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Effect of surface patterning using femtosecond laser on micromechanical and structural properties of micromechanical sensors

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Abstract
A femtosecond laser can be used to fabricate microstructures on a silicon microcantilever surface with high precession and minimal sidewall defects. The aim of this study is to investigate the effect of the creation of microgrooves and sub-microgrooves on the resonance frequency, quality factor, and spring constant of a silicon microcantilever. A single pass of a femtosecond laser with a wavelength of 1026 nm was used to fabricate microgrooves on the microcantilever surface. Different numbers of microgrooves were fabricated on each microcantilever using the femtosecond laser micromachining technique. The separation distance between the center of the two microgrooves was 7 μm. The microstructure of the fabricated microgrooves was investigated through field emission electron microscopy. The resonance frequency increased with the number of microgrooves, but the quality factor of the patterned microcantilever was higher than that of the unpatterned microcantilever. The spring constant increased with the number of microgrooves, increasing from 18.96 to 38.04 mN/m for microcantilevers with 1 and 7 microgrooves, respectively.

1. Introduction
Within the past decade, microcantilevers have been increasingly developed and employed as measurement and detection probes owing to their small size, movability, and low cost compared to other detection techniques [1–4]. Microcantilevers have been used for trace material detection, such as explosives and heavy metal traces [5–10]. Furthermore, they have been used in medical and biological analyses, such as the detection of cancer biomarkers, viruses, and blood fat [11–17]. The surface modification of microcantilever sensors can increase the sensitivity in detecting materials on the pico gram scale. Surface patterning of a microcantilever significantly influences its mechanical properties [18]. The surface patterning of a microcantilever can be achieved using several methods, such as lithography, chemical anodization, and deposition of nanoparticles on the cantilever surface [18, 19]. Microstructures and sub-microstructures can be induced on the silicon microcantilever surface using a femtosecond laser with small sidewall defects and high precision owing to the ultrashort time of the pulses. The fabrication of microstructures and nanostructures on a cantilever surface enhances the sensitivity of the microcantilever by increasing the interfacial surface area for molecular adsorption [18]. However, the surface nanostructuring of the microcantilever has a significant effect on the mechanical properties, such as the resonance frequency, spring constant, and Young’s modulus [18]. The microcantilever surface is typically coated with a functionalization layer for adsorbing specific materials. Adsorbed molecules will cause a change in the
resonance frequency because of the increase in the microcantilever effective mass. The sensitivity of the microcantilever depends on the spectral resolution, which is related to the quality factor of the resonant mode, expressed in equation (1) [20]:

\[ Q = \frac{2\pi \text{ stored vibrational energy}}{\text{energy lost per cycle of vibration}} = \frac{f_0}{\Delta f} \]  

where \( Q \) is the quality factor, \( f_0 \) is the resonance frequency of the mode, and \( \Delta f \) is the full width at half maximum of the resonance peak. When the adsorbed mass is uniformly distributed, the microcantilever resonance frequency decreases. The relationship between the resonance frequency and the mass is expressed using equation (2):

\[ \omega_0 = \sqrt{\frac{k}{m}} \]  

Where \( \omega_0 \) is the resonance angular frequency of the microcantilever, \( k \) is the spring constant, and \( m \) is the effective mass of the microcantilever, \( m \) is expressed as

\[ m = 0.243 \rho L(w t), \]  

Where \( \rho \) is the mass density, 0.243 is the correction factor that reflects the nonuniformity of the microcantilever mass, \( L, w, \) and \( t \) is the length, width, and thickness of the microcantilever, respectively. However, despite adsorbing the mass on the microcantilever surface, the resonance frequency often increases because of changes in the spring constant owing to changes in Young’s modulus (E) [18, 19, 22].

