Recovery of Stiction-Failed MEMS Structures Using Laser-Induced Stress Waves

Vijay Gupta, *Member, ASME*, Richard Snow, Ming C. Wu, *Fellow, IEEE*, Amit Jain, and Jui-che Tsai

***Abstract*—Stiction, or adhesion between suspended structures and the underlying surface, is a hurdle in batch fabricating long, freestanding MEMS structures. A novel technique is presented in this paper to release stiction. In this technique, a nanosecond rise time stress wave is launched on the backside of the Si substrate by impinging a 2.5 ns-duration Nd:YAG laser pulse onto a 3-mm-dia area. The compressive stress wave propagates through the Si substrate and arrives at the site of several stiction-failed cantilevers on the front Si surface. The compressive stress wave propagates through the cantilevered structures and is reflected into a tensile wave from their free surfaces. The returning tensile wave pries off the interface, releasing the cantilevers. The procedure is demonstrated on a MEMS chip with stiction-failed cantilevers with varying lengths from 100 $\mu\mathrm{m}$ to 1000 $\mu\mathrm{m}$. The threshold laser energy to release stiction increased linearly with cantilever lengths. Beam recovery began at a laser fluence of 11 $\mathrm{kJ/m^2}$ laser energy. 70% of the tested beams had been recovered after impingement with a fluence of 26 $\mathrm{kJ/m^2}$. After the highest applied laser fluence of 40 $\mathrm{kJ/m^2}$, 90% of the tested beams had been recovered. No damage to the structures or surrounding features was observed below 40 $\mathrm{kJ/m^2}$. Because of rather low laser fluence, no thermal damage to the back surface of Si was noted. Since it literally takes few seconds to release stiction, the proposed technique can be implemented in MEMS foundry, and for repair of in-use stiction failed MEMS devices. [1178]**

***Index Terms*—Laser, laser heating, MEMS devices, stiction release, stress wave.**

I. INTRODUCTION

In MEMS fabrication, wet chemical etchants are often used to remove sacrificial material to release cantilevered structures. This process often leaves the rinse solution to be trapped between the cantilevered structures and the surface below. During drying, capillary forces are setup which pulls the cantilever down to the substrate. Other forces maintain the stiction effect between the beam and the substrate after the liquid has evaporated.

Numerous techniques have been explored to resolve this problem [1]–[12], illustrated in Fig. 1. However, most of these techniques have undesirable tradeoffs such as requiring expensive and time-consuming processing, altering the design features, or failing to release all the structures without damage. Techniques such as sublimation and supercritical heating reduce stiction by avoiding the evaporative transition from liquid to vapor that often results in stiction failed structures. Both techniques require time for heating and cooling. Supercritical heating provides more consistent results but requires a more complicated setup [3]. The use of dimples to reduce the contact surface area, the use of polymer posts to temporarily support the cantilevered structures before being removed by dry etching, and the use of low surface energy self assembled monolayers all add complexity to the design or manufacturing process which limits their use as a universal solution. Using low surface energy rinses such as methanol does not always prevent stiction. Manually removing stiction with probe tips is often risky and is not a batch fabrication process. Clearly there is a need for a quick, simple method for recovering stiction failed devices.

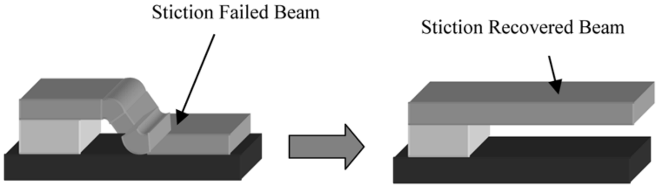

Fig. 1. Representation of a stiction-failed cantilever before and after recovery.

Laser energy has been employed by Rogers and Phinney [13]–[15] to quickly heat up stiction failed structures. Differences in thermal expansion increase the strain energy in beams, which provides the driving force for overcoming the stiction forces. This process requires direct heating of MEMS structures to about 50 °C above the temperature of the substrate. While this relative temperature seems quite low, the absolute temperatures these structures were exposed to were not reported. In any case, directly exposing the MEMS structures to laser energy can cause undesired damage to sensitive structures such as those made out of polymeric and cellular materials in newer types of MEMS devices.

