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Dielectric Properties and Microwave Absorbing Properties of Silicon Carbide Nanoparticles and Silicon Carbide Nanowhiskers

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ABSTRACT

Silicon carbide (SiC) is well known for their outstanding microwave absorbing properties. SiC nanomaterials (SiCNMs) are expected to have better microwave absorption performance due to their high specific surface area. To date, no study was reported to compare the dielectric properties and microwave absorbing properties of different type of SiCNMs. Therefore, the objective of this paper is to compare the dielectric properties and microwave absorption properties of different types of SiCNMs. In this paper, SiC nanoparticles (SiCNPs) and SiC nanowhiskers (SiCNWs) were characterised using SEM and XRD. In addition, their dielectric properties and microwave absorbing properties were measured using network analyser and transmission line theory. It was found that SiCNWs achieved higher dielectric constant and loss factor which are and $\varepsilon_r' = 17.94$ *and* $\varepsilon_r'' = 2.64$ *compared to SiCNPs that only achieved* $\varepsilon_r' = 2.83$ *and* $\varepsilon_r'' = 0.71$*. For microwave absorbing properties, SiCNWs and SiCNPs attained minimum reflection loss of -10.41 dB and -6.83 dB at 5.68 GHz and 17.68 GHz, respectively. The minimum reflection loss of SiCNPs and SiCNWs obtained in this study is much lower than the nanometer-SiC reported previously. These results suggested that SiCNWs can be an ideal candidate of microwave susceptors for various microwave applications.*

Keywords: microwave absorption, dielectric, silicon carbide, nanoparticles, nanowhiskers

1. INTRODUCTION

Electronic equipment and wireless telecommunication that utilize electromagnetic radiation, such as mobile phones and satellite broadcast systems had become essential in our daily life. The extensive usage of these devices was found to lead to electromagnetic interference pollution. This electromagnetic radiation is also potentially harmful to human body, information security and performance as well as shelf-life of electric circuits [1, 2]. Therefore, significant attention was paid to the research that works on electromagnetic wave absorbing materials to improve the electromagnetic interferences shielding. Consequently, there is a high demand for electromagnetic absorber which can effectively convert electromagnetic energy into other kinds of energy, such as thermal energy [3, 4] and these kind of materials are called susceptors.

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Electromagnetic radiation in the range of 0.3 GHz – 300 GHz is called microwave. An ideal microwave absorber should have characteristics such as strong absorption strength, wide absorption band, low density, antioxidation capability, thermally stable, and good mechanical properties [2, 4-6]. Microwave absorber can be used as a microwave susceptor since it can be coupled with microwave and converted into heat. However, not all microwave absorbers can be excellent microwave susceptors. An ideal susceptor should have the criteria of high microwave absorbing and loss ability, where losses can happen even at room temperature and are stable over a wide range of temperatures [7].

Previous studies indicate that metallic powders [8], ferrites [9, 10], conductive polymer [11, 12], and carbon-based materials [1, 13, 14] are widely used as microwave absorbers and susceptors. Metal and metallic powder such as copper and nickel can absorb microwave effectively due to their high conductivity characteristic. However, high density and high corrodibility have restricted their extensive application [13]. Although ferrites also show strong microwave absorption properties at lower frequency (<1 GHz), but high thickness is required to realize the absorption performance [10]. Conductive polymers are considered as favourable materials due to their lightweight, corrosion resistance and inexpensive. Nevertheless, thermal and chemical resistance of conductive polymer in a harsh environment is unsatisfied. Carbon-based materials are most commonly used for microwave absorbing because of their high dielectric loss properties. Yet, their magnetic loss is low and hence impedance matching is difficult to achieve in this case [4].

