

Drastic enhancement of nanoelectromechanical-system fabrication yield using electron-beam deposition

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The most common fabrication processes of nanoelectromechanical structures usually start with a silicon-on-insulator chip and incorporate several lithography and etch steps. The wet etch step, which involves hydrofluoric acid, is generally the most critical of these processing steps. In this letter, we present an enhancement of the wet etch step which relies on electron-beam deposition. The technique of electron-beam deposition utilizes a protective carbon layer which is applied by a scanning electron microscope. It allows us to resolve typical problems associated with the wet etch step and drastically increases the yield.

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For the last decade, freely suspended nanoelectromechanical systems (NEMS) have been the subject of intense research and development. The reason for this interest is that they offer a wide area of important applications which include sensors of unprecedented precision;^{1–4} low-power, highly integrated, narrow-band, ultrahigh frequency filters,⁵ and on-chip mass spectrometers.⁶ However, the fabrication of nanomechanical structures is a low yield process. In this letter, we present an enhanced fabrication technique that resolves problems connected with the wet etch step.

To create NEMS like the one shown in Fig. 1, we obtain a silicon-on-insulator (SOI) chip composed of three layers: A silicon substrate, a 400 nm silicon dioxide layer, and a 200 nm silicon top layer. We spin coat a resist on the chip's surface, write the desired structure into the resist with a scanning electron microscope (SEM), and develop the exposed area. After these steps, we deposit a 2 nm layer of titanium, a 10 nm layer of gold, and a 10 nm layer of aluminium onto the surface of the chip by means of thermal evaporation. We use hot acetone to lift off the unexposed resist and the metal above it. As a result, we are left with a metal structure on top of the SOI chip [see Fig. 1(a)]. Next, we utilize reactive ion etching (RIE) to vertically etch through 200 nm of silicon and into the silicon dioxide layer. The aluminium pattern shields the gold and silicon areas lying beneath it from the RIE. Finally, we are left with the embossed structure sketched in Fig. 1(b) and shown in the electron-beam (e-beam) micrograph of Fig. 3(a). The metal island circled in Fig. 3(a) is fabricated using a second lithography step. The entire sacrificial layer process is illustrated in Refs. 7 and 8.

In the wet etch step, we immerse the structure in a buffered hydrofluoric acid. Usually, buffered hydrofluoric acid will etch silicon dioxide but not silicon. We expect the acid to underetch the thinner beamlike parts of the structure—about 100 nm in width—and to eventually leave them freely suspended. The wider parts of the structure are not completely underetched, because of their width. These parts are

left supported by the silicon dioxide sacrificial layer. After the wet etch step, the final structure should look like those shown in Figs. 1(c) and 1(d).

The most problematic issue arising from the wet etch step is the unintentional damage of the silicon layer under the smaller features of the metal structure [see right box of Fig. 3(d)]. This damage, which could be caused by a local buffer breakdown of the buffered hydrofluoric acid, renders the structure useless. A further problem is that after a structure becomes freely suspended, it is sensitive to external forces. These forces include the surface tensions of fluids used during processing steps. The left box of Fig. 3(d) highlights a cantilever that has been bent down toward the substrate by such forces.

The technique of e-beam deposition (EBD) can be used to overcome these problems. When a structure is pictured with an SEM, residual gas atoms present in the vacuum chamber will be gettered on the areas hit by the electron

