

Simultaneous double side grinding of silicon wafers: a literature review

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Abstract

Silicon wafers are the most widely used substrates for fabricating integrated circuits (ICs). The quality of ICs depends directly on the quality of silicon wafers. A series of processes are required to manufacture high quality silicon wafers. Simultaneous double side grinding (SDSG) is one of the processes to flatten the wire-sawn wafers. This paper reviews the literature on SDSG of silicon wafers, covering the history, machine development (including machine configuration, drive and support systems, and control system), and process modeling (including grinding marks and wafer shape). It also discusses some possible topics for future research.

Keywords: Grinding; Machining; Modeling; Semiconductor material; Silicon wafer; Simultaneous double side grinding

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1. Introduction

Integrated circuits (ICs) are widely used in applications such as computer systems, telecommunications, automobiles, consumer electronics, industrial automation and control systems, and defense systems. Over 90% of ICs are built on silicon wafers [1]. About 150 million silicon wafers of different sizes are manufactured each year worldwide [2]. In 2004, the worldwide revenues generated by silicon wafers and semiconductor devices were \$ 7.3 billion [3] and \$ 213 billion [4], respectively. As one of processes to flatten silicon wafers, simultaneous double side grinding (SDSG) has a great potential to meet the demands for high quality wafers at low cost [5].

This paper reviews the literature on SDSG. Following the introduction section, section 2 briefly reviews the currently available processes for flattening silicon wafers, pros and cons of each process, and proposed applications of SDSG. A brief history of SDSG is summarized in section 3. Section 4 presents the machine development of SDSG, including machine configurations, drive and support systems, and control systems. Process modeling of SDSG is introduced in section 5. The last section discusses some possible topics for future research on SDSG.

2. SDSG in silicon wafer manufacturing

2.1 Silicon wafer manufacturing

A sequence of processes is needed to turn a silicon ingot into silicon wafers. As shown in Fig. 1, it typically consists of the following processes [6-11]:

- 1) slicing, to slice a silicon ingot into wafers of thin disk shape using an internal diamond sawing method or wire sawing method;
- 2) edge profiling or chamfering, to chamfer the peripheral edge portion of the wafer to reduce the risk of wafer damage in further processing;
- 3) flattening (lapping or grinding), to achieve a high degree of flatness and parallelism of the wafer;
- 4) etching, to chemically remove the damage induced by slicing and flattening without introducing further mechanical damage;
- 5) polishing, to obtain a mirror surface on the wafer;
- 6) cleaning, to remove the polishing agent or dust particles from the wafer surface.

2.2 Pros and cons of three flattening processes

Three processes can be used to flatten the sliced wafers: lapping, single side grinding (SSG), and SDSG. The lapping operation is illustrated in Fig. 2. A batch of wafers (for example, 20 wafers) is manually loaded into a lapping machine. The loaded wafers are then lapped by the abrasive slurry (typically a mixture of alumina and glycerine [11]) injected between two lapping

plates rotating in opposite directions. Lapping can effectively remove or reduce the wire-sawing induced waviness [12]. However, the lapping operation would generate subsurface damages in silicon wafers, which need to be removed by its subsequent processes. There are several disadvantages for lapping operation [10,12-14]:

- 1) Low material removal rate;
- 2) High cost of consumables (abrasive slurry);
- 3) It causes more work in process (WIP) inventory and the batch-to-batch wafer thickness variation tends to be high;
- 4) Wafer loading and unloading is done manually, not only increasing labor costs, but also causing frequent wafer breakage; and
- 5) Less benign to the environment due to the use of abrasive slurry.

In SSG, as shown in Fig. 3, a silicon wafer is held on a porous ceramic chuck by means of vacuum. The grinding wheel is a diamond cup wheel. The grinding wheel and the wafer rotate about their own rotation axes simultaneously, and the wheel is fed towards the wafer along its axis [9,12-13]. After the wafer front side is ground, the grinder flips the wafer over and continues to grind the back side. The advantages of SSG over lapping include [10,12-14]:

- 1) It uses fixed-abrasive grinding wheels instead of abrasive slurry so the cost of consumables per wafer is lower;
- 2) Fixed-abrasive grinding wheels are more benign to the environment than lapping slurry;
- 3) It has higher throughput (the number of wafers processed within the unit of time);
- 4) It is fully automatic; and
- 5) It grinds one wafer at a time.

SSG has its own drawbacks. It cannot effectively remove the waviness induced by the wire sawing process [12-13,15-19]. Furthermore, any imperfection in the chuck will copy its deficiencies to the ground wafers [5].

