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Research Article

Infrared Absorption Study of Bonding and Lattice Vibrations in the Cu_2NiTe_2 Chalcogenide Semiconductor

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Abstract

Cu_2NiTe_2 was synthesized, and its crystal lattice and vibrational behavior were investigated in this study. As a consequence, the structural analysis demonstrated a hexagonal arrangement assigned to the space group $P6_3/mmc$, consistent with hexagonal symmetry. Atomic motions were examined using infrared spectroscopy and interpreted spectroscopically. Six dominant absorption maxima appeared distinctly within the 400-4000 cm^{-1} region. These features are primarily linked to the vibrations of metal chalcogen bonds, as described chemically.

Keywords: vibrational properties, infrared spectroscopy, Cu_2NiTe_2, chalcogenide, crystal structure

1. Introduction

Chalcogenide semiconductors are widely used in various electronic technologies. Their usefulness comes from their ability to conduct electricity well and their strong interactions with light, both in terms of electricity and optics [1]. These components are used in many different types of sensors and transducers [2]. Therefore, they remain a popular and active area of research in materials science [3]. With improvements in experimental techniques and modeling, we can now more reliably determine necessary parameters [4]. Therefore, a thorough study of their structural, electrical, and optical properties using modern analytical methods is crucial [5].

Among these materials, the Cu_2NiX_2 (where X is S, Se, or Te) compounds are particularly remarkable. These crystals always exhibit copper in a monovalent state, while nickel is always in a divalent state. The lattice structure is characterized by a highly symmetric hexagonal arrangement, which reflects hexagonal symmetry. This symmetry contributes to a relatively stable structure, both physically and chemically. Differential scanning calorimetry and thermogravimetric results indicate no phase transitions at elevated temperatures, thermally. The release of gas molecules from the sample explains the observed thermoelectric effects [6], [7], [8]. It has been established that these chalcogenides can also serve as model objects for studying thermodynamic functions.

There are many methods for studying crystal lattice vibrations. These methods allow one to study lattice vibrations both theoretically and experimentally. Among the research methods, Raman spectroscopy and infrared (IR) spectroscopy occupy a special place. The applicability of these methods changes depending on the chemical composition and shape of the sample. Since Raman spectroscopy is quite sensitive, it is also used to determine phase transitions [9], [10], [11], [12]. Infrared spectroscopy is one of the most widely used analytical methods for studying solids. It has been established that this method is one of the unique methods for studying the vibration modes of interatomic bonds, determining the properties of the atoms that make up the sample, and the nature of the bonds.

Therefore, various studies are being conducted in the direction of studying functional materials using infrared spectroscopy [13], [14], [15]. Although many physicochemical properties of chalcogenide semiconductors, Cu_2NiX_2 studied using infrared spectroscopy.

In this work, Cu_2NiTe_2 has been studied, their atomic dynamics have not been crystal was synthesized, and its crystal structure and atomic dynamics at room temperature were studied. The research utilized X-ray diffraction (XRD) and infrared spectroscopy (FTIR), which are considered modern analytical methods. The results were analyzed using state-of-the-art software.

2. Materials and Methods

2.1. Synthesis of Samples

The Cu_2NiTe_2 compound was synthesized using a standard method typical for chalcogenide semiconductors. To prevent oxidation during the reaction, the synthesis process was carried out under closed conditions (high vacuum). In a single-zone furnace, the chemical elements of copper, nickel, and tellurium, deposited according to the stoichiometric composition, were collected in a quartz ampoule. The ampoule was reduced to approximately 10^{-4} mmHg, and it was subsequently closed. Following this, the ampoule's temperature was maintained at 300°C, and it was introduced into the furnace. After a one-hour hold, the furnace temperature was gradually increased. The program included 30-minute holds at 800, 900, and 1000°C, in sequence, within the range of 700-1050°C. To achieve uniformity, the closed ampoule was periodically stirred together in the furnace. Afterward, the temperature was adjusted to 50°C and maintained for 1.5 hours steadily. In the next step, the temperature was gradually reduced to T = 600°C. After holding at the homogenization temperature for 3 days, the process was stopped. After the synthesis process was complete, samples were prepared for structural and atomic dynamics studies.

2.2. Study of Crystal Structure

The crystal structure of the Cu_2NiTe_2 compound was studied using X-ray diffraction. The studies were conducted on a D8 ADVANCE diffractometer (Bruker, Germany). The diffractometer parameters are 40 kV, 40 mA, Cu Kα radiation, and λ is 1.5406 Å. A polycrystalline Cu 2 sample was first crushed and ground into powder. An X-ray spectrum of the powder sample was then obtained. The X-ray diffraction spectrum, obtained at room temperature, was analyzed using the Rietveld method in Mag2Pol software. It was established that the sample was obtained in a single-phase state with a highly symmetric hexagonal crystal structure.

2.3. Study of Vibrational Properties

The atomic dynamics (vibrational properties) of the Cu_2NiTe_2 compound were studied at room temperature using infrared spectroscopy. The samples for Fourier-transform infrared experiments were prepared in a cylindrical form with a diameter of 7 mm and a length of 1 mm at a pressure of P is 0.5 kN/cm^2 Cu_2NiTe_2 by using a press machine. The infrared spectra of the samples were analyzed within the wave number range of 400-4000 cm^{-1} by using the Varian 640 FTIR device. The obtained spectrum was analyzed, the modes corresponding to the lattice vibrations were determined, and the atomic dynamics of the Cu_2NiTe_2 were studied using the wave numbers of these modes.

3. Results and Discussion

3.1. Structural Properties

The crystal structure of the Cu_2NiTe_2 compound, synthesized in polycrystalline form, was studied using X-ray diffraction. The spectrum, obtained at room temperature and under normal conditions, was analyzed using the Rietveld method in the Mag2Pol program. During the spectrum analysis, it was determined that the crystal structure of the Cu_2NiTe_2 compound corresponds to hexagonal symmetry with the space group $P6_3/mmc$. The lattice parameters were determined to be a = b = 3.944 Å, c = 17.138 Å. As can be seen, when monovalent copper and divalent nickel atoms combine with tellurium chalcogenide atoms with the formation of covalent bonds, a single-phase, highly symmetric system is formed. Such systems are stable under external influences (temperature, pressure, radiation, etc.). However, under external influences, internal fluctuations may occur. Therefore, when studying the structural aspects of such systems, lattice vibrations, atomic dynamics, and bond characteristics should be studied.

3.2. Vibrational Properties

Based on the above, the atomic dynamics of the Cu_2NiTe_2 semiconductor compound were studied using infrared spectroscopy. The infrared spectrum, obtained under normal conditions at room temperature, in the wavelength range of 400-4000 cm^{-1}, is shown in Figure 1.

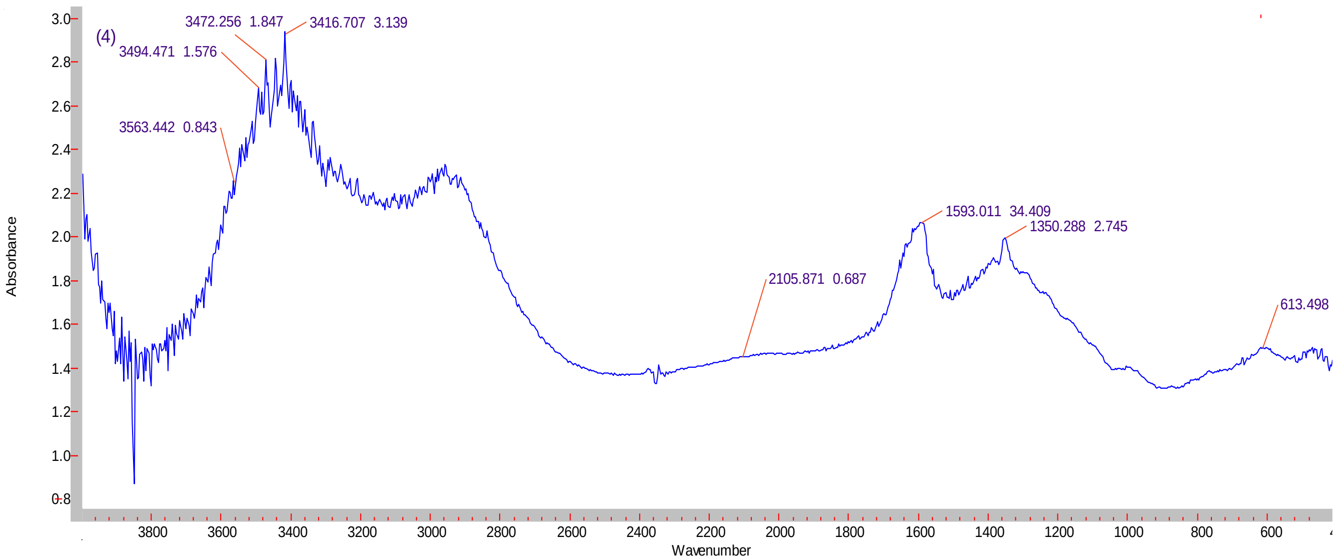

Figure 1. Infrared spectrum of Cu_2NiTe_2 crystal.

The spectrum shown in Figure 1 shows the infrared spectrum of the Cu_2NiTe_2 crystal in the wavenumber range. These peaks correspond to wavenumbers of approximately 500, 600, 1300, 1600, 3000, and 3400 cm^{-1}. These values correspond to vibrations of the bonds formed by metal atoms with chalcogen atoms. When the crystal lattice consists of atoms of heavy elements, the lattice vibration frequencies are low. Examples of such atoms include atoms of metals such as Tl and Pb. The frequencies of the bonds they form are low. However, when light elements such as H, Li, and O enter the crystal, the bond frequencies become higher. Since the atoms that form the Cu_2NiTe_2 crystal are not heavy elements, the frequencies of the vibrational modes observed in the infrared spectrum are quite high. As can be seen from the wavenumbers observed in the spectrum, the intensity of the observed peaks increases with increasing wavenumbers.

The infrared spectrum of Cu_2NiTe_2 indicates a vibrationally active lattice dynamically. When these spectral features are compared with crystallographic results, the Cu–Ni–Te framework is confirmed as highly symmetric and robust, structurally. This high symmetry supports stability against external perturbations, mechanically. As a result, no high-temperature phase transitions are expected for this system, consistently [7].

4. Conclusion

The structure and lattice motions of Cu_2NiTe_2 were examined using modern analytical approaches, systematically. The results show that the Cu–Ni–Te framework behaves as a highly symmetric, vibrationally active system, dynamically. Infrared measurements identified six dominant bands across the 400-4000 cm^{-1} region, clearly. These bands are attributed mainly to vibrations associated with metal-chalcogen bonding, chemically.

Comparison with related chalcogenide semiconductors indicates Cu_2NiTe_2 remains resilient to external disturbances because of its robust symmetry and lattice dynamics.

Author Contributions

All authors reviewed, edited, and approved the manuscript.

Conflict of Interest

The authors declare no conflicts of interest.

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Data Availability Statement

All the data analyzed in this study are included in this published article.

Abbreviations

Nickel Telluride Copper (Cu_2NiTe_2), Sulphur (S), Selenium (Se), Tellurium (Te), Infrared (IR), X-ray Diffraction (XRD), Fourier Transform Infrared Spectroscopy (FTIR), Thallium (Tl), Plumbum (Pb), Copper-Nickel-Titanium (Cu–Ni–Te).

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Journal of Nanotechnology and Innovative Materials

Review Article

Medical Applications of Nanotechnology and Biomaterials

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Abstract

In the present era, biomaterials are defined as substances of natural, synthetic, or composite origin that are used to replace, regenerate, and support tissues that have lost their functional activity or have been damaged. The primary criterion for the efficacy of these materials is their high biocompatibility, defined as their capacity to induce minimal adverse reactions within the body. Despite the long-standing utilization of classic biomaterials (metal alloys, ceramics, and polymers) in medical devices, their mechanical incompatibility, corrosion potential, and limited biological activity at the cellular level have led to a significant demand for more advanced solutions. The application of nanotechnology offers a revolutionary approach to addressing these needs by enabling the control of material properties at the nanoscale (1-100 nm). Because of their high surface area/volume ratios, nanobiomaterials more closely resemble the cell microenvironment, which enables the development of sophisticated scaffolds and physiologically stimulating materials for tissue engineering. The classification of biomaterials, their mechanical and biocompatibility criteria, the contributions of nanotechnology to biomaterial development, and nano-assisted medical systems, including biosensors, biochips, and nano-carrier systems, are all thoroughly examined in this article.

Keywords: nanotechnology, biomaterials, biocompatibility, drug delivery, tissue engineering

1. Introduction

One of the most significant and rapidly evolving areas of medicine is biomaterials science [1]. Biomaterials are materials derived from natural, synthetic, or composite sources that are used in the human body to sustain, regenerate, and replace damaged or dysfunctional tissues [2]. They are widely used in dentistry (dental implants), orthopedics (artificial joints), cardiology (artificial vessels, stents), and cosmetology [3].

Biomaterials have been used since prehistoric times. For example, the Egyptians used animal muscle for sutures. Tissue engineering and materials science have recently contributed to the advancement of the modern biomaterials discipline, which is based on a synthesis of medicine, biology, physics, and chemistry. Biomaterials science has grown rapidly in the last decade thanks to advances in tissue engineering and regenerative medicine.

