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Laser bending for high-precision curvature adjustment of microcantilevers

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This work describes a laser based technique to adjust curvatures of silicon microcantilevers used for chemical and biological detection. In batch fabricated silicon cantilever arrays used for parallel sensing, it is often desirable that all cantilevers have nearly identical curvatures or flatness. We demonstrate that using the laser technique, it is possible to adjust curvatures by an amount as small as 3.5 μrad, for cantilevers with a typical dimension of $110 \times 13 \times 0.6\ \mu$m (length × width × thickness). Different laser parameters can be applied in order to achieve the required curvature adjustment. A two-dimensional finite element model of laser curvature adjustment is presented which enables the prediction of the laser processing parameters. © *2005 American Institute of Physics*. [DOI: 10.1063/1.1851617]

The use of micromechanical cantilevers in an atomic force microscope is a well-established application. Recently, microcantilevers have been successfully used as extremely sensitive physical, chemical, and biological sensors.[1–8] These microcantilevers can be batch fabricated by photolithography processes developed for integrated circuit manufacturing together with additional etching techniques.[9] For sensing applications, thin microcantilevers (less than 1 μm) are desirable in order to obtain higher sensitivity. Consequently, these microcantilevers are often very slender and compliant, vulnerable to external forces during fabrication processes including final steps of releasing, handling, and device operation. For instance, thermal stresses, surface adhesion forces, or tiny debris sitting on the cantilever tip can cause imperfection, resulting in undesired curvature of the microcantilever, out-of-plane deformation or even adhesion to the underlying substrate.[10] On the other hand, the curvature or flatness of a microcantilever is critical for microelectromechanical systems or microsensors where the optical beam deflection technique is used, i.e., a laser beam is focused onto the tip of a microcantilever and the reflected beam is received by a position sensing detector.[11] The microcantilever with an undesired downward-bent tip makes it difficult to be aligned and obtain high sensitivity. For sensors using microcantilever arrays,[4,5] identical curvatures of cantilevers are desirable. Techniques for adjusting curvatures of individual cantilever are needed.

Few methods have been developed to adjust curvature of a microcantilever because silicon is a brittle material and is hard to bend, and the dimensions of the microcantilevers are small. Frühauf, Gärtner, and Jansch proposed plastic reshaping of silicon microstructures.[12] However, their technique requires homogeneous heating over 700 °C and special reshaping tools fabricated from silicon wafer as well as microstructures. Gärtner and co-workers demonstrated that a silicon microcantilever can be bent up to 90° by using a Nd:yttrium–aluminum-garnet laser.[13] Ultrafast laser and nanosecond laser have been applied to repair microcantilevers that adhered to the substrate.[10,14]

In this work, we demonstrate a laser based technique for high precision adjustment of microcantilevers. Unlike previous work involving lasers for repairing microcantilevers that adhered to the substrate,[10,14] our technique is based on producing a residual strain at the surface of the cantilever material caused by the so-called temperature gradient mechanism,[15] which is explained as follows. When the laser beam irradiates the specimen surface, heating from the laser produces a sharp temperature gradient in the thickness direction, causing the upper layer of the heated material to expand more than the lower layers. Compressive stress and strain are produced by the bulk constraint of the surrounding cooler materials. Because of the high temperature achieved, plastic deformations occur. During cooling, heat flows into the adjacent area and the stress changes from compressive to tensile due to thermal shrinkage. However, the compressive strain generated during heating is not completely cancelled because of the temperature dependent nonlinear mechanical property of the material. As a result, the residual strain in the laser-irradiated area is compressive after the target cools, causing a permanent bending deformation toward the laser beam. This theory of laser bending has been confirmed by a number of studies by comparing the experimental data with the results of finite element calculations, and detailed descriptions of the theory can be found elsewhere.[16,17]

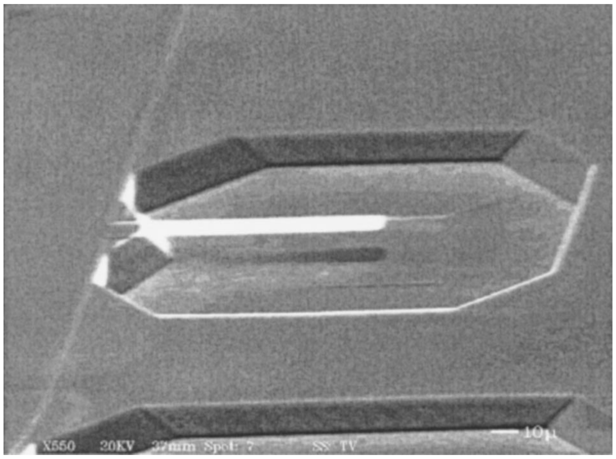

FIG. 1. SEM image of a silicon microcantilever (110 μm long, 13 μm wide, and 0.6 μm thick).

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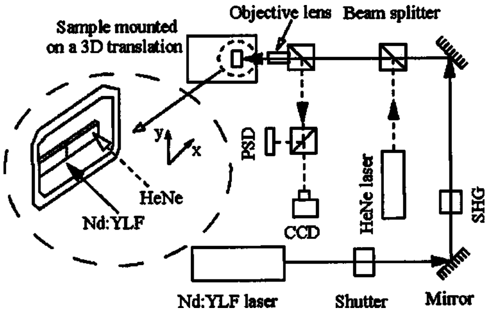

FIG. 2. Schematic experimental setup of the laser bending system.

