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Compression molding of glass freeform optics using diamond machined silicon mold

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Abstract

In precision glass molding of freeform optics, mold material selection and mold fabrication are two major challenges. In this letter, we propose a method to fabricate silicon molds for micro freeform optics using ultraprecision diamond machining. Specifically, two microlens arrays and a kinoform lens molds were created on a 5.0 mm thick silicon wafer using ultraprecision diamond machining. The fabricated silicon molds were coated with a graphene-like carbon coating using chemical vapor deposition to prevent glass to silicon adhesion. To demonstrate the functionality of the single point diamond machined silicon molds, glass micro components were fabricated using precision compression molding. Compared with conventional grinding process required for tungsten carbide, the method investigated in this research provides a more flexible, faster and affordable alternative to fabricate molds for complex precision glass freeform optics.

Keywords: Freeform optics; Diamond micro machining; Grephene; Precision glass molding

In recent years, freeform optics are becoming increasingly popular because of the growing demand for high performance, compact but affordable glass optical devices. Freeform components, or optical elements without rotational symmetry, which often including microlens arrays and kinoform optical elements, see potential applications in head-up displays, LED lighting and remote sensing [1–3]. To fabricate glass freeform optics, precision molding is one of the preferred methods because of its cost-effectiveness, process consistency and short production time. One of the biggest challenges in precision molding is the fabrication of high quality molds, which are required to press glass at elevated temperature [4,5]. Currently, tungsten carbide (WC) is the de facto mold material for large continuous optical surfaces. However, WC molds have to be precision ground thus the process has intrinsic disadvantages due to long cycle time and the associated high fabrication cost. In addition, due to limits on available grinding tool geometries, freeform optics with microstructures are difficult to machine on the WC substrate.

In this letter, we proposed a novel process to fabricate freeform optics by combining precision glass molding and diamond machining of single crystalline silicon (Si). Compared with WC, Si is cost-effective, readily available and can be processed using many well established cleanroom processing methods. Furthermore, since thermal conductivity of Si is about 50% higher than that of WC, a Si mold provides better temperature distribution in a hot forming process. In addition, probably more significant to this research, Si mold can also be fabricated using ultraprecision single point diamond micro machining process as demonstrated in this letter. Ultraprecision single point diamond machining is a much faster, more accurate and flexible fabrication method than grinding, making silicon a promising candidate to replace WC in certain applications, particularly where microstructures with sharp or straight edges are involved.

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1. The fabrication process

1.1. Ultraprecision single point diamond machining of Si wafer

Unlike grinding process using super abrasives, ultraprecision single point diamond machining can provide simplicity and flexibility in creating freeform geometries on silicon surface. In this research, a 100 mm Si wafer with 5.0 mm thickness was machined directly on the Nanotechnology Systems' 350FG 5-axis ultraprecision machine using ultraprecision single point diamond machining. Two types of optical features, a kinoform lens and two microlens arrays were machined on the Si wafer. For the kinoform lens, conventional ultraprecision diamond turning process was utilized. In this process, a half radius diamond tool with a cutting radius of 14.9 μm was used. In order to decrease micro fracture in machining on brittle material, the diamond tool was tilted −24.95° so that a large negative rake angle was established [6]. Initial cutting depth was 300 nm and finish cutting depth was 100 nm. The feedrate was 2 μm/rev.

To machine the microlens arrays, ultraprecision diamond slow tool servo process was used [7]. In this unique approach, a single point diamond tool with relatively large radius of 3.048 mm was utilized in order to achieve a better surface finish quality [8]. Similar to kinoform lens machining, the diamond tool was also setup at a negative rake angle −24.95°. The finish cutting depth was 100 nm and the feedrate was 20 mm/min. The average surface roughness value for the microlens array is about 15 nm (R_a) at the bottom of the concave lens surface.

The micro machined silicon wafer was diced into individual blocks using a diamond saw since the entire wafer was too large for the following coating and molding processes. The diced silicon molds containing both the kinoform lens and the microlens arrays are illustrated in Fig. 1.

