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**Electrochemical preparation of Co-Ag
nanostructured materials for GMR
applications**

Memòria que presenta JOSÉ MANUEL GARCÍA TORRES per optar al
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CHAPTER 3

EXPERIMENTAL PROCEDURE

3

EXPERIMENTAL PROCEDURE

3.1. Preparation of the nanostructured materials

3.1.1. Electrochemical preparation

Electrodeposition has been the technique of choice to grow almost all the Co-Ag nanostructured materials studied in this thesis: granular films, multilayers and nanowires, due to its versatility. Depending on the applied signal, the electrochemical preparation techniques can be roughly divided in continuous (chronomethods) or pulse techniques.

Chronomethods have been the preferred methods to prepare the Co-Ag granular films and granular nanowires due to their simplicity. Both chronoamperometry (potentiostatic technique) and chronopotentiometry (galvanostatic technique) were employed to grow the materials. While potentiostatic deposition consists on the application of a fixed potential and the temporal variation of the current is recorded ($i-t$), in galvanostatic deposition a fix current is applied and the potential-time curve is recorded ($E-t$). Chronoamperometric technique was the method mainly employed to prepare the granular films, whereas chronopotentiometry was selected to fabricate the granular nanowires.

On the other hand, pulse deposition technique was mainly used to grow the multilayered films and nanowires. The electrodeposition of multilayered materials consists on alternatively switching the applied signal between two distinct values corresponding to the non-magnetic and the magnetic metal deposition, respectively. Either galvanostatic or potentiostatic deposition can be applied for each individual layer; this leads to different deposition modes: potentiostatic-potentiostatic (P/P mode), galvanostatic-galvanostatic (G/G mode) or mixed galvanostatic-potentiostatic (G/P mode). Although it may seem quite easy to perform, some undesired problems are expected to occur during individual layer deposition if the

appropriate signal either current or potential and the adequate value are not applied. Figure 3.1 shows a simple example of a pulse plating signal. This signal consists on the application of a first potential E_1 for a given time t_1 , afterwards the potential is change to a fix potential E_2 during a given time t_2 . This cycle is repeated until the desired thickness is reached. The $j-t$ curves for each potential step are simultaneously registered. As one can imagine, pulse combination can be innumerable as a great number of magnitudes can be modified (i.e. current, potential or time). The preparation of granular films by pulse deposition was also attempted. More details will be given in the corresponding chapter as the applied signal was different depending on the material prepared.

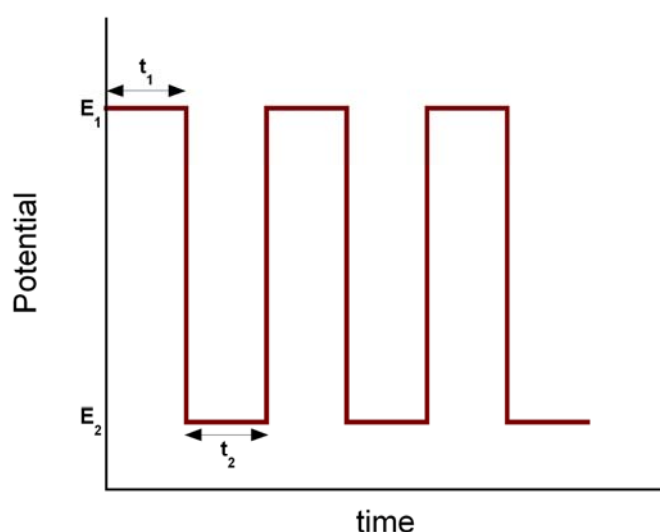


Figure 3.1. Example of a pulse plating signal. Applied potential is switched between two different values (E_1 , E_2) during a given time (t_1 , t_2).

3.1.2. Chemical synthesis: The microemulsion method

A fourth kind of nanostructure that will also be discussed in this thesis are nanoparticles. In contrast to the other nanostructured materials, nanoparticles will not be prepared by electrochemical methods due to the difficulty in their preparation and subsequent characterization. In this sense, a chemical method as the microemulsion method will be used. The micellar method has been mainly selected due to, among other advantages, its simplicity [106] if compare with other procedures [107,108]. The microemulsion method is a micellar method in which nano-sized water(oil) droplets are dispersed in a continuous oil(water) phase and stabilized by surfactant molecules at the water/oil(oil/water) interface, which are

called water-in-oil (W/O) microemulsions (also called reversed micelles) and oil-in-water (O/W) microemulsions, respectively (Figure 3.2). Here, we will focus on the W/O micelles as the salt of the metals to be reduced will only be soluble in water. The chemical reaction between the metallic ions and the reducing agent takes place inside the water droplets. This technique allows obtaining very small and monodisperse nanoparticles with tailored sizes. This characteristic will be useful when studying magnetotransport properties. More details about the synthesis procedure of nanoparticles will be given in Chapter 7.

