Repairing nanoscale scratched grooves on polycrystalline ceramics using optical near-field assisted sputtering

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Abstract We propose an optical near-field assisted sputtering method for repairing scratches on the surface of polycrystalline ceramics in a self-assembling manner. An Al_2O_3 source was sputtered on substrates with laser radiation of wavelength 473 nm. The average depth of the scratched grooves on polycrystalline Al_2O_3 ceramic substrate decreased from 3.2 nm to 0.79 nm. Using a Hough transform, we also confirmed the selective repair of scratches.

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1 Introduction

Recently, optical transmission loss in polycrystalline ceramics has been dramatically decreased to levels as low as those in single crystals. As a result, these transparent ceramics are attracting interest for applications in optical technology [1–4] for use as gain media for solid state lasers or optical windows [5–7]. To realize larger lasing efficiency or to reduce

the scattering loss in optical windows, further decreases in the surface roughness are required. To meet this requirement, chemical–mechanical polishing (CMP) has been employed on single crystalline and amorphous optical materials [8]. However, this method is difficult to apply to polycrystalline ceramics because of their anisotropic interaction with the polishing medium. A key problem with CMP is that it may cause scratches because of collisions with the abrasive grains in the slurry. Furthermore, the CMP may cause bumps on the surface, due to the difference in etching rates between adjacent grains in the polycrystal.

To solve these problems, we propose a novel method that makes use of the optical near field. Its outstanding advantage is not only its high spatial resolution, which is beyond the diffraction limit, but also its self-assembling reaction capability. Because localized optical near fields are generated preferably on a surface with nanoscale curvature, they can be induced on fine scratches, contributing to repair them. In addition, the repairing process stops automatically after the scratches disappear. Such selective self-assembling optical near-field interactions previously have been used for depositing nanoparticles, sputtering, and photochemical etching [9–11]. Here, we employ this novel technique to repair the scratches on polycrystalline Al_2O_3 ceramics.

2 Experimental technique

Figure 1 shows a schematic of our method. As a result of preliminary polish of the Al_2O_3 ceramic, its surface contains nanoscale scratched grooves. Because the edges of the grooves have larger surface areas than the flat surface, the sputtered Al_2O_3 particles have a higher deposition rate at the edge after migration on the surface [12, 13]. As shown in Fig. 1(a), it therefore is expected that Al_2O_3 will be

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deposited preferentially at the edges of scratched grooves, which will not help to repair the scratches. To avoid extra deposition on the edge of the grooves and to repair the scratches, we used optical near-field desorption [10]. Because the optical near field (i.e., the dressed photon) can ex-

cite coherent phonons in the nanoscale structure, a virtual exciton–phonon–polariton (EPP) is generated on the substrate. A multistep transition via the EPP can accelerate the photochemical reaction although the photon energy is lower than the absorption band edge energy of the material [14]. When the ceramic is irradiated, a highly localized optical near field is generated at the edges of scratches, causing the photodesorption of depositing Al_2O_3 nanoparticles. As shown in Fig. 1(b), if the light has a lower energy than the absorption band edge of the nanoparticles, effective deposition will decrease at the edge, and Al_2O_3 will accumulate on the bottom of the groove [10]. This process automatically stops after the scratches disappear, so that the optical near field can no longer be generated.

Fig. 1 Schematics of deposition on the scratched substrate surface (a) without and (b) with irradiation during the sputtering. D is the depth and W is the width of the scratched groove

Fig. 2 Schematic of the experimental setup

Fig. 3 AFM images of substrates (a) before sputtering (substrate A), (b) after sputtering without irradiation (substrate B), and (c) after sputtering with irradiation (substrate C). (d), (e), and (f) Cross-sectional profiles along the white dashed lines in (a), (b), and (c), respectively