Biomaterial science is a multidisciplinary field whose successful application requires the integration of many important scientific disciplines. As shown in Figure 1 [4], this field is closely related to Materials Science (synthesis and characterization of new materials), Biological Sciences (cell-material interactions and tissue responses), Biomechanics (analysis of response to mechanical load), Toxicology Sciences (prevention of toxic effects of materials on the body), and Medical Sciences (clinical application needs and outcomes). The clinical efficacy of materials is also determined by engineering and human health considerations. Through this integration, fourth-generation nanomaterials that actively assist biological activity, going beyond materials that only have a passive replacement function, have become possible.

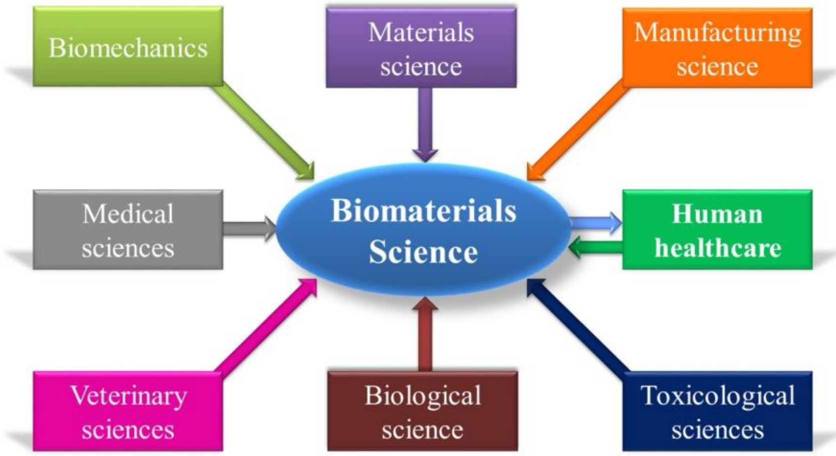

Figure 1. The relationship of biomaterials science with other sciences [4].

There are four primary generations in the history of biomaterial development: The goal of first-generation materials, such as passive polymers, was to reduce the immunological response while solely acting as passive substitutes. Certain bioceramics and other second-generation materials are bioactive, which means they interact favorably with tissue and encourage its integration [5]. Third-generation materials, such as scaffolds that promoted cell growth, were created for tissue engineering. The fourth generation considerably improves cellular functional activity while maintaining nanomaterials at the core of its development.

The mechanical strength of materials is not the only restriction caused by modern therapeutic requirements. Toxic ion leakage from metal corrosion following long-term implantation is one of the biggest issues with conventional biomaterials. The high risk of infection at the implantation site is another significant problem. A fibrous capsule forms around the implant as a result of the body's defensive response to the material surface's incompatibility with the normal biological environment. This significantly reduces the implant's functional success. These drawbacks are motivating scientists to develop a new class of biomaterials with great biocompatibility and the ability to replicate biological processes [6].

2. Classification of Biomaterials

Based on their mechanical characteristics and chemical composition, biomaterials are classified into four major groups (Figure 2) [1].

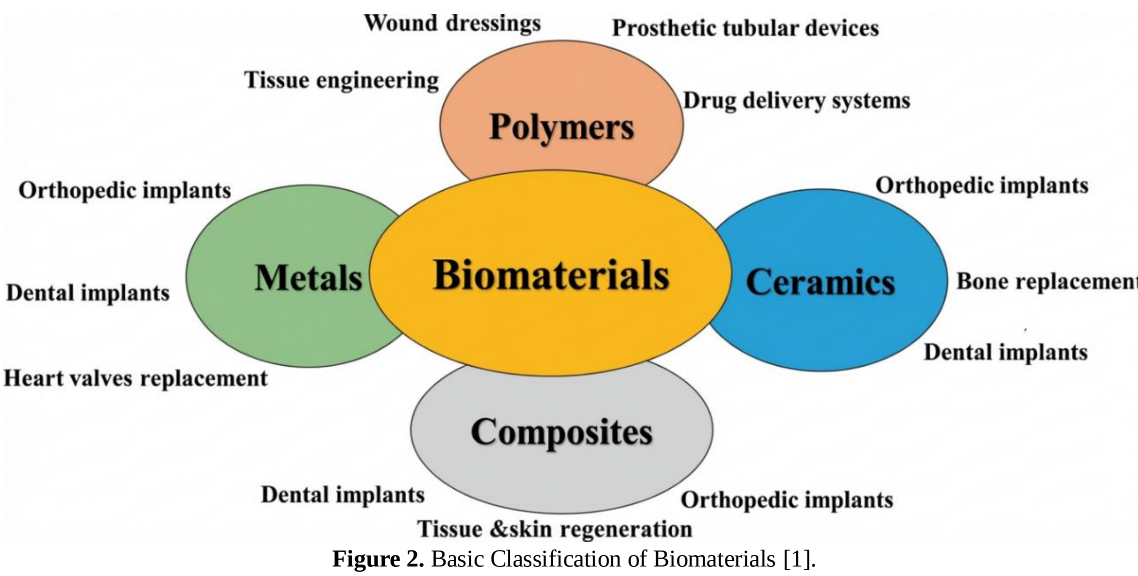

Figure 2. Basic Classification of Biomaterials [1].

2.1. Metallic Biomaterials

Because of their high strength, fatigue resistance, and durability, metallic biomaterials [7] (such as stainless steel, titanium alloys, and cobalt-chromium alloys [8]) are used in areas subjected to high mechanical stress, especially in orthopedic implants (hip-pelvic joints), dental implants, and stents in cardiology. The most popular metallic biomaterials are titanium alloys (Ti-6Al-4V) [9], in particular, due to their superior corrosion resistance and biocompatibility. However, the metal's high elastic modulus may cause issues with stress shielding, which would weaken bone tissue.

2.2. Ceramic Biomaterials

Bioceramic materials have both chemical stability and biocompatibility [10], such as calcium phosphates, which include aluminum oxide, zirconium dioxide, and hydroxyapatite (HAp). These substances can be classified as either bio-active (like HAp), which forms direct chemical connections with bone tissue, or bio-inert (like Al_2O_3), which functions passively. Because HAp replicates the mineral composition of bone tissue, it is essential in applications like implant coatings, bone fillings, and bone cements. Polymers are used to create composites in order to remove brittleness.

2.3. Polymeric Biomaterials

The most adaptable class of biomaterials is polymers since they can easily change the characteristics of the material [11]. These are either permanent (like silicone and polyurethane) or biodegradable (like PLA and PGA), which the body absorbs after a specific amount of time and permits tissue regeneration. Polymers are widely used in contact lenses, vascular grafts, soft tissue replacements, and controlled medication delivery systems.

2.4. Composite Biomaterials

Composite biomaterials, such as ceramic particles embedded in a polymer matrix, are made by combining two or more distinct kinds of materials. The combination of polymers and ceramics offers distinct advantages, including the flexibility of polymers and the bioactivity of ceramics, which are both absent in single materials. An exemplar of this phenomenon is polymer-HAp composites, which have been demonstrated to meet the mechanical and biological requirements of bone [12].

3. Biocompatibility and Mechanical Requirements

3.1. Cell-Material Interaction

The capacity of a material to interact properly with surrounding tissues while producing few negative reactions is known as biocompatibility. Body proteins absorb the material's surface in the initial seconds following implantation. The way fibroblasts and osteoblasts interact with the surface is determined by this layer of proteins. Bioactive materials encourage integration and tissue regeneration [13], whereas bioinert materials (such as certain metals) can cause fibrous encapsulation. To encourage cell adhesion, proliferation, and differentiation in tissue engineering, the material's surface energy, roughness, and chemical structure must be precisely tuned.

3.2. Mechanical Compatibility

An implant's ability to adapt to the mechanical circumstances of the application site is critical to its long-term effectiveness. Because orthopedic biomaterials are subjected to repetitive loads (walking, running) for years, they need to have a high fatigue resistance. Additionally, the elastic modulus of the material must be similar to the surrounding tissue. Stress shielding from metal implants with a modulus much greater than bone can result in implant loosening and bone atrophy [14]. Porous or nanostructured alloys with exceptionally low elastic modulus are being developed to address this issue.

4. Nanotechnology in Biomaterials and Medicine

By manipulating material properties at the atomic and molecular levels, nanotechnology has transformed the study of biomaterials. The biggest benefit of nanomaterials, which range in size from 1 to 100 nm, is their high surface area-to-volume ratio and capacity to interact on a comparable scale with biological systems (cells, proteins) [15], [16].

4.1. Nanostructured Surfaces

The biocompatibility and biological activity of biomaterials are greatly enhanced by nanoscale surface modification. Nanostructured surfaces, such as nanowires, nanofibers, and nanochannels, imitate the extracellular matrix (ECM), which is the natural habitat of cells. These biomimetic surfaces inhibit the colonization of bacteria that cause illnesses while simultaneously promoting cell adhesion, proliferation, and differentiation (particularly bone cells, or osteoblasts).

4.2. Nanocarrier Systems

In the area of nanomedicine, nanocarrier systems are crucial platforms for the targeted and regulated delivery of medications, genetic materials, and bioactive compounds. The main categories of nanocarriers are lipid-based, polymer-based, inorganic nanoparticles, drug-conjugate systems, and viral nanoparticles, as seen in Figure 3 [17].

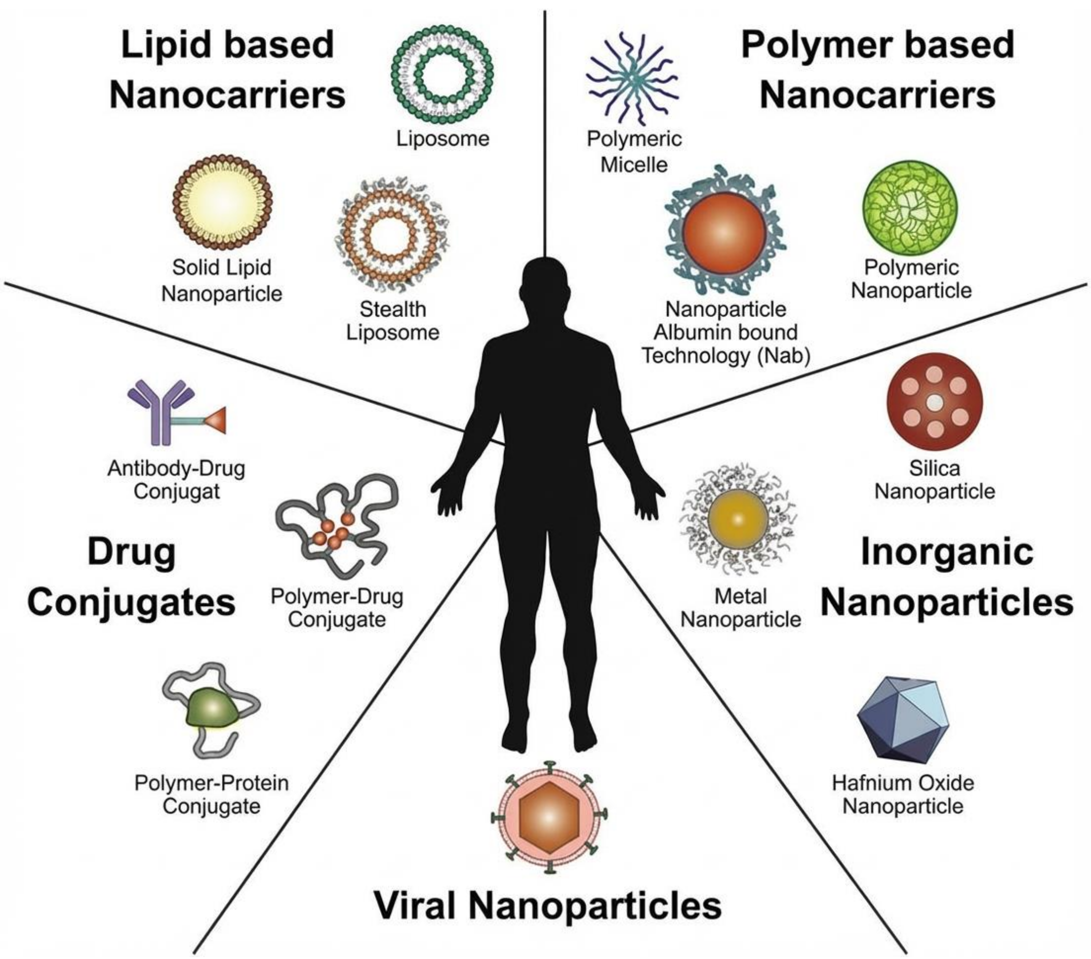

Figure 3. Application of nanomaterials in medicine [17].

Liposomes, solid lipid nanoparticles, and latent (PEG-coated) liposomes are examples of lipid-based nanocarriers. These systems prolong the drug's stay in the bloodstream, prevent enzymatic breakdown, and enable the simultaneous delivery of hydrophilic and hydrophobic medications. High stability, controlled release, and functional surface modification are the benefits of polymer-based nanocarriers, such as polymeric micelles, polymeric nanoparticles, and albumin-bound nanoparticles (Nab technology).

Metal, silicon, and hafnium oxide nanoparticles are examples of inorganic nanoparticles that are primarily employed in radiation, imaging, and combination therapies. Drug molecules attach to proteins, polymers, or antibodies in drug-conjugate systems to target certain cell receptors, greatly increasing the efficacy of targeted therapy. Because of their strong transcriptional capacity, viral nanoparticles are especially significant in gene therapy and vaccine technologies.

