This chapter begins with a brief introduction to metal nanoparticles and their synthesis, where, we have described some of the most prevalent chemical, biological and physical methods to synthesize the metal nanoparticles. This is followed by a detailed description of a novel, physical, top-down technique of electro-exploding wire (EEW) that we have developed in our laboratory and employed to synthesize the metal nanoparticles of Ag, Al, Cu, and Fe. Here, we have described the historical background of the EEW technique, followed by details of the design of the experimental set-up used and the mechanism involved in the EEW process, leading to the formation of metal nanoparticles. In the last section, we have discussed various parameters to control the process of EEW and merits of the EEW technique over other techniques.
2.1 Introduction

In some sense, synthesis and use of metal nanoparticles is not new. It is well known that even in the 4th century A.D. Roman glassmakers [1, 2] were fabricating glasses containing nanosized metal particles. These glass makers knew that small metal particles of Ag, Au and Cu, when embedded in glass impart beautiful colours to glass. The great varieties of beautiful colours of the windows of medieval cathedrals and Lycurgus cup (kept in British museum) are due to the presence of metal nanoparticles in the glass. Metal nanoparticles have been studied because of their diverse optical properties. These colours are not only absent for the bulk materials, but also for the atoms. The most notable colours are found in dispersions of gold, silver and copper. These days metal nanoparticles are in great demand not only because they emit beautiful colours of light but also due to their wide range of application in various fields, like, in catalysis, optoelectronics devices, bio-labeling, sensors, optical data storage, MRI contrast agent, magnetic recording media, as fuel in rocket propellant, environment remediator, in hemoglobinopathy [3-8], as described in detail in chapter 1.

As a result, a variety of chemical, biological and physical processes have been used to synthesize the metal nanostructures. These are broadly classified as top-down and bottom-up approaches. Bottom-up manufacturing involves the building of structures atom-by-atom or molecule-by-molecule. The wide variety of approaches involved in achieving this goal can be split into three categories: chemical synthesis, self-assembly and positional assembly. Positional assembly is the technique in which single atoms or molecules can be placed deliberately one-by-one. More typically, large number of atoms, molecules or particles are synthesized by chemical synthesis and then arranged through naturally occurring processes into a desired structure. Self assembly is a bottom-up production technique in which atoms or molecules arrange themselves into ordered nanoscale structures by physical or chemical interactions between the units. The formation of salt crystals and snowflakes, with their intricate structures, are examples of self-assembly processes. Although, self assembly has occurred in nature for thousands of years, the use of self assembly in human made nanomaterials is relatively new. There is an economic and environmental interest in processes through which materials or product components essentially form themselves, creating less waste and using less energy. Top-
down manufacturing involves starting with a larger piece of material and etching, milling or machining a nanostructure from it by removing extra material, for example, in circuits on microchips. This can be done by using techniques, such as, precision engineering and lithography, and has been developed and refined by the semiconductor industry over the past 30 years or so. Top-down methods offer reliability and device complexity, although, they are generally higher in energy usage, and produce more waste than bottom-up methods.

Here, we will discuss in brief some of the most popular chemical, biological, and physical methods used to synthesize metal nanoparticles and then the electro-exploding wire (EEW) technique, a physical top-down approach that we have established and employed to synthesize the metal nanoparticles of Ag, Cu, Al, and Fe. In this process, amount of waste products are negligible as compared to other physical methods to synthesize metal nanoparticles. The synthesized nanoparticles are free of any extraneous impurity, as no chemicals have been used during the synthesis of the metal nanoparticles. This we will discuss in details in the later part of the chapter but first, we will like to discuss some of the most prevalent chemical, biological and physical methods to synthesize the metal nanoparticles.

2.2 Chemical methods

Various chemical synthesis techniques have been proposed and many of them are widely practiced to fabricate nanostructured materials. Some of the most prevalent chemical routes to synthesize metal nanoparticles are discussed here.

**Sol-Gel method:** Metal nanoparticles (Ag, Cu, Fe etc.) are synthesized by mixing metal salt solution with tetra-ethylorthosilicate (Si(OC₂H₅)₄), ethanol and water then a few drops of HNO₃ as a catalyst (two or more chemical precursors, and a catalyst) to form a gel. The gel is dispersed and dried under pre-determined temperatures. The dried gels are further reduced at predetermined temperature in H₂ gas to synthesize the metal nanoparticles. Sol-gel technique [9, 10] in its present state encounters problems in providing a continuous size control and narrow size distribution.
**Chemical reduction:** In this process, reduction of metal ions by a strong reducing agent (e.g. NaBH₄) in a liquid phase leads to the formation of nanoparticles. The metal salt is dissolved in some solvent to form metal ions; then reducing agent is added to reduce the metal ions to form metal nanoparticles. Most of the metal nanoparticles Au, Ag, Cu etc. can be formed by employing this method [11-15].

