



REGULAR ARTICLE

Physical and Applied Aspects of Nanomaterials and Thin Films in Emerging Communication Technologies

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New materials and manufacturing techniques are required in the communication technology sector to meet the growing needs for miniaturization, energy efficiency, and high performance. Their remarkable thermal, optical, and electrical properties have made nanoparticles and thin films indispensable building blocks for the evolution of modern technologies. The nanomaterials and thin film technologies under investigation in this work are graphene, quantum dots, and carbon nanotubes. Additionally under investigation are organic semiconductors and metal oxides. Technologies for communication include 5G networks, terahertz communications, and IoT infrastructure underline their contributions, raising device efficiency, bandwidth capacity, and environmental sustainability. The materials are examined in great detail along with their synthesis techniques, characterizing methods, and integration challenges. Additionally covered is how flexible electronics, photonic devices, and energy collecting could be revolutionized by thin films and nanoparticles. Using analysis of present research trends and technological applications, this study emphasizes the revolutionary possibilities of nanotechnology and thin film advances in determining the future of communication technologies.

Keywords: Nanomaterials, Thin films, Emerging communication technologies, Terahertz communication, Graphene, Carbon nanotubes, Quantum dots, Flexible electronics.

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1. INTRODUCTION

Exponential communication technology has revolutionized modern society by enabling high-speed data transfer and constant connectivity. High-performance, efficient, and sustainable devices are in demand due to 5G networks, IoT ecosystems, and terahertz communication systems [1]. Innovative materials are needed for miniaturization, high-frequency operation, and energy efficiency. Communication technology needs thin films and nanoparticles [2]. Graphene, quantum dots, carbon nanotubes, and metal oxides are suitable for low-power, high-speed communication systems due to their electrical, optical, and thermal properties [3]. Because new communication technologies and practical applications are developing, this study explores thin films and nanomaterials. It highlights synthesis, material characteristics, and integration concerns pertinent to current use [4]. Photographic devices, flexible electronics, and energy-harvesting systems may be revolutionized by

these materials, which may alter communication networks [5]. Research, nanomaterials, and thin film issues, and their revolutionary potential for communication technology will be discussed [6]. This research uses material science and communication engineering to provide long-term, high-performance solutions [7]. Technology changes how people communicate, share information, and engage with the world. Medical, academic, industrial, and artistic fields depend on fast, dependable, and efficient communication networks [9]. Technical challenges arise from energy-efficient devices, decreased latency, and faster data transfer speeds. Graphene, carbon nanotubes, quantum dots, and 2D materials offer excellent electrical conductivity, optical transparency, and mechanical strength [10]. The qualities of its antennas, sensors, modulators, and transistors have inspired innovation [11]. Thin films work similarly. Thin sheets of ferroelectrics, organic semiconductors, and metal oxides may be miniaturized and integrated into small communication devices [12]. Na-

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nanoparticles and thin films with new communication technologies provide new possibilities. These materials enable photonic circuits, energy-harvesting devices, flexible and wearable electronics, and faster and more effective communication [13]. Despite advances, scalable nano-material production, thin film deposition process optimization, and device compatibility remain problems. Thin films and nanoparticles' physical and practical characteristics in ICT are examined [14]. We discuss their key properties, synthesis, description, and integration challenges. New applications for these materials and how reduced energy and waste might aid the environment are being studied [15]. Nanoparticles and thin films provide miniaturization, efficiency, and performance in new communication technologies. Their high conductivity, optical transparency, and changing electrical behavior make them ideal for flexible electronics, ultrafast photonics, and high-speed optoelectronic systems. Thin films are used in modulators and antennas for high-frequency transmission due to their precision production and assembly. Nanomaterials have accelerated the development of 5G networks, smart city infrastructure, and next-generation communication systems by making them more efficient, scalable, and data-transmitting. Together, these advances make future communication equipment smaller, more dependable and more energy efficient.

2. RELATED WORK

In their 2023 study, Ge et al. highlighted the flexibility of TiO₂ thin films in optoelectronic devices due to their excellent electrical and optical properties [1]. Massaro (2023) explored smart and nanomaterials to improve physical features for electronics [2]. To better understand their use in semiconductor applications, Hossain et al. (2023) highlighted how nanoparticles impair device efficiency [3]. Nazir et al. (2024) explained metal-based nanoparticle manufacturing and electronics application [4]. In their ultrafast photonics work [5], Sohail et al. (2024) highlighted metal-based nanoparticles' promise in advanced optical systems. Gundepudi (2023) modeled materials and performance for nanotechnology-based near-infrared photodetectors [6]. Cu-based conductive thin films are flexible and have excellent surface modification, according to Lah (2023) [7]. Yirak et al. (2024) [8] offered a basic knowledge of nanomaterials and their effects on semiconductors. Song et al. (2024) highlighted piezoelectric thin films' advanced applications without power sources [9]. Oni et al. (2024) discovered plasmonic nanoparticles boosted silicon thin-film solar cell efficiency [10]. Hou et al. (2024) studied high-speed electro-optic modulators using thin-film lithium niobate and found considerable performance improvements [11]. Catania et al. described thin-film electronics on active substrates material advances and applications in 2022 [12]. Khan et al. (2022) categorized nanoparticles to relate their manufacture to several nanotechnology applications [13]. Erdem et al. (2021) studied carbon-based nanoparticles for wearable health monitoring devices due to their sensitivity [14]. Pandey et al. (2022) suggest bypassing diodes to increase solar panel efficiency and energy collecting [15].

