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Electrical conduction mechanisms of metal nanoclusters embedded in an amorphous Al_2O_3 matrix

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Abstract

We present the synthesis and electrical characterization of amorphous nanocomposite layers made of metallic nanoclusters embedded in an alumina matrix (nc-Co:Al_2O_3). The nanostructured materials were fabricated using a pulsed laser deposition (PLD)-derived method based on a nano-cluster generator coupled with a conventional PLD system for host medium co-deposition. The films were subjected to a detailed structural study carried out using high-resolution transmission electron microscopy and atomic force microscopy. The clusters inserted in the alumina matrix are metallic, well crystallized and possess an fcc structure with an average diameter centered at ~2 nm. Dielectric constant and electrical conduction mechanisms of nc-Co:Al_2O_3 layers integrated in metal–insulator–metal capacitive structures were studied for different doping levels and for a broad temperature range (303–473 K). It was concluded that the dielectric constant in the films depends on the doping levels while the major electrical conduction mechanisms are best described by the space charge limited currents formalism, in which the current density J on an applied voltage V follow a power-law dependence ($J \sim V^n$) at applied voltages higher than ~2 V. Such composite may find immediate applications as dielectric layers with controlled discharging conduction paths in Radio Frequency-Micro-Electro-Mechanical Systems capacitive structures.

Keywords: Nanostructures; Pulsed laser deposition; Dielectric and electrical properties

1. Introduction

The non-linear optical and electrical properties of nanocomposite materials trigger nowadays a number of promising technologies in areas like semiconductor physics, optoelectronics, biology, etc. [1,2]. Although the isolated or matrix-embedded metallic nanoclusters were systematically investigated from the optical point of view (especially the surface plasmon resonance properties [2]) less is known about their electrical properties and conduction mechanisms.

Our paper focusses on electrical characterization of amorphous nanocomposite layers made of Co metallic nanoclusters embedded in an alumina (Al_2O_3) matrix (nc-Co:Al_2O_3). Amorphous alumina thin films obtained by Pulsed Laser Deposition (PLD) or by Plasma Enhanced Chemical Vapor Deposition (PECVD) were successfully integrated as dielectric layers in Radio Frequency-Micro-Electro-Mechanical Systems (RF-MEMS) membrane-type capacitive switches [3] since they possess the appropriate properties required for this type of application (high breakdown voltages for relatively low thickness, higher dielectric constant (~9) than the SiO_2 or Si_3N_4 materials usually used in such applications, process-compatible with the microfabrication techniques etc.). The major limiting lifetime mechanism of RF-MEMS capacitive membrane-type switches is taught to be the dielectric charging within the switch dielectric layer [4]. Although the exact mechanisms of dielectric charging within RF-MEMS switches is currently not completely understood, it can be described in a basic way by charge tunneling and their trapping into the dielectric. If there are no convenient conduction paths in the material, the charges remain trapped (the recombination time varies from second to days) and tend to screen the electric fields controlling the actuation and the release of the switch. This causes irregular device behavior or even device failure (charges built-up may end-up with dielectric breakdown). Among different solutions exploited to prevent these phenomena one of them involves the design and fabrication of advanced dielectrics, which have a high dielectric breakdown but in the mean time posses controlled conductive paths for charge

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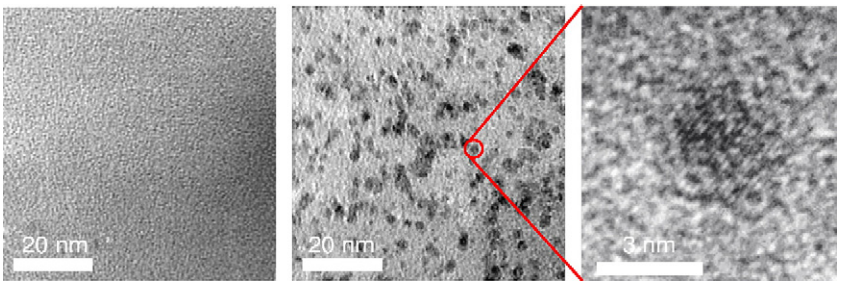

Fig. 1. TEM images of an amorphous Al_2O_3 layer (a), of an amorphous 5 vol.% nc-Co:Al_2O_3 layer (b) and the HR-TEM image of a single Co cluster embedded in the Al_2O_3 matrix (c).

evacuation. Since the alumina layers we currently used for the RF-MEMS device fabrication is prone to medium-to-severe charge built-up (it behave as a perfect dielectric without evident electrical conduction), our research for fabrication of nc-Co:Al_2O_3 composite layers and the study of their electrical properties aim to obtain materials with the characteristics explained above.