**Reverse micelles/ microemulsion:** A microemulsion is a system of water, oil and an amphiphile (surfactant/ stabilizer). Metal nanoparticles can be prepared by simple mixing of two water-in-oil microemulsions, one containing a salt or a complex of the metal and the other containing a reducing agent, such as, sodium borohydride, hydrazine etc. In this process of metal nanoparticles synthesis, the size of the nanoparticles is controlled by the size of reverse micelles [16-18].

The major drawback of the chemical methods is low yield of nanomaterials. Other major disadvantages are contamination of the nanoparticles with chemicals, i.e., nanoparticles remain coated with chemical precursors involved in their synthesis. So, purity of nanomaterials synthesized by chemical methods has always been questionable.

**2.3 Biological methods**

Biological methods [19] for synthesis of metal nanoparticles (Ag, Au etc.) are relatively new but are claimed to be clean, nontoxic and environmentally benign. Microorganisms such as bacteria, yeasts, fungi, enzymes etc. are found as eco-friendly nanofactories and hence, are used for the biosynthesis of metal nanoparticles.

**Bacteria,** like, Bacillus subtilis 168, Pseudomonas stutzeri Ag259, Lactobacillus strains etc. when exposed to metal ions have the strength to reduce the metal ions to produce the metal nanoparticles [20, 21]. Similarly, **fungi** [22-24] like Verticillium sp. is used to reduce metal ions to produce nanoparticles. **Enzymes** [19] act as catalysts for the growth of metal nanoparticles. The enzyme-mediated growth of metal nanoparticles provides a general means to follow bio-catalyzed transformations, and to develop optical sensors for various applications. In biological methods, the monodispersity of the metal nanoparticles...
is far inferior and production rate is low to that obtained through conventional chemical or physical methods.

### 2.4 Physical methods

The synthesis of nanomaterials by physical methods can be broadly classified as originating from deposition, sputtering, ball milling and plasma based techniques. A brief account of the most practiced methods to prepare metal nanoparticles is given here.

**Ball milling:** High energy ball milling [25] has been used for synthesis of magnetic, catalytic, and structural nanoparticles. Here, milling of the bulk metals is done to produce the metal nanoparticles. Common drawbacks of the ball milling process include low surface area for milling, high polydispersity, contamination and the partially amorphous state of the as-prepared powders.

**Sputtering:** Metal nanoparticles can be produced by applying the DC/ RF sputtering technique [26] in which a DC/ RF sputter source is used instead of a laser for vaporizing the bulk metal to synthesize the metal nanoparticles.

**Inert gas condensation:** In this process, a vacuum chamber is used in which inert gas flow at high pressure is maintained. The metal is introduced into a heating element, evaporated and then taken by the gas flow away from the hot element. As the metal vapour cools down, formation of nanoparticles take place [27, 28].

**Laser ablation:** In the laser ablation technique [29, 30], employed to synthesize metal nanoparticles, high power, frequency pulsed laser is focused on the bulk metal kept in aqueous or organic solvents, which leads to vaporization of the metal and formation of the metal nanoparticles.

**Vacuum thermal evaporation:** In this process [31], a metal is heated till evaporation. The metal vapours are allowed to condense on a cold substrate or the walls
of the vacuum chamber. Low pressure is generally used to avoid reaction between the vapour and the atmosphere.

The rate of production for metal nanoparticles is very low in most of these methods. For example, yield of nanomaterials is 50% or less for plasma techniques. In the case of sputtering, a broad particle size distribution is obtained and only 6-8% of sputtered material is reported to be less than 100 nm. A high-energy consumption is a prerequisite for laser ablation and plasma techniques. Broad size distribution, low production rate and above all, the high consumption of energy make most of the physical methods highly expensive and therefore, cannot be adopted for practical commercial applications.