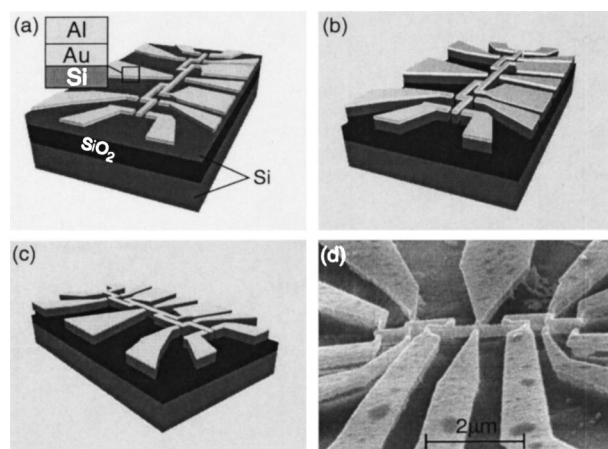


FIG. 1. (a) Structure after thermal evaporation and lift-off steps. (b) Structure after RIE. (c) Freely suspended structure after underetching with a buffered hydrofluoric acid. (d) Electron micrograph of the final, freely suspended structure.

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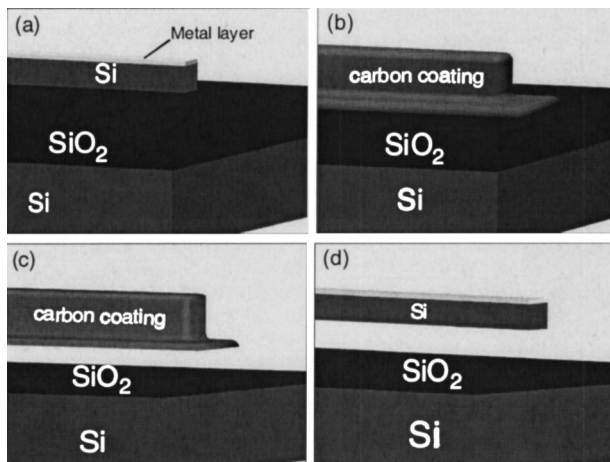


FIG. 2. The figure illustrates the principle of the enhanced fabrication process by EBD. (a) A simple beam structured by RIE. (b) The structure after it was coated with a carbon layer by focusing an electron beam on it. (c) The structure after it was treated by hydrofluoric acid which underetched the beam by removing the silicon dioxide. (d) The freely suspended beam after the carbon layer was removed by oxygen plasma etching.

beam. The deposited material mainly consists of carbon which comes from lubricants used in mechanical parts and pumps of the SEM system.⁹ Hence, a carbon layer is deposited onto the structure. The thickness of this layer depends on the deposition time, the composition of the residual gas, and the energy, current, and focusing area of the electron beam. The undesired damage of silicon parts in the wet etch step can be avoided if such a layer is intentionally deposited by focusing an electron beam onto these structures for about 20 s [see Fig. 2(b)]. Although the deposited carbon layer will protect the silicon structure from being etched, the hydrofluoric acid will still underetch these parts and their carbon coating [see Fig. 2(c)].

As previously mentioned, another problem associated with the fabrication of NEMS is that they lose rigidity during the wet etch step and become prone to damage induced by the surface tensions of liquids. In some cases, applying a sufficiently thick carbon layer will create an excess of material that interconnects closely spaced parts and serves as structural reinforcement. When the NEMS become freely suspended in the wet etch step, this interconnecting layer will serve to increase their overall stability [see Fig. 3(b)]. However, this carbon layer is not a desired element of the final design as it is expected to have negative influence on the mechanical and electrical properties of the structure; therefore, we use oxygen plasma etching to remove it [Fig. 3(c)]. The technique of oxygen plasma etching utilizes a high-frequency field to ionize oxygen and create oxygen radicals which react with organic material to form carbon dioxide and water.

