using special mechanical configurations, one of the ways to improve FBG thermal sensitivity is by embedding FBG with a higher thermal expansion coefficient material than silica [9]. ZnO has higher thermal expansion coefficient which is $4.75 \times 10^{-6} \, C^{-1}$ [10] than SiC and silica. SiC and silica have coefficient of $3.3 \times 10^{-6} \, K^{-1}$ [11] and $0.55 \times 10^{-6} \, C^{-1}$ [12] respectively. The absorbed heat generates a thermal expansion to the material. Due to the mismatch between the coefficient of thermal expansion of coating material and silica, stress is produced that resulted strain in fiber. The fibre is expanding and causes more disturbance to the grating period. This will make more wavelength shifted with only slight temperature changes [13]

Although there is different in sensitivity value throughout the temperature range, the different between them very small. It is due to thickness coating, micro-crack of coating , etching thickness, and adhesion between coating material and FBG [9]. Enhanced these factors perhaps can increase the sensitivity of coated FBG.

From the graph, FBGs tested has good linear relationship between wavelength shift and applied temperature. It shown that the calibration using oil is reliable to find the coefficient of FBG. In this experiment, cooking oil is used instead of water [14] since it has higher boiling point than 100℃. Those

FBG were applied in non-thermal plasma to know their behaviours as temperature sensor. Each coefficient of FBGs that were obtained is used in equation 2.1 to get the temperature of plasma when embedded in plasma surrounding.
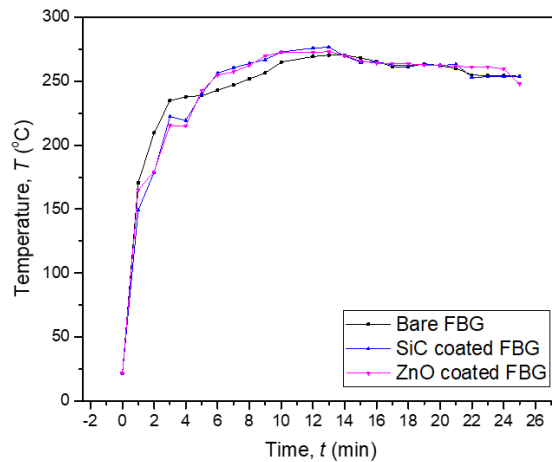

Figure 5. Graph of profile temperature

Figure 5 shows the profile temperature of plasma in DBD reactor measured by three type of FBGs which are bare FBG, SiC coated FBG and ZnO coated FBG for 25 minutes with 6.5 kV of discharge voltage. The gas flow and pressure remain constant at 50 sccm and 0.0004 mTorr respectively. From the graph, the temperature of plasma which measured by all FBGs elevated from room temperature to their respective peak temperature in 5 minutes before slowly increasing for another 9 minutes. Bare FBG shows highest sensitivity than SiC coated FBG and ZnO coated FBG. Then, the temperature maintained at almost the same value ranging from 240℃ to 275℃ if the discharge voltage is supplied. This can be said, ZnO and SiC coated FBG can be use as temperature sensor in plasma since they show good shift in wavelength when embedded in plasma. They are insulator material that did not give spark to plasma when react with plasma.

4. Conclusion
In conclusion, FBGs coating with SiC and ZnO insulator material were succeeded to proposed as temperature sensor of non-thermal plasma inside DBD reactor. To make a comparative study, they were compared with bare FBG. The temperature measurement is based on the thermal equilibrium between the grating of FBG sensor and surrounding environment. Sensitivity is obtained by slope of calibration curve using cooking oil which highly shows linearity with $R^2 \geq 0.99$. Based on thermal expansion coefficient, ZnO has the highest value shows highest result of sensitivity but in this experiment, the sensitivity between FBGs show no significant in different. When applied in plasma, all the FBGs show almost same value of temperature that confirm those FBG can be used as temperature sensor in plasma without disturbing the homogeneity of plasma.

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