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# Normally closed microgrippers using a highly stressed diamond-like carbon and Ni bimorph structure

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A normally closed microgripper with a radius of curvature of 18–50 μm using a diamond-like carbon (DLC) and stress free electroplated Ni bimorph structure has been demonstrated. The large curvature in the fingers of the microgrippers is due to the high compressive stress of the DLC layer. The radius of curvature of the figures can be adjusted by the thickness ratio, and the closure of the devices can also be adjusted by varying the finger length. This device works much more efficiently than other bimorph structures due to the large difference in thermal expansion coefficients between the DLC and the Ni layers. Preliminary electrical tests have shown these microgrippers can be opened by 60°–90° at an applied power of <20 mW. © *2004 American Institute of Physics*.

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The microgripper is an important microsystem component, which is useful in biomedical and biological applications where it can manipulate or isolate microcells and particles, or carry out localized cell probing and measurement. The requirements for microgrippers for such applications are: easy operation with low power consumption; low temperature and low voltage, as high temperature and high voltage will damage or even kill living cells. Much effort has been made to fabricate high performance microgrippers.[1–5] Microtweezers are one type of microgripper, typically made from thin film technology, and they are incapable of confining micro-objects due to their thin structure.[1–3] Microcages with multiple fingers of a bilayer structure are another type of microgripper,[4,5] which are able to confine and manipulate micro-objects. However these devices are normally open. A constant power or pressure is required to keep the microcage closed during operation. This increases the temperature of the microgripper and the surrounding environment. It is also difficult to close the fingers of microgripper solely by heating, except through an extremely high temperature or by use of very long fingers. The built-in thermal stress of a bimorph layer has previously been utilized to form precurved fingers, but the stress is insufficient to form a small closed microcage.[4] It requires long fingers to form a closed microcage but with a diameter typically greater than 500 μm, which is not suitable for biomedical applications.

A new concept has been developed to make nanostructures from strained semiconductors by selectively releasing the strained layers from the substrates.[6–8] The size of the nanostructures can be adjusted down to a few tens of nanometers by controlling the overall layer thickness, strain, and thickness ratio of the top and bottom layers. This technology however has been so far limited to crystalline materials grown by molecular beam epitaxy. Here we demonstrate the fabrication of a normally closed microgripper with a radius of curvature as small as ~18 $\mu$m using a highly stressed diamond like carbon (DLC) and electroplated Ni bimorph structure.

Figure 1(a) shows the cross section of the bimorph structure and Fig. 1(b) is the top view before being released. The bilayer structure consists of a compressively stressed DLC layer and a stress-free electroplated Ni over layer. Once it is released from the substrate, the DLC layer with a high compressive stress expands, lifts the bimorph layer upwards and forms a curved structure. The radius of curvature, R of such a bimorph structure is given by[9]

$$\frac{1}{R} = \frac{6\varepsilon(1+m)^2}{d\{3(1+m)^2+(1+mn)[m^2+(mn)^{-1}]\}} = \varepsilon \cdot S, \qquad (1)$$

where $\varepsilon$ is the strain, $d_1$, $E_1$, and $d_2$, $E_2$ the thicknesses and the Young's modulii of the DLC and the Ni layers, respectively, with $d=d_1+d_2$, $n=E_1/E_2$, and $m=d_1/d_2$. $S$ is a constant when the materials and the structure are fixed. The

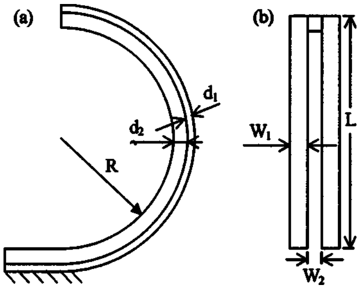

FIG. 1. (a) Cross section of a bilayer structure containing a highly stressed DLC and a stress-free Ni layer. The compressive stress caused the beam to bend upwards when released from the substrate; (b) the top view of a finger before being released.

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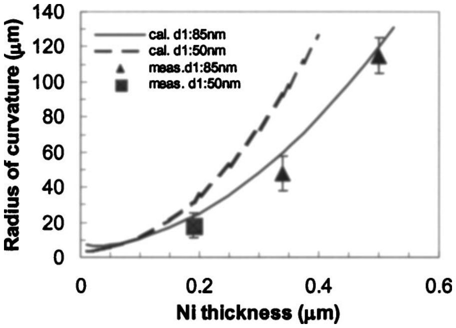

FIG. 2. Radius of curvature of a DLC/Ni bilayer as a function of Ni layer thickness for two thicknesses of DLC layer of 50 and 85 nm, respectively. The discrete points are extracted from the actual devices, showing a good agreement with the simulated results.

