

Nanotechnology in Modern Physics: Materials, Devices, and Applications

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Abstract

Nanotechnology has emerged as a transformative field within modern physics, enabling the manipulation and understanding of materials at scales between 1 and 100 nanometers. At these dimensions, classical physical laws often fail, giving way to quantum mechanical phenomena, size-dependent properties, and surface-dominated effects. This paper provides a comprehensive overview of nanomaterials, including zero, one, two, and three-dimensional systems, highlighting their unique electrical, optical, magnetic, and mechanical properties. Fundamental nanoscale physics, such as quantum confinement, ballistic transport, and enhanced surface interactions, is discussed to explain the deviations from bulk behavior. The role of nanotechnology in device applications is examined through nanoelectronic devices like Single Electron Transistors and MOSFETs, nanosensors, and optoelectronic components, demonstrating how quantum effects and nanoscale interactions influence performance. Additionally, the paper explores the integration of nanomaterials in energy systems, including nanostructured solar cells, lithium-ion batteries, and supercapacitors, as well as in medical and biological applications such as targeted drug delivery, nanoparticle-based imaging, and biosensing. Environmental and space applications are also addressed, emphasizing the importance of nanostructures in pollution detection, lightweight composites, and radiation-resistant materials. Experimental techniques, including Scanning Tunneling Microscopy, Atomic Force Microscopy, electron microscopy, and spectroscopic characterization, are discussed for their essential role in analyzing nanomaterials and validating theoretical models. Overall, this paper highlights the interplay between nanoscale physics, material properties, and practical applications, providing a detailed understanding of the capabilities of nanotechnology in modern physics.

Keywords: Nanotechnology, Nanomaterials, Quantum Confinement, Nanoelectronics, Nanosensors, Optoelectronic Devices, Scanning Probe Microscopy

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1. Introduction

Nanotechnology is a science and engineering discipline that revolves around the creation and use of materials and devices that have at least one dimension between 1 and 100 nanometers. Materials at such a minuscule scale possess physical and chemical properties that are quite different from those of the same materials in the bulk form. The primary reason for these differences is quantum mechanical effects and also the significance of surface, related phenomena, which makes nanotechnology a very important area in modern physics. The fast, paced development of nanotechnology has been the main reason behind the rise of nanophysics as a very important sub, discipline of modern physics. Nanophysics is mainly concerned with the behavior of matter at the nanoscale, a region where the classical theories fail to provide an accurate description of physical phenomena most of the time. The progress in such experimental instruments as scanning tunneling microscopy (STM) and atomic force microscopy (AFM) has led to the ability to see and manipulate individual atoms and nanostructures, which means that physics has become even more important in nanoscale research [1-2].

Many of the assumptions of classical physics fail at the nanoscale. In bulk materials, properties such as electrical conductivity, thermal behavior, and optical response are mainly size, independent. Still, if the size of a material is comparable to the de Broglie wavelength of electrons, quantum effects like energy level quantization, electron tunneling, and wave, particle duality become dominant. Therefore, classical models based on continuous energy bands and diffusive transport cannot be used anymore. The change from bulk materials to nanostructured materials is a fundamental shift in material behavior. Nanostructures such as quantum dots, nanowires, and two, dimensional materials show size, dependent properties, high surface, to, volume ratios, and enhanced reactivity. These features allow the creation of highly efficient nano, devices whose performance is better than that of the conventional systems. This paper discusses nanotechnology based on physics, focusing on nanomaterials, nano devices, and their applications. It explores the fundamental physical principles that dictate behavior at the nanoscale, the impact of quantum mechanics on material properties, and the importance of nanotechnology for advancements in physics [3].

2. Fundamental Physics at the Nanoscale

2.1 Size Effects and Surface Dominance

When the size of a material drops to the nanometer scale, its behavior is influenced by surface properties as well as bulk properties. One major result of this reduction in size is the significant rise in the surface-to-volume ratio. In bulk materials, most atoms are found inside the material and experience balanced forces. In nanostructures, however, a large number of atoms are at or near the surface. These surface atoms have unsatisfied bonds and higher surface energy. This prevalence of surface atoms causes the creation of surface states, which have a strong impact on the electronic, thermal, and mechanical behavior of nanomaterials. Surface energy becomes a key factor in the system's total energy, influencing stability, reactivity, and phase changes. Consequently, nanomaterials often display greater chemical activity and different melting points compared to larger counterparts. The increased scattering at the nanoscale also significantly affects electrical and thermal transport. Electrons and phonons are scattered more often by surface imperfections, which lowers conductivity and changes thermal behavior based on size. From a mechanical standpoint, nanomaterials frequently show greater strength and hardness because the chance of internal defects is lower, and the mechanisms for deformation differ from those found in bulk materials. Table 1 provides a comparison of how physical properties shift when moving from bulk to nanoscale systems, emphasizing the key role of surface effects in nanomaterials.

