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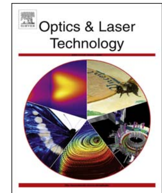

Full length article

Development of a novel non-contact inspection technique to detect micro cracks under the surface of a glass substrate by thermal stress-induced light scattering method

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ABSTRACT

Fine polishing techniques, such as a chemical mechanical polishing treatment, are important techniques in glass substrate manufacturing. However, these techniques may cause micro cracks under the surface of glass substrates because they used mechanical friction. A stress-induced light scattering method (SILSM), which was combined with light scattering method and mechanical stress effects, was proposed for inspecting surfaces to detect polishing-induced micro cracks. However, in the conventional SILSM, samples need to be loaded with physical contact, and the loading point is invisible in transparent materials. Here, we introduced a novel non-contact SILSM using a heating device. A glass substrate was heated first, and then the light scattering intensity of micro cracks was detected by a cooled charge-couple device camera during the natural cooling process. Results clearly showed during the decreasing surface temperature of a glass substrate, appropriate thermal stress is generated for detecting micro cracks by using the SILSM and light scattering intensity from micro cracks changes. We confirmed that non-contact thermal SILSM (T-SILSM) can detect micro cracks under the surface of transparent materials.

1. Introduction

Fine polishing techniques, such as a chemical mechanical polishing treatment (CMP), are some of the most important base manufacturing procedures used for glass substrate and dielectric interlayer (e.g., SiO_2) polishing in semiconductor manufacturing [1,2]. However, these techniques use mechanical friction, which can cause micro-scale cracks (micro cracks) under the surface of the polished product [1–3]. If micro cracks are not detected in the glass substrate after a fine-polishing process, they may remain undetected until the washing process of a high-value-added product, when the micro cracks have become large visible dimples due to the erosional effect of the cleaning process. As this point, these micro cracks can result in a large economic loss in the manufacturing of these products.

Recently, many nondestructive inspection systems that use light scattering from foreign matter particles for their detection have been made commercially available for use in product manufacturing [4]. However, these systems detect all light scattering as foreign matter particles on the surface. In addition, if micro cracks are hidden under the polished surface, they cannot detect those hidden cracks using only light scattering.

We proposed a stress-induced light scattering method (SILSM) [5,6] and not only successfully visualized micro cracks via the light scattering effect but also distinguished the micro crack from other light scatterers such as metal lines and tiny particles. This was accomplished for both a CMP-ed silicon wafer [5] and a polished glass substrate [6]. However, for the intense needs from manufacturing industry, it is emphasized that products are inspected without contact. In the case of transparent materials, such as glass substrates, conventional SILSM cannot measure around the contacted point and may cause new micro cracks at that point. Therefore, micro cracks need to be detected without contact.

This paper proposes a novel non-contact inspection technique for fine-polishing-induced micro cracks, using a light scattering method in concert with an applied thermal stress (T-SILSM) to detect micro cracks. A change in the temperature is applied to polished samples so that stress is induced around the tips of micro cracks, and the photo-elastic effect causes a change in the refractive index around the micro crack tip. In turn, the changed refractive index is detected as a change in the light scattering intensity by a photo detector.

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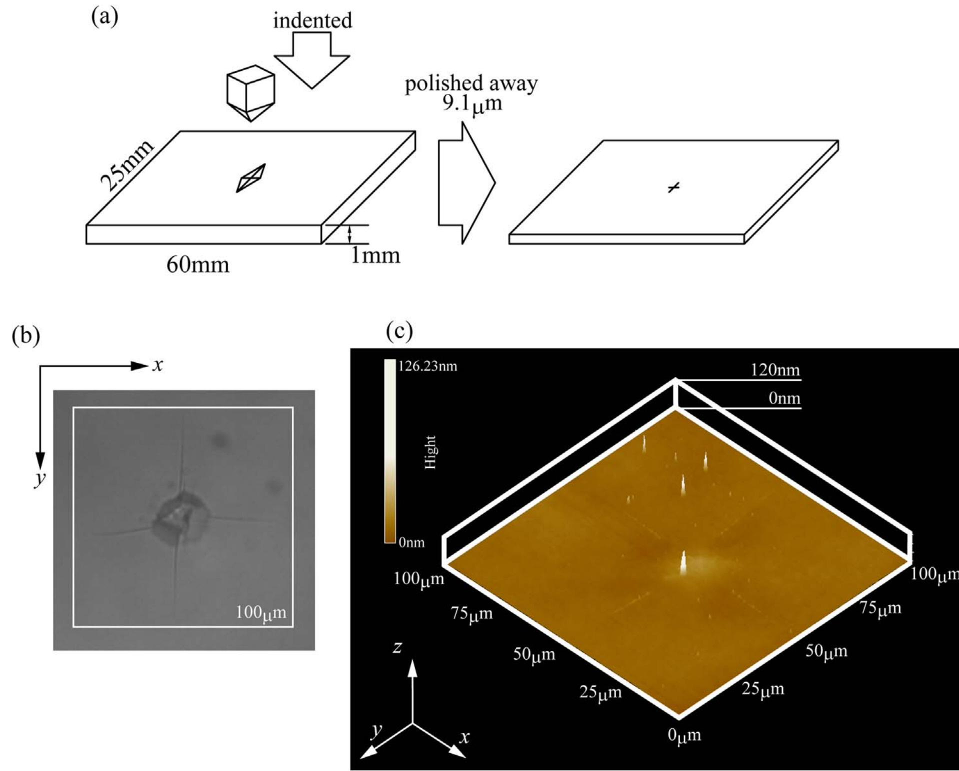

Fig. 1. Schematic images and microscopic images of a sample that has micro cracks: (a) Sample geometry and by a Vickers hardness tester. The sample surface was finely polished, removing 9.1 μm from the surface. (b) Optical microscopic image of the sample. Generated micro cracks can be observed (size approximately 60 μm). (c) Atomic force microscopic image of the sample (at square lines in Fig. 1(b)). These micro cracks were confirmed generated under the sample surface.