An appealing alternative to the above techniques is presented in this paper wherein a previously developed laser spallation technique for measuring the tensile strength of thin film interfaces is adapted to release stiction-failed microcantilevers. In the laser spallation technique, a compressive stress wave is generated on the backside of the substrate disc (e.g., Si wafer) by exfoliating a waterglass-constrained metallic film using a 3–5 ns duration Nd:YAG laser pulse. The compressive wave propagates through the substrate and film and arrives at the free surface where it is reflected into a tensile wave. This tensile wave separates the film from the interface. The transient free surface velocity of the film during its separation is recorded using an interferometer and is used to calculate the desired interface tensile strength. Details of the technique can be found in a series of papers [16]–[20]. The results presented here show remarkable

---

Manuscript received October 15, 2003; revised January 10, 2004. The work of V. Gupta was supported by the ARO under Grant DAAD19-00-1-0491 and the NSF under Grant ECS 0000334. Subject Editor N. de Rooij.

V. Gupta, R. Snow, and A. Jain are with the Department of Mechanical and Aerospace Engineering, University of California, Los Angeles, CA 90095-1597 USA (e-mail: vgupta@ucla.edu).

M. C. Wu and J. Tsai are with the Department of Electrical Engineering, University of California, Los Angeles, CA 90095-1597 USA.

Digital Object Identifier 10.1109/JMEMS.2004.832185

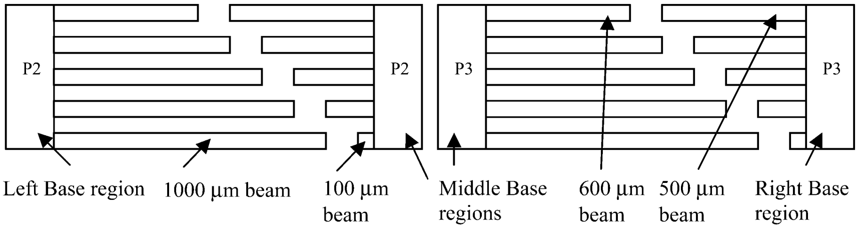

Fig. 2. Spatial pattern of the two arrays of cantilevers used for testing. Base regions are areas where the cantilevers are attached to the substrate.

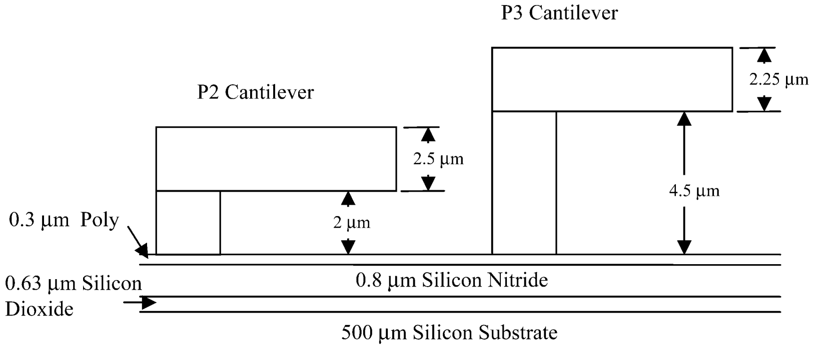

Fig. 3. Dimensions of cantilevered beams and the underlying films.

success in adapting this technique in releasing stiction-failed cantilevers in a MEMS device with lengths ranging from 100 to 1000 μm. The stiction was virtually released within seconds and that too under ambient conditions without any collateral damage to adjacent features.

II. EXPERIMENTAL DETAILS

A. Sample Preparation

The test structures were manufactured with Sandia National Lab's SUMMiT IV process. They consisted of two arrays P2 and P3 of cantilevered beams made from polysilicon ranging in length from 100 to 1000 μm in 100 μm increments, each with a width of 20 μm, as shown in Fig. 2. The cantilevers in the P2 array were nominally 2.5 μm thick with a 2 μm gap below, while the P3 array consisted of beams with 2.25μm nominal thickness and with a 4.5 μm gap (see Fig. 3).

The structures were released in HF according to the SUMMiT release process except no stiction removal or evaporation steps were performed after the final isopropyl alcohol rinse. The chip was stored to allow air evaporation. The cantilevered beams were then observed under an optical microscope. By comparing the focal depth on the top of the cantilevered beam with that of the substrate below, the stiction failed beams were differentiated from the nonfailed beams.