Table 1- Comparison of Physical Properties in Bulk and Nanoscale Materials

Property	Bulk Materials	Nanoscale Materials
Surface-to-volume ratio	Very low	Extremely high
Dominant forces	Volume (bulk) forces	Surface and interfacial forces
Surface energy contribution	Negligible	Significant
Thermal conductivity	Size-independent	Strongly size-dependent
Electrical conductivity	Governed by classical models	Influenced by surface scattering
Mechanical strength	Limited by defects	Enhanced due to fewer defects
Chemical reactivity	Low	High

2.2 Quantum Mechanical Effects

At the nanoscale, classical physics gives way to quantum mechanical descriptions. One of the most notable quantum effects seen in nanostructures is quantum confinement. This occurs when charge carriers, like electrons, are confined in one or more dimensions. As the system size approaches the electron's de Broglie wavelength, energy levels become discrete instead of continuous. This confinement alters energy bands, leading to different electronic and optical properties based on size. For instance, in quantum dots, the band gap widens as the particle size shrinks, causing shifts in absorption and emission spectra. This behavior contrasts with bulk semiconductors, where energy bands remain constant [4]. Another significant effect of quantum confinement is the change in the density of states. In bulk materials, the density of states is continuous, but in nanostructures, it becomes discrete or sharply peaked, depending on the dimensions. This change directly impacts electrical conductivity, optical transitions, and carrier dynamics. Additionally, electron tunneling becomes significant at the nanoscale. Electrons can pass through potential barriers that would be impossible in classical physics. This enables the functioning of devices like tunneling diodes and single-electron transistors. These phenomena illustrate the wave-particle duality of matter and show why quantum mechanics is essential for accurately describing nanoscale systems [5].

2.3 Breakdown of Classical Models

As device sizes approach the nanoscale, many classical transport models struggle to provide reliable predictions. A notable example is the limited accuracy of Ohm's law. In bulk conductors, electrical resistance arises from frequent electron scattering, and current flow follows diffusive patterns. However, in nanoscale conductors, electrons can move through the material with minimal scattering. This behavior is called ballistic transport, where electrons travel coherently over distances comparable to the length of the device. In these situations, resistance is influenced not only by material resistivity but also by contact resistance and quantum effects. The mean free path concept is crucial for understanding this shift. When the size of the device is similar to or smaller than the electron mean free path, classical assumptions begin to fail. Transport behavior becomes non-local, and quantum models are necessary for accurately describing carrier movement [6].

3. Nanomaterials: Structure and Physical Properties

Nanomaterials are the core of nanotechnology and are crucial in modern physics because of their unique behavior based on size. At the nanoscale, the structure of materials significantly affects their electronic, optical, magnetic, and mechanical properties. These changes come from quantum confinement, surface effects, and reduced dimensionality, which don't occur in bulk materials. Based on their dimensional features, nanomaterials can be classified into zero, one, and two-dimensional systems, each showing distinct physical phenomena.

3.1 Classification of Nanomaterials

Zero-dimensional (0D) nanomaterials are structures where all three spatial dimensions are confined to the nanoscale range. Examples include quantum dots and nanoparticles. Because of complete spatial confinement, electrons in these materials occupy discrete energy levels similar to atoms, which gives them atom-like electronic behavior. Quantum dots, in particular, have strong size-dependent optical and electronic properties, making them important in optoelectronic and photonic applications.

One-dimensional (1D) nanomaterials, such as nanowires and carbon nanotubes, are confined in two dimensions while extending along one axis. This structure allows directional charge transport and better electrical conductivity. Carbon nanotubes have outstanding electrical and mechanical properties thanks to their unique cylindrical graphene structure and quantum transport effects.

Two-dimensional (2D) nanomaterials, which include graphene and thin films, are confined in just one dimension. Graphene, consisting of a single layer of carbon atoms arranged in a hexagonal lattice, displays impressive features like high carrier mobility, mechanical strength, and a unique electronic band structure identified by Dirac cones[7]. Thin films are commonly used in electronic, optical, and magnetic devices because their thickness and surface properties can be adjusted.

