Hole mask colloidal lithography on magnetic multilayers for spin torque applications

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Abstract. We demonstrate the fabrication of metallic nano-contacts on magnetic multilayers using a Hole Mask Colloidal Lithography technique (HCL) based on Polystyrene spheres. The method applies PMMA as a sacrificial layer upon which a hole pattern is formed after lift-off of the spheres. An Au layer functions as a hard mask for the PMMA and the PMMA subsequently masks the SiO₂ during its etching. The resulting pattern is a dense collection of randomly located nano-holes through a SiO₂ film. Final devices are made using traditional photolithography to define a 600 nm circular mesa with about 3 to 4 nano-holes per device, and patterning of a metallic top contact.

1. Introduction

The spin torque oscillator [1,2] is a promising new technology for frequency generation in the GHz range and above. The extremely small footprint of the oscillator and the wide tuning range of frequency generation [3] make them ideal candidates for future communication protocols. In general the oscillators are based on nano-pillars or nano-contacts of a diameter of about 100nm. The small lateral size is typically achieved by utilizing electron beam lithography or extreme UV lithography. Both technologies have prohibitive properties such as speed of exposure and cost of installation. While many research groups have done theoretical studies on spin torque oscillators, not very many have made actual experiments and measurements on them and very often collaborations with industrial laboratories are necessary to get access to high-quality samples. Here we present a technique that can open up the possibility to fabricate spin torque oscillators and even arrays of spin torque oscillators without high performance lithography equipment.

By utilizing small spheres of polystyrene or other polymers nanostructures over a wide size range can be fabricated [4]. The structures can both be organized in patterns or more randomly distributed on the surface and the pattern density can be controlled over a significant range. For synchronized STO arrays [5], where the nano-contacts are typically 100 nm in diameter and the region of strong spin wave interaction typically extends about 50 nm from the perimeter of the nanocontact [6], a spacing of 100 nm is expected to ensure strong synchronization with a possible maximum allowed spacing of about 200 nm.
2. The HCL process

The fabrication is conducted in several steps as shown in Fig. 1. First, magnetic multilayers, typically (Cu(25nm)/CoFe(20nm)/Cu(5nm)/NiFe(5nm)/Cu(5nm)/Pt(5nm), are deposited in a high precision sputtering system. The magnetic films are then patterned into contact shaped forms and a mesa is formed in the middle of the large contact by optical lithography and Ar milling. The structure is then covered with 30 nm of SiO$_2$ by plasma enhanced chemical vapor deposition. The bottom contacts are opened up by a lithography step with photolithography and with a CF$_4$/CHF$_3$/Ar etching procedure.

The wafer is then coated with PMMA which is the media that will act as a mask when the SiO$_2$ holes are etched out. The PMMA is put through a short O$_2$ plasma etch to improve hydrophilicity. The coating forms negative surface charges that will attract positively charged polystyrene spheres. An adhesion promoting substance of polyelectrolyte is piped onto the surface. Polystyrene spheres that are positively charged are poured on top of the PMMA and the adhesion layer. The positive charge promotes separation in between spheres and adhesion to the surface. The spheres are suspended in a solvent that is rinsed with deionized (DI) water after two minutes. Blow drying in nitrogen is employed to assist DI water evaporation and to avoid rearrangement of the spheres on the surface. Spheres are around 100 nm in size and acts as a shadow mask. A thin 10 nm gold film is evaporated on top of the spheres to function as a hard mask for subsequent etching of PMMA. After the gold coating the polystyrene spheres are removed by attaching a blue tape (clean room grade) that adheres to the top of the spheres. The removal of the spheres leaves a gold film with a multitude of holes on top of the PMMA. The wafer is now put in an oxygen plasma that will etch the PMMA anisotropically forming vertical channels down to the SiO$_2$. This surface is then covered with photo resist and specific openings in photo resist are opened up by photolithography. The resist developer will not affect
the PMMA, leaving selected areas of holes that expose the SiO$_2$ surface.

The SiO$_2$ is then etched in an Oxford system with Ar (10sccm) and CHF$_3$ (20sccm) plasma with a total pressure of 30 mTorr at a power of 200W. This recipe selectively etches the SiO$_2$. Then both PMMA and resist is removed. The PMMA and photoresist are first ashed in an oxygen plasma followed by a resist remover step (MICROPOSIT 1165), an acetone step, and finally an isopropanol rinse. The original gold film is removed with the PMMA. The wafer now consists of the original metal stack and a SiO$_2$ layer perforated with holes in selected areas as well as large open areas to the bottom contact.

Al is deposited by ion beam sputtering after a short Ar pre etch. The Al layer is formed into contacts by optical lithography and plasma etching with a BCl$_3$(40sccm)/Cl$_2$(30sccm)/N$_2$(40sccm)/CF$_4$-O$_2$(10sccm) mixture at 200 W power and 200 mTorr pressure.

Figure 2. SEM images. (a) top view of gold and PMMA mask. (b) sidewall view of openings. (c) top view of 100nm openings in SiO$_2$ on top of a GMR stack with Pt as top layer (the diameters of the blue circles are 600nm the minimum size openings obtainable by the available photolithography system). (d) 600nm opening in photoresist (e) Nanoholes in the PMMA and Au mask on top of a 2um diameter mesa. the number of nanocounters is around 40. (f) top contact pattern for efficient microwave characterization of HCL STOs. The contacts are of a ground signal ground (GSG) variety for good microwave characteristics

3. Results and Discussion
As can be seen in Fig. 2 (a) the distribution of the holes from polystyrene spheres is not uniform over a smaller area. This means that the number of contacts forming oscillators will be different for each mesa being processed.

Fig. 2 (b) shows a sidewall view of two 100 nm openings in 30 nm SiO$_2$ to a sputtered metal stack on 1 µm thermally oxidized SiO$_2$. From the image we can discern that the holes are fully etched and the sidewalls have a slight slope. The slope is beneficial when the contacts are later filled with metal, as the metal is less likely to form small voids in the hole this way.

By utilizing a 600nm circular area as the limiting area, we can decrease the mean number of contacts to less than 4 as shown in Fig. 2 (c). The separation of the holes is such that the
short range interaction between the STO:s will be quite weak and it is likely that the contacts can thus be studied independently. Should one wish to use the HCL technique to study phase locking, the hole to hole separation should be made smaller by changing the adhesion promoting electrolyte.

Fig. 2 (d) shows a 600 nm opening that has been made with photolithography. The lateral size is very important to the usability of the developed method, as we believe the number of nano contacts will be hard to characterize once more than a threshold number of contacts are present in the junction.

In Fig. 2 (e) the uniformity of nanocontacts on a 2um mesa is shown. The mesa is 60nm high, and as seen the method does not give any discernable difference in coverage of holes on an elevated structure.

Fig. 2 (f) shows top and bottom contacts as formed by reactive plasma etch. The middle pad connects to the mesa with the HCL-holes from the top. The contact is of a ground signal ground (GSG) geometry for good microwave properties.

In conclusion, we have developed a new manufacturing technique for Spin Torque Oscillators that does not require advanced and expensive lithography methods. By utilizing a combination of Hole Colloid Lithography and Photolithography we have been able to limit the number of nanocontacts per device down to 4 or less. Experiments are now carried out on the transport properties of these devices.

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