Repositioning technique in nanowire manipulation by oscillating gripper

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In this study, a manipulation device is developed that is able to pick up and reposition a nanomaterial. In the device, the gripper, composed of two silicon microcantilevers, is actuated by *XYZ* stages on a rotational stage and has eight degrees of freedom. One of the microcantilevers can be vibrated at a resonant frequency by an acoustic oscillator mounted on the gripper base. We successfully picked up a copper (II) oxide NW grown on a substrate and then repositioned the NW. During the picking-up process, the NW was statically bent to break at the root by the gripper motion, or cyclically bent using the acoustic oscillator to induce a fatigue fracture. During the repositioning process, natural adhesion between the NW and the gripping surface often presented a challenge when removing the NW. This difficulty was overcome by vibrating the gripping surface, which resulted in the reduction of the adhesion effects. The mechanism of the reduction of the adhesion effects is discussed concerning the relationship between the adhesion energy and the peeling force acting on the NW. Another technique of repositioning using an inertia force generated by the oscillator is also discussed.

1. Introduction: Various researchers have attempted to apply one-dimensional nanomaterials such as nanowires (NWs) to mechanical and electronic nanodevices, for example, NW-based environment gas sensors [1]. Often in fabricating processes, nanomaterials are synthesised as a bundle on a substrate. Nanomanipulation devices often need to be able to separate a single nanomaterial for application. Moreover, most nanomaterials do not always grow vertically with respect to the substrate. Thus, the devices must have a high degree of freedom (DOF) to be capable of approaching an individual nanomaterial.

Various devices have been proposed for gripping materials at the nanoscale. Akita *et al*. [2] developed nanotweezers consisting of carbon nanotubes, which are operated electromechanically in an atomic force microscope. Hashiguchi *et al*. [3] developed micromachined nanogrippers integrated with thermal expansion micro-actuators. Both the above tools have two probes and move like tweezers, where the gripping motion relies only on actuating the angle between the two probes. That is, the gripping motion has one-DOF. The tools are often equipped on an *XYZ* stage, and the tips of the two probes therefore have four-DOF. The initial gap and the angle between the two probes are fixed so that they are capable of picking up a nanomaterial with its size equal or less than the initial gap of the probes. Moreover, the maximum grip force varies according to the size of the material: the smaller the material to be gripped, the lower the value of the maximum grip force.

Meanwhile, a nanomaterial that has been separated must be repositioned on an arbitrary substrate to study its characteristics [4] and to experiment [5] on the individual nanomaterial. At the nanoscale, the van der Waals force between a nanomaterial and the gripping surface of a manipulation device is usually too strong to release the nanomaterial from the surface. Taking this into consideration, nanomanipulation devices therefore must be capable of overcoming or reducing the adhesion force. However, few reports have been published on this problem.

In the study, we developed a manipulation device that allows us to separate and reposition an individual nanomaterial through high-DOF motions of a gripper consisting of two microcantilevers, together with an acoustic oscillator attached to the base of the gripper for controlling adhesion effects. To demonstrate our manipulation method, we separated a copper (II) oxide (CuO) NW from a bundle of NWs and then repositioned the NW onto a substrate. The device can release the NW onto the substrate by vibrating one of the gripping probes (a microcantilever) where the NW is adhered to. The vibration reduces the critical tensile force for peeling off the NW. Our techniques ensure success in the manipulation with some conditions which are mentioned in the Experiments and results Section. Furthermore, we propose a repositioning technique that controls the adhesion force by generating an inertia force in the NW adhering to the gripping surface.

2. Manipulation device: As shown in Fig. 1, the manipulation device consists of two microcantilevers (μmasch, NSC12/tipless/no Al), which are used as a gripper like a pair of chopsticks (circle in Fig. 1*b*). The device is driven by micropositioners and piezoelectric actuators and is installed on an optical microscope stage, where NWs are visible as diffraction images [4]. An acoustic oscillator is attached to an aluminium frame. The microcantilevers grip an NW by moving one of the cantilevers towards the other with a piezo-actuated rotation around an elastic hinge at the root of the aluminium frames (Fig. 1*c*). The other

