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Abstract — We have fabricated a novel GMR ML flux sensor that is designed to operate in the CPP mode. The GMR sensor is a 0.4 μm diameter, 0.09 μm high Cu-Co ML pedestal. The sensors are patterned using electron beam lithography. The Al_2O_3-TiC substrate is coated with a sputter deposited Al_2O_3 film that is polished to <0.2 nm RMS roughness. Contact to the bottom of the GMR sensor is made by depositing the Cu-Co multilayers onto a smooth 0.45 μm thick Mo-Si ML stack. The top contact is self-aligned to the GMR sensor. This is accomplished, in part, by CMP. The top and bottom contact layers are electrically isolated by a PECVD Si_3N_4 film. The configuration of the contacts allows four point probe resistance measurements. The GMR response of these 0.4 μm diameter sensors is 12%.

INTRODUCTION

We have fabricated and tested the response of a giant magnetoresistive (GMR) multilayer (ML) magnetic flux sensor operating in the current perpendicular to the plane (CPP) mode [1]. The GMR sensor is a 0.4 μm diameter, 0.09 μm high Cu-Co pedestal. A CPP mode GMR sensor has an electrical contact at the top and the bottom of the ML stack and the current flows perpendicular to the ML interfaces. The location of the contacts raises two processing issues unique to CPP mode operation. First, the GMR multilayers must be deposited directly onto the bottom contact material. The contact underlayer must be conductive and smooth enough to allow uniform and continuous GMR multilayer formation. This requires that the bottom contact layer be deposited onto an ultra-smooth surface. Fabricating ultra-smooth underlayers is important to foster high quality multilayer growth. Post deposition ML degradation caused by subsequent processing must be also be avoided. In particular, conformal, pinhole free, high density low pressure chemical vapor deposited dielectrics or low temperature oxides that are typically used as electrical isolation, device passivation, or chemical mechanical polishing (CMP) surfaces can not be used because exposure to temperatures exceeding 300 °C or prolonged exposure to elevated temperatures can cause interface roughening or intermixing of the GMR (and Mo-Si) multilayers [2]. Second, the contact at the top of the sensor must be made to the top layer of the ML stack. This contact must be made using a self-aligning process if the very difficult problem of aligning 0.4 μm features to 0.4 μm pedestals is to be avoided. The reason for fabricating 0.4 μm diameter contacts is that the signal from a GMR CPP mode sensor increases as the contact area decreases. This is an advantage inherent to operating in the CPP mode and is reason why CPP mode GMR sensors can potentially be used to achieve multi-Gbit/in^2 areal recording densities. We present in this paper the process sequence developed to fabricate 0.4 μm diameter CPP mode GMR sensors. In addition, we present the GMR ML quasi-static four point probe test results for these sensors.

FABRICATION

There are six processes that distinguish this CPP mode GMR sensor fabrication sequence from those previously published (e.g., [3] and [4]). (1) Al_2O_3 thin films have been sputter deposited and polished to <0.2 nm root mean square (RMS) roughness. (2) Continuous and uniform Cu-Co ML films have been deposited onto a 0.45 μm thick Mo-Si ML films. (3) 0.4 μm features have been patterned by electron beam lithography. (4) 0.4 μm Cu-Co ML pedestals have been etched by electron cyclotron resonance (ECR) etching. (5) Plasma enhanced chemical vapor deposited (PECVD) Si_3N_4 films have been planarized by chemical mechanical polishing (CMP). (6) Electrical contact using a self-aligning process has been made to 0.4 μm diameter pedestals.

The fabrication of the sensors is done on four inch square Al_2O_3-TiC substrates. A 4 μm Al_2O_3 insulator is sputter deposited and chemically mechanically polished to a RMS surface roughness of <0.2 nm. The bottom contact film is a Mo-Si ML. The Mo-Si ML is deposited by low pressure direct-current (dc) magnetron sputtering. By optimizing the deposition parameters, >0.5 μm thick Mo-Si multilayers can be deposited with resistivity <100 μW-cm and <0.2 nm RMS roughness [5]. The nominal structure is $[Si\ 1.5\ nm/Mo\ 3.0\ nm]_{100}$/Si 1.5 nm. The resistivity of the Mo-Si ML is approximately 25 μΩ-cm. The Mo-Si ML is continuous and exhibits no amplification of roughness or columnar growth throughout the layer stack [5]. Cu-Co ML is deposited onto the Mo-Si ML without breaking vacuum. The nominal structure is $[Co\ 2.0\ nm/Cu\ 3.0\ nm]_{18}$/Co 9.0 nm. The thickness uniformity of the Cu-Co ML better than 1% [6].

