Precision Engineering 33 (2009) 499–504

Contents lists available at ScienceDirect

Precision Engineering

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

Research on chemo-mechanical grinding of large size quartz glass substrate

Libo Zhou [a,*], Takeshi Shiina [b], Zhongjun Qiu [b], Jun Shimizu [a], Takeyuki Yamamoto [a], Toshiaki Tashiro [c]

[a] *Department of Intelligent System Engineering, Ibaraki University, Nakanarusawa 4-12-1, Hitachi-shi, 316-8511, Japan*
[b] *Graduate School of Science and Technology, Ibaraki University, Nakanarusawa 4-12-1, Hitachi-shi, 316-8511, Japan*
[c] *Tokyo Diamond Tool Manufacturing, Murata-machi, Shibata-gun, Miyagi-ken, 989-4774, Japan*

ARTICLE INFO

Article history:
Received 17 July 2008
Received in revised form 9 December 2008
Accepted 31 January 2009
Available online 26 March 2009

Keywords:
Quartz glass
CMG
Fixed abrasive process
Material removal rate
Flatness
Roughness
Transmittance
Reflectance

ABSTRACT

Finishing process of quartz glass substrate is meeting great challenges to fulfill the requirements of photomask for photolithography applications. For the final finishing of the substrate surface, chemical mechanical polishing (CMP) is often utilized. Those free abrasive processes are able to offer a great surface roughness, but sacrifice profile accuracy. On the other hand, the fixed abrasive process or grinding is known as a promising solution to improve accuracy of profile geometry, but always introduces damaged layer. Chemo-mechanical grinding (CMG) is potentially emerging defect-free machining process which combines the advantages of fixed abrasive machining and CMP. In order to simultaneously achieve high surface quality and high profile accuracy, CMG process has been applied into machining of large size quartz glass substrates for photomask use. Reported in this paper are CMG performances in finishing of quartz glass substrates including material removal rate (MRR), surface roughness, flatness and optical characteristics.

1. Introduction

Present 90 nm design rule and the future trend in semiconductor manufacturing pose increasing demands of optical quality and geometrical accuracy on quartz glass substrate for photomask use. In order to improve the resolution in photolithography, Laser sources with ever-shorter wavelength including KrF ($\lambda = 248$ nm) and ArF ($\lambda = 193$ nm) are employed [1]. The optical characteristics of photomask, especially at the short wavelength region, become more important. Those requirements are the great challenges encountered in the manufacturing process of quartz glass substrate.

Currently, CMP with ceria (CeO_2) slurry is widely used for the final finishing of optical glass [2,3]. CMP is a process that has been used in machining optics for centuries, because it is able to offer a great surface quality [4] and relatively high MRR [5]. However, the nature of free-abrasive process established on the pressure-controlled infeed scheme makes it difficult to maintain the geometrical accuracy and unable to meet the requirements of flatness for photomask use as the substrate size increases [6].

On the contrary, fixed-abrasive process following position-controlled dynamics is known as promising solution to maintain or improve the geometrical accuracy [7]. The critical problem of this process is the subsurface damage or damaged layer which is developed by high stress during the process and remains on the surface of substrate after the process [8,9]. Recently, authors have developed a novel chemo-mechanical grinding (CMG) process by effective use of chemical reaction in the grinding process [10,11]. CMG is potentially emerging defect-free machining process which combines the advantages of fixed-abrasive process and CMP. So far, CMG has been successfully applied into machining of single crystal silicon wafer [11–13].

This research aims at applying CMG to machining of large-size quartz glass substrates and optimizing the machining conditions that simultaneously achieve surface quality and geometrical accuracy. Reported in this paper are CMG performances of machining process including MRR, surface roughness, flatness and optical characteristics in transmittance.

2. Basic concept of material removal at CMG

The removal of brittle materials like single crystal Si and non-crystal glass takes place at three different modes; elastic mode, ductile mode and brittle mode [14]. At each correspondent mode, elastic deformation, plastic flow or fracture initiation are developed. Most brittle materials are subject to plastic flow when the strain is restrained within 0.02–0.03% [15]. At the range of the corresponding depth of cut, the material is removed at ductile mode so that there is no crack remaining on the surface after machining.

* Corresponding author. Tel.: +81 294 38 5217; fax: +81 294 38 5217.
E-mail address: lbzhou@mx.ibaraki.ac.jp (L. Zhou).

0141-6359/$ – see front matter © 2009 Elsevier Inc. All rights reserved.
doi:10.1016/j.precisioneng.2009.01.006

However, plastic strains remain in the subsurface, which lead to crystal defects like dislocations and form so-called "damaged layer". In order to further reduce the subsurface damage, smaller processing unit, at which the interactive force is small enough to make the material be removed near its elastic regime, is preferable. Polishing based on pressure-controlled infeed scheme is a typical process possible to produce a surface almost free of plastic strain, but difficult to achieve or maintain good geometry accuracy.

