

DEVELOPMENT OF ONE-STOP MACHINING SYSTEM FOR $\phi 300\text{MM}$ SILICON WAFER

Libo ZHOU*, Hiroshi EDA*, Kazushi WATANABE**,
Hirokami NAKANO*, Ryo KONDO* and Jun SHIMIZU*

* Ibaraki University, Nakanarusawa 4-12-1, Hitachi-shi, JAPAN 316-8511

** Hitachi Via-Mechanics Pte. Ltd, 2100 Kami-Imaizumi, Ebina-shi, JAPAN 243-0488

1. Introduction

According to the roadmap of the semiconductor industry, the silicon wafer will be shifted from $\phi 200\text{mm}$ (8") to $\phi 300\text{mm}$ (12") by the year 2003. Presently the manufacturing of silicon wafer is mainly done by lapping, etching and polishing. These free slurry methods achieve better surface roughness only when smaller abrasives are applied, therefore, require multi-stage equipments and multi-stage processes. The current pressure-controlled process is also unable to fulfill the requirement of global flatness as the wafer size is increased. To combat the problems of throughput rate, post-process cleaning, environmental impact as well as to achieve the total surface integrity of $\phi 300$ silicon wafer, the semiconductor industry is looking for a fixed abrasive solution as the alternative.

This research project has successfully developed an advanced manufacturing system, using fixed abrasive grinding wheel instead of free slurry, to provide a totally integrated environment to achieve one-stop machining. The key component developed for this system is the giant magnetostrictive actuator, which is used to precisely position the grinding head against the workpiece for non-defect grinding, and to control the posture of the silicon wafer as well to achieve the flatness over $\phi 300\text{mm}$ global area.

2. One-stop grinding machine

Fig.1 is the external view of the newly developed one-stop grinding machine, which has two aerostatic spindles configured level facing each other to eliminate the gravity effect. Both spindles come with built-in AC servomotors and rotate at 1.8~18000 rpm with the maximum run-out of 0.02 μm . The left spindle, to hold the workpiece, is equipped with a vacuum chuck made of porous ceramics to attain high rigidity, while mounted on the right spindle is the diamond grinding wheel.

As the details shown in Fig.2, the grinding machine has two degrees of freedom. The linear motion along X direction is given to the work spindle, while the Z directional motion to the wheel spindle. The guide way used is aerostatic box type with six-plane constraint. The tables are designed as 5 times long as the maximum linear stroke of 200mm, and driven by a



Fig.1 Newly developed one-stop grinding machine

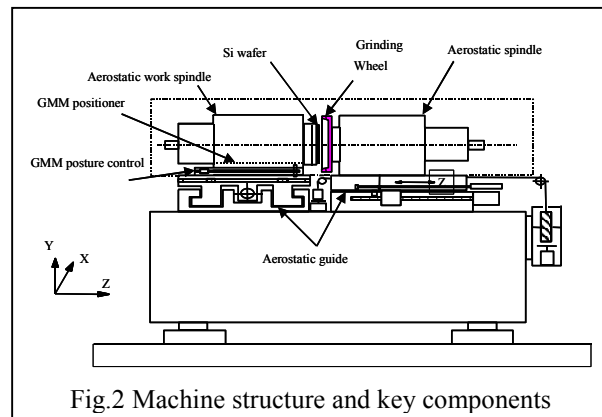


Fig.2 Machine structure and key components

Table 1 specifications and conditions

Specification	Property	Movement
Wheel spindle	Aerostatic bearing, built-in motor	1.8~1800rpm
Work spindle	Aerostatic bearing, built-in motor	1.8~18000rpm
X, Z linear guide	Aerostatic bearing, AC servo motor	10nm/200mm
Position	GMM actuator	1 nm/2 μm
Posture	GMM actuator	10nm/5 μm
Conditions	Property	Dimension
Wheel	SD3000N150DK200B	300D-3W-3X-40T
Coolant	Pure water	20°C
Workpiece	Silicon wafer	300D-0.8t
Operational parameters	Wheel speed V	40~1500rpm
	Work speed v	20~500rpm
	Infeed rate F	0.5~20 $\mu\text{m}/\text{min}$
	Infeed Z	2~20 μm

set of precisely lapped lead screw together with a servomotor. All motion errors in pitching, rolling and yawing are less than $0.15\mu\text{m}$ over 200mm length, and the positioning resolution is as good as 10nm.