Electron beam lithography is used to pattern 0.4 μm circles. The substrate is spin coated with 0.95 μm of Shipley SAL-601-ER7 (SAL601) negative resist. The substrates are soft baked at 80° C for 30 minutes, then exposed using the ETEC AEBLE 150 system operating at 20 keV. The exposure dose is 34 μC/cm^2. A post exposure bake is done for two minutes on a 115° C hot plate. The exposed substrates are developed for five minutes by immersion in Shipley MF-312/CD-27. The as-developed stacks are 0.95 μm tall with nominal diameters of 0.4 μm.

The Cu-Co ML is etched using an ECR etcher. The etch rate of the Cu-Co ML is nominally 45 nm/min. The selectivity is defined as the ratio of the etch rates of two materials. The selectivity of the Cu-Co ML to the SAL601 is 0.45:1. The selectivity of Cu-Co ML to the Mo-Si ML is 1:1. The etched Cu-Co

ML stacks have been analyzed using scanning electron microscopy (SEM) and transmission electron microscopy (TEM). The results show that the sidewalls are nearly vertical, there is no apparent degradation of the multilayers, and there is no evidence of re-deposition of materials. The SAL601 is not removed after the etch because it defines the contact region of the GMR sensor. A cross section of the structure after the Cu-Co ECR etch in shown in Fig. 1(a). A 150 nm Si_3N_4 plasma enhanced vapor deposition is done immediately following the Cu-Co ML etch to passivate the metals and to protect the SAL601 from subsequent resist strips. The substrate is backside heated to 200 °C during the Si_3N_4 deposition. The bottom Mo-Si ML contact is patterned next using optical contact lithography and etched using the ECR plasma source. The Mo-Si etch rate is nominally 48 nm/min. The selectivity of the Mo-Si ML to soft baked positive resist is 0.24:1. A cross section of the structure after the Mo-Si ECR etch is shown in Fig. 1(b).

A 550 nm PECVD Si_3N_4 film provides the necessary electrical isolation between the bottom Mo-Si ML contact and the upper Au contact. The substrate is backside heated to 200 °C during the Si_3N_4 deposition. The contact windows in the Mo-Si ML are patterned using optical contact lithography and etched using the ECR plasma source. The PECVD Si_3N_4 etch rate is nominally 200 nm/min. The selectivity of PECVD Si_3N_4 to soft baked positive resist is 1:1. The PECVD Si_3N_4 provides an excellent surface for "local planarization" by CMP. There are two characteristics of the CMP process that permit local planarization. First, CMP removes surface protrusions at a much greater rate than the removal rate of the surface. The time required to planarize the region occupied by each Cu-Co-ML-SAL601 stack, therefore, is independent of the removal rate of the surface. Second, the CMP removal rate of PECVD Si_3N_4 is typically much slower than the rate of PECVD SiO_2. Using a PECVD Si_3N_4 passivation film allows one to develop a CMP process that reduces the surface roughness and removes surface protrusions (i.e., locally planarizes) while removing less than 50 nm of the PECVD Si_3N_4 film. Because the removal rate is low, the polishing can be continued as long as is required to planarize the region occupied by each Cu-Co-ML-SAL601 stack without excessive, non-uniform PECVD Si_3N_4 film loss. The insensitivity to the end point is particularly important when etching four inch square substrates because the etch rate is very non-uniform at the substrate corners.

