# Surface adhesion reduction in silicon microstructures using femtosecond laser pulses

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A reduction of the adhesion between polysilicon surface-micromachined structures and its silicon substrate using ultrashort pulse laser irradiation has been demonstrated. Polysilicon cantilevers, which adhered to the silicon substrate after final rinse and dry, were freed after irradiation by a 800 nm wavelength laser with pulse duration of 150 fs (full width at half-maximum) and fluences up to 40 mJ/cm$^2$. Increasing the pulse widths to 2.7 ps resulted in significantly fewer freed cantilevers indicating that the process depends heavily on the presence of high-temperature carriers in the silicon. Adhesion reduction has been observed from exposure to a single pulse which results in minimal lattice temperature increase. 
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Silicon surface-micromachined microelectromechanical systems (MEMS) often employ suspended microstructures that have large areas but small gap distances to the underlying substrate. Under certain conditions, these microstructures make contact with and become adhered to the substrate because their restoring force is insufficient to overcome the surface adhesion. This sticking and high static friction is often termed stiction and is a device failure mechanism of major concern in MEMS. Many types of surface adhesion forces are responsible for stiction, but a major contributor appears to be from capillary liquids.[1,2] Stiction often occurs in the final fabrication step of releasing microstructures. During the drying of the rinse liquid after the etch of sacrificial layers, the surface tension of the liquid can pull down the structures into contact with the substrate. Stiction can also occur during operation of the device. External forces from acceleration or electrostatic actuation can cause contact of the microstructure to the substrate and moisture in the ambient environment can lead to trapped capillary liquids. Techniques to reduce such device failure fall into three general categories: (1) preventing contact during release by circumventing drying in a rinse liquid and instead using such methods as critical point drying,[3] sublimation,[4] or dry etching;[5] (2) altering the surfaces to lower adhesion such as by reducing contact area, or by creating stable hydrophobic surfaces to prevent the presence of capillary liquids such as water;[6] (3) freeing structures stuck to the substrate using procedures such as rapid thermal annealing[7] or electromagnetic pulses.[8]

Capillary forces are believed to be significant in the adhesion between silicon surfaces because of the hydrophilic native oxide that readily forms on silicon. The desorption of the trapped capillary liquid would reduce the surface adhesion and possibly allow the separation of the microstructures. Desorption induced by ultrashort-pulse laser irradiation has been recently demonstrated for metals.[9] Adsorbates brought to an excited electronic state by energetic electrons in the solid can desorb from the surface. The excitation of carriers, electrons in metals and electron-hole pairs in semiconductors, can be achieved by laser irradiation less than or on the order of the time scale of the energy relaxation time of electrons to phonons. In silicon, irradiation by a laser pulse with duration less than a picosecond, will result in carriers with extremely high temperatures compared to the lattice.[10]

We describe the use of femtosecond-pulse laser irradiation to reduce the adhesion of silicon microstructures to the underlying silicon substrate and allow the microstructure to free itself. This noncontact procedure requires no additional fabrication and can be performed with minimal lattice heating.

Arrays of undoped polycrystalline silicon cantilevers with varying lengths were fabricated to observe and quantify the reduction in the surface adhesion. Each array had beams with lengths that began at 60 $\mu$m and increased in 20 $\mu$m increments. The cantilevers were 2.3 $\mu$m thick and 2.2 $\mu$m above the substrate. The fabrication involved conventional polysilicon surface-micromachining. A sacrificial layer of low-temperature oxide (LTO) was deposited by low-pressure

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chemical vapor deposition (LPCVD) to a thickness of 2.2 $\mu$m and patterned to allow the polysilicon layer to be anchored to the substrate. The openings for the anchors were etched in fluorine-based ($CF_4$) plasma. Next, the structural undoped polysilicon layer was deposited by LPCVD and annealed at 1050 °C for 60 min. The polysilicon was patterned and etched in a chlorine-based ($Cl_2$) plasma to form the test structures.

The sacrificial layers were removed by wet etching in hydrofluoric acid in order to release the cantilevers. After a water rinse, the silicon surfaces were made hydrophilic by immersion in hydrogen peroxide for 10 min which was followed by another water rinse. The evaporation of the water, under an IR lamp, caused most of the cantilevers to collapse and adhere to the substrate.

