Recent Developments in MRAM Mass-Production Technology in ULVAC

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We have been developing sputtering tool for MRAM mass production, with simple module configuration and smaller footprint. It provides stable magnetic Co films and low damage MgO film with RA uniformity of 3.5%. Novel wide temperature process from −170℃ to 600℃ to fabricate excellent MTJ layers, will also be introduced.

1. Introduction

MRAM (Magnetic Random Access Memory) is expected to be one of the few candidates for next-generation non-volatile memory that has the potential to deal with increases in leakage current due to the miniaturization of DRAM (Dynamic Random Access Memory) and reduce standby power consumption. With a proven track record of delivering sputtering equipment to universities and research institutions, in 2002, ULVAC released MRAM equipment that adopted a platform that had been used in the semiconductor production process for wafer sizes up to 200 mm. In 2010, ULVAC released sputtering production equipment for MRAM as the "EN-TRON Series," which supported ultra-high vacuum processes and had proven performance in the mass production of semiconductors for wafer sizes up to 300 mm. Currently, while working to further adapt it to mass production technologies, ULVAC is developing unique technologies and continuing technical development to prepare the equipment for use in future MRAM mass production.

This paper introduces the equipment configuration specially designed for MRAM and the technical challenges that have to be tackled as an equipment manufacturer.

In general, MRAM devices are constructed to have a tunnel barrier layer made of magnesium oxide between functional layers made of a magnetic material called MTJ (Magnetoresistive Tunnel Junction) and they work by changing the magnetic moment directions of the magnetically anisotropic upper and lower layers so that they are parallel or antiparallel to increase and decrease the resistance and serve as a memory device. Figure 1 shows the film construction optimized by ULVAC based on a report by a research group of Tohoku University[1]. So far, the electric and magnetic characteristics shown in Figure 2 have been confirmed. The film has a bottom pin construction in which the device resistance changes to high or low when the free layer reverses. Currently, to write memory, the STT (Spin Transfer Torque) technique[2], by which the

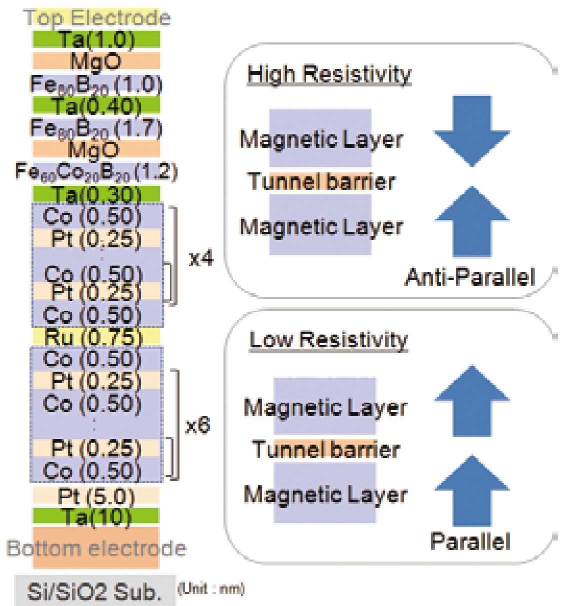


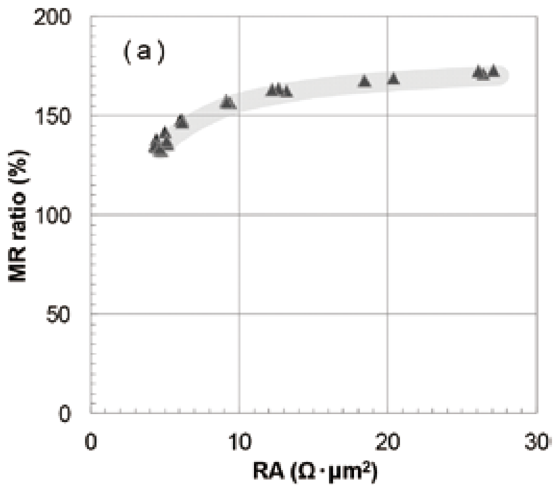
Figure 1 Example of a perpendicular MTJ stack consisting of a bottom synthetic Co/Pt reference layer. The free magnetic moment switches between two states (Parallel and Anti-Parallel).

free layer is reversed with a polarized spin current, has been studied and is expected to reduce the power consumption needed for writes through miniaturization.

