

Experimental Analysis of Nano-carbon Doped Alumina for Industrial Applications

Alok Singh^{1,*}, Savita Singh², Sudhir K Sharma³

Abstract

The use of nano-carbon metal matrix composites can provide a solution to the enduring issue of optimal material selection and optimization for getting metal-insulator transition (MIT) behavior at a particular frequency at ambient temperature. Other substances, like two-dimensional (2D) transition metal dichalcogenides (TMD), vanadium oxide (VO₂), and germanium telluride (Ge-Te), have difficult challenges in achieving effectively the MIT property at a given frequency and temperature. It is also difficult to accurately explain the mechanism by which these materials acquire the MIT characteristic. In this demonstrated research work, nano-carbon doped aluminium oxide has been synthesized by chemical vapor deposition (CVD) methodology. The electrical properties of developed samples were measured by auto-lab PGSTAT with a frequency range of 10 μ Hz–32 MHz with a resolution of 0.003% whereas fractographical analysis of the samples was performed by scanning electron microscopy from Zeiss Evo 18. The experimental frequency response plots illustrated that nano-carbon doped alumina may be utilized as a low-pass filter for top frequency discontinuation at 9000 Hz in electronic industrial applications. The energy dispersive X-ray chemical analysis (EDS or EDX) of nano-carbon doped alumina showed a MIT development happens at 30% (by mass) nano-carbon doping in aluminium. The fractographical analysis of nano-carbon doped alumina revealed the minimum voids, defects, and porosity that cause marginal deviation in electrical properties at a higher temperature. As a result, this nano-carbon doped aluminium oxide material can be the future alternative to engineering materials for electronic industries such as high-frequency switches. Future research might examine the possibilities of various metal oxides doped with nano-carbon for higher cut-off frequency switches.

Keywords: Low-pass filter, CVD method, metal-insulator transition, fractography, EDX

INTRODUCTION

Recently, the shifting from 4G to 5G technologies needs multiband operations using complicated radio frequency (RF) modules for wireless communication systems. The RF shift technologies are then needed with high isolation, high dimensionality, and high dependableness [1–3]. The figure of merit (FOM) that is usually referred to as cut-off frequency for RF switches are of many orders of magnitude beyond solid-state devices [4–5]. Vanadium oxide (VO₂) as a metal-insulator transition (MIT) and Germanium Telluride (Ge-Te) as a state change material (PCM) draw attention towards RF shift materials due to their distinctive properties and transitions from insulator to metal (amorphous to crystal for PCM) or vice-versa at room temperature along with high OFF/ON resistance ratio was observed [6–7]. Transformation metal oxides get appreciable

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Received Date: August 27, 2022

Accepted Date: September 06, 2022

Published Date: November 30, 2022

Citation: Alok Singh, Savita Singh, Sudhir K Sharma. Experimental Analysis of Nano-Carbon Doped Alumina for Industrial Applications. Journal of Polymer & Composites. 2022; 10(Special Issue 1): S44–S49.

interest in physics engineering applications for over few decades. These materials showed MIT triggered by external stimuli [8–10]. Metalloid forms of the elements germanium, antimony, tellurium, and a few others are found. These metalloids produce big structural oxides, metals, electrical intermediates, and heat. Normal elements found in the Earth's outer layer called "metalloids" have mixed qualities between metals and non-metals [11], it took place in a setting that included both organic and inorganic combinations, along with other common synthetics. The unfettered usage of these components is constrained due to the unexpected modern abuse of them and potential risks to humans [12–13]. Some researchers are interested in modifying this material into usable forms for human life in various sectors, such as the alloy used as a thin film, which led to the discovery of similar uses for two-dimensional (2D) transition metal dichalcogenides (TMD) in a variety of fields [14]. Transition metals and other cationic elements are used to make them. The anionic components of chalcogenides are also crucial in many different domains. Additionally, the physicochemical properties are helpful for sensing, in nonvolatile RAM, thermoelectric, and face-changing properties to increase the band gap energy of Ge-Sb-Te (GST). The 2D TMDs exhibit novel features that differ significantly from pure transition bulk compounds. Phase transition materials with a group of chalcogenides have well-known and promising properties for a long time [15]. One of the simplest correlated oxide materials is VO₂, which transitions to a metal-insulator state at 68°C. Monoclinic crystals were used to examine the semiconductor phase at low temperatures. In contrast, it is a tetragonal rutile structure at high temperatures. Monoclinic crystals were used to examine the semiconductor phase at low temperatures. In contrast, it is a tetragonal rutile structure at high temperatures. Due to a number of issues, it is still not prepared for industrial or commercial use. For instance, applications in daily life require a transition temperature of 68°C, which is too high (such as intelligent window applications). Additionally, the impact of grain boundaries on VO₂ MIT is also fascinating. Appavoo et al. investigated the impact of MIT defects on lithographically specified VO₂ nanoparticles using plasmon resonance nano spectroscopy in conjunction with density functional calculations. They demonstrated that an oxygen vacancy present at grain boundaries produced by strain is the most likely point defect nucleating the phase change in MIT [16].

