A silicon ultrasonic horn with a Bézier profile for surgical applications

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ABSTRACT
A novel silicon ultrasonic horn with microprobes is developed for surgical applications. During insertion, penetration force of the microprobes driven by the ultrasonic horn can be reduced and tissue damage is minimized. The new horn has a profile of a Bézier curve. The dynamical characteristics of the horn are examined. Microscale prototypes are fabricated. Using the driving technique, the force reduction of microprobes during insertion will be investigated by experiments. Microprobes driven by the ultrasonic horns have potential applications in cardiac electrophysiology to provide information of wave propagation in hearts for understanding the mechanism of cardiac arrhythmia.

Keywords: Silicon ultrasonic horn, Bézier profile.

INTRODUCTION
Surgical applications of ultrasonic horns require high displacements of 20 to 100 μm in the frequency range 20 to 100 kHz [1]. The horn is usually made of high-strength titanium alloys due to large stress and displacement during operation. Lai and White [2] reported that silicon-based transducers hold the potential of generating higher ultrasonic velocities than the titanium alloys. Higher particle velocity means faster cutting rates [1]. Metal horns heat up at high amplitudes due to viscous losses in the metal. Silicon-based power ultrasonic technology can solve this problem due to the fact that silicon has lower acoustic losses, higher stiffness and higher hardness than high-strength metals [1].

Three-dimensional mapping data are necessary for studying the electrical wave propagation of the heart tissue in order to understand the ventricular fibrillation mechanism, which is likely the cause of sudden cardiac death [3]. Silicon microprobes have been used for three-dimensional electrical activity recording in neural tissues [4-6]. They provide high spatial resolution, reduced tissue damage, and easy integration with microelectronics [3]. Application of silicon microprobes in potential recording within the ventricular wall of the heart requires a larger force during insertion in cardiac tissues. Chen et al. [3] demonstrated that a microprobe actuated by a catenoidal shaped silicon ultrasonic horn can reduce penetration force, which allows the use of microprobes on cardiac tissues.

Stepped, linear, exponential and catenoidal horns for power ultrasonics have been examined by Lal and White [1]. The stepped horn has the largest displacement amplification among the commonly used horns. However, its high stress occurring near the abruptly changing section is not favoured. Except the stepped horn, catenoidal horn has higher predicted displacement amplification than the linear and exponential horns [1]. A new horn with a Bézier profile was presented by Wang et al. [7]. It has larger displacement amplification and lower stress concentration than catenoidal horns.

In this investigation, a silicon horn with a Bézier profile for actuation of silicon microprobes for penetration force reduction is presented. The profile of the horn is based on a cubic Bézier curve. Prototypes of the horn are fabricated. The penetration force of the ultrasonic microprobes excited on tissues will be measured.

METHODOLOGY
Design
Fig. 1(a) is a schematic of a silicon horn with a Bézier profile. Two thin silicon beams are fabricated at the front end of silicon horn as microprobes. A lead zirconate titanate (PZT) actuator is bonded with epoxy to the horn near its vibration node. The d31 mode of the PZT actuator is utilized to drive the horn. A cross-section of the horn is shown in Fig. 1(b). The silicon horn vibrates in a longitudinal resonant
mode excited by the PZT actuator. Fig. 1(c) shows a typical displacement distribution curve of the horn.

As indicated in Fig. 2(a), the length and the widths of the back and front end of the horn are 58 mm, 18 mm and 1.0 mm, respectively. The thickness of the horn is 0.5 mm, which is the thickness of the silicon wafer used for fabrication. Fig. 2(b) is a close-up view of the microprobe. The length, width and thickness of the microprobe are 5.8 mm, 0.2 mm and 0.08 mm, respectively. The working frequency is set to be 63.4 kHz. The length of the horn is equal to a half of the ultrasonic wavelength of the material.

Fabrication

Fig. 4 shows the process flow of the horn. The silicon wafer is (100) orientated and polished on both front and back sides. 0.6-μm of Low-pressure chemical vapour deposition (LPCVD) low stress silicon nitride layers are deposited on both front and back sides of the wafer. The silicon nitride on front side is used as an electrical insulator. The nitride on back side is later patterned to form the masking layer for a potassium hydroxide (KOH) etch process. Next, a 4 μm-thick photoresist (AZ4620) is coated and patterned on the front side of the wafer as an etching mask for the patterning of the horn. The resist layer is then dissolved away in acetone, lifting off the unwanted metal with it to form the bottom electrode for the PZT actuator (see Fig. 4(a)). Then, 1 μm nitride is deposited as a passivation layer. A 4 μm-thick photoresist (AZ4620) is coated and patterned as an etching mask for the fabricated horn.
underlying nitride layer. A plasma etching step was done to define the bonding site of the PZT actuator and the front end of the microprobes. A 4 μm-thick photoresist (AZ4620) is coated and patterned on the front side of the wafer as a masking layer. A deep reactive ion etching (DRIE) step on the front side of the wafer is done to define the shape and depth of the microprobes. The back side nitride masking layer is patterned using double side alignment. Finally, the wafer is placed in a 30 wt% KOH at 70 °C with the front side protected by black wax (Apiezon W). The black wax was removed using Trichloroethylene (TCE) [6].

**Fig. 4.** Fabrication steps of the horn.

- (a) Spurter and pattern Ti metallization
- (b) Deposit silicon nitride
- (c) Coat and pattern photoresist
- (d) Patternable DRIE
- (e) Pattern backside silicon nitride
- (f) Pattern bottom silicon nitride
- (g) Coat and pattern photoresist
- (h) Backside KOH etch
- (i) Remove photoreist

**FURTHER WORK**

In the future, we will verify the performance of the microprobes actuated by the Bézier horn by experiments. A standard diamond saw will be used to separate the silicon horn from the wafer. A PZT actuator will be bonded with epoxy to the bonding pad of the horn. Wires will be soldered to the top electrode of the PZT actuator and the bonding pad of the horn.

Fig. 5 is a schematic of the experimental apparatus for measurement of the penetration force of the microprobes. The probes will be driven into a tissue stimulant (raw yam) using a linear motor. AC voltages will be applied to the PZT actuator by a power supply, a function and an amplifier. The penetration force will be measured by a load cell. The experiments with and without ultrasound will be carried out. It is expected that the value of the penetration force would be decreased when the ultrasonic actuation is turned on.

**REFERENCES**