B. Experimental Setup and Procedure

The 2.8 mm × 6.3 mm chip was sandwiched between two transparent plastic holding plates that had a drilled hole toward their top half sections. The chip was positioned such that the test structures showed through the holes as shown in Fig. 4. The mounted sample was placed onto a x-y-z stage such that the bare Si substrate surface that was free of any MEMS features faced the Nd:YAG laser source. The YAG laser was then focused onto a 3-mm-diameter area as shown in Fig. 5. Unlike the basic laser spallation experiment procedure where a Al laser-energy absorbing film and a sandwiching waterglass layer were used, here, neither one of these layers was necessary as sufficient stress wave amplitudes necessary to release the cantilevers could be generated by directly impinging the laser pulse onto the bare Si surface. To properly align the cantilevers in the path of laser-generated stress waves, a He-Ne laser, which was prealigned with the axis of the YAG laser beam, was used as shown in Fig. 5.

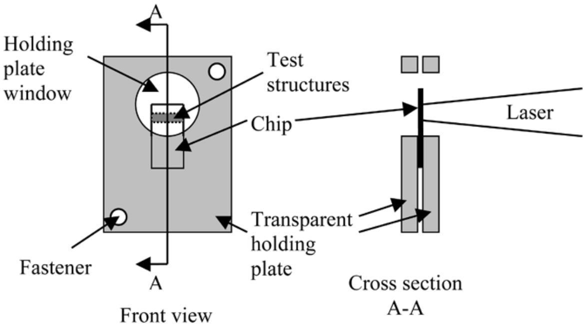

Fig. 4. Chip mounting setup.

Since the purpose of these experiments was simply to release stiction and not quantify the interfacial adhesion, the transient velocity of the cantilever film surfaces was not recorded using interferometry.

The test procedure included, impinging the YAG laser beam onto a 3 mm-diameter area directly behind the test structures. The laser beam energy was measured prior to each shot. After each stress wave pulse loading, the test structures were examined under an optical microscope to observe for any release or damage to adjacent structures.The experiments were started with a laser pulse energy of 52 mJ and increased in increments of 20 to 30 mJ until all cantilevers were fully recovered. Because of the rather low laser fluence, the same spot on the Si wafer could be repeatedly shot by the YAG laser. This was not possible to do in the original laser spallation test where the need to generate higher stress pulse amplitudes resulted in blasting away of both the Al and the waterglass layers from the shot area. The details of the stress wave generation

TABLE I
THE LENGTH OF CANTILEVER BEAMS RECOVERED AT VARIOUS LASER ENERGIES. THE SYMBOL (*) REFERS TO THE SECOND PULSE THE CHIP WAS SUBJECTED TO AT 282 MJ. THIS SECOND 282 MJ PULSE WAS VISUALLY DIRECTED AT THE LEFT P2 BASE. THE CROSSED OUT NUMBERS CORRESPOND TO THE LENGTHS OF THE BEAMS THAT WERE LOST AFTER THE CORRESPONDING LASER PULSE

Laser Energy (mJ)	Laser Fluence (kJ/m^2)	Longest P2 Cantilever Beam Length without Stiction (μm)		Longest P3 Cantilever Beam Length without Stiction (μm)	
		Left	Middle	Middle	Right
Release					300
52	7.36				
77	10.89		100		400
96	13.58				
116	16.41			600	500
127	17.97			700, 800, 900	
143	20.23		200, 300		
166	23.48		400		
183	25.89		500		
209	29.57				
229	32.40	600			
248	35.08				
269	38.06				
282	39.89			1000	~~300~~
282 (*)	39.89	700, 800			~~300, 100~~

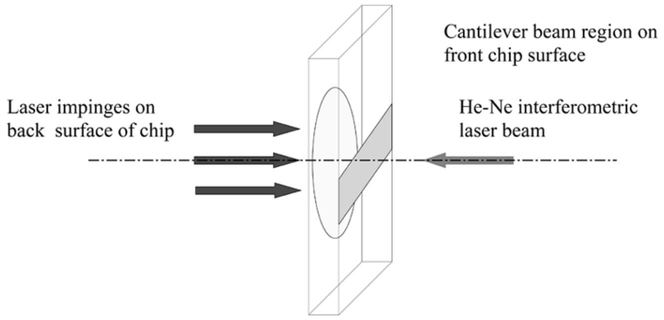

Fig. 5. Perspective view showing the experimental procedure.