Among the reported microwave absorbers, SiC stands out from other microwave absorber in terms of its microwave absorption performance. SiC is well known for their intrinsically dipolar polarization and this makes them an excellent microwave absorber and susceptor [15, 16]. Besides, it offers several outstanding characteristics such as thermal shock resistance, low thermal expansion, high thermal conductivity, chemical inertness, oxidation resistance as well as high mechanical strength and so, they can be considered a suitable candidate to work in high temperature and harsh environment [4, 17]. Liu et al. had compared the microwave absorbing properties of SiC whisker, nanometer SiC and ultrafine SiC [18]. They found that both dielectric constant and loss factor of nanometer SiC are highest among the three types of SiC. Besides, a minimum reflection loss of -5.53 dB was obtained by nanometer SiC and hence, they suggested that nanometer SiC has a better capacity of dielectric loss in microwave range than SiC whisker and ultrafine SiC. They claimed that the high dielectric properties of nanometer SiC is due to its high specific surface area, which is subsequently prone to interface polarization. Besides, the quantum size of SiCNMs induced a new channel for wave attenuation due to the fission-produced energy is in the range of microwave energy [18]. For these reasons, SiCNMs are chosen as the studied material in this study. In this work, two types of SiCNMs, namely SiC nanoparticles (SiCNPs) and SiC nanowhiskers (SiCNWs) were characterized to compare their dielectric properties and microwave absorbing properties in the frequency range of 2-18 GHz.

2. MATERIAL AND METHODS

2.1 Materials

Silicon carbide nanoparticles (SiCNPs, 99+%, diameter 80 nm) and silicon carbide nanowhiskers (SiCNWs, 99+%, diameter 100-250 nm) were purchased from US Research Nanomaterials Inc. and Nanostructured & Amorphous Materials Inc. respectively. Both SiCNPs and SiCNWs were characterised without any further modification.

2.2 Sample Preparation

To measure the dielectric properties, both SiCNPs and SiCNWs were hand pressed into pellet with diameter of 25 mm and thickness of 3 mm. The purpose of this process is to minimise the air gap in the sample to ensure the accuracy of result obtained. 5 pellets were prepared for both SiCNPs and SiCNWs.

2.3 Characterization

Characterization of SiCNMs was carried out using scanning electron microscope (SEM, JEOL JSM-6010LV) and X-ray diffractometer (XRD, Shimadzu XD-6000). Furthermore, the dielectric properties ($\varepsilon_r=\varepsilon_r' - \varepsilon_r''$) of SiCNMs were measured using network analyzer (Agilent Technologies E5071C E-series) support with 8570E software over frequency of 2-18 GHz. An open-ended high temperature probe was connected to the network analyser using a coaxial cable. Before dielectric properties were measured, three calibrations were performed to avoid systematic error. The calibrations performed were air (open), short (short), and water. After calibration, the probe was brought into contact with the SiCNMs pellets, as shown in Figure 1. Five samples were measured and the average value was used to calculate the dielectric properties.

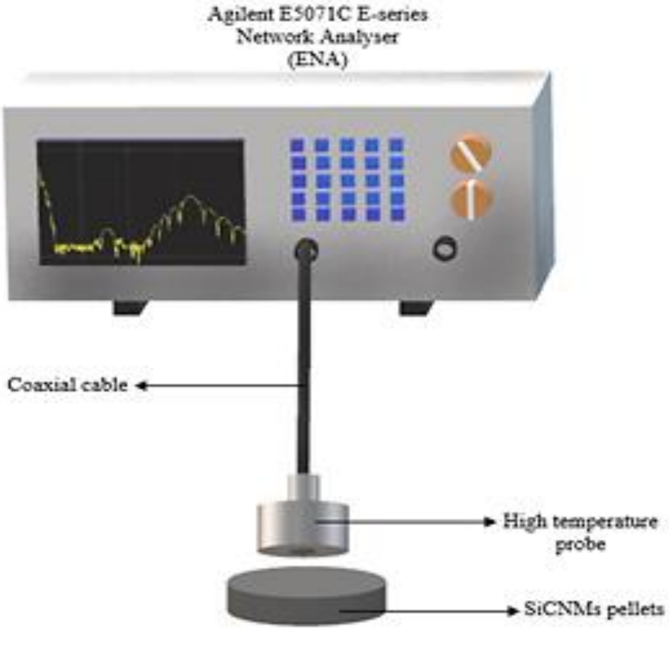

Figure 1. Dielectric properties measurement of SiCNMs.

