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Growth induced anisotropy of cobalt in cobalt/organic semiconductor films

Chiara Pernechele [a,*], Ilaria Bergenti [b], Massimo Solzi [a], Massimo Ghidini [a], Francesca Casoli [c], Valentin Dediu [b]

[a] Physics Department and CNISM, University of Parma, Via G. P. Usberti 7/a, 43100 Parma, Italy
[b] ISMN-CNR, Via P. Gobetti 101, 40129 Bologna, Italy
[c] IMEM-CNR, Parco Area delle Scienze 37/A, 43100 Parma, Italy

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ABSTRACT

We present the study of Co/organic semiconductor (OS) stacks both from the morphological and magnetic point of view. Co has been successfully used up to now as top contact of hybrid vertical devices. While the properties of Co grown on amorphous layers are well established, its deposition on soft materials presents critical aspects such as interfacial damage that affects its electrical and magnetic properties. In this work we focus on the influence of the morphology of the organic underlayer in the magnetic behavior of a Co thin film: tris(8-hydroxyquinoline) aluminum (Alq_3) grown in different conditions by molecular beam evaporation have been considered. A further considered aspect is the effect of the presence of a thin oxide barrier (Al_2O_3) on the Co magnetic properties.

1. Introduction

Spin-dependent transport has been the object of intense research in recent years. The search for new materials in which both efficient spin-injection and long distance transport can be achieved has justified a varied research in the field of material science.

Different materials have been proposed so far as adequate spin-injectors: ferromagnetic metals (FM) [1], dilute magnetic semiconductors [2,3], and Heusler alloys [4,5], half-metallic ferromagnetic oxides, such as $La_{0.7}Sr_{0.3}MnO_3$ and Fe_3O_4 are a good choice for their high degree of spin polarization.

A first attempt of spin-injection into semiconductors has been done exploiting inorganic ones in different configurations. The first spin-electronic device was the Monsma [6] transistor which was fabricated by sandwiching an all-metal spin-valve device between two layers of silicon. Although this represented a very important step forward, however the semiconductor was used only to generate barriers and to shield the spin-dependent part of the device from electric fields. To release the full potential of spin electronics, it is necessary to make devices which exploit spin-dependent transport in the semiconductor itself. More recently, organic semiconductors have attracted a great deal of attention for integration into spintronic devices [7].

In particular, the study of π-conjugated organic semiconductors (OS) such as 8-hydroxyquinoline aluminum (Alq_3) and sexithiophene (T6) has opened new frontiers in spintronics, mainly thanks to their low spin–orbit interactions [8] and their feasibility to be integrated in partially inorganic devices, as they may be fabricated under much less demanding conditions (especially concerning impurity effects) than their inorganic counterparts. It has to be noted that the characteristic spin relaxation rates in OS are lower than for other spin transport materials and typical spin flip times range from 10^{-5} to 10^{-7} s [8]. Spin-injection into organic semiconductors was first demonstrated in lateral devices with highly spin polarized manganite $La_{0.7}Sr_{0.3}MnO_3$ (LSMO) electrodes and sexithiophene (T6) as channel material [9]. Subsequently, magnetoresistance (MR) in vertical organic spin valves (OrgSVs) with LSMO and cobalt electrodes was observed, using tris(8-hydroxyquinoline) aluminum (Alq_3) as interlayer [10,11]. A recent communication reported the propagation of the spin polarization to distances exceeding 100 nm even at room temperature [12].

Several devices based on these materials have been demonstrated, as organic light emitting diodes [13], organic thin film spin valves (SVs) [14], single-molecule spin switches and SVs [15].

Moreover, devices that perform different and complementary operations are one of the aspirations of the electronics industry. In that case, the addition of an extra task to a single organic-layer OrgSV could lead to the production of a multipurpose device (with electrical, magnetic, and even optical addressing). A first experimental demonstration of simultaneous spin and memory functionalities is reported in Ref. [12], in which a MR effect and an

* Corresponding author. Tel.: +39 0521905786; fax: +39 0521905223.
E-mail address: chiara.pernechele@fis.unipr.it (C. Pernechele).

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electric nonvolatile memory effect have been integrated into a hybrid spin-valve device.

Co has been successfully used up to now as top contact of hybrid vertical devices [16]. While the properties of Co grown on amorphous layers are well established, its deposition on soft materials presents critical aspects such as interfacial damage [16] that affects its electrical and magnetic properties.

In this work we present the study of different series of Co/OS samples aiming at exploring the in-plane anisotropy occurrence due to the organic microstructure considering a fixed Co thickness. A growth induced magnetic anisotropy in the plane of the metal film can then strongly influence a device realization and behavior. A further aspect is the dependence of the magnetic properties of Co on the presence of a thin Al_2O_3 barrier with different thicknesses. The morphological characteristics are considered and their connection with the measured magnetic properties are discussed in detail.