It is placed as shown in Fig.9 so that the grinding wheel and silicon wafer are half overlapped. The loop stiffness is about $100\text{N}/\mu\text{m}$. The plunge grinding is adapted for the current research to avoid the variation in the contact area and thereby the grinding pressure, which normally leads to lower the quality of flatness. By disengaging the screw nut, the table of the Z-axis also moves by a low friction pneumatic cylinder which creates a constant the grinding force/pressure. This function is used for the final finishing, instead of the spark-out. The specifications and experimental conditions are summarized in Table 1.

3. Precision positioner

One of the core technologies of this grinding machine is its precision positioner, which is used to give the fine depth of cut and to control the posture of the silicon wafer against the grinding wheel. Fig.3 is the conceptual design of the positioner. The table consists of two pieces of parallel plate ($600\times 600\text{mm}$). They are wire cut into such shapes that the top plate linearly gives elastic deformation in Z direction while the bottom plate gives elastic deformation in yawing, rolling and pitching directions.

The actuator newly developed to drive this positioner is made of GMM (giant magnetostrictive material). Comparing to the piezo material, the GMM offers much better performance in displacement range, resolution, response speed and output power. Fig.4 shows the GMM actuator and the table actually developed. Four GMM actuators are employed; Actuator 1 and 2 for rotational motion around X, Z axes, Actuator 3 for rotational motion around Y axis and Actuator 4 for linear motion along Z axis. Each actuator comes with a capacitive sensor to form a closed feedback loop. Fig.5 is the control diagram for the positioner, which is comprised of a position controller, a current controller and a power amplifier. The symbols used in Fig.5 are the position reference value x^* , the actual position x , and the current reference value i^* and the actual current i . The detailed diagrams of the position controller and the current controller are respectively shown in Fig.6 and Fig. 7.

The position controller is built on a single PC board, which is equipped with a PowerPC 604e processor for fast floating-point calculation at 333MHz, a 16-bit ADC with of $4\mu\text{s}$ sampling time, 14-bit DAC with $5\mu\text{s}$ setting time. The position controller firstly compares the position reference value x^* , which is generated by a signal generator, with the ADC output x from the capacitive sensor. The error signal then regulates the

