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BRIEF REPORTS AND COMMENTS

This section is intended for the publication of (1) brief reports which do not require the formal structure of regular journal articles, and (2) comments on items previously published in the journal.

Method on surface roughness modification to alleviate stiction of microstructures

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Modification on surface roughness has been shown to effectively alleviate both release and in-use stiction in the previous literature. However, the modified materials in the previously reported methods were limited to polysilicon or single crystalline silicon with special properties. Here, the proposed modification method not only can apply to silicon without extra property requirements, but also has the potential to modify other materials, such as oxide, nitride, and some metals. The process here combines spin-on photoresist and reactive ion etching. The proposed low temperature process is simple, and no extra mask is needed. Consequently, there is more flexibility to add the roughness modification to the original fabrication process of microdevices. In this study, polysilicon and silicon nitride are demonstrated as the modified materials. Antistiction effects are characterized by calibrating the water contact angles on the modified surfaces and the detachment lengths of released cantilevers. The experimental results show that the detachment length is almost two times longer than the cantilevers without modified substrates, where the interfacial surface energy between solids is reduced about 15 times. © *2003 American Vacuum Society.* [DOI: 10.1116/1.1592809]

I. INTRODUCTION

Stiction is one of the important factors that affect the reliability and yields of microcomponents.[1] The phenomenon may occur either in the drying step of the sacrificial layer removal process, or by over-range shock during the device operation, so-called the ''release stiction'' and ''in-use stiction,'' respectively.[2] Because surface roughness modification can alleviate the interfacial surface energy by reducing the contact area between the structure and substrate, it can alleviate both kinds of stiction problems.

Referring to the previous research, avoiding the liquid drying process,[3–5] changing water meniscus shape,[6] or using tethers as temporary supports [7–11] can only alleviate release stiction. On the other hand, release and in-use stiction can be alleviated by coating antistiction materials,[12–17] hydrogen passivation,[18] or reducing the surface energy between contact solids by dimples[19] and surface roughness modification.[1,20,21] However, antistiction coating and hydrogen passivation on the partial regions are difficult and may degrade at high temperature. Surface modification methods are attractive, because they can work on the selective region and also can be used in conjunction with dimples and low-energy coatings for the greater effect.[20] In 1993, Alley *et al.* combined thermal oxidation and a reactive ion etching (RIE) process to texture the polysilicon layer with large grains.[20] Resulting from high etch selectivity and passivation effects, the original uneven surface was exaggerated to form pyramid-shaped asperities. Later Yee *et al.* applied heavy doping and thermal oxidation to polysilicon, followed by a two-step RIE, where honeycomb-shaped grain holes were formed on the surface.[1] In 1999, Matsumoto *et al.* performed a silicon anodization process to the silicon on insulator substrate, hillocks were formed on the surface, and a larger water contact angle was obtained.[21] However, the modified materials in the above methods were all limited to polysilicon or single crystalline silicon with special properties.

Here, a method on surface roughness modification by combining spin-on photoresist and a RIE process is proposed. The principle is based on an uneven etch of the photoresist by RIE, where the photoresist acts as the transferring template. Therefore part of the underneath material will be exposed and be etched according to the uneven photoresist template. The roughness of the underneath material is then modified after the proper etch. Since the modification principle is based on the etched photoresist as the modification template, the material underneath the photoresist is not restricted by material properties, but only by RIE recipes. It means that the proposed modification process not only can apply to single or polycrystalline silicon, but also has the potential to modify other materials, such as silicon nitride, oxide, or some metals. Besides, this modification process does not have to change the original fabrication process of the devices, and no extra mask is needed. These advantages

