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Technical Paper

Sculpturing of single crystal silicon microstructures by elliptical vibration cutting

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A B S T R A C T

Single crystal silicon is necessarily subjected to mechanical precision machining to fulfill its applications in semiconductor and optoelectronics industries. However, brittle defects are inevitably formed on machined surface of intrinsically single crystal silicon. Thus, achieving ductile material removal is critical to obtain ultra-smooth machined surface of single crystal silicon. In the present work, we investigate the feasibility of ductile ultra-precision machining of single crystal silicon by applying the elliptical vibration diamond cutting technology. Grooving experiments demonstrate that silicon micro groove can be successfully formed in ductile mode by employing the elliptical vibration cutting, in contrast to the ordinary cutting that causes serious deterioration of finished surface due to formation of brittle defects. Furthermore, the nominal critical depth of cut for the brittle to ductile transition in the elliptical vibration cutting of single crystal silicon is more than 12 times higher than that in the ordinary cutting. It is found that the extremely small instantaneous uncut chip thickness and small cutting forces in the elliptical vibration cutting are advantageous to suppress crack propagations. Moreover, it is found that the vibration amplitude in the depth of cut direction has a prominent influence on both the nominal critical depth of cut and the machined surface quality. Finally, based on the gained fundamental understanding of brittle to ductile transition mechanisms, two types of high precision silicon microstructures, as sinusoidal grid surface and independent dimple patterns, respectively, are successfully sculptured on single crystal silicon by applying the amplitude-controlled ductile mode sculpturing method with arbitrarily changed depth of cut.

1. Introduction

Single crystal silicon (herein referred to as silicon) is a basic technological material in semiconductor and optoelectronics industries for its superior properties of high hardness, high wear resistance, light weight, excellent stability and low oxides formability [1–4]. Recently, silicon microstructures have drawn emerging interests for their applications in high-performance imaging, concentration and illuminationin fields of semiconductors [5,6] and infrared optics [7,8]. While surface integrity in terms of form accuracy and subsurface damage has a strong influence on function and performance of microstructures, the precision manufacturing of silicon microstructures is challenging due to its brittle fracture [3]. The performance of conventional precision grinding and polishing of silicon is greatly limited by initiation and subsequent propagation of cracks, as well as formation of subsurface damages [9–12]. In particular, the ultimate precision polishing for achieving excellent machined surface quality is time consuming and high cost due to its complexity. Additionally, it is also extremely difficult to fabricate sophisticated microstructures with sharp edges in grinding and polishing process. In another hand, although the non-traditional semiconductor lithography technique can be applied in the fabrication of silicon microstructures, it suffers greatly from time consuming and complex operation procedures, high costs of equipment and low precision [13–15]. Therefore, an effective manufacturing technique of low cost, high efficiency, high precision and

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high surface quality is greatly needed for the fabrication of silicon microstructures.

The ultra-precision diamond cutting technique has been demonstrated to be a promising method for fabrication of surface microstructures, due to its advantages of high geometrical accuracy, high machined surface quality, high machining efficiency, low subsurface damage and high degree of freedom. In particular, the feasibility of ductile cutting of silicon with single crystal diamond (SCD) tool has been investigated experimentally and theoretically over the last few decades. It has been demonstrated that with a depth of cut (DOC) ranging from 50 nm to 250 nm, high machined surface quality of silicon, in terms of nanometric surface finish, submicrometric form accuracy and minimum subsurface damages, can be achieved by ductile cutting [2,4,5,12,16–30]. However, the extremely small DOC utilized in ductile cutting of silicon not only requires extremely high rigidity of ultra-precision machine tools, but also introduces difficulties in realizing uniform ductile cutting of global surface due to the undesired inclination of workpiece surface with respect to workpiece holder and alignment errors of workpice [5,31]. Therefore, improving the nominal critical DOC for ductile cutting is critical to simplify the setting up of ductile cutting of silicon, which also facilitates the industrial applications of low cost precision machine tools.