In this analysis work, the synthesis and experimental verification of the MIT property of nano-carbon-doped alumina have been demonstrated. Moreover, the fractographical analysis was additionally performed by scanning microscopy images.

EXPERIMENTAL WORK

Circuits employ filters to remove undesirable frequency components from signals. Increased signal-to-noise ratio and the rejection of undesirable signals are both benefits of filters. Practically all passive devices, such as resistors, capacitors, and inductors—expensive circuit components and physically large for low-frequency designs—will be used to create low-pass filters. Using active components like op-amps makes it possible to do away with the need for inductors. Active filters are those that are created in this manner. They can often save more money, space, and weight than passively built filters. Since they require a high input resistance and a low output resistance, it also eliminates filter loss and is simpler to operate. Active filters even allow simple tuning of the cut-off frequency and variable voltage gain.

Low-pass filters or high cut-off filters attenuate higher frequency signals above the cut-off frequency while allowing lower frequency signals to flow through. A key factor in determining the amount of signal attenuation at each frequency is the material or design of the filter that is used. The cut-off frequency f_c in a series RC circuit is frequently calculated as follows using resistance R in ohms and capacitance C:

$$f_c = \frac{1}{2\pi RC} = \frac{1}{2\pi\tau} \quad (1)$$

Where, the product of resistance and capacitance is a time constant in τ seconds.

The nano-carbon-doped alumina has been synthesized by the chemical vapor deposition (CVD) technique. The aluminium material is then placed within the CVD chamber and was heated at 700°C. A carbon-containing methane gas is allowed to flow within the chamber to deposit nano-carbon molecules over aluminium material with nitrogen gas as a catalyst. The remaining carbon dioxide gas is blown aloof from the furnace chamber. The nano-carbon-doped aluminium is currently cooled at room temperature for the synthesis of nano-carbon-doped alumina. Finally, the developed nano-carbon doped alumina sample was cut-down as per ASTM D 638-03 size for the testing of electrical properties as shown in Figure 1.

RESULTS AND DISCUSSION

The electrical properties of the above prepared nano-carbon doped aluminium oxide samples were measured by auto-lab PGSTAT in the frequency range 10 μ Hz–32 MHz with resolution 0.003%. The experimentally obtained bode plots or frequency response plots are shown in Figures 2 and 3.

Figure 2 illustrates that the lower frequency signals up to 9 kHz can easily pass through the sample while the upper frequency signals over 9 kHz are eliminated due to metal-insulator transition in nano-carbon-doped alumina.

Figure 3 illustrates that the impedance is minimum within the nano-carbon doped alumina up to 9 kHz cut-off frequency that behaves as metal to pass alternating current signals through the sample whereas for cut-off frequency more than 9 kHz the impedance suddenly becomes maximum within the nano-carbon doped alumina that behaves as an insulator to attenuate alternating current signals through it.



Figure 1. Developed nano-carbon-doped aluminium oxide sample as per ASTM D 638-03 size.

