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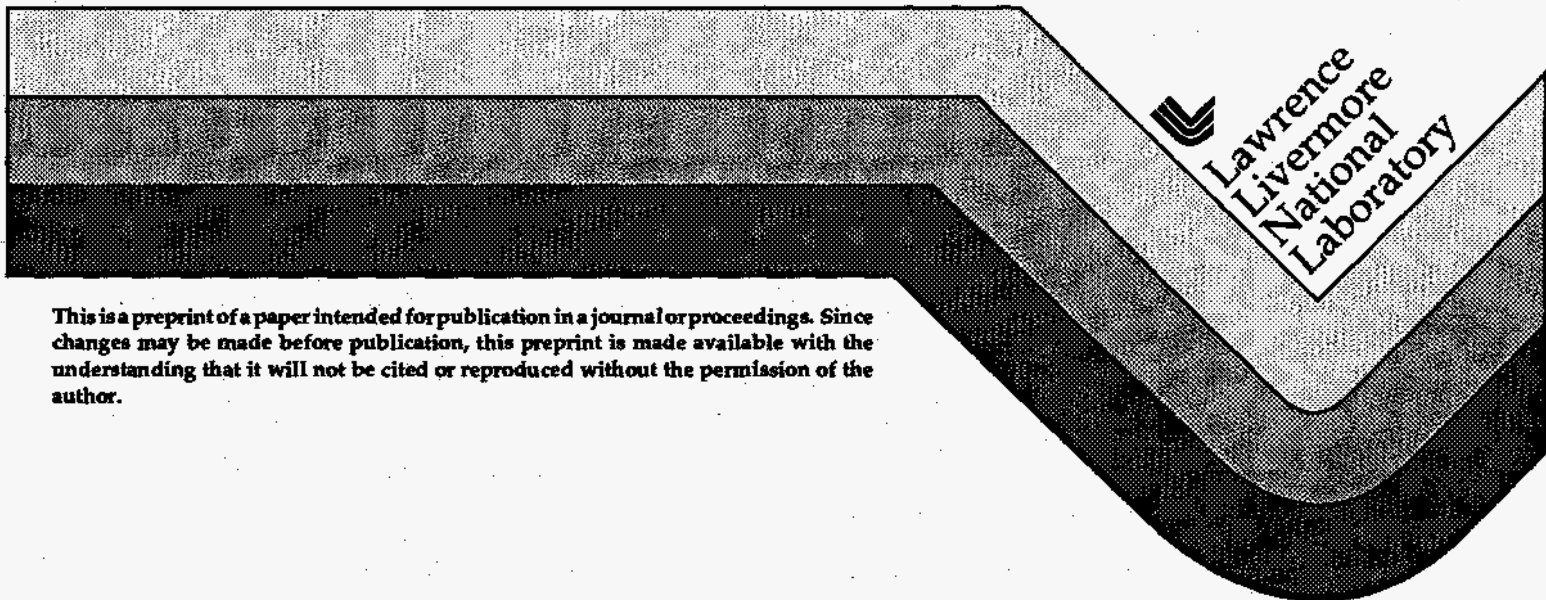

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A PRACTICAL MICROGRIPPER BY FINE ALIGNMENT, EUTECTIC BONDING AND SMA ACTUATION

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SUMMARY

A microgripper with a large gripping force, a relatively rigid structural body, and flexibility in functional design is presented. The actuation is generated by Ni-Ti-Cu shape memory alloy (SMA) films and the stress induced can deflect each side of the microgripper up to 55 μm for a total gripping motion of 110 μm. When fully open, the force exerted by the film corresponds to a 40 mN gripping force on the tip of the gripper.

BACKGROUND

Although microgrippers have been demonstrated in the past [1-6], they have mostly been either small in gripping force, low in structural rigidity, relatively small in opening displacements, or inflexible in the design parameters. Furthermore, many of the designs could not function well in a liquid environment either due to the high temperature required for activation or the high surface tension forces of the liquid limiting the gripping capability. These issues have prevented a practical microgripper from being generated.