2.5 Electro-exploding wire technique

In this section, we describe the novel, physical, top-down process of EEW that we have established in our laboratory and employed to synthesize the metal nanoparticles of Cu, Ag, Al and Fe. It is well established fact that if a sufficiently strong pulsed electric current is applied to a thin metal wire, the wire explodes within fraction of a second. The result of wire explosion is either the plasma or fluid/solid particles, depending on the magnitude of the electric current. In the EEW technique, a high current density ~10^{10} A/m^2 passes through the wires, in a time of ~10^{-6} sec, which leads to wire fragmentation into several nanosegments [32-34]. Here, we will, first, discuss the historical background of EEW technique. Then, we elucidate the practicality of EEW technique to synthesize metal (Cu, Fe, Al and Ag) nanoparticles. Besides illustrating the experimental set-up, designed for synthesis of the metal nanoparticles, we explain the theories and mechanism leading to the formation of nanoparticles. We, further, suggest ways to improve the process of formation of the metal nanoparticles. This is followed by merits of the EEW method over other conventional methods for synthesis of the metal nanoparticles.

2.5.1 Historical background

EEW phenomenon was first observed and described by Edward Nairne [32] as early as 1773. In fact, he used an exploding wire experiment to prove that current in all parts of a
series circuit is same. Further, on discharging the battery through a thin Fe wire, he observed that the wire flew about the room in innumerable red hot balls. The experiments are repeated with wires of various diameters and lengths and similar results were observed in all cases. Figure 2.1 shows the schematic of the basic set-up used for electro-explosion of wire.

In electro-explosion of wire, condenser (C) is charged from source (B) which discharges through the wire. Since, the wire itself has very low resistance and inductance, the circuit parameters are extremely important in any study of wire explosion. The switch (S) is employed to initiate the discharge. The explosions are generally done in an explosion chamber, which is an anti-high-pressure cavity, whose main parts are a pair of stainless steel electrodes. Dry air is introduced into the reaction chamber, where a metal wire is placed. Wire (W) to be exploded is connected between the electrodes. A strongly pulsed high voltage (~KV) is applied to the thin wire. The metal wire is overheated and evaporates swiftly, when a very strong pulse current with current density of ~10^10 A/m^2 is passed through the wire. The pulse converts the wire into plasma, which is confined by the self induced magnetic field and temperatures can rises to ~15000 K, forming metal nanoparticles of different sizes. The particles so prepared are collected under vacuum [34].
In 1915, more experiments involving exploding wires were reported in which the destructive and driving forces were investigated by Singer and Singer et al. [35, 36]. In particular, a series of experiments were described in which metal cylinders are filled with water and a needle is connected to a battery. On discharging the battery, they found that the cylinder of bismuth was shattered to pieces and dispersed the parts to a distance with considerable violence. In 1857, Faraday [37] reported using exploding wires to produce a metal film or mirror. In the 1920's, Anderson [38], whose primary interest was in spectroscopy, made extensive studies on exploding wires. He showed that the temperatures produced approached those on the sun. It wasn't until 1931 that the first scientific investigation of exploding wires, in their own right, was undertaken by W. Kleen [39]. This paper, not only, contains the experimental details, but also, numerous plates of the photographic records of exploding wires. He also reported that the metal aerosol produced is electrically charged.

From that time onwards the EEW technique has attracted the attention of scientists for application in various fields. There has been a continued interest in the process of exploding wires for the spectacular flash of light emitted during the process. The phenomena of EEW have been widely used by plasma physicists for generation and confinement of plasma. Apparently, the production of ultrafine powders by the EEW was initiated by Abrahams [32, 34]. The use of EEW technique to produce nanopowder had its genesis in Russia. In the early 1970s, Siberian scientists exploded wires in inert gas and collected the resulting powders for subsequent use.

2.5.2 Experimental set-up

In order to achieve explosion from the metal wires, we have used an adaptation of the EEW apparatus, for which a reaction vessel [40] is designed. A DC voltage source is employed instead of a capacitor bank (which discharges through an inductor) to deliver the current to the wires. In the EEW technique, very high currents density ($\sim 10^{10} \text{A/m}^2$) is passed through a metal in the thin wire-plate geometry, in a time $\sim 10^{-6} \text{sec}$. A wire is driven and exploded on a plate of the same material. De-ionized water (hence forth referred as water) is used as a medium to collect the synthesized nanoparticles instead of
inert gas and high vacuum. A schematic of the experimental set-up designed and employed for production of the metal nanoparticles is shown in Figure 2.2.