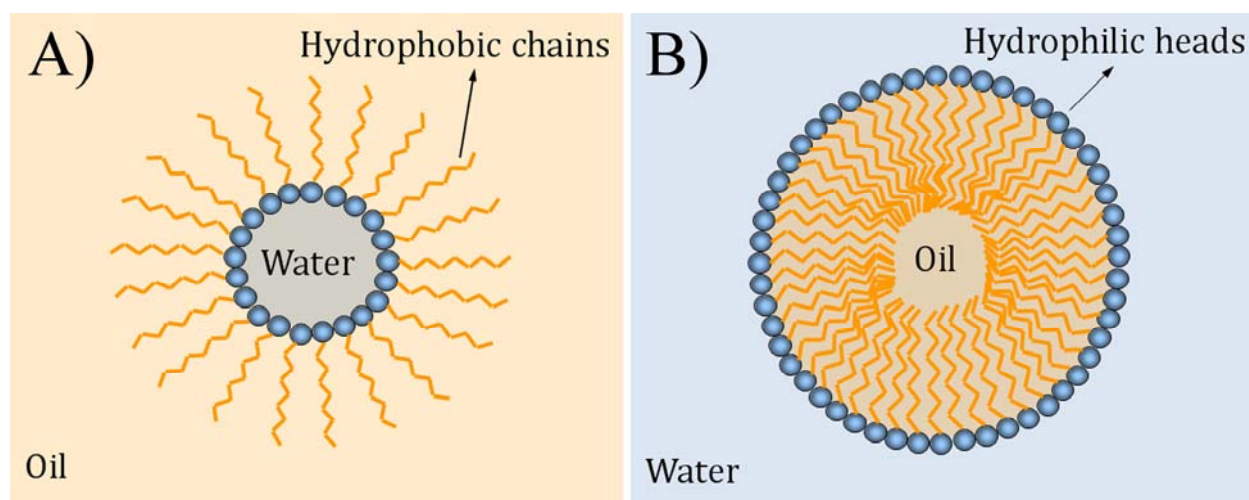


Figure 3.2. Schematic representation of A) water-in-oil (W/O) and B) oil-in-water (O/W) microemulsions.

3.2 Electrochemical experiments

3.2.1. Experimental setup

A) Instrumentation

The electrochemical experiments were mainly performed with a potentiostat/galvanostat Autolab with PGSTAT equipment and GPES software (Figure 3.3A) or with a computer-controlled EF 453 potentiostat/galvanostat (Electroflex, Hungary) (Figure 3.3B).

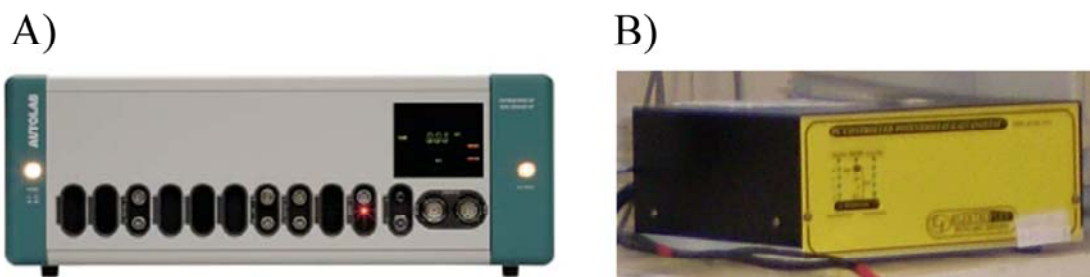


Figure 3.3. Pictures of the electrochemical equipments employed. A) Potentiostat/galvanostat AUTOLAB. B) EF 453 potentiostat/galvanostat (Electroflex, Hungary)

B) Electrochemical cells and electrodes

All the electrochemical experiments have been carried out with a three-electrode cell configuration. Depending on the cell geometry, two different arrangements (horizontal and vertical) of the working electrode were employed. The electrochemical cell with a vertical arrangement of the working electrode was employed to prepare the granular films (Figure 3.4A), whereas that with a horizontal arrangement of the substrate was used to prepare both multilayers and nanowires (Figure 3.4B).