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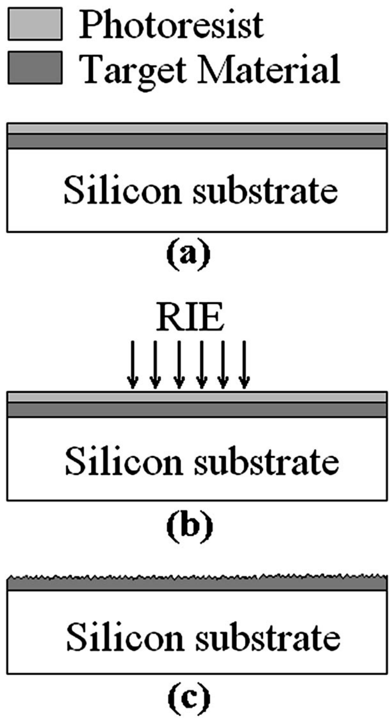

FIG. 1. Processes of modification on surface roughness: (a) spinning photoresist on the target material; (b) etching the photoresist and target material by RIE; and (c) modifying the target material successfully.

make design or fabrication processing of microdevices more flexible. Here, polysilicon and silicon nitride are demonstrated as the modified materials. The water contact angle measurement and cantilever beam array technique are used to characterize the antistiction effects of the proposed method.

II. SURFACE MODIFICATION

The general process of the proposed surface-modification method is schematically shown in Fig. 1. The modified materials can be polysilicon, single-crystalline silicon, nitride, oxide, or metals, and there is no special property requirement. First, a thin layer of positive photoresist is spun on the surface of the material that is desired to be modified, the so-called target surface [Fig. 1(a)]. After hard bake of the photoresist, RIE with proper gases is performed to etch the photoresist, then the underneath target surface [Fig. 1(b)]. Uneven etching is achieved on the photoresist, which then serves as a transferring template to make the target material experience an uneven etch also. Consequently, the target surface is modified to be a rough surface, as shown in Fig. 1(c).

Here, polysilicon and silicon nitride are used as target materials to demonstrate the surface roughness modification. The detail parameters of the process are listed in Table I.

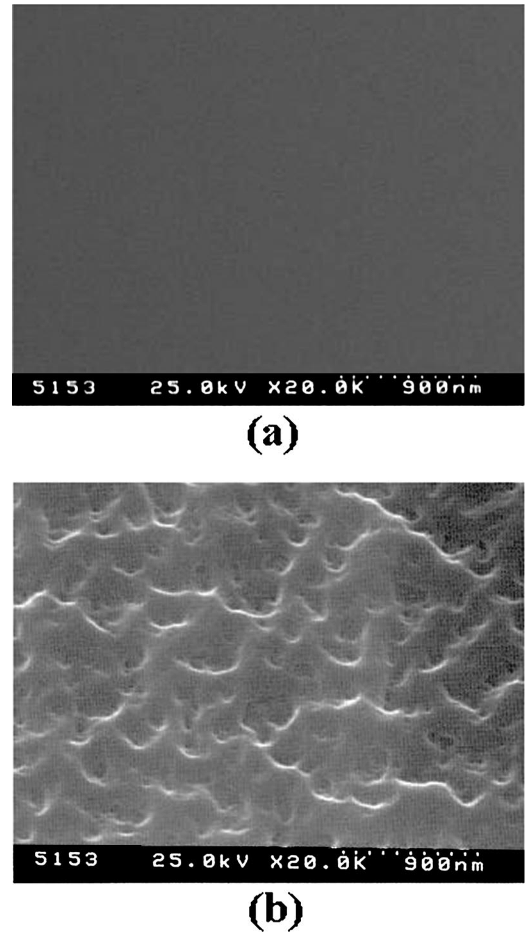

FIG. 2. (a) Topography of the photoresist after hot bake but before RIE process and (b) topography of the photoresist after RIE for 3 min.

TABLE I. Processes of surface roughness modification for polysilicon and silicon nitride.