![Schematic of experimental set-up designed and used in EEW process.](image)

Figure 2.2. Schematic of experimental set-up designed and used in EEW process.

Here, a thin wire (Wire) of the desired metal and the plate (Plate) of the same metal are the two electrodes in the container. V is the DC voltage source. The container is filled with water, which acts as a medium to cap the formed nanoparticles. The EEW is a physical, top-down, semi-continuous process in which a wire has to be continuously fed. When contact of the wire is made with the metal plate, explosion occurs and nanoparticles are blasted into the water. Again, the wire is fed into the explosion vessel, and contact is made with plate, explosion occurs and nanoparticles are formed. In this way, the process of EEW works to form the metal nanoparticles. Following are the key factors affecting the electro-explosion of wires.

1. The current density should be large enough to cause explosion of wires, i.e., very high current density $\sim 10^{10}$ A/m$^2$ is required for the explosion of the wires to occur.

2. The initial stage of EEW is a Z-pinich, which essentially decreases the cross-sectional area at the point of contact to $1/100^\text{th}$ during explosion, thereby tremendously increasing the current density which is required for explosion to take place.
2.5.3 Theories and mechanism of EEW

It is now well known that if sufficient electric energy is given to a thin metal wire, the wire explodes within fraction of a second. In the EEW technique established by us, a high current density ($\sim 10^3 \text{A/m}^2$) is passed through a metal in the wire-plate geometry and dipped in the water to produce the metal nanoparticles of Ag, Cu, Fe and Al. High density current passes through the wire in a very short time ($\sim \mu\text{sec}$), which leads to breaking of the wire-plate material with a bright flash of light into several nano-fragments. Energy (E) given to the wire in EEW can be calculated by simultaneous measurement of Current (I) and Voltage (V), i.e, energy is calculated by $E = \int I V \, dt$. The result of the wire explosion can be either the plasma or fluid/solid particles, depending on the magnitude of the electric energy given to the wire. If the energy given to the wire before the voltage breakdown is less than the solid state enthalpy (before melting), the wire survives intact. If the energy given to the wire is between the solid state and liquid state enthalpies (during melting), the wire disintegrates into macropieces. For a high level of energy given to the wire (more than the vaporisation energy), the wire core exists in a gas-plasma state and nanoparticles are formed. For an intermediate energy given to the wire (after melting and before vaporisation), the wire disintegrates into hot liquid clusters of submicron sizes. So, the state of the wire in the EEW depends both on the amount of energy deposited before the voltage breakdown and on the heating conditions [32, 34 & 40]. Various theories have been put forth to explain the electro dynamical changes that occur during the explosion of the thin wires.

Graneau [41] proposed a theoretical explanation for this phenomenon, supporting his argument based on the axial forces expected to exist between separate elements of a current circuit according to Ampere–Neumann electrodynamics, as they apply to steady currents. Graneau effectively specified an open circuit condition, by which, isolated circuit elements are subjected to axial forces generated by mutual action of current in
different parts of the element. The force \( F \) is of the form \( F = I^2 \log(L/D) \), where \( I \) is current in amperes and \( L/D \) is ratio of the length of element \( L \) to a quantity \( D \) of the order of its thickness. Graneau's explanation that fractures are tensile in character, whereas, pinch forces that are generally observed during explosion are compressive and cannot cause wire fragmentation of the form observed, is questioned in the light of the experimental research by Bridgman [42]. The application of compressive forces to the cylindrical surface of a rod specimen can cause fractures even though there is no longitudinal stress. Also, Graneau's theoretical account does not explain why the wire breaks into so many fragments and each of these fragments is of insufficient length to develop adequate force according to Graneau's method of calculation.