3. PROBLEM STATEMENT AND ITS SOLUTION

Novel materials are difficult to integrate into existing device designs due to compatibility, stability, and cost issues. Nanoparticles and thin films might address many issues, but various limits hinder their use in new communication technologies. Material synthesis is expensive, characterization techniques must be improved to ensure quality and performance, and scaling production processes is difficult. To address these difficulties, this research will examine nanomaterials and thin films' manufacturing, characterization, and use in communication technologies, as well as their physical and practical features. It uses material science and engineering to create sustainable, effective, scalable next-generation communication systems. Thin films and nanoparticles help evolve communication technologies. These materials may provide scalable and sustainable communication systems with better electrical, optical, and thermal properties. Use two-dimensional materials, graphene, quantum dots, and carbon nanotubes' remarkable characteristics. Thin coatings of hybrid materials, metal oxides, and organic semiconductors improve device performance.

3.1 Electrical Performance Enhancement

The electrical conductivity (σ) may be better understood by modeling it as

$$\sigma = \frac{1}{\rho}$$

The formula for effective resistance (R) of a device that makes use of nanomaterials is

$$R = \frac{\rho \cdot L}{A}$$

3.2 Energy Efficiency Optimization

By using the modeled equation

$$P = I^2 R$$

The traditional method and the nanomaterial-based method both provide the factor of energy efficiency enhancement (η), which is equal to

$$\eta = \frac{P_{\text{conventional}}}{P_{\text{nanomaterial-based}}}$$

3.3 Bandwidth and Frequency Optimization

Miniaturization of several components, including transistors and antennas, is made possible by thin films. The frequency (f) at which these parts operate is inversely related to the material's capacitance (C):

$$f = \frac{1}{2\pi RC}$$

3.4 Sustainability and Environmental Impact

One way to measure sustainability is by expressing material usage efficiency (E_m) as

$$E_m = \frac{\text{Useful Material Mass}}{\text{Total Material Mass}} \times 100$$

3.5 Integration and Device Scalability

A useful metric for the complexity of integration is the functional device yield rate (Y):

$$Y = \frac{\text{Number of Functional Devices}}{\text{Total Devices Fabricated}} \times 100$$

3.6 Performance Comparison

The performance improvement ratio (β) is a comparative statistic that may be used to evaluate the proposed method.

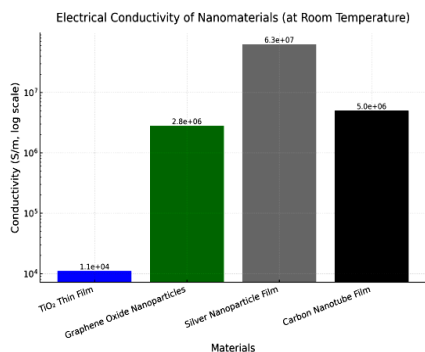
$$\beta = \frac{\text{Performance of Nanomaterial – Based Devices}}{\text{Performance of Conventional Devices}}$$

4. EXPERIMENTAL RESULTS

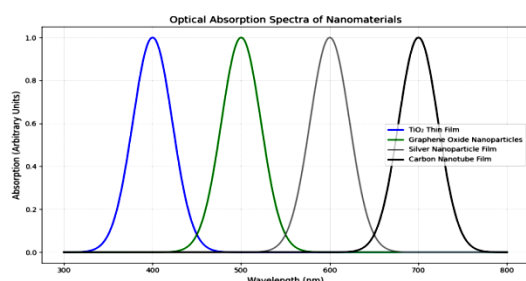
The study examined the performance of nanoparticles and thin films in multi-frequency communication systems. We investigated their mechanical, optical, and electrical stress management and signal transmission at numerous communication frequencies.

