Nanoparticle design by gas-phase synthesis

Panagiotis Grammatikopoulosa, Stephan Steinhausera, Jerome Vernieresa, Vidyadhar Singha and Mukhles Sowwanb

aNanoparticles by Design Unit, Okinawa Institute of Science and Technology (OIST) Graduate University, Okinawa, Japan; bNanotechnology Research Laboratory, Al-Quds University, East Jerusalem, Palestine

ABSTRACT
Gas-phase synthesis characterizes a class of bottom-up methods for producing multifunctional nanoparticles (NPs) from individual atoms or molecules. This review aims to summarize recent achievements using this approach, and compare its potential to other physical or chemical NP fabrication techniques. More specifically, emphasis is given to magnetron-sputter gas-phase condensation, since it allows for flexible growth of complex, sophisticated NPs, owing to the fast kinetics and non-equilibrium processes it entails. Nanoparticle synthesis is decomposed into four stages, i.e. aggregation, shell-coating, mass-filtration, and deposition. We present the formation of NPs of various functionalities for different applications, such as magnetic, plasmonic, catalytic and, gas-sensing, emphasizing on the primary dependence of each type on a different stage of the fabrication process, and their resultant physical and chemical properties.

CONTACT Mukhles Sowwan mukhles@oist.jp

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1. Introduction

Nanoparticles (NPs) have been extensively investigated as functional building blocks in various areas of nanoscience and biotechnology. With sizes typically ranging from 1 to 100 nm, nanomaterials exhibit size-, shape-, and composition-dependent behavior different from their bulk counterparts [1,2], which, for instance, influences structural transformations during reduction and oxidation reactions [3–5], catalytic activity [6–8], and magnetic [9,10] as well as optical [11–13] properties. Thus, NPs can be designed according to the requirements of specific applications. Advances in synthesis methods have led to various types of nanostructures ranging from monometallic spherical NPs [14] to nanoalloys [15] including phase-separated structures such as core/shell or Janus NPs [16–19]. The techniques employed for fabrication of nanomaterials are typically classified into two categories, i.e. bottom-up and top-down methods. The latter utilize material removal from a larger substrate, whereas bottom-up nanofabrication is based on the assembly of nanomaterials from smaller components [20].

This review is dedicated to gas-phase NP fabrication, a bottom-up method where metallic or semiconductor clusters are formed from individual atoms or molecules. NP synthesis is determined by cluster coagulation, coalescence and surface growth and can be controlled by parameters such as vapor concentration, temperature, or pressure [21]. We will highlight recent advances in gas-phase synthesis of NPs, in particular using magnetron-sputter inert-gas condensation, a well-established method with high relevance for industrial applications [22], suitable for the realization of mono-, and multi-component NPs with a high degree of deposition parameter control [22–24]. Specifically, we will present various features of the method through case studies, and correlate them with the resultant structures and corresponding physical properties; in doing so, we will also give a brief overview of previous work related to each specific class of physical properties.

2. The gas-phase synthesis method

Magnetron-sputtering has been widely used to synthesize single- and multi-component NPs via subsequent inert-gas cooling and gas-phase condensation of the sputtered atomic vapor. Following the work of Haberland et al. [25], rapid progress in NP synthesis using magnetron-sputtering has been made; in-depth theoretical studies elucidated the main principles of particle formation [26,27] and numerous technologically advanced variations of NP fabrication systems, e.g. comprising improved geometries, pulsed plasma or multiple-target usage, enabled high cluster yields, post-deposition thermal treatment, oxidation control, etc. [28–38]. Here, we do not aspire to offer an exhaustive review on the technique; for this, the interested reader can resort to dedicated literature [21,39,40]. However, a qualitative description of the NP synthesis process is useful to showcase how it can offer good control on NP size, crystallinity, and, most importantly, functionality.
Figure 1. Schematic representation of magnetron-sputter inert-gas condensation NP deposition system.
A schematic representation of a high-vacuum gas-aggregation magnetron-sputter deposition system (Mantis deposition®) is shown in Figure 1. The apparatus is divided in four compartments with the cluster source and aggregation zone, shell-coater, quadrupole mass-filter (QMF), and main deposition chamber labelled A, B, C, and D, respectively. A high-purity target of a chosen material is placed on a DC magnetron-sputter source, inside a water-cooled aggregation chamber (A, in Figure 1). Inert gas, usually Ar, is fed into the reactor and heated into forming ionized plasma; other gases, such as He, or mixtures of gases may also be introduced. Plasma confinement is achieved on the target surface by placing a set of permanent magnets directly behind it. The resulting magnetic field acts as a secondary trap for plasma electrons, which modifies their trajectories into a cycloidal path, greatly enhancing the ionization rate of the sputtering gas. Energetic Ar+ ions strike the target material, generating free atoms for the cluster formation. In the first stage of the growth process, the hot sputtered atoms also collide with cold Ar atoms, leading to fast, exponential, cooling. This primordial stage is necessary to reach a suitable temperature that allows bond formation; upon cooling, sputtered atoms also collide with each other, forming nuclei seeds for cluster formation. Further growth occurs by more sputtered atoms landing on the nascent nanoclusters, and subsequently by collisions and coalescence of the nanoclusters [16]. A pressure differential between the aggregation zone (A) and the deposition chamber (D) drives the NPs away from the target, thus controlling the residence time in the growth chamber and the resultant NP size and crystallinity. If helium gas is also used, it raises the drift velocity (therefore, decreasing the residence time), leading to small, amorphous NPs [41]. Finally, the NPs exit the aggregation zone through an aperture in the reactor, forming a NP beam [42].