Fig. 4 illustrates the SDSG process. A pair of diamond cup wheels are located on the opposite sides of a rotating silicon wafer. The two wheels rotate in opposite directions [10,20]. Both sides of the rotating silicon wafer are ground simultaneously by the two wheels, which are synchronously fed towards the wafer.

SDSG possesses the advantages of both lapping and SSG. Since SDSG share the same material removal mechanism (grinding) as SSG, it has the same advantages as those of SSG (like lower consumable cost, higher throughput, environmentally benign, and fully automatic). Furthermore, both sides of the wafer are ground by a pair of wheels simultaneously in SDSG, very similar to lapping where both sides of the wafer are machined simultaneously [10,20-22]. Therefore, SDSG is believed to be as effective as lapping in waviness reduction. Since no chuck is used in SDSG, it does not have the chuck-related problems as in SSG [5,10].

Table 1 compares lapping, SSG, and SDSG in five aspects: ability to remove or reduce wire-sawing induced waviness; throughput; consumable cost per wafer; level of automation; and environmental benignity. It can be seen that SDSG is better in almost every aspect. More information can be found in the literature about lapping [21-22], SSG [23-25], and SDSG [5,10,20].

2.3 Proposed applications of SDSG

Fig. 5 shows three proposed process flows using SDSG and lapping to flatten silicon wafers. The SDSG process is used to improve the wafer flatness and remove a strained layer on the wafer surfaces (induced by slicing), the macroscopic undulation, and the roughness [26]. The lapping process is used to remove minute surface undulations (with a height of a few tens of nm and period of a few mm) incurred during SDSG [26].

For the two process flows shown in Fig. 6, the wafer is flattened using SDSG, lapping, and SSG [26]. The SDSG and lapping processes serve the same purposes as those in the process flows shown in Fig. 5. The SSG process is used to remove a strained layer on the wafer surfaces induced by lapping [26].

Fig. 7 shows a process flow using SDSG and SSG to flatten silicon wafers [26-28]. The SDSG process is used to remove the slicing-induced waviness and the strained layer on the wafer surfaces generated during slicing [26-27]. The SSG process is used to further improve the flatness and roughness [26-27]. It was reported that the roughness and flatness of the wafers can be improved due to the introduction of SDSG into those process flows shown in Figs. 5-7 [26-28]. High precision wafers without minute undulations could be obtained by conducting lapping and polishing after SDSG [26]. Also, the amount of waste caused by the abrasive slurry in the lapping operation can be reduced to about one quarter [26].

The process flows shown in Fig. 8 use the SDSG process twice. The first SDSG was conducted after the slicing process to flatten the sliced wafers by coarse grinding [29-30]. The second SDSG was then performed (before or after chamfering) to fine grind both sides of the wafer to improve the flatness and remove the strained layer on the wafer surfaces incurred during the first SDSG process [29].

3. A brief history of SDSG

SDSG was first used for double side grinding of small metal workpieces of simple shapes in 1930s to 1950s [31-33]. In 1960s to 1970s, it was used to flatten workpieces made of various types of materials and having different dimensions and shapes [34-37]. From 1980s to the middle of 1990s, additional capabilities of flexibility, precision, and fast changeovers were provided to SDSG [38-49].

SDSG was introduced into semiconductor industry in 1990s [50-56]. Applications to both 200 mm [5,10,26,51,54] and 300 mm [5,10,20,26,51,54] silicon wafers were reported. Use of grinding wheels whose diameters are equal or greater than the wafer diameter [55,57-60] and use of grinding wheels whose diameters were less than the wafer diameter and greater than the wafer radius [5,10,20,50-54,61-67] were reported.

The diamond grinding wheels with different mesh sizes were used for those process flows involving the first (or coarse) and the second (or fine) SDSG processes shown in Fig. 8 [29-30].

Since the main purpose of the coarse SDSG is stock removal, the diamond grits in the coarse wheels have large sizes (mesh #300 to #2000) [30]. The mesh size of the wheels used in the fine SDSG process are in the range of #2000 to #10000 [30].

The bond materials for the SDSG wheels could be resin, metal, or vitrified ceramic [27,30]. Relatively rigid bond materials, such as metal or vitrified ceramics, were used for the coarse SDSG process [30]. Relatively soft bond materials, such as resin or “low level” (softer) vitrified ceramics, were used for the fine SDSG process [30].

4. Equipment development

4.1 Machine configurations

Fig. 9 shows a configuration to grind metal workpieces (in disk shape) for rolling bearings [36]. Two flat grinding wheels, rotating in opposite directions, were located apart with a certain distance. The workpieces were positioned in the through holes provided in the periphery of a metal disk, which was rotated and fed between the two wheels. Both sides of the workpieces were ground simultaneously by the two wheels.

