Materials Science in Semiconductor Processing 63 (2017) 97–106

Contents lists available at ScienceDirect

Materials Science in Semiconductor Processing

journal homepage: www.elsevier.com/locate/mssp

Surface integrity and removal mechanism of silicon wafers in chemo-mechanical grinding using a newly developed soft abrasive grinding wheel

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ARTICLE INFO

Keywords:
Silicon wafer
Chemo-mechanical grinding
Soft abrasive
Surface finish
Subsurface damage

ABSTRACT

A new soft abrasive grinding wheel (SAGW) used in chemo-mechanical grinding (CMG) was developed for machining silicon wafers. The wheel consisted of magnesia (MgO) soft abrasives, calcium carbonate ($CaCO_3$) additives and magnesium oxychloride bond. Surface topography, roughness and subsurface damage of the silicon wafers ground using the new SAGW were comprehensively investigated. The results showed that the grinding with the new SAGW produced a surface roughness of about 0.5 nm in R_a and a subsurface damage layer of about 10 nm in thickness, which is comparable to that produced by chemo-mechanical polishing. This study also revealed that the chemical reactions between MgO abrasive, $CaCO_3$ additives and silicon material did occur during grinding, thereby generating a soft reactant layer on the ground surface. The reactant layer was easily removed during the grinding process.

1. Introduction

During the fabrication of silicon wafers, diamond grinding is used for planarization and back thinning of the wafers [1,2]. Previous studies focused on the understanding of the fundamental removal mechanism of silicon wafers, as well as the development of the so-called “ductile” mode grinding processes [3–7]. However, diamond grinding unavoidably induced subsurface damage in the forms of crystallite defects and amorphous materials [5,8–11]. As a consequence, the subsurface damage layer must be removed in the subsequent finishing process, normally by the chemo-mechanical polishing (CMP) [12,13]. Although widely used for silicon wafer fabrication, CMP has apparent disadvantages, such as low efficiency, high cost and difficulties for process automation and wafer cleaning [14–16]. Those drawbacks become more apparent as wafer size increases. Therefore, a great research effort has been directed towards developing new machining processes, aiming at replacing CMP.

In recent years, a sustaining effort has been made towards developing a new surface finishing technique that utilizes the advantages of both conventional diamond wheel grinding and CMP [17–21]. For example, Zhou et al. [17,18] pioneered this study and proposed chemo-mechanical grinding (CMG) for low-damage machining of silicon wafers. In the CMG process, abrasives that are not only softer than silicon material but also chemically reactive with it were employed to fabricate a CMG wheel, which is often called soft abrasive grinding wheel (SAGW). The previous studies also indicated that the CMG process using special SAGWs could achieve super surface finishing comparable to that obtained from CMP by decreasing the wheel abrasive hardness and introducing chemical effects into the machining process [19–21]. Although CMG is considered as a promising technology for low-damage grinding of silicon wafers, but it is still at the initial stage and some issues need to be further investigated. A key issue that needs to be resolved in a timely fashion is how to enhance the chemical effect or promote the chemical reaction between CMG abrasives and silicon material. Also, it is believed that the combined effect of heat and pressure induced by the mechanical friction between a grinding wheel and a silicon wafer should promote the chemical reactions, so how to select the CMG parameters will influence ground surface quality and machining efficiency. In other words, the effect of SAGW composition and machining parameters on surface integrity and removal mechanism of CMG needs to be systematically investigated.

In this study, we presented a newly developed SAGW using magnesia (MgO) as the abrasives and magnesium oxychloride as the bonding agent. The surface integrity of silicon wafers ground by this new SAGW was systematically investigated in terms of surface roughness, surface topography and surface/subsurface damage characteris-

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http://dx.doi.org/10.1016/j.mssp.2017.02.001
Received 10 October 2016; Received in revised form 5 January 2017; Accepted 1 February 2017
1369-8001/

tics. The chemical reactions between abrasives, additives and silicon wafer involved in the CMG process were also studied and the corresponding material removal mechanism was discussed.

2. Fabrication of the SAGW

The SAGWs being used for grinding silicon wafers must meet the following requirements: (i) the wheel abrasives should be softer than silicon, (ii) the wheel abrasives can chemically react with silicon during grinding and (iii) the wheel additives can promote the chemical reactions between abrasives and silicon. Previous research of SAGWs primarily employed Ceria (CeO_2) as the wheel abrasives and phenol resin as the bonding material and demonstrated promising performance in silicon wafer grinding [17–21]. However, as the hardness of CeO_2 abrasive is close to silicon, the CMG with CeO_2 abrasives could generate deep scratches on the ground surface. Also, resin bond SAGWs have to be fabricated at high temperature and pressure [17,19,21], so the wheels often have low porosity and poor self-dressing ability [19,21].