strain is related to the stress $\sigma$ and the Young's modulus $E_1$ of the DLC layer, by $\varepsilon = \sigma / E_1$. For a fixed DLC film thickness, the radius of curvature can be adjusted by varying the stress of the DLC layer and the thickness of the Ni layer or the thickness ratio. In order to make a normally closed microgripper, each finger has to curl up by ~180°. This can be realized by varying the radius of curvature at a fixed finger length, or by adjusting the finger length at a fixed radius of curvature. As demonstrated by other groups, the best way to make nanoscale curved structures is to reduce the layer thicknesses rather than by relying on in-plane patterning.[6–8] However, for biomedical applications such as capturing microcells, microgrippers with a certain strength and size are required, therefore microgrippers that are able to capture objects 10–100 µm in diameter are considered here. Figure 2 shows the calculated radius of curvature as a function of Ni layer thickness for two DLC thicknesses. The radius of curvature increases with increasing Ni thickness, as the thin DLC is not strong enough to lift the fingers. For a fixed Ni thickness, increasing the DLC thickness reduces the radius of curvature. The angle of curvature of the fingertip in degree is related to the finger length $L$ by:

$$\theta = 180L/\pi R. \tag{2}$$

In order to obtain a closed microgripper ($\theta = 180°$), the radius of curvature must be $R \sim L/\pi$. For a microgripper with a size of 10–100 µm in diameter, a Ni layer with a thickness of 100–350 nm is required if a DLC layer of 40–80 nm is used.

The operation of this device is simple. An increase in temperature causes the Ni metal to expand more than that of the DLC layer due to the difference in thermal expansion coefficients, and the radius of the curvature changes from $R_1$ to $R_2$, thus the thermal strain leads to an opening of the fingers by $\Delta\theta$:

$$\Delta\theta = \frac{180L}{\pi}\left(\frac{1}{R_1} - \frac{1}{R_2}\right) = \frac{180L}{\pi}\Delta\alpha \cdot \Delta T \cdot S, \tag{3}$$

where $\Delta\alpha\Delta\mathrm{T}$ is the thermal strain generated through resistive Joule heating of the Ni layer. For this normally closed microgripper, it is sufficient to open the fingers by 90° to release or catch a specimen.

There are two advantages in choosing the DLC layer as a bottom layer: First, the as-grown DLC films have a high compressive stress in the range of 4–10 GPa, which is equivalent to a strain of 0.7%–1.7%, which is similar in magnitude to that attained in nanostructures with strained semiconductors.[6–8] Second, the DLC has a low thermal expansion coefficient, $\alpha < 1 \times 10^{-6}$ and combination with a Ni layer of large $\alpha$ ($\sim 15 \times 10^{-6}$) makes this bimorph structure very efficient as thermal actuator. Furthermore, the DLC layer has a high stiffness and is a biocompatible material.

TABLE I. Summary of device parameters and results.

| Par. Name | S1 | S2 | S3 | S4 |
|---|---|---|---|---|
| DLC (nm) | 0 | 85 | 85 | 50 |
| Ni (nm) | 500 | 500 | 340 | 190 |
| L (µm) | 100 | 200 | 160 | 60 |
| Curv. (measured °) | 0 | 100 | 190 | 190 |
| Curv. (calculated °) | 0 | 80 | 170 | 180 |
| Radius (measured, µm) | $\propto$ | 115 | 48 | 18 |
| Radius (calculated. µm) | $\propto$ | 120 | 59 | 32 |

The fabricated microgrippers consisted of five or six fingers with layer thicknesses given in Table I. The finger length varied from 40 to 200 µm with 20 µm intervals. The width, $W_1$ of the metal stripes of the fingers and the gap, $W_2$ between them were both 4 µm. The fingers were connected to each other electrically and extended to the bond pads. The central part of the grippers was fabricated with a sufficiently large area so that it remained attached to the substrate after the fingers were released.

The fabrication process began with the deposition of DLC on the Si substrate using the filtered cathodic vacuum arc method.[10] The DLC layer had ~85% *sp*$^3$ content with a Young's modulus of ~600 GPa and a stress ~8 GPa.[10–12] As-deposited DLC films are insulators with a resistivity up to $10^7$ Ω cm, which ensures the isolation of the devices from the Si substrate. After deposition, a seed layer Cu/Cr with a thickness of ~30/2 nm was sputtered on the DLC layer. A plating mould was formed by optical photolithography using AZ5214 photoresist. It was then electroplated in a nickel sulphamate bath at optimal conditions of 4 mA/cm$^2$ and 60°C.[13,14] After plating, the photoresist and the seed layer away from the devices were removed by acetone and a chromium etchant, respectively. The DLC outside the active area was removed by an $O_2$ plasma etching using the patterned Ni metal as an etch mask. Finally the devices were released by $SF_6$ reactive ion etching to remove the Si substrate beneath the fingers.

