Development of Microelectromechanical Systems (MEMS) forceps for intraocular surgery

R B Bhisitkul, C G Keller

MATERIALS AND METHODS

MEMS fabrication process

Original designs for a variety of MEMS forceps were manufactured at the University of California Berkeley Microfabrication Laboratory. Forceps were constructed from two dimensional designs using boron doped silicon wafers (orientation (100), resistivity 0.02 ohm-cm). Photoreist was spun onto wafers and patterned using a photomask, then hard baked at 125°C. Deep etching was performed using the Bosch process in an STS plasma etcher. After cleaning wafers with acetone, piranha (H₂SO₄/H₂O₂), and deionised (DI) water rinse, a 1 μm thermal oxide coat was grown (1100°C, O₂, steam). Oxide was removed from the backside of the wafer using 5:1 buffered oxide etch (aqueous hydrofluoric acid (HF) with ammonium fluoride). A ring of oxide was preserved at the outer diameter of the wafer, to preserve the full wafer thickness around the edge to prevent it from becoming too fragile to handle. Wafers were placed in 25% tetramethyl ammonium hydroxide at 60°C until the etch front reached the bottom of the plasma etched pattern (where only oxide windows remain). Wafers were rinsed in DI water and all oxide was removed with 49% HF. A 1 μm thick layer of wet thermal oxide was grown (1100°C, O₂, steam) to remove sharp corners and stress concentrations, then all oxide was removed with 49% HF. Finally, silicon parts were obtained, and for some designs assembled with epoxy to a forceps actuator shaft.

Scanning electron microscopy

Scanning electron microscopy (EM) was done with a Jeol 6400. Silicon specimens were mounted on standard aluminium scanning EM stubs using colloidal carbon paint. Gold coating was not necessary for visualisation as the silicon alone is sufficiently conductive. Micrographs were obtained and stored digitally.

Forceps design and construction

Two different actuator designs were developed to control forceps operation. The initial design was an electrically heated thermal expansion actuator, which incorporated tweezer tips and heat sink fins as a single piece (fig 1A). A manual potentiometer was used to apply current to rapidly heat and cool the semiconductive silicon of the thermal actuator, causing expansion and contraction in length, to open and close the tips via a lever linkage.

The second generation of forceps used a more conventional mechanical actuation (figs 1B and 2). MEMS silicon forceps tips were joined to a 20 gauge stainless steel instrument shaft enclosing a spring loaded opening mechanism, which included a microcalibration system for fine adjustments of the forceps tip excursion. To maximise stability, the mechanical actuator itself is electrically activated, via wire connections to a control switch, much like the automated MPC scissors familiar to retinal surgeons.

Several tip configurations were designed to be suitable for intraocular surgery. The stiffness of tips made for these forceps ranged from 1 nanonewton/μm to 100 micronsnewtons/μm.

Abbreviations: DI, deionised; EM, electron microscopy; HF, hydrofluoric acid; MEMS, Microelectromechanical Systems; MVR, microvitrectomy
Intraocular surgery

For surgical testing in human cadaver eyes, an eye cup was formed by excising the cornea, iris, and lens, then filling the vitreous cavity with balanced salt solution after vitrectomy. Surgery was done in an “open sky” fashion under the operating microscope (Zeiss Op-Mi6, Carl Zeiss, Germany). For in vivo surgical testing, standard three port 20 gauge vitrectomy (Storz Millenium, Rochester, NY, USA) was performed on adult New Zealand White rabbits (Charles River Laboratories Inc, Wilmington, MA, USA), anaesthetised with 3–5% isoflurane mask inhalation (Baxter, Deerfield, IL, USA). Both lensectomy and lens sparing vitrectomies were done. The MEMS instruments were introduced into the eye through standard sclerotomies made with a 20 gauge microvitreoretinal (MVR) blade. At the completion of surgery animals were euthenised with intramuscular ketamine (30–50 mg/kg, Fort Dodge Animal Health, Ft Dodge, IA, USA) and xylazine (5–10 mg/kg, Phoenix Pharmaceutical Inc, St Joseph, MO, USA), followed by intramuscular sodium pentobarbital (>150 mg/kg, Schering-Plough, Kenilworth, NJ, USA) and bilateral thoracotomy. All rabbit experiments were done in accordance with UCSF committee on animal research guidelines.

