

RESEARCH ARTICLE | DECEMBER 03 2013

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Appl. Phys. Lett. 103, 232404 (2013)

<https://doi.org/10.1063/1.4837677>



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Optimization of tunneling magnetoresistance of MgO based tunnel junctions by tuning the stage impedance for radio frequency sputtering of the barrier

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(Received 23 September 2013; accepted 12 November 2013; published online 3 December 2013)

In this article, we describe a method to maximize the tunneling magnetoresistance of magnetic tunnel junctions with MgO tunneling barrier by optimizing the stage impedance for the RF MgO deposition. The impedance can be varied continuously using a matchbox that is in place to apply a RF bias to the stage. It is measured by means of a network analyzer connected to a dummy wafer on the stage. For positive stage reactance, both resistance area product and tunneling magnetoresistance are observed to drop, related to the stage impedance resonating with the plasma sheath capacitance. At high negative stage reactance, resputtering is minimized and tunneling magnetoresistance maximized. © 2013 AIP Publishing LLC. [<http://dx.doi.org/10.1063/1.4837677>]

Magnetic tunnel junctions (MTJs) have been used for many years in devices like hard disk drive read heads,¹ magnetic field sensors,² or Magnetic Random Access Memory.³ Typically, MgO is used as the tunnel barrier material which allows for high values of tunneling magnetoresistance (TMR) to be achieved.^{4,5} High TMR values had been predicted from first principles calculations for epitaxial Fe/MgO/Fe films;⁶ however, it was shown that good TMR values can be achieved even with polycrystalline films fabricated by sputter deposition. The MgO barrier layer can be formed by sputtering with various methods, the most common being RF sputtering from a stoichiometric MgO target,⁷ reactive sputtering of Mg in an Ar/O₂ atmosphere,⁴ and post oxidation of a layer of metallic Mg.⁸ The deposition conditions need to be optimized for each of the methods to achieve best morphology of the barrier and thus highest values of TMR. For different deposition tools, these optimized conditions can be different due to variations in chamber volume, geometry, base pressure, electrical properties of the stage, etc. In this article, we describe a technique for measurement and optimization of the stage impedance for the RF sputter deposition of the MgO barrier in an Anelva sputtering tool.

All results shown here are obtained in an Anelva C-7100 cluster sputtering tool with various chambers with 4 or 5 physical vapor deposition (PVD) guns. MgO deposition is carried out in an EX type 4 PVD module. Here, the target substrate distance is 240 mm. During deposition, the wafer rests on a rotating insulating chuck which has the capability of applying RF bias to the substrate by means of an electrode embedded inside it. This electrode is connected to an electrical feedthrough by a rod that runs in the center of the stage assembly. A matching network is installed on the outside of the chamber between feedthrough and power supply (PS). This matchbox consists of two inductors (L1, L2) and two variable vacuum capacitors (C1, C2). A schematic of stage and matchbox is shown in Figure 1. In the experiments reported here, no RF bias is applied but the matchbox is used

to change the impedance of the stage assembly. In order to determine the dependence of MgO film properties and MTJ performance on the impedance of the stage during deposition, one needs to know the magnitude of the impedance and be able to control it. This will allow for optimization of the TMR as well as the possibility to verify and match performance for different types and sizes of stage. If the substrate RF bias is not used during MgO deposition, the lead at the power supply is grounded. The variable capacitors, which are used for impedance matching, can now be set manually to a desired value and the impedance of the stage can be varied in this manner. To determine the impedance of the whole stage assembly, one has to take into account not only the current path through the matchbox and RF power supply. Due to finite capacitance between substrate and shielding (some grounded others floating) as well as the capacitance between electrode and rod to grounded parts of the stage, the overall impedance is given by an interplay of a large number of unknown capacitances and inductances and thus difficult to determine. It hence becomes necessary to measure this impedance directly.