An alternate explanation was then given by Aspden [43]. The most obvious cause for an axial force in the path of current flow is the direct action of electromotive force (EMF) on charge in the conductor. When an EMF is applied to a conductor, the field intensity \( E \) applies force to an electron having the mobility, which accounts for current flow. The forces impart momentum to the electrons, which is transferred by collision to the atomic lattice. The collision forces are balanced by the action of \( E \) upon the positive charge of the atomic lattice. In steady state current conditions, there is no resultant axial force on the conductor because the EMF and the potential drop determined by the collision related ohmic losses are in balance. Now, when the EMF is changing owing to magnetic induction effects, including self-induction within the conductor, the applied EMF and the potential drop are no longer in balance. Their difference can be measured experimentally and account for an axial force in line of the current flow. Such a force can cause rupture of the conductor if the current build up is rapid enough, but it cannot separate the conductor body from the electron population owing to their strong electric coupling. All that can be expected is that conductor will disintegrate into elements, which are contained during the explosion within the plasma formed by the current discharge. The reason for this is that the force acting on each positive element of the atomic lattice of the conductor is not, in general, the same throughout the conductor. Further quantitative analysis suggested by Aspden show the induced stress to be proportional to the current, contradicting the Graneau [41] explanation where induced stress is shown proportional to the square of the current based on electrodynamics.
Further, Ternan [44] argued that the first stage of a wire explosion is solid-state fragmentation. Solid-state fragmentation of the exploding wires is the result of a standing stress wave. According to his analysis, the longitudinal stress is created by the rapid heating of the wire and inability of the metal to elongate as fast as the temperature rises, on account of resisting inertial forces. A little latter, the wire velocity is assumed to be greater than the expansion velocity and this causes tension in the wire. The oscillations between stored kinetic and elastic energy are said to be in full swing long before heat generation stops. The ingenious mechanism suggested by Ternan requires the wire to be freely suspended and straight. Such a wire might elongate with a certain velocity profile which is out of phase with the temperature rise. Eventually, momentum acquired by the wire atoms has to be destroyed by tensile deceleration forces. Then elasticity of the metal give rise to longitudinal stress oscillations, which are strong enough to break the wire at temperature near the melting point. The standing stress waves have a node half-way along the wire, where tension builds until fracture occurs after several cycles. Since, an arc forms across the fracture gap, current will kept flowing and new standing stress waves are believed to develop in the fragments, leading to further breaks.

Ternan’s model was contradicted by Graneau [45] on many fronts. The Ternan model overlooked the fact that standing stress waves can only exist when the wire is straight and its ends are free. In experiments, where Nasilowski [34] first discovered wire fragmentation, wires were firmly clamped to the laboratory frame at both ends. Nasilowski wires were fragmented into as many pieces as were produced with freely suspended vertical wires in the MIT series of experiments. Also, M. J. Pike-Biegunski [46] proposed that longitudinal forces in wires, conducting currents, have a quantum mechanical origin and not electromagnetic as proposed earlier. The longitudinal forces created in wires by an electrical current were explained as resulting from the transfer of momentum from electrons to lattice. Electron collisions with a lattice are inelastic. When electrons collide with lattice, energy and momentum is exchanged. The energy is transformed into heat and deformation of the lattice, but momentum is a source of longitudinal forces. Amplitude of these forces increases with increase in current density. From the above discussion, it is clear that the mechanism of EEW is poorly understood. Some parts of the process are devoid of an explanation and others have been explained by
a host of theories. The quantification of the EEW phenomena has been made in various laboratories by various methods. Optical methods are useful both for direct investigation of the exploding wire and with suitable modifications for the study of shock waves accompanying the explosion. Oscilloscopes have been used to record the histories of the current in EEW and the voltages developed across the wire. The most accepted mechanism of what actually is happening during the EEW process, based on the optical and oscilloscopic measurements have been described here, which leads to formation of the metal nanoparticles. When measurements of the current flowing in an EEW are made throughout the whole time of event, curves such as shown in Figure 2.3 are obtained [32]. Had there been no explosion (e.g., if the wire had been replaced with a thick metal bar), the current would have followed a damped sine wave shape. The beginning of such a curve is shown as a dotted line in Figure 2.3. But when explosion takes place, this process consists of, according to most accepted experimental explanations, of the following behaviour: at t0 the wire is brought in contact with the plate, current rises, heating the wire, which eventually melts. The melted wire is further heated by the ever-increasing current. Since, whole process occurs in less than a microsecond, physical shape of the wire is maintained by inertia and magnetic pressure. As heating of the melted wire continues, temperature rises, eventually reaching boiling point followed by evaporation of the wire (t1 to t2 in Figure 2.3). After evaporation of the wire, current drops to a low value and remains at that value for some time, so called dwell time or dark time (t3 to t4). During this time, current continues to flow at a constant, low rate, carried by a limited supply of carrier ions or electrons or both. Since, change from liquid to gas has occurred within a fraction of a microsecond, the resulting gas is momentarily at a very high density. The density is, in fact, so high that the electrons moving in the field between the electrodes do not acquire sufficient energy between collisions to produce ionization by impact. Hence, the number of carriers remains constant, as governed by thermionic emission or field emission etc. High density is short lived. Expansion is retarded only by inertia and ambient atmosphere. Hence, in a few microsecond (t4) as the pressure drops increasing the mean free path of electrons, resulting in ionisation by impact with attendant avalanching. This increases the current again, giving the second stable current peak, which is called restrike or reignition.
At this point, formation of a high density vaporized gas core surrounded by low density ionized corona starts (plasma). Compression of the coronal plasma by the self induced magnetic field produces shock waves, which propagates through the plasma. When vapour pressure of the plasma overwhelms the self induced magnetic field, explosion occurs and plasma products are dispersed in the medium with high speed. This leads to formation of the nanoparticles. The current then drops to zero as the contact between the two electrodes breaks. Also, spectacular flash of light is emitted during the EEW process. Figure 2.4 shows the optical micrographs of the visible flash of light observed experimentally during the EEW process (a) Al wire-plate, brownish light emission (b) Ag wire-plate, green light emission (c) Fe wire-plate, reddish-yellow light emission (d) Cu wire-plate, bluish light emission. The visible flash of light emitted during the EEW is from the metal in vapour-gas state, which further indicates the formation of plasma at the point of contact. A very high temperature can be produced by underwater wire explosions, making them valuable as high intensity light sources.

