Nano Trends: A Journal of Nanotechnology and Its Applications

ISSN: 0973-418X
Volume 26, Issue 1, 2024
January—April
DOI (Journal): 10.37591/NTs

https://journals.stmjournals.com/nts

Research NTs

Monitoring Eddy Current Density Fluctuation and Power Management in Doped Al_2O_3 Nanowire

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Abstract

Al_2O_3 nanowires exhibit fascinating electrical properties that span from insulating (dielectric) to superconducting properties. A model was designed to describe the phenomenon of the eddy electric current and eddy current density fluctuations. An Ohmic-type theorem was developed using the modified Green–Kubo theorem. With little modification, the Green–Kubo theorem was incorporated to explain the relationship between the eddy current density, electric field, and electric conductivity. Then, the factors contributing to eddy current density fluctuations were demystified. The current density fluctuation is therefore responsible for the resulting power dissipation in Al_2O_3 based transmission lines. A systematic approach is required to reduce dissipative effects and current density fluctuations. The electrical conductivity test is conveyed from the $J - \vec{E}$ graph while the electrical parameters characterizing the electrical transport phenomenon are determined from the J-Δn graph. The effects of coating nanowires, wireless sensor networking systems, and electrical power distribution monitoring and management systems are expected to minimize the electric power fluctuations caused by eddy current density fluctuations. This research presents insight into electric current density fluctuations and stimulates new vision for monitoring power dissipations caused by eddy current fluctuations.

Keywords: Al_2O_3 nanowire, eddy current, density fluctuation, power management

INTRODUCTION

Nanowires are quantum nanostructures with sizes in the range 1 nm -100 nm. Nanowires are one-dimensional (1D) nanomaterials that exhibit various physical, chemical, and biological properties. Al_2O_3 is a nontoxic, flammable, and noncrystalline solid at room temperature. Mikihalve et al. 2017 [1] revealed that Al_2O_3 is transparent, chemically inert, corrosion-resistant, and stable at high temperatures. This was a conductive nanowire. Benea et al. 2022 [2] revealed that anodizing aluminum in acid electrolyte solutions improves the mechanical properties of the material, such as hardness, corrosion resistance, and abrasion. Poinern et al. 2011 [3] demonstrated that anodic Al_2O_3 synthesized from citric acid, tartaric acid, and oxalic acid exhibits photoluminescence.

However, their optical characteristics are analogous to those of SiO_2. For example, both Al_2O_3 and SiO_2 exhibit optical bandgaps varying from 5.0 eV–10 eV, depending on the intrinsic and extrinsic conditions.

Eddy currents can be generated in ferromagnets, superconductors, and nanomagnetic materials (Figure 1). Eddy current sensors are available for high-precision displacements, oscillation frequencies, and ferromagnetism (Figure 2).

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Received Date: June 04, 2024
Accepted Date: July 26, 2024
Published Date: July 31, 2024

Citation: Gizachew Diga Milki. Monitoring Eddy Current Density Fluctuation and Power Management in Doped Al_2O_3 Nanowire. Nano Trends: A Journal of Nanotechnology and Its Applications. 2024; 26(1): 35–45p.

However, the precision of eddy current sensors, such as the micro-epsilon sensor, is affected by temperature fluctuations. As D A. Alencar et al. 2009 [4] demonstrated, eddy current is a nondestructive test (NDT) that is widely used in the aerospace industry to measure aluminum foil and plate thicknesses. They are also used to detect the surface and subsurface cracks in structural components and turbine blades.

Nanomaterials such as Al_2O_3 and SiO_2 have wide bandgaps and high dielectric values. Xinyi Xia et al. 2022 [5] $E_g = 8.7 - 8.8\, eV$, Oliver A Oick et al. 2019 [6] $E_g = 8.6\, eV$ and Santos et al. (2015) [7], $E_g = 8.826\, eV$ are the approximate optical and electronic band gaps of Al_2O_3. Similarly, Astasawkas et al. 2020 [8] calculated the band gap of SiO_2 by deconvolution of multiple ion scattering to be 9.1 eV. Fe_2O_3 also has a high dielectric value; however, it is a narrowband semiconductor with a gap energy close to 2 eV. These nanomaterials exhibit promising conductivity. In terms of conductivity, the resulting electrical conductivity has an exponential relationship with the activation (ionization) energy and temperature. Such transport mechanisms occur in direct trap-to-trap tunneling and phonon-assisted elastic-inelastic tunneling transport. This transport reflects the hopping conductivity.