In order to measure the impedance of the stage, we use a TenTec vector network analyzer (VNA) with a frequency range of 1 to 100 MHz.⁹ The measurement is performed with the deposition chamber vented and opened. We connect the Transmit terminal of the VNA to an AlTiC dummy wafer on the stage by means an unshielded wire affixed with copper electrical tape. The Receive terminal is connected to the wall of the deposition chamber with an unshielded wire and alligator clips. No fixture calibration was performed. Figure 2 shows both the real (R) and imaginary (X) part of the stage impedance ($Z = R + iX$) for a frequency range from 10 to 24 MHz (13.56 MHz being the frequency of interest which is the frequency of the RF for MgO gun). Multiple resonances can be observed where X diverges and R increases significantly. These resonances are typical for networks of inductors and capacitors. The measurement was repeated for various settings of the variable capacitor C2. This capacitor can be adjusted between 0 and 2000 steps. Figure 2 shows results for three different settings of C2 (200, 450, and 0 steps). One of the resonances does move to different frequencies with changing C2 and other resonance remains at the

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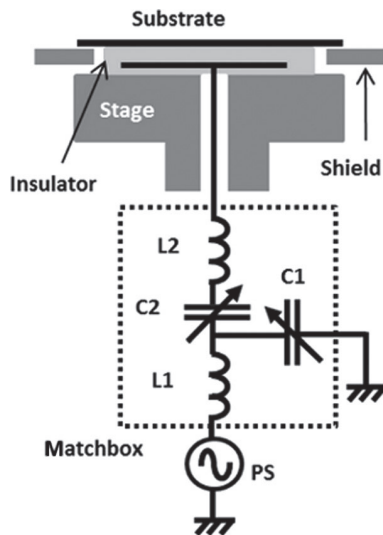


FIG. 1. Cartoon of 4PVD chamber stage which shows the substrate on the insulating stage, counter electrode embedded in the stage and connection to matchbox. The capacitors (C1, C2) and inductors (L1, L2) depicted reside inside the matchbox. The PS is used to (optionally) apply RF bias to the stage. C1 and C2 are adjustable and can be set manually to a fixed value if RF power is off and/or no impedance matching is desired.

same frequency. As the resonance moves through the frequency of interest (13.56 MHz) X can be adjusted continuously between high negative and positive reactance. Figure 3 shows the reactance and resistance at 13.56 MHz for different values of C2. By careful adjustment of C2, a large range of impedance values can be implemented.

To investigate the dependence of resistance area product (RA) and TMR on the stage impedance during the MgO deposition, we have prepared MTJs where the MgO barrier is deposited at varying C2 settings which correspond to

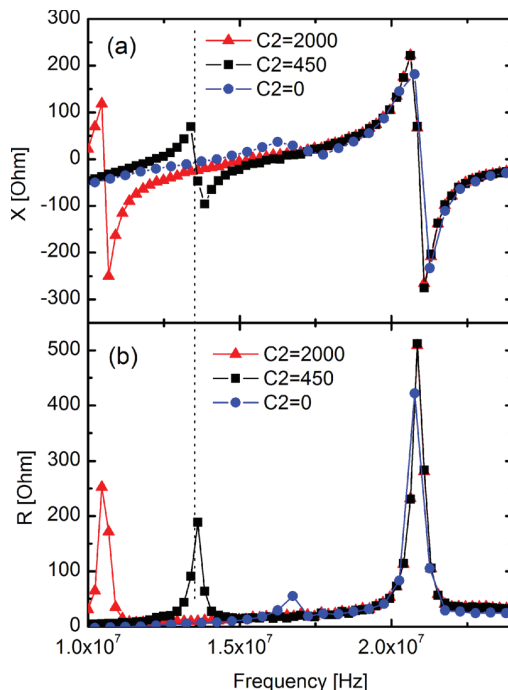


FIG. 2. Resistance (R) and Reactance (X) of stage impedance versus frequency. The measurement was taken for a C2 capacitor setting of 2000 (red triangles), 450 (black squares), and 0 (blue dots).