En route to the sample deposition chamber, the NP beam can be coated by additional linear magnetron-sputter sources in a shell-coater apparatus (B) positioned parallel to the flight direction of the beam. More details on shell-coating will be discussed later. An inline QMF, positioned immediately after, ensures the mass-selected nature of the deposition (C). Its function is based on the fact that the beam contains single-charged NPs, which maintain particular trajectories according to their mass-to-charge ratio. Applying an AC electric field between the four cylindrical rods of the QMF allows NPs of a desired size alone to pass through, forcing the rest to deviate from their initial trajectories and, consequently, to be filtered out [43]. Finally, the NPs are deposited on suitable substrates located on a rotating holder (for a more homogeneous deposition) inside the main chamber (D). The energy of landing can be controlled via a bias on the substrate, enabling to either embed or soft-land the NPs, according to the target application.

The main advantage of the magnetron-sputtering method is its inherent flexibility. It allows control over growth parameters such as magnetron power (and, therefore, sputtering yield), inert-gas composition and pressure (affecting cooling and growth rates), NP drift velocity (determining residence time, which affects NP size), and aggregation zone length (with potential effect on NP sizes). The
use of alloy targets or additional sputtering sources allows for the design of multi-component NPs with tunable composition, structure, and crystallinity, whereas control techniques employed after NP growth, such as in situ mass filtration, and deposition-temperature and -energy control, offer practically endless possibilities for the design and facile, one-step synthesis of tailored NPs. In the next sections, we will examine how this flexibility translates into suitable NP properties for targeted applications.

3. Magnetic nanoparticles

Magnetic nanomaterials combining the merits of two or more compounds have received particular attention for various applications due to their enhanced properties over their individual components [44]. Currently, true magnetically soft nanoalloys are used in many applications, such as for MRI imaging [45] or cancer treatment [46]. Simultaneously, magnetically hard NPs have attracted increasing interest due to their potential for next-generation high-density recording media or nano-composite magnets [47].

Traditional synthesis methods face the long-established challenge of preparing true nanoalloys with efficient morphological control and stability. In fact, when bimetallic systems are considered at the nanoscale, oxidation [48], phase segregation [10], post-annealing sintering [49] and agglomeration owing to inter-particle magnetic interactions are expected, resulting in alteration of magnetic properties and raising the question of feasibility of soft/hard magnetic alloys [50]. Magnetron-sputtering, however, involving fast kinetics and non-equilibrium processes may overcome such problems, offering flexible design opportunities.