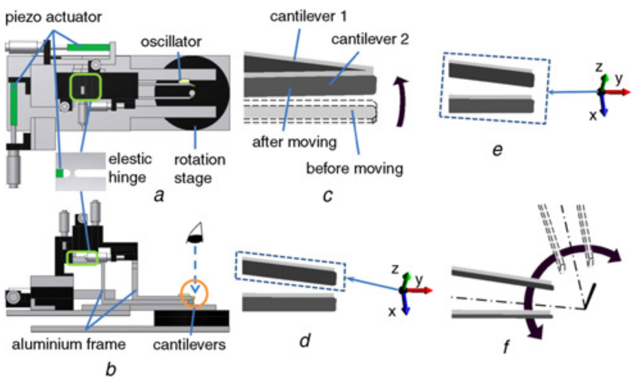

Figure 1 *Schematic illustration of the manipulation device*
a Overhead view of the manipulation device
b Lateral view of the device
Highlighted circle area shows the gripper, which consists of microcantilevers on the aluminium frame
c Gripping motion of tips (enlargement of circled area in *b*)
Cantilever 2 moves towards cantilever 1 with a piezo-actuated rotation around an elastic hinge at the root of the aluminium frames
d Cantilever 1 (in Fig. 1*c*) can move in three directions
e Cantilevers 1 and 2 (in Fig. 1*c*) can move in three directions at the same time
f Device is rotatable around an observing point of microscope

cantilever is movable in the *x*-, *y*- and *z*-directions, independent of the rotationally actuated cantilever (Fig. 1*d*). Therefore the initial gap of the two cantilevers is adjustable. In other words, the maximum grip force is adjustable according to the NW size. In addition, the cantilevers as a whole are not only movable in the *x*-, *y*- and *z*-directions (Fig. 1*e*), but also rotate around a point near their tips (Fig. 1*f*). This rotation enables the cantilevers to change their direction in the microscope viewing field without disappearing from it. Thus, the device has a total of eight-DOF.

3. Experiments and results: We manipulated a CuO NW to demonstrate the separation and repositioning of it using the device we developed.

Numerous CuO NWs were grown from the surface of a Cu wire by heating the wire in air at 673–873 K for 4 h [6]. The fabrication technique of NWs is based on a self-assembly method called the vapour–solid mechanism.

One CuO NW from the numerous NWs was gripped by the microcantilevers and then displaced to induce stress concentration at the root for separation. Fig. 2 shows the separating procedure. The initial gap between the cantilevers was adjusted to obtain maximum gripping force. The NW was first attached to one of the cantilevers with a van der Waals attractive force (Fig. 2*b*), and the NW was then gripped by the cantilevers (Fig. 2*c*). The NW was bent to concentrate the stress at the root via the cantilevers (Fig. 2*d*), which contributed to separation of the NW from the surface of the Cu wire (Fig. 2*e*). When the gripper opened, the NW remained on the cantilever because the van der Waals attractive force between the cantilever and the NW was larger than that between the other cantilever and the NW owing to the difference in contact length (Fig. 2*f*).

When the bonding force between the NW and the surface of the Cu wire was too strong for separation by concentrated stress, we instead used the acoustic oscillator (Fig. 3). After the cantilevers gripped an NW (Fig. 2*c*), they were vibrated at a resonant frequency by the oscillator to induce cyclic fatigue at the root of the NW (Fig. 3*a*). The frequency and voltage applied to the oscillator (piezoelectric element) were 20–25 kHz and 100 V (peak-to-peak), respectively. As a result, fatigue failure occurred at the root of the NW (Fig. 3*b*).

Fig. 4 shows the repositioning procedure. The separated NW was repositioned onto another substrate with the aid of the oscillator, which vibrated one of the cantilevers to which the NW was adhered to (Fig. 4*b*). The frequency and voltage applied to the oscillator were 17–20 kHz and 10–20 V (peak to peak), respectively. The oscillation periodically yielded a relative angle between the cantilever and the substrate. The relative angle produced the difference in peeling forces between both ends of the NW. As a result, the manipulation device released the NW from the gripping surface,