RESULTS

The instruments were manufactured at tip lengths from 100 µm to 2 mm; scanning EM confirmed the accurate construction of serrated teeth as small as 10 µm. Figure 2 shows a MEMS forceps with a serrated jaw design alongside a commercial stainless steel subretinal forceps, demonstrating the relative scale of the instrument tips as well as the high design tolerance made possible with MEMS technology.

Two different actuator systems were designed for the MEMS forceps. In the first prototypes, a thermal expansion actuator adapted from engineering applications was redesigned for intraocular surgery. With this design, electrically heated beams (fig 1A), allow tip excursions as small as several micrometres. This actuator was usable in the eye only with an “open sky” approach, and frequently had thermal coagulation of materials on its surface after repeated current application which interfered with its mechanism.

Therefore, a redesign was made, based on a mechanical actuation system. A variety of MEMS designs were incorporated in a more conventional 20 gauge stainless steel spring loaded system. The circuit for its automated activation was enclosed within the shaft of the instrument and no thermal coagulation of surface materials was noted with repeated activation. For in vivo surgery in rabbit eyes with standard three port, 20 gauge vitrectomy, operation of the forceps was done in a conventional handheld fashion, and also by mounting the forceps on a Sutter Instruments three axis micromanipulator. Handheld operation was found to be feasible, but the micromanipulator provided greater stability and movement precision commensurate with the small scale of the instrument tips.

Surgical tests confirmed the viability of silicon as a material for intraocular instruments. The tensile properties...
of silicon proved to be non-distensible and not plastically deformable under conditions of standard vitreoretinal surgery. Also, silicon was found to be antireflective with standard endoillumination, aiding visibility of the small tips. In surgical manoeuvres with serrated forceps (fig 3, and see video on BJO website), we were able to firmly engage tissues and displace membranes without slippage. No breakage or fracture of the silicon tips was observed in multiple trials.

**DISCUSSION**

This project indicates the viability of MEMS forceps for intraocular surgery. The miniaturisation and construction tolerance of the MEMS forceps surpass that of commercially available stainless steel instruments. The tensile properties of silicon confer durability and function at small scales at which stainless steel would be plastically deformable. The material biocompatibility and sterisilisability of MEMS devices and materials appear from initial studies to be satisfactory.5 4

MEMS fabricated instruments have potential applications in eye surgery. For example, the innovation of the 25 gauge vitrectomy system10 11 has necessitated a rescaling of the full array of handheld vitreoretinal instruments, which MEMS instruments could complement and expand. Besides forceps, MEMS technology could be used to design membrane picks, blades, scissors, etc, on a scale much smaller than current products. The miniaturisation allowed by MEMS instruments could be used to advantage in advances such as non-vitrectomy retinal surgery.11 12 Furthermore, since any two dimensional design template can be rapidly fabricated at a large scale, MEMS processes may facilitate advances in instrument design and even allow customisability for individual surgeons. Emerging research in biomedical MEMS includes drug delivery devices, micro-pumps, sensors, and retinal prostheses.11-15 Challenges remain with the development of MEMS intraocular instruments. In these tests, the initial prototype thermal expansion actuator was adapted from engineering and microscopy applications, but had disadvantages during eye surgery, exemplifying the disparities in transferring this technology from the laboratory setting to the intraocular environment. Improved systems for operative imaging, stabilisation, and micromanipulation may be required to realise the potential of MEMS microsurgery. In this project, we have not departed substantially from standard designs, but instead have advanced the scale and material of conventional forceps archetypes. However, MEMS technology may offer the capability to evolve instrument designs for surgical applications not foreseen presently.

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