Three-dimensional (3D) nanomaterials are materials with tiny structures that extend in all three dimensions. They create interconnected or bulk-like forms. Examples include nanocomposites, nanoporous materials, and hierarchical nanostructures. Unlike low-dimensional systems, 3D nanomaterials do not have strong quantum effects in all directions. However, their properties are greatly affected by the nanoscale building blocks and internal interfaces. The many grain boundaries, pores, and interfaces increase surface-related effects while keeping structural stability. These materials combine the benefits of tiny functionality with larger forms. This leads to better mechanical strength, thermal stability, and electrical performance. Three-dimensional nanomaterials are commonly used in energy storage devices, catalysis, sensors, and structural applications. These areas rely on high surface area and efficient charge or mass transport Fig.1 [8].

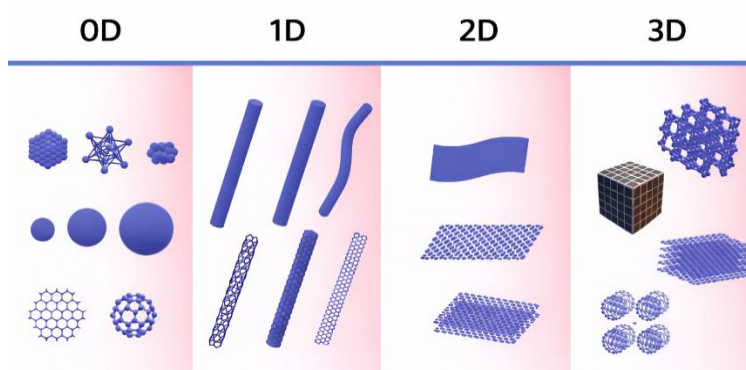


Figure-1 Classification of nanomaterials based on dimensionality, including zero, one, and two-dimensional nanostructures.

3.2 Electrical Properties

The electrical conductivity of nanomaterials strongly depends on size, shape, and dimensionality. As a material's dimensions decrease, electron scattering at surfaces and interfaces becomes more significant, causing variations from traditional conduction models. In some nanostructures, reduced scattering allows for near-ballistic transport, which improves conductivity.

In two-dimensional systems subjected to strong magnetic fields, effects like the quantum Hall effect can be seen. This effect comes from the quantization of electron motion into Landau levels and shows clear evidence of quantum behavior in nanoscale systems. Charge carrier mobility in nanomaterials is affected by confinement effects, defects, and surface interactions. Materials like graphene have extremely high carrier mobility due to minimal scattering and linear energy dispersion, making them strong candidates for new electronic devices.

3.3 Optical Properties

Nanomaterials have special optical properties due to their interaction with electromagnetic radiation at the nanoscale. One key phenomenon is surface plasmon resonance (SPR), which occurs in metallic nanoparticles. SPR happens when conduction electrons collectively oscillate in response to light, leading to strong absorption and scattering at certain wavelengths. Another important aspect is size-dependent absorption and emission, particularly in semiconductor nanostructures. As the particle size decreases, the effective band gap increases due to quantum confinement, causing changes in optical spectra. Photoluminescence in quantum dots directly results from electron-hole recombination across discrete energy levels. The emission wavelength can be precisely controlled by altering the size of the quantum dots, making them very useful in displays, lasers, and bio-imaging applications [9].

3.4 Magnetic and Mechanical Properties

At the nanoscale, magnetic behavior changes significantly. Many magnetic nanoparticles show superparamagnetism, a state where thermal energy is enough to randomly flip magnetic moments, preventing permanent magnetization without an external field. This property is particularly useful in data storage and biomedical applications. From a mechanical standpoint, nanomaterials usually show increased strength and hardness compared to bulk materials. The reduction in structural defects and the presence of surface atoms lead to better load distribution and resistance to deformation. Carbon nanotubes and graphene stand out, showing exceptional tensile strength and elasticity.

4. Nano-Devices and Their Physical Working Principles

Nano-devices bring nanophysics to life. Here, quantum mechanical effects and size-dependent transport phenomena directly impact how devices work. When device sizes reach the nanometer scale, traditional electrical models fall short. Quantum transport, tunneling, and surface interactions take center stage. Nano-devices provide better performance, lower power use, and greater sensitivity compared to standard devices. This makes them crucial in today's technology.