The objective of this project is to develop a microgripper that can be locally actuated at low temperatures (<100°C), with large gripping force (>1mN) and high structural rigidity. The capability to lock the target gripping object is another desirable feature to ensure that frictional force, which is often unpredictable, is not the only means of securing the grip.

The microgripper presented in this paper is fabricated by aligning and selectively eutectic bonding [8] two pre-processed silicon wafers and dicing up the individual microgripper structures. The process involves bulk silicon etching with double-sided alignment, precision depth-controlled sawing, and fine alignment for eutectic bonding. The fabrication process allows the designer some flexibility in shaping the gripping jaws as specified by the object to be gripped. Also, batch fabrication allows for highly automated processing and reduces manufacturing costs. Ni-Ti-Cu shape memory alloy (SMA) films are deposited to generate low temperature, high force actuation. This type of SMA film [7] can generate actuation stresses up to 500 MPa at transformation temperatures between 30°C to 70°C. This is a lower temperature range than all thermal bimorphic microgrippers that have been published. At present, the microgripper is actuated by external heating and a video tape is prepared to demonstrate the opening and closing motions. Applications for the microgripper include assembling small parts for manufacturing, minimally-invasive *in vivo* biopsy tissue sampling, catheter-based endovascular therapeutic procedures, and remote handling of small particles in extreme environments (high/low pressures, hazardous fluids).

DESIGN AND FABRICATION

The microfabrication process can be categorized into bulk micromachining, fine alignment, eutectic bonding and Ni-Ti-Cu SMA thin film deposition. Figure 1 shows

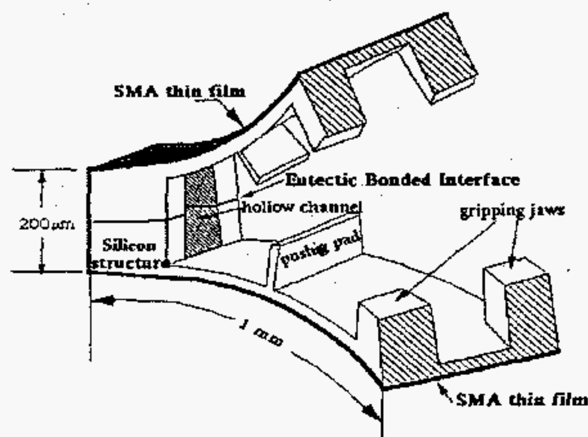

Figure 1. Three-dimensional schematic of micrgripper.

a schematic of an LLNL silicon microgripper and Fig. 2 is an SEM micrograph of a completed device. The microgripper is 1000 x 200 x 380 μm^3 in dimension. Each silicon cantilever is 12.5 μm thick and 5 μm Ni-Ti-Cu SMA thin films [7] are deposited on both sides of the microgripper for actuation. The pushing pad is designed to assist in releasing the gripped object by pushing forward as the gripper is opened. This pad is 30 μm wide

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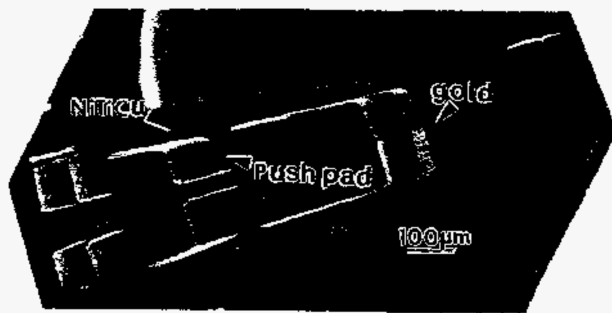

Figure 2. SEM micrograph of silicon microgripper.

while the gripping jaws are 60x110x100 μm^3. The hollow channel is 110 μm wide. The gripping jaws, pushing pads, and hollow channel are shaped by a combination of precision sawing and bulk machining of silicon. The connection of the microgripper to external leads and milli- end effectors, requires assembly and there is ongoing effort to develop assembly and packaging techniques.