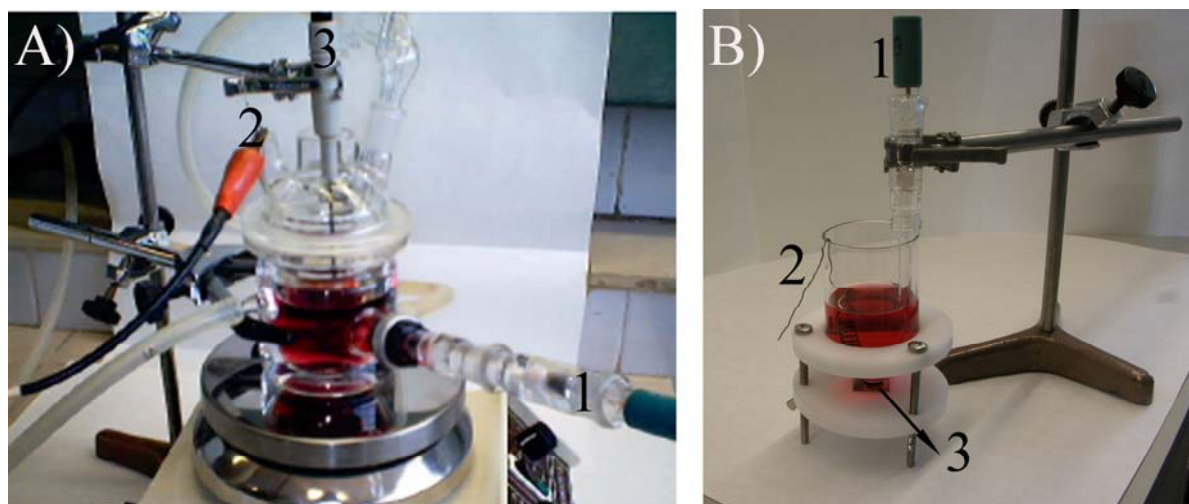


Figure 3.4. Electrochemical cells employed. A) Vertical arrangement and B) horizontal arrangement of the working electrode. Numbers indicate (1) Reference electrode, (2) counter electrode and (3) Working electrode.

The reference electrodes employed were either Ag/AgCl/1 mol dm⁻³ NaCl electrode or saturated calomel electrode (SCE). The counter or auxiliary electrode was a platinum spiral.

Depending on the electrochemical experiments, different working electrodes have been employed. The treatment of each electrode to reach reproducibility during successive experiments has been different. The working electrodes employed were the following:

- Vitreous carbon rods (Metrohm) ($\emptyset = 0.0314 \text{ cm}^2$). The basic electrochemical studies were carried out with this electrode as no electrochemical response is observed in a wide range of potentials. The electrode was polished mechanically to a mirror finish using alumina of different grade (3.75 and 1.87 μm) before each experiment. After that, the electrode was cleaned ultrasonically during two minutes in Milli-Q water to remove the alumina leftovers.
- Nickel foils were employed to perform the basic studies when dealing with multilayers preparation. The surface of the electrode was regenerated by electrochemical oxidation after use and cleaned with ultrapure Milli-Q water after that.
- Graphite rods (Alpha Aesar) ($\emptyset = 0.541 \text{ cm}^2$) were employed when higher area was required to perform subsequent analysis (i.e. XRD). Graphite was also polished mechanically employing alumina of different grades (3.75 and 1.87 μm). The electrode was also ultrasonically cleaned in Milli-Q water.
- Silicon/Ti(100 nm)/Ni(50 nm). P-type silicon electrodes of 4-40 $\Omega \text{ cm}$ and (1 0 0) orientation modified with Ti/Ni seed layer were the substrates mainly employed to prepare the materials. The later characterization was performed over Si/Ti/Ni substrates, except when the magnetoresistance was measured. In this case, silicon/Cr(5 nm)/Cu(20 nm) electrodes were employed to prepare the deposits in order to avoid response from the substrate. Seed layer allows the conductivity of the silicon electrode. Si/seed layer electrodes were firstly cleaned with acetone, followed by ethanol and later with water.
- Electrodes based on a mixture of indium and tin oxides (ITO) cathodically pulverized over glass. The thickness of the ITO layer is 25 nm. Glass/ITO electrodes were mainly employed when the final objective was the measurement of the magnetoresistance. This kind of electrode was firstly cleaned with acetone, followed by ethanol and later with water.

- Polycarbonate membranes (Millipore) were used to prepare the nanowires. Membranes with around 20 μm thick and different pore diameters (200, 100 and 50 nm) were employed. The pore density of the membranes is $5.8 \cdot 10^8$ pores cm^{-2} . One side of the polycarbonate membrane was coated with a thin gold layer (around 100 nm thickness) in order to make it conductor. Prior to the electrodeposition the porous template was kept in distilled water for several hours to make the pores hydrophilic for uniform filling of the pores.

C) Chemicals

The electrochemical experiments were carried out with solutions freshly prepared with water first double distilled and then treated with a Millipore Milli-Q system. Before and during experiments the solutions were de-aerated with argon of high purity (99.99 %). All the reagents employed were of analytical grade. Table 3.1 summarizes the chemicals used to prepare the solutions employed for the preparation of the different nanostructured materials.

3.2.2. Electrochemical techniques

Cyclic voltammetry

Cyclic voltammetry has allowed studying the general electrochemical behaviour of the different solutions employed to grow the nanostructured materials not only under quiescent conditions but also under stirring ones. Only one cycle has been run in all experiments, initiating the scan from a potential at which no current was detected and toward negative potentials (negative scan). During the negative-going scan, the reduction of the electroactive species takes place. Once the cathodic limit is reached, the scan is reversed. During the scan toward positive potentials (positive scan) the total or partial oxidation of the species previously electrodeposited occurs. Whereas the cathodic limit must be adjusted in order to avoid or minimize hydrogen evolution, the anodic limit must be controlled to avoid oxygen evolution or substrate oxidation. Cyclic voltammetry has normally been performed at a scan rate of 50 mV s^{-1} . Cyclic voltammetry allows comparing the charges recorded during both oxidation and reduction processes ($Q_{\text{ox}}/ Q_{\text{red}}$). This comparison gives an idea about the ease or the difficulty of the oxidation of the deposits prepared and the presence of side reactions taking place simultaneously with electrodeposition.