4.1 Nanoelectronic Devices

One key nanoelectronic device is the Single Electron Transistor (SET). It functions through controlled electron tunneling across a tiny island. In SETs, adding or removing a single electron greatly changes the electrostatic energy of the system. This is known as the Coulomb blockade. This effect stands out when the charging energy surpasses thermal energy, allowing precise control over current at the single-electron level. SETs represent the pinnacle of electronic miniaturization and clearly show the impact of quantum effects in nanoscale circuits. As traditional MOSFETs shrink to nanometer sizes, they face fundamental physical challenges like short-channel effects, higher leakage current, and gate-oxide tunneling. These issues emerge as the gate gradually loses effective electrostatic control over the channel. This leads to poorer device performance and reliability. At these small sizes, the quantum mechanical tunneling of charge carriers through ultra-thin insulating layers becomes inevitable. This pushes the need for new device

designs, high-k dielectric materials, and innovative channel materials [10]. At the nanoscale, ballistic and quantum transport mainly dictate electron movement. When the channel length is similar to the electron mean free path, electrons can move through the channel with little scattering. This leads to ballistic transport. In this scenario, electrical resistance isn't determined by bulk resistivity but by quantum conductance and contact resistance. The shift from diffusive to ballistic transport is shown in Figure 2. It depicts how electrical conductance changes with channel length, highlighting the clear move away from classical transport models as device sizes decrease.

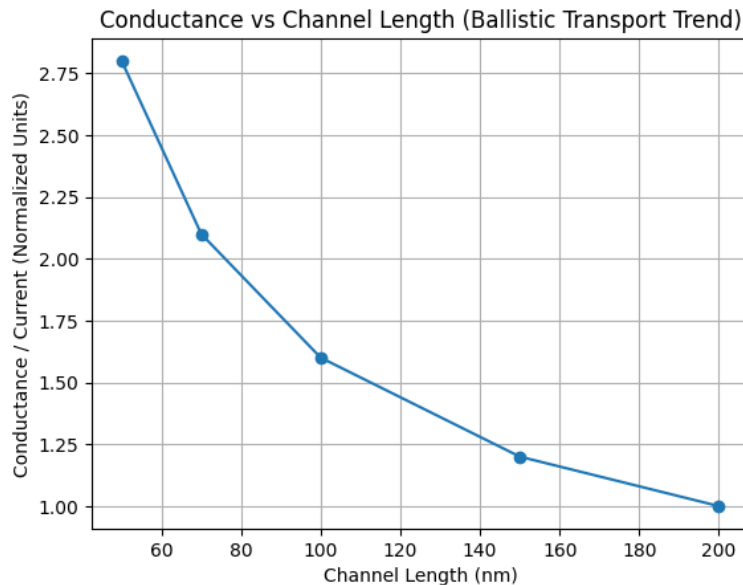


Figure-2 Variation of electrical conductance with channel length in nanoelectronic devices, illustrating the transition from diffusive to ballistic transport.

4.2 Nanosensors and Detectors

Nanosensors take advantage of the high surface-to-volume ratio of nanomaterials for outstanding sensitivity. Many atoms are on the surface, so even minor physical or chemical changes in the environment can lead to noticeable shifts in electrical or optical signals. This makes nanosensors very effective for detecting gases, biological molecules, temperature, and mechanical strain. Nanosensors primarily use electrical or optical sensing mechanisms. In electrical nanosensors, the adsorption of molecules on the sensor's surface changes the concentration of charge carriers or resistance. In contrast, optical nanosensors depend on changes in absorption, emission, or refractive index. These sensing methods come from fundamental interactions between matter and electromagnetic fields at the nanoscale, making nanosensors a significant application of modern physics [11].

4.3 Optoelectronic and Photonic Devices

Nanotechnology has greatly improved optoelectronic and photonic devices by allowing precise control over light and matter interactions. Quantum dot lasers are a key example. The discrete energy levels in quantum dots lead to lower threshold currents, better temperature stability, and tunable emission wavelengths. These characteristics stem directly from quantum confinement effects.

Photodetectors made from nanomaterials show better responsivity due to higher absorption and effective charge separation. Engineers can design nanostructured photodetectors to respond selectively to specific

wavelengths, enhancing their performance in imaging and communication systems. Plasmonic devices take advantage of surface plasmons, which are collective oscillations of conduction electrons at metal and dielectric interfaces. This helps confine electromagnetic energy below the diffraction limit, creating strong field enhancement. It enables ultra-compact photonic components for use in sensing, spectroscopy, and nano-optics.