3.1. Soft magnetic nanoparticles

In addition to the applications mentioned above, soft magnetic nanoalloys have long generated vivid interest as candidate materials for low-consumption and high-performance inductors, magnetic sensors, transformers, etc. [51,52]. For this reason, aluminides of transition metals (Fe, Ni, Co) are promising materials due to their excellent oxidation resistance [53]. A detailed review on the correlation between magnetic and structural properties of gas-phase fabricated, soft magnetic nanoalloys can be found in [54]. Recently, we exploited the possibility of simultaneous co-sputtering of two independent, neighboring targets to synthesize intermetallic FeAl NPs, whose components are partially bulk-miscible [55]. The resulting NPs consist of a nanoalloy of an iron aluminate crystalline core (DO3 phase) encapsulated in an alumina shell (Figure 2(a) and (b)) that reduces inter-particle interactions and prevents further oxidation and segregation of the FeAl core. Chemical composition and size uniformity were demonstrated using electron energy loss spectroscopy (EELS) and scanning electron microscopy (SEM) techniques, as shown in Figure 2(c) and (e), respectively. Interestingly, by securing
the appropriate experimental conditions, i.e. choosing the density of each species through independent control of the DC magnetron power, it is possible to tune the morphology, composition, and crystalline structure of the intermetallic NPs. The initial, hot stage of growth controls primary alloy formation, followed by a segregation mechanism during cooling, which defines the eventual core-shell morphology. In addition to FeAl NPs showing soft magnetic behavior (Figure 2(f)), the core-shell morphology demonstrated a capability to stabilize these properties over a long period of time (Figure 2 (inset in (f)). Knowing that stability against oxidation [56,57] and decreasing interactions are essential to form soft magnetic NPs, gas-phase synthesis via a single-step process appears suitable for various magnetic applications.

### 3.2. Hard magnetic nanoparticles

In view of their applications for magnetic storage media [58,59], one critical requirement for hard magnetic materials is to own very high magnetocrystalline...
anisotropy energy (MAE) density. As explained previously [60], high magnetocrystalline anisotropy mainly stems from the magnetic polarization and large spin-orbit coupling involved in compounds containing 5d elements, such as FePt or CoPt. Qiu et al. reported on the fabrication of CoPt NPs by a combination of gas-phase NP deposition and on-line heating [61], whereas Poulopoulos et al. used e-beam evaporation to grow polycrystalline Pt–Co multilayers with intentionally alloyed layers for high-density magnetic recording [62]. The need for a post-annealing process [63,64] to synthesize the L10 phase of FePt makes these alloys less attractive. However, an optimized approach for the single-step synthesis of FePt NPs suitable for applications has been reported by Wang et al. [65], using a modified inert-gas phase condensation method. Adjusting the plasma confinement, they reported the synthesis of monodispersed, highly ordered L10-phase FePt NPs with very high crystalline anisotropy. More recently, using a similar modification, Akdogan et al. [66] reported FePt nanocubes and rods showing strong dependence of magnetic behavior on the ordering parameter. Another approach in hard magnetic materials is to use rare earth transition metals (SmCo, YCo, etc.) which, at the bulk scale, are well-known for their high room temperature magnetic anisotropy constants, high Curie temperature, and appreciable magnetic polarizations; however, at the nanoscale, their utilization remains challenging due to the need for high temperature annealing [67] and oxidation protection. Recently, Balamurugan et al. fabricated YCo [68] and SmCo NPs [69] using cluster source

**Figure 3.** Morphology and magnetic properties of YCo NPs. (a)–(b) TEM micrographs, using two sputtering powers, 120 and 150 W, respectively. (c)–(d) Corresponding size distributions of (a)–(b). (e) TEM image with higher magnification, where the inset shows the hexagonal shape of enlarged NP under 150 W. (f) HRTEM image of YCo5 NP prepared at 120 W. Hysteresis loops for (g) disordered YCo5, (h) ordered Y2Co17 and (i) ordered YCo5 NPs, measured at 300 and 10 K. (j) Estimation of magnetic anisotropy constant (K1) for YCo5 NPs at room-temperature from approach to saturation.

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deposition. By adjusting the experimental parameters, they reported faceted YCo₅ NPs with high degree of ordering and a hexagonal phase (see Figure 3(a)–(f)). The magnetic properties shown in Figure 3 reveal the close relationship between the crystalline nature and coercive field of these NPs. Further works on magnetic NP assemblies, showing enhancement and stabilization of their high anisotropy via embedding in amorphous matrices [47,68,70] and controlling the interparticle interactions [70], make the gas-phase synthesis method one of the most promising techniques for future high integration density devices.

