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The effects of a spray slurry nozzle on copper CMP for reduction in slurry consumption†

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Abstract

The environmental impact of semiconductor manufacturing has been a big social problem, like greenhouse gas emission. Chemical mechanical planarization (CMP), a wet process which consumes chemical slurries, seriously impacts environmental sustainability and cost-effectiveness. This paper demonstrates the superiority of a full-cone spray slurry nozzle to the conventional tube-type slurry nozzle in Cu CMP. It was observed that the spray nozzle made a weak slurry wave at the retaining ring unlike a conventional nozzle, because the slurry was supplied uniformly in broader areas. Experiments were implemented with different slurry flow rates and spray nozzle heights. Spray nozzle performance is controlled by the spray angle and spray height. The process temperature was obtained with an infrared (IR) sensor and an IR thermal imaging camera to investigate the cooling effect of the spray. The results show that the spray nozzle provides a higher Material removal rate (MRR), lower non-uniformity (NU), and lower temperature than the conventional nozzle. Computational fluid dynamics techniques show that the turbulence kinetic energy and slurry velocity of the spray nozzle are much higher than those of the conventional nozzle. Finally, it can be summarized that the spray nozzle plays a significant role in slurry efficiency by theory of Minimum quantity lubrication (MQL).

Keywords: Copper (Cu); Chemical mechanical polishing (CMP); Spray slurry nozzle; Slurry flow rate; Nozzle height; Cooling effect; Computational fluid dynamic (CFD); Turbulent flow; Minimum quantity lubrication (MQL)

1. Introduction

Multilevel miniaturization has been required to reduce the RC delay time due to finer and longer interconnect lines on ULSI semiconductor devices. Global planarization is unavoidable to realize multilevel metallization for demanding a higher integration and increased circuit density. Copper chemical mechanical planarization (Cu CMP) is one of the major mass-production processes for fabricating interconnectting layers in multilevel metallization [1]. However, CMP is becoming to be an increasingly expensive and limiting step in the semiconductor manufacturing process without an improvement in planarization efficiency. In Cu CMP, the slurry consumption largely impacts environmental sustainability and cost-effectiveness [2]. Thus, the reduction of slurry consumption in this process is indispensable for the environment and economic efficiency.

Many approaches for reducing Cu CMP slurry have been conducted, such as slurry development for strengthening chemical dissolution and a slurry recycling method to increase sustainability. Several researchers have studied the effects and the roles of primary slurry chemicals such as the oxidizer, complexing agents, and inhibitors, which react with the copper surface, and form Cu oxide films [3, 4]. Ihnfeldt [5] improved Cu CMP slurry by adding nano-sized contact release capsules (nano-CRC). He found that slurries with core-shell nanoparticles made from porous colloidal silica abrasive with glycine could increase the planarization efficiency and Material removal rate (MRR). Wang et al. [6] reported on an inhibitor-free alkaline slurry with a high dissolution rate and applied it in the first step of Cu CMP for copper bulk removal. Testa et al. [7] treated slurry with ultrafiltration to concentrate the silica phase and made balanced chemical adjustments for environmental benefits.

However, few researchers have reported on slurry supply methods in Cu CMP. Horacek et al. [8] and Sai et al. [9] reported on spray nozzles that supply fine fluid droplets dynamically and on their cooling effect. Spray cooling occurs when liquid forced through a small orifice breaks into a dispersion of fine droplets that then impact a heated polishing pad. Although spray nozzles have long been used in a variety of industrial applications, the use of spray slurry nozzle in a

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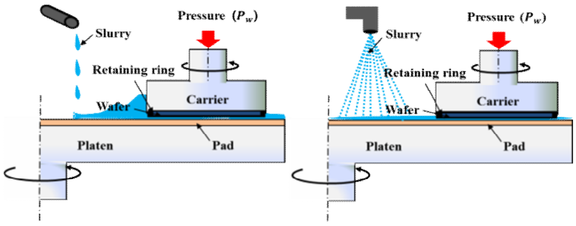


(a) (b)

Fig. 1. Comparison between conventional slurry nozzle and spray slurry nozzle (a) conventional slurry nozzle; (b) spray slurry nozzle.

CMP system is a recent development, and limited studies have reported experimental data for only SiO_2 CMP [10]. Chemical reactions are known to be a more dominant factor in Cu CMP than in SiO_2 CMP. Therefore, authors have investigated the efficiency of a full-cone spray slurry nozzle in comparison with a conventional tube-type slurry nozzle in Cu CMP.

