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Synthesis And Electrical Conductivity Investigation Of Silicon Carbide Fiber As Electronic Semiconductor

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ABSTRACT

Silicon carbide shows advantage characteristics to be used as electronic devices that operated in extreme conditions. It potentially improves many limitations compared to the silicon. The applications of SiC are used in high power, high frequency, and high-temperature conditions. Intrinsic semiconductor properties of SiC has high thermal conductivity, mechanically and chemically stable and excellent resistance to the radiation. In this research, SiC fiber was synthesized from polycarbosilane polymer precursor (PCS) that solved in N, N-dimethylformamide (DMF), and toluene. This solution was processed using electrospinning to form fibers. The fibers were cured at 200 °C and continued with pyrolyzed varied at 1200, 1300 and 1400 °C for 1 hour. The fiber's electrical conductivity was carried out by LCR meter. The electrical conductivity for the lower frequency at 62.36 Hz showed 7280 nS, achieved by the fibers that pyrolyzed at 1200 °C. For high frequency at 100 kHz showed the fibers pyrolyzed at 1400 °C were acquired for 12400 nS.m-1 for its electrical conductivity. The value of its band gap based on the Kubelka Munk Equation was take placed for fibers that showed significant value at high frequency using UV-Vis DRS. The band gap value was achieved at 2.56 eV.

Keywords: *Silicon carbide, polycarbosilane, semiconductor, electrospinning, electrical conductivity, band gap energy*

1. INTRODUCTION

Since the 1930s, many countries have shown that SiC is one of the most promising and valuable materials for solid-state electronics. Due to the high hardness, chemical inertness, and radiation resistance, this material had no competitors in the design of devices aimed at operating under extreme conditions. SiC-based semiconductors have the potential to improve many of the silicon's limitations as semiconductor materials that have been widely used today. The high needs for electrical devices that resistant to extreme environmental conditions, many advantages of silicon carbide could be used, especially for power electronics [1–3]. Compared to the silicon, the SiC has characteristics to sustain higher voltages almost ten times, higher currents almost five times, and higher thermal conductivity roughly three times [4,5]. The power devices made from SiC can switch roughly ten times faster due to its higher band gap compared to the silicon. The SiC as semiconductors can be operated at environment temperature up to 400 °C.

SiC has low diffusivity of impurities and defects, the electronic parameters of SiC-based devices degrade very slowly. Silicon-carbide devices satisfy the strictest performance requirements; specifically, their resistance to neutron fluxes exceeds that of Si, GaAs, and GaP devices by 1.5–2 orders of magnitude; and they can operate in corrosive media and strong magnetic fields [6,7].

Electrospinning is a highly versatile method that, through the processing of polymeric solutions or melts, produces fibers with diameters ranging from a few microns to tens of nanometers [8]. Several researchers have done the use of polycarbosilane (PCS) as SiC-forming precursor polymer, wherein processing PCS into SiC fibers consist of several stages of methods:

synthesis, spinning, curing and pyrolysis [5,9–12]. In this paper, we discussed the electrical conductivity of SiC fibers forms PCS that processed by electrospinning. The SiC fibers were sintered at different temperatures would show different compositions [11].

2. METHODS

The SiC was produced from polycarbosilane as a precursor dissolved in toluene and N, N-dimethylformamide (DMF) solution. The ratio of DMF in toluene at 30:70. This solution was stirrer and used as a feeder solution for electrospinning apparatus.

During the electrospinning process, the apparatus was set up in a vertical arrangement. The voltage was set at 17 kV with the tip of the needle to fibers collector distance was set at 15 cm. Aluminum plate was used as the collector. The PCS fibers then took off from the collector and continued to curing process at 200 °C for 1 hour in an air atmosphere. The obtained cured PCS fibers continued by pyrolysis at 1200, 1300, and 1400 °C in an inert atmosphere. The heating rate for all of the thermal processes was set at 2 °C/min in a muffle furnace with special apparatus for flowing an inert gas when needed.

Characterization of a functional group of SiC fibers was done by Fourier Transform Infrared (FTIR) analysis. The AC electrical conductivity of SiC fibers was characterized by LCR meter with frequency from 0 to 100 kHz, and the highest electrical conductivity continued by band gap analysis from UV-VIS DRS result that calculated using Kubelka-Munk equation. The optical and SEM image also showed for the fibers that processed at 1400 °C.