After accomplishing the experimental set-up, the wire is brought in contact with the plate for an infinitesimally small time $\sim \mu$ sec, leading to formation of the nanoparticles following the above discussed mechanism. The formed nanoparticles are capped in water. Several parameters, such as, current density, material type, wire-plate dimension, and the
medium in which the explosion is carried out can be varied to have a control over the entire process.

Figure 2.4. Optical micrographs of the visible flash of light observed during the EEW process (a) Al wire-plate (b) Ag wire-plate (c) Fe wire-plate (d) Cu wire-plate.

Because no chemicals are involved in the nanoparticle preparation, the nanoparticles are free of extraneous impurities arising from added chemicals during preparation. Hence, synthesized nanoparticles are extremely pure. This opens a wide range of possibilities for the study and control of surface properties of the metal nanoparticles through the introduction of specific capping/binding agents of interest and dispersing the nanoparticles in a medium of choice.

2.6 Extraction of powder

To extract the nanoparticles in powder form, nanoparticles dispersed in water are centrifuged at a speed of 10,000 RPM for about 30 min by employing a Remi Equipments R24 Research Centrifuge. Under the action of centrifugal forces the nanoparticles get separated from water and settle to the bottom. The supernatant is thrown and the nanoparticle powder is extracted. The extracted nanopowder is then used for further characterization and applications.
2.7 Precautions

Here, we mention some of the crucial precautions that are to be taken into consideration during the procedure for synthesis of the nanoparticles by this method.

1. Purity: As nanoparticles are to be formed from metal wires and plate. So, the materials of the wire and plate must be 99.999% pure to avoid any impurity in the nanoparticles.

2. Continuity check: Conductivity of wire and plate should be checked to inspect the presence of any insulating layer of oxide etc. (due to exposure in environment) on the metal surface. This test is done before explosion.

3. Extraneous Impurities: To avoid any kind of extraneous impurities, it is essential that all the vessels to be used, reaction vessel, and place where synthesis is being done must be extremely clean. These vessels are, hence, thoroughly washed using detergent, mild chromic acid and de-ionized water.

2.8 Merits of EEW technique

The EEW technique employed, here, to synthesize the metal nanoparticles (Cu, Ag, Fe and Al) leads to formation of much smaller metal particles (10 -20 times smaller in size) than the metal nanoparticles prepared by employing other existing techniques. Their small size leads to the increase in surface area to volume ratio, increased reactivity, and improved characteristics. The powders formed are unique in their structure compared with evaporation and condensation methods, which produce almost defect free crystals.

No chemicals are used in the synthesis process of metal nanoparticles. We have used only water from which extraction of powder is easy, by centrifuge, and extracted powders are extremely pure.

The EEW method provides a sufficiently high production rate, requires relatively small energy, and allows powders extraction with no contamination from chemicals.
We have used this novel method of EEW to produce metal (Cu, Ag, Fe, and Al) nanoparticles. The methodology of EEW can be employed to produce nanoparticles of a wide range of conducting metals. Also, following the same procedure, it is possible to synthesize AB type bimetallic nanoparticles, where A, and B are different metals.

References

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