We performed optical near-field assisted sputtering to repair the scratches on the surface of the translucent Al_2O_3 ceramic SAPPHAL®.¹ Figure 2 shows a schematic of the experimental setup. Planar surfaces of SAPPHAL® substrate were prepared by polishing using diamond abrasive grains with a diameter of 0.5 μm . The Al_2O_3 was deposited using radio-frequency (RF) magnetron sputtering (RF power: 300 W; frequency: 13 MHz). The total gas pressure was 7×10^{-1} Pa, with a gas flow of 16 sccm Ar and 1.2 sccm O_2 [15]. We also used SAPPHAL® as the target material for sputtering. The CW second harmonic of a Nd:YAG laser with a wavelength of $\lambda = 473$ nm was used as the light source for optical near-field generation. During the sputtering process, the surface was irradiated with light with an optical power density of 2.7 W cm^{-2} . As stated previously, the photon energy of this laser was lower than the absorption band edge energy of Al_2O_3 ($\lambda = 250$ nm) [16]. The light was introduced to the ceramic surface through a multimode optical fiber. After 30 min of sputtering, the thickness of the deposited Al_2O_3 layer was about 100 nm. We observed the surface of the substrates using an atomic force microscope (AFM).

3 Results and discussion

Figures 3(a), (b), and (c) show typical AFM images of SAPPHAL® surfaces before sputtering, after sputtering without irradiation, and after sputtering with irradiation, respectively. Figures 3(d), (e), and (f) show the cross-sectional profiles of typical scratches along the white dashed lines in Figs. 3(a), (b), and (c), respectively. The depth of the scratched grooves in Fig. 3(e) is 4.4 nm, which is deeper than that in Fig. 3(d) (4.0 nm). This was caused by the extra deposition at the edges of the scratch due to the low surface potential, as described in Fig. 1(a). In contrast, Fig. 3(f) shows that the depth decreased to 1.8 nm without extra deposition at the edges of scratches after sputtering with irradiation. For more quantitative evaluation, we calculated the surface roughness R_a . The R_a values over the AFM images of Figs. 3(a)–(c) were $R_{aA} = 1.3$ nm, $R_{aB} = 1.1$ nm, and $R_{aC} = 0.49$ nm, respectively. These results indicated that the repair of scratched grooves by optical near-field desorption at the edge of the scratches resulted in a drastic decrease in the surface roughness.

To selectively evaluate the profiles of the scratched grooves, we used the Hough transform [17]. After the AFM image of Fig. 4(a) was leveled by a least squares-method and binarized, the linear features of scratches were automatically extracted using a Hough transform; see Fig. 4(b).

Fig. 4 (a) An AFM image is leveled by a least-squares method. (b) Schematic of the Hough transform. *Straight lines* of the scratches are detected using the Hough transform of (a). (c) Histograms of depths, D_n . (d) Widths (W_n) of scratches on alumina ceramics substrates; A (before sputtering), B (after sputtering without irradiation), and C (after sputtering with irradiation)

Through this method we obtained the depth D and width W of the detected scratches. Figures 4(c) and (d) show statistical analyses of D and W obtained from the images in Figs. 3(a), (b), and (c), respectively. As shown in Fig. 4(c), the average values of D were $\overline{D}_A = 3.2$ nm, $\overline{D}_B = 3.8$ nm, and $\overline{D}_C = 0.79$ nm, respectively, which confirmed that the depth of the scratches was drastically decreased using near-field assisted sputtering. Figure 4(d) shows that the width of the scratches after the sputtering without irradiation (W_B) was increased beyond the original value W_A , which also supports our deposition model; see Fig. 1(a). In addition, the width W_C also increased in comparison to W_A , supporting the model of Fig. 1(b). Further decreases in the width could be achieved by optimizing laser and sputtering conditions.

4 Conclusion

In conclusion, we proposed an optical near-field assisted sputtering method for repairing the scratched grooves on a

¹A product of the Covalent Materials Corporation: <http://www.covalent.co.jp/>.

translucent polycrystalline Al_2O_3 ceramic surface. We confirmed that the depth of the grooves was decreased by RF sputtering of Al_2O_3 with laser irradiation at a wavelength of $\lambda = 473$ nm. We found a drastic decrease in surface roughness and obtained an average depth of 0.79 nm. Furthermore, we analyzed the surface profile using a Hough transform. This approach clearly revealed the effects of the optical near-field assisted sputtering, which selectively repaired the scratched grooves. We believe our technique is applicable to a variety of substrates, including ceramic and crystal substrates. Furthermore, this method is compatible with mass production.

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