Among known nanomaterials, Al_2O_3 nanowires have been studied for novel applications in various sectors. As Simone Bianconi et al. 2019 [9] noticed, reliable and accurate control of the electrical conductivity of Al_2O_3 nanowires enables enhanced chemical sensing technologies. FETs with Al_2O_3 are widely used for sensing PH value and photocatalytic applications. Lachlan E. Black, 2014 [10] verified that the major interest in Al_2O_3 is its ability to passivate highly doped silicon substrates for photovoltaic applications.

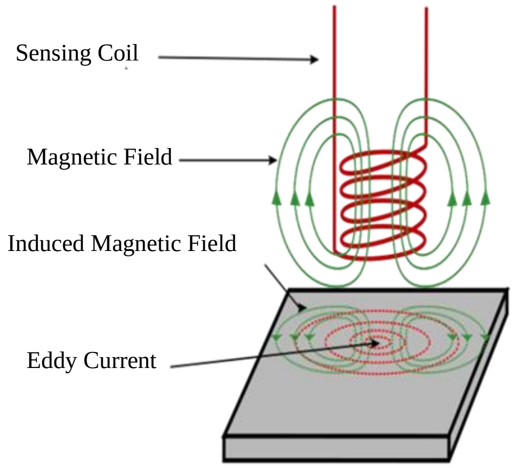

Figure 1. Sensing the origin of eddy current.

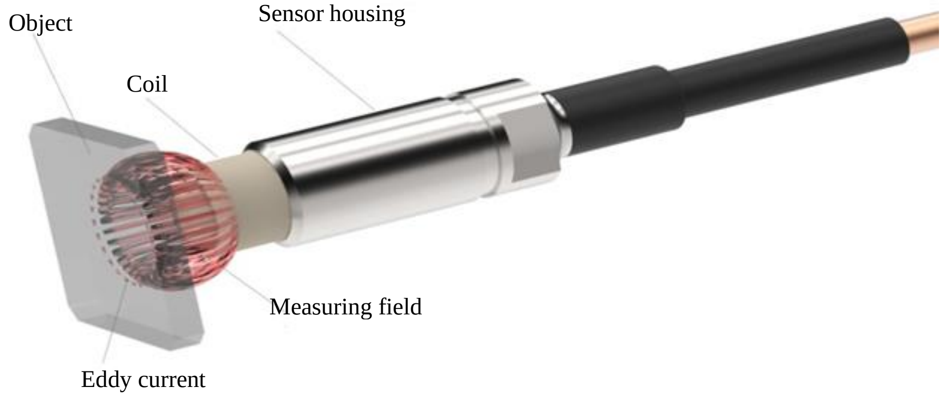

Figure 2. Structure of eddy current sensor.

Nanocomposites of Al_2O_3, typically Al_2O_3/HfO_2, can be used in flexible polyamide substrates for application in flexible thin-film transistors (FTFT). Al_2O_3 nanowires have a high K-dielectric value and can be integrated into MOSFETs for biosensing applications. Reddy Jr. et al. 2011 [11] revealed that devices with Al_2O_3 gate dielectrics exhibit superior sensitivity to pH when compared to devices with SiO_2 gate dielectrics. Owing to its high dielectric value and thermal stability, Al_2O_3 sapphire is used as a substrate for the growth of magnetic nanoparticles such as ZnMnO, CdTeSe, GaMnAs, and αFe_2O_3. Huang et al. 2020 [12] proved that Al_2O_3 can enhance the dielectric performance of composites, which increases with increasing mass fraction. Al_2O_3 was used as the anticorrosive material. Al_2O_3 is also used as an absorbent, material with a high-frequency, catalytic component, and high dielectric constant. Shin et al. 2023 [13] also verified that Al_2O_3 can be used to coat non-woven poly vinylidene fluoride (PVDF)/polyacrylamide separators to improve the electrochemical performance and safety of lithium metal batteries. Vu Quoc Trung et al. 2019 [14] proposed that the PPy/Al_2O_3 nanocomposite is an effective electromagnetic absorbent. Eddy currents have novel applications in power/force generators, magnetic levitation, actuation, and biomedicine, whereas eddy current sensors are used for transformer sensors. Harms J. 2021 [15] Al_2O_3 is used as an absorbent, material with a high-frequency, catalytic component, and high dielectric constant.