2. Experimental procedure

2.1. Femtosecond laser patterning of microcantilever surfaces

A rectangular, \( (100) \) silicon microcantilever array with a free end was purchased from Micromotive (Germany). Each microcantilever in the array had a length, width, and thickness of 500, 90, and 1 \( \mu m \), respectively. A femtosecond laser wavelength (\( \lambda \)) of 1026 nm with a pulse duration of 220 fs and a repetition rate of 100 kHz was focused on the microcantilever surface using a 4X objective with a numerical aperture (NA) of 0.1, an average laser power of 31 mW, and a scan speed of 10 mm s\(^{-1}\). The cantilever chip was fixed on the 3D XYZ programmable translation stage. The radius of the Gaussian laser beam (\( W_0 \)) is 12.517 \( \mu m \) which is given by equation (4) [23]

\[ W_0 = \frac{1.22 \lambda}{\text{NA}} \]  

The laser fluence (\( F \)) is 0.12596 J cm\(^{-2}\) which is calculated by equation (5) [24, 25]

\[ F = \frac{2 P}{R \pi W_0^2} = \frac{2E_p}{\pi W_0^2} \]  

where \( P \) is the average laser power, \( R \) repetition rate, and \( E_p \) is the pulse energy.

Single microgroove was fabricated on microcantilever number 1 and 2 microgrooves on microcantilever number 2 up to 7 microgrooves on microcantilever number 7. Each microgroove was fabricated to a length of 500 \( \mu m \); the separation distance between the centers of the two microgrooves was 7 \( \mu m \). Each microgroove was composed of sub-microgrooves in a direction nearly perpendicular to the microgroove direction as illustrated in figure 1. The patterned microcantilevers were immersed in piranha solution for 5 min, followed by immersion in ethanol and deionized water, to remove the debris. Subsequently, the patterned microcantilevers were dried in a drier at 250 °C for 10 min. Microstructure of the fabricated microgrooves on the \( (100) \) silicon surface was investigated by using field emission electron microscope (Fe-SEM), width, and length of the induced sub-microgrooves, and the separation distance between two induced sub-microgrooves were calculated from the (FE-SEM) images, the depth of the induced sub-micro-groove were measured by using Atomic force microscope (AFM).

2.2. Resonance frequency measurements

The resonance frequency values of the microcantilevers were measured before and after patterning. A picomeasure PM3 system from Fourien Inc., Canada, was used for the resonance frequency measurements. The resonance quality factor of microcantilevers was calculated using equation (1). The spring constant was calculated using equations (2) and (3). Equation (3) was used to calculate the effective mass of the microcantilever. For the patterned microcantilevers, the mass was calculated in two parts: \( m_1 \) and \( m_2 \), where \( m_1 \) is the mass of the unpatterned region,
and \( m_2 \) is the mass of the patterned region, as illustrated in figure 1. Figure 2 shows a simple diagram of the measurement system.

### 3. Results and discussion

Figure 3 shows the microstructure of the fabricated microgroove on the cantilever surface by using linear horizontal polarized femtosecond laser. In each microgroove composed of induced sub-microgrooves in a direction perpendicular to the microgroove direction with a deviation of a few degrees. The width, length, and depth of the induced sub-microgrooves were \( 224 \pm 9.51 \) nm, \( 6.3 \pm 0.076 \) \( \mu \)m, and \( 441 \pm 1.20 \) nm, respectively. The separation distance between two induced sub-microgrooves was \( 513 \pm 4.086 \) nm. These induced sub-microgrooves are laser induced periodic surface structures (LIPSS). It has been reported in literature that LIPSS on the silicon surface are aligned perpendicular to the laser polarization orientation \([26, 27]\). When the ultrafast laser pulses are absorbed on the material surface, the Surface Plasmon (SP)-laser interference will induce low spatial frequency LIPSS (LSFL), which is called initial sub-microgrooves with periodicity near the laser wavelength \([26, 28–30]\). As the number of femtosecond laser pulses increases, a new
electromagnetic mode will be generated which induces new sub-microgrooves in the regions between each two initial sub-microgrooves hence the periodicity of LIPSS decreased \[30\]. Figures 4 and 5 show that the fundamental resonance frequency of the microcantilevers increased as the number of microgrooves increased. The increase in the resonance frequency was caused by two factors. The first factor was the decrease in the effective mass owing to ablation, and the second factor was the changes in Young’s modulus and spring constant.