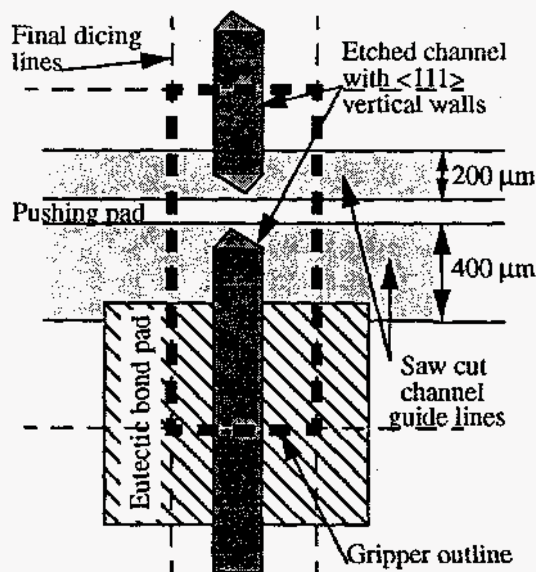

Figure 3. Illustration of the top view of a single wafer process.

Figure 3 illustrates the top-view of one half of a microgripper processed on a wafer. This process starts with two 100 μm thick (110) p-type wafers, which were ground and polished from 200 μm thick wafers. The common masking film for patterning and etching silicon was 1000Å of silicon nitride.

A test pattern is essential to identify the exact (111) plane as opposed to the wafer flat, which is typically offset 2°-3°. Alignment targets are imprinted on the wafer using this crystal plane identifying pattern to ensure the subsequent aligning to the exact crystal planes. Two types of alignment targets must be defined, one to carry out front-to-back alignment and another etched through the wafers to provide holes for precise pin alignment for eutectic bonding (see Fig. 4). Dicing lines (2 μm deep) are then patterned on the backside of the wafer. On the front side, saw cut channel guide lines (Fig. 3) are patterned for the precision saw to form the silicon cantilevers and the pushing pad. These patterns are imprinted by etching into the silicon 1 μm. After reapplying the masking silicon nitride, lithography is carried out for the gripping jaws and the hollow channel. The wafers are then etched in 44 *wt %* KOH, creating vertical walls 85 μm deep. The silicon nitride mask is then stripped and ready for the precision saw. The precision saw used is a model 780 by Kulicke & Soffa, with positioning accuracy as high as 2.5 μm. Precision sawing is chosen to avoid the anisotropic etching limitations of (110) silicon that does not allow vertical-wall etch channels 90° apart without careful corner compensation and sacrifice of finished surfaces. Since the width of the two cut channels are 200 μm and 400 μm, the blade selected is 200 μm thick. The wider cut channel (400 μm) is formed by making two adjacent saw cuts. The saw is indexed to leave a pushing pad width of 30 μm.

The two identical wafers are now ready for bonding. The process for selective eutectic bonding is described in detail in [8]. By aligning the shadow mask to the gripper patterns, a selective bond pad can be defined as in Fig. 3. Through this shadow mask, 500 Å of titanium followed by 1 μm of gold is evaporated. The titanium serves as a diffusion barrier so that when an opposing silicon wafer is brought into contact, eutectic Au-Si will be formed only on this bare silicon wafer. The wafers were pressurized together and held in low vacuum (nominally 10^{-4} torr) and soaked at 380°C for 3 minutes. The Au-Si bond strength was measured in an instron pull test, where the eutectic bond pads were pulled and failed at a pull stress of 5.5 GPa. The eutectic bond areas were intact, as fracturing of the silicon surrounding the bond areas occurred in the process.

Mechanical alignment using precise diameter pins was applied to ensure controlled processing and prevent shattering of the fragile thin wafers. Figure 4 illustrates the pin-alignment technique.