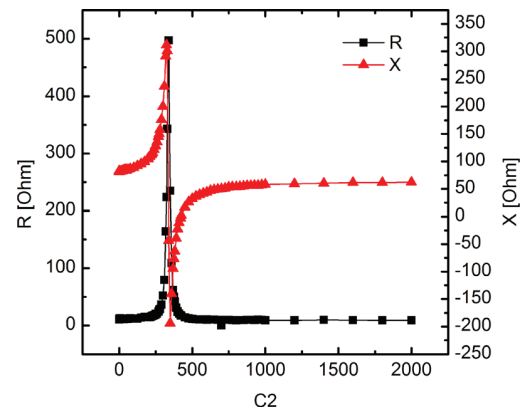


FIG. 3. Real (R) and Imaginary (X) part of stage impedance measured at 13.56 MHz for C2 varied from 0 to 2000. A resonance can be observed around $C2 = 430$ where X diverges. By careful adjustment of C2, X can be varied continuously from $>100\ \Omega$ to $<-100\ \Omega$.

different values of stage impedance. The TMR film stack deposited was as follows: AlTiC substrate /Ru/IrMn/CoFe/Ru/CoFeB/CoFe/MgO/CoFe/CoFeB/NiFe/Ru/Ta/Cu/Ta/Ru. The base pressure for all PVD chambers was better than 5×10^{-9} Torr. After deposition, the wafers are annealed in a vacuum anneal oven with applied magnetic field. RA and TMR are measured using the current-in-plane tunneling (CIPT) method on un-patterned films. Various samples with RA values $\sim 0.7\ \Omega\ \mu\text{m}^2$ were prepared. Figure 4 shows the results for TMR plotted together with reactance versus C2 setting. TMR is $\sim 50\%$ for high C2 settings, does have a maximum of $\sim 60\%$ close to $C2 = 400$, and drops to almost zero for lower C2 values. Evidently, the TMR is maximized when the reactance is very negative (capacitive). Figure 5 shows both RA and TMR plotted versus stage reactance. The minimum in RA and TMR corresponds to positive (inductive) reactance of $\sim 150\ \Omega$; while for capacitive (negative) reactance, the TMR is maximized. There is some dependence of TMR on RA (TMR is reduced at lower RA); however, the dependence is much smaller as what is observed here. High TMR is also achieved for $X \sim 300\ \Omega$.

The results can be explained by taking into account the RF sputtering process and the interaction of the sheath

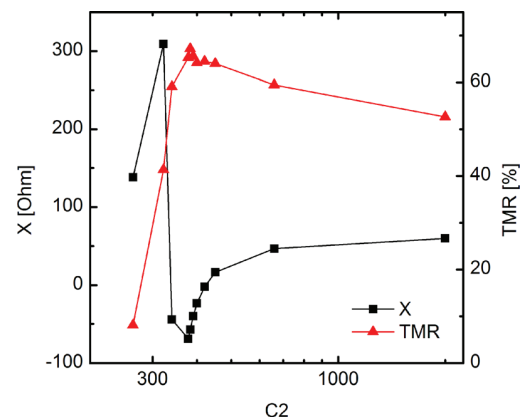


FIG. 4. TMR (red triangles) for a MTJ with MgO tunnel barriers deposited with different values of stage impedance (by changing of C2 capacitor setting). For comparison, the stage reactance (black squares) is also plotted. Note the log scale for the C2 setting.

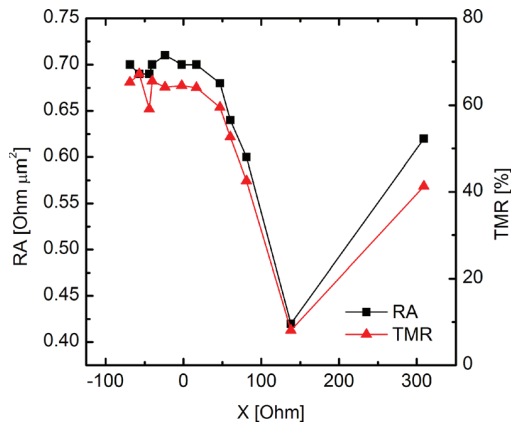


FIG. 5. RA (black squares) and TMR (red triangles) plotted versus stage reactance.