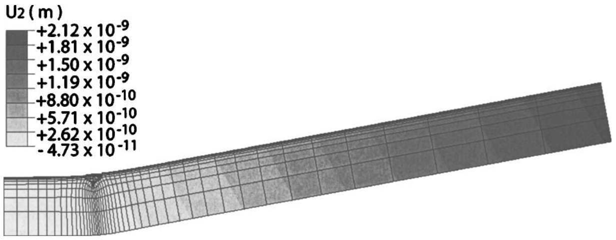

FIG. 4. Deflection distribution of the microcantilever after laser bending (laser pulse energy 0.32 μJ).

The samples used in our work are silicon microcantilevers fabricated using merged epitaxial lateral overgrowth of silicon followed by chemical mechanical polishing, which have been used for sensitive chemical and biological detection.[7,8] A scanning electron microscopy (SEM) image of the microcantilever is shown in Fig. 1. The dimensions of the microcantilever are 110 μm long, 13 μm wide, and 0.6 μm thick. In the laser bending experiment, the silicon wafer on which the microcantilever is fabricated is clamped on a three-dimensional (3D) motorized translation stage, as shown in Fig. 2. In order to irradiate the laser beam on the microcantilever precisely, a charge coupled device imaging system is used. The objective lens has a long work distance of about 20 mm. The same microscope objective lens is used for focusing laser beam to obtain an 8-μm-diam laser spot on the cantilever surface. The laser used is a pulsed frequency doubled Nd:YLF laser with a wavelength of 524 mm, pulsewidth of 20 ns, and a repetition rate of 2 kHz. The pulse energy varies from 0.18 to 0.32 μJ in the experiment. The advantage of using the frequency doubled green laser beam instead of its fundamental wavelength is that silicon has a much shorter optical absorption depth at the wavelength of 524 nm than that at infrared (1.047 μm).[14] The optical beam deflection technique for measuring cantilever bending is also shown in Fig. 2. A HeNe laser beam (the dashed line) is focused onto the free end of the cantilever and the reflected beam is received by a position sensing detector (PSD). The PSD readings can be converted into microcantilever bending angles after calibration. In the experiment, the cantilever moves along the *y* direction on the motorized stage at the constant speed of 250 μm/s.

The measured bending angle versus the laser pulse energy is shown in Fig. 3. The bending angle increases when the input laser pulse energy increases because high temperature and higher stress strain are produced with the use of higher pulse energy. The microcantilever always bends towards the laser beam direction, which agrees with the temperature gradient mechanism. (This means that only downward pre-curvature can be corrected, a limitation of this technique.) The sensitivity of bending is about 3.5 μrad. The maximum bending angle obtained at these experimental settings is 14 μrad while using 0.3 μJ pulse energy and the corresponding deflection at the microcantilever tip is about 1.3 nm. The surface of the cantilever melts when the laser pulse energy is higher than 0.32 μJ. If a larger bending angle is needed without melting the surface, one can scan multiple lines on different locations of the cantilever. In this case, the separations between the lines should be large enough so that the residual strains caused by each line do not overlap with each other. It is estimated from our calculation (see below) and experiment that the residual strain field is about 10 μm wide. A total of eight lines can be applied to the cantilever of 110 μm long, causing a maximum bending angle of 112 μrad using laser energy of 0.3 μJ.

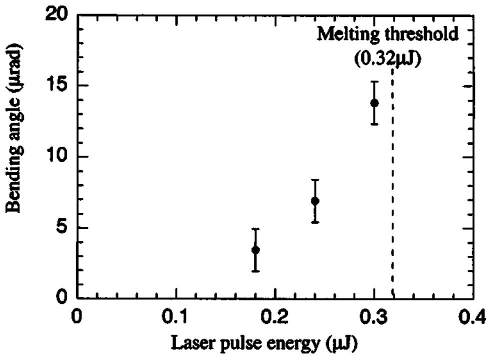

FIG. 3. Bending angle vs laser pulse energy (scan speed 250 μm/s, laser beam diameter 8 μm).

A finite element model is also developed to simulate the laser bending of the microcantilever. This model computes the laser induced heating, stress and strain development, and the residual stress and strain. Details of thermal and stress analyses in pulsed laser bending can be found elsewhere.[17,18] A single laser pulse with a uniform intensity across the width of the specimen is assumed (the *y* direction in Fig. 2), i.e., a line shape pulse is irradiated onto the sample surface. Thus, a two-dimensional (2D) thermal-stress model can be applied. The computed deflection contour of the cantilever is shown in Fig. 4. For this calculation, the intensity of the line shape pulse is 0.6 J/cm^2, which is the same intensity for a 0.3 μJ pulse focused in an 8 μm diameter. The bending angle obtained by simulation is 23.6 μrad, which is larger than the experimental data, 14 μrad. The difference between the experimental and numerical results is mainly caused by the simplified 2D model. This model simulates the laser pulses scanning by using a line shape pulse. A three-dimensional (3D) model calculating pulse by pulse will be more accurate. However, the computational cost of calculating the total 100 pulses in a scan line is prohibitively time consuming.

In summary, we developed a highly sensitive laser bending technique for adjusting the curvature of microcantilevers. Such a technique is simple to implement, yet very useful for applications involving arrays of cantilevers for parallel chemical and biological sensing.

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