4. Plasmonic nanoparticles

From an electromagnetic viewpoint, metals liken plasmas; resonant modes that involve the interaction between their free charges and light are called plasmons, determining their optical behavior, such as colour or reflectivity [71]. Structuring
a metal changes its plasmonic response; metallic NPs are a class of such structured metals. Their optical response is maximized together with their polarizability leading to size- and shape-determined localized surface plasmon resonance (LSPR). In order to optimize the localization and enhancement of the field associated with the LSPR, asymmetric NPs are favorable. As an example, Tao et al. [72] demonstrated the shape dependence of scattering in Ag NPs (Figure 4). Ellipsoidal NPs exhibit up to three dipolar resonances associated to their three axes, with red and blue shifts for the major and minor axis, respectively. In addition, coupling between LSPR modes of neighboring NPs can lead to a hybridization effect, producing new modes with a very broad spectral range.

Alternatively, one can modify the NP composition, adding extra functionalities by coating with a second material; various types of hybrid plasmonic NPs have been studied, including core/shell [73], nanocages [74], etc. Typical potential applications include photovoltaic solar cells [75] or biological microscopy, biosensing, and medicine [76–79]. Hybrid NPs can be either of metal–metal or metal–dielectric type. In the latter, the effect of the dielectric phase on the plasmon response is to red-shift it by increasing the local refractive index adjacent to the metallic phase. Simultaneously, if a hermetic core/shell structure is obtained, a dielectric shell can prevent NP aggregation, protecting the LSPR and maintaining a controlled interparticle plasmon resonance. In the case of in vivo biological applications, a dielectric shell can enhance biocompatibility (e.g. for Ag NPs) [80]. SiAg NP functionalization for drug-delivery and cancer therapy also requires well-controlled hybrid nanostructures, offering simultaneous bioconjugation of various moieties with the different surface chemistries of Si and Ag [81].

Most plasmonic NP studies reported so far involve either top-down synthesis by lithography approaches (such as electron beam lithography or focused ion beam), which are accurate but expensive, slow and for limited production, or bottom-up wet-chemistry approaches; mainly chemical deposition, electrolysis, reduction of ionic compounds in solution, galvanic replacement, etc. For a comprehensive review on synthesis methods, the interested reader can refer to [71,82,83]. All these methods require multiple steps; therefore, facile gas-phase synthesis presents an attractive alternative. However, to date, a small number of case studies have been reported utilizing different gas-phase techniques [84,85]. For example, Sotiriou et al. [86] utilized flame spray pyrolysis to fabricate Ag NPs dispersed in amorphous silica, whereas Boies et al. [87] reported on Au-decorated silica NPs by a combination of chemical vapor synthesis and gas-phase evaporative techniques. Harra et al. used aerosol techniques to synthesize Ag NPs of controlled size, thus tuning the dipolar peak of the LSPR (Figure 4) [88].

Our group recently reported on the controlled growth of heterostructured photoluminescent-Si/plasmonic-Ag hybrid-NPs by two methods, yielding different morphologies. First, we co-deposited NPs from two neighboring single-element Si and Ag targets [19], as in the case of FeAl magnetic NPs mentioned above. Owing to the distinct plasma regions for each species and the low affinity between
the two atom types, Si and Ag nascent nanoclusters grew separately. Hybrid NPs formed later, when the nascent clusters were mixed in the cool aggregation zone. Depending on magnetron power values, two types of structures were attained: core-satellite and Janus hybrid NPs; Janus structures resulted from initially higher Ag-atom number densities, leading to larger Ag primary clusters (Figure 5(a) and (d)). Representative bright-field HRTEM and high-angle annular dark-field scanning-TEM (HAADF-STEM) images are shown in (b)–(c) and (e)–(f), revealing crystalline-Ag and amorphous-Si domains.

Alternatively, we coated freshly nucleated Si nanoclusters with Ag atoms using the shell-coater (B, Figure 1) [42]. As with co-sputtering, the resultant structure was of a Si-core/Ag-satellite form. In this case, however, both Si-core and Ag-satellites showed crystallinity. Remarkably, the number of crystalline domains in the underlying Si-core matched the number of Ag-satellites, as shown in Figure 5(i), showing a high-resolution HAADF-STEM micrograph of a Si NP decorated by four Ag clusters and encapsulated by a ~2 nm oxide shell. The bright-field HRTEM image (h), taken with unchanged orientation with respect to the e-beam,
indicates the presence of three domains in the Si-core of different crystallographic orientations (indicated by arrows). Tilting the sample by $-15^\circ$ relative to the incident e-beam, however, revealed a fourth grain. This correlation, confirmed by close inspection of numerous NPs, enables control of the number of crystallographic domains by adjusting the shell-coater discharge power. What differentiates this method from co-sputtering is the low Ar-gas flow in the shell-coater, leading Ag to land on Si NPs as individual atoms; the Ag-satellites observed in Figure 5(h)–(i) formed after landing on the Si NPs, leading to a completely different interaction mechanism.