These nanocarrier systems reduce systemic toxicity and boost therapy efficacy by selectively depositing the medicine in tumor tissue, particularly in oncology treatment.

5. Nano-enabled Medical Systems

5.1. Biosensors

Biosensors based on nanomaterials offer extremely sensitive, real-time molecular diagnostic data gathering. Because of their high electrical conductivity and surface area, nanocarbon-based materials like graphene and carbon nanotubes make excellent sensor platforms for identifying biological substances, including proteins, DNA, and glucose. These sensors are crucial for both the ongoing monitoring of chronic illnesses (like diabetes) and the early detection of diseases [18].

5.2. Biochips

Micro and nanofluidic technologies are used in biochips, also known as micro-total analysis systems or laboratory-on-a-chip. On a tiny chip, they incorporate complex laboratory procedures including drug testing, cell analysis, and genetic testing. Reduced sample volume, quicker processing times, and lower costs are made possible via nanoscale channels and surface changes. This technology has a lot of promise for quick diagnoses, especially in places with limited resources or distant locations [19].

5.3. Nanorobots

Nanorobots are nanoscale robotic constructs that can carry out particular tasks in a biological setting. They are created at the nanometer scale (1–100 nm). Targeted medication delivery, identifying sick cells, molecular diagnosis, and minimally invasive medical procedures are their primary goals. An inner and an outer component make up the structure of nanorobots. The external component is robust enough to interact with the body's diverse chemical surroundings. The interior is a vacuum-sealed, fully enclosed space that permits fluid flow only when required. Through auditory impulses, nanorobots can interact with the physician and carry out instructions [20].

Cosmetics are another area where nanorobots are being used. Nanorobot-containing creams, for instance, can eliminate extra oil, exfoliate dead cells, and supply vital components for the skin. They can be combined with antiseptics in oral and dental care to eradicate bacteria and stop the development of plaque and tartar.

6. Clinical Applications and Future Perspectives

Many medical fields are already being revolutionized by nanobiomaterials:

Tissue Engineering and Regenerative Medicine: In the area of electricity, skin, bone, cartilage, and nerve tissue are regenerated using polymer scaffolds made by electrospinning. These scaffolds' nanostructures encourage optimal cell development.

Cardiology: Nanomaterial-modified biological stents speed up vascular tissue regeneration and decrease inflammation following insertion [21].

The goal of future research is to turn biomaterials into "responsive/intelligent" systems that manage drug release and react to changes in the body's environment, such as a drop in pH during an infection or a temperature rise. New biomaterials with desirable biological characteristics will be designed more quickly by incorporating AI and machine learning techniques into materials science. This will make it possible to develop treatments that are specific to each patient's needs and conditions.

7. Conclusion

It is helpful to examine the past and present before talking about future objectives in the field of biomaterials. In the past, the primary remedy for tissue injury or loss of function was tissue removal. Later, new fields of application developed with the discovery of antiseptics, penicillin and other antibiotics, hygiene, and vaccinations. The lifespan of implants is finite. When orthopedic prostheses are physiologically compatible with tissues, they last longer. Restoring tissue function, metabolic and biochemical activity, and biomechanical performance are all part of tissue regeneration. Nanorobots based on nanotechnology can eliminate dangerous compounds from the bloodstream, treat viral and bacterial infections, kill cancer cells, and monitor and diagnose a variety of illnesses.

Therefore, by creating materials that are compatible with biological structures, biomaterials research, a subfield of bioengineering, seeks to enhance our quality of life. Future studies should concentrate on creating biomaterials that allow for the remodeling of natural tissues and make use of or improve the body's ability to self-renew.

Author Contributions

The authors confirm responsibility for the conception, drafting, critical revision, and final approval of the manuscript.

Conflict of Interest

The authors declare no conflicts of interest.

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Data Availability Statement

The authors declare that the data supporting the findings of this study are available within the article.

Abbreviations

Titanium Alloys (Ti-6Al-4V), Hydroxyapatite (HAp), Aluminum Oxide (Al_2O_3), Polylactic Acid/ Polylactide (PLA), Polyglycolic Acid/Polyglycolide (PGA), Extracellular Matrix (ECM), Pegylated (PEG), Nanoparticle Albumin-Bound Technology (Nab Technology).

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Journal of Nanotechnology and Innovative Materials

Research Article

Effect of Irradiation on Nanoisland Formation and Structural Evolution of Bi_2Te_3 Thermoelectric Materials

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Abstract

Thermoelectric materials, particularly those derived from Bi_2Te_3, have received significant interest because of their capacity to directly transform thermal energy into electrical power, thereby making them suitable for energy conversion applications. This research centered on the surface morphology of Bi_2Te_3 crystals, specifically examining the (0001) surfaces both prior to and following irradiation, employing Atomic Force Microscopy (AFM) for analysis. The formation of nanoislands and their fractal nature were studied, which helped to understand their nucleation and growth through Ostwald ripening (OS), a process where smaller islands combine to form larger ones. This research also examined radiation affecting the structure and thermoelectric properties of materials made from Bi_2Te_3. The fractal characteristics of these nanostructures lead to the appearance of nanoislands of different sizes. The present investigation centered on the fractal characteristics inherent in nano-objects, thereby facilitating the emergence of multi-scale nanoislands. This research investigated the fractal features of nano-objects, which are instrumental in the generation of nanoislands across a spectrum of length scales. Consequently, the fractal morphology exhibited by nanoscale formations gives rise to nanoislands that encompass diverse size regimes.

Keywords: thermoelectric material, energy conversion, Bi_2Te_3, nanoislands, AFM, XRD

1. Introduction

Thermoelectric materials can convert heat directly and reversibly into electrical energy [1]. Because of these properties, along with their small size and reliable performance, they are very useful in environmentally friendly and energy-efficient technologies [2], [3]. Bi_2Te_3 is known to be one of the most effective materials at room temperature, which is due to its layered crystal structure that has different properties in different directions. This structure promotes superior electrical conductivity alongside diminished thermal conductivity [4]. Enhancing the thermoelectric efficiency coefficient (ZT) frequently necessitates optimizing phonon scattering while preserving relatively high carrier mobility [5], [6]. The incorporation of nanoscale characteristics, including nanoislands, holes, and grain boundaries, proves beneficial. These features can be generated via environmental influences like radiation or through meticulously controlled synthesis methods. Nanoscale surface structures primarily form through nucleation, growth, coupling, and Ostwald ripening. Radiation exposure has been reported to cause defects, change the surface structure, and increase atomic mobility [7], [8]. This study aims to investigate the surface properties and structural changes of irradiated Bi_2Te_3 crystals, focusing on the formation of nanoislands and their relationship with diffusion-driven processes.

2. Materials and Methods

2.1. Sample Preparation

Bi_2Te_3 crystals were synthesized using a standard method. These were then cleaved along the (0001) plane to create both pure and atomically smooth surfaces. Many studies on the structural integrity of Bi_2Te_3 demonstrate that the creation of these high-quality crystal surfaces is critical for the accurate separation of surface effects resulting from irradiation [9], [10].

2.2. Irradiation Conditions

The samples were exposed to a total radiation exposure of 30 Mrad (MegaRad). The chosen dose was based on earlier experiments that illustrated controlled irradiation could successfully induce point defects. This method improves atomic movement and surface modifications in tellurium compounds [11]. The irradiation parameters were carefully adjusted to generate significant structural changes while yet maintaining the crystal structure.

2.3. AFM Analysis

Atomic force microscopy (AFM), specifically in tapping mode, was employed to examine surface morphology across scan areas spanning from 1 to 5 μm^2. To ensure accurate topographical measurements, standard silicon probes, which possess a typical spring constant of approximately 40 N/m, were utilized in combination with a high-resolution commercial AFM instrument. AFM is a common tool for studying nanoscale surface phenomena, such as Ostwald ripening and coalescence, which were the main focus of this research [11], [12]. In addition, to accurately measure the size of the created nanoislands, height profiles were obtained from the AFM images using specialized image processing software.

2.4. XRD Measurements

X-ray diffraction (XRD) analyses were conducted employing a diffractometer utilizing CuKα radiation ($\lambda \sim 1.5418$ Å). To facilitate the detection of minor alterations in the crystal structure, diffraction patterns were gathered across a 2θ range extending from 50 to 800 [13], [14], incorporating an extended integration period and a minimal step size. The generated patterns were subsequently studied to ascertain the modifications in peak width (indicative of microleaflet or crystallite dimensions), position (reflective of variations in lattice parameters), and intensity (related to structural irregularities) produced by the irradiation-induced structural transformations.

3. Results and Discussion

3.1. AFM Surface Morphology Before and After Irradiation

On the surface of pure Bi_2Te_3, uniform terraces typical of layered crystals were observed. After irradiation, numerous nanoislands appeared on the surface, along with pore-like features and curved edge defects. The island dimensions were verified using a height profiling approach and were found to be approximately 20 nm wide and 35 nm high. The development of these islands is a hallmark of increased atomic mobility and nucleation activity caused by radiation. Ostwald ripening (OS) is characterized by growth mechanisms where smaller, more abundant structures dissolve and reconnect to larger, energetically more favorable islands. Even without direct physical contact, small clusters coalesce through surface diffusion in this process. Upon contact, larger islands (those with a diameter greater than 20 nm) coalesce, exchanging mass through the junction region. It has been shown that misoriented islands form transient internal grain boundaries before dissolving through mass diffusion (Figure 1).

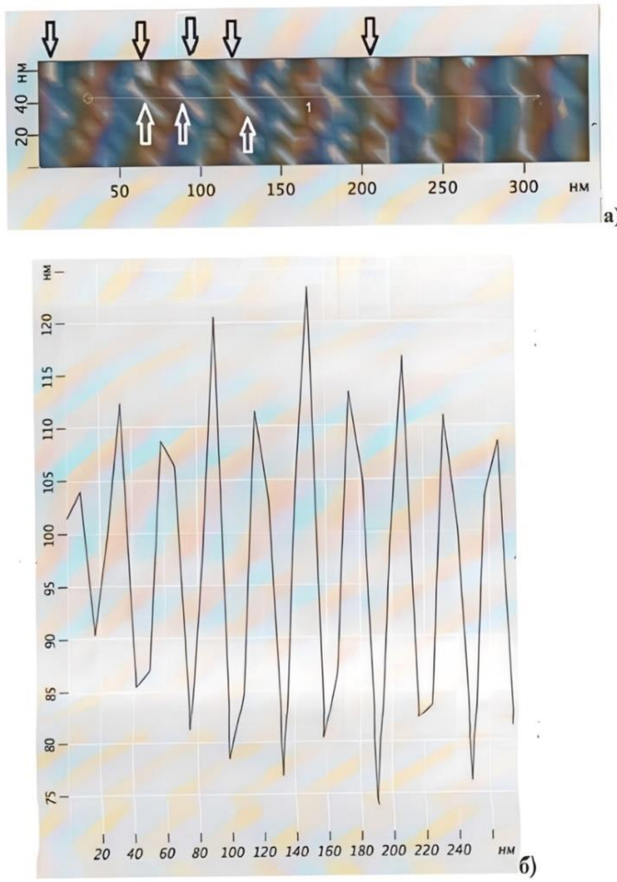

Figure 1. AFM image and height profilogram of irradiated Bi_2Te_3 surface depicting nanoislands and 2D surface defects.

3.2. 3D AFM Topography Analysis

In the 3D AFM map, a significant surface rearrangement consistent with increased Te and Bi atom diffusion is observed on the (0001) surface. The increased roughness seen after irradiation, which is caused by flaws, supports the creation of active nanostructures (Figure 2).

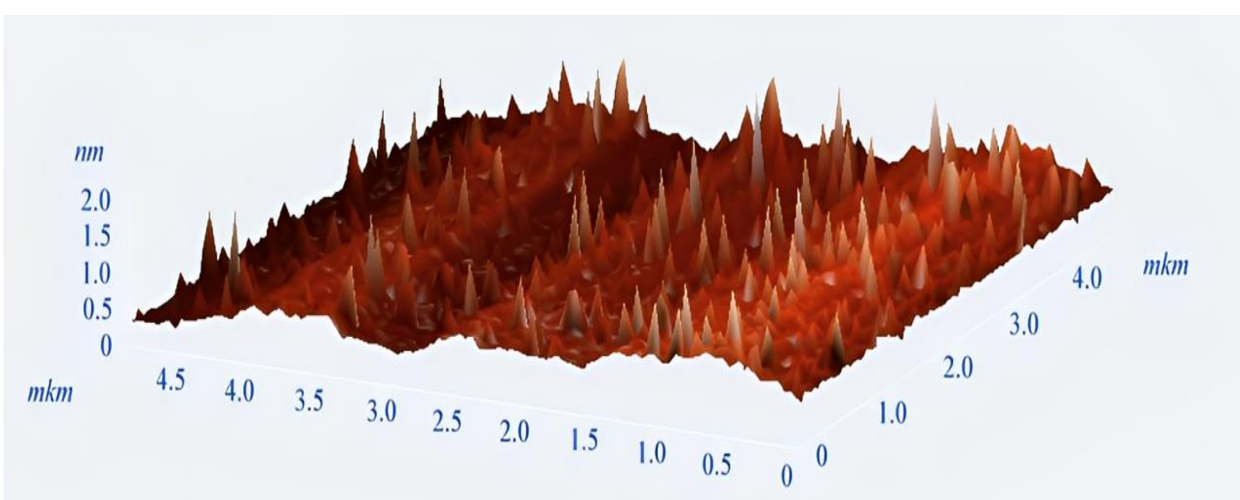

Figure 2. The 3D AFM topography of the irradiated Bi_2Te_3 surface exhibiting nanoscale roughness and the distribution of islands.