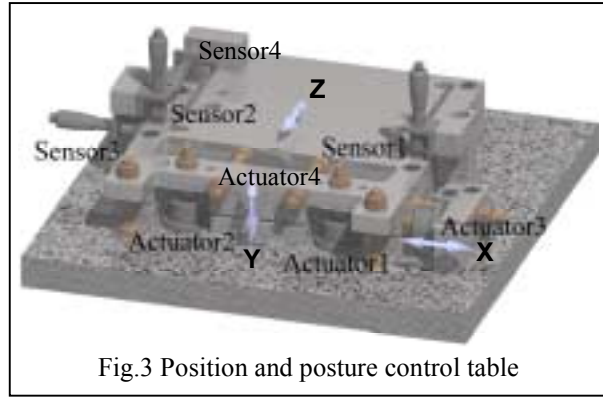


Fig.3 Position and posture control table

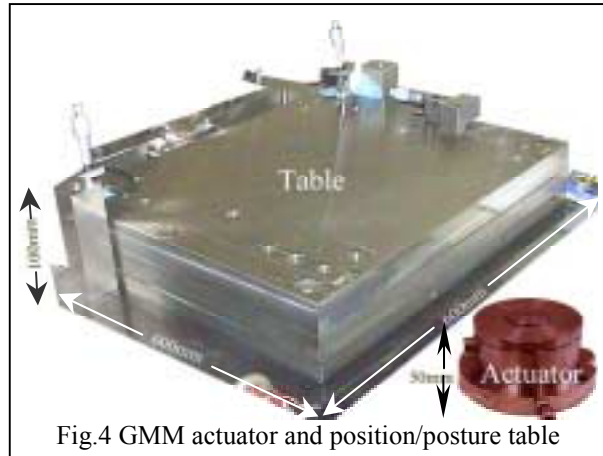


Fig.4 GMM actuator and position/posture table

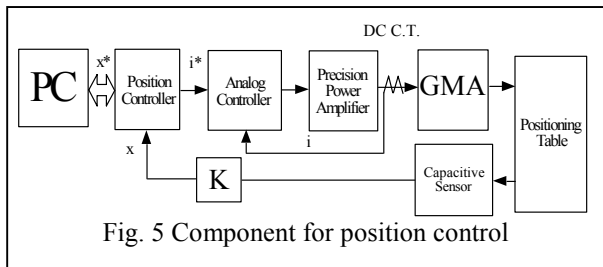


Fig. 5 Component for position control

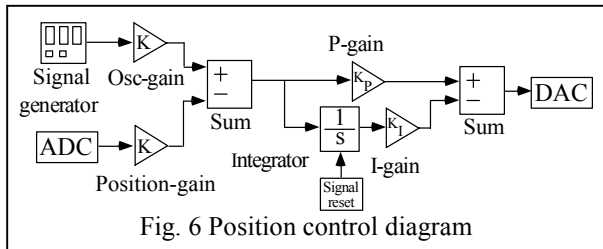


Fig. 6 Position control diagram

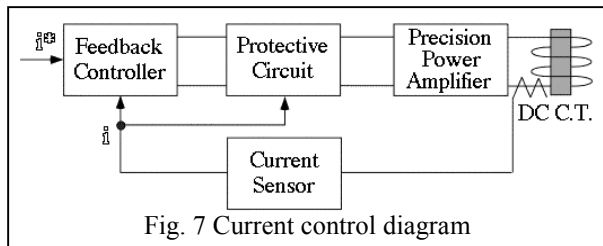


Fig. 7 Current control diagram

current reference value i^* by means of the proportional

control gain or P-gain, and the integral gain or I-gain.

The actual current i flowing into the GMM actuator is detected by the DC current transducer and amplified by the current sensor. A feedback control is done in the current controller so that the actual current matches the current reference value.

The performance of the positioner has been evaluated with 500kgf payload. It is found that the positioner has about $2\mu\text{m}$ actuating range as it is designed. Fig.8 shows step responses of the table at the 10nm and 6.25\AA . At such large payload, the motion error is less than 1\AA . Being mounted on the positioner, the workpiece spindle is able to offer very fine depth of cut to achieve the ductile mode material removal and to align the posture to achieve high global flatness.

4. Grinding test

Infeed grinding is applied at the position shown in Fig.9, where the wheel is aligned half overlapping with the silicon wafer. The operational conditions are co-listed in Table 1. The cutting path formed on the wafer by each abrasive is dependent only upon the rotational speed ratio v/V of the wafer against the wheel. Examples given in Fig.9 are $v/V = 0.02$ and $v/V = 0.46$. For each case, the cutting path is denser in the center than that in the fringe. The wafer after grinding therefore tends to be concave (Fig.10a). On the other hand, tilting the wafer around X-axis makes its ground profile convex (Fig.10b). The flatness can be significantly achieved if the appropriate condition is chosen to offset these two factors. A typical result attained is shown in Fig.11 that has the global flatness of $0.2\mu\text{m}$ over $\phi 300\text{mm}$ diameter.

The result in Fig.9 also shows that each cutting edge forms 50 passes for both $v/V = 0.02$ (or $1/50$) and $v/V = 0.46$ (or $23/50$), but with different locus. It is meant that the denominator m of irreducible fraction v/V of Eq (1) determines the number of the cutting path as grinding reaches the steady state.

$$\frac{v}{V} = \frac{n}{m} \quad (1)$$

where n, m are integers, n/m is irreducible. Once the grinding reaches the steady state, the cutting edge goes over the same path. In order to achieve a better surface roughness, the cutting path density, namely, the denominator should not be too low. Fig.12 compares the surface roughness resulted from different rotation speed combination. The cutting path at $v/V = 495/1500$ (or $33/100$) is three times denser than that at $v/V = 50/1500$ (or $1/30$). It is clearly proven that the density of cutting path contributes in the surface roughness improvement. In the meantime, an

