STM JOURNALS

International Journal of
Radio Frequency Innovations

Volume 2, Issue 2, 2024
July–December
DOI (Journal): 10.37591/IJRFI

https://journals.stmjournals.com/ijrfi

Review IJRFI

Exploring the Potential of Laser Ablation for Multi-Functional Nanoparticle Production

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Abstract

The extraordinary class of materials known as nanomaterials has come into being. A large variety of elements with minimum one dimension between 1 and 100 nm are included. Reasonably designed nanomaterials can have exceptionally large surface areas. Outstanding magnetic, electrical, optical, mechanical, and catalytic capabilities that differ significantly from their bulk counterparts can be created in nanomaterials. To achieve the necessary features tuning, nanomaterials' size, shape, synthesis conditions, and proper functionalization can all be precisely controlled. One technique for creating several types of nanoparticles is laser ablation. These include core shell nanoparticles, semiconductor quantum dots, carbon nanotubes, and nanowires. Using this technique, species that have been laser-vaporized in a background gas nucleate and proliferate to form nanoparticles. By rapidly quenching vapor, high purity nanoparticles across the quantum size range (< 10 nm) can be produced. This paper reports the laser ablation method's benefits, including precise material removal, minimal heat damage, and applicability across various fields, highlight its potential as a key tool in nanoparticle synthesis and material processing.

Keywords: Laser ablation method, benefits, nanoparticle synthesis, material processing

INTRODUCTION

There are numerous unique characteristics of nanoparticles that are absent from bulk materials. The primary attribute of nanoparticles is their great dependence on their size and size distribution, which affects their electrical, optical, magnetic, and other capabilities. For instance, at room temperature, silicon nanoparticles exhibit photoluminescence in the visible spectrum; the particle size may be adjusted to change the wavelength of light emitted. Titania particles at the nanoscale have also drawn interest as potential components for photovoltaic and photocatalytic systems. Both crystal structure and particle size have a significant impact on the photochemical characteristics of titania nanoparticles. When a particle's size reaches the nanoscale, several different types of nanoparticles display unique properties (ferromagnetism, paramagnetism, pinned emission, fluorescence, spin quantum effect, etc. The distinctive characteristics are significantly influenced by the particle size and size distributions [1,7].

The bottom-up strategy has been used to produce a variety of liquid phase (sol-gel, chemical reduction, etc.) and vapor phase (physical/chemical vapor deposition, flame synthesis, etc.) nanoparticle production techniques. Every fabrication technique has benefits and drawbacks. At the laboratory scale, liquid phase technologies are economical and are employed to synthesize different types of nanoparticles with precisely regulated shapes. High purity nanoparticles can be synthesized more effectively using vapor phase methods thanks to its

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Received Date: August 28, 2024
Accepted Date: October 21, 2024
Published Date: November 23, 2024

Citation: Kaushki Kanna, Darshpreet Singh, Usha Shukla. Exploring the Potential of Laser Ablation for Multi-Functional Nanoparticle Production. International Journal of Radio Frequency Innovations. 2024; 2(2): 36–41p.

continuous flow reactor. The nucleation of supersaturated different species, which are created by precursor processes and/or solids disappearing in both liquid and gas bottom-up procedures, results in solid nanoparticles. Laser ablation is the process of ablating solid target materials with laser intensity. Laser is an acronym for light amplification by stimulated emission of radiation. This method involves concentrating incredibly high energy at a single spot on a solid surface in order to vaporize material that absorbs light. The removal of surface atoms is referred to as "ablation," and it includes both multiphoton excitation (thermal evaporation) and single photon processes (breaking chemical bonds). Laser ablation can produce high-purity nanoparticles because the target and ambient medium (gas or liquid) must be pure for the particles to be produced, with no reactor contamination.

However, the conventional laser ablation process makes it difficult to control size distribution, aggregation, and crystal structure since nanoparticles are created by the random (Brownian) motion of molecules. As a result, several sophisticated laser ablation methods have been created for creating nanoparticles with controlled shape.

Where are Nanomaterials Found?

A lot of commercial goods and processes now use engineered nanoparticles (EN), which are created for use in these kinds of processes. While some nanomaterials exist naturally, EN are of special importance. These materials are utilized in numerous commonplace products, including sunscreens, cosmetics, athletic goods, tires, stain-resistant apparel, and electronics. They are also utilized in medical for imaging, diagnostics, and medication administration.