Figure 3 presents a more detailed three-dimensional AFM reconstruction of the irradiated Bi_2Te_3 surface, offering further insights into nanoscale height fluctuations and the arrangement of surface characteristics. The scan data reveals a diverse surface, marked by the presence of nanopeaks and clusters. This surface shows considerable roughness and the development of islands of different sizes. Bright yellow and white areas, indicative of high atomic deposition sites, suggest enhanced surface diffusion and clustering of Bi/Te atoms in areas with a high density of defects. Consequently, these observations provide additional support for a radiation induced, diffusion-driven Ostwald ripening process.

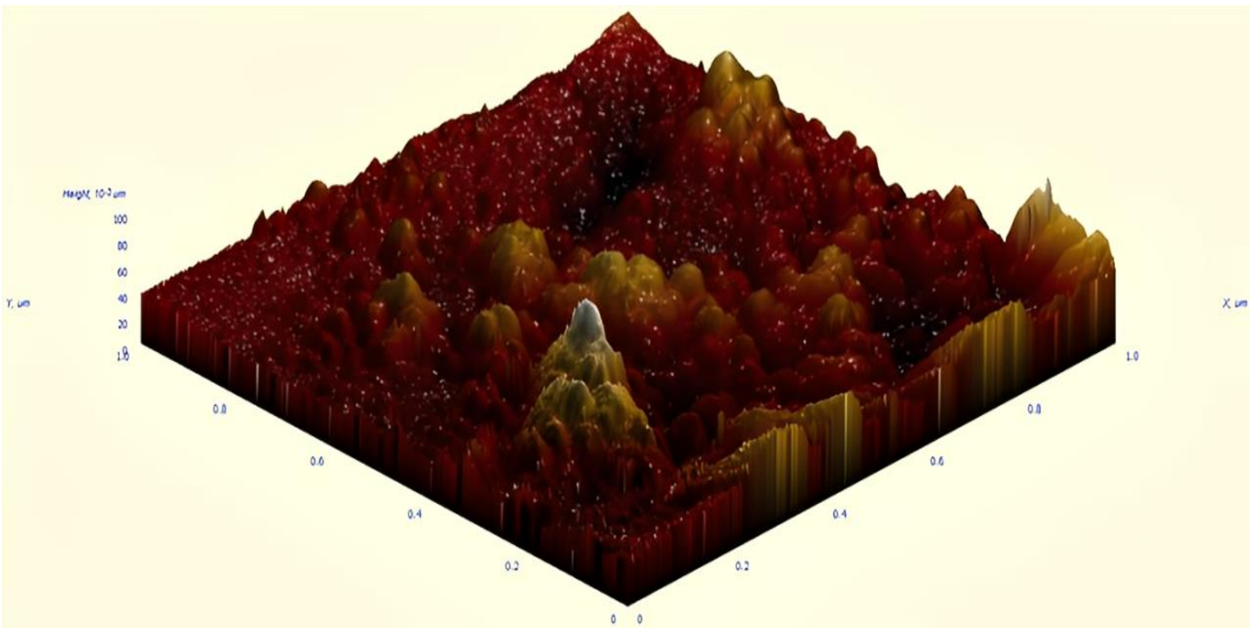

Figure 3. 3D AFM topography of the irradiated Bi_2Te_3 (0001) surface, exhibiting significant nanoscale roughness and height fluctuations linked to nanoisland formation after a 30 Mrad irradiation dosage.

3.3. XRD Analysis

According to XRD analysis, irradiated Bi_2Te_3+Te material exhibits significant structural changes after irradiation. Peak broadening was considered a characteristic of high concentration defects and microstress formation. Partial disorder and lattice disruption within the crystal structure can cause a proportional decrease in peak intensity. Small differences in peak positions indicate slight changes in interlayer distance due to radiation damage. All these effects point to a higher concentration of radiation-induced defects such as dislocation of clusters, gaps, interstitial atoms, and displacement defects (Figure 4).

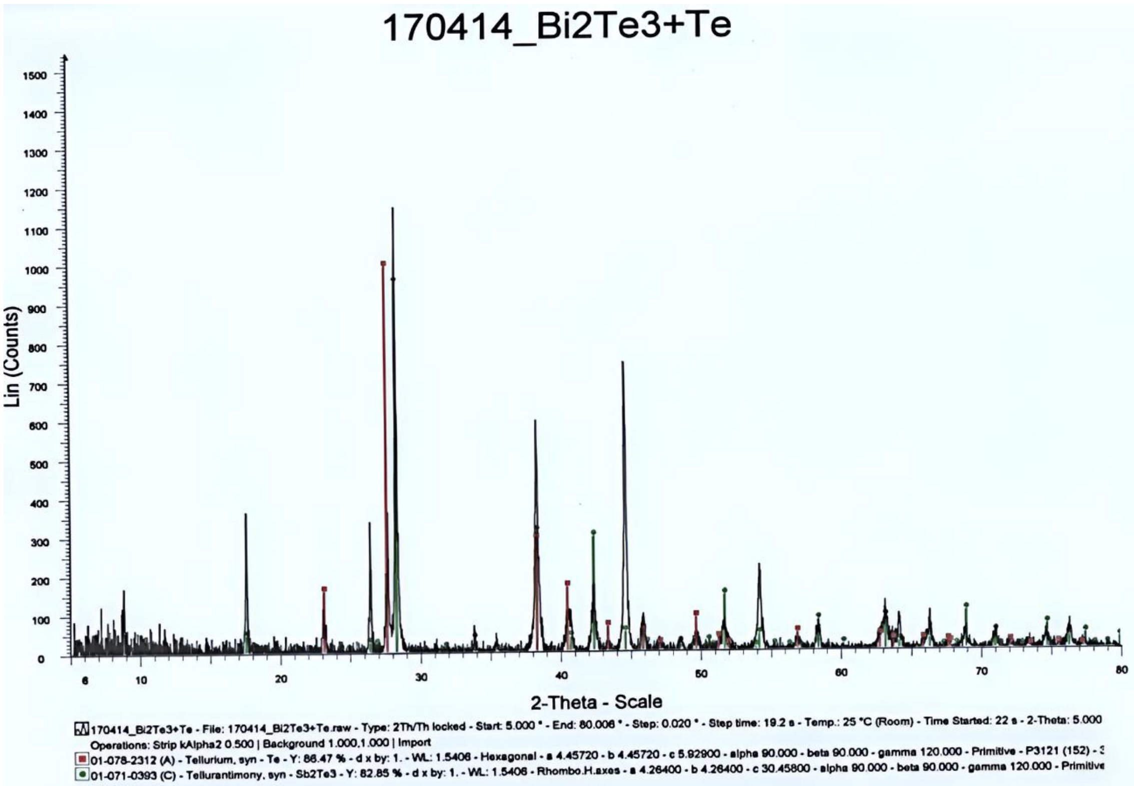

Figure 4. XRD pattern of Bi_2Te_3 + Te post-irradiation (30 Mrad).

3.4. Interpretation of Defect-Mediated Nanostructuring

Radiation-induced mechanisms interact in a complex manner to produce the observed nanoislands and diffraction changes. Multilayer structure and higher atomic mobility accelerate surface diffusion. High concentration of radiation-induced point defects promotes mass diffusion. Preferential nucleation occurs within pore domains or defect clusters. Interlayering of atoms into van der Waals vacancies of the layered structure leads to structural instability or the formation of nanostructures [15], [16]. When radiation-induced defects are present, atomic mobility increases, and island-like defect development is promoted. These generated nanoscale structures have been shown to significantly affect phonon scattering, which can decrease thermal conductivity and increase the thermoelectric ZT value. On the other hand, too many defects can restrict how well carriers move. This underscores the necessity to carefully adjust the parameters for controlled irradiation, to find a compromise between these contradictory effects.

4. Conclusion

Thermoelectric materials are environmentally friendly and offer potential solutions for energy and pollution challenges, though their thermoelectric conversion efficiency remains limited by material properties. Under the influence of radiation defects, nanostructures may either partially amorphize or stabilize due to the presence of numerous interfaces. The mechanisms of nanostructure formation on the Bi_2Te_3 (0001) surface during Ostwald ripening provide a model for studying self-organized nanostructure growth in layered materials. Studying interlayer systems helps us comprehend how moving atoms on a surface interacts with true structural flaws, such as vacancies and tiny pores.

Author Contributions

S. Nabieva conceived and designed the experiment. D. Rustamova reviewed and edited the manuscript.

Conflict of Interest

The authors declare no conflicts of interest.

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Data Availability Statement

All the data analyzed in this study are included in this published article.

Abbreviations

Atomic Force Microscopy (AFM), X-ray Diffraction (XRD), Ostwald (OS), Bismuth Telluride (Bi_2Te_3).

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Journal of Nanotechnology and Innovative Materials

Review Article

Nano-enabled Approaches for Pregnancy Care: Early Detection, Monitoring, and Risk Prediction

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Abstract

Pregnancy, a complex developmental process, begins with the fertilization of an egg by a sperm and culminates in childbirth. Throughout the gestational period, the maternal organism experiences significant hormonal, metabolic, and anatomical alterations. Consequently, the well-being of both the mother and the developing fetus depends upon the early diagnosis and precise monitoring of the pregnancy. Nanotechnology has improved the early, accurate, and safe detection of pregnancy, in addition to current diagnostic methods. This review explores the use of gold nanoparticles to create highly sensitive tests for human chorionic gonadotropin (hCG) in home pregnancy tests. This paper highlights the use of wearable nanosystems for monitoring the health of mothers and babies. It also covers early risk assessments utilizing biosensors made with nanomaterials and blood tests designed with nanoengineering. Furthermore, it explores the potential and practical uses of new, portable technologies during pregnancy. These advancements underscore the transformative capacity of nano-assisted methodologies in continuous monitoring, early detection, and the assessment of pregnancy-related risks. The incorporation of nanotechnology into wearable devices presents significant prospects for enhancing the protection of maternal and fetal well-being in the future.

Keywords: prenatal care, nano-enabled diagnostics, maternal-fetal monitoring, wearable technologies, nano-enabled biosensors

1. Introduction

The complex biological process of pregnancy begins with the fertilization of an egg cell by a sperm cell and ends with the formation of a zygote. The zygote proceeds through rapid mitotic divisions after fertilization in the ampulla of the fallopian tube, starting with the 2-cell stage and moving on to the 4-cell stage and finally the 8-cell stage. After around 72 hours of fertilization, it develops into a morula. This embryonic stage develops into a blastocyst on the fourth or fifth day, at which point it starts to travel via the fallopian tube. About six to ten days following ovulation, it implants into the uterine endometrial lining (Figure 1) [1], [2]. Implantation, the initial phase of gestation, triggers the production of human chorionic gonadotropin (hCG), a hormone crucial for the early development of both the embryo and the placenta [3]. Gestational age, a key metric in clinical obstetrics, is calculated from the first day of the last menstrual period (LMP) [4]. Accurate monitoring of fetal development, the identification of critical periods of vulnerability, and the provision of appropriate obstetric care all necessitate a standard duration of approximately 40 weeks, or 280 days.

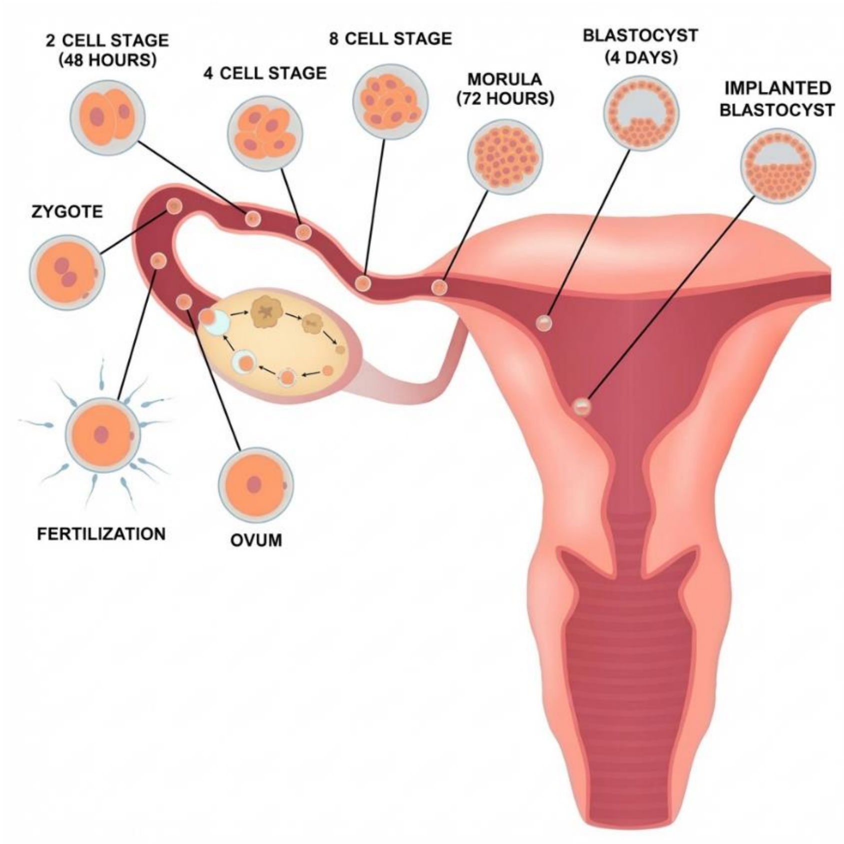

Figure 1. Description of the fertilization process.

