Emulation Process Designs and Experimental Assessments of a Refined DC Magnetron Sputter

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***Abstract*—With proper controls on the magnetic and electric fields inside a DC magnetron sputter (MS), more target atoms can be sputtered and smoother depositions onto the substrate surface can be achieved. In addition to the detailed three-dimensional field information, adequate analyses of such processes will need to incorporate the operations of ion bombardments onto the target and collisions among sputtered target atoms and plasma ions. Based on appropriate emulation process designs and performance index selections, operations of the refined DC MS prototypes at different structural compositions are thoroughly investigated. By probing selected regions on the deposited substrate surface, performances of the refined DC MS can be assessed and the desired improvements can then be systematically validated.**

***Index Terms*—Atomic force microscopy, smoothing methods, sputtering, substrates, thickness control.**

I. INTRODUCTION

The DC magnetron sputters (MS) are commonly adopted in microelectronics industries for sputtering the desired target materials onto the substrates to accomplish the related thin film deposition processes [1], [2]. With their mass installed volumes in the existing production lines, based on specific operational objectives [3], efforts to seek reliable and affordable refinements that can better the performance of the entire sputtering process are certainly expected.

Since the operations of DC MS are mainly governed by the electric and magnetic fields in the vacuum chamber between target and substrate, as indicated in [4], appropriate parts can be attached onto those existing DC MS to control the magnitudes and directions of those fields. Hence, distributions of those ionized argon (Ar) gas that are filled in the vacuum environments can be adjusted for accomplishing the ion bombardment and atom collision processes of the DC MS [5]. By detailed emulations on the entire system sputtering and deposition processes from the 3-D field information [6], refinement designs based on the aforementioned substrate smoothing methods and thickness control schemes will be thoroughly investigated both quantitatively and qualitatively, and the improvement capabilities for the specific design objectives can then be assessed.

In addition to the numerical verifications that were conducted on certain predefined operational environments of the DC MS, more reliable assessments are certainly expected from the hardware implementations of those structural refinements. By following the design concepts as indicated in [5] for achieving both faster target sputtering and smoother substrate deposition objectives, several experimental prototypes will be composed to perform the desired processes. Obtained from thickness gauge and atomic force microscopy (AFM), measurements on the substrate surfaces can further confirm the structural refinement and emulation designs.

II. EMULATION PROCESS AND REFINED DC MS DESIGNS

The basic Lorentz forces that can characterize the magnetic and electric fields to the system operations are:

$$\begin{cases} m_e[v_r' - (v_\theta)^2/r] = q(v_\theta B_z) \\ m_e[v_\theta' - (v_r v_\theta)/r] = q(v_z B_r - v_r B_z) \\ m_e[v_z'] = q(E_z - v_\theta B_r) \end{cases} . \qquad (1)$$

For investigating the possible collisions effects among those sputtered target atoms and the ionized Ar gas, the kinetic energy and the momentum conservation laws are introduced as:

$$1/2\{m_a|\boldsymbol{v}_{ab}|^2 + m_i|\boldsymbol{v}_{ib}|^2\} = 1/2\{m_a|\boldsymbol{v}_{aa}|^2 + m_i|\boldsymbol{v}_{ia}|^2\}, \text{ and} \qquad (2)$$

$$m_a\boldsymbol{v}_{ab} + m_i\boldsymbol{v}_{ib} = m_a\boldsymbol{v}_{aa} + m_i\boldsymbol{v}_{ia} . \qquad (3)$$

The designed entire emulation processes are depicted in Fig. 1. For illustrations, one of the confined electron trajectory on top of the target surface is shown in Fig. 2(a), and its counterpart trajectory of ion that will bombard the target surface can thus

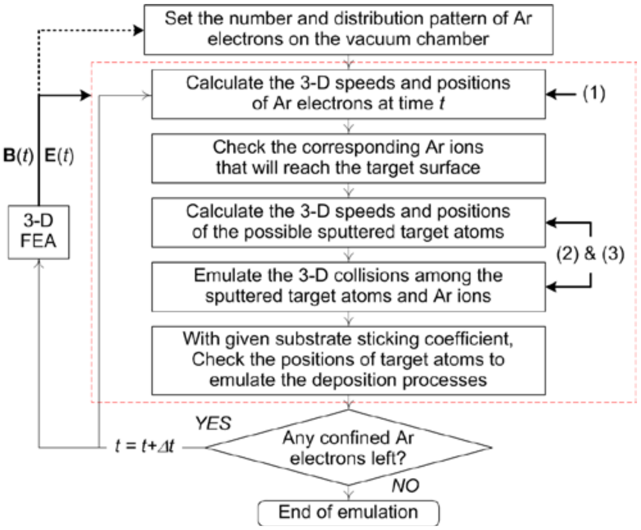


Fig. 1. The designed entire emulation processes.

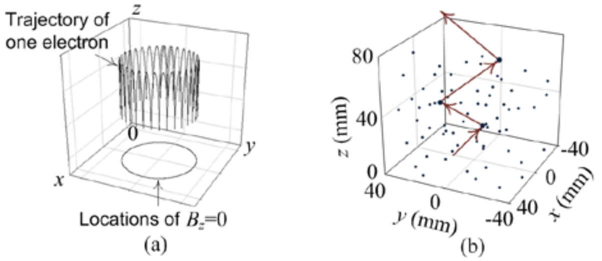


Fig. 2. Emulations of the sputtering process of DC MS. (a) One confined electron trajectory. (b) Collisions among one target atom and the Ar ions.