Developments in urbanization, technology, and industrialization demand high energy consumption and energy-saving technologies. This has led to the development of cutting-edge technologies including eddy current sensors, electric sensors, wireless electric energy sensors, energy storage, and transmission technology. Moreover, these technologies are characterized by low carbon emissions and are environmentally friendly. Therefore, the demand for energy storage, transmission, and utilization is becoming increasingly sophisticated. To this end, this study aims to present a more specialized power monitoring and management system for energy sustainability. This was achieved by determining the electric current density fluctuations considering the surface phenomenon.

PROPERTIES OF AL_2O_3 NANOWIRE

Electrical Properties of Al_2O_3

The electrical properties of the nanowires were investigated by determining their current-voltage characteristic of an Al_2O_3 nanowire. Some factors determine the electrical conductivity of Al_2O_3 nanowires. Among these factors, mass concentration, temperature, and thickness are important. It should also be noted that the fixed charging of Al_2O_3 renders it suitable for p-type surface passivation. Fal et al. 2015 [16] indicated that increasing the mass concentration increased the electrical conductivity of Al_2O_3-EG base Nanofluids. On the other hand, Gui Cang He et al. 2018 [17] had noted that Ag nanowire exhibit Ohmic type electrical conductivity. It shows a linear voltage-current characteristic.

In this study, the formation and effects of eddy current fluctuations were studied. Hence, the relationship between the eddy current density and physical parameters, such as the electric field, electrical conductivity, and temperature, was explored. Eddy currents are generated in FMs, superconductors, and nanomagnetic materials. However, the eddy current density fluctuated with increasing temperature. Choe et al. 2010 [18] revealed that oxygen vacancies could be reduced by SiO_2. To reduce the oxygen vacancies, interfacial SiO_2 was integrated with Al_2O_3 using a post-deposition analysis method.

As shown in Figure 3, Al_2O_3/Si serves as a heavily doped *p*-type substrate from sapphire, whereas the heavily doped p-type silicon substrate acts as a back-gate electrode. As the currents flowed up the Al_2O_3 Nanowire, they fluctuated in proportion to their length to a small extent. This effect resulted in an increase in the resistivity of the nanowires as their length increased. The relation between the thermal and electrical current densities along the nanowire is given by

$$J = ne\mu E \quad (1)$$

$$J = \sigma\vec{E} \quad (2)$$

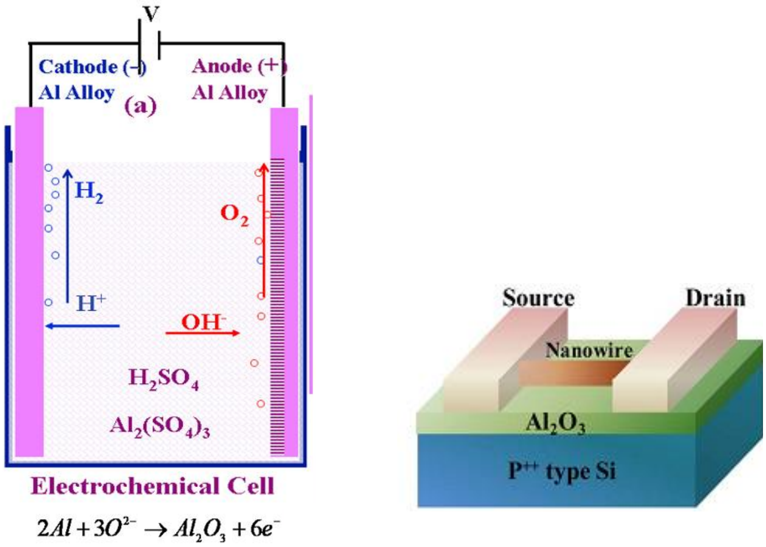

Figure 3. Electrochemical synthesis and application of Al_2O_3 nanowire in semiconducting media.

Where, ρ is the resistivity, which is the reciprocal of the conductivity σ of the nanowire; l is the length of the wire; and q is the electrical charge. Charge carrier fluctuations In AlOx nanowire led to fluctuations in the electrical current density. Charge carrier fluctuations are caused by surface absorption, electric polarization, or velocity retardation of giant magnetoresistance. This mechanism directly affects the normal-state conductance of granular aluminum oxides used in commercial nanodevices. According to Aoulaiche et al. 2023 [19], incorporating Al_2O_3 below or above HfO_2 results in a slightly higher trap density, slightly lower performance, and a shorter Negative bias temperature instability (NBTI) lifetime.