Certain nanomaterials have been around for years or even decades, and they are currently being used in the commercial sector. Numerous consumer goods, including windows, sports equipment, bicycles, and cars, are using nano coatings and nanocomposites.

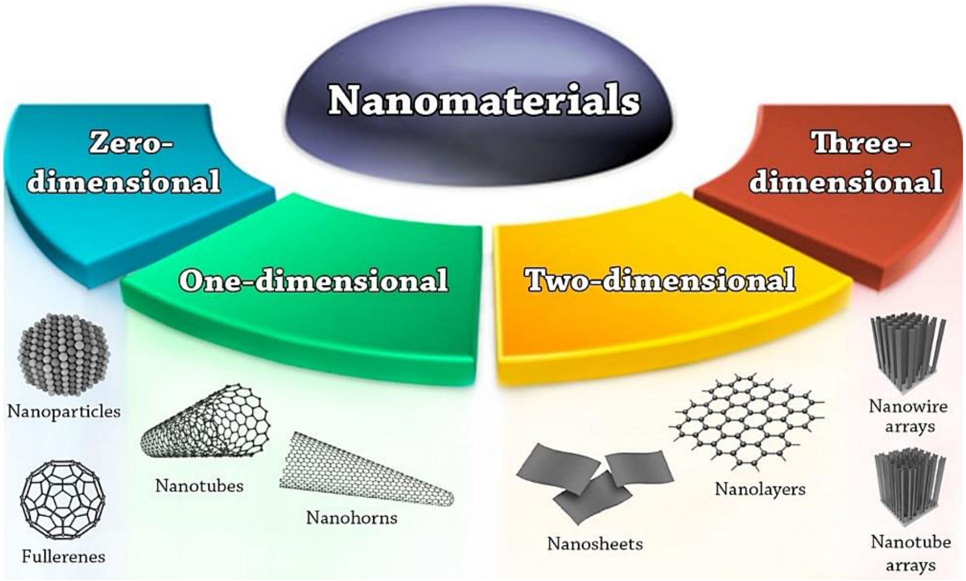

Figure 1. Classification of Nanomaterials.

Engineered nanomaterials are resources that are created at the molecular (nanometre) scale to benefit from their unique features and small size, which are typically absent from their bulk, conventional counterparts. Increased relative surface area and novel quantum phenomena are the two main causes of materials' variable characteristics at the nanoscale. Compared to their traditional forms, nanomaterials have a substantially higher surface area to volume ratio, which can increase their chemical reactivity and change their strength. Quantum effects can also play a significantly larger role in defining a material's properties and characteristics at the nanoscale, which can result in unique optical, electrical, and magnetic behaviours [11].

Materials with ultra-small grain sizes (less than 50 nm) or dimensionalities under 50 nm are referred to as nanomaterials. According to Richard W. Siegel, nanomaterials can be produced with one modulation dimension (multilayers), two modulation dimensionalities (ultrafine-grained overlayers or buried layers), three modulation dimensionalities (atomic clusters, filaments, and cluster assemblies), and zero (nanophase materials made of equiaxed nanometre-sized grains) as shown in Figure 1.

Although they have been employed for a wide range of purposes for a long time, nanomaterials are also present in nature. For instance, in the smoke from a fire, the sea breeze, and the clouds of ash left behind by volcanoes. The need for accuracy, sustainability, interdisciplinary cooperation, and application-specific innovations will influence the direction of research in nanomaterial synthesis in the future. New technology and uses in a variety of industries, including electronics, energy, and medical, will be made possible by these developments. Nanomaterials are finding more and more applications in the physical sciences. Energy is one key area where nanomaterials are present, including its conversion, storage, and harnessing [12].

Synthesis Methods of Nanomaterials

Compared to other particles of a similar size, nanomaterials exhibit distinct behaviours. Therefore, techniques for integrating and monitoring their effects on the environment and human health need to be created. To control the size and surface area of nanomaterials, synthesis procedures are essential [5]. The synthesis of nano dispersed particles, size and shape control, repeatability, large-scale synthesis, and the synthesis of complicated structures are a few of the main difficulties in the synthesis of nanomaterials [6].

There are different types of methodologies for synthesising nanoparticles, depending on how atoms, ions, or molecules are assembled, how bulk materials are divided, how the raw materials are generated, and how the protocol for synthesising nanoparticles is followed.