In the MRAM equipment market, the following characteristics are required of laminated films deposited by sputtering production equipment:

(1) High output (high resistance change ratio (MR ratio))
(2) Long-term data retention durability (dependent on magnetic characteristics)
(3) Heat resistance in the back-end processes (≥ 400℃)
(4) Low power consumption writes (dependent on the material and film thickness of the recording layer)

In particular, (1) and (2) are the key issues to tackle for production equipment, and it is important to make the numeric values and film quality as ideal as possible.



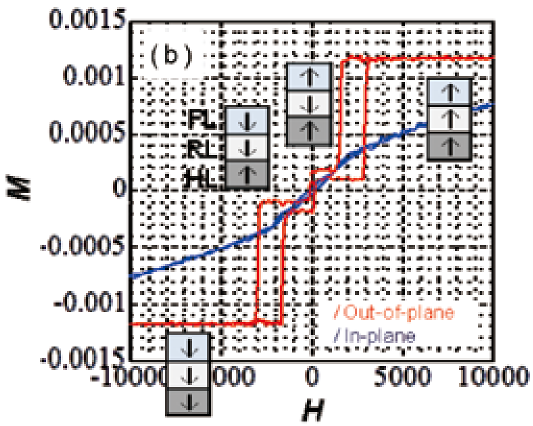


Figure 2 (a) Magnetoresistivity Property of Perpendicular magnetized MTJ consisting of bottom pin structure. (b) Example of VSM property and Schematic diagram of magnetic moment (FL : Free Layer, RL : Reference Layer, HL : Hard Layer).

2. Improvement of the performance of mass production equipment specially designed for MRAM

2.1 Throughput improvement of artificial lattice Co/Pt multilayer film with perpendicular magnetic anisotropy

As shown in Figure 1, the film is made up of ultra-thin Co and Pt films with a thickness of 1 nm or less stacked with multiple periods by using perpendicular magnetic anisotropy. With the conventional method, when the Co and Pt layers were stacked, the deposition time and non-deposition time occurred intermittently. To reduce the process time, the non-deposition time was omitted so that continuous discharge occurred, thereby reducing the time by approximately 70%. In addition, we were able to slightly reduce the change ratio of the anisotropy magnetic field. Table 1 shows the magnetic characteristics and improvement ratios for different conditions (A to D). The difference in the deposition pressure between Co and Pt with condition D was made smaller than that with condition A of the conventional process and in addition, the movement of the cathode shielding plate with condition D was restricted.

2.2 Life extension of Co targets

Magnetic materials are essential for MRAM. A problem to tackle for mass production is that, for the cathode with magnetron sputtering, it is extremely difficult to extend the target life while maintaining discharge at a low voltage.

The current cathode mechanism was reviewed to identify problems. By solving these problems, the life was increased by about five times. Table 2 shows a summary of the problems identified and measures taken to solve

Table 2 Issue list to improve Co target life.

Issue	Conventional	Current
Erosion Area	Localized	Whole
Target Thickness	3.0 mm	Thicker
Pass Through Flux	Low	High
Target – Magnet distance	Long	Short
Cathode Magnet	Unbalanced Size (Target - Magnet)	Care with Magnet Shield

Table 1 Process Time and Magnetic Properties of several conditions A, B, C, D.

Item	Pressure (Pa)		Process Time (Normalized)	Cathode Shutter Motion	M_S x Thickness (T・nm)	Anisotropy Field (T)
	Co	Pt				
A	0.011	1.4	T_A	[Co] Open ➔ [Pt] Open	3.16	2.42
B	0.011	1.4	**0.4 x T_A**	[Co] & [Pt] Open (Not Move)	3.23	2.23
C	0.011	0.22	**0.3 x T_A**	[Co] & [Pt] Open (Not Move)	2.91	2.40
D	0.037	0.22	**0.3 x T_A**	[Co] & [Pt] Open (Not Move)	2.75	2.27