Figure 3(a) shows a SEM picture of a six-finger Ni microgripper frame without a DLC layer (device S1). The Ni

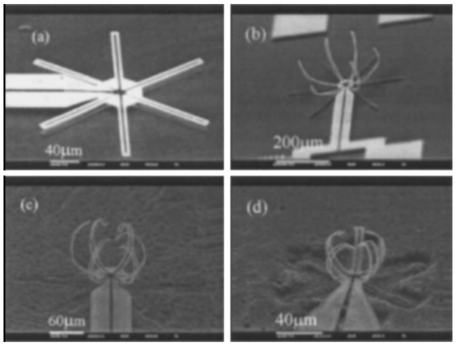

FIG. 3. (a) SEM picture of a Ni microgripper frame (device S1, without a DLC layer) with a finger length of 100 µm; (b)–(d) SEM images of devices S2–S4 with various DLC/Ni thickness ratios and finger length. Device S4 is a fully closed microcage with a diameter of ~40 $\mu$m.

fingers are straight without any curvature visible, indicating there is no gradient stress.[14] Figure 3(b) shows a SEM micrograph of a six-finger microgripper (device S2). The fingers curled up with a curvature of ~100°, which is not sufficient to form a closed cage. From the analysis above, it was calculated that with this thicknesses of DLC/Ni layers, a finger with a length of ~400 $\mu$m would form a closed microgripper with a diameter >100 $\mu$m. Figure 3(c) shows a SEM picture of device S3. The fingers curled upwards by ~190° forming a fully closed microcage. The radius of curvature of the fingers is ~50 $\mu$m. Although this microgripper is suitable for capturing objects of size 100–150 μm, it is still too big to manipulate biological specimens of size 20–50 μm, such as *E*-coli. By reducing the Ni thickness, devices with a smaller radius of curvature may be realized. Figure 3(d) is SEM photograph of a five-fingers microgripper (device S4). The fingers curled up by ~190°, forming a closed microgripper with a radius of curvature of ~18 $\mu$m. The device parameters, measured, and calculated, are summarized in Table I. The extracted radii of curvature of these devices were plotted in Fig. 2 together with the simulated results. In these calculations for the curvatures $1/R$, the Cu seed layer has been treated as a part of the Ni layer with the same Young's modulus. The agreement between the experimental results and the simulated ones is good, but the difference becomes greater as the DLC layer becomes thinner. The extracted radius of curvature $R\sim 18$ $\mu$m for device S4 is much smaller than the theoretical value $R\sim 32$ $\mu$m. There are a few reasons for this difference. First, the thermal stress of the electroplated Ni layer at 60°C has been ignored. When cooled to room temperature, the contraction of the Ni layer will curl the bimorph structure slightly upwards. Second, the DLC film has a high differential stress, which typically makes the released layers curl upward.[15] Third, the Cu seed layer has a smaller Young's modulus than Ni and thus the bimorph structure should curl up more than calculated. The factors make more significant contribution as the Ni film becomes thinner. A detailed study taking all factors is underway.

The operation of this normally closed microgripper is fundamentally different from normally open devices. A pulsed current is required to open the cage, rather than supplying a constant current. The heat generated by a pulsed current can be minimized without raising the temperature of the environment, which is an important criterion for biomedical applications. Preliminary electrical tests have confirmed that these devices work well, and the fingers can be opened by 60°–90° at a power of <20 mW. Also it is confirmed that a pulsed current with a duration of a few tens milliseconds is sufficient to open the micro cages. Figure 4(a) shows an optical micrograph of device S3 with no current applied and Fig. 4(b) the same device when a current pulse of 8.1 mA was applied. The finger opened laterally by ~60 $\mu$m (~70°) at a power of ~16 mW, which is much lower than other devices.

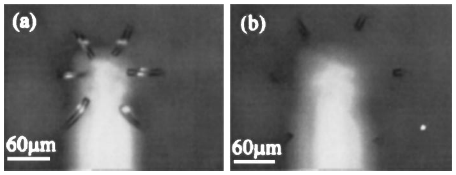

FIG. 4. (a) Micrograph of device S3 with $L=160$ $\mu$m with no current applied; (b) the same device when a current of 8.1 mA was applied, the fingers opened laterally by ~60 $\mu$m.

In conclusion, a normally closed microgripper has been proposed and fabricated. This device is made from a highly stressed diamond like carbon and stress free electroplated Ni bimorph structure. By adjusting the ratio of the bilayer thickness and the finger length, a normally closed microgripper has been demonstrated. The radius of curvature is in the range of 18–50 μm, which is suitable the capture of microstructures with the sizes of 20–100 μm, such as biological cells. This type of device has the advantage of low power consumption and a low operation temperature. The preliminary electrical test has shown that they can be opened by 60°–90° at a power of less than 20 mW.

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