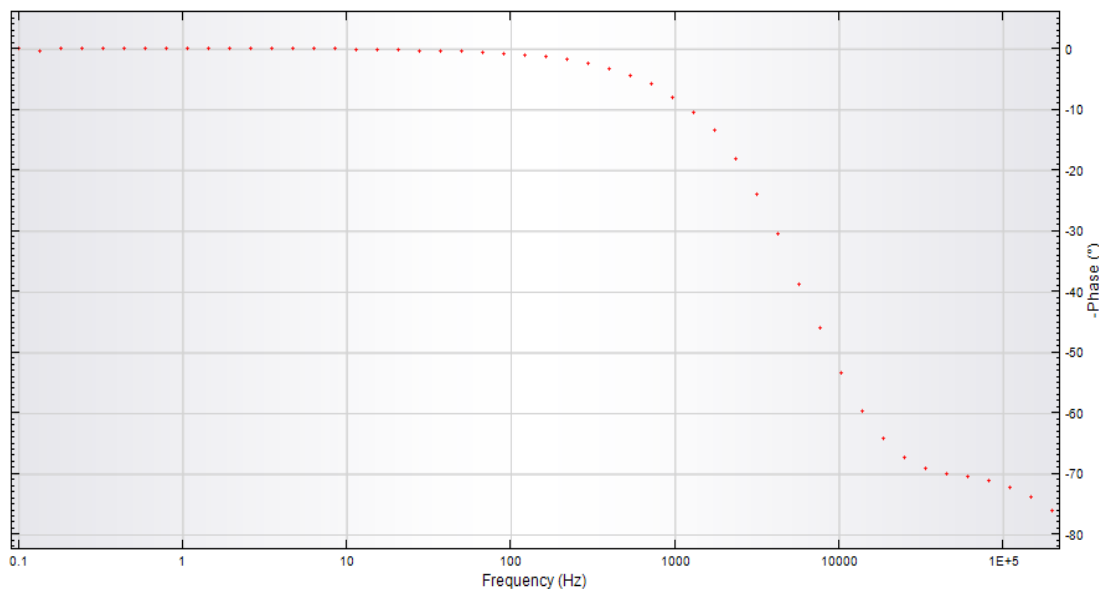


Figure 2. Frequency versus phase plot of nano-carbon doped aluminium oxide.

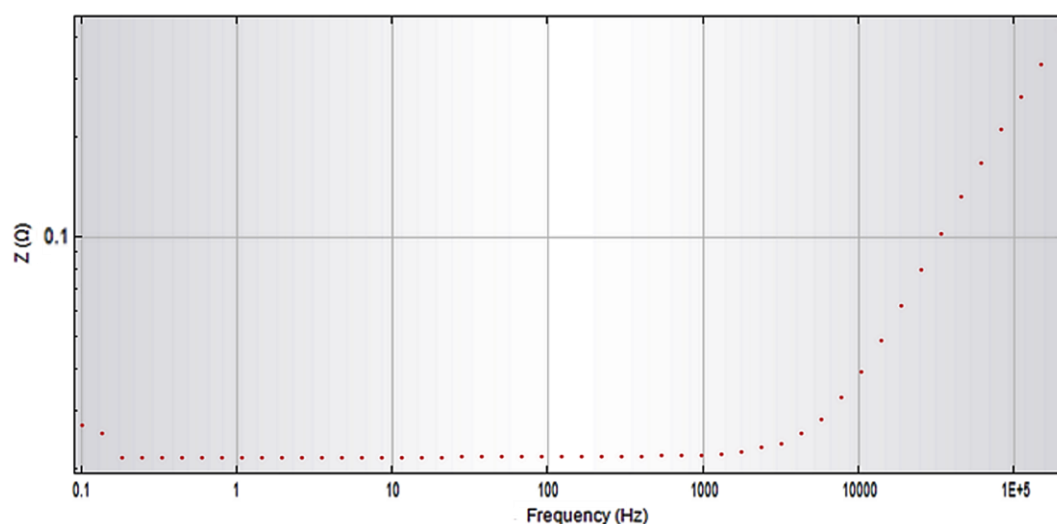


Figure 3. Frequency versus impedance plot of nano-carbon-doped aluminium oxide.