Furthermore, the rapid growth of waste slurry disposal costs and the increasing need for environmentally friendly production techniques have increased the demand for a substitute to CMP processes using large amount of slurry. This study focuses on the superiority of a newly proposed spray slurry nozzle to conventional slurry nozzle in Cu CMP from standpoints of MRR, non-uniformity, and temperature.

2. Experimental

The most common rotary CMP polisher has a high removal profile at the edges [11]. Thus, the full-cone type spray, which has coverage concentrated in the center of the circle, was used for our experiments. Fig. 1 shows a comparison of CMP systems with a conventional nozzle and a spray nozzle. With the conventional nozzle, a limited amount of slurry can be supplied to the pad-wafer interface, as shown in Fig. 1(a). A CMP experiment was done with both nozzles using a 4-inch wafer with copper film (Cu: 1.5 µm, Ta: 0.03 µm on the thermal oxide film). The colloidal silica slurry (Nitta Haas Inc., Japan) had an oxidizer concentration of 3 wt% (hydrogen peroxide; H_2O_2). A rotary-type CMP machine (POLI-500, G&P Technology, Korea) and an IC1000/SUBA IV stacked pad (Nitta Haas Inc., Japan) were used with for the CMP test. Also, both nozzles position is wafer center. Table 1 shows the experimental conditions.

Experiments were performed by varying the slurry flow rate and spray nozzle height, which control the spray coverage. The slurry flow rate to the spray nozzle was controlled within the range of 50 ml to 140 ml because the orifice outlet diameter (0.63 mm) had a limit to increase of the flow rate.

After 1 min of CMP, the thickness of the Cu films was measured using a 4-point probe (Changmin Tech.). The measurement pattern was a 21-point diameter scan with an edge exclusion of 3 mm. During the CMP process, the process temperature and its distributions on the polishing pad were measured with an infrared (IR) sensor installed on the CMP equipment and an IR thermal imaging camera (Thermo Tracer TH9100, NEC San-ei Instruments, Ltd.).

Table 1. Experimental conditions.

Parameters	Conditions	
Pressure [g/cm^2]	Wafer	300
	Retaining ring	400
Velocity [rpm]	Carrier/platen	90
Slurry	Colloidal silica slurry+ 3 wt% H_2O_2	
Polishing pad	IC1000/SUBA IV stacked pad	
Process time	1 min	
Oscillation	On	
Slurry nozzle	Tube type nozzle	Full cone type spray nozzle
Slurry nozzle height [mm]	30	10, 30, 50
Slurry flow rate [ml/min]	50, 80, 110, 140, 170, 200, 230	50, 80, 110, 140

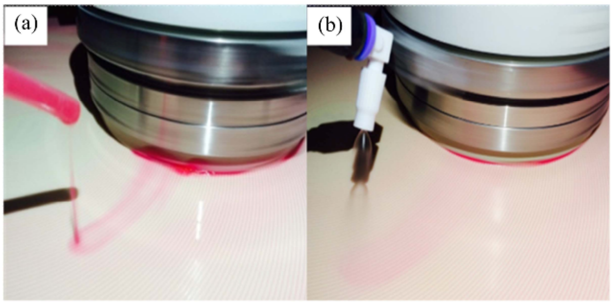


Fig. 2. Images of slurry waves at the retaining ring at 110 ml/min (a) conventional slurry nozzle; (b) spray slurry nozzle.

3. Results and discussion

Red dye was used to clearly observe the flow distribution of the slurry. In conventional tools, Fig. 2(a) shows slurry flow wave formation at the retaining ring, which results in low slurry utilization. A higher amount of slurry waves at the retaining ring wastes more slurry and less slurry re-enters the pad-wafer interface [12]. However, Fig. 2(b) shows there are low slurry waves at the retaining ring when using the spray nozzle, because slurry is supplied uniformly, unlike with the conventional nozzle.