NANOSTRUCTURED MATERIAL	SOLUTIONS EMPLOYED		
	Solution 1:	Solution 2:	Solution 3:
GRANULAR FILMS	$\text{AgClO}_4 \cdot 1 \text{H}_2\text{O}$ $\text{Co}(\text{ClO}_4)_2 \cdot 6 \text{H}_2\text{O}$ NaClO_4 Thiourea Sodium gluconate H_3BO_3 pH = 3.7	$\text{AgClO}_4 \cdot 1 \text{H}_2\text{O}$ $\text{Co}(\text{ClO}_4)_2 \cdot 6 \text{H}_2\text{O}$ NaClO_4 $\text{Na}_2\text{S}_2\text{O}_3$ pH=3.5	AgNO_3 $\text{CoCl}_2 \cdot 6 \text{H}_2\text{O}$ NaCl pH=2.7
MULTILAYERS	$\text{AgClO}_4 \cdot 1 \text{H}_2\text{O}$ $\text{Co}(\text{ClO}_4)_2 \cdot 6 \text{H}_2\text{O}$ NaClO_4 pH=2-2.5		
NANOWIRES	AgNO_3 $\text{CoCl}_2 \cdot 6 \text{H}_2\text{O}$ NaCl pH=2.7		
NANOPARTICLES	$\text{AgClO}_4 \cdot 1 \text{H}_2\text{O}$ $\text{Co}(\text{ClO}_4)_2 \cdot 6 \text{H}_2\text{O}$ Sodium borohydride (NaBH_4) Hydrazine (N_2H_4) Polyethyenglycol-dodecylether n-heptane		

Table 3.1. Chemicals employed for the electrolyte preparation used for the fabrication of the different nanostructured materials.

Linear sweep voltammetry (LSV)

This electrochemical technique allows obtaining information about the reduction and oxidation processes separately. First, the positive scan is initiated at a potential at which no current is detected and until the cathodic limit is reached. After that, the negative scan is also initiated at a potential at which no current is detected and toward positive potentials. The information obtained by means of LSV technique is complementary to that obtained by cyclic voltammetry. The reason is that in the cyclic voltammetry the reduction processes not only take place during the negative scan but also during the positive sweep until the current is zero (crossover). Figure 3.5 allows comparing the applied signals and the recorded responses for both techniques.