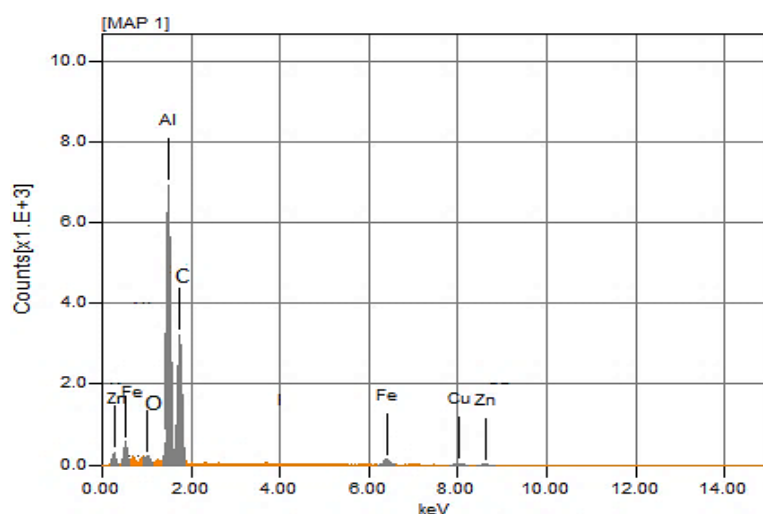


Figure 4. Energy dispersive x-ray spectroscopy of nano-carbon doped aluminium oxide.

Table 1. Chemical mass percentage composition of nano-carbon doped aluminium oxide.

S.N.	Chemical	Mass%
1	C	30
2	Al	69.10
3	Fe	0.60
4	Cu	0.04
5	Zn	0.26
	Total	100

The energy dispersive x-ray spectroscopy (EDS or EDX) or chemical microanalysis technique used with scanning electron microscopy (SEM) of nano-carbon doped aluminium oxide samples were measured by the JEOL EDS system which is shown in Figure 4 and Table 1.

Figure 4 and Table 1 are illustrating that 30% of the nano-carbon mass in the developed aluminium sample produces the MIT phenomenon in the nano-carbon doped aluminium oxide at a 9 kHz operating frequency. Furthermore, the fractured surface microanalysis of nano-carbon doped aluminium oxide using SEM revealed the minimum voids, defects, and porosity as shown in Figure 5 which in turn causes minimal deviation in electrical properties at a higher temperature.

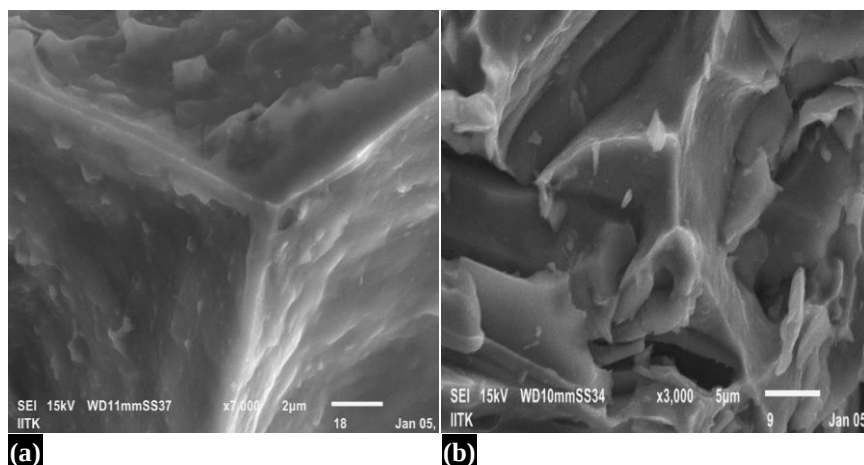


Figure 5. Scanning electron microscopic image of nano-carbon doped aluminium oxide (a) magnification 7000, (b) magnification 3000.

CONCLUSIONS

This paper reports the development of nano-carbon doped aluminium oxide material by CVD methodology. The electrical properties and analysis of nano-carbon doped aluminium oxide results in the conclusion that the nano-carbon doped aluminium oxide acts as a MIT material at a cut-off frequency of 9 kHz as shown in Figure 2 and Figure 3. Moreover, the energy dispersive x-ray spectroscopic analysis (EDS or EDX) of nano-carbon doped aluminium oxide demonstrated that MIT development happens at 30%. Nano-carbon mass doping in aluminium as shown in Figure 4 and Table 1. Furthermore, fractured surface analysis by scanning electron microscopic images has revealed the minimum voids, defects, and porosity and minimal deviation in electrical properties at a higher temperature. Consequently, this nano-carbon doped aluminium oxide material can be the future alternative to engineering materials for electronic industries such as high-frequency switches. In the future, the potential of nano-carbon-doped other metal oxides can be explored for higher cut-off frequency switches.

Acknowledgments

We are gratefully acknowledged to AICTE sponsored quality improvement program coordinator Prof. Kamal K. Kar and the Advanced Center of Material Science (ACMS) Laboratory, Indian Institute of Technology, Kanpur, India, for providing a testing facility.

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