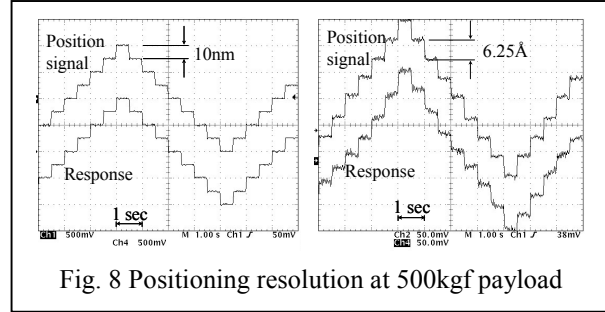


Fig. 8 Positioning resolution at 500kgf payload

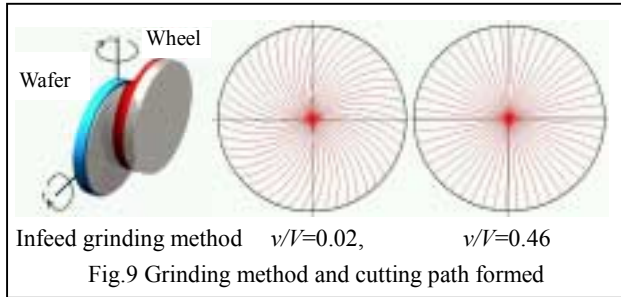


Fig.9 Grinding method and cutting path formed

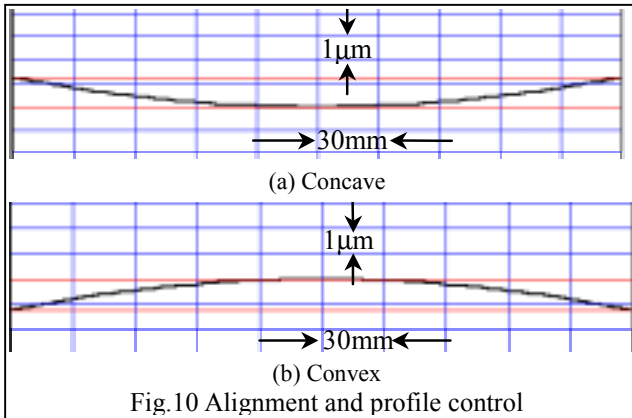


Fig.10 Alignment and profile control

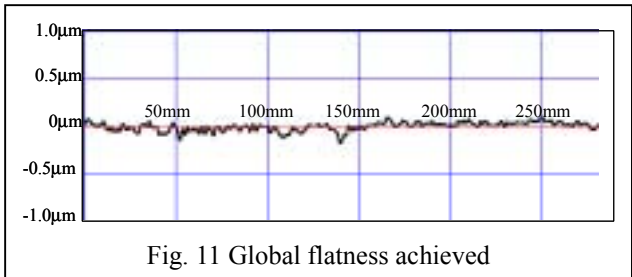


Fig. 11 Global flatness achieved

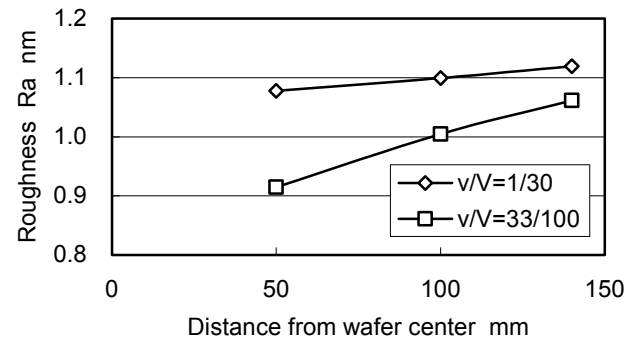


Fig.12 Cutting path density and roughness

excessive m takes a long time to reach the steady state, which often leads to the burn marks on the wafer surface. Fig.13 is the critical condition of burn mark, which is discovered by a series of experiment. The results spell out as long as the operational parameters meet the Eq.(2) that the burn mark is avoidable.

$$Z\left(\frac{V}{F}\right)^2 \leq a \quad (2)$$

where a is a constant dependent on the properties of the wheel and workpiece. In the current condition, a is about $4 \sim 5 \times 10^4$. In Eq.(2), F/V stands for the depth of cut per wheel revolution. A finer depth of cut normally leads to a better surface roughness, but risks more in burn mark.