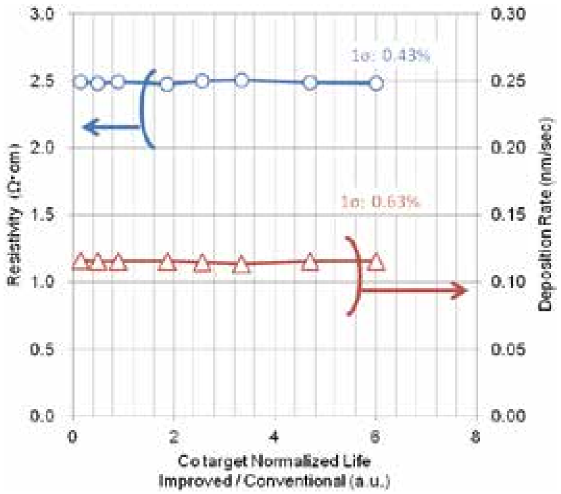


Figure 3 Performance Stability of Co material with Magnetron Sputtering Cathode.

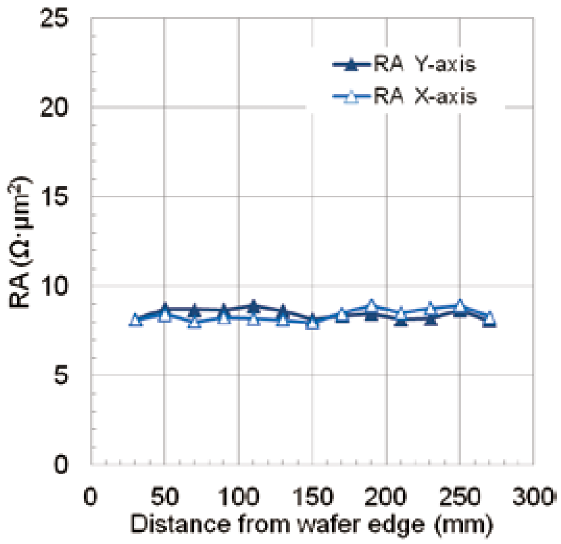


Figure 4 Uniformity of the RA at 300 mm wafer after several cathode arrangements optimized.

them. Figure 3 shows the performance stability until the target reaches the end of its life. The figure shows that the deposition rate and specific resistance are stable.

2.3 Reduction of damage to MgO by RF sputtering

It is known that when an oxide target is directly RF sputtered, oxygen ions collide with the substrate and damage it, resulting in characteristic deterioration or distribution deterioration on a large-diameter subsrate[2]. Working with a university, ULVAC learned how to identify damage sources and assess its impact[3]. It was found that the damage causes the RA (resistance-area product) value, which represents the standardized MTJ device resistance, to increase drastically. Through further optimization, a mechanism was successfully developed that provides improved distribution on a large-diameter substrate with the resistance change ratio maintained. Figure 4 shows the result of measurement of the in-plane distribution of the RA value on a 300-mm substrate at 13 points each in the X-axis direction and Y-axis direction. The RA value was measured using the CIPT (Current In-Plane Tunneling) method[6]. The results indicate that the RA value distribution had achieved 1σ : 3.5%. Regardless of whether or not any impact is caused by the damage, if a film thickness distribution of 1σ : 0.5% or less is not achieved, it is difficult to achieve the above RA value distribution. This is the result obtained from detailed studies to find out the optimal layout of the mechanism.

Various approaches were attempted to achieve the above high output (Table 3). The plasma control technology is under development based on the knowledge that, not only can it reduce damage, but it may also help improve the characteristics. A certain effect has been confirmed by improving the cathode configuration so that sputtering particles can reach the substrate with high mobility maintained. It is also important to reduce impurities

Table 3 Key Technology for High MR Ratio at Low RA.

Item	(1) Plasma	(2)Temperature		(3) Contamination	
Key Technology	Plasma Control	Heating /Cooling during Deposition	In-situ Annealing, Post Annealing after MTJ stack	Vacuum Quality	High Purity of Process Gas
Purpose	Low Damage, Enhance Energy Particles in Sputter Plasma	High Mobility (Crystal arrangement) / Low Surface Roughness	Crystallization, CoFe/MgO Epitaxial Growth	Low Impurity, Low Vacancy, Dislocation Rejection	
Parameter	Power, Pressure, Cathode Arrangement, Cathode Magnet	Temperature with deposition, Under layer selection	Temperature, Heat-Stable stack structure for MTJ	H_2O,O_2 Gas Reduction	Gas Purity

Table 4　Comarison of Process time and Configuration of Annealing system.