3.1 Slurry flow rate

Fig. 3 indicates that the effects of the spray nozzle on the MRR in comparison with the conventional nozzle according to the slurry flow rate. The spray nozzle at the slurry flow rate of 110 ml/min has higher Cu removal rate than the conventional nozzle of 140 ml/min, resulting in 21% less slurry consumption. Moreover, the MRR increases with the slurry flow rate because a larger amount of the slurry results in more chemical reaction and mechanical abrasion with the copper film. However, if the slurry flow rate is too high, the MRR

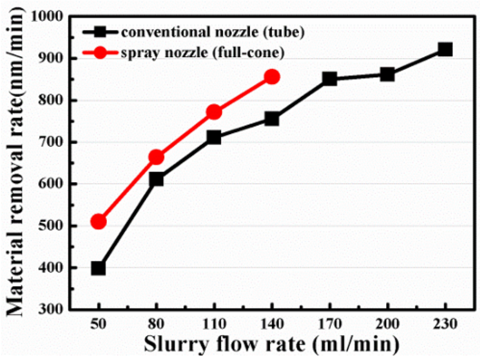
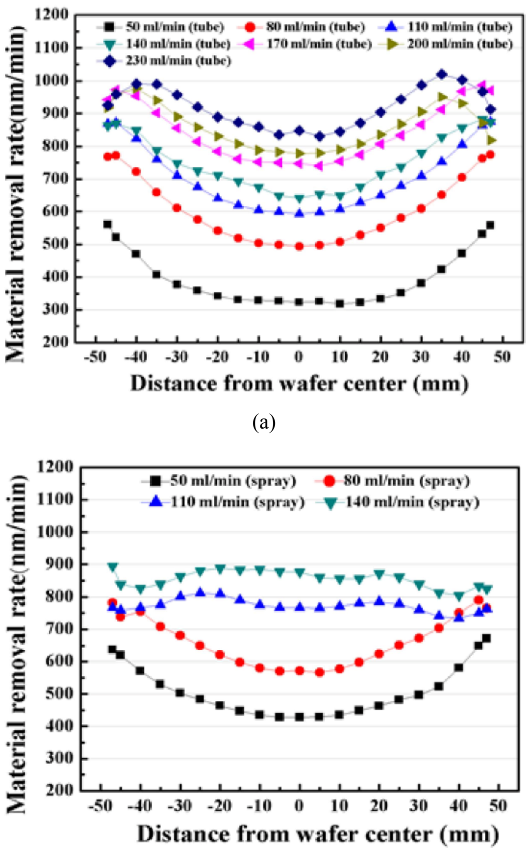


Fig. 3. Material removal rate comparison between conventional slurry nozzle and spray slurry nozzle according to slurry flow rate (D : 30 mm).



(a)

(b)

Fig. 4. Variations of the material removal rate profiles under different slurry flow rate: (a) conventional slurry nozzle; (b) spray slurry nozzle (D : 30 mm).

decreases a little because of the cooling effect from the excess slurry remaining after fully reacting with the wafer. The MRR distributions of the both nozzles are represented in Figs. 4(a) and 4(b).

Generally, a rotary CMP polisher has a high pressure profile at the edges. Wang et al. [13] simulated the von-Mises stress distribution on a wafer surface and proved that the stress distribution is related to the removal rate. Zhou et al. [14] showed that a concave pad profile results in a convex wafer shape. Fig. 4(a) shows that the MRRs increase near the edge of the wafer and then decrease at the outermost radius.

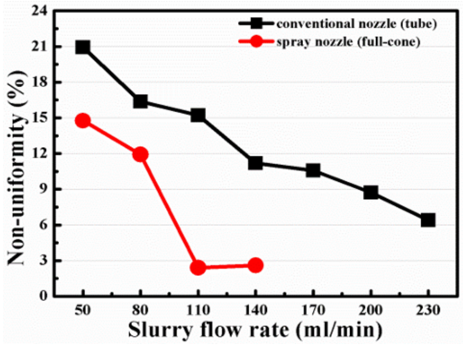


Fig. 5. Non-uniformity comparison between conventional slurry nozzle and spray slurry nozzle as a function of slurry flow rate (D : 30 mm).

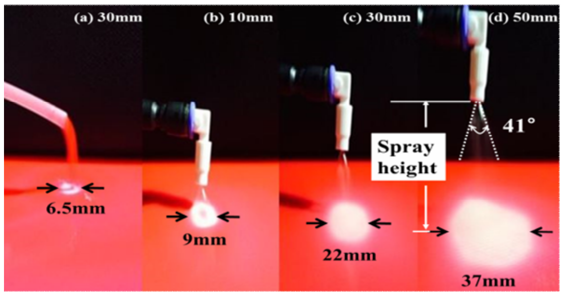


Fig. 6. Spray coverage as a function of slurry heights at 80 ml/min (a) 30 mm tube; (b) 10 mm spray; (c) 30 mm spray; (d) 50 mm spray.