Fetal development proceeds across three trimesters, each characterized by specific developmental phases and maternal adaptations. The initial trimester, spanning from the first week to the twelfth week, experiences substantial developmental transformations. Organogenesis, the process of organ formation, is particularly noticeable during this period, leading to the formation of crucial structures like the brainstem and the early development of the heart. Excessive fatigue, mood swings, morning sickness, migraines, swollen or sore breasts, frequent urination, and constipation are among the hormonal problems women frequently experience during this period of pregnancy.

The fetus continues to grow quickly during the second trimester (weeks 13-28), at which time its organ systems mature, its limbs begin to move, and its skeleton clearly begins to ossify. Many of the initial symptoms, like nausea, may disappear on the maternal side, but additional changes can appear. These include discomfort in the back, belly, groin, and thighs; stretch marks; darkening of the skin; swelling in the cheeks, ankles, and fingers; tingling in the hands; and itching in the palms or abdomen.

The fetus shows rapid weight gain during the third trimester (weeks 29-40), and the brain and lungs continue to develop. During this time, the fetus usually shifts into a head-down position. In addition, the mother may develop varicose veins, heartburn, back and pelvic pain, edema, increased weariness, sleep disruptions (due to the baby's movements, leg cramps, or frequent urination), and other discomforts from the growing uterus (Figure 2) [5], [6].

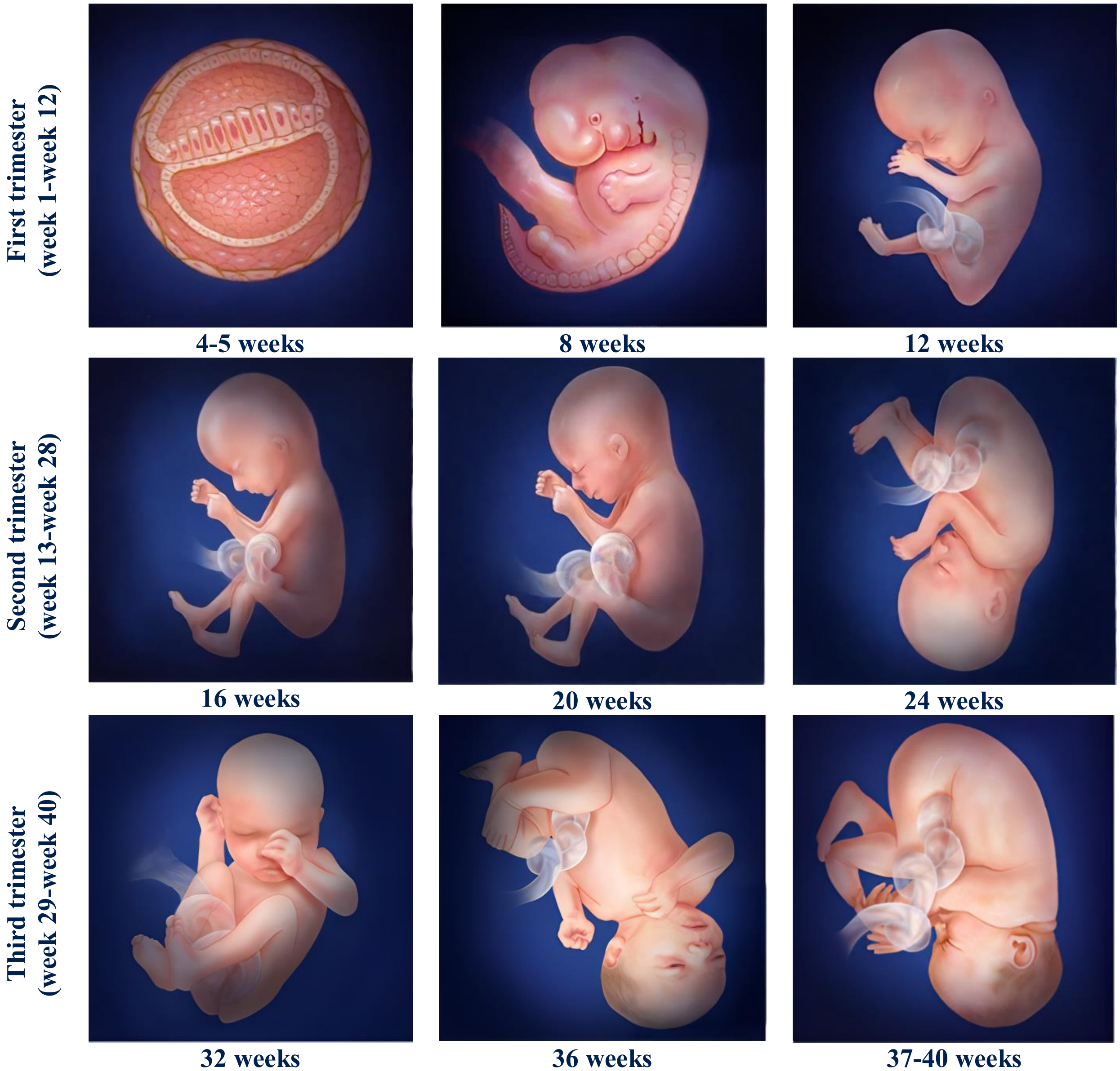

Figure 2. Demonstration of gestational age with trimesters [5].

The term "pregnancy term" refers to the time frame within which labor is expected to occur, with the optimum health outcomes for both mother and child. Significant developmental changes continue during the last weeks of pregnancy, according to recent research. Consequently, medical organizations such as the NICHD and ACOG have developed a more precise system for categorizing the gestational age [7]. Specifically, early term is characterized by a gestational age of 37 weeks, full term by 39 weeks, late term by 41 weeks, and post-term by 42 weeks or later [8]. These variations are very crucial in a clinical setting because the liver, brain, and lungs, which are all developing organs, expand quickly between 37 and 39 weeks of pregnancy. Therefore, babies born prematurely are less likely to face breathing problems, temperature imbalances, feeding difficulties, and other health issues. To make the best decisions concerning labor induction, monitoring, and the timing of delivery, a full comprehension of term classifications is necessary. This is crucial for achieving the best possible outcomes for both mothers and their newborns (Table 1) [9].

Table 1. Categorizing the terminology of gestation.

Term Category	Gestational Age Range	Brief Meanings
Preterm	20 weeks 0 days – 36 weeks 6 days	Immaturity of organ systems
Early Term	37 weeks 0 days – 38 weeks 6 days	Still maturing
Full Term	39 weeks 0 days – 40 weeks 6 days	Best outcomes
Late Term	41 weeks 0 days – 41 weeks 6 days	Increased monitoring
Post-Term	≥ 42 weeks 0 days	Higher risks

To support the developing fetus and prepare the mother's body for childbirth, the hormonal environment experiences significant and intentional changes. During the first trimester, from week one to week twelve, human chorionic gonadotropin (hCG), which is necessary for maintaining pregnancy, increases rapidly, reaching its highest level between weeks eight and twelve. Later, the level lowers dramatically. Progesterone and estrogen, often known as estradiol, are steroid hormones that increase throughout pregnancy. The levels of these hormones rise sharply, particularly in the second and third trimesters, and generally reaches its highest concentration at about the 40th week, shortly before labor begins (Figure 3). Both the development of the fetus and the maintenance of the uterine lining depend on these hormones. Other hormones, such as prolactin, hPL (human placental lactogen), and relaxin, also gradually increase and perform specific functions such as relaxing the pelvic cavity and preparing the mammary glands for milk production. Finally, the hormone oxytocin, which is necessary for the initiation of uterine contractions for labor and delivery, increases just before the last stage of pregnancy. The transition to the postpartum period is characterized by a rapid decrease in progesterone and estrogen levels and an increase in oxytocin immediately after birth [10], [11].

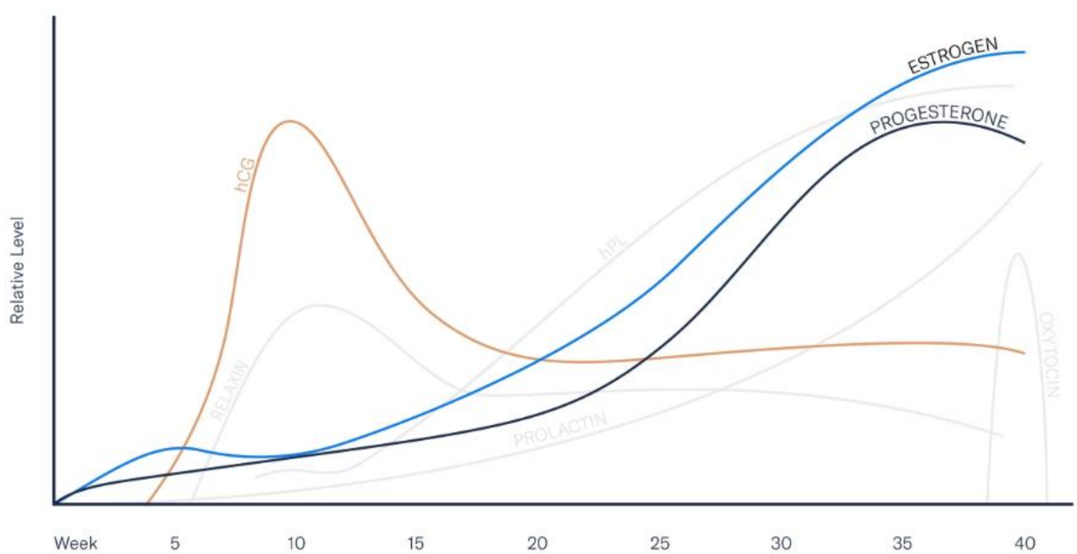

Figure 3. Graphical illustration of hormonal changes during pregnancy [12].

A variety of biochemical and imaging methods can be used to confirm pregnancy, including ultrasound examinations, blood tests, and urinalysis are the main methods. Urine pregnancy tests, widely used in both clinical and home settings, can detect human chorionic gonadotropin (hCG) [11]. Usually, these tests get accuracy when menstruation is late. Blood tests with higher sensitivity in measuring human chorionic gonadotropin (hCG) can detect pregnancy sooner, about seven to ten days later [13]. Blood tests are generally divided into two types: quantitative tests, which measure specific hormone levels to monitor early development, and qualitative tests, which confirm pregnancy. In addition, ultrasound, a non-invasive imaging technique, is often used to determine gestational age [14]. The gestational sac, which reveals where the fertilized egg implants, can be seen on an ultrasound between the fourth and fifth weeks of pregnancy. The fetal heartbeat is then detectable between the fifth and sixth weeks of gestation, providing important information about the timing and health of the pregnancy.

This research seeks to provide a thorough analysis of nanotechnology's role in prenatal care, specifically concentrating on early diagnosis, ongoing monitoring, and the evaluation of potential risks to both mother and fetus. To clarify recent developments, clinical relevance, and future possibilities within nanotechnology-supported prenatal healthcare, this article will integrate perspectives from prenatal biology, established diagnostic techniques, and novel biosensor technologies enhanced by nanotechnology.

2. Nano-enabled Early Pregnancy Detection: Label-based Biosensor

Home pregnancy tests provide a rapid, straightforward, and reliable early pregnancy detection, thereby illustrating the widespread application of nanotechnology within reproductive healthcare. These tests utilize a gold nanoparticle (AuNP)-assisted lateral flow immunoassay (LFA) design (Figure 4) in which a urine sample is passively drawn via capillary action, generating a diagnostic response on a nitrocellulose membrane [15], [16]. The application of the urine sample to the sample pad initiates the dissolution of the dehydrated antibody-gold nanoparticle complex, thereby enabling the migration of the gold-labeled antibodies along the test strip. Home pregnancy tests serve as a prominent illustration of nanotechnology's extensive utilization within reproductive healthcare, offering a quick, easy, and precise method for the early detection of pregnancy.