Step	Process
Photoresist spin	1 μm Fujifilm FH-6400 spin and baking at 120 °C for 5 min
RIE with proper working time	$SF_6:O_2=20:4$ sccm at 20 mTorr and rf = 100 W
Removal of residual resist	$H_2SO_4:H_2O_2=3:1$ with hot bath for 15 min

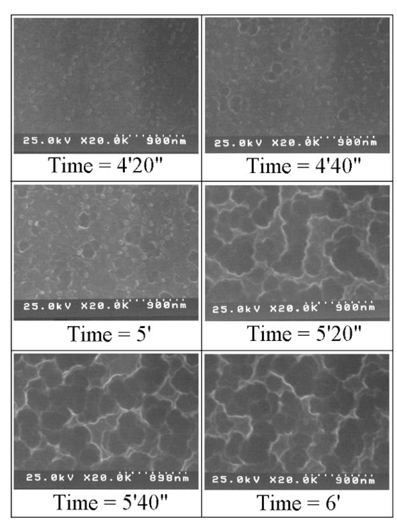

FIG. 3. SEM of the surface of polysilicon with different modification times.

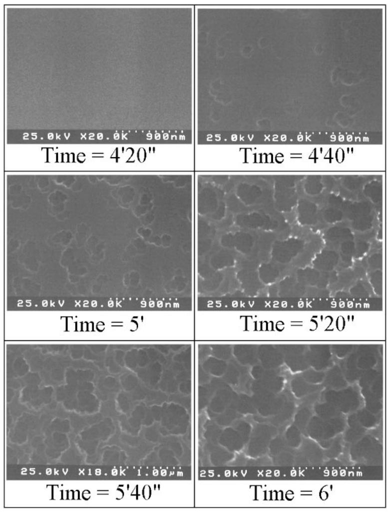

FIG. 4. SEM of the surface of silicon nitride with different modification times.

First, a thin layer of positive photoresist is spun and baked. This layer just serves as the transferring template, so the exposure process is not needed. Then, the wafer is put into the RIE (SAMCO RIE-10N) chamber with the etch gases of SF_6 and O_2. The etch rates of this recipe are about 2300, 2000, and 1400 Å/min for photoresist, polysilicon, and silicon nitride, respectively. Using the same etch gases for the photoresist and the target material has the advantage of simplifying the modification process. The RIE time in the process, the so-called modification time, is determined from the thickness of photoresist and the antistiction effect of the target material. After the RIE process, residual photoresist is removed by the solution of sulfuric acid and hydrogen peroxide.

Figures 2(a) and 2(b) show the scanning electron microscope (SEM) images of the photoresist before and after the RIE process, respectively. Before RIE, the surface of the photoresist is very smooth even at 20 000× magnification. After RIE for 3 min, the surface of the photoresist has been roughened by the etch, and a lot of pinholes can be observed, as shown in Fig. 2(b). At this point the target material is not yet revealed and still protected by photoresist. With longer etching time, the target surface underneath the pinhole region is then attacked by the RIE, and the attacked area of the target surface will grow with the increasing pinhole region of the photoresist. Therefore, the rough topography of photoresist is transferred into the target material due to this time difference. Figures 3 and 4 show the surface status of polysilicon and silicon nitride as the target materials for various modification times, respectively. The modification time varies from 4 min 20 s to 6 min with an interval of 20 s. The experimental results indicate that the target material below the photoresist layer starts to etch at around 4 min 40 s. With the increase of etching time, the topography of the photoresist is transferred into the target materials gradually, and a greater percentage of the target surfaces is etched. It is also found that the topography shows an evident transformation between 5 min and 5 min 20 s. The photoresist layer is presumed to be fully stripped within this interval because the thickness of the modified polysilicon is averagely reduced by 310, 1000, and 1750 Å at 5 min 20 s, 5 min 40 s, and 6 min, respectively.

III. CHARACTERIZATION

In order to further characterize the properties of the modified surfaces by the proposed method, some techniques in addition to SEM are used here. First, an atomic force microscope (AFM) is used to obtain the surface roughness and surface profile. Figure 5 shows one example of a surface profile measurement using an AFM. Then the water contact angles are measured to calibrate the change of the adhesion energy due to the roughness variation. Finally, a detachment length technique, i.e., different lengths of cantilevers above the target materials, is performed to verify the effects in alleviating stiction between the contact solids.

