Optical detection of quasi-static actuation of nanoelectromechanical systems

Christine Meyer,[a] Heribert Lorenz, and Khaled Karrai
Center for NanoScience and Sektion Physik, Ludwig-Maximilians-Universität, 80539 Munich, Germany

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An all optical method designed to test the functionality of nanoelectromechanical systems is presented. Silicon tweezers consisting of freestanding nanometer-sized prongs are prepared using electron beam lithography. Images of the tweezers structures are taken by scanning confocal microscopy while the prongs are electrostatically actuated under a low frequency ac voltage. The images, which are demodulated at the actuation frequency and its higher harmonics, clearly resolve the actuating parts of the tweezers. An actuation amplitude down to 6 pm (rms)/$\sqrt{\mathrm{Hz}}$ can be detected. © *2003 American Institute of Physics.* [DOI: 10.1063/1.1608491]

Tweezers capable of manipulating nanometer-sized objects are tools being central to the development of nanoscience. Such tools are available in the form of optical tweezers operating in liquids[1] or tips of scanning probe microscopes used for sliding objects on surfaces.[2–4] A nanoscopic analog of a pair of normal laboratory tweezers would be a more versatile tool. Recent reports show that such tweezers can be made out of a pair of carbon nanotubes[5,6] or metallized silicon dioxide prongs.[7] They are actuated using electrostatic forces between prongs oppositely biased.[5–7] Such devices are still in their early stage of design, and so far only one direct case of particle manipulation has been demonstrated.[5] When the tweezers are fabricated in submicron size, they cannot be imaged with traditional optical microscopy due to the diffraction limit (about 0.5 μm in spatial resolution). Optical techniques are thus only used to look at larger devices or to detect mechanical resonance modes.[8–10] Alternatively, mechanical actuation can be investigated by electrical measurements of charge transport properties.[11–13] Such methods, however, cannot be easily transferred to the detection of static or quasi-static mechanical displacements. Instead, scanning electron microscopy (SEM) is often used.[6,7,14] As it turns out, unfortunately, the probing electron beam strongly affects the actuating electric fields, leading to a modified operation and a deformed image. Furthermore, once the tweezers have been imaged, a carbon based solid contamination layer is deposited on the device that ends up changing its mechanical properties or even closing the gap between the prongs after a few minutes of probing.[7] During our measurements we also observed that metallized nanotweezers often melt under SEM imaging, when they are electrically connected to metal wires. This effect is still not understood. In this letter we present a much less invasive technique based on optical microscopy implemented in order to detect quasi-static actuations of nanoelectromechanical systems. It operates in air and on nanometer-sized structures. Our tweezers are fabricated using electron beam lithography and consist of two highly arsenic-doped silicon ($n \approx 2 \times 10^{20}$ cm^{-3}) prongs with two electron beam deposited (EBD) tips[7,15] grown on top of them as shown in Fig. 1. Each prong is individually contacted so that an activating voltage U can be applied. We found out that the prongs melt when a current density exceeding about 10^6 A/cm^2 is allowed to flow through them.[16] Consequently, field emission electron tunneling limits the applied voltage to about 10 V or even less,[17] depending on the structure's geometry. We limited the maximum actuating voltage drop to about 3 V. Using a simple capacitor model regarding the prongs as slightly bent, we estimated the deflection of each prong in the geometry of Fig. 2(b) to about 1 Å only for a dc voltage of 3 V. Such a small motion is not detectable with conventional SEMs.

An image of the device shown in Fig. 2(a) was taken using a homemade scanning confocal microscope operating in reflectivity. By comparing it to the SEM micrography of the same structure shown in Fig. 2(b), the tweezers' locations can be clearly identified as seen in Fig. 2(c). The overlay

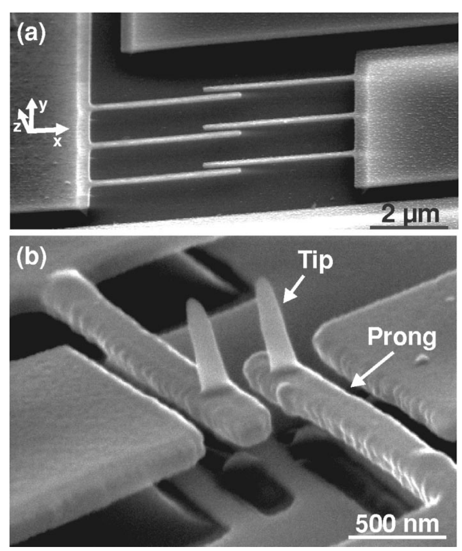

FIG. 1. SEM micrographies of nanotweezers. The devices are defined by electron beam lithography and reactive ion etching on silicon-on-insulator (SOI) material. After removing the oxide layer, the structures are dried in a critical point dryer. (a) An example of three parallel tweezers structures with 4 μm long prongs; (b) single pair of tweezers (3 μm long, 200 nm wide, and about 150 nm thick) with electron beam deposited tips on the prongs. Since the latter are insulating, gripped conducting objects should not short-circuit the tweezers.