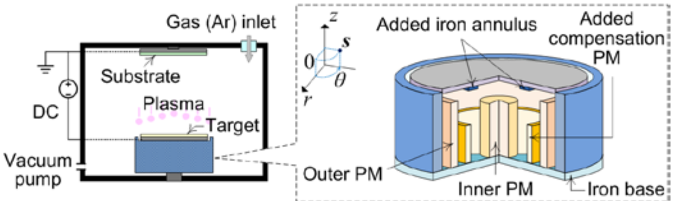


Fig. 3. Conceptual view of a DC magnetron sputter with refined attachments.

be indirectly described. The conceptual collision process of one sputtered target atom and the Ar ions in the plasma can be emulated and illustrated in Fig. 2(b).

Based on the original design of a 3” cylindrical DC MS as provided in [7], the refined system structure for achieving faster sputtering and smoother deposition objectives are provided in Fig. 3. The added iron annulus is aimed for providing a zero axial-directional magnetic flux environment to confine ion trajectories on top of the target surface. The added compensation permanent magnet (PM) is intended both to compensate magnetic fluxes in the radial and tangential directions that were deducted from iron annulus effects, and to contribute adjustment on the effective kinetic energies of those ions that were bombarding the target surface.

III. EXPERIMENTAL VERIFICATIONS OF THE REFINED DC MS

As illustrated in Fig. 4, one solid tube- and twelve rod-types PMs at the designed dimensions and positions are implemented to investigate the compensation effects of different PM compositions at various DC MS sections. The results obtained from thickness gauge and AFM at one set of the measurements are illustrated in Fig. 5, and the summarized results are provided in Table I for comparisons. Apparently, thicker surfaces will be achieved on the refined DC MS structures with their compensation PM polarities (Tube and Rod A) identical to the original system inner PM. While for the compensation PM compositions with opposite polarities (Rods B and C), the overall reduced magnetic flux distributions in the chamber will cause lower Ar plasma densities. Thus, proper compositions of these compensation PMs can recover the possible uneven plasma distributions of the DC MS due to its inherent structural inlet/outlet effects.

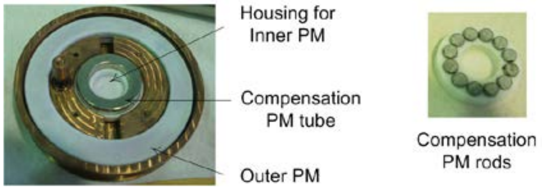
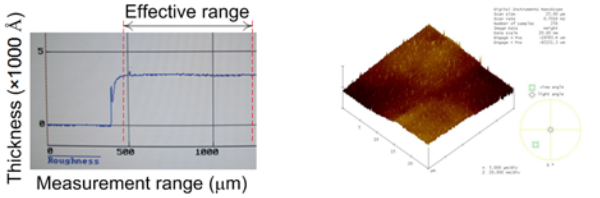


Fig. 4. Setups of the compensation PM compositions for the refined DC MS.



Measurements from the thickness gauge at one region

Measurements from the AFM at a 25 μm × 25 μm area in one region

Fig. 5. Measurements by thickness gauge and AFM from the refined DC MS with compensation PM tube at one substrate surface region.

TABLE I
COMPARISONS OF SUBSTRATE DEPOSITION RESULTS

Thickness measurements	Compensation PM structures				
	Original[a]	Tube[b]	Rod A[c]	Rod B[d]	Rod C[e]
Averaged value (Å)	3428.4	3504.4	3516.0	3365.2	3204.4
Max. regional difference (Å)	297.00	223.25	255.00	303.50	435.75
Standard deviation (Å)	124.59	101.10	115.05	126.76	200.95
Maximum roughness depth R_{max} (nm)	36.472	17.484	N/A	N/A	N/A
Mean roughness R_a (nm)	1.433	1.484	N/A	N/A	N/A
RMS roughness R_q (nm)	1.898	1.786	N/A	N/A	N/A

[a] Original: No compensation PM.
[b] Tube: Tube-type PM with polarity identical to the main inner PM.
[c] Rod A: Rod-type PMs with all polarities identical to the main inner PM.
[d] Rod B: Rod-type PMs with half of their polarities identical to the main inner PM while the other half oppose to.
[e] Rod C: Rod-type PMs with all polarities opposite to the main inner PM.

For the area images detected from AFM, since more target atoms will be deposited onto the substrate for the refined system within the same experimental period, the resultant averaged thickness will also be increased. It is thus hard to make assessment of the surface smoothness simply from the indices R_a and R_q. However, with less spikes exhibited on the 3-D surface images and a significant reduction of the maximum roughness depths R_{max} index (36.472 nm → 17.484 nm), such remarkable improvement from the refined system certainly confirm the better smoothness of the substrate surface.

IV. CONCLUSION

To investigate the performances of a cylindrical DC MS with refined structural designs, adequate emulation processes and experimental setups have been designed. With proper performance index selections, the system sputtering rate and deposition smoothness improvements can be precisely assessed. Supported by the measurements from thickness gauge and AFM, adequacies of the DC MS emulation processes and structural refinements can thus be confirmed.

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