Magnetic Property

The magnetic properties of Al_2O_3 are attributed to the presence of defects and metal composites. Al_2O_3 exhibits room temperature ferromagnetism owing to oxygen vacancies. The study of magnetization by Mikihalve et al. 2017 [1] shows the existence of long-range ferromagnetism. The origin of the eddy current is estimated by determining the magnetoresistance of the electromagnet. It increased with an increase in the magnetic field. An eddy current is usually formed by magnetization, which is caused by oxygen vacancies. The eddy current is a surface effect that may be influenced by the surface geometry. It is argued that because the magnetic flux (Φ_m) is directly related to the area of the surface geometry, the eddy current must be caused by the surface irregularity and leaning of the current-carrying conductor. The eddy current was perpendicular to the magnetic field. This current is the source of the electric current density. X. G. Liu et al. 2008 [20] demonstrated that metal/Al_2O_3 nanocapsules involving both magnetic and dielectric shells are nanocomposites that exhibit low eddy current loss, which is significant in high-frequency devices. The working principles of eddy current sensors can be tuned by controlling their magnetic properties. Most Eddy current sensors, typically με eddy current sensors, are based on this principle, and are widely used for measuring tidal energy flow and distance in Maglev trains. In a later section, the effects of magnetic fields, influence of electrons, magnetic field strength, activation energy, and temperature are discussed.

METHODS

The Green–Kubo theorem is employed to determine the electrical current density. The Green–Kubo theorem describes the relationship between electric current density, electric conductivity, and electric field. However, it was modified to a small extent to describe electric current density fluctuations. This modification is relevant because (1) the introduction of electron mobility can describe the motion of conduction electrons or valence band charges (holes) in relation to the temperature gradient, and (2) it enables the investigation of the variations in charge density as long as the temperature gradient. In addition, the element of such a magnetic field can be determined using the classical Biot–Savart Law and Maxwell's equations. Because Al_2O_3 is an Ohmic-type material, its electrical properties, including electrical current density, can be expressed in terms of the Modified Green–Kubo Model. Moreover, Kriezis et al. 1992 [21] and Tiffany Chhim et al. 2020 [22] developed theoretical models for eddy current and eddy current density.

For large-scale industrial applications, Al_2O_3 can be synthesized via electrochemical anodization (Figure 3). This technique involves a two-step anodization with chemical etching. According to Mastroorch, Seyedi, and Mozhdeh Saba et al. 2008 [**23**], Al_2O_3 prepared in this manner has a high crystal quality and ordered crystal morphology. Dshelke and Srajbhhoj, 2017 [**24**] verified that γ-Al_2O_3 nanowires can be synthesized using the electrochemical reduction method, which can be characterized by XRD, SEM, and EDX. Zhang et al. 2008 [**25**] introduced a vacuum-free and cost-effective synthesis method for Al_2O_3 nanowires and nanobelts. This method is a vapor-solid condensation method that is operated at partial pressure and takes place at the supersaturation point. Moreover, sol-gel methods can be used to synthesize Al_2O3 nanocomposites. In the preceding sections, the properties related to the electric current density fluctuations and the parameters contributing to the hotspot phenomenon are briefly discussed. In addition, preferred electric power management systems for minimizing the power dissipation caused by the electric current density are paraphrased.

DISCUSSION

Electric Current Density Fluctuations

We assumed that the high cross-sectional area allowed more charge carriers to pass through. However, the current density must be maintained, because the current flow increases in proportion to the cross-sectional area. It is proportional to the size of the electric charge, number of charge carriers, electron mobility, and the electric field.

With a slight modification, the Green–Kubo theorem was incorporated to explain not only the electric current density but also the relationship between the electric conductivity, electric flux, energy, and temperature. The electric current density fluctuates in proportion to the electron number density. Each successive

$$J = \sum_{i=1}^{n} (\mathrm{n} - \mathrm{i})\mathrm{e}\mu\vec{\mathrm{E}} \quad (3)$$

where n is the total number of electrons per unit volume, i is the number of electrons absorbed by the surface interaction, n-i is the fluctuation in electron number per unit volume, μ is the electron mobility, and $\vec{E}$ is the electric field. As Shi Q. et al. 2022 [**26**] revealed, Al_2O_3/HfO_2 presents a carrier mobility of $9.7\frac{Cm^2}{Vs}$ and threshold voltage $V_t \sim 0.1V$.

