Microfabrication of High Aspect Ratio Complex Components based on Soft Ferromagnetic FeCo(V) Alloy by combining Lithography and Electrodeposition

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A microfabrication process consisting of optimized lithographic and electrodeposition steps has been used to develop ferromagnetic components with complex shapes. The process allows the specific engineering of the magnetic properties via tuning of the growth parameters. In this work, FeCo-based alloys have been used to obtain functional soft ferromagnetic parts, i.e., reduced coercivity (50 Oe) accompanied by a high saturation magnetization (1300 emu/cm^3). FeCo alloy has been doped with vanadium to enhance the properties and finishing quality of the fabricated parts. Optimizing the wafer-based process has allowed for obtaining hundreds of units per run with a high aspect ratio (>1:20), complex contours, and micrometer accuracy. The developed methodology is scalable and extensible to other magnetic materials.

Index Terms—**complex ferromagnetic parts, iron-cobalt alloy, lithography and electrodeposition, microfabrication**

I. INTRODUCTION

THE MICROFABRICATION of functional parts is opening the path to novel and advanced applications such as micro-electro-mechanical systems (MEMS) in key technological sectors such as electronics, aerospace and medicine. Combining lithography and electrochemistry makes it possible to fabricate unique functional components with tunable properties accompanied by high dimensional and replication accuracies [1, 2]. This combination allows for obtaining parts with a high aspect ratio, smooth surface finish, high form accuracy, and complex shapes (originated by the ample freedom in the geometry of the masks used in the lithography method). Moreover, a key advantage of this micro-manufacturing process is the fabrication of parts with parallel side walls with flank angles extremely close to 90º [2-4].

Herein, micrometer size parts made of the ferromagnetic FeCo-based alloy with different shapes were manufactured by an optimized combination of lithography and electrodeposition.

II. EXPERIMENTAL

In order to fabricate the lithographed photoresist molds, shadow masks with the desired shape were first manufactured using a laser writer and a glass plate as substrate covered by chromium and positive optical photoresist. The masks were obtained by controlled development of the photoresist and selective chemical etching of the chromium layer.

The substrate used for fabricating the lithographed molds, which afterwards were filled with the metallic alloy by electrodeposition, was a silicon wafer coated with a thin gold layer to work as the electrical contact required for the electrodeposition. The photoresist molds (Fig. 1a) were fabricated by lithography using KMPR as a negative photoresist. The molds were created employing the fabricated shadow masks and a mask aligner which allowed to obtain high aspect ratio molds (i.e., tens of µm in one dimension and above 200 µm in the other one –mold depth).

The potentiostatic electrodeposition was performed in a three-electrode electrochemical cell configuration using an Ag/AgCl reference electrode and platinum as the counter electrode. The electrolyte composition was tailored to grow a FeCo alloy with high saturation magnetization (i.e., $Fe_{65}Co_{35}$) using the sulfates of both metallic elements. For the vanadium-dope samples, a small content of the corresponding sulfate was added to the mixture. For the continuous electrodeposition, a voltage of -1.8 V vs. Ag/AgCl electrode was applied for the time required to fill the molds according to their geometry and size (Fig. 1b and inset in Fig. 1c). On the other hand, for the pulsed electrodeposition, the same voltage was applied with a duty cycle of 2/3, maintained for the necessary total electrodeposition time to fill the molds.

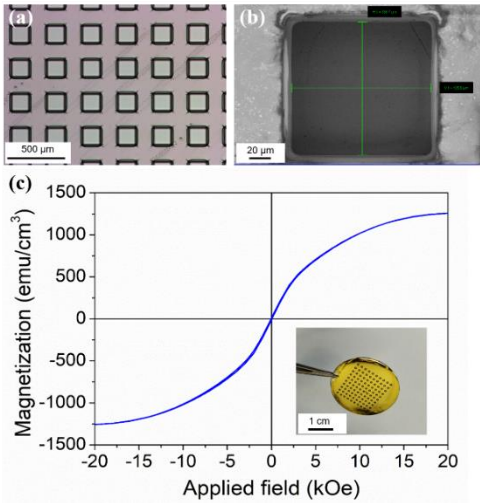

Fig. 1. Top view Scanning Electron Microcopy images (SEM) of: (a) photoresist mold made of an array of cubes with dimensions of 150 x 150 x 150 µm; and (b) metallic cube made of FeCoV alloy grown by electrodeposition on the lithographed molds in (a). (c) Room temperature hysteresis loop measured by Vibrating Sample Magnetometry (VSM) for the electrodeposited FeCoV alloy showing its soft ferromagnetic behavior. Inset in (c) shows a representative array of FeCoV parts grown by electrodeposition into the photoresist molds used for the magnetic characterization.

