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Towards the sub-50 nm magnetic device definition: Ion beam etching (IBE) vs plasma-based etching

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ABSTRACT

Conventionally, the tunneling magneto resistive (TMR) devices for both hard drive and magnetic random access memory (MRAM) are defined via photolithography and subsequent ion mill processes. Due to non-volatility of ion milling byproducts, re-deposition of device materials across the tunneling barrier will increase the critical dimension (CD) and reduce the pattern transfer fidelity; moreover, it causes electrical shunting and TMR ratio drop. Therefore, either relatively large angle primary or two-step mill with a subsequent large angle side mill is required to clean-up such re-deposition across the barrier. Such primary milling angle and side milling time at a fixed primary mill angle have been determined experimentally to be ∼20–30° and above 30 s, respectively, in this study. However, it was found that extended side milling can cause substantial damage for sub-∼30 nm. We also investigated the plasma-based etching of such TMR devices using various chemistries and presented optical emission spectrum of such chemistries. The plasma etched TMR device profile and the possible interaction between the chemistry with the MgO barrier was also discussed.

1. Introduction

With the ever-increasing requirements to handle huge amount of data in modern information/communication systems, there is an increasing demand for higher hard disk drive capacity and better performance. For the areal density approaching ∼1 TB/in^2, the magnetic reader sensor size must be decreased to read narrower recorded bits with minimal side reading. From recording aspect, one effective way to increase the recording density is to pre-define small magnetic dot-arrays as the media, i.e. bit patterned media (BPM). For the magnetic random access memory (MRAM) applications, magnetic devices are packed more closely than for the hard drive application due to package density requirements. This creates huge challenges for a definition process for magnetic devices (tunneling magneto resistive (TMR) sensors or BPM) that does not result in re-deposition of device materials. Re-deposited material tends to grow on the sidewall of the initial photo resist and thus inflates the final device physical critical dimension (CD) and causes the pattern fidelity issue. More importantly, re-deposited material results in electrical shunting across the barrier (for TMR devices) if not fully cleaned-up. A side mill process at large angle is normally added after the primary ion beam mill definition to remove re-deposited materials and to provide a better CD control. Unfortunately, large angle side mill has drawbacks: (1) it creates damages at the edges of devices and degrades device performance; (2) at high package density, side milling is sometimes impossible due to shadowing effects; and (3) the same shadowing effect can cause poor process uniformity at large angle due to clamps used at wafer edges. To minimize edge damage of devices, a low beam energy can be used, however, the beam divergence angle increases at lower beam energy and compromises milling uniformity [1–4]. The shadowing effect due to device package density is very difficult to solve; it can be minimized by optimizing clamp design at edges, though it cannot be fully avoided since electro static chucks (ESCs) are very difficult to implement for rotating wafer stages.

As a result, plasma-based etching has been very actively researched [5–9] by both industry and academia to supplement conventional ion beam etching (IBE). Plasma-based etching should be easier to scale up to large wafer dimension, compared with IBE. Plasma-based etching tools do not require grids, hence less grids-related contaminations, and the operation/maintenance cost is cheaper. However, there are challenges in various aspects of plasma-based etching: (1) selection of the right etching chemistry with sufficient byproduct volatility; (2) reduction of chemical reactions or damage to the device edges; (3) choice of hard mask

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which enables a high etching selectivity; and (4) subsequent process considerations. For example, if a hard mask has to be used, how can it be removed after device definition.

In this paper, we present results and challenges for sub-50 nm magnetic device definition via both conventional IBE and plasma-based etching.

2. Experiments

2.1. Device stack

2.1.1. TMR

We have used a conventional TMR device with the following structure layout in this study: Seed layer/AFM/SAF/MgO/free layer/Cap layer (AFM is the abbreviation of “Antiferromagnet”, while SAF is the abbreviation of “Synthetic Antiferromagnet”).

2.1.2. Patterned media

For patterned media study, the following film stack structure was used: Seed layer/CoPtCr/Cap layer, which was deposited with a magnetron physical vapor deposition (PVD) cluster tool.

2.2. Device definition

2.2.1. TMR device

After the TMR stack film deposition, photolithography and ion beam milling or plasma-based etching were used to define the final device dimension and profile. For conventional ion beam milling, commercially available radio frequency (RF) ion sources with a three-grid design were used. A typical beam is operated at 1.33×10^{-2} Pa using Ar. Beam current and voltages can be varied for better process uniformity. The incident beam angle can be changed from 0 to 80° to control the junction profile and re-deposited material. For plasma-based etching, inductively coupled top RF source and a capacitively coupled bottom RF source, both at 13.56 MHz, were used. The chuck temperature was set at 353 K and the shielding was set at 473 K to facilitate the vaporization of etching byproduct. Available etching chemistries in the system include Ar, CF_4, O_2, NH_3, and CH_3OH.