The electric current density fluctuation was proportional to the electron number density. However, as the surface absorption increases, the electric current density fluctuates significantly. As the total number of electrons became equal to the number of absorbed electrons, the total current density became zero. As shown in Figure 4, the electric current density first increased rapidly and then declined rapidly until the number of electrons absorbed by the surface became equal to the initial number of electrons. Hence, the electric current density fluctuation is caused by bending, leans, or any surface irregularities in the current-carrying wire, and the growth of giant magnetoresistance with surface irregularities. In addition, the electric current density fluctuation observed in the nanowire was due to surface absorption, surface irregularities, defects, and voltage fluctuations (Figure 4).

The current is $I = \Phi_E \sigma_o e^{-\frac{E}{K_B T}}$ (4)

Where Φ_E is the electric flux, σ_o is the electrical conductivity, K_B is Boltzmann's constant, $\vec{E}$ is the electrical field, and T is the temperature. However, the Al_2O_3 nanowires exhibited hopping conductivity.

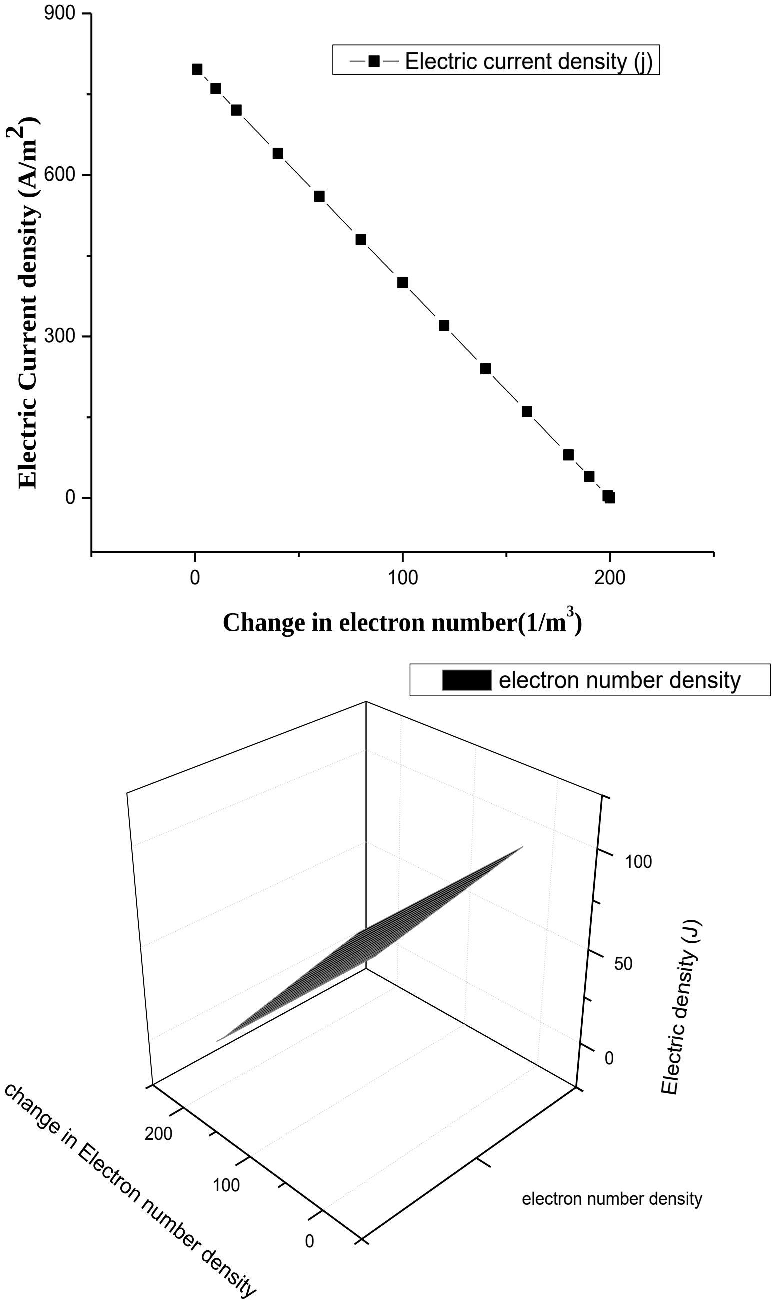

Figure 4. Electric current fluctuations as a function of the electron number density.