The bonded pair of wafers is now ready for the SMA thin film deposition. The material chosen is Ni-Ti-Cu, and the sputtering technique described in [7] was used to identify the ideal composition for our application. In brief, three separate targets are used to sputter the alloy such that the power can be individually controlled to actively determine the alloy composition. Then a single target is generated to match this composition. The film is deposited on two sides sequentially so that one side is annealed

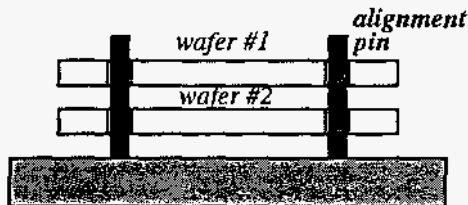

Figure 4. Mechanical alignment for eutectic bonding using alignment pins.

twice at 505°C. This is not ideal since the film deposited first must undergo a second thermal cycle at 505°C. An improvement in the future would be to deposit SMA before eutectic bonding. The final step is to dice up the individual microgrippers. The processing sequence is summarized below.

(a) pattern crystal plane test marks, alignment targets and alignment holes.
(b) pattern saw cut channel guide lines.
(c) pattern silicon etch channels following the (111) plane direction.
(d) anisotropic etching of the silicon etch channels by KOH.
(e) shadow mask alignment to wafer and deposition of Ti/Au film.
(f) mechanical pin alignment and eutectic bonding at 380°C (3 mins) and 10^{-4} torr.
(g) sputter deposition of Ni-Ti-Cu films on both sides (2 runs) with *in situ* annealing at 505°C.
(f) dice up individual microgrippers.

ACTUATION OF THE MICROGRIPPER

The microgripper is actuated using dc magnetron sputter deposited nickel-titanium-copper shape memory film. Shape memory actuation is based on a crystalline phase transformation in which the low temperature phase (martensite) is easily and reversibly deformable via twins, while the high temperature phase (austenite) has one rigid configuration [9]. The $Ni_{42}Ti_{50}Cu_8$ alloy transforms just above body temperature (37°C), making it useful for implantable medical devices, and has a narrower hysteresis (see Fig. 5) than binary nickel-titanium, resulting in increased efficiency and faster response time. Furthermore, the addition of copper makes the transformation temperature less sensitive to film composition [7].

In this application, actuation occurs by the recovery of tensile residual stress in the shape memory film, as shown by the data in Fig. 5 which was obtained by measuring substrate curvature as a function of temperature. The curvature change induced by the Ni-Ti-Cu film on a silicon wafer is measured by a Tencor FLX-2320 laser system. This curvature is then translated into stress using the modified Stoney's equation [10]. The film, which is deposited near 500°C, develops a tensile thermal stress as it is cooled after deposition. When cooled below the temperature at which the martensitic transformation starts, M_s, the thermal stress in the film can relax by twin-related deformation. This tensile thermal stress can be recovered by re-heating the film. Thus, the silicon gripper cantilevers act as bias springs which are opened by the contracting shape memory film when heated, then deflect back to a neutral position and stretch the shape memory film when cooled. Films with up to 500 MPa recoverable stress (σ_r) have been deposited, but the film on the grippers presented here have $\sigma_r = 375$ MPa.

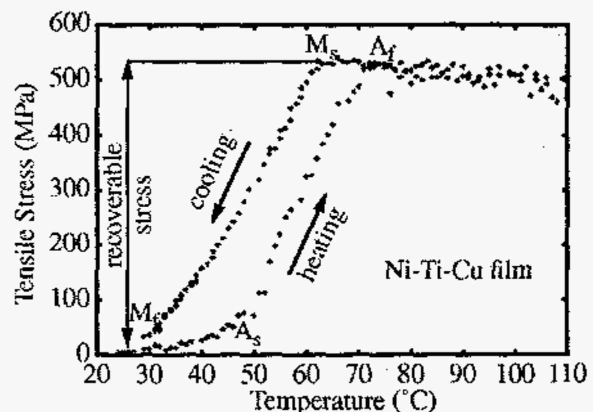

Figure 5. Substrate curvature hysteresis loop. M_s, M_f, A_s, and A_f designate the martensite and austenite start and finish temperatures.