A measurement of the surface adhesion can be made by observing the length at which the beams in the array have enough restoring force to free themselves from the substrate. Typically, only the 60 $\mu$m long cantilevers were stiff enough to remain free-standing. A relation between the surface adhesion energy, $\gamma_s$, and the detachment length, $l$,[11] is given in Eq. (1), where $E$ is Young's modulus, $t$ is the thickness of the beam, and $h$ is the gap between the beam and the substrate.

$$\gamma_s = \frac{3}{8}\frac{Et^3h^2}{l^4}. \tag{1}$$

For a Young's modulus of 170 GPa and a detachment length of 60 $\mu$m, the surface adhesion energy is calculated to be 290 mJ/m$^2$ which is in good agreement with results by Mastrangelo and Hsu.[11] Surface adhesion reduction after laser irradiation would cause additional cantilevers to be freed.

The laser system used in the experiment is a Ti:sapphire oscillator regenerative amplifier system which produces 800 nm wavelength laser pulses at 600 $\mu$J per pulse with a repetition rate of 1 kHz. Each sample consisted of 14 arrays of cantilevers and was illuminated by laser pulses of variable pulse width and fluence. The pulse width was changed by translating the retroreflector in the compressor stage and was measured using second harmonic autocorrelation. To vary the laser fluence, the beam spot size on the sample was changed by placing the sample at different distances from the lenses used to focus the light.

The first samples were irradiated for 5 s by laser pulses of 150 fs in duration at a fluence of 20 mJ/cm$^2$. As is shown in the scanning electron microscope (SEM) picture in Fig. 1(b), cantilevers up to 120 $\mu$m in length were freed. In this sample, 60% of the beams stuck on the surface that were 120 $\mu$m long or less were freed after laser irradiation. Another sample was also irradiated under the same laser conditions except for the pulse width which was increased to 2.7 ps. Even though the energy deposited was the same, no cantilevers were freed (beyond the 60 $\mu$m beam that was free after release). An example of which is shown in the SEM picture in Fig. 1(a).

Experiments were further performed where the fluence was varied from 10 mJ/cm$^2$ to 20 mJ/cm$^2$ for the two different pulse widths. The results as presented in the plot in Fig. 2, show that the number of cantilevers freed increases as the

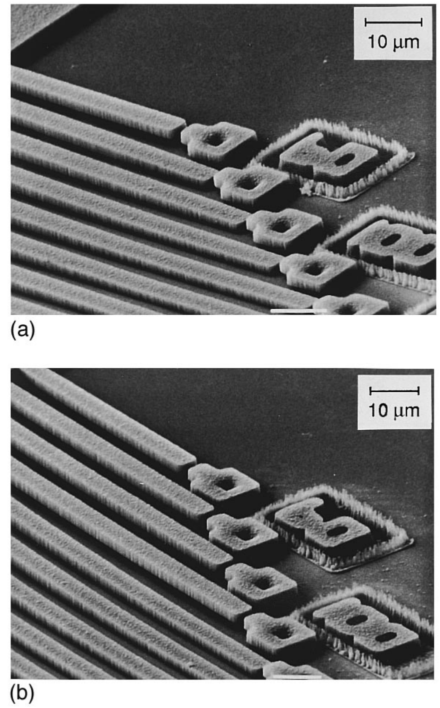


FIG. 1. (a) Scanning electron microscope image of a cantilever array after exposure to 2.7 ps laser pulses at a fluence of 20 mJ/cm$^2$ no change was observed. (Only first beam from the top, which is 60 $\mu$m long, is free.) (b) Image of an array after exposure to 150 fs laser pulses at a fluence of 20 mJ/cm$^2$. Beams up to 120 $\mu$m have been freed. (The first four beams from the top are free.)

fluence increases for the samples illuminated by the 150 fs pulses. The plot also clearly show that much fewer cantilevers were freed in those samples exposed to the 2.7 ps pulses. These results make it evident that subpicosecond pulse widths are necessary for this technique and strongly indicates that the reduction in the adhesion force of the cantilever to the substrate is closely related to the presence of high carrier temperatures.