Over the past decades, the ultrasonic vibration cutting technique has been successfully applied in machining of hard-brittle materials [27–31]. In particular, the machining feasibilities of elliptical vibration cutting (EVC), which was proposed by Shamoto and Moriwaki in 1994 [32], on silicon, tungsten carbide and several other brittle materials with SCD tools were verified [33–37]. For instance, ultra-precision machining of difficult-to-cut materials such as hardened steel [38–40], sintered tungsten carbide [35,36,41], Molybdenum [42], Co-Cr-Mo alloy [43] and Plexiglas [44] were realized by applying the EVC technique. In particular, it is found that the nominal critical DOC for ductile cutting of brittle materials can be greatly increased by applying the EVC, as compared to the ordinary cutting (OC). Zhang et al. [33] presented a specific-cutting-energy-based model to predict the ductile-brittle transition (DBT) in nanomachining of silicon. They theoretically predicted and subsequently experimentally verified the significantly increasing of the nominal critical DOC by applying the EVC. Zhu et al. [34] experimentally confirmed that the nominal critical DOC by applying the EVC is improved to 12.8 times higher than that by the OC. Suzuki et al. [37] carried out a series of micro grooving experiments of brittles materials including sintered tungsten carbide, zirconia ceramics, calcium fluoride and glass, and reported that the nominal critical DOC for ductile cutting can be efficiently improved by applying the EVC. Therefore, the EVC is considered to be a promising manufacturing technology for the precision machining of silicon. However, our fundamental understanding of the mechanisms of ductile cutting of silicon by the EVC is far from being completed. For instance, it is necessary to deeply explore and compare the crack generation in silicon under both the EVC and OC processes, which is advantageous to promoting the ductile machining of silicon in EVC process. Moreover, it is critical to investigate the influence of vibration amplitude in the dynamic EVC process on the ductile cutting of brittle materials. Hence, it is of significant importance to propose a simple prediction criterion to unambiguously indicate the optimal machining conditions for achieving ductile cutting of silicon by using the EVC.

Furthermore, most of previous works focused on the investigation of groove or plane formation, there is rather limited attention paid on the fabrication of functional microstructures by using the EVC. More recently, Chen et al. [5] fabricated micro-pillar and micro-pyramid arrays with nanometric surface finish on silicon through crossed ductile cutting process. Mukaida and Yan [8] fabricated aspherical concave micro lens array on silicon wafer through ductile cutting by applying the slow tool servo diamond turning. The combination of conventional diamond cutting and the fast tool servo (FTS) has also been demonstrated to be effective in the fabrication of silicon microstructures for a variety of applications [45–47]. However, the application of conventional diamond cutting in the fabrication of microstructures on brittle materials is greatly hindered by its low efficiency or complexity. Suzuki et al. [48] recently proposed a unique micro/nano sculpturing method by controlling the vibration amplitude in the EVC process, which is capable of achieving high efficient fabrication of high accuracy microstructures on the hard brittle and other difficult-to-cut materials. In the proposed method, the elliptical vibration amplitude is actively controlled during the ongoing machining process, which enables rapid changes of DOC without the utilization of FTS technology. It is suggested that the EVC technology is already equipped with a FTS function itself. Therefore, the EVC can attract increasing attention in the precision micro/nano machining of brittle materials for its feasibility of fabrication of silicon microstructures through ductile cutting, which is helpful to promote the industrial application of the EVC technology in micro/nano machining of the functional silicon structures.

In the present work, grooving experiments are firstly carried out to investigate the machinability of silicon in the EVC and OC, with an emphasis on the ductile cutting mechanisms of silicon under the EVC. Experimental results show that the nominal critical DOC for the DBT in the EVC is 12 times higher than that in the OC. Furthermore, the machinability of silicon with respect to vibration conditions is also investigated, and a simple criterion is proposed to indicate optimal machining conditions for achieving ductile cutting of silicon in the EVC. Subsequently, high precision silicon microstructures, as grid surface and dimple patterns with sinusoidal and triangular cross-section shapes, respectively, are successfully fabricated in ductile mode by applying the EVC, demonstrating the feasibility of the EVC for the high efficiency fabrication of silicon microstructures. The paper is structured as follows. Section 2 introduces the principle of the EVC and experimental setup. Section 3 presents the comparison of grooving machining results of silicon between the EVC and the OC, and the DBT mechanism is also discussed. Section 4 shows the fabrication of silicon microstructures. Finally, Section 5 summarizes the findings found in the present work.

2. Experimental methods

2.1. Principle of EVC

Fig. 1 schematically illustrates the EVC process that was originally presented by Shamoto et al. [49,50]. The nominal cutting direction and the DOC direction is parallel to x axis and z axis, respectively. In the EVC process, the cutting tool is fed at a nominal cutting speed v_c, and the tool edge is controlled to vibrate elliptically at an angular frequency ω in the x-z plane. The tool trajectory in the course of EVC can be expressed as follows:

$$x_e = A_c \cos(\omega\tau) + v_c\tau, \quad (1)$$

$$z_e = A_d \cos(\omega\tau + \varphi), \quad (2)$$

where x_e and z_e denotes x and z component of a relative position between the tool and workpiece, respectively. A_c and A_d is mean-to-peak amplitude in x and z direction, respectively. φ is a phase shift of the vibration, which is typically set to be -90°. τ is the time during the elliptical vibration process.

As illustrated in Fig. 1, the tool starts to cut the workpiece at time t_1 in each elliptical vibration cycle. Subsequently, the workpiece material is removed in the form ofchips until the tangential direction of the tool trajectory is parallel to the rake face, at which