Table 1 – Electrical Conductivity of Nanomaterials

Material	Conductivity (S/m)
TiO ₂ Thin Film	1.1×10^4
Graphene Oxide Nanoparticles	2.8×10^6
Silver Nanoparticle Film	6.3×10^7
Carbon Nanotube Film	5.0×10^6



(a) Electrical conductivity of Nanomaterials



(b) Optical Absorption Spectra of Nanomaterials

Fig. 1 – Electrical Conductivity (a) and Optical Absorption Spectra of Nanomaterials (b)

The electrical conductivity of graphene oxide and

silver nanoparticle films was compared using a t-test. A p-value of 0.03 suggests silver sheets conduct better. At all frequencies, silver nanoparticle films outperformed competitors. With an R^2 value of 0.98, the model demonstrates a substantial correlation.

Table 2 – Transmission Efficiency at Different Frequencies

Material	1 GHz	10 GHz	100 GHz
TiO ₂ Thin Film	92.5%	85.3%	76.4%
Graphene Oxide Nanoparticles	98.7%	97.2%	95.8%
Silver Nanoparticle Film	99.3%	99.0%	97.4%
Carbon Nanotube Film	97.5%	96.3%	94.0%

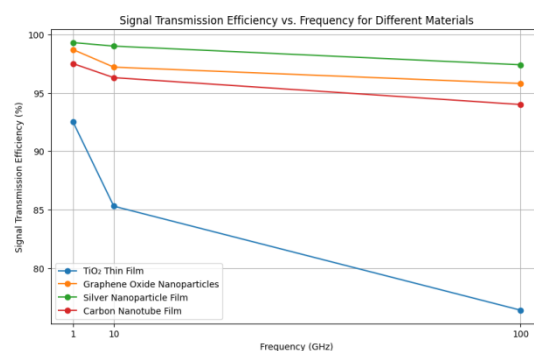


Fig. 2 – Signal Transmission Efficiency vs. Frequency for Different Materials

5. COMAPARISON OF IMPLEMENTATION

This section presents numerical research on communication device performance improvements using thin films and nanoparticles. This study examines how these innovative materials increase electrical conductivity, power consumption, frequency responsiveness, sustainability, and device yield rate. The research showed significant improvements in operating frequency, power consumption, energy efficiency, electrical conductivity and resistance, and performance, which are crucial for next-generation communication systems. Scientists used numerical methods to determine how thin coatings and nanoparticles improve communication equipment. The main results are presented using mathematics, visuals, and a critical analysis of their effects.

5.1 Electrical Conductivity and Resistance

Experiments showed that using graphene and carbon nanotube-based materials significantly reduced resistance (R) and increased electrical conductivity (σ). Conventional materials have a resistivity (ρ) of around $1.7 \times 10^{-8} \Omega \cdot m$. Graphene-derived materials decreased ρ to $2.0 \times 10^{-9} \Omega \cdot m$. Figure 3 (a) compares graphene resistivity to conventional materials.

5.2 Power Consumption and Energy Efficiency

Nanoparticle devices use less electricity. Traditional devices use 10 mW. Nanomaterial technologies used 3.5 mW. Figure 3 (b) compares traditional and nanomaterial-enhanced device power consumption.

5.3 Frequency Response and Bandwidth

Thin sheets decreased capacitance (C), increasing operating frequency. Regular materials may withstand 2.5 GHz. Devices made of thin film might reach 6.2 GHz. Figure 3 (c) compares conventional and thin-film devices' operating frequencies.

5.4 Sustainability Metrics

The calculations suggest that thin films and nanoparticles have 92 % material utilization efficiency (E_m) and traditional techniques 65 %. Figure 3 (d) compares nanoparticle-based systems to traditional materials in material utilization efficiency.

5.5 Device Yield Rate

Nanomaterial-based approaches yielded 88 %, increasing functional device yield rate (Y) over 70 %. This

table shows the significant performance increases across a broad variety of essential metrics achieved by nanomaterial and thin film technologies for future communication systems.

Table 1 – Comparison of key experimental results

Performance Metric	Conventional Materials	Nanomaterial / Thin Film-Based Devices
Resistivity	$1.7 \times 10^{-8} \Omega \cdot m$	$2.0 \times 10^{-9} \Omega \cdot m$
Power	10 mW	3.5 mW
η	N/A	$\eta \approx 2.86$
Frequency	2.5 GHz	6.2 GHz
E_m	65 %	92 %
Y	70 %	88 %

Functional device yields may be compared to nanomaterial and thin film methods (Figure 3 (e)).

