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Ex-Situ Conditioning Based on Constant Material Removal Rate for a Digital Twin CMP System

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Conditioning is a process of regenerating the pad surface deteriorated during chemical mechanical polishing (CMP) in order to keep a constant material removal rate (MRR). The state-of-the-art in the CMP conditioning process changes from in-situ to ex-situ in order to reduce the micro-scratches induced by the pad debris generated in-situ conditioning. However, the ex-situ conditioning is required to understand how the pad surface roughness is changed by the CMP, and how long the conditioning time is required to get a constant MRR. In this study, changes of surface roughness and MRR according to polishing pressure and time were investigated, and the minimum conditioning time to recover to the initial state after polishing was also obtained. the authors found that the slope of reduced peak height (Rpk) and pad-wafer real contact area (RCA) increased sharply at higher pressure conditions, requiring a longer conditioning time for sufficient regeneration. When sufficient conditioning was performed, Rpk and RCA returned to their initial state, and the MRR remained constant. Using multiple linear regression techniques on the constructed experimental data, a model for predicting MRR according to pad surface roughness was developed. Finally, it will be possible to realize the automatic process control by building big data of the pad surface roughness by the CMP conditions and applying it to the digital twin.

1. Introduction

Chemical mechanical polishing (CMP) is an ultraprecision hybrid machining process that removes material with chemical reaction and mechanical force to obtain a highly planar surface. The CMP proceeds with the fine asperity on the pad surface in direct contact with the device patterns, so the material removal rate (MRR) is highly dependent on the condition of the pad surface roughness [1].

After polishing, the pad surface asperities deteriorate due to mechanical deformation and accumulation of polishing residues, increasing the real contact area (RCA). This reduces the real contact pressure applied per unit area, which deteriorates the MRR and polishing quality [2].

The deteriorated pad surface is recovered by cutting with diamond abrasives bonded on the conditioning disc. Sufficient conditioning time can remove the abrasive residue accumulated on the pad and reproduce its initial surface roughness. Recently, the CMP conditioning has been changed to ex-situ in order to reduce micro-scratches caused by pad debris generated from in-situ conditioning [3]. In ex-situ conditioning, it is not clear how long the conditioning time is required and the state of the appropriate surface roughness to obtain a uniform MRR. Therefore, it is necessary to analyze the change in the pad surface roughness according to each process state and sufficient conditioning time for reproduction.

In this study, the reproducibility of pad surface roughness according to the conditioning time for each polishing pressure was analyzed to maintain the MRR continuously. Changes in pad surface roughness were characterized by the RCA and the reduced peak height (Rpk). The surface roughness and MRR were compared and verified before polishing, after deterioration, and immediately after conditioning.

2. Experiment and Result

2.1 Experiment

Table 1 shows the experimental conditions for polishing and conditioning. The polishing was done in the order of 1, 2, 3, 5, and 10 minutes under the conditions of 2, 3, 4, and 5 psi to confirm the difference in the MRR according to pressure. After the pad surface was sufficiently degraded by polishing for 10 minutes, the conditioning was done for 10 sec, 30 sec, 1 min, 3 min, and 5 min respectively, in order to find a sufficient time to recover the initial surface. After each polishing and conditioning, RCA and Rpk were measured and the MRR was compared to verify the surface roughness.

Figure. 1 Experimental equipment and set up

2.2 Results

Figure 2 shows the change in MRR and surface roughness parameters Rpk and RCA as a function of polishing time. The 0 minute in the graph indicates the state immediately after the break-in. The MRR and surface roughness have the sharpest gradient changes within the first minute after break-in. Afterwards, as decrease in Rpk. Even with the same pad state, the higher the pressure, the higher the RCA because new contact points are generated by the pad protrusion elasticity. At high pressure, mechanical strain increases the RCA more rapidly and reduces the actual contact pressure acting per unit area, resulting in reduced MRR.

Table 1 Experimental conditions

Polishing Machine		POLI-500, G&P Technology
Wafer		8inch oxide blanket
Pressure [psi]	Head	2, 3, 4, 5
	Retainer	3, 4, 5, 6
Velocity [rpm]	Head	87
	Platen	93
Slurry flow rate [ml/min]		150
Polishing time [min]		1, 2, 3, 5, 10
Conditioning	Sweep cycle [cyc/min]	9
	Rotation speed [rpm]	101
	Down force [psi]	0.7
	Time [sec]	10, 30, 60, 180, 300

This surface degradation is restored after 5 min conditioning. This shows that full recovery of the pad is possible if sufficient conditioning is performed.

Figure 3 shows the recovery under five conditioning conditions by pressure. Conditioning for just 10 seconds at 2 psi is sufficient for recovery. This is caused by small pad deformation under low pressure. On the other hand, 30 seconds at 3 psi, 1 minute at 4 psi, and 3 minutes at 5 psi are required for sufficient pad recovery. It can be seen that the greater pad deformation under high pressure conditions requires a longer time for sufficient recovery.