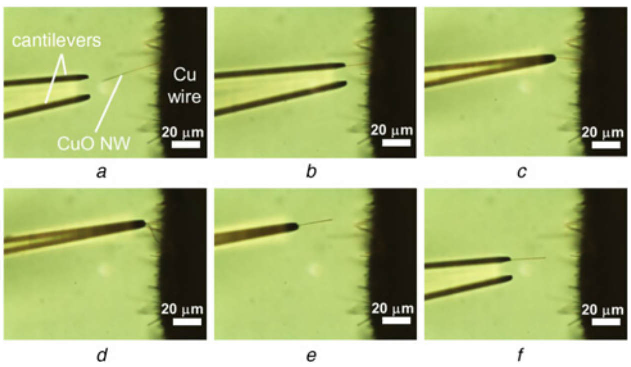

Figure 2 *Series of successive optical images showing separation of a CuO NW from a Cu wire surface via the concentration of stress by using the device*

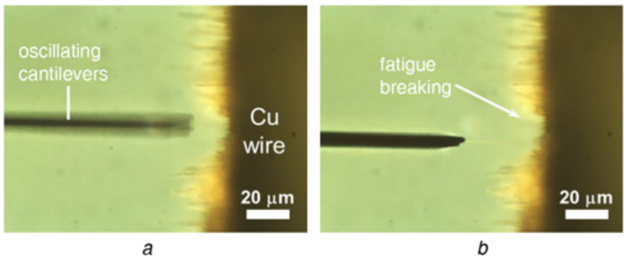

Figure 3 *Series of successive optical images showing separation of a CuO NW from a Cu wire surface via fatigue failure by resonating the cantilever of the device*

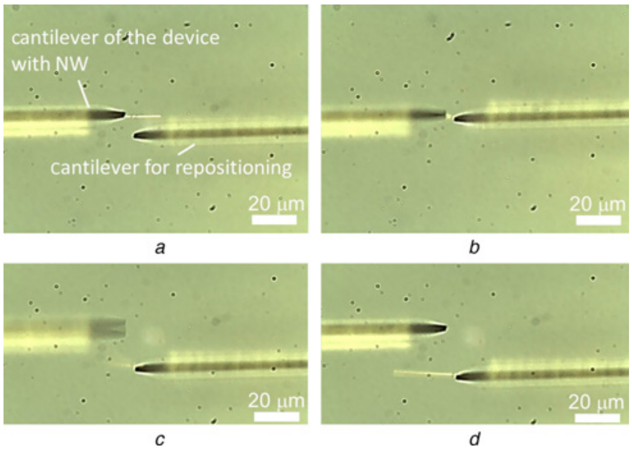

Figure 4 *Series of successive optical images showing repositioning of an NW onto the surface of another cantilever*

and the NW was easily repositioned onto another substrate (Fig. 4*d*).

4. Discussion: To calculate the van der Waals force between the NW and the cantilever, we used a simple model of a cylinder and a plane substrate, as shown in Fig. 5. Here, D is the distance between the cylinder and the substrate and R is the radius of the cylinder. According to the calculation in [7], the interaction energy $w(D)$ per unit length of the cylinder is derived as

$$w(D) = \frac{A}{6}\int_0^{\infty} \frac{2\sqrt{2Rz}}{(D+z)^3}\,\mathrm{d}z \qquad (1)$$

where A is the Hamaker constant, and $D \ll R$ is assumed.

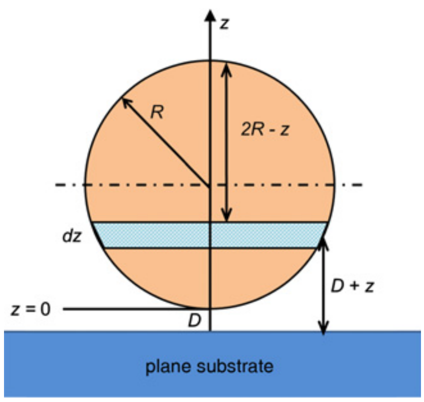

Figure 5 *Cross-section of a cylindrical beam model and a plane substrate*

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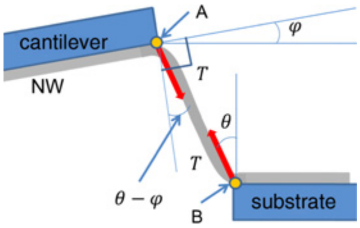

Figure 6 *Forces acting on the NW during repositioning*

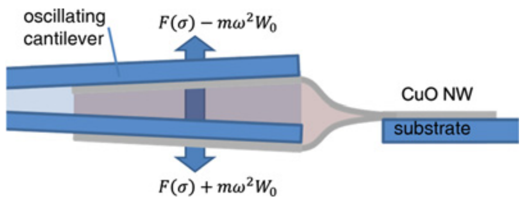

Figure 8 *Oscillating cantilever generates an inertia force in the NW during repositioning onto the substrate*