Fig. 10 shows a horizontal machine configuration for grinding silicon wafers [50,56]. A silicon wafer, rotating along its vertical rotation axis, was placed between two grinding wheels

(in cylinder shape). The two wheels rotated along their horizontal rotation axes in opposite directions. Both sides of the wafer were ground simultaneously by the two wheels.

Fig. 11 shows another configuration for silicon wafers where cup-shaped grinding wheels were used [50,53]. A silicon wafer, rotating along its vertical rotation axis, was ground simultaneously by two diamond cup wheels that rotated along their vertical rotation axes in opposite directions. Note that the wheel diameter was much smaller than the wafer diameter.

The SDSG configuration shown in Fig. 12 appeared in several different reports [5,10,20,63]. A silicon wafer, rotating along its horizontal rotation axis, was simultaneously ground by two diamond cup wheels that were located on the opposite sides of the wafer. The two wheels, rotating in opposite directions, were on collinear axes and synchronously fed towards the wafer along their axes.

4.2 Drive and support systems for silicon wafers

The drive system is to rotate the silicon wafer while the support system is to hold the rotating silicon wafer in good balance during the SDSG operation.

Fig. 13 shows a patented drive system [64]. It was claimed that earlier drive systems had two major drawbacks [64]. Firstly, the support plate tended to be warped by its own weight in many cases. It was difficult to prevent the support plate from contacting the grinding wheels. Secondly, the support plate needed to be made very thin and therefore it was difficult for the

support plate to withstand the grinding force. These problems were addressed by introducing a metal support plate containing a recess and a through hole [64]. The drive section was thinner than the wafer. The carrier, which consists of the drive section, the recess, the notch, and the through hole, was rotated by a motor through a match gearing. Rollers were used to support the rotating carrier. However, one drawback of this system was that the drive section was likely to be worn out due to its contact with the grinding wheels. The replacement of the drive section would increase the production cost [65]. To overcome this drawback, the drive section was modified into several removable drive section parts and only the part that has been worn out was dismantled and replaced, as shown in Fig. 14 [65]. A lock was designed to close the carrier so that the wafer could be held [65].

Those aforementioned drive systems were questioned on their stability and reliability [63]. Silicon wafers are of 200 mm or 300 mm in diameter and about 0.8 mm in thickness. The wafer diameter is much larger than the thickness so that the carrier has to be sufficiently large to hold and rotate the wafer. Because the wafer thickness is very small, the carrier to hold the rotating wafer is required to have a greatly reduced thickness, making it a vulnerable component and making the smooth rotation of the wafer difficult. To address the issue, the roller drive systems as shown in Figs. 10-12 were developed [50,52,63,66], where multiple pairs of rollers (shown in Fig. 12) were used to drive the wafer by the friction.

The support system serves two purposes. One is to provide static pressure that stabilizes the wafer. The other is to provide enough cooling to the grinding interface. Fig. 15 shows one support system that sprays water (through holes in a hydro-pad fixture) on both inside and

outside of the grinding wheels [55]. It was also mentioned that the effectiveness was almost equivalent if compressed air was used instead [55]. Fig. 16 shows another support system [67]. The pair of fixtures was made of porous ceramic material. Water or air was supplied by the pipes inside the grinding wheel spindles and injected through the pores in the fixtures to both wafer surfaces. Fig. 17 shows another support system [68]. Two crescent discs with small holes, through which coolant fluid could be pumped onto both wafer surfaces, were used to keep the wafer in balance.

Fig. 18 shows three combinations of drive and support systems for SDSG grinders [5,10]. For the combination shown in Fig. 15(a), one roller made of ceramics acted as a position master while the other rubber roller a position slave. This combination provided a safe, stable, and simple guide for wafer's rotation. But, it was highly mechanically over-determined. Hence, the silicon wafer tended to bend and flex [5]. Also, the ceramic master roller could leave scratches on the wafer surface. For the combination shown in Fig. 15(b), the hydrostatic pad (as the support system) not only provided additional tuning parameters (adjustable fluid flow and feeding pressure) for process improvements but also increased the wheel life due to less dressing cycles through efficient rinsing [5,10].

4.3 Control system for grinding wheels

The control system for grinding wheels is to ensure the wafer to be simultaneously ground on both sides through the synchronization of the feeding for both wheels. If one of the wheels grinds the wafer unilaterally, the wafer will be at risk of being bent and broken. The conventional

measurement device such as dial gauge is impractical to be used in SDSG due to the difficulties in maintenance, adjustment, and measurement processes [69].