[a]Electronic mail: christine.meyer@physik.uni-muenchen.de

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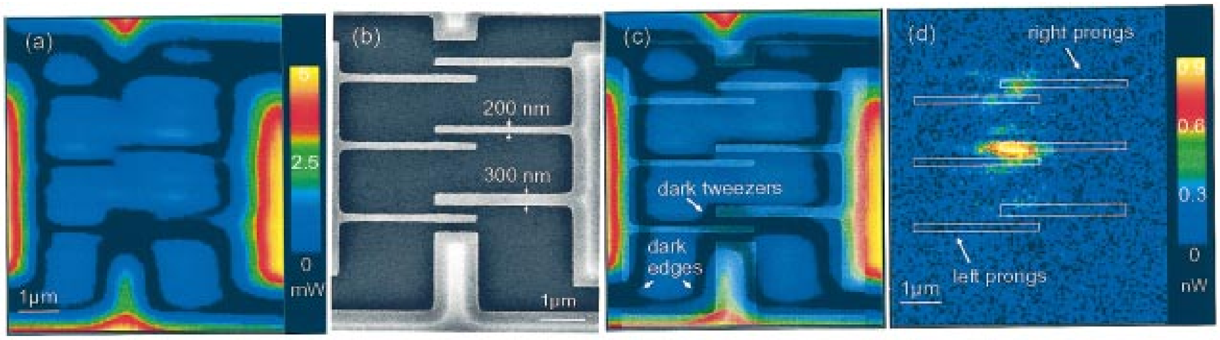

FIG. 2. (Color) (a) Scanning confocal reflectivity micrography (128×128 pixels); (b) corresponding SEM image, showing a device with three tweezers (3 μm long prongs); (c) superposition of (a) and (b) images. Due to the nonlinearity of our piezos, a perfect match in all regions of the scan could not be reached. The alignment in both directions was done on the large structures on the left and right side in the middle of the image. A good alignment in the region of the tweezers was assumed, since they are located within the area that was aligned. (d) The reflected image of the signal amplitude, taken simultaneously with (a), demodulated at twice the voltage excitation frequency $f=7$ kHz. The tweezers were actuated under an ac voltage of $u_{\rm rms}=2.3$ V (128×128 pixels, time constant 3 ms). The power of the incident signal is about 35 μW. The white boxes indicate the prongs' positions as determined from (c). The signal clearly shows the actuated parts of the tweezers. As expected, the pair with the wider prong is less deflected than the others. The difference between the signals of the top and middle 200 nm pairs of tweezers is surprising at first glance. It can be explained by their different surrounding areas that are to be taken into account because of the large spot size compared to the structure. This point was confirmed by our numerical simulations (Ref. 18).

between the two images was optimized on a large sized feature of the structure, not limited by diffraction resolution. A perfect match was not possible in our case, due to the nonlinearity of the piezo stage used, but a conservative precision of the accuracy of ± 200 nm was found. Using linearized piezos and an appropriate sample design, the accuracy should be improved down to some 10 nm or less. In order to detect their deflections, the prongs were actuated quasistatically with a small ac voltage $u_{\rm rms}$ between the left and the right prongs in Fig. 2. The reflected light was demodulated at the actuation frequency as well as its higher harmonics. This way, we detected an optical signal only from the regions of the device where there are moving parts. The setup shown in Fig. 3 consists of a scanning confocal microscope and a lock-in amplifier. The confocal arrangement is required to minimize background reflectivity from the device substrate located only 400 nm away from the prongs' plane. An image is obtained by scanning the sample across the focused laser spot. We tested the sensitivity of our setup to small amplitude displacements by moving the sample as a whole at a frequency of 350 Hz using a piezo stage. A periodic oscillation of 2 Å (peak to peak) was clearly detectable in the amplitude image of the demodulated signal in the region of the tweezers. The integration time used of 10 ms per data point and the background noise corresponding to a signal of about 1.7 Å (peak to peak) lead to a noise equivalent displacement of 1.7 Å$/(2\sqrt{2})\ \sqrt{10\ \rm ms}\approx 6$ pm (rms)/$\sqrt{\rm Hz}$. In order to detect the prongs' displacements, a periodic voltage drop at a frequency f set between 200 Hz and 7 kHz was applied across the prongs, in a range which is much lower than the tweezers' resonance frequencies estimated to be about 20–25 MHz. All measurements were performed in air at room temperature. The amplitude and the phase of the modulated reflected intensity showed a signal only in the tweezers' regions. In particular, the image mapping the amplitude shown in Fig. 2(d) demonstrates that the tweezers were electromechanically actuated. The prongs' deflection amplitude $x=1/k\ \partial(CU^2/2)/\partial x$ depends on the voltage U between the prongs, the spring constant k and the capacitance C between the prongs. Consequently, using $U=\sqrt{2}u_{\rm rms}\sin(\omega t)+U_0$, we obtain $x=x_0+x_\omega+x_{2\omega}$ where $x_0=a_0(U_0^2+u_{\rm rms}^2)$, $x_\omega=a_0[2\sqrt{2}u_{\rm rms}U_0\sin(\omega t)]$ and $x_{2\omega}=a_0[u_{\rm rms}^2\sin(2\omega t-\pi/2)]$. Here, we defined $a_0=1/(2k)\partial C/\partial x$, $\omega=2\pi f$, and $U_0=U_{\rm dc}+\Phi$ where Φ is an uncontrolled contact potential across the prongs and $U_{\rm dc}$ is an offset voltage kept to zero in our experiments. We obtained demodulated signals at both, f