Besides, reflection loss of SiCNMs can be determined via transmission line theory as shown in equation (1) [17, 18].

$$\mathrm{RL(dB)}=20\log\left|\frac{\sqrt{\frac{\mu_r}{\varepsilon_r}}\tanh\left(\frac{2\pi fdj}{c}\right)\sqrt{\mu_r\varepsilon_r}-1}{\sqrt{\frac{\mu_r}{\varepsilon_r}}\tanh\left(\frac{2\pi fdj}{c}\right)\sqrt{\mu_r\varepsilon_r}+1}\right| \tag{1}$$

where μ_r is complex relative permeability, ε_r is complex relative permittivity, f is frequency, d is thickness of sample and c is the speed of light (3.0×10^8). For the case of SiCNMs, it is type of dielectric material with no magnetic properties, hence the complex relative permeability of SiCNMs is 1.

3. RESULTS AND DISCUSSION

3.1 SEM

Figure 2(a) and (b) display the morphology of SiCNPs at different magnification. As in Figure 2(a), it is clearly shown that SiCNPs were composed of sphere shape nanoparticles with particle size ranging from 64 – 148 nm. Besides, agglomeration of SiCNPs was also observed in Figure 2(b) in which the SiCNPs tend to aggregate together to form larger blocks. Figure 2(c) and (d) demonstrate the morphology of SiCNWs at magnification 7k and 15k, respectively. SiCNWs have the shape of needles with consistent diameter along the length. As measured in Figure 2(d), the diameter of SiCNWs ranged from 130 - 400 nm.

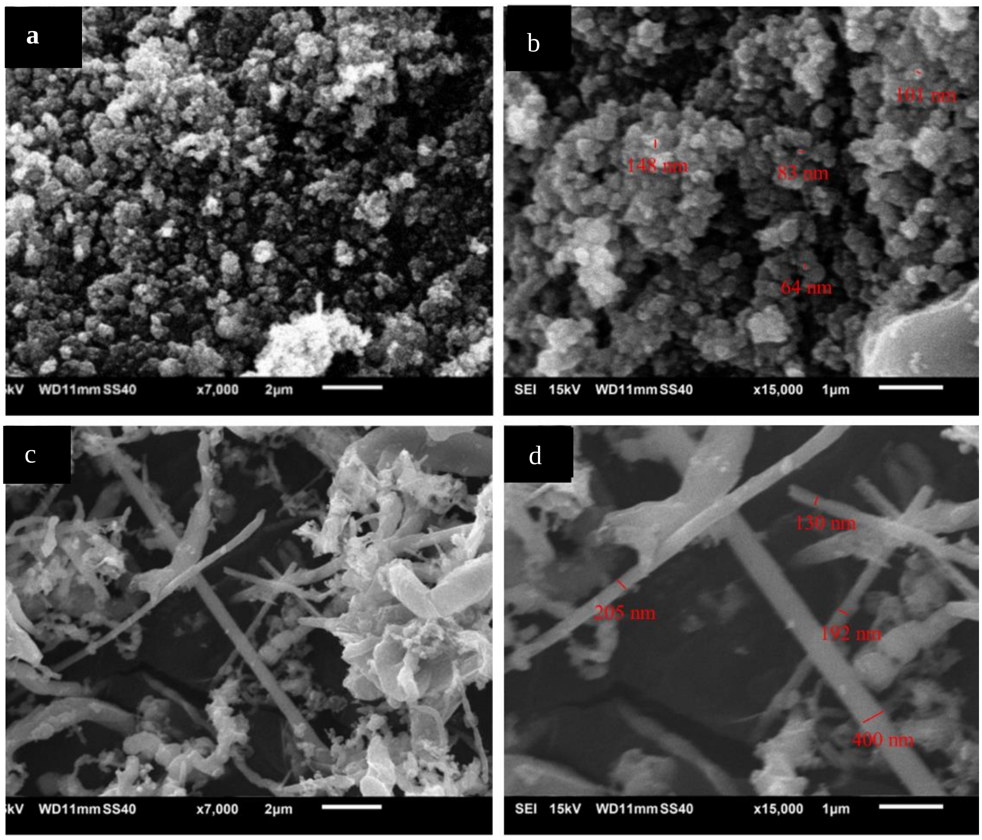

Figure 2. SEM image of (a, b) SiCNPs and (c, d) SiCNWs at magnification 7k and 15k.