In this study, the SAGW segments being developed consisted of magnesia (MgO) abrasives with #3000 mesh size, calcium carbonate ($CaCO_3$) additives and a room-temperature curing bond material named magnesium oxychloride. MgO abrasives and $CaCO_3$ additives were first dried in an oven at 40 °C, and then passed through a #500 mesh sieve to remove large grains. After that, MgO abrasives and $CaCO_3$ additives were blended with magnesium chloride ($MgCl_2$) solution at a specific molar ratio to form the magnesium oxychloride pastes (also called $MgO\text{-}MgCl_2\text{-}H_2O$ ternary system). The pastes with abrasives and additives were blended in a mixer until they were homogeneous and then were poured into precision molds to form the SAGW segments. The molds filled with pastes were then placed on a vibration table for approximately 5 min to eliminate air bubbles in SAGW segments. The pastes in wheel segment mold were cured at room temperature and pressure for 48 h before removing the molds. At room temperature and pressure, two bond phases of $3Mg(OH)_2{\cdot}MgCl_2{\cdot}8H_2O$ (also called phase 3 or P3) and $5Mg(OH)_2{\cdot}MgCl_2{\cdot}8H_2O$ (also called phase 5 or P5) were the main hydration products in magnesium oxychloride pastes by regulating the molar ratio of $MgO:MgCl_2:H_2O$ [22,23]. Compared with phase 3, phase 5 is more preferred as the bond of SAGW segments due to its better physical and mechanical properties [23]. Therefore, in order to improve the mechanical properties of SAGW segments, the molar ratio of $MgO:MgCl_2:H_2O$ of 8:1:13 was employed in this study, in which the molar ratio of 5:1:13 was used to form phase 5 as the bond of SAGW segments, and the rest of MgO and $CaCO_3$ were involved in the phase 5 as the abrasives and additives. The detailed compositions of magnesium oxychloride bond (MOB) MgO SAGW segments are listed in Table 1.

So the SAGW developed for this study has some new features. First, MgO abrasives was employed, which have lower hardness than silicon. Second, the room-temperature curing bond material of magnesium oxychloride was used, rather than the conventionally used resin bond, which should avoid the defects in SAGW. For comparison, a conventional resin bond (RB) CeO_2 SAGW was also fabricated in order to compare its grinding performance with our new MOB MgO SAGW. The conventional RB CeO_2 SAGW segments consisted of #3000 CeO_2 abrasives, Na_2CO_3 additives and phenolic resin bond [17–21]. The detailed compositions of RB CeO_2 SAGW segments are shown in Table 2. The fabrication process of resin bond (RB) CeO_2 SAGW was slightly different from that for the MgO SAGW. After mixing CeO_2 abrasives and Na_2CO_3 additives with phenolic resin bond powders, the mixture was poured into a wheel segment mold and solidified under relatively high temperature and pressure. The solidified temperature and pressure was about 250 °C and 9 MPa, respectively.

Table 1
Composition of the MOB MgO SAGW segments.

Composition	MgO	$MgCl_2$	$CaCO_3$	H_2O
Content (mol%)	23	4.5	13.5	59

Table 2
Compositions of the RB CeO_2 SAGW segments.

Composition	CeO_2	Phenolic resin	Na_2CO_3	Porosity
Content (vol%)	45	25	20	10

The arc-shaped abrasive segments for the SAGW were 36 mm long, 6.5 mm thick and 8 mm high. The abrasive segments were mounted on the rim of an aluminum alloy wheel body with a diameter of 350 mm. After bonding the abrasive segments, the SAGWs were balanced using a dynamic balancer. The SAGWs being fabricated and corresponding surface microstructure are shown in Fig. 1.

3. Experimental details

3.1. Grinding tests

All grinding tests were conducted on an ultra-grinding machine (VG401 MKII of Okamoto Inc., Japan) using workpiece rotational face-grinding mode, which has a high-precision vertical air spindle for the grinding wheel, as shown in Fig. 2. A silicon wafer was held on the rotary table via a vacuum chuck. During machining, both the silicon wafer and the grinding wheel rotated around their own axes of rotation, and the grinding wheel was fed downwards the wafer along its own rotational axis. By adjusting the angle between the rotational axes of workpiece and wheel, the grinding wheel would just contact with half of the wafer, so the wafer shape and total thickness variation could be precisely controlled. A real-time thickness measurement unit with an accuracy of 1 µm was incorporated into the machining system to monitor workpiece thickness.

As-received polished (100) monocrystalline silicon wafers of 6 in. in diameter (Zhonghuan Semiconductor Inc., China) were used. The wafers were pre-ground by the resin bond diamond grinding wheel with a grit size of mesh #3000 (DK301 of Asahi Inc., Japan) prior to CMG. The grinding parameters of diamond grinding and CMG were optimized through the preliminary grinding experiments to achieve the best possible surface integrity. Because surface roughness was the most direct parameter to reflect surface and subsurface quality (In general, the surface roughness Ra of the machined workpiece surface is low, the corresponding subsurface damage is also smaller), it was chosen as the index to optimize the grinding parameters of diamond wheel and CMG in this study. For comparison purposes, the surface layer characteristics of as-received monocrystalline silicon wafers machined by the CMP were also examined. After being mounted onto the grinder, the diamond wheel and the SAGWs were trued by employing an electroplated diamond truing plate with a grit size of mesh #320. The truing plate was hold on the rotary workpiece table using the vacuum chuck, and the truing process had the same conditions to those of the grinding process. The conditions for truing, diamond grinding and CMG are listed in Table 3.

3.2. Characterization techniques

After grinding, the wafer surfaces were examined by use of a scanning electron microscopy (SEM, Quanta 200 FEG of FEI Inc., Netherlands). The surface roughness Ra (also called arithmetic average roughness) and microtopography of the machined wafers were measured using an atomic force microscopy (AFM, XE-300 of Park Systems Inc., USA) and the scanning areas for roughness measurement were $5{\times}5\ \mu m^2$. For each machined wafer surface, six surface roughness Ra measurements were conducted at different locations and the average