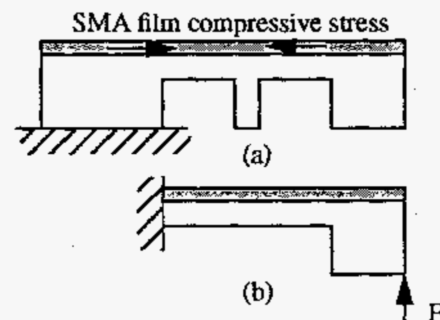

Figure 6. Illustration of gripping force model.

Figure 6 illustrates the simple mechanical models used for evaluating the gripping force induced by the Ni-Ti-Cu film (Fig.6a), assuming an equivalent model with an opening force at the tip (Fig.6b). By applying the bimetallic stress equations derived in [11], the relation between the Ni-Ti-Cu film stress and the deflection of the gripper tip can be calculated. Figure 7 is a plot of the deflection of the tip of one side of a gripper and gives the parameters used. For a film thickness of 5 μm, the deflec-

tion is calculated to be 53 μm. Experimental results showed the gripper opening to 55 μm when fully actuated. Using the model of Fig. 6b, it will require 20 mN to deflect the microgripper to 55 μm. Therefore a gripping force of 40 mN is applied for a fully opened microgripper.

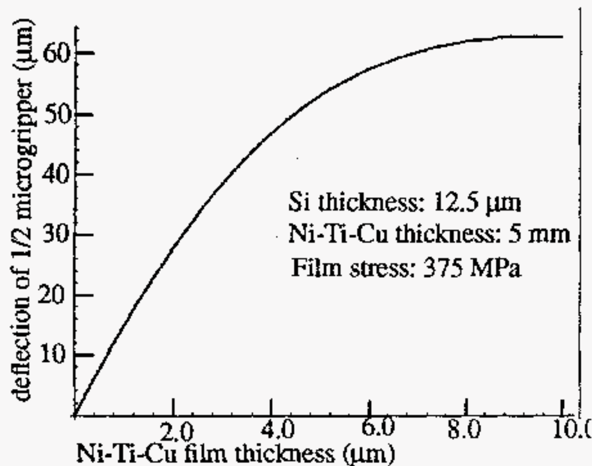

Figure 7. Microgripper jaw tip deflection vs. the film thickness of the Ni-Ti-Cu.

TESTING

The heat on the microgripper is applied by an IC fabricated thin film resistor heater pad. The microgripper is placed on this heater pad and as current is applied, the heat is transferred from the heater to the Si gripper to induce phase transformation in the Ni-Ti-Cu film. The actuation was viewed through a microscope onto a video screen, and video recordings will be presented at the conference. No local measurement of the temperature was attempted at the time.

DISCUSSION AND SUMMARY

In this paper a process of a practical silicon microgripper is described. Using processes that can be automated for batch fabrication, this microgripper has large gripping force (40 mN) and is actuated and at relatively low actuation temperatures (70°C). Fine alignment, Au-Si eutectic bonding, precision sawing, Ni-Ti-Cu SMA deposition, as well as bulk silicon machining are the core of the process. Processes in this paper, although not standard, do not involve exotic fabrication equipment. All the individual processes could be streamlined for batch processing and therefore reduce fabrication costs.

For future developments, the outer surfaces of the gripper are being integrated with heaters and strain sensors for remote active heating and feedback control. The hollow channel has the potential for either wire connection or injection of liquids and therapeutic medicine. Another important advantage is the possibility to apply alternative actuation mechanisms on the microgripper structure, either hydraulic or simply thermal bimorphic. Many creative designs of practical microgrippers can be conceived using this basic process.

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