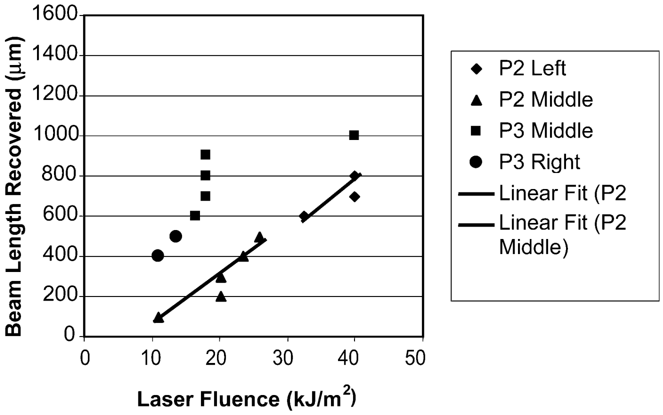

Fig. 6. A plot showing the variation in the required laser fluence to release stiction-failed cantilevers of a given length.

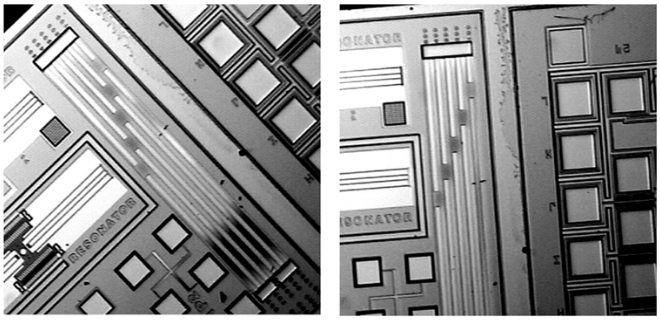
(a) (b)

Fig. 7. (a) A picture of the P3 array just before release. (b) The same array after the 166 mJ pulse loading.

mechanism through laser ablation and its measurement though interferometry are not provided here as they have been amply discussed previously [16]–[20].

III. RESULTS AND DISCUSSION

The experimental procedure was remarkably successful in releasing stiction-failed cantilevers. The critical laser energy for releasing cantilevers of different lengths is summarized in Table I. The same data is represented graphically in Fig. 6. The cantilevers are categorized as P2 Left, P2 Middle, P3 Middle, and P3 Right to describe their positions with respect to the axis of the Nd:YAG laser beam. Several points are noteworthy.

First, the critical laser fluence necessary to release stiction increases with the lengths of the failed cantilevers. This increase follows a linear trend for the P2 cantilever set but such a relationship cannot be claimed for the P3 set because of a lack of sufficient data points. This issue is somewhat less important as future users of this technique will have specific interface chemistries requiring different laser fluences for stiction release than those reported in this paper.

Throughout the testing, no visible damage to the test structures or their surrounding features was observed. This was confirmed by observing the chip under an optical microscope after each stress wave loading. Fig. 7(a) and (b) demonstrate this by showing no damage to the P3 array and its surrounding features after loading from a stress wave generated by a 166 mJ laser pulse. The first damage occurred with the first 282 mJ pulse, after which the 300 μm P3 beam was completely uprooted at its base. A subsequent second loading at the same intensity also led to a complete removal of the 100 μm long P3 beam. This can be seen in Fig. 8. Some laser-induced surface heat scarring on the backside of the Si substrate was also observed (Fig. 9). This

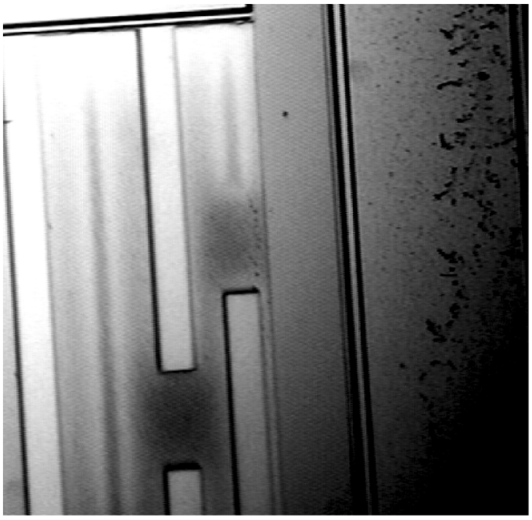

Fig. 8. Increased magnification of P3 array showing the missing 100 and 300 $\mu\mathrm{m}$ beams after the second 282 mJ pulse loading.

