Applied Surface Science 389 (2016) 713–720

Contents lists available at ScienceDirect

Applied Surface Science

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

Perspective Article

Study on planarization machining of sapphire wafer with soft-hard mixed abrasive through mechanical chemical polishing

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ARTICLE INFO

Article history:
Received 27 April 2016
Received in revised form 26 July 2016
Accepted 27 July 2016
Available online 30 July 2016

Keywords:
Sapphire
Mixed abrasive
Solid state reaction
Removal mechanism

ABSTRACT

This study investigated the material removal mechanism of sapphire wafer with soft-hard mixed abrasives through mechanical chemical polishing (MCP). The polishing film, which contains diamond as hard abrasives and high reactivity silica as soft abrasives, is prepared through sol-gel technology. Silica abrasives with regular spherical shape and high reactivity are prepared through hydrolysis-precipitation. Diamond grits with three different particle sizes are used as abrasives. Results show that the rate of material removal of mixed abrasives during MCP is more than 52.6% of that of single hard abrasives and the decrease in surface roughness is more than 21.6% of that of single hard abrasives. These results demonstrate that the ideal planarization of sapphire wafer with high removal rate and good surface quality can be achieved when the effect of mechanical removal of hard abrasives and the chemical corrosion effect of soft abrasives are in dynamic equilibrium. A model that describes the material removal mechanism of sapphire with mixed abrasives during MCP is proposed. The results of thermodynamic calculation and polishing residue analysis are used to demonstrate the rationality of the model.

1. Introduction

Sapphire has excellent mechanical and optical properties and is widely used in a range of applications, such as optics, electronics, and temperature sensing. Sapphire is the most common substrate used in light emitting diodes (LEDs) [1–5]. The quality of wafer surface plays a critical role in these applications, as well as in subsurface damage [6–9]. The high-quality method for processing single crystal sapphire wafers has attracted considerable attention. Despite its popularity, sapphire is difficult to polish because of its intrinsic nature (high hardness and chemical inertness) [10,11]. Traditional mechanical finishing techniques, such as mechanical polishing, and chemically assisted polishing techniques, such as chemical mechanical polishing (CMP), are widely used in the industry to remove material and form wafer. Mechanical finishing techniques will cause considerable surface and subsurface damage because of hardness of diamond abrasives. Sapphires with high hardness and great thermal stability become chemically inert and insoluble in most substances during CMP. This finding suggests the difficulty in polishing sapphire substrates using traditional CMP technology at room temperature to achieve high material remove rate (MRR) and a perfect polished surface. Moreover, a significant amount of liquid waste, which is extremely difficult to degrade, will be produced during CMP.

Many studies have investigated the solid state reaction between active abrasives and sapphire during mechanical chemical polishing (MCP). This process is an efficient and environmentally friendly approach to acquire high-quality surfaces by removing the reaction layer on the surface of sapphire [12–18]. Several active abrasives, such as magnesium oxide, silicon dioxide, and ferric oxide, were discussed in existing studies. Our previous study showed that silica has the highest reactivity with sapphire among active abrasives [19].

Active abrasive facilitates chemical reaction and mechanical removal during traditional MCP. This mechanism decreases the rate of material removal rate and allows reactants to exist on the wafer surface because of poor removal property of active abrasives. The effects of mixing different abrasive grits for the rate of material removal and surface roughness were studied in previous research [20,21]. Jindal et al. improved the CMP performance of metal and dielectric films using mixed abrasive slurries that contain different compositions of alumina/silica particles [22]. Bhagavat used mixed abrasive grits prepared by mixing black silicon carbide abrasive grits of two different sizes in slurries on free abrasive machining

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http://dx.doi.org/10.1016/j.apsusc.2016.07.155
0169-4332/

Table 1
Experimental design scheme.

Experiment	Abrasive type	Experiment	Abrasive type
A	Silica		
B	Diamond (W0.2)	C	Diamond (W0.2) + Silica
D	Diamond (W1)	E	Diamond (W1) + Silica
F	Diamond (W3)	G	Diamond (W3) + Silica

processes. This study showed that the mixture of abrasive grits can increase the amount of removed material [23].

Given the strong chemical reaction and weak mechanical removal of nano-active abrasive, diamond was chosen as hard abrasive in the present study to determine the effect of mechanical removal. Nano-silica was chosen as the soft abrasive to determine the chemical corrosion effect and create a polishing pad through sol-gel technique. The material removal mechanism of MCP using mixed abrasives was studied through transmission electron microscopy (TEM). This process was employed to characterize the chemical products formed on the sapphire surface during MCP. The present study discussed the effect of abrasive particle size on the dynamic equilibrium between mechanical and chemical function to achieve efficient planarization.