In the water contact angle measurement, a de-ionized (DI) water droplet is placed on the surface of the target material, and a contact angle is formed between the liquid and the

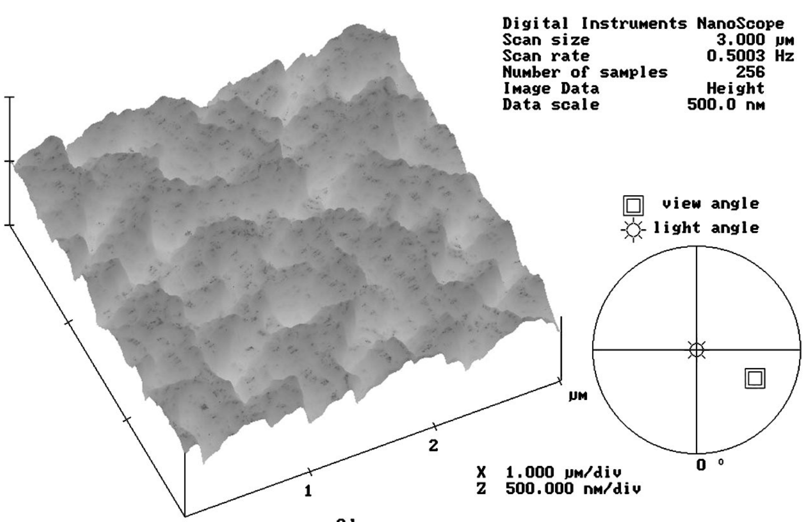

FIG. 5. Surface profile of modified polysilicon with the modification time of 5 min 20 s by AFM.

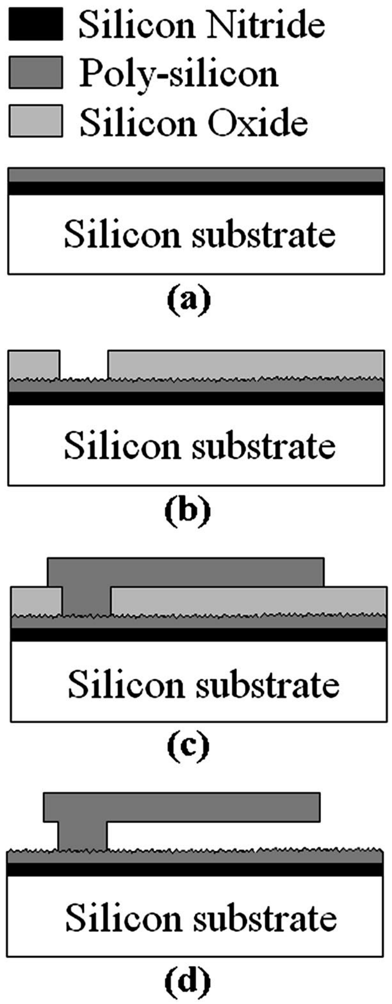

FIG. 6. Fabrication process of the cantilever beam array for the test of antistiction effect.

solid surfaces due to the equilibrium of the surface tensions. The adhesion energy between the water and the surface in the unit area W_{SW} can be written as

$$W_{SW} = \gamma_L (1 + \cos\theta), \quad (1)$$

where γ_L is the surface tension of water and θ is the water contact angle.[22,23] According to the above equation, the adhesion energy can vary from $2\gamma_L$ ($\theta = 0$) to zero ($\theta = \pi$). It can also be found that a larger water contact angle represents smaller adhesion energy between the water and the surface. In this study, the water contact angle is determined from the image captured by a digital camera.