2. Experimental

In this report we concentrate on different aspects concerning both the organic-layer structure and the OS/Co interface quality studied in terms of the Co magnetic properties reproducibility. Tris(8-hydroxyquinoline) aluminum (Alq_3) is a π-conjugated molecule with remarkable properties in organic luminescent devices like OLEDs. It consists of one aluminum ion (Al^{3+}) and three 8-hydroxyquinoline molecules in which one nitrogen atom and one oxygen ion for each ligand coordinates the Al^{3+} ion with a pseudo-octahedral structure. Vacuum-sublimed thin films are typically amorphous and have been shown to be morphologically stable at room temperature [17,18]. It is important to note that Alq_3 is an electron charge carrier, while most OS are hole conductors. The electron mobility in this material is almost two orders of magnitude higher than hole mobility [19]. For this work, Alq_3 5, 10, 100 nm layers were deposited by Organic Molecular Beam Deposition (OMBD) in UHV conditions (10^{-9}–10^{-10} mBar) on Si substrates both at low and high temperatures (that means $T > 150\,^{\circ}C$).

After having optimized the OS layer growth at room temperature in terms of quality and surface roughness, an Al_2O_3 tunnel barrier with variable thickness (ranging from 1 to 3 nm) was inserted between the OS and the Co layers, in order to prevent Co interdiffusion, as reported in [14]. The oxide layer was grown by Pulsed Plasma Deposition (PPD). The choice of Al_2O_3 was based on its well-known properties as a tunnel barrier in magnetic tunnel junctions. The 3d ferromagnetic metal top electrode was deposited by RF sputtering with thicknesses of 5 and 15 nm. A capping layer of Pt or Au was deposited in order to prevent Co oxidation.

The samples microstructure was investigated by means of Atomic Force Microscopy (AFM) using a Digital Instrument Nanoscope IIIa in tapping mode, while the magnetic analysis was performed by means of a MPMS-XL 5 Quantum Design Superconducting Quantum Interference Device (SQUID) magnetometer and Magneto Optical Kerr Effect (MOKE) magnetometry.

3. Results

As far as Alq_3 is concerned, it was found that a critical parameter in the growth of this molecule is the temperature. In fact this organic layer displays a rather high roughness, if deposited at $T > 150\,^{\circ}C$, while the interface becomes smoother if it is grown at room temperature. In particular, in the case of the considered organic-layer thicknesses deposited at high T (5 and 10 nm), a typical rms roughness value is of the order of 2 nm evidenced by AFM images reported in Fig. 1. For the RT deposited organic layer, the measured rms roughness is of the order of fractions of nanometer.

In order to investigate the magnetic properties and qualities of (rf sputtered) Co grown on top of OS we have performed both room temperature and low temperature analysis on three different series of samples. The main distinction that can be made has to do with the OS: Alq_3, both deposited at high and low temperatures. We have investigated 15-nm-thick Co layers deposited on top of Alq_3 deposited at high T (with 5 and 10 nm thickness). In Fig. 2 the SQUID in-plane and perpendicular to plane magnetic analysis performed on the sample 10 nm Alq_3/15 nm Co is reported.

It was found that the roughness of Alq_3 induces a strong anisotropy in the film plane and that a perpendicular component

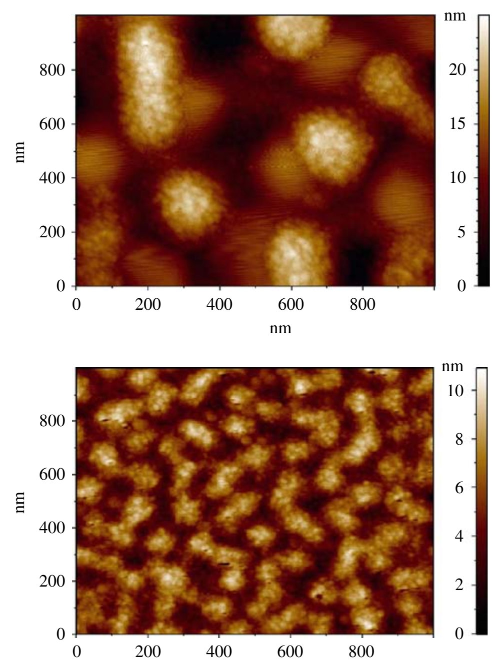

Fig. 1. AFM images of Si/10 nm Alq_3/15 nm Co/1 nm Pt sample (top panel) and Si/5 nm Alq_3/15 nm Co/1 nm Pt sample (bottom panel), the considered scan area is 1 μm × 1 μm. The organic layer is deposited at high T.

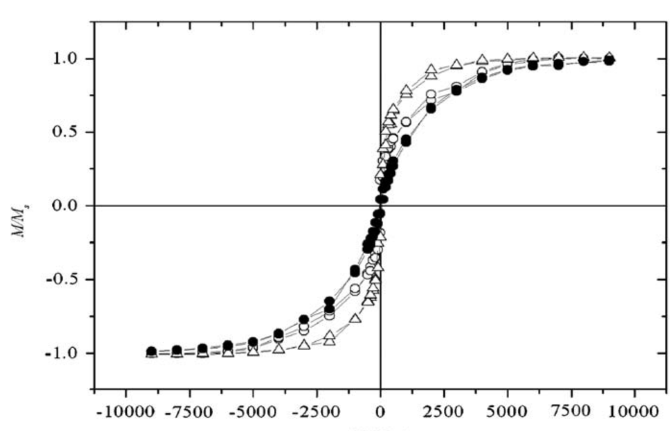

Fig. 2. In-plane along two orthogonal directions (open circles and open triangles) and perpendicular (dots) RT measured hysteresis loops for the Si/10 nm Alq_3/15 nm Co/1 nm Pt sample. In this case Alq_3 was deposited at high temperature.