$$J = \vec{E}\sigma_o e^{-\frac{\Delta G}{K_B T}} \tag{5}$$

Where, $\vec{E}$ is the electric field, σ_o is the electrical conductivity, ΔG is the activation energy, and T is temperature. As this equation reveals, the electric current density decreases exponentially with the temperature. This is also influenced by the activation energy.

Figures 5 and 6 illustrate that the induced electric current density with a time-varying magnetic field is given by $J = \frac{N}{L} d\vec{B}$, where J is the electric current density, N is the number of turns of the coil, L is the inductance of the nanowire (coil), B is the magnetic field, and t is the time in microns. The magnetic equivalent electric current density is $J = \frac{NB_o sin\omega t}{L}$.

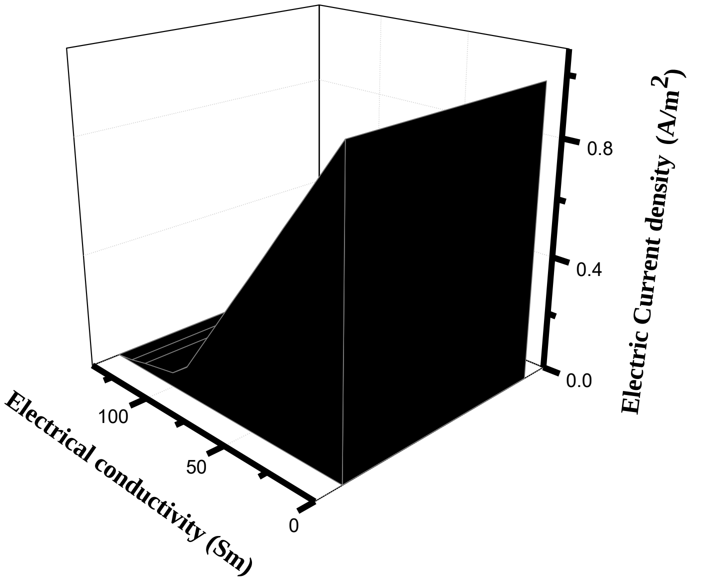

Figure 5. Current density fluctuations as a function of electrical conductivity.

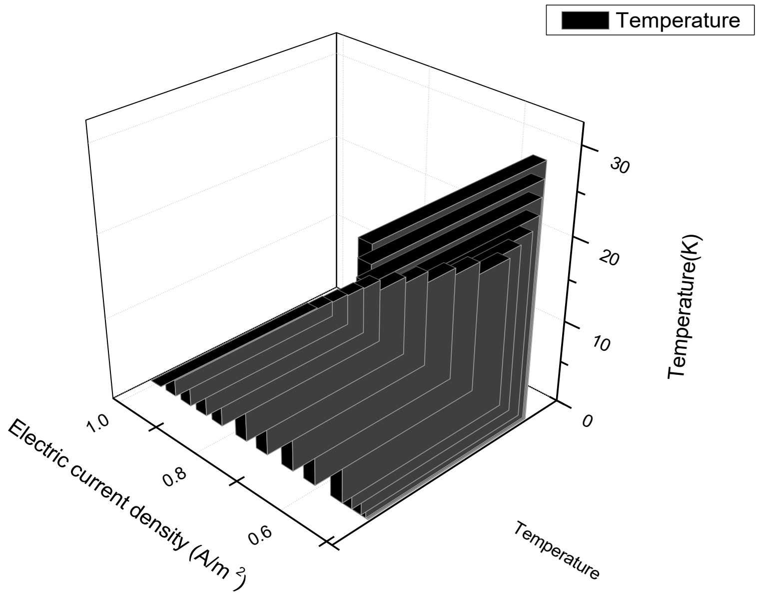

Figure 6. Current density fluctuations as a function of electrical conductivity.

As shown in Figure 7, the induced EMF decreases in proportion to the magnetic field strength below 0G. However, the induced EMF increases with an increase in the magnetic field density. The peak values of the induced EMF corresponded to a magnetic field of 3000G. Figure 8 illustrates the relationship between the electric current density and magnetic parameters.