The percentage value of reflectance that obtained can be used as the basis for determining the energy value of the band gap by using the Kubelka-Munk equation as follows [13],

$$F(R) = \frac{K}{S} = \frac{(1-R)^2}{2R} \quad (1)$$

The reflection factor $F(R)$, where the reflectance value denotes by R, proportional to the absorption coefficient (K) divide by the scattering coefficient (S). The value of K is directly proportional to the photon energy's root square, corresponding to the Tauc equation [14]. The form of the equation as follows,

$$K = A.(hv - Eg)^{m/2} \quad (2)$$

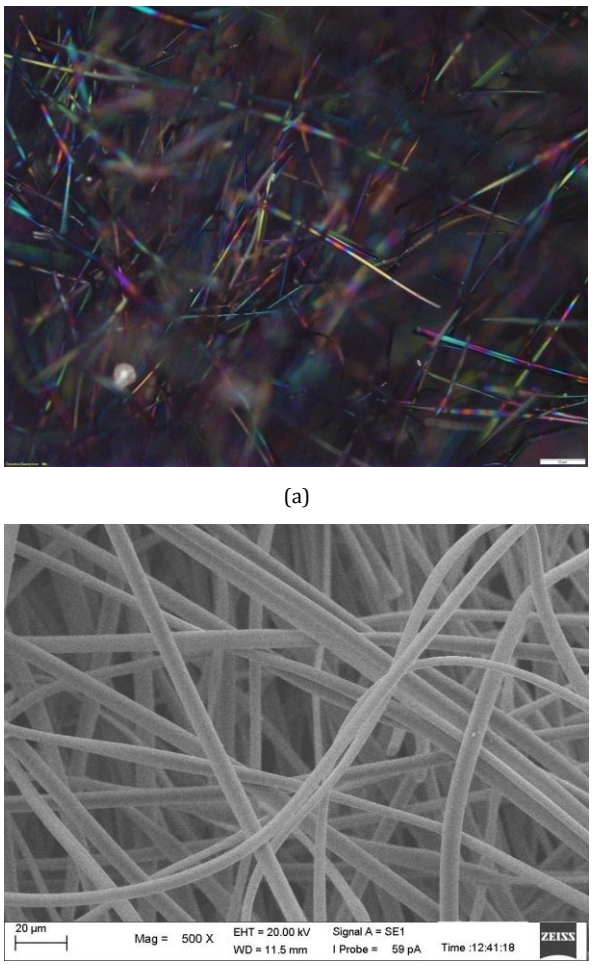
Where A is proportional constant, h is Planck's constant, v is frequency, Eg is band gap energy, and m = 1 (for allowed transitions). By substituting K in equation one into equation two, we have the equation as follows,

$$F(R)^2 = \left(\frac{A}{S}\right)^2 hv - \left(\frac{A}{S}\right)^2 Eg \quad (3)$$

The band gap value was determined from the relationship between F(R)2 with Eg.

3. RESULTS AND DISCUSSION

The SiC fiber's images were shown in figure 1. The color for SiC fibers was shiny black, with a cylinder shape.



(a)

(b)

Figure 1. SiC fibers processed at 1400 °C (a) Microscope optical and (b) SEM image.

3.1. Functional group of SiC fiber

The results of functional group characteristic of the SiC fibers using FTIR showed in figure 2. The results of the functional group characteristic of the SiC fibers using FTIR showed in figure 2. Figure 2 showed that the organic parts of PCS were transformed into an inorganic state during pyrolysis. Large weight losses and gaseous evolution mainly in the form H_2 and CH_4. The group functions of Si-H and C-H bonds were readily broken. The FTIR results indicates that the major bonds present were Si-CH_3 (1250 cm^{-1}) and Si-CH_2-Si (1020 cm^{-1}) and Si-OH (3400 cm^{-1}). The peak at 3700 cm^{-1} was broadening that could have been due to the O-H stretching of Si-OH. Along with the temperature increase, the C-H bond was decreased while the Si-H, and Si-CH_3 bonds disappeared.