3.2 XRD

Figure 3 presents the XRD pattern of SiCNPs and SiCNWs. It can be observed that the XRD patterns and the diffraction peaks of SiCNPs and SiCNWs are similar. Four diffraction peaks at 35.7°, 41.5°, 60.1°, 72.0° correspond to the cubic structure of SiC or β-SiC (ICDD 01-073-1708) in the (1 1 1), (2 0 0), (2 2 0) and (3 1 1) orientation were observed in Figure 3. X. Wang et al. reported a similar result that pure SiC nanowires has diffraction peaks located at 35.6°, 41.4°, 60.0° and 71.8°, corresponding to (1 1 1), (2 0 0), (2 2 0) and (3 1 1) crystal planes, referring to 3C cubic SiC crystal [19]. Noted that the peak intensity and the peak width of the (1 1 1) peaks of SiCNWs are higher and narrower than SiCNPs, which indicates that the crystallinity of SiCNWs is higher than SiCNPs [20].

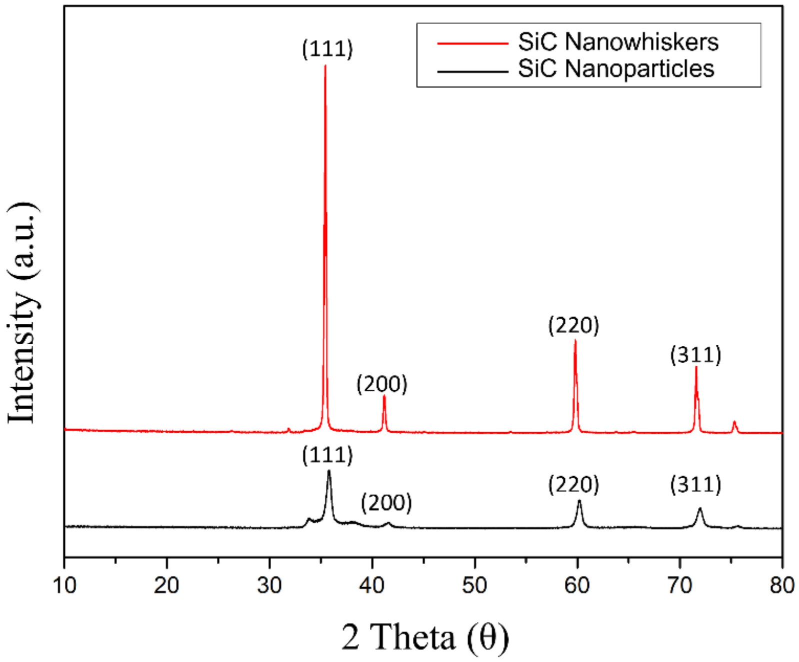

Figure 3. XRD of SiCNPs and SiCNWs.

3.3 Dielectric Properties

In general, the dielectric properties of dielectric material can be derived from their complex permittivity ($\varepsilon_r = \varepsilon_r' - j\varepsilon_r''$). The real part of the complex permittivity (ε_r') is known as dielectric constant, which also can be defined as the storage ability of the electric energy. On the other side, the imaginary part of the complex permittivity (ε_r'') is known as loss factor, represent the loss capability of the electric energy. Therefore, for an excellent microwave susceptor, it should have the properties of high dielectric constant and loss factor [4].