2. Experimental section

2.1. Synthesis of nano-silica abrasives with high activity

To improve the activity of abrasive silica, silica micro-sphere abrasives were prepared through hydrolysis–precipitation. A certain amount of sodium silicate ($Na_2SiO_3{\cdot}9H_2O$) was dissolved in ethanol aqueous (1:8 volume mixture of alcohol and deionized water). The sodium silicate solution slowly dripped into the ammonium chloride solution until the pH value of the solution was 8.5. The solution was heated at 40 °C and stirred by a thermostatic mixer for 1 h to obtain white precipitate. The white precipitate was further processed by centrifugal cleaning and thermal treatment. The X-ray diffraction (XRD) profile of synthetic silica was obtained via an X-ray diffractometer (X'Pert PRO, PANalytical B.V.) using Cu Kα radiation (λ = 1.54055 Å) with an accelerating voltage of 40 kV and a current of 40 mA. Fourier transform infrared spectra (FTIR) measurements of synthetic silica were conducted using a FT-IR spectrometer (Thermo Scientific Nicolet iS10, Thermo Fisher Scientific). The morphology of the nanostructures was observed by TEM (Tecnai F30, Philips-FEI) with an accelerating voltage of 300 kV. The commercial silica abrasives were purchased from Xuan Cheng Jing Rui New Material Co., Ltd. (Hangzhou, China). The abrasives had an amorphous structure with an average particle size of 50 nm.

2.2. Polishing setup and process control

The ultra-fine abrasive polishing films reported in our previous work were prepared through sol-gel technique. The process satisfies the processing demands because of yielding effects during polishing [24–26]. Single and mixed abrasives were used to make polishing films. Table 1 lists the experimental design scheme. Mixed abrasives were prepared by mixing nano-silica and diamond abrasives with three different particle sizes (W0.2, W1, and W3). The proportion of soft and hard abrasives in the mixture was 1:4 (weight ratio). Diamond abrasives with similar shape and uniform particle size distribution were produced by Element Six Company. The epi-ready sapphire wafers were purchased commercially. Sapphire wafer-oriented (0 0 0 1) plane with two-inch diameter after grinding was used. The original surface roughness (Ra) of the wafer was about 10 nm. A Nanopoli-100 ultra-precision polishing machine with conditioning ring was used in the sapphire-polishing experiments. The pressure between the sample clamp and the polishing pad was 3 kg. The speed of pad rotation was 120 rpm and treatment time was 2 h. Deionized water was applied as coolant. After processing, the wafers were cleaned immediately with ethanol and deionized water under sonication.

The polishing residue that emerged in the coolant during processing was analyzed by TEM, selected area electron diffraction (SAED), and energy dispersive spectrometry (EDS). The Raman spectra of the processed wafer surface was obtained by a confocal microscope Raman spectrometer with a coherent INNOVA 400 copper ion laser operated at a 532.1 nm line for excitation. Surface roughness (Ra) that observed by a 3D optical interferometry profiler (New View 7300, Zygo) was the average value of the 10 areas that evenly dispersed on the wafer surface. The weight of the wafers before and after polishing was measured by a precision electronic balance with 0.1 mg precision (BSA224S, Sartorius) to calculate the MRR according to the following formula [27,28]:

$$MRR = \frac{10^7 \times \Delta m}{\rho \times 2.54^2 \times \pi \times t} \quad (1)$$

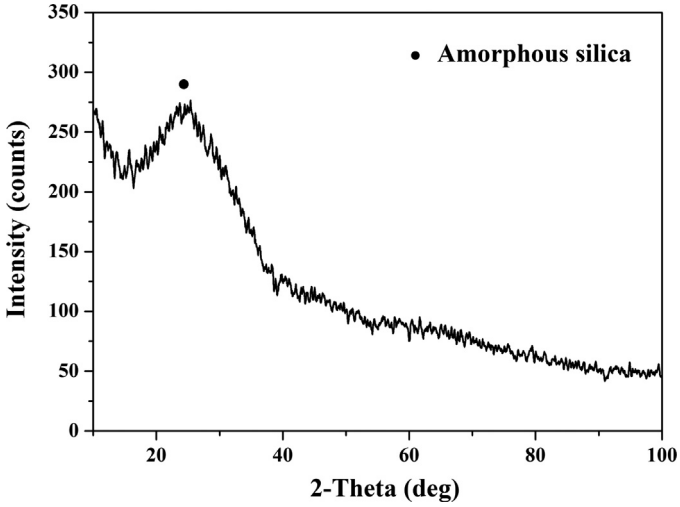

Fig. 1. XRD pattern of synthetic silica microspheres.

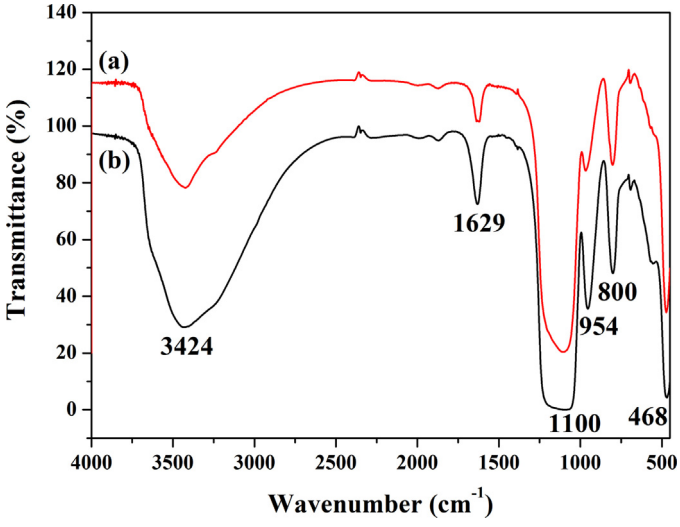

Fig. 2. FTIR spectra of the commercial and synthetic silica: (a) commercial silica, (b) synthetic silica.