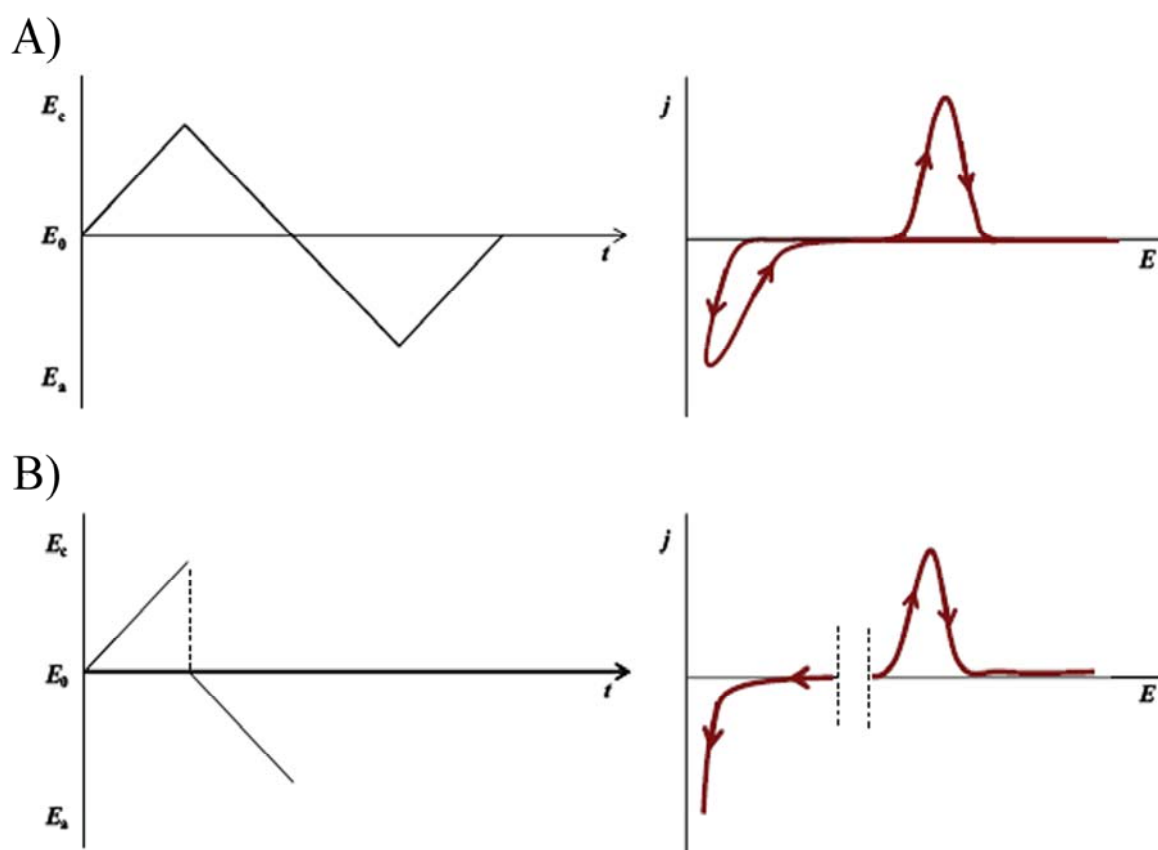


Figure 3.5. Scheme of the applied signal and the recorded response A) cyclic voltammetry and B) two combined linear sweep voltammeteries where E_0 is the starting potential; E_c is the cathodic potential; E_a is the anodic potential; t is the time and j is the current density.

Anodic redissolution techniques (*stripping*)

The anodic redissolution techniques allowed an *in-situ* characterization of the prepared deposits, thanks to the fact that the different phases present in the deposit can oxidize at different potential values. The oxidation can be either potentiodynamic or galvanostatic. The former, called anodic *stripping* voltammetry (ASV) or anodic linear sweep voltammetry (ALSV), consists on starting the scan at a potential where no current is measured and making a potential sweep toward positive potentials. A slow scan rate (10 mV s^{-1}) was preferred in order to clearly favour the oxidation of each phase separately. In the second case, the oxidation of the deposit takes place at a positive and constant current density. Moderate current densities were selected in order to favour a slow deposit's oxidation. The solution where the *strippings* were performed was usually a blank solution as interferences were detected in certain solutions.

3.3. *Ex-situ* characterization techniques

3.3.1. Morphological analysis

Film's morphological characterization was made using different scanning electron microscopes (SEM): Hitachi S-2300, Jeol JSM-840 and Leica Stereoscan 360 as well as a scanning electron microscope Hitachi S-4100 with field emission (FE-SEM: Field Emission Scanning Electron Microscope) in order to obtain the film's surface topography images. Scanning electron microscope images the sample surface by scanning it with a high-energy beam of electrons in a raster scan pattern. The electrons interact with the atoms that make up the sample producing signals that contain information about the materials i.e. surface topography or composition, among others. When higher resolution was needed the FE-SEM microscope was used, as the spatial resolution is from 3 to 6 times higher than conventional SEM equipment.

Sample preparation for SEM observation did not require great efforts. Samples must be electrically conductive at the surface and electrically grounded to prevent the accumulation of electrostatic charge on top of the sample. According to it, films prepared over vitreous carbon were directly examined by SEM without any previous treatment. Meanwhile, it was necessary to apply a colloidal silver strip between the surface and the stub where the samples were mounted to make electrical contact in films prepared over Si/seed layer or glass/ITO due to the low-conductive character of these substrates. No carbon coverage was needed due to the conductive character of the Co-Ag deposits. On the other hand, polycarbonate

membranes employed for nanowire's growth were coated with an ultrathin film of carbon due to their isolating nature before being observed.

3.3.2. Compositional analysis

The elemental composition of the deposits has been determined by different methods summarized below:

Energy dispersive X-ray spectroscopy (EDS) is an analytical technique used for elemental analysis or chemical characterization of a sample. The EDS system is found in connection with the Leica Stereoscan 360 SEM equipment. EDS spectroscopy relies on the analysis of X-rays emitted by the matter in response to being hit with an electron beam. Its characterization capability is due to in large part to the fundamental principle that each element, which possesses a unique atomic structure, emits a characteristic X-ray radiation. Previous to the measurements, calibration of the equipment was necessary. EDS has been the main method used to determine the composition of the materials.

Inductively coupled plasma mass spectrometry (ICP-MS) and *inductively coupled plasma atomic emission spectroscopy (ICP-AES)*. The equipments employed were a Perkin-Elmer spectrometer Elan 6000 model and a Perkin-Elmer Optima 3200 RL spectrometer, respectively. The primary goal of ICP is to get elements to emit characteristic wavelength specific light which can then be measured. The analytical instruments are *mass spectrometry (MS)* and *atomic emission spectroscopy (AES)*. The deposits were dissolved in HNO₃ 3 % to carry out the compositional analysis. ICP technique allowed us not only to know the chemical composition of the samples but also the weight of the different elements present in the deposit because of the dissolution is carried out in known volumes. This information is necessary when dealing with magnetic measurements.

Electrochemical methods. Due to reproducibility problems encountered with the last technique, it was imperative to look for alternatives when evaluating the weight of the samples. In this sense, a new voltammetric method for silver analysis was developed in our laboratory. Meanwhile, cobalt was analyzed by polarography. For more details, see reference [105].

X-Ray photoelectron spectroscopy (XPS) and *Auger spectroscopy (AES)*. Both techniques are quantitative spectroscopic technique that measures the elemental composition, chemical state or electronic state of the elements that exist within a material. The technique consists on the measurement of the kinetic energy (KE) and the number of electrons that escape from the top 1 to 10 nm of the material when it is irradiated with an X-ray beam. XPS requires ultra high vacuum (UHV) conditions.