In order to make a homogenous ground surface, the operational parameters need further to fulfill the condition in Eq.(3).

$$V \frac{Z}{F} = k \cdot m \quad (k : \text{a natural number}) \quad (3)$$

Shown in Fig.14 are three typical patterns with $m = 300$ that the cutting path forms. When $0 \leq k < 1$, grinding has yet reached to its steady state and there are some places where the cutting path is lacking. When $k = 1$, the wafer is most uniformly ground. When $k > 1$, there are some places having the cutting path multiplied. When k takes other natural number than 1, the cutting paths are homogeneously distributed, but multiply cut by the same abrasives. This fact deepens the cutting marks and results in a rough surface. Fig. 15 shows the experimental results corresponding to the parameter settings in Fig.14, in which the best the roughness is achieved at $k = 1$.

The final finishing is done under a constant force controlled between 0.15~1.5kgf. The ground 3D profile is given in Fig.16 which show that roughness is below 1nm.

5. Conclusion

In this research, an advanced grinding machine with the capability of one-stop finishing for $\phi 300\text{mm}$ Si wafer has been developed. The core technology is the GMM actuated positioner which is able to move half a ton of payload at the resolution of 5 \AA . By optimizing the operational parameters, the first trial test has achieved the result of surface roughness $R_a < 1\text{nm}$ and global flatness less than $0.2\mu\text{m}$ over $\phi 300\text{mm}$.

Acknowledgement

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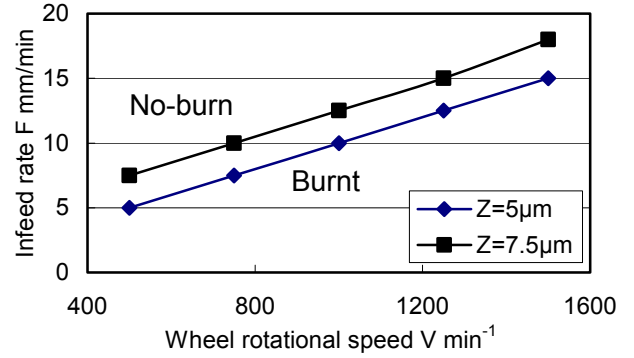


Fig.13 Critical condition of burn mark

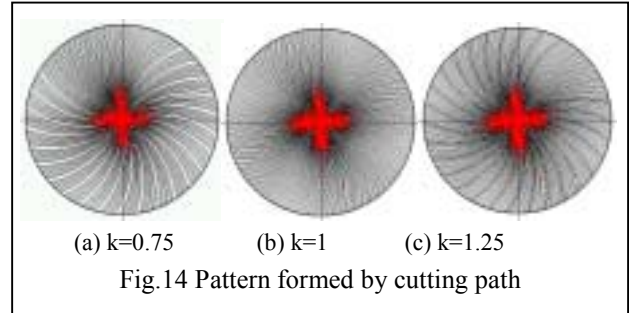


Fig.14 Pattern formed by cutting path

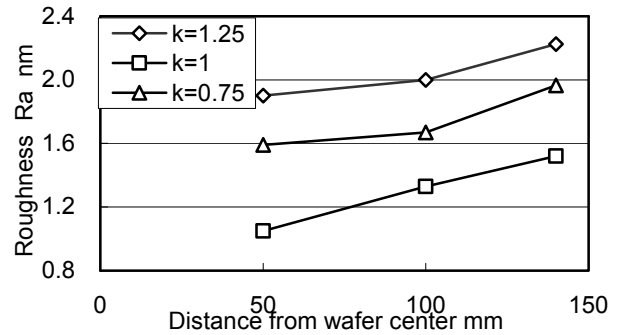
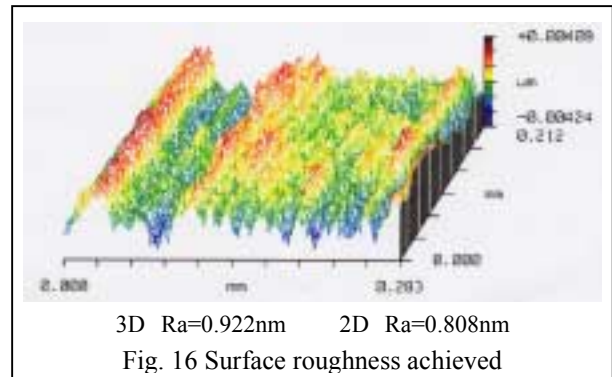


Fig.15 Effect of the cutting path distribution



3D $R_a = 0.922\text{nm}$ 2D $R_a = 0.808\text{nm}$
Fig. 16 Surface roughness achieved

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