The SAL601 is removed after CMP to create a self-aligned conduit to only the top Co layer. It is unlikely that the top contact will short to the ML sidewall because PECVD films are conformal. The PECVD Si_3N_4 need not be etched back to expose the SAL601 as long as the total deposited dielectric film thickness is less than the post-Cu-Co-ML-etch SAL601 stack height. The SAL601 is stripped by reactive ion etching using the ECR plasma source. An Ar-O_2 plasma is used with a total gas pressure of 15 mT. The SAL601 etch rate is nominally 200 nm/min. The top 9.0 nm of Co generally provides sufficient protection against Cu corrosion induced by exposure to the O_2 plasma. A cross section of the structure after the SAL601 ECR etch is shown in Fig. 1(c).

Atomic force microscopy (AFM) using an ion milled tip is used to analysis the contact. The sidewall angle is greater than 79° (the AFM tip profile angle) and is probably near vertical. The contact depth is 375 nm. The shape of the contact and the shape of the GMR sensor are determined by the shape of the as-exposed SAL601 stack. The contacts (and sensors) described here are circular. The contact diameter measures 364 nm. This value is slightly smaller than the measured SAL601 diameter because of the AFM tip profile and scan angle.

The top contact to the GMR sensor is fabricated by electro-chemical plating. The plating seed layer is a sputter deposited Ti-Cu film. A dark field mask is used to pattern the negative contact layer pattern in positive resist. The top contacts are formed by plating through the resist windows. The target Au thickness is 3 μm. When the plating is complete, the resist is stripped and the Ti-Cu seed layer is etched in an alkaline solution.

CPP QUASI-STATIC MEASUREMENTS

The quasi-static four point probe measurements on the GMR CPP test structures are made using a ILX LDC-3712 modulatable current source and a Stanford Research Systems SRS-850 digital lock-in amplifier. The lock-in amplifier produces a signal from its internal reference source that modulates the dc output of the current source. The current is passed through the sensor via the top and bottom contacts while a second pair of probes monitors the voltage drop across the remaining two contacts. This voltage is measured by the lock-in as the field is swept. All measurements were performed at room temperature.

The modulation frequency used is 35 kHz. The current is 2 mA dc with a 1.0 mA 0 to peak sinusoidal modulation. An average of three measurements were made at each field point. Each measurement was stored, then averaged and smoothed. Fig. 2 shows the change in resistance verses the transverse magnetic field. The peak resistance at 64 Oe is 8.724 Ω. The maximum GMR change is approximately 16 mΩ. The GMR response is hysteretic. The width of the response curve at full-width-half-maximum is approximately 296 Oe. The GMR response is defined as, $(R-R_S)/R_S$, where R is the maximum resistance of the GMR sensor and R_S is the saturation resistance. The current in the plane (CIP) GMR response of a $[Co\ 2.0\ nm/Cu\ 3.0\ nm]_{18}$ ML deposited onto single crystal (100) silicon without a buffer layer and annealed 60 minutes at 200 °C is 6%. The resistivity of the Cu-Co ML is approximately 20 μΩ-cm. The CPP GMR response can be estimated using the measured values for the Cu-Co ML pedestal height (0.09 μm) and diameter (0.4 μm). The estimated CPP GMR response is 12%, approximately two times larger than the corresponding CIP GMR response. This result is consistent with the work reported by other experimental groups [4].

CONCLUSION

We have fabricated a 0.4 μm diameter GMR flux sensor designed to operate in the CPP mode. The GMR sensor is a 1.5 nm Si/[Co 2.0 nm/Cu 3.0 nm]$_{18}$ ML terminated by a 9.0 nm Co layer. The thickness uniformity of the Cu-Co ML better than 1%. The Cu-Co ML is deposited on a conductive [Si 1.5 nm/Mo 3.0 nm]$_{100}$ ML. The Mo-Si ML is continuous and exhibits no amplification of roughness or columnar growth throughout the layer stack. The GMR sensor is patterned by electron beam lithography and etched using an ECR reactor. The top contact is self-aligned to the GMR sensor. This is accomplished, in part, by CMP. The top and bottom contact layers are electrically isolated by a PECVD Si_3N_4 film. Quasi-static four point probe testing shows a maximum change in the GMR of 16 mΩ. The GMR response is estimated to be 12%. The process sequence presented here is uniquely suited to CPP GMR sensor fabrication because it is designed to make electrical contact to the top surface of 0.4 μm pedestals; the shape and minimum diameter of the pedestals being determined only by lithography. In addition, we believe that this process sequence is compatible to and suitable for high yield integrated circuit manufacturing.