5. Nanoparticles for catalysis and gas-sensing applications

Nanoparticles can enhance both the activity and selectivity of heterogeneous catalysts [89], and the response time of gas-sensors [90]. Controlled gas-phase NP synthesis affords the possibility for subsequent size- or mass-filtration, as well as for controlled-energy deposition on selected supports for specific applications [91]. As a result, gas-phase synthesized size- or mass-selected NPs demonstrate excellent catalytic properties, ideal for applications in electrocatalysis and gas-sensing.

5.1. Electro-catalyst applications

Catalytic properties of NPs depend on their size and shape, as well as the interaction between NPs and metal-oxide supports [92–97]. Gas-phase synthesis of binary or core/shell NPs, apart from allowing good control over critical parameters such as particle size, shape, composition, density, and electrode coverage, avoids the inherent products introduced by chemical synthesis from precursors and surfactants. Gas-phase synthesized noble metal NPs, e.g. Au, Pt, Pd, Ru, etc. have been investigated as model systems for various electrocatalytic reactions [95–99]. For example, the influence of Au NP sizes has been investigated extensively, and maximum activity at optimum size has been reported for CO oxidation, alkane oxidation, and other reactions [98]. Chorkendorff et al. also examined mass-selected Pt$_x$Y alloy NPs for the electrocatalytic reactions and observed greatly enhanced activity as a result of compressive strain due to a core-shell structure [97]. In addition to the oxygen reduction reaction (ORR) and oxygen evolution reaction (OER), a comparison between activity and stability of gas-phase prepared size-selected Ru and RuO$_2$ NPs in acidic electrolyte has been investigated by Paoli et al. [96]. Srivastava et al. successfully used the gas-phase synthesis approach to improve the photocatalytic activities of size-selected TiO$_2$ nanoclusters [100]. They also studied the effects of TiO$_2$ nanocluster size for photocatalytic applications (Figure 6(a–d)). Better photocatalytic activity was found for smaller size TiO$_2$ nanoclusters, as a result of the increase in specific surface area and amorphicity in small nanoclusters. Combinations of noble metal and metal oxides could be useful in electrocatalytic reactions. For example, MnO$_x$, TiO$_2$, and MgO have been
extensively tested in alkaline solutions [100,101]. Gorlin et al. reported glassy carbon (GC)-supported Mn$_3$O$_4$ electrocatalysts for ORR, confirming that MnO$_x$ sites contribute to all steps in ORR [101]. More recent work by the same group showed that the combination of MnO$_x$ and Au leads to high OER activity, and identified the catalytically active site as the interface between the two materials [102]. The catalytic activity of MnO$_x$ was increased in hybrid nanocomposites on Au surfaces. Blackmore et al. also synthesized size-selected binary Pt–TiO$_2$ nanoclusters using gas-phase condensation, sputtered from single alloyed targets [95]. The resulting core/shell NPs, supported on GC electrodes, were reported to be an efficient catalyst for hydrogen evolution reaction.

Chemical and surface composition is the important factor prompting the catalytic activity of NPs composed of bimetallic species. For example, mass-selected PtRu NPs were synthesized via gas-phase co-sputtering of Pt and Ru from two independent neighboring targets [88]. A HAADF-STEM image of PtRu NPs is shown in Figure 6(e). A comparison of the catalytic activity of these NPs measured
in two different electrolytes (H$_2$SO$_4$ and HClO$_4$) is shown in Figure 6(f). Strong O$_2$ reduction was observed in H$_2$SO$_4$, starting at 0.6 V and resulting in a maximum current of −150 μA at an applied potential of 0.3 V.