The morphology of the samples was determined by Scanning Electron Microscopy (SEM) equipped with an Energy Dispersive Spectroscopy (EDS) detector to obtain the composition of the electrodeposited parts. The hysteresis loops of the synthesized materials were measured by Vibrating Sample Magnetometry (VSM).

III. Results and Discussion

For the grown pieces, it was observed that the electrodeposition into lithographed molds with different shapes and similar sizes in the two dimensions (i.e., tens of µm in surface and in-depth), the FeCo alloy replicated the shape of the molds with micrometer accuracy, covering the exposed surface homogeneously. However, when fabricating high aspect ratio parts, it was observed that the growth was not homogeneous and the molds were partially filled, originating irregular shapes. This has been attributed to the surface tension and the gas bubbles that emerge during the electrodeposition process, which prevents the electrolyte to be in contact with the working electrode (mold bottom), summed up to the effect of the electric field lines distribution along the experiment.

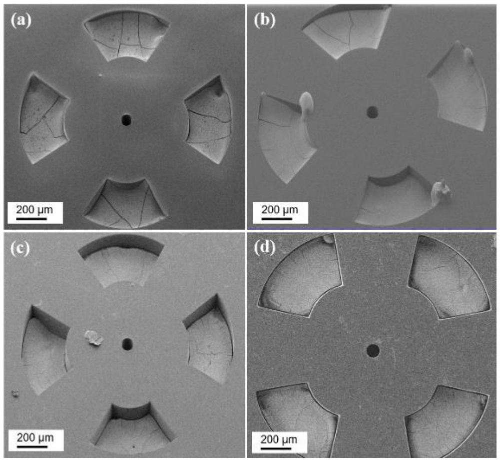

Fig. 2. Top view SEM FeCo-based parts grown by electrodeposition into lithographed photoresist molds with complex shapes and 200 µm depth using the following experimental parameters: (a) FeCo parts grown using a constant magnetic stirring along the continuous electrodeposition; (b) FeCo parts prepared under constant magnetic stirring and pulsed electrodeposition; (c) FeCo and (d) FeCoV parts grown using the conductive protective coating at the bottom of the molds, constant magnetic stirring and pulsed electrodeposition.

For enhancing the homogeneity of the parts, a constant magnetic stirring was kept during the electrodeposition, despite still numerous cracks with considerable size were observed (Fig. 2a). The number of cracks and their size were reduced by performing pulsed electrodeposition instead of applying the growing potential continuously (Fig. 2b). Further improvement in the avoidance of cracks and enhancement of the planarity of the top surface of the parts was carried out by covering the mold surface with a conductive protective coating (Fig. 2c) and by doping the FeCo alloy with a 1.5 at.% of vanadium (Fig. 2d). The optimized combination of the different experimental parameters allowed to obtain arrays of soft ferromagnetic pieces made of FeCoV alloy (Fig. 3a) with complex shapes (see a closer view in Fig. 3b) and a coercivity of 50 Oe and a saturation magnetization of 1300 emu/cm^3 (Fig. 1c).

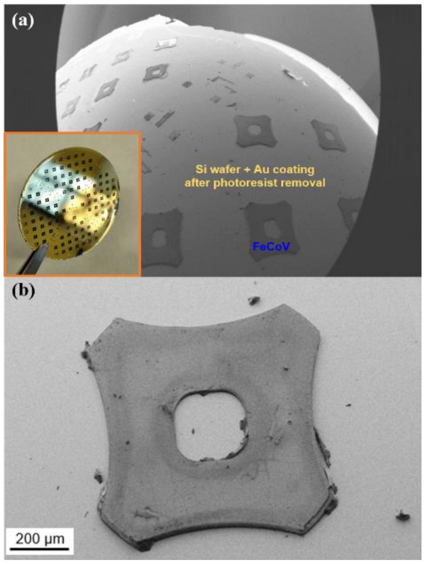

Fig. 3. SEM images of (a) an array of FeCoV parts with complex shape grown by electrodeposition into lithographed molds on top of the silicon wafer after selective removal of the photoresist mold; and (b) close view of a single FeCoV part after mold removal. Inset in (a) shows an image of the silicon wafer with the array of FeCoV parts grown into the lithographed molds.

IV. Conclusions

An optimized combination of lithography and electrodeposition methods has allowed us to perform the microfabrication of functional parts with a soft ferromagnetic behavior. Due to the methodology used, the stoichiometry of the grown alloy and the resulting magnetic properties can be tailored by tuning the electrolyte and electrodeposition parameters according to the final application. Our approach allows the fabrication of hundreds of components in each run. This microfabrication process is industrially scalable to higher throughputs, allowing the fabrication of thousands of parts per run and drastically reducing the unit cost of each component.

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