5. Applications of Nanotechnology in Modern Physics

Nanotechnology has greatly expanded how modern physics applies by allowing precise control over material properties at atomic and molecular levels. The distinct electrical, optical, and magnetic behaviors of nanostructured materials come from quantum confinement, surface effects, and stronger interfacial interactions. These properties have been effectively used in energy systems, medical physics, environmental monitoring, and space technologies, where traditional materials often struggle to perform well.

5.1 Energy and Power Systems

Nanotechnology is crucial for making solar energy conversion more efficient through nanostructured solar cells. The use of quantum dots, nanowires, and thin-film nanostructures improves light absorption by increasing the effective optical path length and allowing for band-gap engineering. Quantum confinement helps tune absorption spectra to match the solar spectrum better, while reduced recombination losses aid charge carrier collection. These advances are based on semiconductor physics and the interaction of light and matter at the nanoscale.

In lithium-ion batteries, nanomaterials enhance energy density, charging speed, and cycle life. Nanostructured electrode materials provide shorter diffusion paths for lithium ions, leading to faster charge transport and better electrochemical performance. Increased surface area also improves the interaction between the electrode and electrolyte, enhancing energy storage efficiency. The boost in performance relates closely to nanoscale charge transport, interfacial physics, and ion diffusion mechanisms.

Supercapacitors gain from nanotechnology through nanoporous carbon materials, graphene, and metal oxide nanostructures. These materials provide very high surface area and better electrical conductivity, enabling quick charge accumulation and release. The physical principles at work include electrostatic charge storage, quantum capacitance effects, and surface-controlled charge dynamics, which help supercapacitors function between standard capacitors and batteries [12].

5.2 Medical and Biological Physics

In medical and biological physics, nanotechnology has led to major progress in imaging and diagnostics. Nanoparticle-based imaging agents enhance contrast in techniques like magnetic resonance imaging (MRI), optical imaging, and computed tomography. How nanomaterials interact with electromagnetic radiation and magnetic fields improves signal sensitivity and spatial resolution, offering more accurate diagnostic information at the cellular level.

Targeted drug delivery systems use nanocarriers such as liposomes, polymeric nanoparticles, and magnetic nanoparticles to deliver therapeutic agents directly to specific locations in the body. The physics of diffusion, surface functionalization, and external field manipulation are crucial for controlling drug release mechanisms. By minimizing interaction with healthy tissues, these systems boost treatment efficiency and cut down on side effects.

Biosensing applications take advantage of the high sensitivity of nanostructured sensors to identify biological molecules at very low concentrations. Changes in electrical resistance, optical response, or magnetic properties during molecular binding serve as measurable signals. These sensing mechanisms follow fundamental principles of surface physics, charge transfer, and light-matter interaction[13-14].

5.3 Environmental and Space Applications

Nanotechnology provides effective solutions for environmental monitoring and pollution detection. Nanomaterial-based sensors can identify tiny amounts of pollutants, toxic gases, and heavy metals with high accuracy. This enhanced sensitivity comes from strong surface adsorption and efficient conversion of physical signals into measurable outputs, making these systems excellent for real-time environmental analysis.

In space applications, nanotechnology aids in creating radiation-resistant materials that can endure extreme cosmic environments. Nanostructured coatings and composites increase resistance to radiation-induced damage by limiting defect propagation and improving material stability. These effects tie closely to nanoscale defect physics and energy dissipation mechanisms.

Lightweight nanocomposites are widely used in aerospace structures due to their high strength-to-weight ratio and thermal stability. By reinforcing traditional materials with nanoscale fillers, mechanical strength improves significantly without adding weight. The better performance of these materials relates to interfacial bonding, stress transfer, and nanoscale mechanical behavior, making them suitable for advanced space and defense technologies [15].

6. Experimental Techniques in Nanophysics

Experimental characterization is crucial in nanophysics. Understanding behavior at the nanoscale requires precise measurement tools that can resolve atomic and molecular structures. At this scale, numerous physical phenomena, including quantum effects and surface-dominated interactions, cannot be directly inferred from the properties of bulk materials. Specialized methods like scanning probe microscopy, electron microscopy, and spectroscopic analysis are essential for examining surface morphology, electronic states, structural composition, and interfacial interactions in nanomaterials. They provide a direct connection between theoretical predictions and actual behavior.