System	Conventional	Current
Temperature	500C	600C
Heat Source	Pedestal heater	Pedestal heater + Lamp
Thermal Conduction	ESC chuck	Radiation
Process Time	210 sec	80 sec

in the MgO layer; therefore, some consideration is required for the vacuum performance and gas purity in the deposition chamber.

2.4　Heating mechanism for improving the crystallinity in the MgO layer

In laminated film formation, crystallization may be further accelerated by formation of the under-layer, temperature control during deposition, and heating control after deposition. The following introduces ULVAC's attempts at temperature control technology.

As the first attempt, we will introduce is heating treatment after MgO deposition. In order to achieve a high resistance change ratio, accelerating crystal growth by heating treatment is considered to be effective[5]. It is presumed that heating treatment provides high polarizability with improved crystal orientation, thereby making it possible to achieve a high resistance change ratio. To simply improve the crystallinity in the MgO layer, accelerating crystallization with heat treatment with a higher temperature is easy. However, when heat treatment is applied, it should not be forgotten that the characteristics of the previously formed under-layer need to be maintained.

In addition, short process times are required for mass production. Therefore, ULVAC identified the processes using the conventional heating mechanism whose process times had the potential to be shortened and optimized them. As a result, it was found that the total process time could be shortened by changing the heat conduction method, and adjusting the heating time and temperature retention time. As specific measures, the suction/release time was shortened by omitting the electrostatic chuck mechanism and, in addition to the stage, a lamp was used for heating to prevent the heating time from becoming longer. In addition, although it took a long time to reach the optimal value of each characteristic with the conventional maximum reachable temperature, that time was able to be shortened by heating with a higher temperature. This reduced the process time by 62%. A comparison is shown in Table 4.

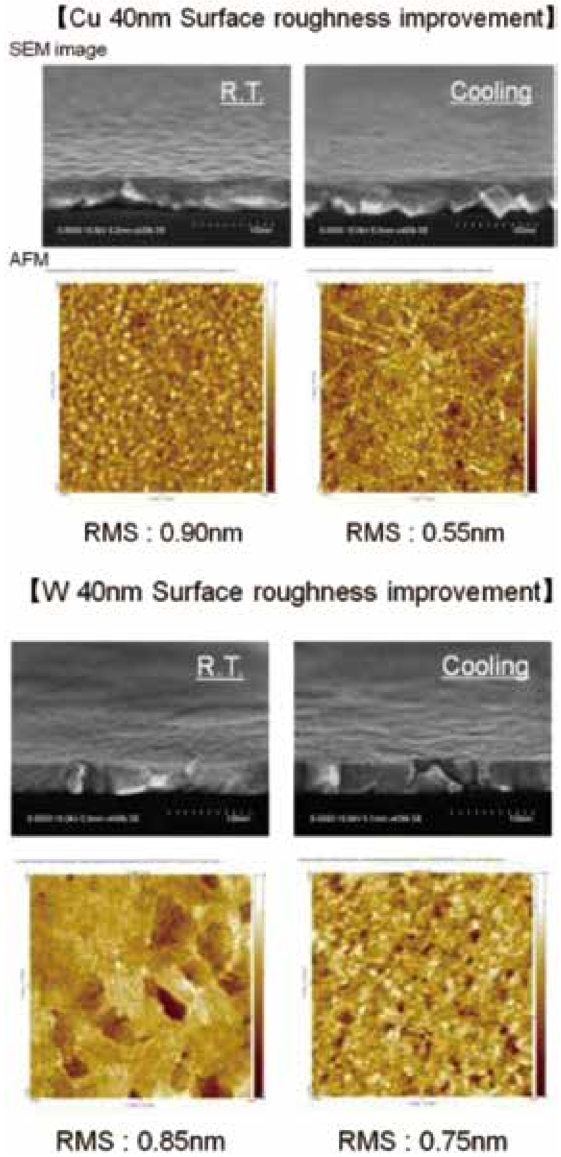


Figure 5　Cooling effect for General Metal materials.