The average dielectric properties of both SiCNPs and SiCNWs versus frequency in the range of 2-18 GHz were shown in Figure 4 (a) and (b). The SiCNWs has the average value of $\varepsilon_r' = 17.94$ and $\varepsilon_r'' = 2.64$ while SiCNPs only has the average value of $\varepsilon_r' = 2.83$ and $\varepsilon_r''= 0.71$. As compared to dielectric properties of pure micro-SiC reported by B. Du et al., at both high and low frequency, the dielectric properties of SiCNWs were higher compared to micro-SiC, but SiCNPs attained lower value than micro-SiC. For example, the dielectric constant and loss factor of SiCNWs are $\varepsilon_r' = 21.21$ and $\varepsilon_r'' = 2.00$, but SiCNPs only attained $\varepsilon_r' = 3.41$, $\varepsilon_r'' = 0.17$ compared to pure micro-SiC with the dielectric constant, $\varepsilon_r' = 10$ and loss factor, $\varepsilon_r'' = 0.8$ at frequency 2 GHz [21].Obviously, the dielectric properties such as dielectric constant and loss factor of the SiCNWs are higher than those of SiCNPs over the measured frequency region. This improvement might be due to the fact that SiCNWs have a higher specific area compared to SiCNPs. A similar result was observed in study conducted by Kumar et al. in which they studied the dielectric properties of SiC with various particle size [22]. They reported that with the increasing surface area of SiC due to the reducing particle size, the space charge polarization becomes more dominant and leads to the improved dielectric constant and loss factor.

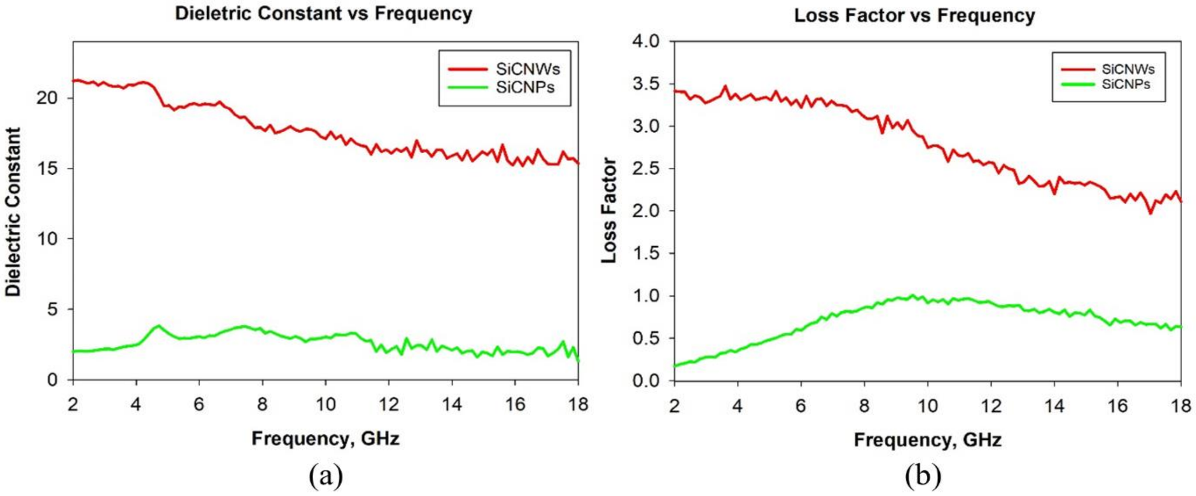

Figure 4. (a) Dielectric constant and (b) loss factor of SiCNMs.