Our calculations[12] have shown that for a single laser pulse, extremely high electron-hole pair temperatures would

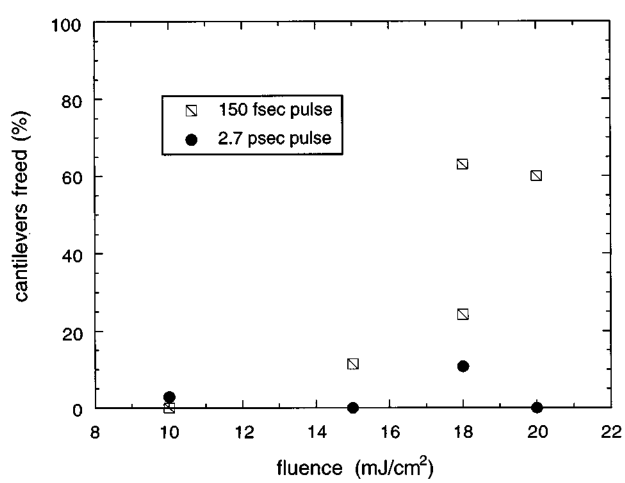


FIG. 2. A plot of the percentage of stuck cantilevers 120 $\mu$m in length or less that were freed after exposure to laser pulses of 150 fs and 2.7 ps.

TABLE I. Surface adhesion energy after laser irradiation.

| Fluence ($mJ/cm^2$) | Detachment length ($\mu m$) | Surface adhesion energy ($mJ/cm^2$) |
|---|---|---|
| 0 | 60 | 0.029 |
| 20 | 120 | 0.0018 |
| 40 | 140 | 0.00098 |

exist throughout the cantilever, while the lattice remains cool. Excited carriers would also be present in the surface region of the silicon substrate. In a final experiment, samples were irradiated by a single 150 fs pulse at a fluence of 40 $mJ/cm^2$. Many cantilevers up to 140 $\mu m$ in length were freed. We estimate using a simple energy balance that for this single pulse exposure, the lattice temperature increased no more than 20 °C. That cantilevers were freed under these conditions strongly suggests that thermal mechanisms are not involved and add further evidence that this technique depends on excited carriers in silicon.

The amount of surface adhesion energy reduction caused by the laser irradiation can be calculated using Eq. (1) and is shown in Table 1. For a change in the detachment length from 60 to 140 $\mu m$, the surface adhesion energy was reduced by a factor of 30, from 290 $mJ/m^2$ to 9.8 $mJ/m^2$.

These results confirm the feasibility of stiction recovery for silicon microstructures using ultrashort-pulse laser irradiation. A factor of 30 decrease in adhesion energy between polysilicon cantilevers and their silicon substrate has been demonstrated. The results also indicate that this technique strongly depends on the presence of high-temperature carriers generated by femtosecond laser pulses and that the lattice temperature can remain relatively unchanged. Further studies with different test structures will be needed to obtain more precise measurements of the adhesion energy reduction and to better measure and improve yield.

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[1] P. R. Scheeper, J. A. Voorthuyzen, W. Olthuis, and P. Bergveld, Sens. Actuators A **30**, 231 (1992).
[2] R. L. Alley, K. Komvopoulos, and R. T. Howe, J. Appl. Phys. **76**, 5731 (1994).
[3] G. T. Mulhern, D. S. Soane, and R. T. Howe, in *Proceedings of the 7th International Conference on Solid-State Sensors and Actuators (Transducers '93)*, Yokohama, Japan, 7–10 June 1993 (Institute of Electrical Engineers, Japan, 1993), p. 296.
[4] H. Guckel, J. J. Sniegowski, T. R. Christenson, S. Mohney, and T. F. Kelly, Sens. Actuators **20**, 117 (1989).
[5] D. Kobayashi, C.-J. Kim, and H. Fujita, Jpn. J. Appl. Phys. **32**, L1642 (1993).
[6] M. R. Houston and R. Maboudian, J. Appl. Phys. **78**, 3801 (1995).
[7] T. Abe, W. C. Messner, and M. L. Reed, J. Microelectromechanical Systems, **4**, 66 (1995).
[8] B. P. Gogoi and C. H. Mastrangelo, in *Proceedings of the 8th International Conference on Solid-State Sensors and Actuators (Transducers '95) and Eurosensors IX*, Stockholm, Sweden, 25–29 June 1995 (Royal Swedish Academy of Engineering Sciences IVA, Stockholm, Sweden, 1995), p. 214.
[9] J. A. Prybyla, T. F. Heinz, J. A. Misewich, M. M. T. Loy, and J. H. Glowina, Phys. Rev. Lett. **64**, 1537 (1990).
[10] J. R. Goldman and J. A. Prybyla, Phys. Rev. Lett. **72**, 1364 (1994).
[11] C. H. Mastrangelo and C. H. Hsu, J. Microelectromechanical Systems, **2**, 44 (1993).
[12] K. Fushinobu, L. M. Phinney, and N. C. Tien, Int. J. Heat Mass Transfer (to be published).