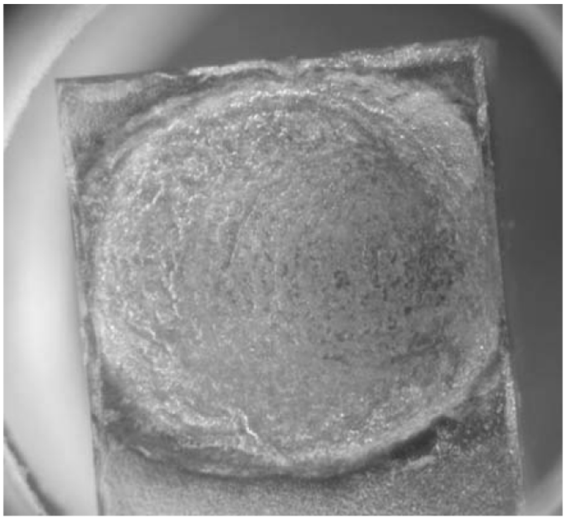

Fig. 9. An optical micrograph of the back surface of the Si substrate after the second impingement from the 282 mJ laser pulse. Some laser pulse-induced heat scarring can be observed.

damage was very near the surface and did not lead to any cracks in the substrate and in no way disturbed the MEMS features on the front surface.

From a practical standpoint the data above clearly demonstrates the usefulness of the technique in repairing stiction. Because it takes only few seconds to release the cantilevers, the technique should be easy to implement in any MEMS foundry, research lab setting, and can also be used to repair MEMS devices that fail due to in-use stiction.

It is of fundamental interest to understand the relationship between the laser fluence versus the lengths of repaired beams in different sectors. Qualitatively, the variation must be related to the minor spatial variation in the stress wave amplitude arising from the Gaussian distribution of the laser energy across its 3 mm-diameter area. A quantitative analysis is outside the scope of this paper because of the lack of sufficient data points. Similarly, the observed increase in the threshold laser energy to release cantilevers of increasing lengths can be explained qualitatively. The stiction-failed cantilevers trap strain energy by virtue of bending. This energy is higher for smaller length cantilevers for same subsurface gap or higher for higher subsurface gaps for same-length cantilevers. This trapped strain energy is however insufficient to overcome the fundamental interfacial energy necessary to release stiction. It appears that the additional strain energy is provided by the stress wave loading. This hypothesis is consistent with the data in Fig. 6, which shows that the P3 array with a higher subsurface gap than P2 array, requires lower laser threshold energy and hence a lower stress wave amplitude to release stiction. Additionally, for the same subsurface gaps, such as cantilevers within the P2 and P3 arrays, the required laser energy increases with the lengths of the cantilevers.

In addition to above, the longer cantilevers have a larger contact area with the substrate, and thus have a higher total interfacial energy compared with their shorter counterparts. Consequently, the longer cantilever beams should require higher stress wave energy for their release, which is consistent with the experimental observations.

IV. CONCLUSION

With long, free-standing structures often desirable in MEMS devices, effective and consistent processing techniques that do not lead to stiction failures are needed to manufacture them. In this communication, a novel method to repair stiction of long-aspect ratio cantilever structures is presented. The technique uses a laser-generated stress wave to decohere the interfaces of cantilevers.

The procedure was demonstrated on a MEMS chip with stiction-failed cantilevers with lengths increasing from 100 $\mu\mathrm{m}$ to 1000 $\mu\mathrm{m}$. The threshold laser energy to release stiction was found to increase with the cantilever lengths. Beam recovery began at a laser fluence of 11 $\mathrm{kJ/m^2}$ laser energy. 70% of the tested beams had been recovered after impingement with a fluence of 26 $\mathrm{kJ/m^2}$. After the highest applied laser fluence of 40 $\mathrm{kJ/m^2}$, 90% of the tested beams had been recovered. The technique works within few seconds, and it does not damage the test structures or their surroundings. Thus, the technique can be easily implemented in a MEMS foundry. Additionally, if access to the backside of an in-use stiction failed device can be gained, that device could be recovered.

REFERENCES

[1] B. P. Gogoi and C. H. Mastrangelo, "Adhesion release and yield enhancement of microstructures using pulsed Lorentz forces," *J. Microelectromech. Syst.*, vol. 4, pp. 185–192, 1995.

[2] V. Kaajakari, S. H. Kan, L. J. Lin, A. Lal, and S. Rodgers, "Ultrasonic actuation for MEMS dormancy-related stiction reduction," *Proc. SPIE*, vol. 4180, pp. 60–65, 2000.