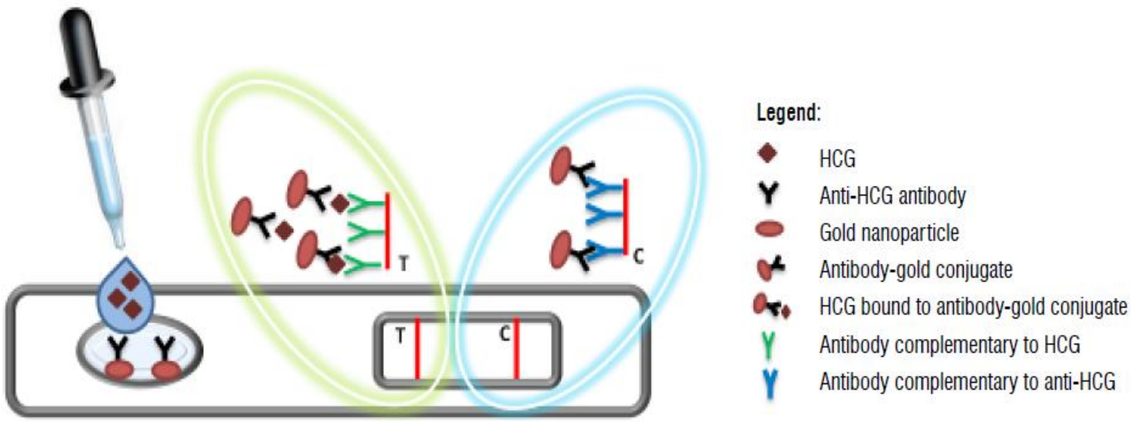

Figure 4. Operational mechanism of hCG detection in a gold nanoparticle-based lateral-flow pregnancy test [17].

Gold nanoparticles are essential to this technology due to their special optical, chemical, and physical characteristics [18]. Localized surface plasmon resonance [19], [20] allows for quick, equipment free diagnosis at home by producing a strong, consistent red coloration [21] that is visible to the naked eye. AuNPs are perfect labels for antibody-based detection because of their strong and controlled binding to biomolecules, high biocompatibility, and exceptional durability. Thanks to their nanoscale size, they have a large surface area for antibody conjugation, which increases sensitivity and makes it possible to detect pregnancy at extremely early stages, often even before a missed period. Traditional LFAs are distinguished from µPADs [22] or LOC systems by the lack of regulated flow mechanisms, constructed fluidic channels, and the incapacity to carry out sequential or multi-step processes. Rather, label-based biosensing [23] and point-of-care testing (POCT) [24] are present in a more primitive but highly effective form. Despite this, gold nanoparticle-enabled LFAs continue to be an excellent example of nanotechnology utilized in routine healthcare, and they are the technology behind the billions of home pregnancy tests that are used worldwide each year.

3. Nano-enabled Early Pregnancy Detection: Paper-Based Microfluidic (µPADs)

Recently, there has been increased interest in the use of microfluidic paper-based analytical devices (PADs) as cutting-edge research-level platforms for pregnancy detection, offering a versatile and affordable alternative to commercial LFAs. These µPAD devices are laboratory-developed prototypes made from patterned cellulose [25] or nitrocellulose channels using wax printing or hydrophobic barriers, rather than lateral flow assays that use standardized nitrocellulose strips and are mass-produced for consumer markets. Instead of using these devices in standard clinical settings, researchers can position them to perform best in experimental detection formats by customizing the flow pathways, reaction sites, and multi-step amplification.

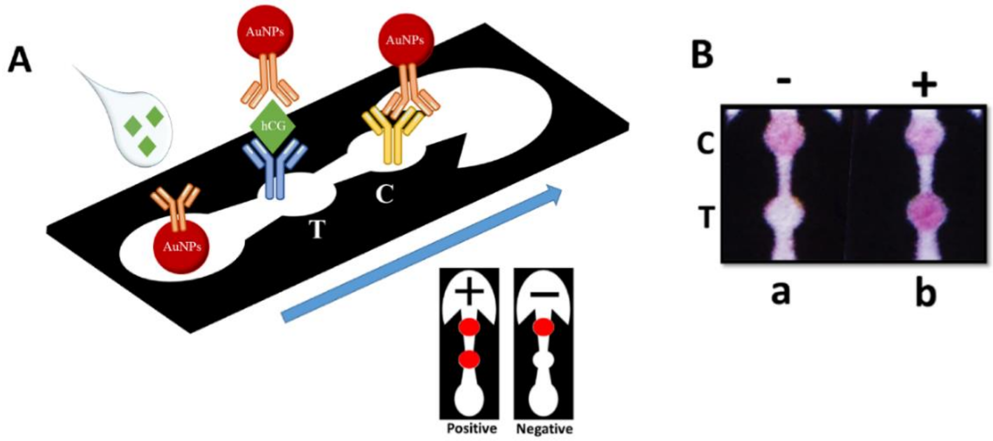

Figure 5. Operational mechanism of hCG detection in a gold nanoparticle-based paper-based microfluidic pregnancy test [26].

Figure 5 illustrates the working mechanism of a pregnant µPAD, employing gold nanoparticle (AuNP)-labeled antibodies. As depicted in panel A, a urine sample is introduced to the device, where hCG in the sample binds to AuNP-conjugated detecting antibodies. As the combination progresses, immobilized anti-hCG antibodies hold complexes in the test (T) region, creating a visible red dot due to the bright plasmonic color of the AuNPs. The test's efficacy is demonstrated by the presence of excess AuNP-antibodies within the control (C) region. Panel B presents the µPAD results, which differentiate between a positive sample (illustrated in image B, displaying both T and C regions and generating distinct red signals) and a negative sample (depicted in image A, where only the C region is visible) [26]. This observation confirms the hypothesis that AuNPs generate a bright, clearly visible color without requiring supplementary instruments, thereby emphasizing their essential role in visual outputs for both lateral flow assays (LFAs) and paper-based diagnostic (PAD) pregnancy tests.

4. Physiology of Normal Birth: Cervical Ripening and Dilation

Cervical ripening is a crucial beginning to vaginal delivery, reliant upon the cervix undergoing a timely transformation. This essential physiological process involves the cervix's transformation from a firm, collagen-rich structure that sustains pregnancy into a flexible, elastic canal, thereby facilitating fetal passage [27]. This transformation, distinguished by a complex interplay of hormonal and inflammatory signals that induce extracellular matrix imbalance, results in collagen fiber degradation and heightened tissue hydration [28], [29]. Consequently, this maturation is critical for the efficient advancement of labor.

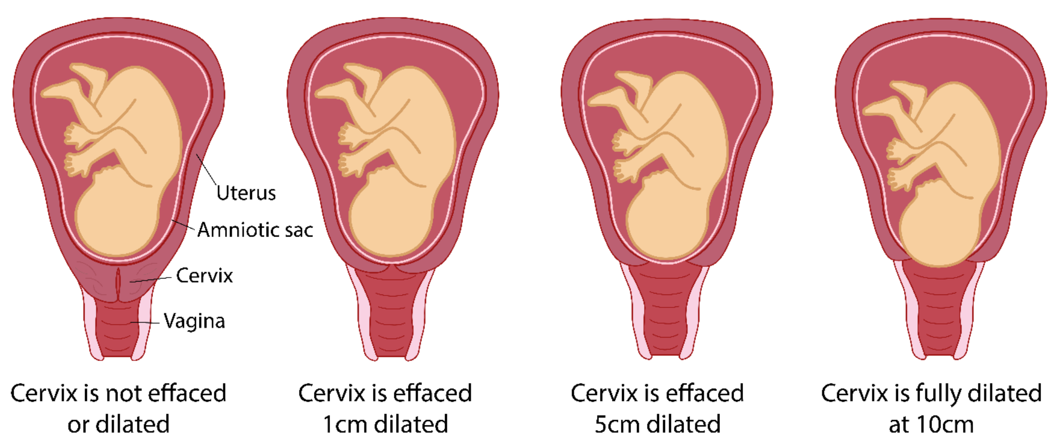

Figure 6. The progression of cervical dilation [31].

Effacement and dilation are two key mechanical changes that happen during labor. Effacement involves the cervix thinning and shortening, while dilation is the gradual opening of the cervical os. This process is described in Figure 6, which illustrates the changes that occur during labor. The cervix goes through a transformation, moving from a closed, undeveloped state to a fully thinned and dilated state, with an opening of 10 cm [30], [31]. The cervix's dilation is significant for the fetal head to pass through the birth canal. This observable physical change reveals the cervix's ability to stretch. Given that aberrations in this maturation process can result in cervical rigidity, as observed in post-term pregnancies, the condition of the cervix is a crucial clinical factor influencing successful delivery and overall obstetric outcomes. Consequently, the capacity to monitor these mechanical indicators with precision and without invasive procedures is essential for both the prevention and management of these complications.

Without this period of maturation, when the cervix is firm, long, and closed, vaginal delivery is not possible. This is because uterine contractions cannot create enough mechanical openings. Therefore, cervical ripening significantly influences the course of labor, the results of childbirth, and the method of delivery.

5. Physiology of Abnormal Birth: Post-term Pregnancy and Risks

Aberrant birth physiology is linked to maternal-fetal incompatibility and increased perinatal risk when gestational age exceeds 42 weeks. Placental aging [32], which is characterized by reduced oxygen and nutrition supply, impaired endocrine function, and placental perfusion (blood flow) [33], is the main source of the underlying pathophysiology. Consequently, fetal homeostasis is disturbed. In addition to the miscalculated pregnancy date, several physiologic variables contribute to this extended time. Adipose tissue releases pro-inflammatory cytokines, including TNF-α, which can reduce the myometrium's sensitivity to labor cues, making maternal obesity a major risk factor [34]. Furthermore, male fetal sex is an independent risk factor since male fetuses are statistically linked to longer pregnancies and exhibit increased vulnerability to oxidative stress and nutritional scarcity brought on by an aging placenta [35]. The risk of adverse outcomes increases significantly with gestational age due to umbilical cord compression (UCC), oligohydramnios (low levels of amniotic fluid) [36], and chronic fetal hypoxia (lack of adequate oxygen). The risk of stillbirth increases exponentially between weeks 41 and 43. Prolonged pregnancy is an independent risk factor for stillbirth, as shown in Figure 7 [32]. The risk is steady and relatively modest until the end of the pregnancy, but it rises quickly after 40 weeks [37]. Additionally, pregnancies in which the placenta is still functioning have a much-increased risk of fetal macrosomia (birth weight >4,500 g) [38]. The risk of shoulder dystocia, brachial plexus damage, and postpartum hemorrhage in mothers is significantly increased by this aberrant growth, which is frequently "asymmetrical" with disproportionately big fetal shoulders and trunks [39]. Vaginal birth becomes physiologically impossible in the absence of this maturational phase, which is characterized by a lengthy, dense, and closed cervix. This condition is because uterine contractions are unable to produce sufficient mechanical openings. Cervical ripening, therefore, significantly influences the course of labor, the obstetric results, and the final delivery method.

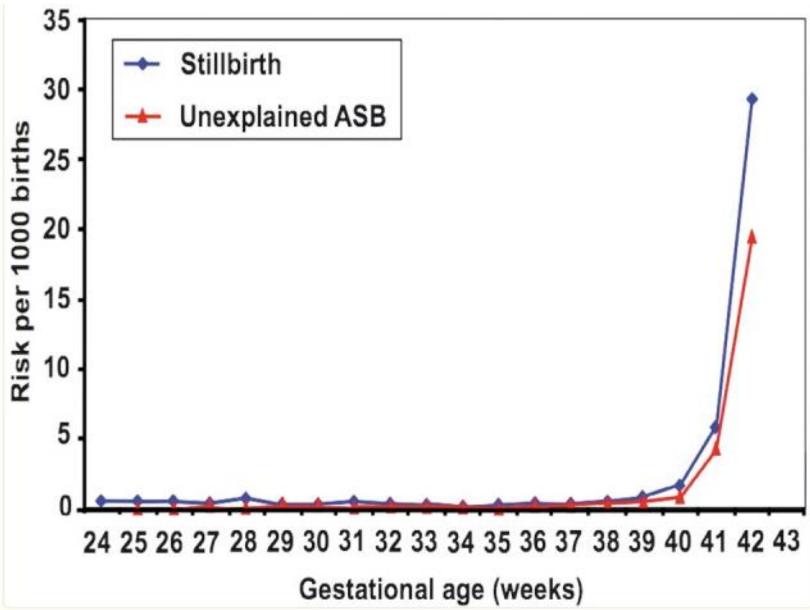

Figure 7. Risk of stillbirth and unexplained antepartum stillbirth per 1,000 ongoing pregnancies according to gestational age [32].

Clinical treatment usually begins while the cervix is still "immature," and rapid intervention is important to reduce these risks. Cervical maturation is the first stage of this process and can be achieved with pharmacological drugs such as prostaglandins like Dinoproston or Misoprostol to chemically soften cervical collagen, or with mechanical techniques such as Foley catheters to physically dilate the cervix [40].

Once the cervix is ready, regular uterine contractions are induced, and active labor is initiated by amniotomy (artificial membrane rupture or AROM) and administration of titrated synthetic oxytocin [40]. Since the late-term fetus has limited physiological reserves to withstand the stresses of labor, continuous fetal heart rate monitoring is necessary to detect late decelerations during this process. The clinical approach shifts to cesarean delivery [41] when the fetal heart rate is concerning (often due to depleted placental reserves) or when cephalopelvic disproportion occurs due to macrosomia (excessively large baby). The physiological difficulties of post-term gestation led to a far greater rate of surgical intervention to prevent avoidable perinatal morbidity and mortality, even though the aim is a safe vaginal birth.

