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Surface modification of single-crystalline silicon carbide by laser irradiation for microtribological applications

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ABSTRACT

Carbide-derived carbon layers were locally formed on the surface of 4H-SiC single crystalline wafers by irradiation with an infrared laser (λ = 9.3 μm) in a low vacuum. Longer laser irradiation time produced thicker carbon layers and improved the bonding continuity. For an irradiation duration of 4.5 s, the modified layer was formed without surface damage and identified as amorphous carbon containing gradient amount of Si with a layer thickness of several nm. The results of friction tests conducted on the modified layer under micro-loads using a friction force microscope revealed the improvement of lubricity of the modified layer with a friction coefficient of 0.01 that is lower than that of the original SiC surface. No wear tracks were detected after scanning the Si probe over the layer surface 10,000 times with maintaining lubricity. The layer also preserved its lubricity after heating up to 550 °C in an air atmosphere; however, the lubricity disappeared at 600 °C owing to decomposition of the lubricating layer caused by oxidation.

1. Introduction

The use of micro electromechanical systems (MEMS) in harsh environments requires materials with excellent mechanical strength, corrosion resistance, heat resistance, and electrical characteristics at high temperatures. Silicon carbide (SiC) is one of candidate materials and have recently been studied as a potential substrate material for MEMS [1–4]. For example, the practical upper limit for the use of SiC as gas turbines is its oxidation temperature at 1500 °C, while the use of silicon is restricted by the onset of creep at 600 °C; furthermore, the yield stress and the specific strength of SiC are almost constant up to 1230 °C [5]. These characteristics are promising for the application of SiC in MEMS for microscale gas turbines as well as other devices that require both of high heat resistance and high strength. In addition, improvements in single-crystalline SiC production technology and advances in research on micromachining technology have significantly contributed to the development of SiC-based MEMS [6–8].

One of the key issues in the performance of MEMS is frictional force. Because surface forces have a much greater influence than volume forces in small objects, it is essential to suppress friction in applications involving sliding components such as micromotors [9], microbearings [10], and turbines [5]. Although one of the strategies to reduce friction is to supply liquid or solid lubricants to micro-sized mechanical elements, the lubricants can generate a harmful effect on the actuation of the systems. Another method for improving lubricity in MEMS is the application of highly lubricative coatings. In particular, many researchers have investigated the potential use of diamond-like carbon (DLC) coatings in terms of the dependence of tribological characteristics on the type of DLC and the coating configuration/structure in the context of applications to MEMS motors [11–13]. However, DLC coatings have several drawbacks such as low adhesion without the use of an intermediate layer, the generation of large residual stresses in itself. In addition, DLC coatings are deposited by chemical or physical vapor deposition so that patterning processes are required for lubrication of selected local areas.

Alternatively, heating SiC in specific atmospheres converts the surface into carbon layer. This layer of carbon is termed carbide-derived carbon (CDC) and is formed by elimination of non-carbon atoms from the carbide surface [14]. The CDC layer is expected to have higher adhesion than DLC coatings because CDC process is based on conversion of the surface of SiC substrate itself and the rearrangement of carbon atoms, therefore CDC layer forms a continuous structure with a substrate, while DLC is deposited on a substrate with an interface [15]. Moreover, the CDC exhibits various carbon structures depending on its process conditions including temperature, atmosphere, pressure, and crystalline structure of raw materials. There have been reports concerning various structure of CDC such as graphene [16], carbon nanotubes [17,18], diamonds [14], and carbon onions [19]; some of which have achieved lubricity comparable with DLC [15,19]. For example, CDC obtained by annealing at 1000 °C in a mixed gas atmosphere of

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Table 1
Properties of SiC substrate.

Crystalline structure	Hexagonal crystal
Off angle	4°
Surface condition	C-face (CMP)/ Si-face (polished)
Thickness (mm)	0.33
Length × width (mm)	10 × 10

Table 2
Laser irradiation conditions.

Wave length (µm)	9.3
Spot diameter (µm)	160
Power (W)	20
Pressure (Pa)	< 6
Time (s)	3, 4.5, 6

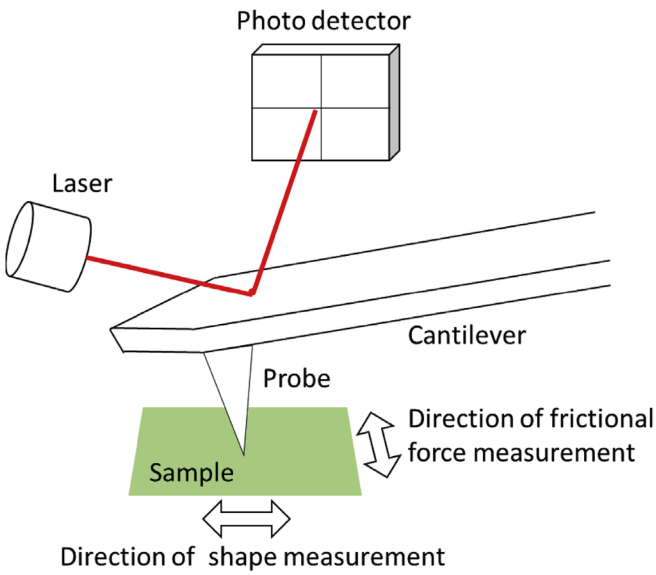

Fig. 1. Schematics of friction and wear tests.