In order to remove the material from its outmost surface, an extra surface barrier potential energy in addition to its lattice energy is necessary to break the chemical bond between atoms [16]. The surface barrier potential energy is very much dependent on the temperature, the degree of chemical equilibrium and the magnitude of reaction rate. Although theory of reaction rate process and statistical thermodynamics are needed to quantify the free (thermal) energy of each atom, it is possible to qualitatively lower the barrier energy by introducing a proper chemical reaction [16]. Reduction in energy necessary for bond breaking results in a fractional interactive force between the workpiece and the tool. Those atoms on the topmost surface are expectedly removed from the bulk material only by a fractional interactive force in the elastic mode, at which the arrangement of rest atoms in the neighborhood remains unchanged.

At CMG process, the expected chemical reactions are the interactions of the workpiece against the abrasives, the additives contained in bonding material and the coolant. CMG wheels containing colloidal silica (SiO_2), ceria (CeO_2) and barium sulfate ($BaSO_4$) as abrasives were purposely developed for Si wafer machining [10,11]. It has been reported in CMP process that such abrasives possess a chemical capability that expedites both bond sharing at the Si surface and transportation of reaction products away from the surface [17]. Unlike the conventional CMP which must involve water or hydroxyl group, solid state reactions between silicon and ceria were discovered at the dry CMG process. This solid reaction dissociated Si atoms from its bulk material under certain pressure and temperature. The evaluation of Si surface and subsurface suggested that no defects like plastic flows and dislocations were developed during CMG and ground Si surface remains as a single crystal structure after CMG [12,13].

Recent findings from the quantum chemical molecular dynamics (QCMD) simulation [18] help to understand the mechanism of the chemical aspect involved at the CeO_2–SiO_2 interface. The findings indicated that electrons transfer from p-orbital of some O atoms to the f-orbital of Ce atoms. Of particular interest was the electronic state change from Ce^{4+} to Ce^{3+}. Cerium takes a typical rare earth atomic configuration $[Xe]4f^1 5d^1 6s^2$. Therefore, its ion falls in either the lanthanide ion Ce(III)/Ce^{3+} or the ceric ion Ce(IV)/Ce^{4+}, which forms two oxidations of CeO_2 or Ce_2O_3, dominated by the chemical equilibrium in CMG process. Further detailed analysis of grinding waste elucidated that the grinding products were a kind of amorphous of Ce–O–Si, which was weak enough to be mechanically removed by soft abrasives like CeO_2 [12]. As the result, Si atoms are dissociated from the substrate surface as the reactions proceed, and a fresh and undisturbed Si crystal is always presented at the topmost surface.

3. Experimental methodology

As the quartz glass is mainly made of SiO_2, CMG is expected to be an effective process to simultaneously achieve surface quality and geometrical accuracy of quartz glass substrate. Shown in Fig. 1 was the grinding machine (NAGASE INTEGREX Co., Ltd. KTC-1) used in this study. The grinding machine incorporates two hydrostatic spindles. The work spindle moves along *Z*-direction, while the wheel table oscillates along *X*-direction about 10 mm. The rest specifications of the machine tool were listed in Table 1. Two kinds of CMG wheels with different bond material and different geometry were purposely developed for quartz glass finishing. Their external views were shown in Fig. 2 and specifications were listed in Table 2. The wheel type (a) was bonded by epoxy resin and shaped in a ring, while the wheel type (b) was bonded by phenol resin and radically shaped.

Fig. 1. Grinding machine.

Table 1
Specifications of grinding machine.

Key components	Specification	Workable range
Wheel spindle	Hydrostatic	20–1000 rpm
Work spindle	Hydrostatic	20–1000 rpm
Z-axis guide	LM linear guide	10 μm/100 mm
X-axis guide	LM linear guide	10 mm (Osci.)

The quartz glass substrates were prepared in the forms either with orientation flat or without orientation flat. The common dimension was 150 mm (6 in.) in diameter and 1.1 mm thick. Their external views were shown in Fig. 3 and their properties were listed in Table 3. Prior to CMG test, the substrates were pre-ground by SD1000, and their surface roughness Ra was initialized to around 40–50 nm. After CMG, the surface roughness, MRR and optical characteristics were evaluated.

4. Improvement in productivity

At the beginning of experiment, two different CMG wheels were first tested at a standard grinding condition to evaluate their MRR for quartz glass. From the results shown in Fig. 4, it was found that the MRR of both wheels was as low as several nanometers to dozens nanometers per minute although the wheel type (b) gave three folds

Table 2
Specifications of CMG wheels.

Wheel	Type (a)	Type (b)
Geometry	Ring	Redial
Abrasive	CeO_2	CeO_2
Bonding agent	Epoxy	Phenol
Additive	None	Na_2CO_3
Content of CeO_2	56 vol%	40 vol%
Content of bonding agent	11 vol%	45 vol%
Content of additive	–	15 vol%
Content of porous	33 vol%	–