Since the surface roughness modification can reduce the interfacial surface energy between the suspended structure and substrate to alleviate both release and in-use stiction, the popular cantilever beam array technique[24] is also used here to characterize the antistiction effect. The relationship between the detachment length of the cantilever, l_d, and the interfacial surface energy, W, can be expressed as the following equation:

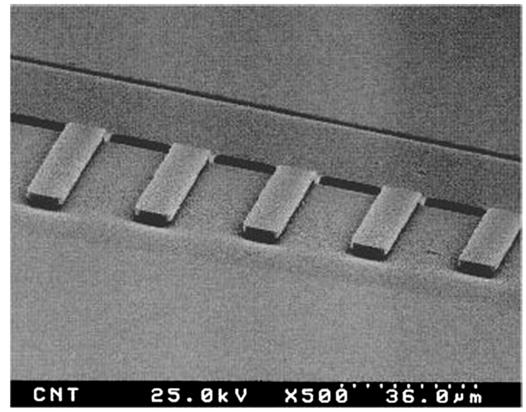

FIG. 7. Fabrication result of a cantilever array for the test of antistiction effect.

$$W = \frac{3}{8} \frac{E h^2 t^3}{l_d^4}, \quad (2)$$

where E is Young's modulus, h is the spacing between the cantilever and the substrate, and t is the thickness of the cantilevers.[2] The efficiency of antistiction then can be characterized by comparing the detachment lengths and the interfacial surface energy with and without the modification process.

In experiments, a cantilever array made of polysilicon with various lengths is fabricated above the target material. The width, thickness of the cantilevers, and height above the substrate are 10, 2, and 2 μm, respectively. The cantilever lengths range from 50 to 1500 μm in every 10 μm. Here, polysilicon and silicon nitride are used as the target materials in the antistiction tests. The fabrication process with polysilicon as the target material is shown in Fig. 6. First, 0.5 μm thick silicon nitride and 0.6 μm thick polysilicon are deposited on a (100) silicon wafer, respectively [Fig. 6(a)]. This polysilicon layer is used as the target material, and the surface modification process described in Fig. 1 and Table I is performed with different modification times. Later, a 2 μm thick oxide layer is deposited as the sacrificial layer. The regions of anchors are defined by mask No. 1, as shown in Fig. 6(b). Then, another polysilicon layer with 2 μm thickness is deposited as the structure layer of cantilevers, followed by annealing at 1100 °C for 2 h in N_2 ambient. Cantilever beams with various lengths are patterned by mask No. 2 and etched by RIE [Fig. 6(c)]. Finally, the cantilevers are released by pure HF solution for 10 min, rinsed by isopropyl alcohol for 1 h, and dried by a hot plate at 120 °C for 1 h [Fig. 6(d)]. When silicon nitride acts as the target material, the process is similar, only the 0.6 μm thick polysilicon is not grown on the silicon nitride layer. Figure 7 shows the fabrication result of a cantilever array with various lengths for the test of antistiction effect. The detachment length is determined by SEM observation, and the results will be shown and discussed together with the surface roughness and the water contact angles in Sec. IV.

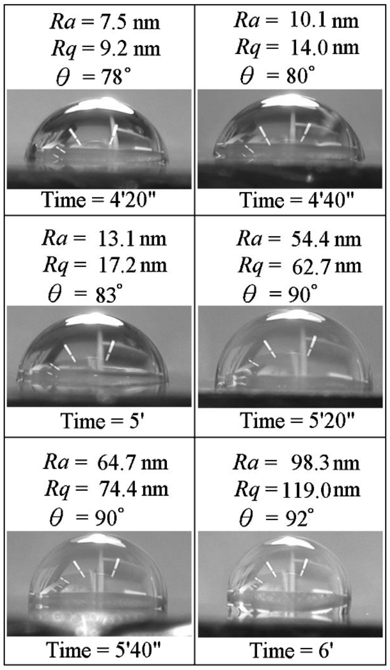

FIG. 8. Surface roughness Ra and Rq and the water contact angle θ on polysilicon surfaces for various modification times.