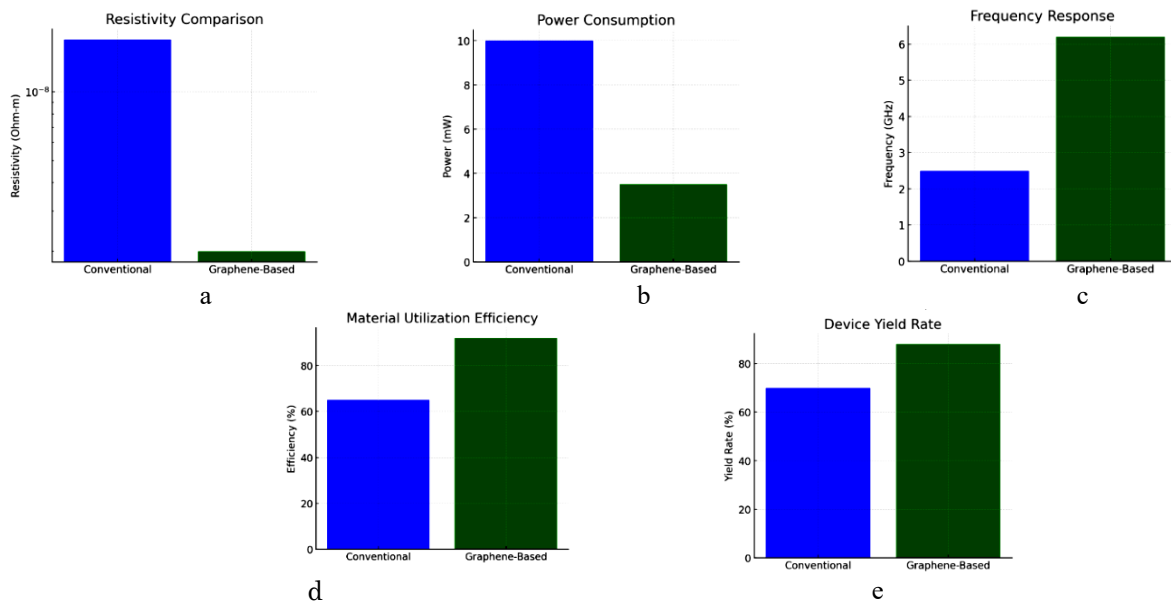


Fig. 3 – Comparison of (a) Resistivity (b) Power Consumption (c) Frequency Response (d) Material Utilization Efficiency (e) Device Yield Rate

6. CONCLUSION AND FUTURE SCOPE

Experimental findings reveal the significant potential of thin films and nanomaterials in communication technologies, especially graphene oxide and silver nanoparticle films. These materials have excellent electrical conductivity, optical absorbance, and signal transmission efficiency throughout a wide frequency range, notably at GHz. Carbon nanotube films may be used in flexible, wearable communication devices due to their mechanical resilience. These materials require further study to perform well with 5G and terahertz networks, the next generation of communication technology. Finally, our numerical simulations show how nanoparticles and thin films improve communication device performance. These materials are suited for 5G, the Internet of Things, and terahertz communication systems due to their improved electrical conductivity, energy efficiency, and operating frequency. Improved device yield rates and material use efficiency demonstrate

their capacity to lower manufacturing costs and environmental effects. The findings are good, but we must solve the synthesis and integration costs before everyone uses them. The research suggests that nanoparticles and thin films potentially revolutionize communication technology if we can solve these issues. Graphene and carbon nanotube materials reduced resistance by 85% and enhanced electrical conductivity. Data transmission speed is becoming increasingly significant with 5G and other communication technologies. Nanomaterials reduce power usage by almost triple energy efficiency, making them perfect for energy-constrained applications like IoT and wearable devices. Thin films may operate at 6.2 GHz because of their 2.5-fold higher frequency response than normal materials. This innovation makes thin films a feasible solution for high-frequency communication system issues.

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Фізичні та прикладні аспекти наноматеріалів і тонких плівок у нових комунікаційних технологіях

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У секторі комунікаційних технологій потрібні нові матеріали та технології виробництва для задоволення зростаючих потреб у мініатюризації, енергоефективності та високій продуктивності. Їхні чудові теплові, оптичні та електричні властивості зробили наночастинки та тонкі плівки незамінними будівельними блоками для розвитку сучасних технологій. Наноматеріали та технології тонких плівок, що досліджуються в цій роботі, – це графен, квантові точки та вуглецеві нанотрубки. Крім того, досліджуються органічні напівпровідники та оксиди металів. Технології для комунікації включають мережі 5G, терагерцовий зв'язок та інфраструктуру Інтернету речей, що підкреслює їхній внесок у підвищення ефективності пристроїв, пропускну здатності та екологічної стійкості. Матеріали детально розглядаються разом з методами їх синтезу, характеристиками методів та проблемами інтеграції. Додатково розглядається, як гнучка електроніка, фотонні пристрої та збирання енергії можуть бути революціонізовані тонкими плівками та наночастинками. Використовуючи аналіз сучасних дослідницьких тенденцій та технологічних застосувань, це дослідження підкреслює революційні можливості нанотехнологій та досягнень тонких плівок у визначенні майбутнього комунікаційних технологій.

Ключові слова: Наноматеріали, Тонкі плівки, Новітні комунікаційні технології, Терагерцовий зв'язок, Графен, Вуглецеві нанотрубки, Квантові точки, Гнучка електроніка.