Moreover, XPS technique also allows obtaining information throughout the film's thickness (depth profiling) after ion beam etching. The objective is to examine the material beyond the uppermost layers. XPS measurements were made with a PHI 5600 multitechnique system and Auger spectroscopy measurements were done with a PHI 670 scanning Auger nanoprobe system. The radiation employed was the Al K α radiation with a 0.1 eV resolution.

3.3.3. Structural characterization

Different techniques have been used in order to reveal some aspects about the microstructure/nanostructure of the materials:

X-Ray diffraction (XRD) is an analytical technique which reveals information about the crystallographic structure, phase's composition, and physical properties of materials. This technique is based on observing the scattered intensity of an X-ray beam hitting a sample as a function of incident and scattered angle, polarization, and wavelength or energy. Powder diffraction has been used to characterize the crystallographic structure, crystalline size (grain size), and preferred orientation in polycrystalline or powdered solid samples. Grazing incidence X-ray diffraction has also been employed to characterize the crystallographic structure and preferred orientation of several tens of nanometers thick films. Different equipments have been used: Siemens D-500 and Phillips MRD diffractometers. The Cu K α radiation ($\lambda = 1.5418 \text{ \AA}$) was selected by means of a diffracted beam curved graphite monochromator. The X-ray patterns were mainly recorded in the $5\text{-}110^\circ$ 2θ range with a step range of 0.05° . The measurement time was different depending on the sample analyzed.

Transmission electron microscopy (TEM) and *selected area electron diffraction (SAED)* were employed in order to reveal microstructural aspects of the Co-Ag materials. TEM is a microscopy technique whereby a beam of electrons is transmitted through an ultra thin specimen, interacting with the specimen as it passes through. An image is formed from the interaction of the electrons transmitted through the specimen; the image is magnified and detected by a sensor such as a CCD camera. Moreover, selected area electron diffraction, which is a crystallographic experimental technique, were performed together with TEM analysis.

High resolution transmission electron microscopy (HRTEM), which is an imaging mode of the transmission electron microscope and allows the imaging of the crystallographic structure of a sample at an atomic scale, was used as it is an invaluable tool to study nanoscale properties of crystalline materials because of its high resolution. Moreover, the use of the *fast fourier transform (FFT)* together with

high resolution images also allowed studying the crystalline structure. TEM, HRTEM, SAED and FFT measurements were performed on the Phillips CM-30 and Jeol 2100 equipments with Gatan software.

The preparation of the granular films and multilayers for TEM/HRTEM observation was a complex procedure. Specimens were required to be at most tens of nanometers thick. In order to achieve it, different steps were followed. First of all, a small thin section was obtained by cutting the samples with a diamond disk in a power saw. After that, mechanical polishing was required to reduce the total thickness down to 70 μm . A final mechanical concave polishing was needed to reduce the thickness down to around 20 μm . Finally, a finishing polish of the specimens by ion etching was carried out in order to have the required thickness for observation (around 30 nm).

On the other hand, the preparation of nanoparticles and nanowires for observation was rather simple. A dilute sample containing the specimen was directly cast onto a carbon-coated copper grid sample holder. Before it, acetone was added to the microemulsion in order to release the nanoparticles from the micelles because of their breaking. On the other hand, nanowires were extracted from the membrane after dissolving first the gold layer with I_2/I^- solution and then the polycarbonate membrane with chloroform. These materials have dimensions small enough to be electron transparent.

3.3.4. Roughness and thickness measurements

Film's roughness measurement was performed with a New View 100 white light interferometer from Zygo Corporation with MetroPro software. This technique is a fast and non-destructive technique with a vertical resolution in the nanometer level. From a dark and bright fringe pattern (interferogram) the surface profile is obtained. Roughness is expressed by the rms (root-mean-squares) values, which are obtained by means of the equation:

$$rms = \sqrt{\frac{1}{l} \int_0^l Z^2(x) dx}$$

where $Z(x)$ is the function that describes the height profile along a x axis of length l .

The thickness of the deposits has been also measure by the white light interferometer based on the height difference between deposit and substrate.

3.3.5. Differential scanning calorimetry. Thermogravimetric analysis

Differential scanning calorimetry (DSC) is a thermoanalytical technique that measures heat flows associated with thermal transitions like phase transitions or oxidation reactions. On the other hand, thermogravimetric analysis (TA) is also an analytical technique that measures changes in weight as a function of temperature under a controlled atmosphere. It is usual to perform the simultaneous measurement of heat flow and weight changes in a material as a function of temperature (simultaneous DSC-TGA analysis) as it simplifies interpretation of the results. The complementary information obtained allows differentiation between endothermic and exothermic events which have no associated weight loss (e.g., melting and crystallization) and those which involve a weight loss (e.g., degradation). These experiments were performed in Co-Ag granular films in order to detect possible phase transitions, oxidation reactions or decompositions processes of the third species that could be entrapped into the samples.