6. Monitoring and Prevention of Pregnancy Complications: Clinical Management

Continuous and multi-parameter monitoring of physiological well-being is crucial to prevent maternal and fetal complications arising from post-term pregnancies and other high-risk obstetric conditions. To detect hypertensive diseases, metabolic abnormalities, and infectious processes [42] at an early stage, maternal monitoring includes routine monitoring of blood pressure, urinary protein excretion [43], blood glucose levels, body temperature, heart rate, and oxygen saturation, while fetal monitoring, to detect early signs of placental insufficiency and impaired fetal perfusion, includes daily fetal movement assessment, serial ultrasonographic biometry [44], assessment of amniotic fluid volume, and Doppler flow studies of the umbilical and middle cerebral arteries [45], [46]. Cardiotocography (CTG) [47], which allows for simultaneous assessment of fetal heart rate (FHR) patterns and uterine activity and early detection of fetal hypoxia or distress, remains a vital component of fetal monitoring [48]. A necessary part of maternal fetal monitoring is the use of internal and external electronic technology for fetal heart rate (FHR) monitoring [49], [50]. The real-time data on fetal circulation, oxygenation patterns, and acid-based balance provided by these methods can indicate potential problems. Internal monitoring with fetal scalp electrodes produces more accurate and consistent data, even though external FHR monitoring with Doppler is a non-invasive technique frequently used in prenatal care and delivery, where external signals are inconsistent. These techniques help doctors identify problematic patterns that may indicate fetal distress in high-risk pregnancies, enabling early clinical assessment and intervention (Figure 8) [51].

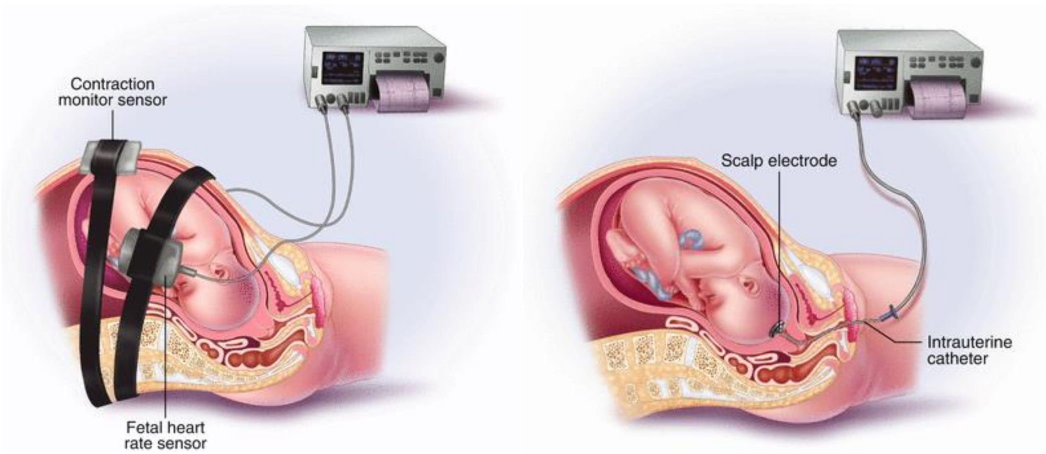

Figure 8. External and internal fetal heart rate monitoring techniques [51].

Two highly useful structured testing methods are contraction stress testing (CST) and biophysical profiling (BPP), which allow for the early diagnosis of fetal reserve declines, such as fetal oxygenation and neurological integrity, before a significant clinical decline [52]. These tests are performed more frequently (twice a week) in terms of high-risk pregnancies to detect even the slightest changes in fetal condition early on. These coordinated monitoring technologies operate as early warning systems, helping to prevent complications throughout labor and delivery. They also provide vital information about the changing risks for both the mother and the developing fetus.

7. Monitoring and Prevention of Pregnancy Complications: Wearable Technologies

Beyond traditional, hospital-based assessments, maternal-fetal monitoring has been greatly enhanced by recent advances in wearable technologies. Wearable electrocardiography (ECG) [53] and photoplethysmography (PPG) [54], [55] sensors, smart patches, wearable ultrasound belts, smart abdominal belts, and textile-integrated biosensors [56], [57] are examples of contemporary wearable systems that enable continuous, non-invasive monitoring of maternal and fetal physiological parameters in both home and outpatient settings. In addition to monitoring maternal heart rate, blood pressure, oxygen saturation [58], glucose levels, body temperature, physical activity, sleep patterns [59], and uterine contraction dynamics [60], these platforms can also record fetal heart rate (FHR) [61] and fetal movement data [62], [63] through increasingly advanced abdominal wearables (Figure 9) [64]. Wearable technology supports proactive surveillance by producing longitudinal physiological data outside of clinical settings [65], especially in high-risk and late-term pregnancies where intermittent clinician-based monitoring may not be sufficient.

(a) **(b)** **(c)**

Figure 9. Commercial wearable devices: (a) Philips remote fetal monitoring (Model: 989803219951) [66], (b) MERIDIAN M110 disposable electrode patch [67], (c) Avalon beltless fetal monitoring (Avalon CL) [68].

Although cardiotocography (CTG) is still the conventional clinical standard for evaluating fetal heart rate and uterine activity, many advanced wearable monitoring systems are made to use small, portable, non-invasive sensor technologies that are appropriate for long-term or at-home monitoring to record CTG equivalent physiological signals, such as fetal heart rate variability, uterine contraction patterns, and maternal ECG [69]. Wearable fetal ECG and Doppler-based technologies serve as outpatient options that allow long-term evaluation of fetal well-being, in contrast to traditional CTG, which is frequently not wearable and is limited to short-term, in-hospital recordings. Fetal hypoxia, uteroplacental insufficiency, abnormal uterine activity, and impaired fetal autonomic regulation are examples of obvious complications that may be identified by subtle abnormalities in baseline heart rate, variability, accelerations, and decelerations.

8. Nanotechnology-enabled Biosensing and Diagnostic Innovations in Pregnancy Care

Nanotechnology has revolutionized prenatal diagnosis by enabling the highly sensitive, rapid, and low-invasive diagnosis of pregnancy-related disorders. Detection of even the smallest molecular changes associated with placental dysfunction, fetal risk, and adverse pregnancy outcomes is possible thanks to the extraordinary electrical, optical, and biochemical sensitivity of nanofeature biosensors made from materials such as graphene [70], carbon nanotubes [71], gold nanoparticles [72], and polymer nanocomposites. Recent progress includes blood tests employing nanotechnology that can identify serious pregnancy abnormalities before they exhibit any obvious symptoms. These tests use nanostructured platforms, like the NanoVelcro Chip, to collect rare trophoblast cells from the placenta found in the mother's blood [73], [74]. This approach provides a more precise initial diagnosis of placenta accreta spectrum disorders than traditional ultrasound examinations [75]. Furthermore, newly engineered rapid nanosensors can detect symptoms of preeclampsia, gestational diabetes, fetal growth restriction, and preterm labor during the first trimester, thereby facilitating early risk evaluation and the implementation of preventive strategies [76], [77]. Through enhanced diagnostic sensitivity and ongoing assessment, nanotechnology is improving maternal-fetal monitoring and prenatal imaging.

The application of functionalized nanoprobes and nanoparticle-based contrast agents in MRI and ultrasonography can refine fetal and placental imaging, thereby facilitating earlier and more accurate detection of structural and developmental anomalies [78]. Moreover, innovative wearable and wireless nanosensor technologies are emerging [79]. These are designed to track the well-being of mothers and babies in real-time, eliminating the need for invasive methods. This advancement allows for constant monitoring of pregnancy health, extending beyond the limits of traditional medical settings. These advancements collectively underscore the increasing significance of nanotechnology within prenatal care, particularly concerning early detection and diagnosis. Furthermore, they emphasize the necessity for further evaluations of safety, placental interactions, and clinical applicability prior to its widespread implementation.

9. Portable and Handheld Technologies Enhancing Maternal and Fetal Health

Recent advancements in diagnostic methods using nanotechnology have led to the quick manufacturing of portable and handheld devices. These devices are designed to promote maternal and fetal health during pregnancy. Portable fetal Doppler technologies and compact fetal heart rate monitors have made it possible to monitor a baby's heartbeat without direct contact [80]. Portable ultrasound systems [81] (Figure 10) enable imaging of the fetus, facilitating both home-based and remote applications. These devices, which do not utilize nanotechnology, are gaining significance in decentralized prenatal care due to their capacity to enhance accessibility, offer early confirmation of fetal well-being, and permit more frequent monitoring beyond conventional clinical environments. In the future, integrating wearable nanomaterials, advanced data analysis, and biosensors with nanoscale features into these portable devices could greatly improve real-time monitoring, diagnostic accuracy, and individualized prenatal care.

(a) **(b)**

Figure 10. Commercial handheld devices: (a) FetalPlus fetal doppler [80] and (b) Pulsenmore ultrasound [81].

10. Conclusion and Future Directions

Nanotechnology is revolutionizing prenatal care by facilitating ultra-sensitive detection, improved monitoring, and the early prediction of maternal and fetal complications. Nano-enabled biosensors, microfluidic platforms, and diagnostic tools incorporating nanomaterials have demonstrated considerable promise in addressing the shortcomings of conventional pregnancy tests and monitoring methods, particularly during the initial phases of gestation. Furthermore, advancements like wearable nanosystems and nano-engineered blood tests are providing novel opportunities for minimally invasive, real-time, and personalized prenatal care. The growing demand for decentralized, home-based prenatal care is further evidenced by the rapid advancement of portable and handheld technologies designed for fetal and maternal monitoring. Although these devices may not directly incorporate nanoscale elements, their functionality can be enhanced through integration with wireless platforms, sophisticated data analytics, and nanotechnology-driven sensors, thereby improving the precision of continuous monitoring and diagnostic capabilities. Further research should focus on improving biocompatibility, safety, and clinical validation, along with creating regulatory guidelines for using nanomaterials during pregnancy. Wearable technology, nanotechnology, and portable testing methods offer the potential to make prenatal care more personalized, preventive, and predictable.

Author Contributions

Both authors contributed equally to the conceptualization, data collection, and writing of this manuscript.

Conflict of Interest

The authors declare no conflicts of interest.

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Data Availability Statement

All data analyzed during this study are included in this published article.

Abbreviations

Human Chorionic Gonadotropin (hCG), Last Menstrual Period (LMP), American College of Obstetricians and Gynecologists (ACOG), National Institute of Child Health and Human Development (NICHD), Human Placental Lactogen (hPL), Gold Nanoparticle (AuNP), Lateral-flow Immunoassay (LFA), Paper-based Microfluidic Devices (µPADs), Point-of-Care Testing (POCT), Lab-on-a-Chip (LOC), Tumor Necrosis Factor-alpha (TNF-α), Umbilical Cord Compression (UCC), Artificial Rupture of Membranes (AROM), Cardiotocography (CTG), Fetal Heart Rate (FHR), Contraction Stress Testing (CST), Biophysical Profiling (BPP), Electrocardiography (ECG), Photoplethysmography (PPG).

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Review Article

Application of Nanomaterials for Improving the Tribological Performance of Oil and Gas Equipment

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Abstract

Oil and gas equipment, during its operational lifespan, encounters a multitude of natural and technological influences, which subsequently alter its functional capabilities, thereby precipitating defects and failures. A principal contributor to the malfunctioning of the working surfaces within wellhead components, such as Christmas tree assemblies and gate valves, is wear, which is generated by elevated pressure and friction. Understanding wear's properties and working principles is vital for improving equipment reliability, extending its lifespan, and increasing operational efficiency. Recently, using nanoparticles has been a key area of research for improving tribological processes. Nanoparticle-based lubricant additives, nano-scale ceramic reinforcements, and high-hardness nanocomposite coatings like TiN, CrN, DLC, and AlTiN, reduce energy losses caused by friction, minimize micro-wear on contact surfaces, and improve mechanical durability. These nanotechnology solutions significantly enhance the tribological performance of contact zones in wellhead equipment, which leads to a longer operational lifespan. Studies exhibit that machinery with nanostructured surface coatings experiences less wear over time and maintains consistent mechanical properties, even when subjected to pressures as high as 105 MPa. The use of these nanostructured coatings helps to reduce early defects, improve the control of friction-related factors, and notably lower the chance of equipment failure.

Keywords: christmas tree assembly, gate valve, tribological parameters, nanocomposite coatings, wear volume, wear rate

1. Introduction

Gate valves are fundamental components in the wellhead systems of industrial and oil production operations. These valves work in environments with high pressure, fast flow, turbulence, and aggressive chemicals. These harsh conditions increase frictional energy losses on the valve's working surfaces, which leads to faster wear over time [1].

This study investigates how wear rate and wear volume change over time in gate valves, which are used at pressures up to 105 MPa [2]. Gate valves work by moving a disc or wedge-shaped sealing element vertically, and they are mainly designed to be either fully open or fully closed. Although friction is low when the valve is fully open, it increases significantly when the valve is closed. This is due to the concentrated contact stress, which leads to considerable wear [3].

2. Wear Analysis of Gate Valve Components

During the design of gate valves, accurately assessing mechanical and tribological stress in friction areas is vital. At this stage, engineering solutions using nanotechnology have become increasingly relevant, including:

Nano-scale hard coatings
(diamond-like carbon (DLC), titanium nitride (TiN), chromium nitride (CrN), aluminum titanium nitride (AlTiN))
- Strong hardness and low friction
- Higher corrosion resistance
- Lower micro-wear on working surfaces

Nanocomposite reinforcements
(titanium silicon nitride (Ti–Si–N) and chromium aluminum nitride (Cr–Al–N))
- Strong resistance to impact loads
- Thermal stability at higher temperatures

Nanoparticle-enhanced lubricants
(molybdenum disulfide (MoS_2), tungsten disulfide (WS_2), graphene (C_n), titanium dioxide (TiO_2), Copper (II) oxide (CuO) nanoparticles (NPs))
- 20-40% less friction
- Lower wear rate [4].