The synthesis of nanoparticles can be broadly divided into two categories:

1. Bottom-up methodology
2. Top-down methodology

BOTTOM-UP METHOD

Using this method, smaller building blocks like atoms, molecules, or clusters are assembled to create nanostructures. Short-range forces like van der Waals forces, electrostatic forces, and different interatomic or intermolecular forces cause these atoms or molecules to combine to produce nanometer-sized particles. The chemical production of nanoparticles is the primary application of the bottom-up approach. The primary advantages of the bottom-up approach are the creation of a wide range of nanoparticles with incredibly small to large scale sizes and a more uniform particle size distribution. Bottom-up methods are typically the most desirable for the synthesis of nanomaterials on an industrial and laboratory scale because they provide exact control over reaction conditions.

Top-Down Method

To create nanostructured material from large bulk material, size reduction methods like top-down or physical operations are employed. A big advantage of the top-down strategy is that it can synthesize enormous amounts of materials. It is challenging to regulate size and shape with this procedure, though. This technique is often helpful in the synthesis of nanostructured bulk materials rather than nanoparticle production.

The Process of Laser Ablation

Laser ablation production produces nanoparticles by striking the target material with a powerful laser beam. The source material or precursor vaporizer and forms nanoparticles because of the high energy of the laser irradiation throughout the laser ablation procedure [2].

The Fundamental Idea Behind Laser Ablation

When the laser beam is directed onto the surface of a solid target material in the surrounding media (gas or liquid), the target material vaporizes, and the internal temperature of the irradiated spot rapidly increases. A laser-induced plasma plume is created when the evaporated species (atoms and clusters) collide with the surrounding molecules, excitation of the electron state, light emission, and the creation of electrons and ions (Figure 2). Target material, surrounding medium (liquid or gas), surrounding pressure, and laser parameters all affect the plasma structures, which include the plume's size and emission spectrum. Figure 3 shows typical transmission electron micrographs of nanoparticles created by laser ablation of various materials. Producing a big plume and producing small particles is best achieved using laser ablation in low-pressure background gas (Figure 4(a)). To directly disperse nanoparticles in the liquid phase, the plasma plume is contained in a narrow area by laser ablation (Figure 4(b)). Nevertheless, because the laser-generated particles readily combine with surrounding molecules to form complexes like oxides and other unwanted species, the ambient media needs to be carefully chosen (Figures 4(b) and (c)). Another crucial process that needs to be carefully regulated in the last phases of nanoparticle creation is coagulation. Another crucial process that needs to be carefully regulated in the last phases of nanoparticle creation is coagulation. Agglomerated particles form chemical connections at the contact point (neck) of laser-generated particles, which seriously impairs the characteristics of the original particles due to their extremely clean surface. In addition to decreasing the size of the primary particles, the low-pressure gas technique also has the benefit of not causing coagulation.

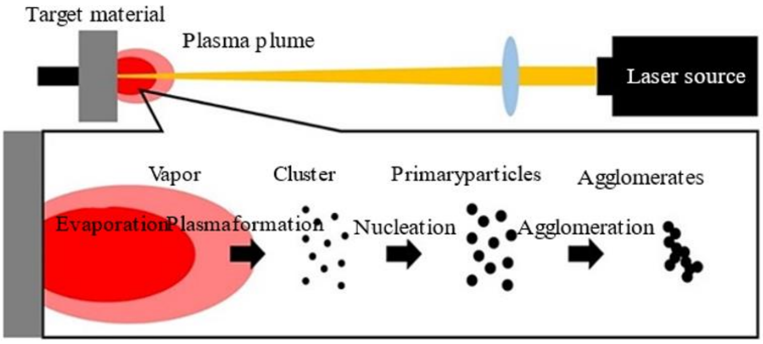

Figure 2. Schematic of particle generation procedure in the laser ablation process [1].

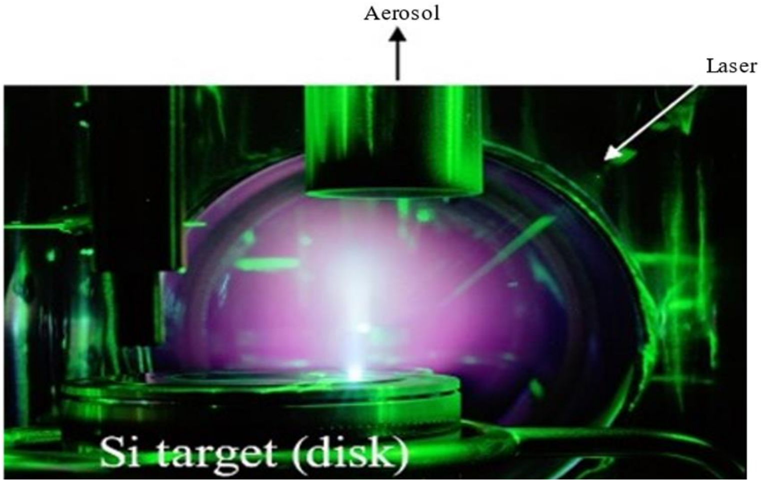

Figure 3. Laser-induced plume of silicon in low pressure [1].

