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Effect of pad groove width on slurry mean residence time and slurry utilization efficiency in CMP

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ABSTRACT

This paper studies the effect of pad groove width on slurry mean residence time (MRT) in the pad–wafer interface as well as slurry utilization efficiency (η) during chemical mechanical planarization. Three concentrically grooved pads with different groove widths were tested at different polishing pressures to experimentally determine the corresponding MRT using the residence time distribution (RTD) technique. Results showed that MRT and η increased significantly when the groove width increased from 300 to 600 μm. On the other hand, when the groove width increased further to 900 μm, MRT continued to increase while η remained constant. Results also indicated that MRT was reduced at a higher polishing pressure while η did not change significantly with pressure for all three pads.

1. Introduction

It is well known that the presence of slurry in the pad–wafer interface is critical to the chemical mechanical planarization (CMP) process [1–3]. Various factors such as slurry mixing and transport, slurry film thickness and the tribological mechanism in the pad–wafer interface can affect material removal rate and planarization efficiency. Different pad groove designs are used to transport fresh slurry into the pad–wafer interface [4,5]. In addition, pad grooves discharge polish debris, heat and spent slurry from the pad–wafer interface and also prevent wafer hydroplaning [4,5]. The effect of different pad groove designs on coefficient of friction (COF), pad surface temperature, and material removal rate for interlayer dielectric (ILD) and copper CMP has been investigated extensively [5–9]. Additionally, Muldowney introduced a 3D fluid flow model for simulating the influence of pad groove pitch, width and depth on slurry flow in the pad–wafer gap which revealed that it took longer to renew the slurry in the pad–wafer gap for a pad with larger groove pitch and wider and deeper groove design [10]. While pad groove width is an important factor that impacts slurry flow during wafer polishing, no experimental study has been performed to illustrate the effect of groove width on slurry mixing and transport in the pad–wafer interface.

In previous studies, classical residence time distribution (RTD) technique was used to investigate slurry mean residence time (MRT) in the pad–wafer interface [11,12]. MRT represents the average time it takes for fresh incoming slurry to replace the existing slurry in the region bound between the pad and the wafer. As the used slurry contains polishing by-products and pad conditioning debris that have been shown to cause polishing defects [13], a shorter slurry MRT is preferred to reduce polishing defects and increase process yield.

In this study, MRT was obtained for three concentrically grooved pads with different groove widths at different polishing pressures using the RTD technique. Results illustrated how groove width affects slurry mixing and transport in the pad–wafer interface. In addition, slurry utilization efficiency was calculated to show that the pad groove width can be optimized to increase slurry utilization and minimize slurry usage for CMP processes.

2. Theoretical approach

For a typical CMP process, MRT can be extracted from the corresponding RTD curve by employing classical reactor design principles to CMP as described by Levenspiel [11]. According to Levenspiel, an imaginary reactor can be assumed to form between the pad–wafer as shown in Fig. 1, with its volume defined as the space bound in that interfacial region. The slurry may enter or exit the reactor anywhere along its circumference. The slurry remains within the reactor for a finite amount of time, and the average period that the fluid remains in the system can be quantified using the reactor design theory. With silica nano-particles, the extremely low values of Stokes number (calculated to be less than 0.1) suggest that we can assume to have creeping flow in the pad–wafer interface where the abrasive nano-particles present in the slurry ought to follow along the same flow fields as the bulk fluid. Based on

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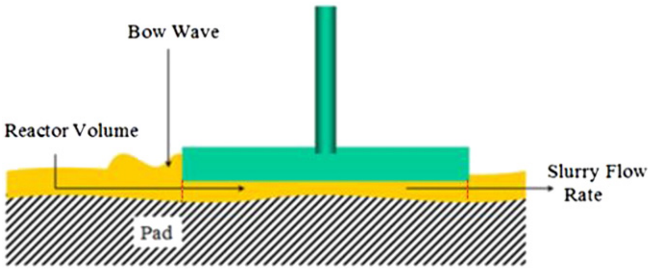

Fig. 1. Cross section of a CMP reactor.

this assumption, the slurry MRT obtained for the CMP process is considered to be representative of both the fluid and the suspended solid abrasive particles.

To understand and predict the fluid dynamics behavior of a reactor, it is important to determine how long fluid elements reside in the system. The distribution of residence times of the flowing fluid can be determined by introducing a stimulus in the form of a tracer and then measuring the response at the outlet. Due to the fact that fluid elements take different routes through the reactor, they require different lengths of time to exit the reactor. The distribution of these times for the fluid leaving the vessel is referred to as the residence time distribution (RTD).

RTD measurements are done by abruptly introducing a tracer into a system that has been running at steady state. The tracer may be introduced into the reactor in the form of a step input of a particular fluid. Beginning with the introduction of a tracer input, a series of steps are required to construct an RTD or E-curve and to calculate MRT values.