[3] C. J. Kim, J. Kim, and B. Sridharan, "Comparative evaluation of drying techniques for surface micromachining," *Sensors and Actuators A: Physical*, vol. 64, pp. 17–26, 1998.

[4] N. Tas, T. Sonnenberg, H. Jansen, R. Legtenberg, and M. Elwenspoek, "Stiction in surface micromachining," *J. Micromech. Microeng.*, vol. 6, pp. 385–397, 1996.

[5] C. H. Mastrangelo, "Adhesion-related failure mechanisms in micromechanical devices," *Tribology Lett.*, vol. 3, pp. 223–238, 1997.

[6] R. Maboudian and R. T. Howe, "Critical review: Adhesion in surface micro-mechanicalstructures," *J. Vac. Sci. Technol.*, vol. B 15, pp. 1–20, 1997.

[7] G. T. Mulhern, D. S. Soane, and R. T. Howe, "Supercritical carbon dioxide drying of microstructures," in *Proc. Transducers '93, 7th Int. Conf. Solid-State Sensors and Actautors*, Yokohama, Japan, 1993, pp. 296–299.

[8] H. Guckel, J. J. Sniegowski, T. R. Christensen, and R. Raissi, "The application of fine-grained tensile polysilicon to mechanically resonant transducers," *Sens. Actuators*, vol. A21, pp. 346–351, 1990.

[9] T. Abe, W. C. Messner, and M. L. Reed, "Effective methods to prevent stiction during post-release-etch processing," *J. MEMS*, vol. 4, pp. 66–75, 1995.

[10] M. R. Houston, R. Maboudian, and R. T. Howe, "Self-assembled monolayer films as durable anti-stiction coatings for polysilicon microstructures," in *Proc. Tech. Dig. IEEE Solid-State Sensor and Actuator Workshop*, Hilton Head Island, SC, 1996, pp. 42–47.

[11] W. R. Ashurst, C. Yau, C. Carraro, C. Lee, G. J. Kluth, R. T. Howe, and R. Maboudian, "Alkene based monolayer films as anti-stiction coatings for polysilicon MEMS," *Sens. Actuators*, vol. A91, pp. 239–248, 2001.

[12] W. R. Ashurst, C. Yau, C. Carraro, R. Maboudian, and M. T. Dugger, "Dichlorodimethylsilane as an anti-stiction monolayer for MEMS: A comparison to the octadecyltrichlosilane self assembled monolayer," *J. Microelectromech. Syst.*, vol. 10, pp. 41–49, 2001.

[13] J. Rogers and L. Phinney, "Nanosecond laser repair of adhered MEMS structures," *ASME J. Heat Transfer*, vol. 124 , no. 2, pp. 394–396, 2002.

[14] L. M. Phinney and J. W. Rogers, "Pulsed laser repair of adhered surface-micromachined polycrystalline silicon cantilevers," *J. Adhes. Sci. Tech.*, vol. 17, no. 4, pp. 603–622, 2003.

[15] ——, "Process yields for laser repair of aged, stiction-failed, MEMS devices," *J. Microelectromech. Syst.*, vol. 10, pp. 280–285, June 2001.

[16] J. Yuan and V. Gupta, "Measurement of interface strength by the modified laser spallation technique. I. Experiment and simulation of the spallation process," *J. Appl. Phys.*, vol. 74, no. 4, pp. 2388–2396, 1993.

[17] V. Gupta and J. Yuan, "Measurement of interface strength by the modified laser spallation technique. II. Applications to metal/ceramic interfaces," *J. Appl. Phys.*, vol. 74, no. 4, pp. 2397–2404, 1993.

[18] J. Yuan, V. Gupta, and A. Pronin, "Measurement of interface strength by the modified laser spallation technique. III. Experimental optimization of the stress pulse," *J. Appl. Phys.*, vol. 74 , no. 4, pp. 2405–2410, 1993.

[19] A. N. Pronin and V. Gupta, "Measurement of thin film interface toughness by laser-generated stress pulses," *J. Mech. Phys. Solids*, vol. 46, no. 3, pp. 389–389, 1998.

[20] V. Gupta, J. Yuan, and A. N. Pronin, "Recent developments in the laser spallation technique to measure the interface strength and its relationship to interface toughness with applications to metal/ceramic, ceramic-ceramic and ceramic-polymer interfaces," *J. Adhes. Sci. Tech.*, vol. 8, no. 6, pp. 713–747, 1994.