3.3.6. Thermal treatments

In order to perform the annealing of the samples an oven with the following characteristics was design. The samples are placed on a block of copper in the middle of the oven which is insulated from the oven walls by a ceramic material. Three holes in the copper block accommodate halogen lamps which constitute the source of heat (Figure 3.6). The temperature is controlled by means of a thermocouple. The vacuum inside the oven is made by a rotary pump with the objective to provide with an oxygen-free environment in order to avoid sample oxidation.



Figure 3.6. A) Oven employed to perform the thermal treatments. B) View of the copper block (1) and the heating system (2).

3.3.7. Magnetic measurements

The magnetic characterization of the Co-Ag samples was based on recording the hysteresis loops of the films at room temperature by means of a SQUID magnetometer Quantum Design MPMS XL. The magnetization-magnetic field curves (M - H curves) (Figure 3.7) were mainly recorded with the magnetic field applied parallel to the samples. In some occasions, the magnetic field was applied perpendicular to the films. The main parameters one could get from the M - H curves were saturation of magnetization (M_s), coercivity (H_c) and magnetic susceptibility related to the M/H slope. Whereas M_s is the maximum possible magnetization of a material, H_c is the applied magnetic field required to reduce the magnetization of the material to zero after the magnetization of the samples has been driven to saturation. In other words, the coercive field measures the resistance of a ferromagnetic material to become demagnetized.

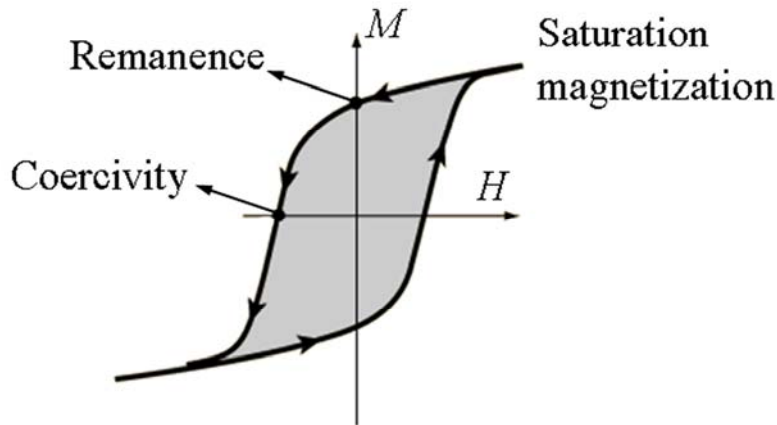


Figure 3.7. Example of a magnetization-magnetic field hysteresis loop. Main parameters that characterize the M - H curves are shown.

3.3.8. Magnetotransport properties measurement

The measurement of the electrical resistivity in a varying magnetic field was carried out by using the four-point probe method (Figure 3.8). In this method, the four-point probes are arranged in line along narrow strips of the films. While continuous current is made flow between the external electric contacts, voltage is measured between the internal contacts. On the other hand, the magnetic field can be either parallel (Figure 3.8A) or perpendicular (Figure 3.8B) to the current flow which allows obtaining the longitudinal magnetoresistance (LMR) and the transverse

magnetoresistance (TMR), respectively. Both measurements are interesting to be performed in order to detect anisotropic magnetoresistance contribution (AMR) in the GMR. The difference between LMR and TMR magnitudes is due to the AMR contribution ($AMR = LMR - TMR$). Figure 3.9 shows typical LMR and TMR curves for a multilayer showing antiferromagnetic coupling.

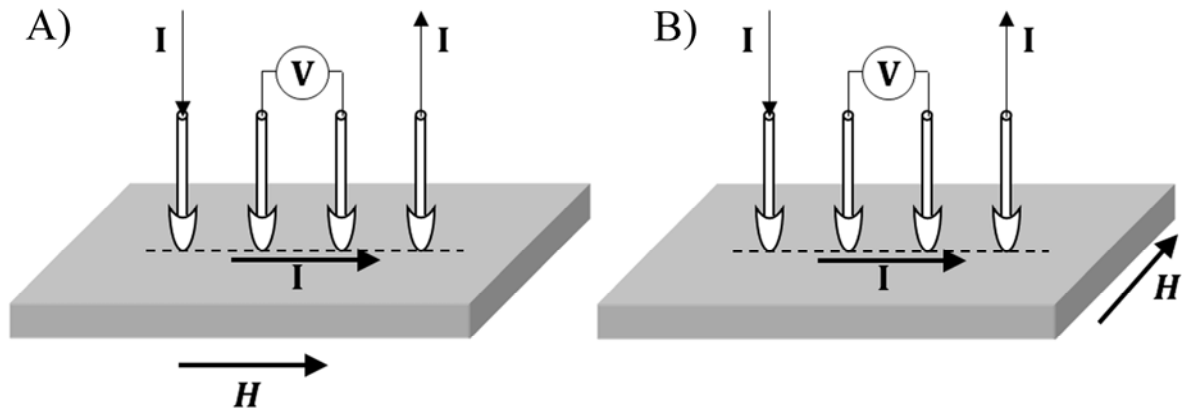


Figure 3.8. Measurement of the magnetoresistance by the four-point probe method. Current and magnetic field can be either A) parallel or B) perpendicular which allows the measurement of the longitudinal and transverse magnetoresistance, respectively.