With no tracer present initially, a step input of a tracer of concentration (C_0) is imposed on the fluid stream that is entering the system. At the moment of introduction, the tracer concentration at the exit stream (C) is measured. The results are normalized such that time is reset to zero ($t_0 = 0$) when the tracer is introduced. The concentration of the tracer in the exit stream is normalized as C/C_0, thus resulting in a response curve that rises from 0 to 1 over time. This plot is referred to as the F-curve. Furthermore, the E-curve can be plotted by differentiating the F-curve with time:

$$E = \frac{dF}{dt} \quad . \tag{1}$$

The slurry mean residence time (τ) is then calculated from the E-curve:

$$\tau = \int_0^\infty t \times E dt, \tag{2}$$

where Edt represents the fraction of the fluid leaving the reactor with an age between t and $t+\Delta t$.

It should be noted that by definition, the slurry mean residence time (τ) is defined as:

$$\tau = \frac{V_{total}}{q_{actual}}, \tag{3}$$

where V_{total} is the total volume of the CMP reactor and q_{actual} is the actual slurry flow rate through the reactor.

Table 1
Pad dimension comparison.

Pad	Groove width (μm)	Groove depth (μm)	Land area width (μm)
A	300	400	1200
B	600	400	1200
C	900	400	1200

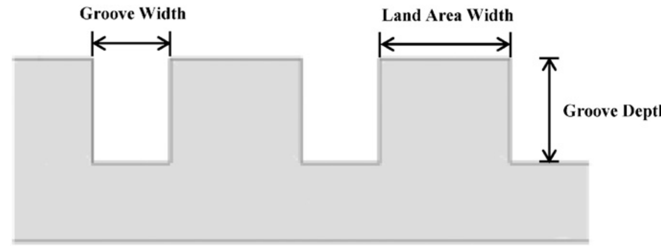

Fig. 2. Schematic of pad dimensions.

3. Experimental procedure

All polishing work was performed on an Araca APD-500 polisher, which is capable of measuring shear force and down forces in real-time. The polisher and its associated hardware for tribometry have been described in details elsewhere [14–15]. Three different Dow IC1000 pads [16] were used each one with a different concentric groove pattern. The groove width and depth, as well as the land area width are listed in Table 1. The three pads have the same land area width and groove depth, but different groove width (see Fig. 2).

Blanket 200-mm silicon wafers were used as the polishing substrate. A 3M A165 diamond disk [17] was used to condition the pads. Prior to polishing, each pad was conditioned at a down force of 25.8 N for 30 min with deionized (DI) water at a flow rate of 150 mL/min. The conditioner rotated at 95 RPM and swept across the pad surface 10 times per minute. The same rotational velocity and oscillation frequency were used for *in-situ* conditioning. During polishing, a Hitachi Chemical ceria slurry was applied near the pad center at a fixed flow rate of 200 mL/min. The distance between the slurry application point to the wafer carrier was about 2.5 cm. The silicon wafers were polished at 3 and 5 PSI at a sliding velocity of 0.83 m/s (*i.e.* 55 RPM). Both the carrier head and platen rotated counter-clockwise at the rotational velocity.

For each experiment, a wafer was first polished with the ceria slurry containing 1 wt% abrasives until a stable frictional force was achieved. Then the 1 wt% initial fluid was switched instantaneously to 0.1 wt% ceria slurry. A 70-second polish was performed after switching to the 0.1 wt% slurry to allow the system to achieve a new steady state. Throughout this entire process, COF was measured at 1000 Hz in real-time and recorded as a function of time. To confirm the experimental reproducibility, at each pressure, 2 wafers were polished.

4. Results and discussion

As an example, Fig. 3 shows the calibration curves obtained for three pads at 5 PSI at four different ceria concentrations (*e.g.* 0.1, 0.25, 0.5 and 1.0 wt%). As seen from the shape of the best fitting curve, the

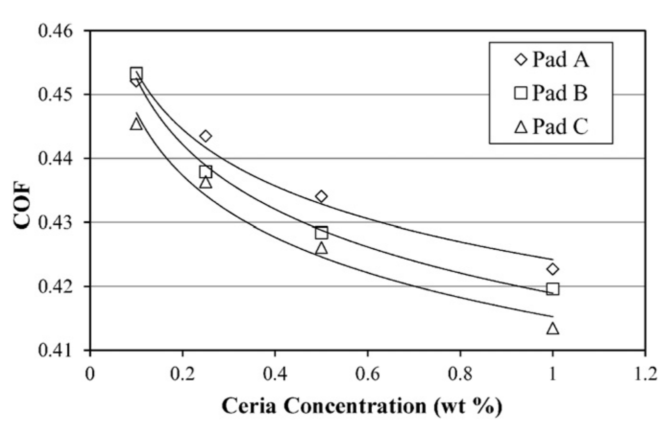

Fig. 3. Calibration curves relating ceria concentration of the slurry to COF at 5.0 PSI ($R^2 = 0.98$ for Pad A, $R^2 = 0.99$ for Pad B, and $R^2 = 0.98$ for Pad C).