capacitance with the stage reactance. If the stage reactance is positive and matches the sheath capacitance in magnitude, the resulting impedance will be very low and ions will be drawn to the substrate.¹⁰ These can cause resputtering of the deposited MgO film and deteriorate the film quality. Evidence for this can be seen in the dependence of RA on the C2 setting. Where the TMR is low the RA is also low, indicative of low MgO tunnel barrier thickness caused by ion bombardment and resputtering. According to the data above, best film properties can be achieved when keeping the stage impedance high capacitive. It can be expected that these results are universal and can be applied to different sputtering tools.

To check for the universal nature of the optimization result, we have carried out above experiment for two different types of stages (for 6 in. and 8 in. substrate) and two different L2 inductors with 6 and 8 turns. The stages for the different size substrate differ not only in size but also in the wafer lift mechanism as well as the shield design. For the 8 in. stage with 6 turn L2, 8 in. stage with 8 turn L2, and 6 in. stage with 6 turn L2, we measure the resonance at C2 of 340, 40, and 420, respectively. Off resonance, the reactance is +11 Ω for the 6 in. stage and +65 for 8 in. stage (no difference for the two different inductors). Figure 6 shows the results for the TMR. The experiments were carried out with slightly different films with different RA and TMR value; thus, in order to be able to compare the results, we normalize the TMR to the highest value in each group. One can see qualitatively that the data are similar. Best TMR performance is achieved for most negative stage reactance. For the 6 in. stage, the TMR starts to drop at smaller inductive reactance, which might be due to the reduced sheath capacitance due to the reduced area of the substrate.

For different sputter systems, the geometry and electrical properties of plasma sheath and stage will be different, but a similar optimization as described above can be carried out for all tools. Inserting a network of adjustable capacitors and inductors into the ground path of the stage can allow effective control of stage impedance (especially, if this network can be tuned to resonance where a wide range of reactance values are accessible).

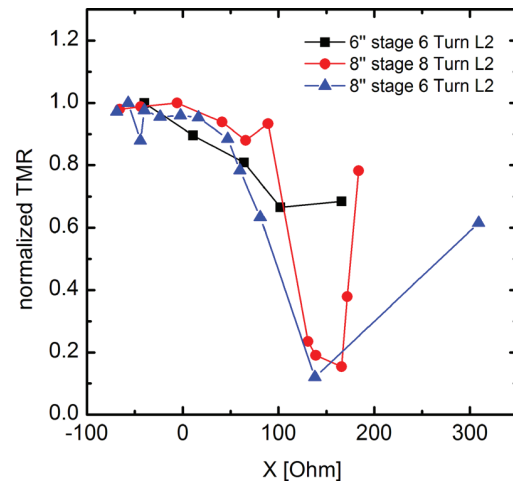


FIG. 6. TMR normalized to the highest TMR in the dataset vs reactance of the stage. Data from different hardware configuration is shown: 6 in. stage + 6 turn L2 (black squares), 8 in. stage + 8 turn L2 (red circles), 8 in. stage + 6 turn L2 (blue triangle).

In summary, we have carried out measurements of the RF impedance of the stage of an Anelva sputtering tool. We show that using the adjustable capacitors in the matchbox for the stage RF the impedance can be continuously varied from high negative (capacitive) to positive (inductive). Preparing MTJs with MgO tunnel barriers deposited at different values for stage impedance, we can find the optimum condition that yields best performance. This optimum condition corresponds to very negative reactance. When the stage is tuned to resonate with the plasma sheath capacity a high level of resputtering can be achieved (evidenced by reduced RA) and TMR can be significantly suppressed. The above result gives a guideline that can help optimize the performance of MTJs based on RF MgO barriers for different sputtering tools.

The authors thank S. Shinde, K. Nishimura, and Y. Nagamine from Canon-Anelva Corp. for technical help and useful discussions.

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