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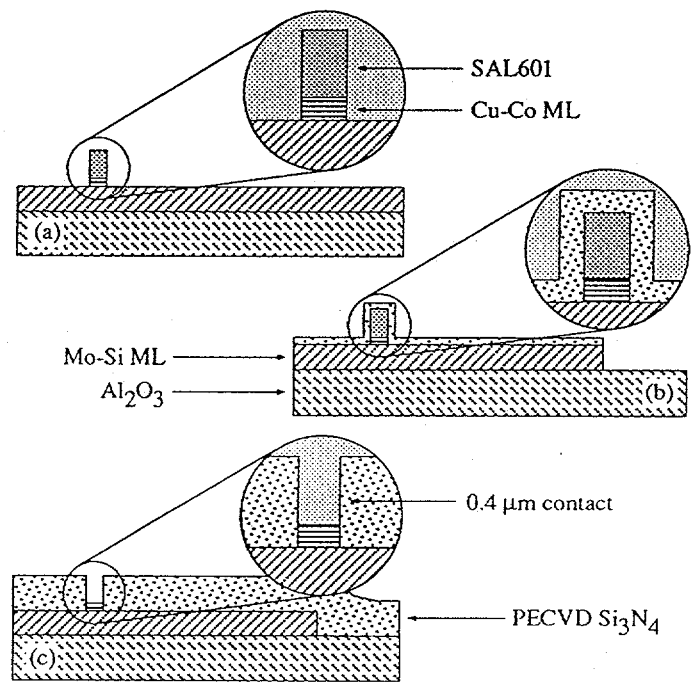
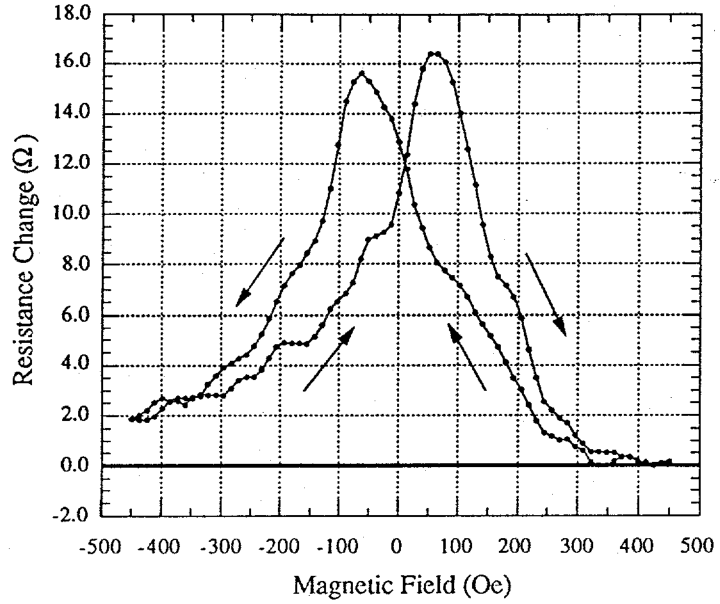
Figure 1. A cross section of the process sequence showing the structure after (a) the electron beam lithography and Cu-Co ML etch, (b) the 150 nm PECVD Si_3N_4 deposition and Mo-Si ML etch, and (c) the CMP and SAL601 ERC etch.

Figure 2. The CPP GMR sensor resistance change verses the transverse magnetic field. The maximum resistance change is approximately 16 mΩ at 64 Oe. The width of the response curve at the full-width-half-maximum is 296 Oe. The GMR response is 12%.



SAL601
Cu-Co ML
(a)
Mo-Si ML
Al2O3
(b)
0.4 μm contact
PECVD Si3N4
(c)



18.0
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
-2.0
Resistance Change (Ω)
-500 -400 -300 -200 -100 0 100 200 300 400 500
Magnetic Field (Oe)