Scanning Tunneling Microscopy (STM) is one of the key tools for investigating conductive and semi-conductive surfaces at the atomic level. STM works on the principle of quantum mechanical tunneling. A current flows between a sharp metallic tip and the sample when they are only a few angstroms apart. The amount of tunneling current depends highly on the distance between the tip and the surface, enabling the creation of atomic-resolution topographic maps. In addition to imaging, STM can measure the local density of electronic states. This gives insight into surface reconstructions, atomic defects, and energy states. By using different modes, such as constant current or constant height, STM allows researchers to study the physical and electronic landscape of nanostructures. It helps confirm quantum mechanical models of electron behavior at the nanoscale[16-17].

Atomic Force Microscopy (AFM) complements STM by enabling high-resolution imaging of both conductive and insulating materials. AFM works by sensing the forces between a sharp tip attached to a cantilever and the sample's surface. The deflection of the cantilever, detected through optical or piezoelectric methods, gives precise information about surface topography, mechanical stiffness, adhesion, and even magnetic or electrical properties. AFM can operate in contact, non-contact, or tapping modes. Each mode provides

unique insights into the surface and mechanical characteristics of the sample. This flexibility makes AFM especially valuable for studying polymers, biomaterials, and nanostructured thin films, where both structural and force-based information matter.

Electron microscopy, which includes Scanning Electron Microscopy (SEM) and Transmission Electron Microscopy (TEM), offers complementary ways to visualize at the nanoscale. SEM images are produced by detecting secondary or backscattered electrons emitted from the sample's surface. This reveals detailed surface morphology and composition with nanometer resolution. TEM allows for atomic-level imaging by transmitting electrons through ultra-thin specimens. It captures internal structures, crystal lattices, and defects, while electron diffraction provides information about crystallography. Both SEM and TEM rely on precise electron-matter interactions and are fundamental for verifying nanoscale architectures, defects, and material composition. They offer direct visualization of quantum and surface-dominated phenomena [18].

Spectroscopic techniques are essential for examining the electronic, optical, and chemical properties of nanomaterials. Methods like Raman spectroscopy, UV-Visible absorption, and X-ray photoelectron spectroscopy (XPS) reveal vibrational modes, band gaps, and surface chemistry. These analyses allow researchers to quantify electronic transitions, phonon behaviors, and chemical states. They connect the performance of macroscopic devices to nanoscale physical properties. Combining spectroscopic and microscopic methods provides a thorough understanding of nanomaterials. This knowledge guides their design and use in nano-devices, sensors, and optoelectronic systems [19-20].

7. Conclusion

Nanotechnology has changed the field of modern physics by allowing precise control and understanding of materials at the atomic and nanoscale levels. At these scales, classical physical laws often give way to quantum phenomena, surface effects, and size-dependent properties, leading to new behaviors in materials. By studying zero-, one-, two-, and three-dimensional nanomaterials, researchers have discovered unique electrical, optical, magnetic, and mechanical properties that differ from their larger counterparts. Quantum confinement, ballistic transport, and improved surface interactions have enabled the creation of nanoelectronic devices, nanosensors, and advanced optoelectronic systems, pushing the limits of performance, sensitivity, and efficiency. The use of nanomaterials in energy, biomedical, environmental, and space applications demonstrates their significant potential. Nanostructured solar cells, lithium-ion batteries, and supercapacitors show better energy efficiency and storage capacity due to nanoscale charge transport and surface interactions. In medical physics, nanoparticle-based imaging, targeted drug delivery, and biosensing provide higher precision, increased sensitivity, and fewer side effects. Environmental monitoring and space technologies also benefit from nanotechnology through lightweight, strong composites, radiation-resistant materials, and highly sensitive pollutant detection systems. Experimental techniques such as Scanning Tunneling Microscopy, Atomic Force Microscopy, electron microscopy, and spectroscopic characterization have been essential in revealing the structural, electronic, and optical properties of nanomaterials. These techniques validate theoretical models and help design and improve nanodevices with exceptional control and accuracy. In conclusion, nanotechnology connects fundamental physics and practical applications, allowing the exploration of phenomena that were once out of reach. By leveraging the unique properties of nanomaterials and using advanced experimental methods, modern physics can keep pushing technological boundaries, creating new opportunities in energy, medicine, electronics, and more. The study of nanotechnology illustrates both the predictive power of physics and a path to innovations that can greatly affect science and society.

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9.Conflict of Interest

The authors declare that there are no conflicts of interest associated with this article.

10.Funding

No funding was received to support this study.