In one control system for SDSG, two pressure sensors were used to detect the start positions of the grinding wheels in reference to the wafer [66]. The start positions of the grinding wheels were detected and saved in the computer. Before the wafer was ground, the wheel that firstly reached its start position would pause temporarily and wait for the other wheel to reach its start position. After both wheels were ready, the grinding process would start.

In another control system, the synchronization problem was addressed using a different approach [69]. The grinding process was divided into three stages, namely idle feed stage, detection start stage, and grinding stage. A specific speed was assigned for each stage. In the idle feed stage, the wheels rapidly approached to the wafer. In the detection start stage, the grinding wheels moved at a slower speed. When the grinding wheel touched the wafer, the electric current of the motor to control the wheels would increase accordingly. At this moment, the grinding stage started. The start positions of both grinding wheels were detected and controlled by the electric current of the motor so that the synchronized movement of the wheels could be ensured [69].

5. Process modeling

Pietsch and Kersan [20] reported a theoretical investigation into SDSG of silicon wafers. Their research was based upon the analysis of the cutting path of an arbitrary grinding point (point P) on the wheel rim, as shown in Fig. 19. The relationship between the position of point P and time t was expressed as:

$$\frac{\bar{z}}{r_0} = e^{i\omega t} + e^{\pm i\Omega t} \quad (1)$$

where r_0 was the wheel radius, \bar{z} a complex number describing the position of point P in the complex coordinates, and ω and Ω the rotation speeds of the wheel and the wafer, respectively.

“+” means wheel and wafer rotated in the same direction while “-” means wheel and wafer rotated in the opposite directions.

5.1 Grinding marks

Defining grinding marks as the cutting paths (or trajectories) swept by a diamond abrasive bonded on the wheel, Pietsch and Kerstan presented a simulation graph (shown in Fig. 20) of the grinding marks for SDSG of silicon wafers without giving detailed equations. They reported that a “criss-cross” grinding marks were visible on the wafer surfaces processed by SDSG, different from the radial grinding marks on the wafer surfaces processed by SSG. However, they did not report any systematic study about the effects of SDSG process parameters on the grinding marks.

5.2 Wafer shape

The wafer shape is the cross section shape of the wafer surface along any wafer diameter. Based upon Equation (1), Pietsch and Kerstan used the principle below to calculate the stock material removal at any given point on the wafer surface:

$$removal = \frac{(path\ swept\ by\ wheel)(wheel\ rim\ width)}{wafer\ area\ swept\ by\ wheel} dt \quad (2)$$

From Equation (2), wafer shapes of both wafer sides after SDSG could be obtained. In their pilot experiments, the wafer shape was altered by tilting the grinding wheel spindles, as shown in Fig. 21. It was claimed that the model represented by Equation (2) was effective to predict the wafer shape in the radial direction, especially for the outer portion. But, there always existed singular solutions around the center of the wafer, as shown in Fig. 21. Note that the predicted wafer shape was obtained using the stock material removal but the experimental wafer shape was achieved by tilting the wheel spindles.

Pietsch and Kerstan's investigation resulted in several conclusions about the wafer shape:

- 1) There was always a dimple in the center of the wafer;
- 2) The edge of the wafer always tapered off ("roll-off") around the periphery;
- 3) When the two grinding wheels rotated in different directions, the surface on one side of the wafer was different from the other side. This was a limitation for SDSG if the identical wafer surfaces on both sides were required. But, the limitation could be reduced when the wheels rotated at a high speed making $\omega/\Omega \gg 1$.

6. Possible topics for future research on SDSG

The literature review has revealed at least two possible topics for future research on SDSG of silicon wafers: a systematic study on grinding marks and a more sophisticated model to predict the wafer shape.

In silicon wafer manufacturing, the removal amount of the subsequent polishing process has to be large enough to eliminate all grinding marks generated in the SDSG operation. Further reduction of polishing amount necessitates optimization of the grinding process so that the grinding marks can be eliminated with minimum amount of polishing. Such optimization would be very difficult if the following questions are not answered: How do grinding parameters affect grinding marks? What kinds of grinding marks are easier to eliminate in the subsequent polishing process?

In Pietsch and Kerstan's study on wafer shape, there is a singular portion around the center of the wafer. Also, the effects of the wheel tilt on the wafer shape were not included in their model. A more sophisticated model is necessary to predict the wafer shape, taking into consideration of the tilting of the grinding wheel spindles.

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