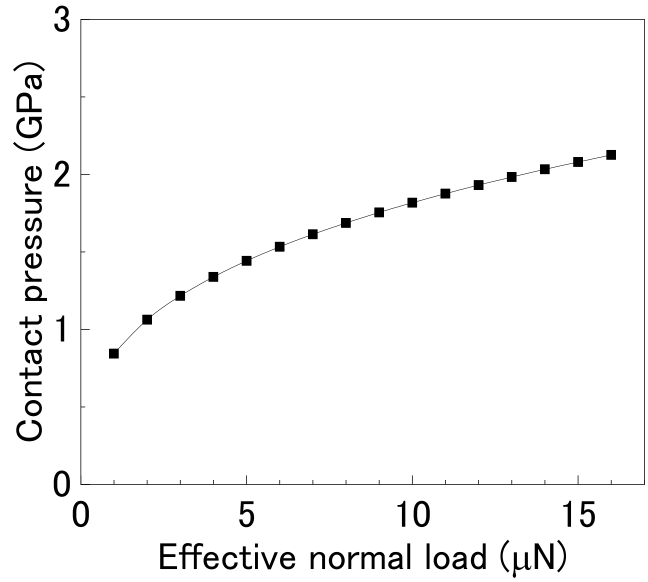

Fig. 3. Maximum contact pressure as a function of effective normal load.

chlorine and hydrogen exhibited a low friction coefficient of 0.03 in dry nitrogen [19].

For MEMS applications in which polymeric materials such as photoresists and various metallic thin film materials are integrated, processes involving annealing of the entire substrate in a corrosive atmosphere is not suitable. Therefore, we have proposed and demonstrated a new method to form CDC layers in targeted local areas on SiC by infrared laser irradiation in a low vacuum [20]. Surface modification by laser irradiation has high spatial selectivity and can suppress the heat damage over the surrounding area. In addition, patterning is not necessary because the CDC layer can be formed only on the laser beam scanned area.

Our previous studies found that it is possible to locally form highly lubricative CDC on polycrystalline-sintered SiC and amorphous SiC thin films [20]. In this study, CDC layers have been formed by infrared laser irradiation as localized solid lubricant layers on single crystalline 4H-SiC wafers. Furthermore, friction and wear tests of the laser-induced CDC layers were conducted under micro-loads to determine their

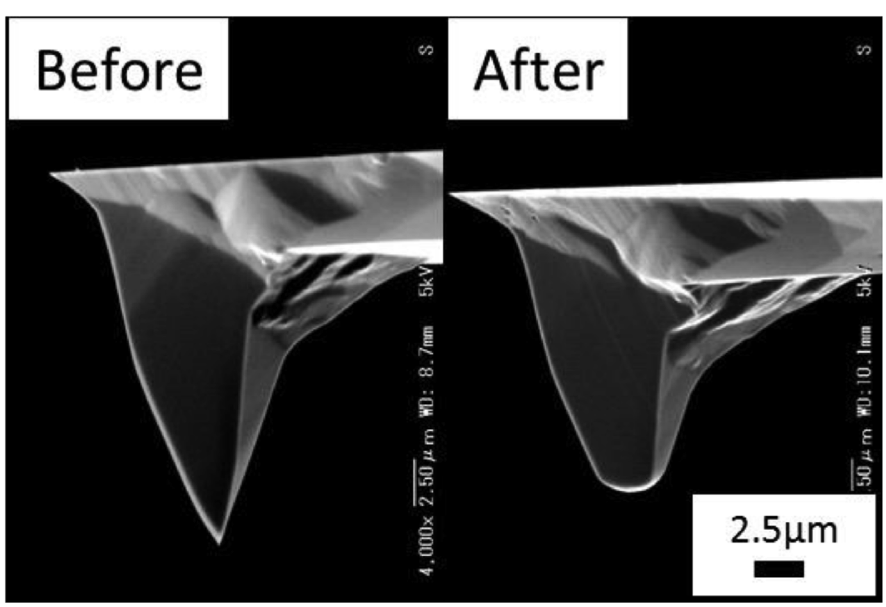

Fig. 2. Silicon probe tips before and after processing using focused ion beam.