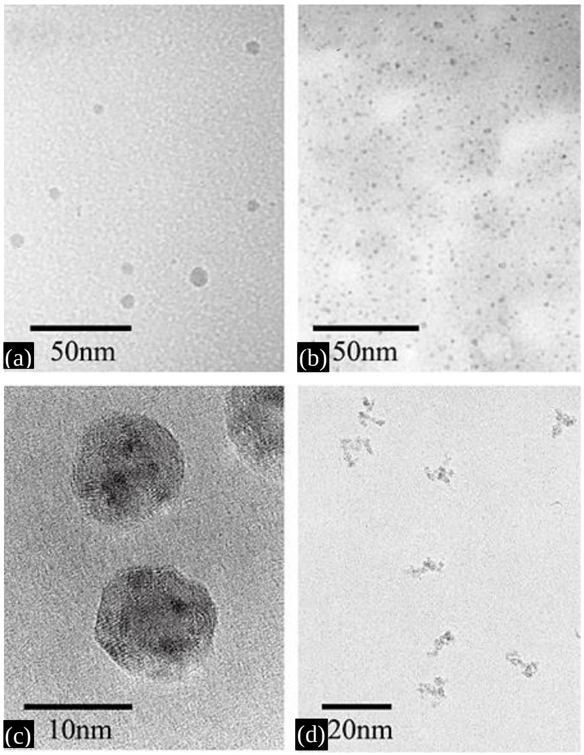

Figure 4. Typical transmission electron micrographs of laser ablation-generated (a) silicon, (b) carbon and (c) surface-oxidized nickel nanoparticles. (d) Aggregates of nickel nanoparticles as a result of coagulation and necking [1].

Since no additional chemicals or stabilizing agents are required to produce noble metal nanoparticles, using laser ablation for this process can be regarded as environmentally friendly. This method can be used to create a broad variety of nanomaterials, including oxide composites, metal nanoparticles, carbon nanomaterials, and ceramics [4]. Pulsed laser ablation in liquids is an interesting technique for generating monodisperse colloidal nanoparticle concentrations without the need of ligands or surfactants. By varying fluency, wavelength, and laser salt addition, the nanoparticle characteristics, including average size and distribution, may be adjusted [2].

Benefits of Laser Ablation Method

There are many advantages to laser ablation. It is easier to automate, provides accurate material removal with little heat damage, and is kinder to fragile or heat-sensitive materials. Because laser ablation produces less waste, it also helps to safeguard the environment [3].

1. A laser beam is used in the procedure known as "laser ablation" to remove material.
2. It is used in many different fields, including biology, chemical analysis, industrial, and medicine.
3. Benefits of laser ablation include environmental friendliness, minimum heat damage, and exact material removal.
4. Drilling, texturing, cleaning, and laser marking are examples of industrial applications.
5. One economical and effective method for treating materials is laser ablation.

CONCLUSIONS

The laser ablation method proves to be a versatile and effective technique for synthesizing a wide range of nanoparticles, including core-shell nanoparticles, semiconductor quantum dots, carbon nanotubes, and nanowires. This method's ability to precisely control nanoparticle size and shape, combined with its capacity to produce high-purity nanoparticles, underscores its significance in the field of nanomaterials. The laser ablation process, which involves the vaporization of a solid target material by a high-energy laser beam, offers several advantages, such as minimal contamination and the absence of additional chemicals or stabilizing agents, making it an environmentally friendly approach. But there are still issues with managing size distribution, aggregation, and crystal structure, which calls for the creation of sophisticated laser ablation methods. Despite these challenges, the laser ablation method's benefits, including precise material removal, minimal heat damage, and applicability across various fields, highlight its potential as a key tool in nanoparticle synthesis and material processing. Future studies should concentrate on improving the method to get over present restrictions and broadening its use in cutting-edge technologies.

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