The van der Waals force $F(D)$ per unit length is obtained by differentiating (1). This gives

$$F(D) = \frac{\partial w(D)}{\partial D} = -\frac{A\sqrt{2R}}{16} D^{-(5/2)} \tag{2}$$

We assumed a hard-sphere model, where the atoms behave like a billiard ball with a hard-sphere radius. The cylinder therefore contacts the substrate when the distance D coincides with the sum σ of the atom radii of the sphere and the substrate. We can estimate the adhesion energy $w(\sigma)$ and the adhesion force $F(\sigma)$ by using the experimental conditions of $R = 55$ nm, $A = 10^{-19}$ J [7] and $\sigma = 3.62 \times 10^{-1}$ nm [8]. The values of $w(\sigma)$ and $F(\sigma)$ were estimated to be 0.26 nJ/m and 0.83 N/m, respectively.

Fig. 6 shows the forces acting on an NW during repositioning. The critical tensile force T_{cr} (unit is Newton) for peeling off the NW takes a different value at point A from that at point B because of the relative angle ϕ. As shown in Fig. 7, T_{cr} is expressed as follows [9]

$$T_{cr} = \frac{w(\sigma)}{1 - \cos\alpha} \tag{3}$$

The angle α is $(\pi/2) - (\theta - \varphi)$ at point A, which is larger than the value of α at point B, that is, $(\pi/2) - \theta$. Therefore the critical tensile force at point A is reduced compared with that at point B. As a result, the NW is released from the vibrating cantilever, which corresponds to the cantilever inclined with an angle φ.

As shown in Fig. 8, the inertia force is generated in the NW by oscillation of the cantilever. The oscillation is expressed as $W = W_0 \sin \omega t$, where W_0 is the amplitude of the cantilever, ω is angular frequency and t is time. The inertia force $F_I(t)$ is given by

$$F_I(t) = m\omega^2 W_0 \sin \omega t \tag{4}$$

where m is the mass of the NW per unit length ($m = 6 \times 10^{-11}$ kg/m). This force changes periodically with oscillation of the cantilever. The force $F(t)$ applied to the NW on the cantilever's surface may therefore be $F(\sigma) - m\omega^2 W_0 \le F(t) \le F(\sigma) + m\omega^2 W_0$. It is noteworthy that the inertia force apparently reduces the adhesion force. We estimated the inertia force by using the experimental conditions of $W_0 = 1.5$ µm and $\omega = 120 \times 10^3$ rad/s. The maximum value of F_I was estimated to be 1.3×10^{-6} N/m. This value is too small in comparison with $F(\sigma)$ (=0.83 N/m). As seen from (4), the inertia force is proportional to the square of the angular frequency. Therefore a high oscillation frequency (more than 10 MHz) could make the repositioning process easier.

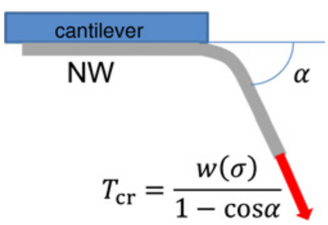

Figure 7 *Peeling mechanism of a thin wire adhered to a cantilever*

5. Conclusions: We successfully developed a manipulation device able to pick up and reposition an NW. The device comprises a gripper composed of two microcantilevers, which can be vibrated at a resonant frequency. To demonstrate this, we manipulated one of a number of copper oxide NWs synthesised as a bundle. Bending of the NW, which induced stress concentration at the root of the NW, was effective for separation. In addition, fatigue failure at the root of the NW, which was induced by vibrating the gripping cantilevers at the resonant frequency, was more effective for separation.

Moreover, oscillation of the cantilever made the repositioning process more straightforward because the oscillation reduced the problem of adhesion, which had presented a challenge in releasing the NW. The deflection angle of the vibrating cantilever periodically reduced the critical tensile force for peeling off the NW. Use of the cantilever oscillation, instead of the rotational stage, for increasing the peeling angle has an advantage in that miniaturisation of the device is possible for application in small spaces such as a scanning electron microscope chamber. Another effect of the oscillation is that it reduces the adhesion force by the inertia force generated in the NW.

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