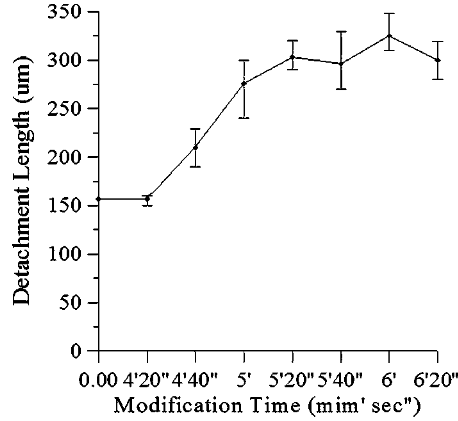

FIG. 9. Detachment lengths of 10 μm wide cantilevers for various modification times with polysilicon as the target material in roughness modification.

IV. RESULTS AND DISCUSSION

In the experiments, the modified polysilicon surface is first treated with rinsing in DI water for 10 min, dilute HF for 1 min, DI water for 10 min again, dried by N_2 purge, and baking at 90 °C on a hot plate for 30 min. Instantly, the water contact angle is determined from images captured by the digital camera. Figure 8 shows the calibrating results of water contact angle and surface roughness on the modified surface when the target material is polysilicon, where the mean roughness Ra and root-mean square roughness Rq are determined by AFM. In the period from 4 min 20 s to 5 min the surface roughness slightly increases with the time, as does the water contact angle. At 5 min 20 s, surface roughness and the water contact angle both have more obvious changes compared to the previous period. The results can be explained by the SEM photographs shown in Fig. 3, where the topography at these modification times changes more evidently. After 5 min 20 s, the photoresist above the target material is fully etched away, and longer modification times can increase surface roughness further. However, longer modification times may not be able to further reduce the contact area and does not have an evident effect on the contact angle. From Eq. (1), this means that the adhesion energy before 5 min and after 5 min 20 s of modification time only changes slightly. Therefore the critical modification time falls in the period from 5 min to 5 min 20 s, where the adhesion energy between the water droplet and the modified surface is reduced evidently. When silicon nitride is used as the modified material, a similar trend is observed, which is not shown here.

The measurement results of the detachment lengths with the upper and lower bounds are plotted in Fig. 9 using polysilicon as the target material under different modification times. Without the surface modification, the detachment length is found to be about 155 μm. At 4 min 20 s modification time, the improvement on the detachment length is not obvious, because the photoresist still protects the target surface. With longer modification times, the detachment length increases until 5 min 20 s. After 5 min 20 s, the detachment length does not always increase, but just falls in the region around 300 μm, which is almost two times longer than the cantilever without a modified surface, and the interfacial surface energy of solids is reduced about 15 times according to Eq. (2). These results are consistent with the measurement results of the water contact angle. This indicates that longer modification times can increase the surface roughness, but does not always reduce the adhesion energy and the interfacial surface energy. For the case of silicon nitride as the target material, the trend of the detachment length variation is almost the same as the results of polysilicon. But the detachment lengths are slightly different; they are approximately equal to 180 and 320 μm for 4 min 20 s and 5 min 20 s of modification times, respectively. This indicates that the interfacial surface energy of polysilicon–polysilicon and polysilicon–silicon nitride is different.

V. CONCLUSIONS

A method to modify surface roughness, which combines spin-on photoresist and RIE processing, is proposed and verified here. The method only needs to add several steps in the original fabrication process of microdevices and no extra mask is needed. In addition, because the principle is based on etching photoresist as the modification template, the modified material underneath the photoresist can be more flexible, and not limited to polysilicon and single crystalline silicon. Experimental results show that by using the proposed method, detachment lengths can be almost twice as long as the cantilevers without modified substrates, where the interfacial surface energy between the solids is reduced about 15 times. However, the proposed method on antistiction has its limitation once a critical modification time is reached, about 5 min 20 s in our case.