Vijay Gupta received the Bachelor of Technology degree in 1985 in civil engineering from the Indian Institute of Technology, Bombay, and the M.S. degree in Civil Engineering (structures) and the Ph.D. degree in mechanical engineering from the Massachusetts Institute of Technology (MIT), Cambridge, in 1987 and 1989, respectively.

Currently, he is a Professor of Mechanical and Aerospace Engineering, and Professor of Materials Science and Engineering at the University of California, Los Angeles (UCLA). After starting as an Assistant Professor at Dartmouth College in 1990, he joined UCLA as a Full Professor in 1995. His research spans mechanical characterization of thin-film interfaces, biomechanics, ice mechanics, and composite materials. His work combines both experimental approaches and computer simulation. He has published over 120 journal articles and books, one patent, and has made over 200 invited presentations at international conferences, governmental agencies, and companies worldwide. He has chaired numerous international symposia in his field.

Prof. Gupta's honors include the 1993 Outstanding Young Scientist and Engineer Award from the International Union of Materials Research Societies, the 1998 Junior Achievement Award from American Academy of Mechanics, The Theodore Tromovitch Award from the American College of Mohs Micrographic Surgery, Institute Silver Medal from IIT Bombay, and the J. N. Tata Fellowship for the most outstanding engineering graduates of India in 1985. He is a member of the Sigma Xi, and Tau Beta Pi Engineering Honor Societies, and a Member of ASME, AAM, and MRS.

Richard Snow received the B.S. degree in mechanical engineering from Santa Clara University, CA, in 2000.

He worked as a product design engineer for a year before entering the Mechanical Engineering graduate school at University of California, Los Angeles (UCLA), receiving the M.S. degree in 2003. At UCLA, his interests included MEMS, microfabrication, and process control and optimization.

Ming C. Wu (S'82–M'83–SM'00–F'02) received the B.S. degree in electrical engineering from National Taiwan University in 1983 and the M.S. and Ph.D. degrees in electrical engineering and computer sciences from the University of California, Berkeley, in 1985 and 1988, respectively.

From 1988 to 1992, he was a Member of Technical Staff at AT&T Bell Laboratories, Murray Hill. In 1993, he joined the faculty of Electrical Engineering Department of UCLA, where he is currently Professor. He is also Director of UCLA's Nanoelectronics Research Facility, and Vice Chair for Industrial Relations. His current research interests include MicroElectroMechanical Systems (MEMS), Optical MEMS (MOEMS), biophotonics, microwave photonics, and high speed optoelectronics. He has published over 360 papers, contributed four book chapters, and holds 11 U.S. patents.

Dr. Wu was the founding Co-Chair for IEEE LEOS Summer Topical Meeting on Optical MEMS in 1996. The meeting has now evolved into IEEE LEOS International Conference on Optical MEMS that rotates among Europe, Asia, and U.S. Dr. Wu has also served in program committees of many other conferences, including optical fiber communications (OFC), conference on lasers and electrooptics (CLEO), IEEE Conference on Micro Electro Mechanical Systems (MEMS), LEOS Annual Meetings (LEOS), International Electron Device Meeting (IEDM), Device Research Conference (DRC), International Solid-State Circuit Conference (ISSCC), and Microwave Photonics (MWP) Conferences. He is a David and Lucile Packard Foundation Fellow (1992–1997).

Amit Jain received the B.S. degree in mechanical engineering from Indian Institute of Technology, Bombay, in 2001 and is currently pursuing the Ph.D. degree in mechanical engineering from University of California, Los Angeles.

His current research includes stress wave-induced direct pattern transfer procedure for efficient manufacturing of ICs and MEMS devices, quantification of moisture content in polyimide/silicon nitride interface, its effect on the tensile strength of the interface and its implications for electronic device reliability, and mechanism and quantification of intrinsic toughness in steel/composite joints under shock stress wave loading.

Jui-Che Tsai received the B.S. degree in electrical engineering from National Taiwan University (NTU), Taiwan, in 1997. He entered the Graduate Institute of Electro-optical Engineering at NTU after he completed his undergraduate study, and received the M.S. degree in electrooptical engineering in 1999. Between 1999 and 2001, he served in the military as a second lieutenant. Since 2001, he has been working towards the Ph.D. degree in the Electrical Engineering Department at the University of California, Los Angeles.

His research interests include Optical MEMS, and optical fiber communication.