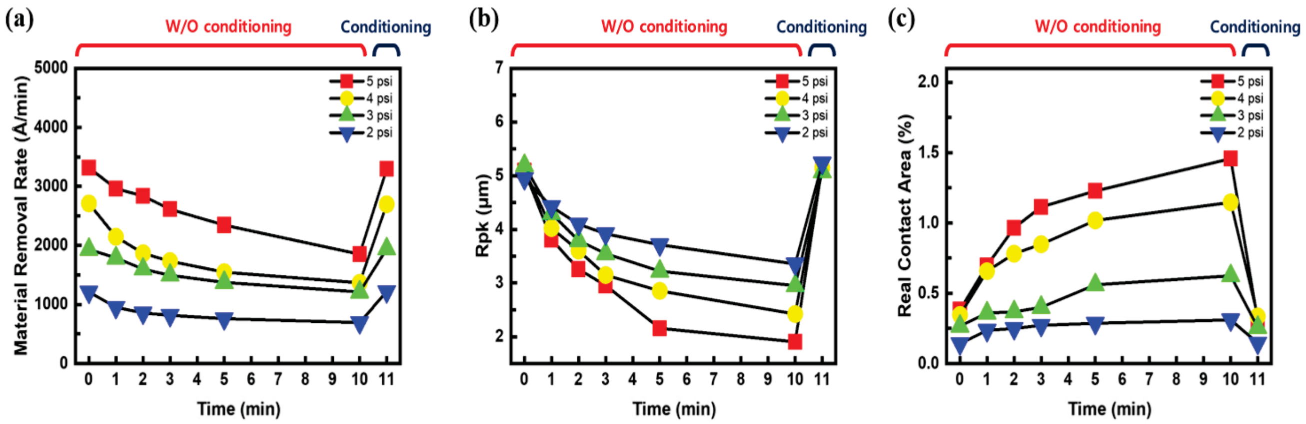

Figure. 2 Comparison of CMP results in parameters over time by pressure (a) material removal rate (b) Rpk (c) RCA

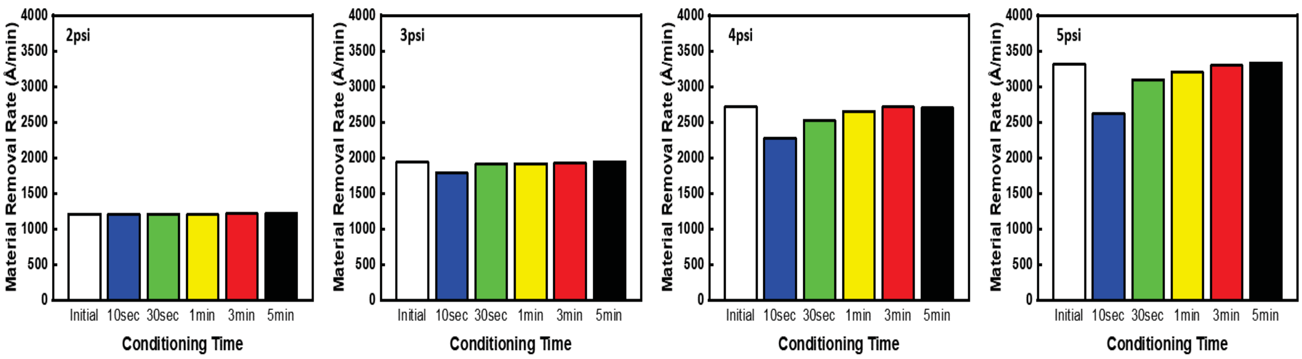

Figure. 3 Recovery of material removal rate with conditioning time at each polishing pressure

3. Machine learning model

Multiple linear regression is one of the machine learning techniques that models the linear relationship between two or more independent variables and one or more dependent variables. A multiple regression equation for material removal rate according to polishing pressure and surface roughness was derived through Scikit-learn's Linear Regression class for 220 data sets constructed through experiments.

$$MRR = -1194.3 + 762A - 629.6B + 186.9C \quad (1)$$

In Equation 1, A is the applied pressure (psi), B is RCA (%), and C is Rpk (μm). The accuracy of the derived linear regression equation is determined by the R^2 value, which is the coefficient of determination, and the closer the R^2 value is to 1, the higher the accuracy. The estimated R^2 value in this study was 0.945, proving that a high level of explanation is possible with this regression equation. This model is used to constantly control the desired material removal rate by recognizing the surface roughness state of the pad in the CMP equipment and setting additional process parameters.

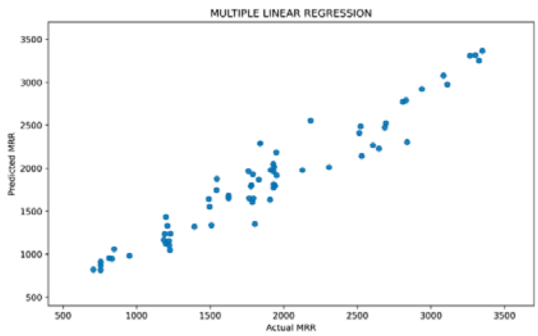

Figure. 4 Comparison by scatter plot of actual and predict MRR

4. Conclusions

In this study, changes in surface roughness and MRR with respect to polishing pressure and time were investigated, and the minimum conditioning time to recover to the initial state after polishing was also obtained. First of all, it was confirmed that Rpk and RCA can return to their initial state and MRR can remain constant if sufficient conditioning is performed. Second, It was found that a longer conditioning time is required for sufficient regeneration because the slope of the Rpk and RCA increase rapidly at higher pressure conditions. Third, data-based decision-making became possible by developing a machine learning model to obtain a uniform polishing rate under ex-situ conditions based on multiple linear regression. This study aims to build big data of pad surface roughness according to CMP process conditions in the future and apply it to machine learning and digital twin to realize automatic process control.

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