Figure 4. Frequency of microcantilevers without and with microgrooves: (a) 1 microgroove (b) 2 microgrooves (c) 3 microgrooves (d) 4 microgrooves (e) 5 microgrooves (f) 6 microgrooves (g) 7 microgrooves.
due to the change in the microstructure of the patterned microcantilever [18]. The quality factor of the patterned microcantilevers is higher than the quality factor of the unpatterned microcantilevers, as depicted in figure 6. The quality factor of the patterned microcantilevers increased owing to the increase in the total vibrational energy and decrease in the energy loss. Different loss energy sources exist, such as internal material loss, loss from cantilever to its substrate, and viscous (acoustic) loss to the surrounding medium [31, 32]. The total quality factor (Q) corresponding to the energy loss is determined using equation (6): [31, 32]

\[
\frac{1}{Q} = \frac{1}{Q_i} + \frac{1}{Q_s} + \frac{1}{Q_a}.
\]  

where \(Q_i\), \(Q_s\), and \(Q_a\) are the corresponding quality factors to the internal material loss, loss from cantilever to its substrate, and loss viscous (and acoustic), respectively. The sub-microgrooves on the microcantilever surface caused a decrease in the energy loss from the cantilever to the chip substrate through its support. The quality factor of the microcantilevers 5, 6, and 7 decreased owing to the increase of the number of sub-microgrooves on the microcantilever surface which causes an increase in the internal energy loss. Enhancement of the microcantilever quality factor leads to a reduction of the energy loss consequently the microcantilever sensitivity for target molecules will be increased [20]. The spring constant of the microcantilevers increased with the number of microgrooves fabricated on the microcantilever surface, as shown in figure 7. The spring constant increased from 18.96 to 38.04 mN m\(^{-1}\) for microcantilevers with 1 and 7 microgrooves, respectively. The increase in spring constant values is attributed to the decrease of effective mass and changes in the microstructure.
of microcantilever which, in turn, causes a change in the mechanical properties of the microcantilever such as its moment of inertia. Figure 8 shows that the effective mass decreases as the number of microgrooves increases due to the increasing of the ablated volume. The effective masses were 25.22882 and 23.79602 pg for the microcantilevers with 1 and 7 microgrooves, respectively. The spring constant increased with a high ratio, compared with the ratio of decreasing of the effective mass, which indicated that the noticeable increase in the spring constant was attributed to the changes in Young’s modulus and moment of inertia of the microcantilever which is confirmed by equation (7) [33]:

$$k = \frac{3E}{L^3} I$$

(7)

Where E is Young’s modulus and I is the moment of inertia of the microcantilever. For a rectangular cantilever, equation (7) is redefined as equation (8) [34]:

$$k = \frac{E w t^3}{4L^3}$$

(8)

The spring constant equation can be expressed as equation (9) [21, 35]

$$k = 2\pi^3 \omega \sqrt{\frac{\rho}{E}} (f)^3$$

(9)
Figures 9 and 10 show that the inverse of square resonance angular frequency does not linearly depend on the number of microgrooves and microcantilever effective mass; this confirms that the changes in resonance frequency and spring constant does not only depend on the changes in the microcantilever effective mass, but it also related to the effect of femtosecond laser surface patterning on the Young’s modulus and microstructure of the microcantilever.

4. Conclusion

Microgrooves were successfully fabricated on the microcantilever surfaces using a femtosecond laser, having a separation distance of 7 μm between the center of each two grooves. The resonance frequency was seen to be significantly depending on the number of microgrooves, specifically it increased with the increase of the number of microgrooves owing to the reduction of the effective mass and the changes in Young’s modulus. The spring constant in addition increased due to the increase in the resonance frequency.

The fabrication of microgrooves and sub-microgrooves on the microcantilever surface decreased the energy dissipation. Hence, the quality factor of the microcantilever for patterned microcantilevers increased, compared with that for microcantilevers before performing laser patterning.
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