3.4 Microwave Absorbing Properties

The reflection loss, R_L of SiCNPs and SiCNWs was calculated using formula (1) and a graph of R_L is plotted as shown in Figure 5. As illustrated in Figure 5, the reflection loss of SiCNPs decreases as the frequency increases, and it reaches a minimum value of -6.83 dB at frequency 17.84 GHz. For SiCNWs, two minimum peaks were observed where the first peaks with R_L -10.41 dB was observed at 5.68 GHz while second peak with R_L -7.35 dB was observed at 17.68 GHz. From the results, for low frequency that is lower than 6 GHz, only SiCNWs is able to achieve reflection loss of less than -10 dB. A reflection loss of -10 dB means that 90 % of incident microwave was absorbed by the materials [4]. So, only SiCNWs is suitable to play the role as susceptor in low frequency whereas SiCNPs does not. Furthermore, SiCNPs and SiCNWs might have peak with reflection loss < -10 dB when the frequency increased to above 18 GHz. In sum, SiCNPs only can be excellent susceptor when it is employed in high frequency application while SiCNWs can be used in either low frequency or high frequency application. It is worth mentioning that the minimum reflection loss achieved by SiCNPs and SiCNWs (-6.83 dB and -10.41 dB respectively) in study are lower than those nanometers SiC (-5.53 dB) reported by Liu et al. [18]. This is because the particles size of SiCNPs (< 80 nm) in this study is significantly smaller than nanometer SiC (<100 nm) reported by Liu et al. When the particles size gets smaller, the specific surface area increases. In this case, multi-scattering and reflection can occur easily and leads to the improvement in interfacial polarization. Consequently, the dielectric properties and microwave absorbing properties of SiCNPs and SiCNWs were enhanced.

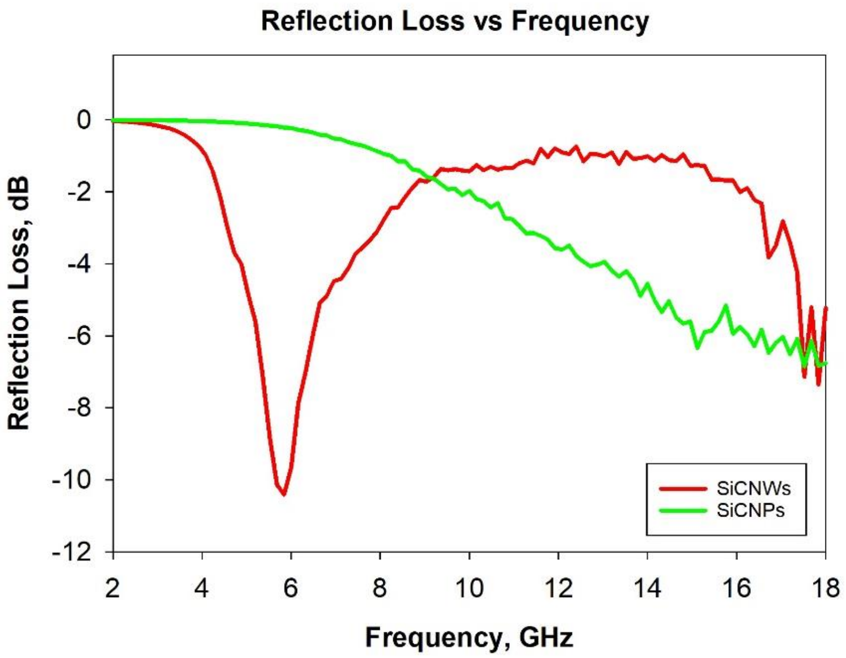

Figure 5. Reflection loss of SiCNMs.

4. CONCLUSION

In this paper, SiCNMs were studied as the candidates for microwave susceptors. Two types of SiCNMs which is SiCNPs and SiCNWs were examined using SEM and XRD. Besides, the dielectric properties ranging from 2-18 GHz were also measured using network analyzer support by Agilent software 8570E. Based on the results obtained, A maximum dielectric constant and reflection attained by SiCNWs (ε_r' = 17.94 and ε_r'' = 2.64) were higher than SiCNPs that only have the values ε_r' = 2.83 and ε_r'' = 0.71. In addition, when comparing the reflection loss of SiCNPs and SiCNWs, the reflection loss of SiCNWs shows good microwave absorption with -10.41 dB and -7.35 dB at frequencies 5.68 GHz and 17.68 GHz. The results show that SiCNWs can significantly absorb microwave energy and can be used as microwave susceptors for microwave application.

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