Overall, we processed fifty-five structures with the wet etch step. In thirty-three cases in which no EBD was facilitated, the structures were not only underetched but also strongly damaged by the hydrofluoric acid [Fig. 3(d)]. We attribute successful processing of the twenty-two undamaged structures to the fact that they had all been coated with a protective carbon layer before the wet etch step. These results indicate an increase of the yield up to a 100% in this etch step. To provide further evidence that it is, in fact, the carbon layer which protects the structures from being etch damaged, we simultaneously processed structures on the

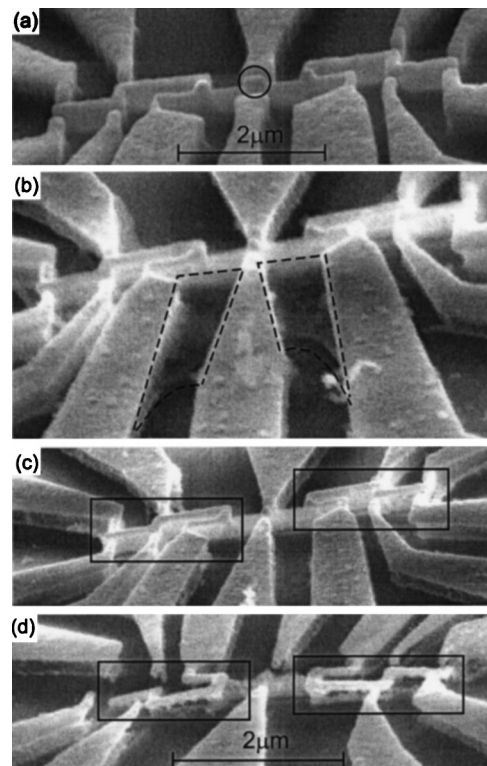


FIG. 3. (a) The structure just after the RIE on which a carbon layer is deposited before the wet etch step. (b) The freely suspended structure after the wet etch step; the area encircled by the dashed line identifies the carbon reinforcement. (c) The structure shown in (b) after it has been exposed to oxygen plasma etching. The carbon reinforcement present in (b) is completely removed. The beam structures identified by the squares are not destroyed like those shown in (d). The freely suspended structure is shown in its final stage. (d) A damaged structure not treated with EBD before being etched with buffered hydrofluoric acid. The squares identify parts of the structures which have been significantly damaged by the etch procedure. In these areas, the silicon directly under the metal coating is almost completely removed. The beamlike structure in the left square is bent down.

same chip with the wet etch step. We only treated some of these structures with EBD. We found that only those structures which had been coated with a carbon layer were protected from etch damage.

In related work, similar difficulties with the wet etch step were encountered.¹⁰ We conclude that our EBD coating has a significant impact on the yield of silicon-based NEMS structures; therefore, we expect that our application of EBD will lead to a significant reduction of development time and cost in the research field of silicon-based NEMS. This technique may also bring NEMS technology one step closer to commercial production. It has to be noted that, in principle, laser light can be used for material deposition as well.¹¹

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¹M. L. Roukes, *Phys. World* **14**, 25 (2001).

²X. M. H. Huang, C. A. Zorman, M. Mehregany, and M. L. Roukes, *Nature* (London) **421**, 496 (2003).

³A. N. Cleland and M. L. Roukes, *Appl. Phys. Lett.* **69**, 2653 (1996).

⁴B. Ilic, D. Czaplewski, and H. G. Craighead, *Appl. Phys. Lett.* **77**, 450 (2000).

- ⁵C. T.-C. Nguyen, IEEE Trans. Microwave Theory Tech. **47**, 1486 (1999).
- ⁶Nickolay, V. Lavrik, and P. G. Datskos, Appl. Phys. Lett. **82**, 2697 (2003).
- ⁷A. Erbe, C. Weiss, W. Zwerger, and R. H. Blick, Phys. Rev. Lett. **87**, 096106 (2001).
- ⁸D. V. Scheible, A. Erbe, and R. H. Blick, New J. Phys. **4**, 86.1 (2002).
- ⁹M. Wendel, H. Lorenz, and J. P. Kotthaus, Appl. Phys. Lett. **67**, 3732 (1995).
- ¹⁰A. Erbe, Ph.D. dissertation, Ludwig-Maximilians-Universität, 2000.
- ¹¹K. Ghandehari, B. LaFontaine, and B. Singh, U.S. Patent No. 6,589,717.