However, Figs. 4(b) and 5 show that the spray nozzle at the slurry flow rate of 110 ml/min has less non-uniformity than obtained with the conventional nozzle of 230 ml/min, resulting in 52 % reduction of slurry consumption. As the slurry flow rate increases, the flow through the spray nozzle increases and the drop size decreases. This result demonstrates that the spray nozzle can prevent non-uniform removal near the wafer edge region and improve MRR at the center of wafer. The spray nozzle can uniformly distribute the slurry like a thin layer supplied to the wafer and make a weak slurry wave at the retaining ring, resulting from the many small drops. Therefore, the spray nozzle minimizes the slurry wasted during the CMP process. In contrast, the conventional nozzle forms high slurry waves formed at the retaining ring. Most of the slurry does not engage in the material removal process, and finally is wasted to outside of the pad by centrifugal force.

3.2 Slurry nozzle height

The theoretical spray coverage C of the spray patterns at various height can be calculated with the equation below for spray angles less than 180 º.

$$C = 2D\tan\left(\frac{\theta}{2}\right), \tag{1}$$

where D is spray nozzle height or distance from the nozzle

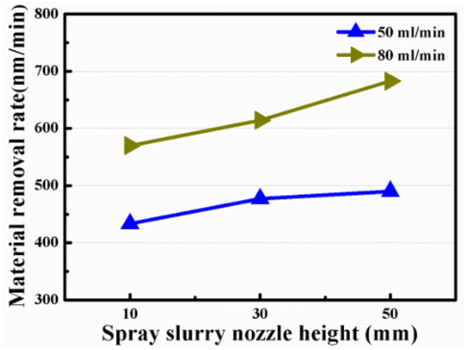


Fig. 7. Material removal rate according to spray slurry nozzle height at 50 ml/min and 80 ml/min.

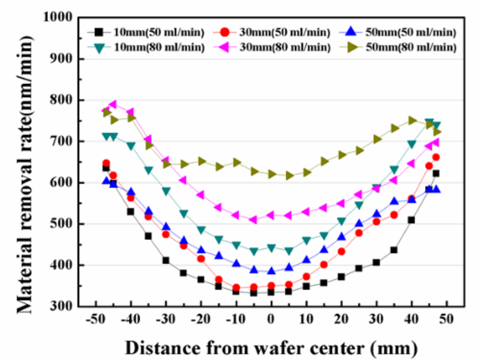


Fig. 8. Variations of the material removal rate profiles under different spray slurry nozzle heights at 50 ml/min and 80 ml/min.

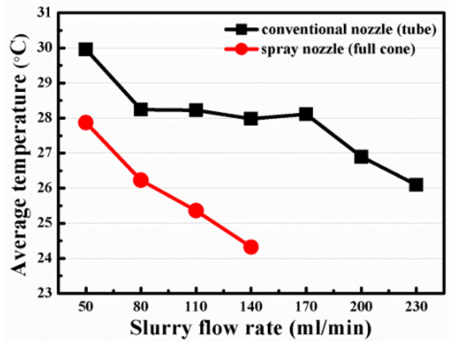


Fig. 9. Average temperature obtained with the conventional slurry nozzle and spray slurry nozzle according to slurry flow rate.

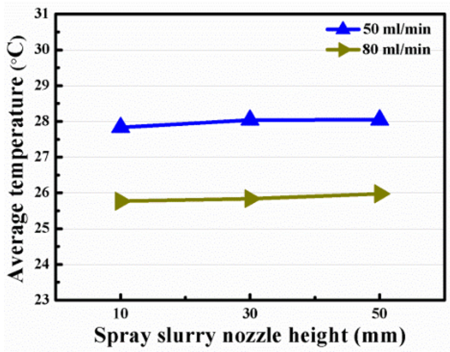


Fig. 10. Average temperature under different spray slurry nozzle heights at 50 ml/min and 80 ml/min.

orifice, θ is spray angle.