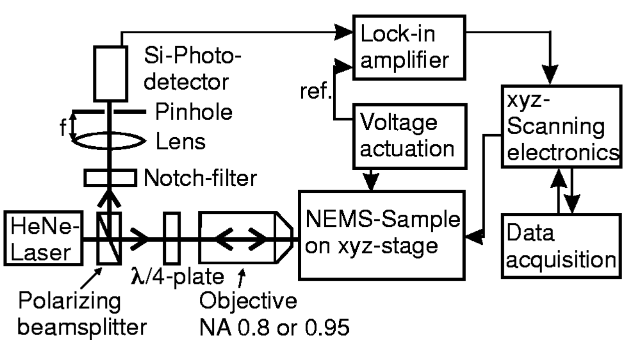

FIG. 3. Setup schematics. A HeNe-laser ($\lambda=633$ nm) was focused at its diffraction limit with a numerical aperture of 0.8 or 0.95 respectively. The spot diameter was measured to be 600 nm (FWHM). The reflected collimated beam (4.5 mm in diameter) was focused with $f=100$ mm focal length on a 30 μm pinhole. This way a depth of field of less than 700 nm (FWHM) was reached. The Si photodetector was connected to a lock-in amplifier demodulating the signal at the actuation frequency and higher harmonics.

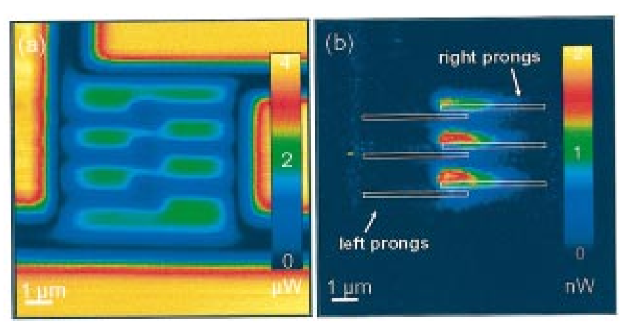

FIG. 4. (Color) (a) Scanning confocal reflectivity image of the tweezers shown in Fig. 1(a); (b) corresponding image of the signal demodulated at the tweezers actuation frequency $f=710$ Hz (integration time constant 10 ms). Here, the right prongs were biased against the substrate with $u_{\rm rms}=2$ V. The white boxes symbolize the prongs' positions. It is clearly seen that the floating left prongs show no signal.

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and 2 f, which is expected from the above formulas assuming $\partial C/\partial x$ constant to the zero order of its Taylor expansion. However, we additionally detected a weaker signal at the third harmonic (typically the fifth part of the first harmonic), indicating presumably that the first order term in the expansion of $\partial C/\partial x$ in x is also to be taken into account. In order to obtain a rough estimation of the actuation amplitude, a reference measurement was performed by modulating the position of the whole sample with a known displacement. This way, we determined that applying a voltage of 3 V (rms) across the prongs, the tweezers were actuated with an amplitude per prong of about 2 Å (peak to peak) in y direction [Fig. 1(a)], a value which is in agreement with our model estimation.

Surprisingly, the regions of the optical reflectivity image where the prongs are located are darker than the background. Dark fringes are also present at the edges of the nonsuspended areas as seen in Figs. 2(a) and 4(a). In order to understand the contrast, we simulated the intensity of the reflected signals using an optical transfer matrix model for plane waves carried out at a wavelength of $\lambda = 633$ nm. Within this model,[18] the dark fringes at the edges as well as the reduced reflectivity in the prongs' regions are understood as originating from destructive interference between different parts in the focal spot. Namely, the focal spot is reflected from both, the substrate and the nonsuspended areas (or the prongs, respectively).

The presence of a surface potential on the substrate induces parasitic electrostatic forces normal to the prongs' plane [i.e., in z direction in Fig. 1(a)], leading to an undesired out-of-plane actuation component. To estimate the strength of this effect, the right prongs in Fig. 4 were biased against the substrate consisting of p-type silicon (20 Ω cm). A modulated voltage applied between the right prongs and the substrate led to a signal in their region only whereas the floating left prongs were nearly unaffected. Here, the dominant deflection is directed towards the substrate [z direction in Fig. 1(a)] due to the applied voltage drop in this direction. More generally, using selective contacting, our technique is capable of identifying deflections in all spatial directions. Ideally, the device substrate should be removed from the prongs' vicinity to fully exclude the undesired out-of-plane actuation.

In summary, we have presented a simple all optical method to detect the quasi-static actuation of nanoelectromechanical systems down to the Å range. This technique proves to be noninvasive and easy to implement.

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