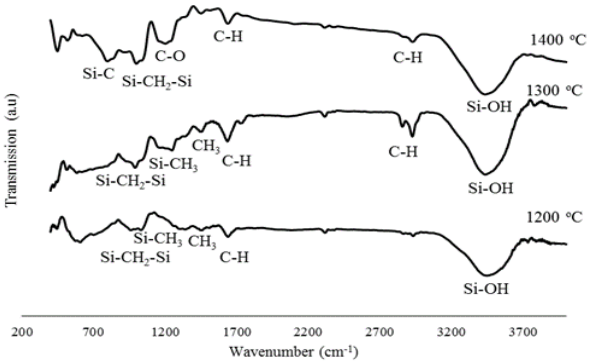


Figure 2. FTIR spectra of SiC fibers.

The FTIR results for SiC fibers that temperature processed at 1400 °C connectivity increased the Si-C-Si bonds and the network structure formed via condensation reactions between CH_4 and CH_3 units. So the Si-C (820 cm^{-1}) bonds starting appeared and also C-O (1200 cm^{-1}) bonds which were caused by chemical decomposition with the reaction as follows [15]:

$$SiC_xO_y(s) \rightarrow SiO(g) + CO(g) + C(s) \quad (4)$$

$$SiO(g) + C(s) \rightarrow SiC(s) + CO(g) \quad (5)$$

$$SiO(g) + CO(g) \rightarrow SiC(s) + CO_2(g) \quad (6)$$

The oxygens were introduced during the oxidation cured process. The oxygen bonds actually will be broken to form gases as SiO and CO during heating during the pyrolysis process. However, the CO gas evaporates at a temperature above 1500 °C, so in order to remove all oxygen content, it needs to be heated more than 1500 °C. The crystals of SiC were formed from the temperature at 1300 °C or above were probably because of the crystal growth of β-SiC [16–19]

3.2. Electrical conductivity

The results of the electrical conductivity of SiC fiber showed in figures 3 and 4.

Figure 3 shows the electrical conductivity of the SiC fibers characterized using LCR meter with frequency from 0 to 100 kHz. The electrical conductivity relatively increased during frequency measurement increased. The results showed SiC fibers that processed at 1400 °C had higher electrical conductivity value at 100 kHz; it reached 12400 $nS.cm^{-1}$. The other phenomena, oscillation at a lower frequency, shown in *f*igure 4, showed that the electrical conductivity at lower frequency showed the SiC fiber processed at 1200 °C had higher value at 7280 $nS.cm^{-1}$. The other values showed oscillated with the frequency increased. The SiC fibers that processed at 1400 °C showed crystalline characteristics more than the fibers for other processes.

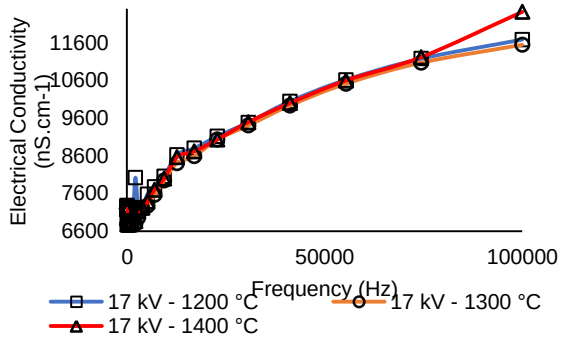


Figure 3. Electrical conductivity of SiC fibers at frequency 0-100 kHz.

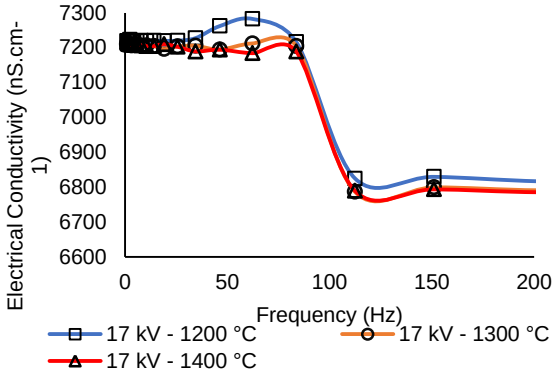


Figure 4. Electrical conductivity of SiC fibers at frequency 0-200 Hz.