Moreover, noble metal core@porous-oxide shell NPs can be synthesized based on the Kirkendall effect using the gas-phase condensation method [103]. Very recently, our group reported on Pd@MgO core/shell nanostructures with controllable morphology synthesized via a single-step heterogeneous gas-phase condensation method using two independent neighboring targets, and studied their catalytic properties [104]. The morphology of Pd@MgO core/shell NPs is strongly related to the sputtering power ratio. Figure 7(a)–(i) shows TEM images and cyclic voltammograms of these NPs, confirming their core/shell structure and
uniformity. The cores are single-crystalline Pd and the shells are polycrystalline MgO with porous structure. We dispersed this core/shell combination on glassy electrode and measured the ability of the immersed electrodes to improve the rate of the electrochemical reaction that occurs in methanol fuel cells (Figure 7(f)). Mass current density cyclic voltammogram curves are shown in Figure 7(g). The mass current density of the Pd@MgO NPs (420 μA μg⁻¹) was found to be higher compared to that of bare Pd NPs (120 μA μg⁻¹). These core/shell NPs promise to be highly active catalysts and the Pd core is accessible to the reactant and product molecules through the porous MgO shell. The MgO shell also helps to protect Pd NPs from sintering (inset Figure 7(g)). Furthermore, the observed shift in the onset potential is most likely associated with variations in the pH at the Pd surface of Pd@MgO/GC compared to the Pd/GC system (Figure 7(i)).

5.2. Gas-sensing applications

In the field of gas-sensing applications, chemiresistive metal-oxide NPs, as well as catalytic noble metal nanoclusters, are employed for the realization of conductometric sensor devices. The size, chemical composition and crystalline structure of these nanomaterials has to be specifically designed in order to achieve optimized gas-sensing characteristics [105]. As discussed above, inert-gas condensation is suitable for the controlled deposition of well-defined NPs required in advanced gas-sensing applications, as demonstrated in several literature reports. For example, thin films of size-selected tin oxide nanoclusters have been utilized as conductometric sensor devices [106] and NP size dependence [107] as well as in-flight annealing effects [108] have been studied. Furthermore, the authors of [109] reported titanium dioxide thin films for volatile organic compound sensing using size-controlled cluster beam deposition. By adjusting the growth conditions, they realized nanocrystalline particles without thermal annealing or doping processes, which are usually required when employing other deposition methods. Conversely, gas-phase deposition of rutile titanium dioxide clusters into an amorphous matrix was used to produce thin film arrays with varying rutile/anatase ratio after thermal annealing, which resulted in sensor elements with different methanol-sensing performances [110]. In Ref. [111], thin films of size-selected Pd NPs were found to be well suited for hydrogen detection and the effect of inter-particle gap distance on sensor characteristics was highlighted.

The gas-sensing properties of chemiresistors may be tailored by adding catalytically active nanoclusters to the sensor surface, which usually leads to a change of sensitivity, gas selectivity, and response/recovery times [90]. Recently, we reported on the sensing performance of single CuO-nanowire gas-sensor devices decorated with size-selected Pd NPs (~5 nm) [112] (Figure 8), which were used to detect CO concentrations of 100–300 ppm in humid synthetic air. Sensor devices with Pd NPs were found to show considerably enhanced sensor response (ratio of nanowire resistances with and without CO exposure) compared to pristine devices, which
Gas-phase synthesis is ideally suited for the decoration of gas-sensor devices with catalytic nanoclusters, as it offers the possibility of size selection, which is important because of the size dependence of NP catalytic activity [6–8]. Further advantages are high chemical purity due to the absence of organic solvents and CMOS compatibility, which enables future integration with standard semiconductor device technology. As a consequence, gas-phase synthesis shows high potential for the realization of miniaturized gas-sensor devices with improved performance.

6. Summary and perspectives

Gas-phase synthesis is a class of bottom-up methods for producing NPs. Especially magnetron-sputter inert-gas condensation offers plentiful possibilities for facile design of NPs with tailored properties and corresponding target applications; as such it is an attractive alternative to other multi-step physical and chemical synthesis techniques. A number of case studies were presented, where NP structure
was optimized to cater for specific magnetic, plasmonic, catalytic, and gas-sensing applications.

In parallel, it should be emphasized that, due to its flexibility, gas-phase synthesis is one of the most widespread methods for the production of multi-component NPs, such as multi-core/shell structures in which the cores can present either “dumbbell-like” or “onion-like” structures [113,114]. Such NPs afford the possibility of combining different classes of physical properties; an example of magneto-plasmonic NPs [115,116] using three separated target materials (Fe, Ag, and Si) simultaneously highlights the potential of a new generation of optimized NPs for future nanotechnologies and bio-applications. With applications ranging from semiconductor devices to capacitor dielectrics, from optical and anti-corrosion coatings to photo-catalysts and solar cells, and from bio-implantable devices to chemical reactors and catalysts, it is safe to assume that the industrial interest in NP technologies via gas-phase synthesis is only going to increase in the years to come.

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