As shown in Figure 8, the electric current density fluctuated as the magnetic field varied**.** Varying the periodic magnetic field induces a small current around the coil surface. Moreover, as the magnetic field diverged from the initial value, the electric current density increased gradually. As Figure 8 shows, the electric current density is inversely proportional to the inductance of the wire (coil). This must also be true because according to Lenz's law, the induced emf is as opposed to the production of an electric current and current density. This opposition was a consequence of the internal resistance caused by the self-inductive nanowire. It should also be noted that the eddy current density must decrease exponentially as a function of the magnetic field penetration depth (skin depth).

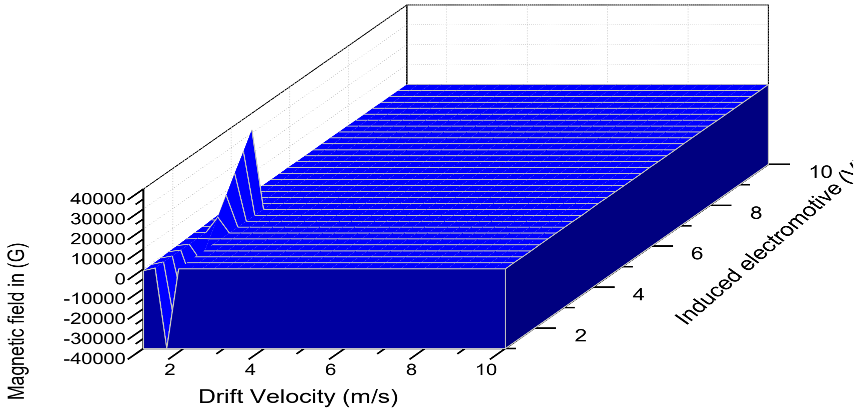

Figure 7. Induction of EMF with varying magnetic fields.

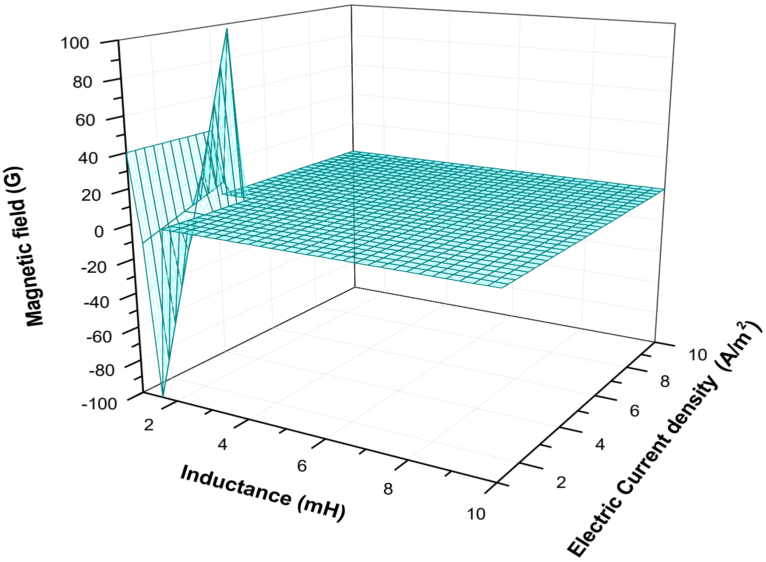

Figure 8. Variation in the induction current density with varying magnetic field.

Electrical Power Management Systems

In this article, a brief summary of the applications, including the dielectric and biosensing capacity of Al_2O_3 nanowires, will be explored. Controlling the electrical conductivity of Al_2O_3 nanowires can help Al_2O_3 for Optoelectronics such as MOSFETs. By carefully measuring electric current fluctuations and power with inductive sensors, unnecessary effects such as biofouling and polarization can be reduced. This can also be achieved by controlling and managing the electric current density fluctuations. The electric current density fluctuation is caused by circular magnetic fields. This field was always in the direction transverse to the electric current. As the cross-sectional area increases, the current density decreases.

Coating Al_2O_3 with Nonconductive Polymers

Coating the nanowire with a nonconductive polymer reduces surface absorption and enables a one-way flow of current. Hence, it helps prevent current density fluctuations. In addition, to reduce the power dissipation caused by eddy currents, nanowires are coated with shielding materials, typically magnetic metal oxides and polymers such as chitosan. It should also be noted that coating with the chitosan nanocomposite improved the mechanical hardness of the Al_2O_3 nanowires.