3. Effect of Nanomaterials on Wear Reduction

These nanotechnology-based approaches significantly minimize wear, potentially extending the lifespan of equipment by 1.5 to 3 times [5].

In this research, the change in wear volume over a period of 9 years (scale factor: 1/720) and the influence of nanomaterial application on this trend were comparatively analyzed. Results indicate that surfaces modified with nanocomposite coatings demonstrate significantly lower wear compared to conventional metallic surfaces, ensuring long-term functional reliability of Christmas tree components [6].

Wear rate over a period of 1 month: $V_{y1} = \frac{0.05}{1} = 0.05$ µs (1)

Wear rate over a period of 2 months: $V_{y2} = \frac{0.2}{2} = 0.1$ µs (2)

Wear rate over a period of 3 months: $V_{y3} = \frac{0.36}{3} = 0.12$ µs (3)

Wear rate over a period of 4 months: $V_{y4} = \frac{0.6}{4} = 0.15$ µs (4)

Wear rate over a period of 5 months: $V_{y5} = \frac{0.75}{5} = 0.15$ µs (5)

Wear rate over a period of 6 months: $V_{y6} = \frac{0.72}{6} = 0.12$ µs (6)

Wear rate over a period of 7 months: $V_{y7} = \frac{0.7}{7} = 0.1$ µs (7)

Wear rate over a period of 8 months: $V_{y8} = \frac{0.64}{8} = 0.08$ µs (8)

Wear rate over a period of 9 months: $V_{y8} = \frac{0.72}{9} = 0.08$ µs (9)

The symbol "µs" means microsecond.

These results are presented in Figure 1 [7]. Also, Table 1 presents the time-dependent wear rate in conventional wells. Figure 2 presents the time-dependent wear volume in conventional wells [8].

Table 1. Time-dependent wear rate in conventional wells.

Jy (mkr)	0.05	0.2	0.36	0.6	0.75	0.72	0.7	0.64	0.72
t-(sec)	1	2	3	4	5	6	7	8	9
$V_Y(mkr/sec)$	0.05	0.1	0.12	0.15	0.15	0.12	0.1	0.08	0.08

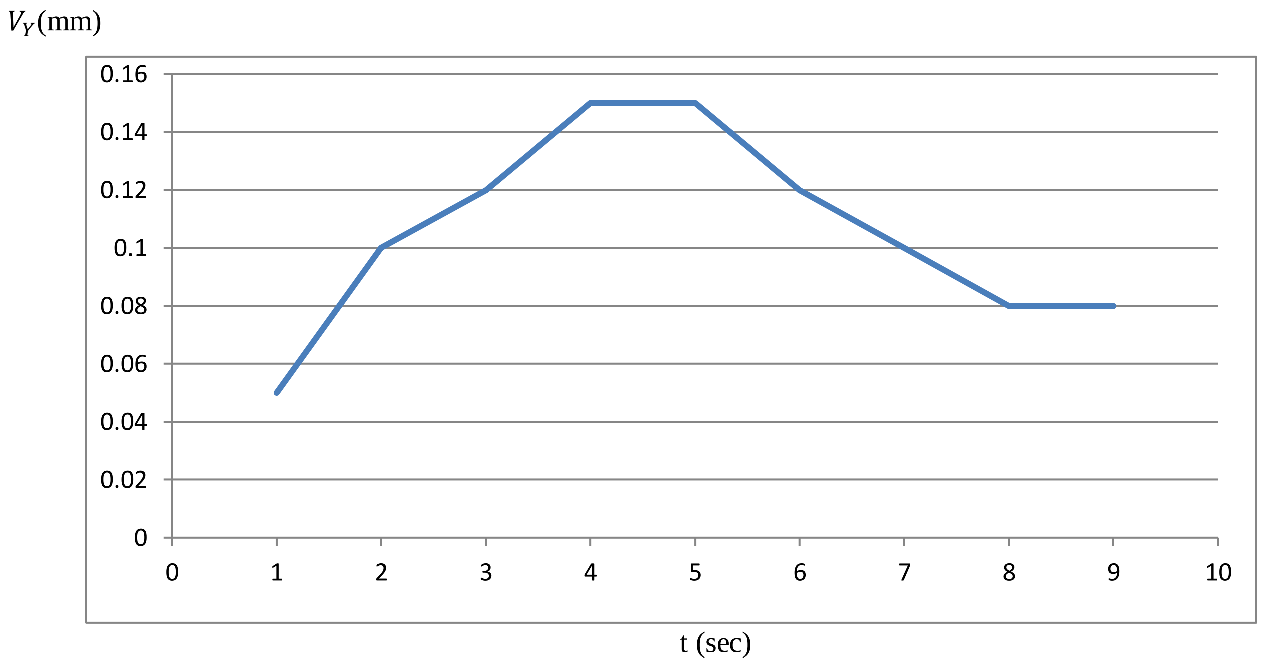

Figure 1. Time-dependent wear rate in conventional wells.

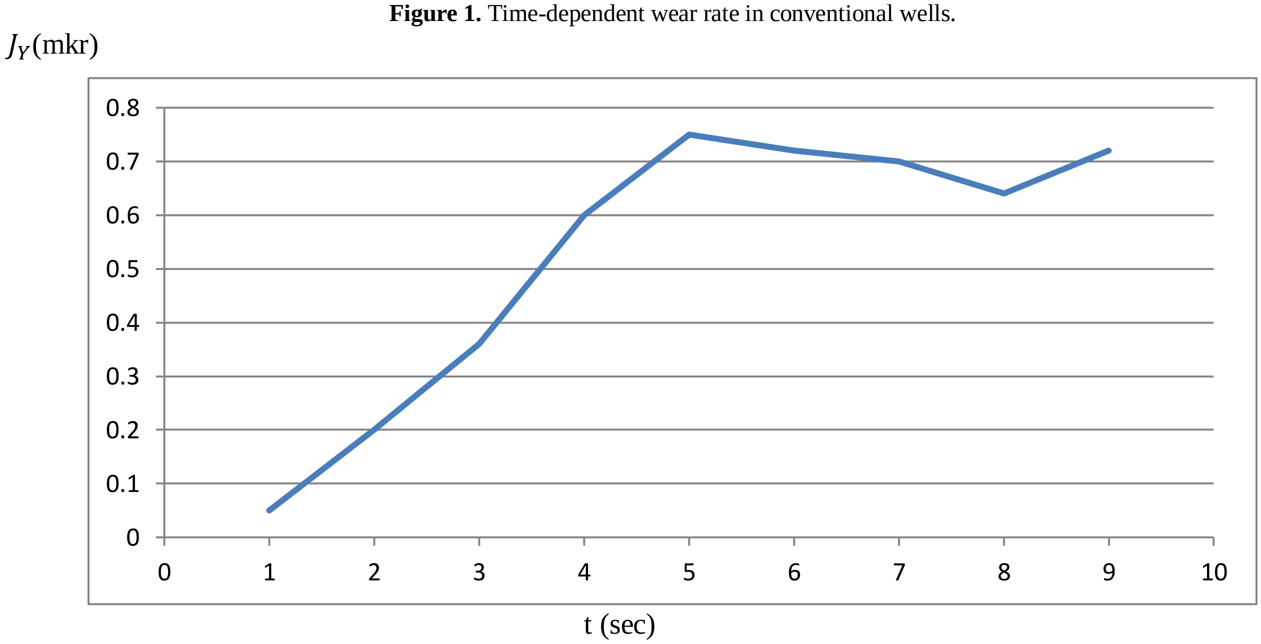

Figure 2. Time-dependent wear volume in conventional wells [8].

The wear rate in sandy wells is analyzed. Based on the wear volume, the wear rate is determined over a period of 9 months.

Wear rate over 1 month: $V_{y1} = \frac{0.5}{1} = 0.5$ mkr/sec (10)

Wear rate over 2 months: $V_{y2} = \frac{0.12}{2} = 0.6$ mkr/sec (11)

Wear rate over 3 months: $V_{y3} = \frac{0.27}{3} = 0.9$ mkr/sec (12)

Wear rate over 4 months: $V_{y4} = \frac{0.36}{4} = 0.9\ \mathrm{mkr/sec}$ (13)

Wear rate over 5 months: $V_{y5} = \frac{0.3}{5} = 0.6\ \mathrm{mkr/sec}$ (14)

Wear rate over 6 months: $V_{y6} = \frac{0.36}{6} = 0.6\ \mathrm{mkr/san}$ (15)

Wear rate over 7 months: $V_{y7} = \frac{0.35}{7} = 0.5\ \mathrm{mkr/san}$ (16)

Wear rate over 8 months: $V_{y8} = \frac{0.16}{8} = 0.2\ \mathrm{mkr/san}$ (17)

Wear rate over 9 months: $V_{y9} = \frac{0.18}{9} = 0.2\ \mathrm{mkr/san}$ (18)

The obtained results are presented in Figure 3. Table 2 presents the time-dependent wear rate in sandy wells.

Table 2. Time-dependent wear rate in sandy wells [9].

$V_Y(\frac{mkr}{sec})$	0.5	0.6	0.9	0.9	0.6	0.6	0.5	0.2	0.2
t-(sec)	1	2	3	4	5	6	7	8	9
J_y (mkr)	0.5	0.12	0.27	0.36	0.3	0.36	0.35	0.16	0.18

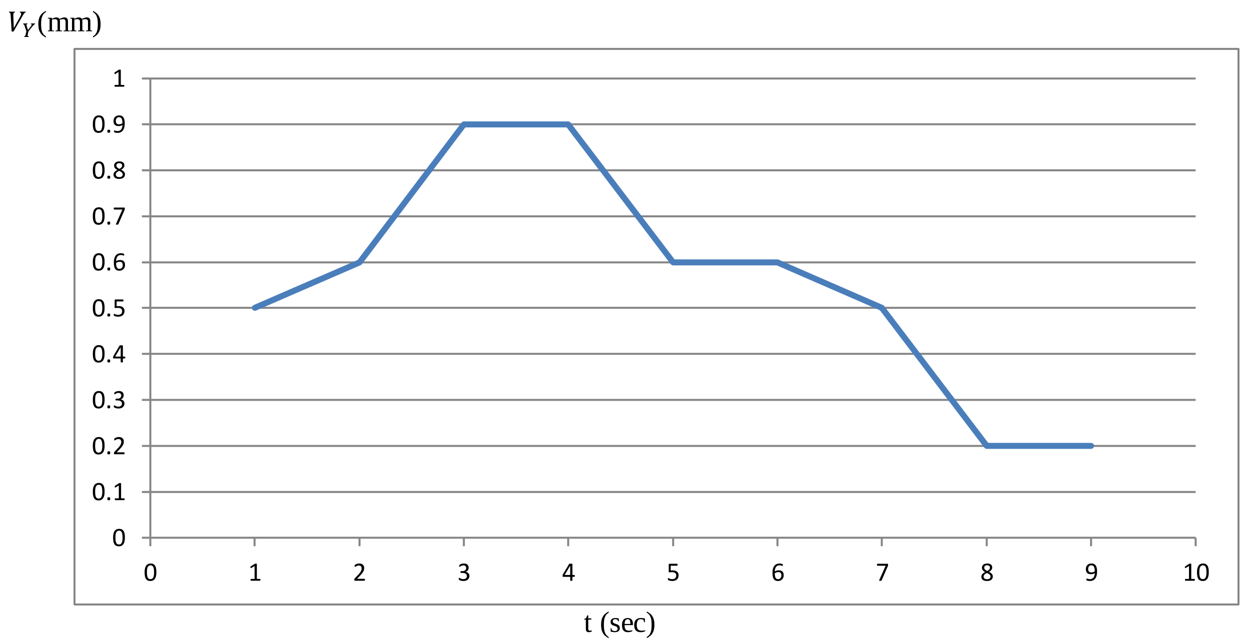

Figure 3. Time-dependent wear rate in sandy wells.

4. Conclusion

Under specific friction conditions, a material's resistance to wear is characterized by its wear resistance. Wear resistance is expressed as the inverse of the wear rate or wear volume and serves as a key parameter in evaluating tribological processes. An increase in temperature within the friction zone leads to changes in the physical and mechanical properties of the surface layers, resulting in structural weakening and, consequently, an increase in the wear rate.

The conducted studies indicate that, under various operating conditions and different friction pairs, similar types of micro-roughness form on the surface immediately after initial material processing. This demonstrates that, in the initial stage of the wear process, tribological behavior exhibits a certain degree of universal characteristics.

Author Contributions

The author confirm responsibility for the conception and final approval of the manuscript.

Conflict of Interest

The author declares no competing interests.

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Data Availability Statement

The author declares that the data supporting the findings of this study are available within the article.

Abbreviations

Diamond-like Carbon (DLC), Titanium Nitride (TiN), Chromium Nitride (CrN), Aluminum Titanium Nitride (AlTiN), Titanium Silicon Nitride (Ti–Si–N), Chromium Aluminum Nitride (Cr–Al–N), Molybdenum Disulfide (MoS_2), Tungsten Disulfide (WS_2), Graphene (C_n), Titanium Dioxide (TiO_2), Copper (II) Oxide (CuO), Nanoparticles (NPs).

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