Fig. 6 presents the spray coverage which is larger for the spray nozzle than for the conventional nozzle. The spray coverage was measured with an optical method. The spray coverages with heights of 10, 30 and 50 mm are 10, 22 and 37 mm, respectively. However, the coverages calculated by Eq. (1) ($\theta = 41^{o}$) are 7.5, 22.4 and 37.4 mm. In practice, the value of theoretical coverage deviates from the actual value. In Fig. 7, the experimental results show that the MRR at high spray nozzle height is about 100 nm greater than that at low spray nozzle height at the same flow rates of 50 ml/min and 80 ml/min. This is related to the fact that higher spray nozzle height results in more spray coverage in the pad.

Furthermore, the MRR profile curve at greater height is more stable than that at low height, as shown in Fig. 8. It confirms that even if the slurry flow rate is very low, the NU decreases sharply at greater nozzle height. It is predicted that increasing the spray nozzle height increases the amount of slurry that enters the gap between the pad and wafer at the same flow rate.

3.3 Process temperature

Spray cooling is an important technology used in industry for cooling materials. A spray nozzle facilitates the dispersion of liquid into a spray in broader areas. In addition to the substantial convection effect, the droplets can spread on a surface, absorb heat, and change into water vapor, which escapes from the polishing pad and removes heat. To verify the cooling effect of the spray nozzle, we measured the pad surface temperature using an in-situ monitoring system. The set point temperature of the platen was 20°C.

Fig. 9 shows that the spray nozzle has a lower average temperature than the conventional nozzle. Also, as the slurry flow rate increases, the process temperature decreases due to the cooling effect of the new incoming slurry. However, from Fig. 10, the temperature does not change remarkably with the nozzle height. It is likely that the temperature rarely affects the spray coverage at the same flow rate.

The MRR in CMP has been traditionally characterized using the generalized Preston's equation

$$MRR = kp\overline{v}\ , \tag{2}$$

where k is Preston's constant, p is the applied wafer pressure, and $\overline{v}$ is the average linear pad-wafer velocity.

$$k_a = A\exp\left(-\frac{E_a}{RT}\right), \tag{3}$$

where Preston's constant, k, includes the effect of polishing temperatures through an Arrhenius relationship (Eq. (3)). k_a

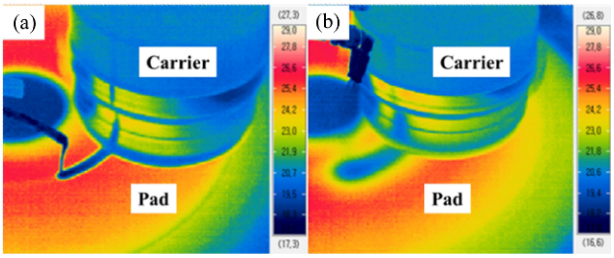


Fig. 11. Images of temperature measured with a thermal imaging camera during CMP at 40 s CMP: (a) conventional slurry nozzle; (b) spray slurry nozzle.

is the rate constant of a chemical reaction, A is a thermally independent constant, E_a is the activation energy, R is the universal gas constant, and T is the process temperature, respectively [15].

In Eq. (3), either increasing the temperature or decreasing the activation energy will increase MRR. Thus, lower temperature commonly causes less chemical reaction in the Cu CMP process, resulting in a lower removal rate. However, at lower temperature, higher MRRs are shown in the spray nozzle. Using the spray nozzle, the slurry can increase the polishing and thus boost the MRR and uniformity, in spite of the slight cooling effect due to rapid evaporation. Fig. 11 represents the temperature of the pad during CMP to investigate the droplet evaporation. The spray system may be used for controlling pad temperature instead of pad rinsing for lowering the pad temperature.

3.4 Computational fluid dynamics

Computer simulation can be a very useful tool to study the physics of the spray and to study unknown factors in the experiments at minimal cost and effort. Modeling has been done using Pro-engineer and the commercial computational fluid dynamics software ANSYS-CFX. The performance factors are the slurry properties, viscosity, buoyant, specific gravity, and surface tension. The turbulence is generally interspersed with laminar flow below a Reynolds number of approximately 2100 until a larger number of about 4000. The Reynolds number is defined as:

$$\mathrm{Re} = \frac{\text{inertial forces}}{\text{viscous forces}} = \frac{\rho v L}{\mu}, \tag{4}$$

where ρ is the density of the slurry, v is the kinematic viscosity, L is the linear dimension, and μ is the viscosity of the slurry.