2.2.2. Patterned media

Imaging resist was applied using a propriety mask imaging technique and was patterned using ion mill technique to define the media pattern. After ion milling, the resist residual was stripped using an inductive coupled plasma (ICP) source with CF_4/O_2 chemistry.

2.3. Device isolation and hard bias formation

After device definition by either IBE or plasma-based etching, an electrical isolation layer (such as Al_2O_3) is deposited by sputtering, chemical vapor deposition or atomic layer deposition. To reduce the thermal budget during the isolation process, the substrate temperature is limited to below 473 K. The isolation layer is generally less than 100 Å to balance the good electrical isolation property and good permanent magnet hard bias strength to the magnetic free layer.

Following isolation formation the hard bias and top electrode are deposited.

2.4. Device testing

2.4.1. TMR device

Finished devices were tested on a 4-probe tester with the external field sweeping from −1000 to +1000 Oe to gauge their electrical and magnetic responses. For each device category, at least 64 sites on a 150 mm diameter wafer were tested. Device performance was then analyzed statistically. Transmission electron microscopy (TEM) was used for selected samples to provide details of the junction profile, the reaction layer around the junction, and failure mechanism.

2.4.2. Patterned media

Patterned media were tested using magneto-optical Kerr effect (MOKE) technique. The parameters tested included H_c (coercivity), thermal stability (K_uV), nucleation field (H_n), and switching field distribution (SFD). Measurements were conducted using multiple locations at each stage of the process.

3. Results and discussions

3.1. Conventional IBE definition process

3.1.1. Re-deposition

Fig. 1 summarizes the trend of both the TMR (a) and the resistance × area product (RA) (b) as a function of the primary milling angle. No side clean-up mill was applied in this case, simplifying data interpretation. It is evident that both TMR and RA reach a stable level when the primary milling angle is about 25–35° from wafer surface normal. Generally, the rejected atoms from a surface subjected to primary ion beam irradiation will follow a cosine

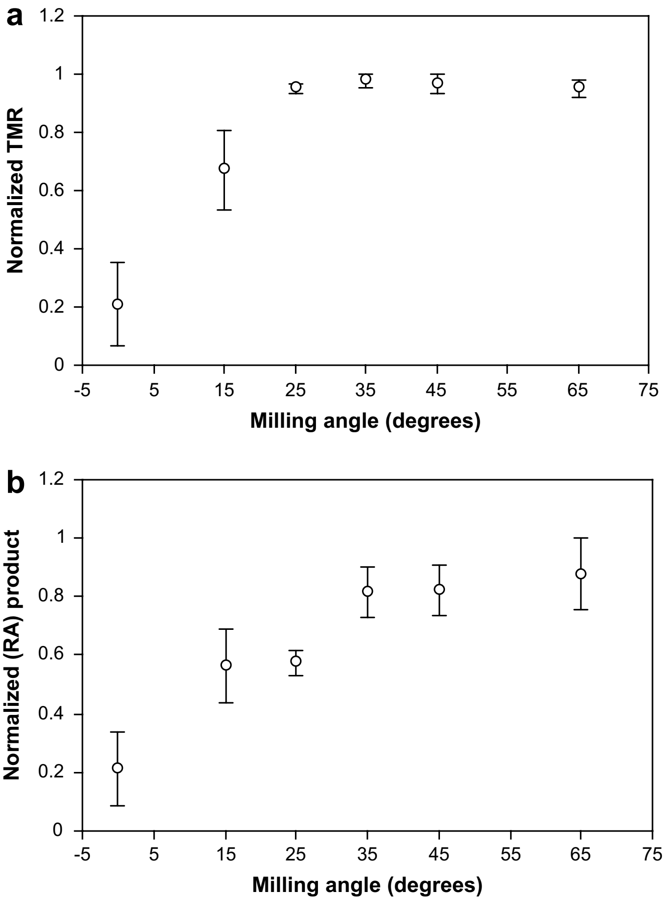

Fig. 1. Normalized (a) TMR and (b) resistance × area (RA) product for a various TMR wafers as a function of primary mill angles. No side mill was applied here post-primary mill. It is obvious that a primary milling angle of 25–35° is required to avoid re-dep across the barrier if no 2nd side mill is applied.