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[1]Y. Yee, K. Chun, J. D. Lee, and C-J. Kim, Sens. Actuators A **52**, 145 (1996).
[2]R. Maboudian and R. T. Howe, J. Vac. Sci. Technol. B **15**, 1 (1997).
[3]H. Guckel, J. J. Saniegowski, and T. R. Christenson, Proceedings of IEEE Micro Electro Mechanical Systems, Salt Lake City, UT, 20–22 February, 1989, p. 71.
[4]G. T. Mulhern, D. S. Soane, and R. T. Howe, Proceedings of 7th International Conference on Solid-State Sensors and Actuators, Transducer '93, Yokohama, Japan, 7–10 June, 1993, p. 296.
[5]J. H. Lee, W. I. Jang, C. S. Lee, Y. I. Lee, C. A. Choi, J. T. Baek, and H. J. Yoo, Sens. Actuators A **64**, 27 (1998).
[6]T. Abe, W. C. Messner, and M. L. Reed, J. Microelectromech. Syst. **4**, 66 (1995).
[7]D. Kobayashi, C.-J. Kim, and H. Fujita, Jpn. J. Appl. Phys., Part 1 **32**, 1642 (1993).
[8]C. H. Mastrangelo and G. S. Saloka, Proceedings of IEEE Micro Electro Mechanical Systems, Fort Lauderdale, FL, 7–10 February, 1993, p. 77.
[9]F. Kozlowski, N. Lindmair, T. Scheiter, C. Hierold, and W. Lang, Sens. Actuators A **54**, 659 (1996).
[10]Z. Xiao, Y. Hao, T. Li, G. Zhang, S. Liu, and G. Wu, J. Micromech. Microeng. **9**, 300 (1999).
[11]M. A. Benitez, J. A. Plaza, S. Q. Sheng, and J. Esteve, J. Micromech. Microeng. **6**, 36 (1996).
[12]P. F. Man, B. P. Gogoi, and C. H. Mastrangelo, J. Microelectromech. Syst. **6**, 25 (1997).
[13]B. K. Smith, J. J. Sniegowski, G. L. Vigne, and C. Brown, Sens. Actuators A **70**, 159 (1998).
[14]U. Srinivasan, M. R. Houston, and R. T. Howe, J. Microelectromech. Syst. **7**, 252 (1998).
[15]R. Maboudian, W. R. Ashurst, and C. Carraro, Sens. Actuators A **82**, 219 (2000).
[16]W. R. Ashurst, C. Yau, C. Carraro, C. Lee, G. J. Kluth, R. T. Howe, and R. Maboudian, Sens. Actuators A **91**, 239 (2001).
[17]B. H. Kim, T. D. Chung, C. H. Oh, and K. Chun, J. Microelectromech. Syst. **10**, 33 (2001).
[18]M. R. Houston, R. Maboudian, and R. T. Howe, Proceedings of 8th International Conference on Solid-State Sensors and Actuators, Transducer '95, Stockholm, Sweden, 25–29 June, 1995, p. 210.
[19]T. Abe, W. C. Messner, and M. L. Reed, Proceedings of IEEE Micro Electro Mechanical Systems, Amsterdam, Netherlands, 29 January–2 February, 1995, p. 94.
[20]R. L. Alley, P. Mai, K. Komvopoulos, and R. T. Howe, Proceedings of 7th International Conference on Solid-State Sensors and Actuators, Transducer '93, Yokohama, Japan, 7–10 June, 1993, p. 288.
[21]Y. Matsumoto, T. Shimada, and M. Ishida, Sens. Actuators A **72**, 153 (1999).
[22]A. W. Adamson, *Physical Chemistry of Surfaces*, 5th ed. (Wiley, New York, 1990).
[23]B. W. Rossiter and R. C. Baetzold, *Physical Methods of Chemistry, Part A*, 2nd ed. (Wiley, New York, 1993).
[24]C. H. Mastrangelo and C. H. Hsu, Proceedings of Solid-State Sensor Actuator Workshop, Hilton Head, SC, 22–25 June, 1992, p. 208.