Electrical Network Monitor and Control System

An electric power monitoring system integrated with a smart electrical panel continuously monitors the use of electrical energy. It can control electrical loads automatically, record electricity usage, provide comprehensive reports, and analyze energy usage. Electrical monitoring and control systems receive data from nanosensors, biosensors, telemetry devices, actuators, and programming devices. This software decodes the electrical signals or telecommands to actuators, computer systems, and digital machines. It is then connected to a remote terminal unit (RTU). A remote terminal unit is a microprocessor-controlled electronic device that links an electrochemical signal to a distributed-control system. It is equipped with a supervisory control system and a data acquisition (SCADA).

Wireless Sensor Networks

Wireless sensor networks have the ability and capacity to manage and monitor sensitive information for different intelligent services such as electric power management systems. A wireless sensor network (WSN) is designed to detect threats and fault operations in electric systems and environmental monitoring. It can perform the functions of the sensors and actuators. A WSN system was implanted with a processing unit capable of collecting data regarding environmental conditions, such as moisture, humidity, temperature, and electrical signals. The station was equipped with the most sensitive magnetic nanomaterials, which were interconnected with the transceiver. It has nanorods composed of nano-processors, nano-memory, nano-batteries, nano-transceivers, nano-antennas, and nanosensors. These components perform data processing, signal storage, energy generation, signal collection, signal detection, and diagnostics. They can perform simple tasks, such as sensing, computing, and actuation. Therefore, every node is equipped with a wireless transceiver and must act as a router to process packets to their destination.

Wireless sensors are advantageous because they avoid contamination with electric wires and help remotely control current density fluctuations. Hence, it maintains steady power flow and is safe. This significantly contributes to energy security and sustainability. Wireless sensor networking management systems can manage and monitor intelligent activities such as power management and sensitive appliances. It can sense and detect electrical signals and frequencies, where data are wirelessly transferred to the ZigBee protocol and then to the ethernet shield. These data are then controlled by the Internet of Nanothings (IoNts).

Distribution Management System

A distribution management system (DMS) is a set of applications designed to monitor and control an electric power distribution network effectively. It acts as a voltage, electric current, and frequency regulator, similar to supercapacitors. DMS have significant functions in network connectivity analysis, switchable scheduling, voltage-level and reactive power control systems, and state control systems. It helps automation systems and rooms, and facilitates field operators to monitor and control electric distributions. The DMS also improves the reliability and quality of services by minimizing time and power consumption. This ensures power distribution, services, and safety management. Intelligent electronic devices (IED) integrated with microprocessors have been designed to control and automate services. Cloud-based power optimization and intelligent distribution systems have emerged as economical systems. As Ahmed Hadi Ali Jumailis et al. 2021 [27] presented a conceptual and systematic intelligent power management system based on cloud computing. Miniature circuit breakers, digital relays, transformers, and supercapacitors are specialized to perform this task. Currently, the Internet of Nanothings (IoNTs) is emerging as a means to perform this task. As Imad Hussaini Al Hussaini et al. 2019 [28] revealed, cutting-edge developments in sensors, transmissions, electricity storage systems, and power distribution management systems, such as the Internet of Nanothings (IoNts), provide reliable and flexible power saving and consumption.

By installing SCADA systems, we can establish a power distribution control system for monitoring and real-time system analysis. Finally, integrating appliance load monitoring (ALM) allows energy managers to obtain appliance-specific energy consumption data and statistics.

CONCLUSION

Al_2O_3 is studied from electrical and transport phenomenon. It exhibits a high dielectric constant and has been used for PH sensing. It was found that eddy current formation is favored by magnetic and electric field effects. However, the relationship between the electric current density and the other parameters was determined using the modified Green (MGK) theorem. Accordingly, time-varying electric and magnetic fields can produce an eddy current density that is directed in the transverse direction. This study revealed that the electric current density fluctuation was significantly caused by variations in the number of electrons as a function of the temperature gradient. It is also caused by electric charge carrier fluctuations due to surface absorption, surface passivation, electric polarization, and velocity retardation, which minimize electron mobility. Advanced electric power management systems are used to minimize electric power dissipation, which leads to energy loss due to electric current density fluctuations.

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