2. Thermal stress-induced light scattering method

The T-SILSM can detect micro cracks under a fine-polished surface. It is a technique to expose micro cracks by exploiting the stress resulting from the change in light scatterings from micro crack tips due to temperature variations. Additionally, optical properties change due to temperature variations. Here, we assumed two points that I: optical properties, including the refractive index, changed uniformly, and II: light scattering variations are caused by stress effect and that a linear stress-strain relation can be defined around the micro crack tips. Thus, Eq. (1) shows the change in the refractive index when a thermal stress $\sigma_{\mathrm{thermal}}$ is produced by temperature variation ΔT:

$$\Delta n = A\sigma_{\mathrm{thermal}} = A(\alpha E\Delta T), \tag{1}$$

where A, α and E are the material constant of the photo-elastic coefficient, the linear expansion coefficient, and the Young's modulus of the sample, respectively. Because the refractive index around micro crack tips varies with stress, a pseudo-scatterer appears or disappears at the micro crack tips. We developed our model for the temperature-induced scattering based on the Rayleigh scattering equation. Additionally, it was assumed that the scattering angle with respect to the incident beam direction and the change in the scatterer volume remained constant between before and after applying temperature changes. Thus, above points were assembled and defined as κ and the light scattering intensity I_{out} is described Eq. (2) as,

$$I_{\mathrm{out}} = \kappa\left\{\frac{n^2 - {n_0}^2}{n^2 + 2{n_0}^2}\right\}^2 I_{\mathrm{incident}}, \tag{2}$$

where, I_{incident}, n, and n_0 are the incident beam intensity, the refractive index of the scatterer and the refractive index around the scatterer, respectively. When temperature variation is applied to the sample, it is considered that the sample was heated uniformly and the heated sample surface was also expanded uniformly. Thus, the refractive index around the tips of micro crack is $n+\Delta n$. Therefore, the change in the light scattering intensity $|\Delta I_{\mathrm{out}}|$ between before and after applying the thermal stress is described as Eq.(3):

$$|\Delta I_{\mathrm{out}}| = |I_{\mathrm{after}} - I_{\mathrm{before}}| = \left|\kappa\left\{\frac{(n_0 + A(\sigma_{\mathrm{r}} + \alpha E\Delta T))^2 - {n_0}^2}{(n_0 + A(\sigma_{\mathrm{r}} + \alpha E\Delta T))^2 + 2{n_0}^2}\right\}^2 - \kappa\left\{\frac{(n_0 + A\sigma_{\mathrm{r}})^2 - {n_0}^2}{(n_0 + A\sigma_{\mathrm{r}})^2 + 2{n_0}^2}\right\}^2\right| I_{\mathrm{incident}}, \tag{3}$$

where, σ_{r} is the residual stress around the micro crack tips. If the change in the refractive index due to residual stress and applied stress is approximated assuming that it is less than n_0 and when the 4th power term are ignored from expansion of Eq. (3), then the following equation is obtained as Eq.(4):

$$|\Delta I_{\mathrm{out}}| = |I_{\mathrm{after}} - I_{\mathrm{before}}| \approx \left|\frac{4A^3(\sigma_r + \alpha E\Delta T)^3 n_0 + 4A^2(\sigma_r + \alpha E\Delta T)^2 {n_0}^2}{9{n_0}^4} - \frac{4A^3{\sigma_r}^3 n_0 + 4A^2{\sigma_r}^2 n_0}{9{n_0}^4}\right| \kappa I_{\mathrm{incident}} = \frac{4A^3\alpha^3E^3}{9{n_0}^3}\left|\Delta T^3 + \frac{3A\sigma_{\mathrm{r}} + n_0}{A\alpha E}\Delta T^2 + \frac{3A{\sigma_{\mathrm{r}}}^2 + 2n_0\sigma_{\mathrm{r}}}{A\alpha^2E^2}\Delta T\right|\kappa I_{\mathrm{incident}}. \tag{4}$$

The light scattering intensity variation $|\Delta I_{\mathrm{out}}|$ has a relationship with temperature variation ΔT. We carried out the T-SILSM experiment to evaluate as a useful way to detect micro cracks by an optical, non-invasive technique.

3. Experimental procedure

3.1. Sample

A glass substrate sample, 60×25×1 mm, was intentionally indented by a Vickers hardness tester. Fig. 1(a) shows schematic images of the glass sample geometry. The indenter contacted the sample surface at only one point, generating a fracture layer and underlying micro cracks.

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