2.5　Ultra-low temperature cooling stage mechanism

The next attempt to be introduced is on the effects of the cooling deposition technology. ULVAC has so far offered a mechanism to cool the stage to −30℃ or so. Because lower temperatures are required today, ULVAC has been attempting to cool the stage with a cooler that has a G-M (Gifford-McMahon) cycle and then cool the substrate with a gas transfer or electrostatic chuck mechanism. With this method, the stage can be cooled to −170 ℃ or so. The cooled substrate is transferred to the deposition chamber and deposition is performed on the cooled substrate, by which a great effect of this modification has been confirmed. With common metals, a noticeable state change is that the surface roughness is decreased (Figure 5). This phenomenon probably occurs because when sput-

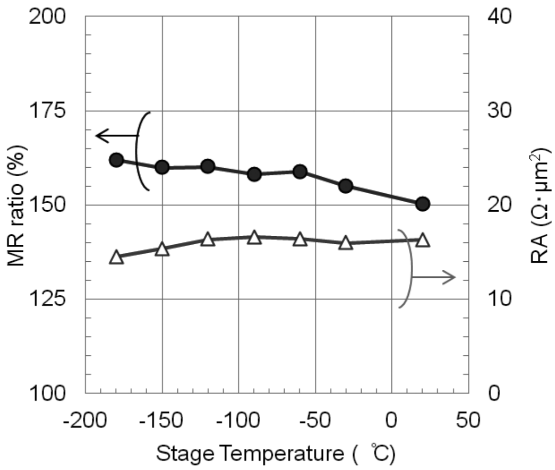


Figure 6 Cooling effect for MTJ stacks.

Figure 7 Reliable Emerging PVD Tool ENTRON EX W300 for STT-MRAM.

tering particles are deposited, they lose their ability to aggregate and crystallization is slowed down, thereby preventing surface roughness deterioration.

An improvement effect was confirmed with MTJ as well. Figure 6 shows the improvement effect obtained when cooling deposition was performed for the magnetic layer FeB on the MgO layer. It was confirmed that the RA value decreased and at the same time, the resistance change ratio increased by 12%. No clear cause has been identified, but it is presumed that the improvement of the surface roughness, or the decrease in the resistance in the interface between MgO and FeB has caused the apparent resistance change ratio to increase.

3. Equipment configuration

As shown in Figure 1, the equipment configuration for MRAM must be such that a continuous, ultra-thin film can be deposited. In addition, as previously mentioned, achieving high characteristics requires maintaining high smoothness of the boundary between layers. At the same time, because magnetic and oxide films are sensitive to contamination by particles and water in the air, an ultra-high vacuum is required in the transfer chamber. The production equipment is required to meet these conditions and, at the same time, have improved mass productivity.

The number of substrates that can be treated per hour depends not on the transfer speed, but on the process time of each chamber. In order to achieve the current target value of 20 substrates per hour, the time needed for each formation and treatment, including transfer time, must be 180 seconds or less. Figure 7 shows a photo of the equipment. (The process configuration can be changed flexibly according to the film configuration desired by each customer.) For example, the equipment consists mainly of seven deposition chambers, a natural oxidation film removal chamber (or a surface modification chamber), a heating chamber, an ultra-low temperature cooling chamber, and a load lock chamber that can perform degassing.

In each chamber, the temperature of the deposited substrate is controlled so that the process conditions most suitable for achieving the desired film characteristics can be developed. The controllable temperature range is from −170℃ to 600℃, and various processes can be performed successively without contamination due to exposure to the atmosphere, which is one of the most remarkable features of this MRAM production equipment.

4. Conclusion

This equipment was developed based on the "ENTRON Series," which has proven performance in semiconductor lines and has been providing the specifications required by customers for MRAM processes. Because this equipment employs more compact, simpler mechanisms than competitors' equipment, it has extremely excellent maintainability.

This paper did not introduce all the MTJ production processes, and in addition to the processes introduced in this paper, we are aiming not only to improve the mass production equipment performance, such as extending the maintenance cycle and improving the target use efficiency, but also to develop more advanced etching and RF sputtering technologies. By incorporating cutting-edge technologies into existing sputtering technologies, we are working hard on development with the aim of contributing to developing higher-performance devices.

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