3.3. Band gap

The result from the LCR meter showed high electrical conductivity at high frequency. We decided to characterize the band gap for the SiC fiber that processed at 1400 °C. The results of UV-VIS-DRS from SiC fibers were shown in figure 5 and calculated from the Kubelka-Munk Equation in figure 6.

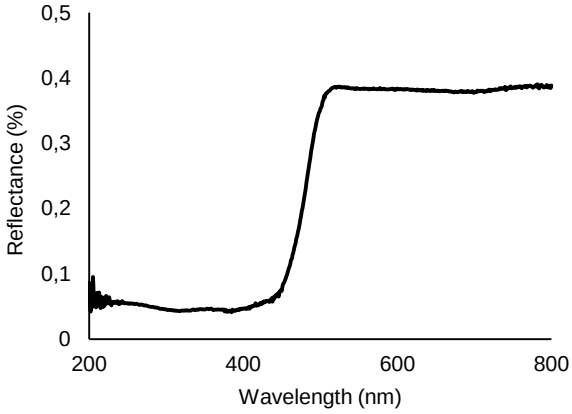


Figure 5. UV-Vis DRS curve of SiC fibers.

Some fractions of the UV-Vis rays passed to the sample will be absorbed to excite the electrons from the valence band to the conduction band. In contrast, other

fractions of light that do not match the energy level will be reflected and detected on the detector. Figure 2 showed that reflectance values were very lower below 0.5 %. The percentage of reflectance appears to be rising at 430 nm of a wavelength then constantly at around 500 nm of wavelength. The percentage value of reflectance obtained can be used as the basis for determining the energy value of the band gap by using the Kubelka-Munk equation, as showed in equation (1)-(3). The relationship of reflectance factor versus band gap energy showed in figure 6.

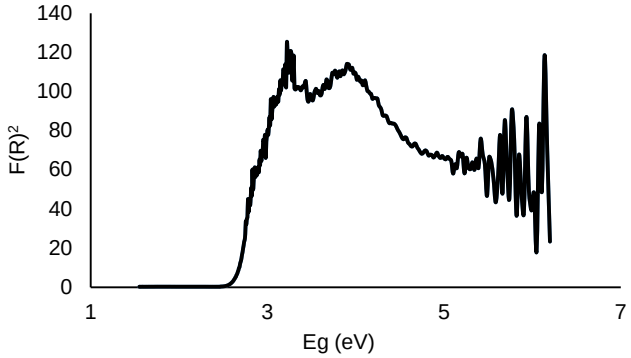


Figure 6. Band gap energy of SiC fibers.

The silicon carbide is having distinct electronic structures as well as electrical and optical characteristics for different polytype. For instance, the indirect band gaps at room temperature of 3C-SiC, 4H-SiC, and 6H-SiC showed in table 1.

Table 1. Indirect band gaps at room temperature for SiC polytype.

SiC Polytype	Band Gap (eV)
3C-SiC	2.4
4H-SiC	3.2–3.3
6H-SiC	2.86 (or 3.02)
Current experiment	2.56

Source: [5,20,21]

The band gap value depends on the temperature, and even when measured at room temperature, a specific polytype may result in a varying value in a small range. It is depending on the uncertainty in determining the optical absorption line and measurement conditions in different laboratories.

The calculated band gap value from the UV-Vis measurement of SiC fibers synthesized with the pyrolysis process at 1400 °C was 2.65 eV. This value was slightly higher from the theory that is 2.4 eV for 3C-SiC. Regardless this value was within the range for the band gap value of 3C-SiC around 2.39 eV and less than 3.31 eV [5,20,21].

4. CONCLUSION

Electrospinning methods have been successfully used for the synthesis of SiC fibers. The electronic properties of SiC fibers were determined for the electrical conductivity and calculated its band gap value. At the higher frequency around 100 kHz, the electrical conductivity of fiber that processed at 1400 °C showed a higher value; it reached 12400 $nS.cm^{-1}$. The electrical conductivity value of the fiber that processed at 1200 °C showed higher value at lower frequencies. The band gap of SiC fibers that processed at 1400 °C was 2.56 eV. According to this value, the fibers were processed with higher temperature as long as formed a crystalline structure; the electrical conductivity value at higher frequency also increased.

5. ACKNOWLEDGMENTS

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