On the other hand, current can flow either parallel (current-in-plane configuration (CIP), which is the case previously explained) or perpendicular (current-perpendicular-to-plane configuration (CPP)) to the film plane. The disadvantage of the CPP configuration is that the electrical resistance of the films is extremely small normal to its plane due to the low film's thickness (below about $1 \mu\text{m}$), making measurements difficult. That is why the CIP configuration was the preferred configuration for the magnetoresistance measurement of granular films, multilayers and nanoparticles. However, the configuration for nanowires magnetoresistance measurement always corresponded to the CPP case since the current flows along the nanowire and thus perpendicular to the substrate.

The magnetic field (H) was generated by means of an electromagnet which allows varying the field between -8 kOe and $+8 \text{ kOe}$. H was measured with a Lake shore 421 Gaussmeter in the centre of the electromagnet coils with a precision of $+ 2 \text{ Oe}$. The current is applied by a Keithley 6221 DC and AC Current Source and the voltage measured with a Keithley 2182A Nanovoltmeter. Low current intensities were applied (around 1 mA) in order to avoid film's heating. The four electrical contacts were made with copper wires pressed with metallic indium over the samples (Figure 3.10). The cryostat in the centre of the electromagnet allows modifying the temperature down to 20 K .

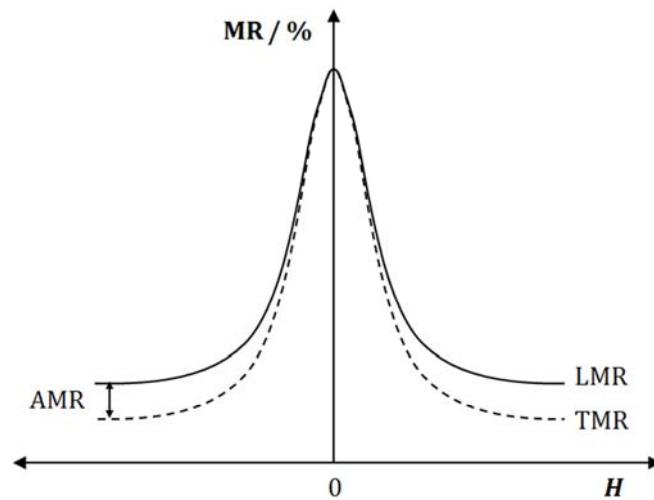


Figure 3.9. Longitudinal (LMR) and transverse (TMR) magnetoresistance curves for a multilayer showing antiferromagnetic coupling.

3.3.9. Optical properties: Surface plasmon resonance

The optical properties of the Co@Ag core-shell nanoparticles were studied by ultraviolet-visible spectroscopy using a Shimadzu UV-1700 spectrophotometer provided with a 10 mm quartz cell. It is possible to study the optical properties of silver nanoparticles or silver-coated nanoparticles due to the surface plasmon⁽¹⁾ of silver. The excitation of surface plasmons by light is denoted as surface plasmon resonance. This phenomenon is the basis of many standard tools for measuring adsorption of material onto the surface of metal nanoparticles or onto planar metal surfaces (typically gold and silver).

(1) Coherent electron oscillations that exist at the interface between any two materials where the real part of the dielectric function changes sign across the interface (e.g. a metal-dielectric interface, such as a metal sheet in air)

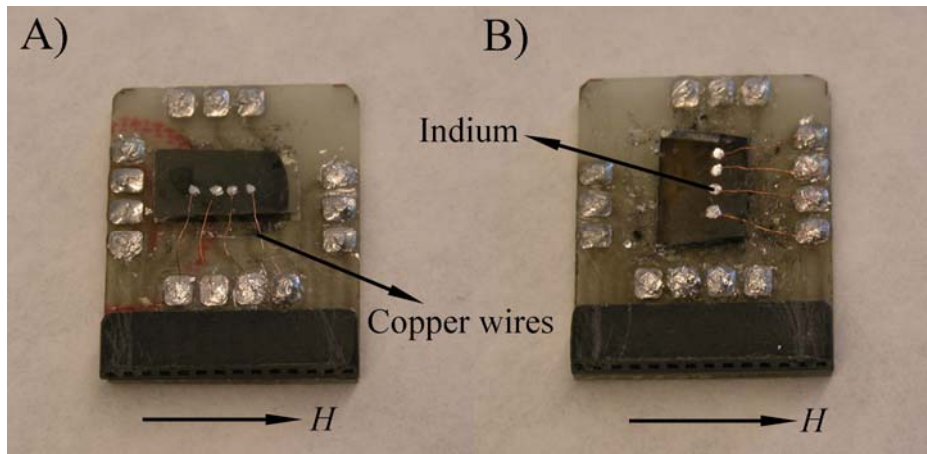


Figure 3.10. Measurement of the magnetoresistance of the films. The copper wires were mechanically attached to the sample by small amounts of metallic indium. Measurement of the A) longitudinal and B) transverse magnetoresistance.