2. Experimental details

The fabrication concept is based on generation of nm-sized Co clusters and their insertion in a thin dielectric layer host (alumina). We developed a PLD-based method for controlled synthesis of nanostructured materials based on a nano-cluster generator (a modified Smalley source (Low-Energy Cluster Beam Deposition Technique)) coupled with a conventional PLD system for host medium co-deposition. This approach offers a large flexibility on the choice of aggregates and matrix materials as well as of cluster organization within the matrix. The details of the experimental set-up for nano-cluster fabrication were previously described in Refs. [5,6].

The electrical and conduction mechanisms investigations were conducted on metal–insulator–metal (MIM) capacitive structures (80×100 μm^2) by placing 200 nm-thick composites made of nc-Co:Al_2O_3 films with different doping levels (2 vol.%, 5 vol.% and 10 vol.%) between two gold electrodes. The films were subjected to a detailed structural study carried out using high-resolution Transmission Electron Microscopy (HR-TEM), electron and X-ray diffraction and atomic force microscopy.

3. Results and discussion

Fig. 1a–c shows typical TEM images of amorphous films of un-doped alumina, of nc-Co:Al_2O_3 films and the HR-TEM image of a single Co cluster embedded in the Al_2O_3 matrix. The TEM analysis was carried out on 20 nm thick nanocomposite layers (5 vol.%-doping level) deposited directly on TEM-observation copper grids. For the specific experimental conditions we used the Co particle size distributions is very sharp, centered at ~2.3 nm. According to the electron diffraction results the nanoclusters are metallic, well crystallized, with no evidence of metallic oxide formation.

The insertion of 2.3 nm-size Co nanoclusters in an Al_2O_3 matrix leads to nanocomposite materials whose dielectric and electric properties are modified compared with those of pure alumina [6].

The dielectric constant, ε_r, of un-doped alumina and of the Al_2O_3 layers doped with Co nanoclusters in different concentrations were studied by applying a.c. signals of different frequencies on the MIM capacitive structures containing the films under investigation (200 nm in thickness). Fig. 2 shows the variation of the dielectric constant with frequency for the entire investigated domain. It may be observed that the dielectric constant of pure alumina remains constant at a values of $\varepsilon_r \approx 9$. In the 50 MHz–3 GHz regions the ε_r for the doped films increase linearly with the nano-cluster concentration but its value remains rather low (from 9.5 for the 2 vol.%-doped films to 13 for the 10 vol.%-doped ones). In the low frequency region (1 Hz–1 MHz) the dielectric constant varies from 46 to 14 for the 5 vol.%-doped films and from 148 to 17 for the 10 vol.%-doped ones. This enhancement of the ε_r values for the nano-cluster-doped films is witnessing on the non-linear properties of the nanocomposite materials, as indicated in [2].

The resistance of pure (un-doped) alumina films as well as that of the 2 vol.% nc-Co:Al_2O_3 is higher than 50 MΩ (measured using a digital multimeter at $V=0.1$ V). They behave like perfect insulators. Instead, for the 5 vol.% and 10 vol.% nc-Co:Al_2O_3 the resistance is strongly decreasing down to values of 25 MΩ and 21 KΩ, respectively.

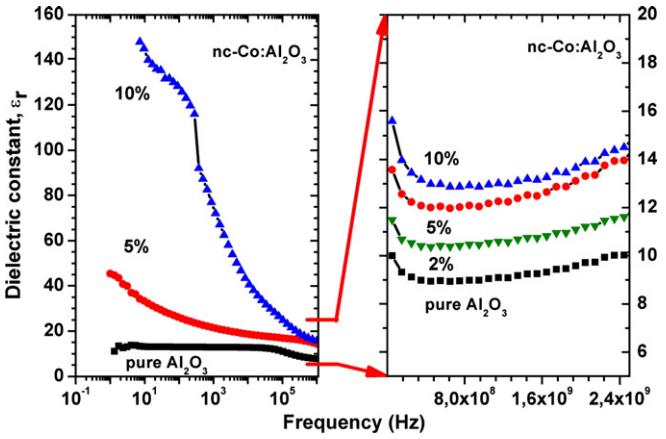

Fig. 2. Dielectric constant dependence with frequency for un-doped Al_2O_3 films and nc-Co:Al_2O_3 layers with different nano-cluster concentrations.