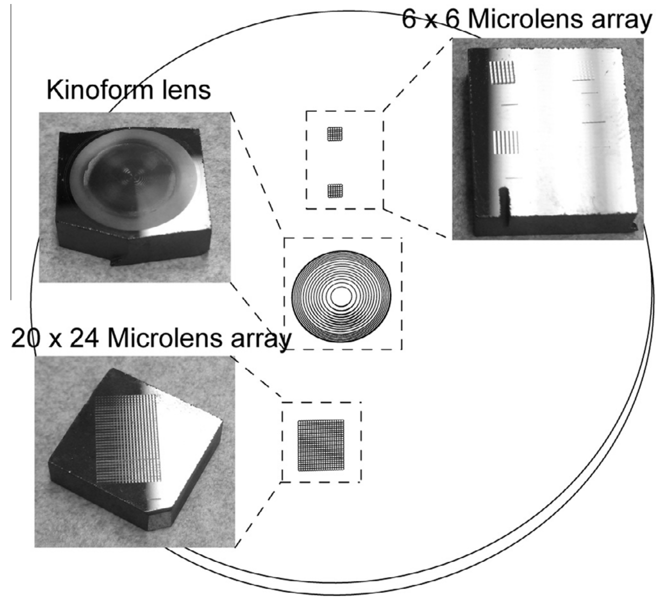

Fig. 1. Three silicon molds were diced off the silicon wafer.

1.2. Coating of silicon mold using CVD

Silicon cannot be used directly as mold material due to adhesion to glass at high temperature. The adhesion can either be caused by a process similar to anodic bonding or chemical bonding. Fortunately, it has been demonstrated that carbide-bonded graphene coating can effectively prevent adhesion between silicon and glass [9]. In this research, a chemical vapor deposition (CVD) coating was developed to produce a covalent-bonded graphene-like network coating on silicon substrate using benzene as carbon source under an inert gas flow at high temperature briefly described below.

The silicon substrate was placed in a nitrogen gas purged furnace. When the temperature in the furnace reached 950 °C, benzene was turned to gas in the form of bubbles outside of the furnace. The bubbling rate was about 3 to 5 bubble/s. The benzene bubbles were blown into the furnace under Ar gas flow (200 ml/min). After

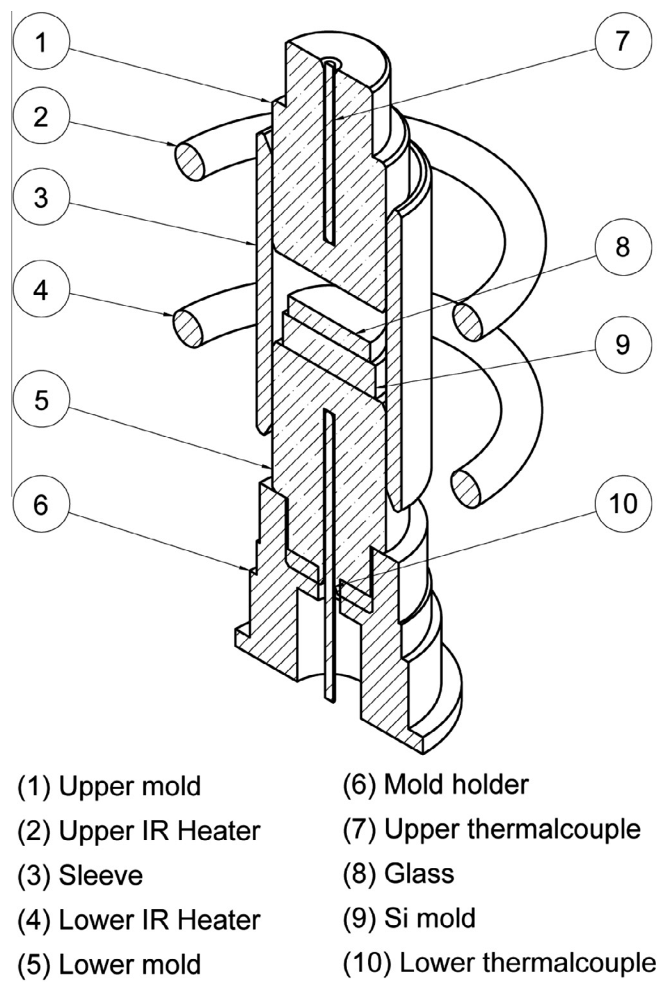

Fig. 2. Schematic of molding configuration. In this setup, glass is compression molded between a movable upper mold and a fixed lower mold.