The Turbulence kinetic energy (TKE) is the mean kinetic energy per unit mass associated with eddies in turbulent flow. In the Reynolds-averaged Navier Stokes equations, the TKE can be quantified by the mean of the turbulence normal stresses [16]

$$T = \frac{1}{2}(\overline{(u_1')^2} + \overline{(u_2')^2} + \overline{(u_3')^2}). \tag{5}$$

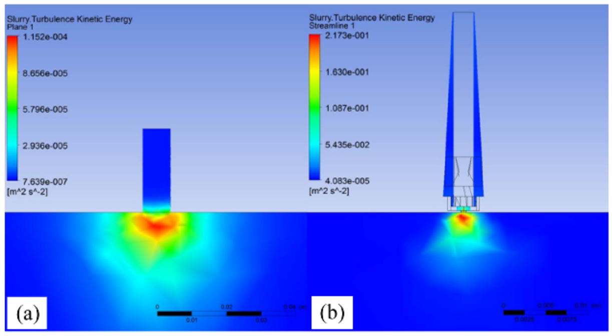


Fig. 12. CFD simulation ZX plane image of slurry turbulence kinetic energy: (a) conventional slurry nozzle; (b) spray slurry nozzle (slurry flow rate : 80 ml/min).

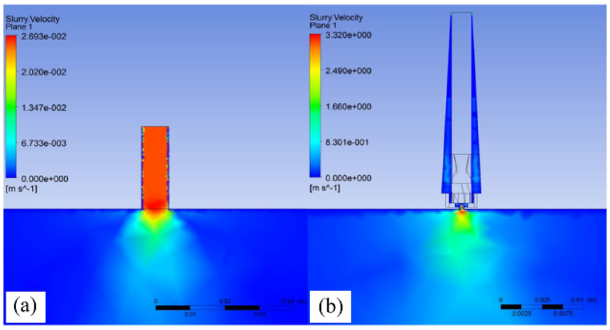


Fig. 13. CFD simulation ZX plane image of slurry velocity: (a) conventional slurry nozzle; (b) spray slurry nozzle (Slurry flow rate : 80 ml/min).

Turbulent flow is characterized by chaotic property changes, including low momentum diffusion, high momentum convection, and rapid variation of the pressure and flow velocity in space and time. TKE of the spray nozzle $(4.08 \times 10^{-5} - 2.17 \times 10^{-1}\,\mathrm{m}^2/\mathrm{s}^2)$ is over 1000 times higher than that of the conventional nozzle $(7.64 \times 10^{-7} - 1.15 \times 10^{-4}\,\mathrm{m}^2/\mathrm{s}^2)$, as shown in Fig. 12. The slurry flow is turbulent with the spray nozzle, in contrast to the laminar flow of the conventional nozzle, which has parallel layers with no disruption between them. It utilizes the kinetic energy of the liquid to break it up into droplets in spray nozzle. This type of spray nozzle is most widely used and is more energy efficient at covering a surface area than other types. Physically, the turbulence kinetic energy is characterized by the measured Root-mean-square (RMS) of velocity fluctuations. Fig. 13 presents that the slurry velocity in the spray nozzle (~3.32 m/s) is over 100 times higher than that of the conventional nozzle ($\sim 2.69 \times 10^{-2}$ m/s). When high velocity fluid passes through a contraction, cavitation can occur. Using the spray nozzle provides wide, uniform, abundant slurry on the pad.

4. Conclusions

Slurry use was studied in view of changing slurry supply method for reducing the costs and environment pollution of the CMP slurry. We have compared a conventional tube slurry nozzle and spray slurry nozzle at different slurry flow rates and spray nozzle heights. The experimental results according to slurry flow rate, showed that the spray nozzle had higher MRR and lower NU than the conventional nozzle, resulting in 21%, 52% slurry flow rate reduction. The high spray nozzle height has higher MRR and lower NU than that at low spray nozzle height at the same flow rate.

Also, using an IR sensor, we confirmed that the spray nozzle has a lower average temperature than the conventional nozzle due to cooling effect by rapid evaporation. Finally, we verify that the slurry velocity and TKE in the spray nozzle had higher than the conventional nozzle in terms of slurry flow motion by analytical studies. It shows that spray nozzle can supply slurry uniformly, widely and abundantly on the pad by turbulence flow. We strongly recommended that the spray slurry nozzle be substituted for the conventional tube-type slurry nozzle in Cu CMP to reduce slurry consumption for environmental sustainability and cost effectiveness.

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