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Implementation of a Piezoresistive MEMS Cantilever for Nanoscale Force Measurement in Micro/Nano Robotic Applications

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The nanoscale sensing and manipulation have become a challenging issue in micro/nano-robotic applications. In particular, a feedback sensor-based manipulation is necessary for realizing an efficient and reliable handling of particles under uncertain environment in a micro/nano scale. This paper presents a piezoresistive MEMS cantilever for nanoscale force measurement in microrobotics. A piezoresistive MEMS cantilever enables sensing of gripping and contact forces in nanonewton resolution by measuring changes in the stress-induced electrical resistances. The calibration of a piezoresistive MEMS cantilever is experimentally carried out. In addition, as part of the work on nanomanipulation with a piezoresistive MEMS cantilever, the analysis on the interaction forces between a tip and a material, and the associated manipulation strategies are investigated. Experiments and simulations show that a piezoresistive MEMS cantilever integrated into a microrobotic system can be effectively used in nanoscale force measurements and a sensor-based manipulation.

Key Words : Piezoresistive MEMS Cantilever, Atomic Force Microscope (AFM),
Microrobotics, Micro Force Sensing, Van der Waals Force,
Micro/Nano-manipulation

1. Introduction

Recently, the nanoscale sensing and manipulation have become a challenging issue in micro/nano-robotic applications. In particular, the force feedback is indispensable for a reliable and non-destructive manipulation of fragile micro objects in micro/nano assembly and manipulation of biomolecules. Due to recent advances in micro/nanofabrication technology, several nanogrippers have appeared in the literature (Kim and Lieber, 1999 ; Sitti and Hashimoto, 1999 ; Kim et al., 2002). For example, Kim and Lieber (1999) reported a nanotube-based nanotweezer without sensing capability, which can grasp 310 nm polystyrene beads by utilizing electrostatic force. On the other hand, several microgrippers integrated with a piezoresistive force sensor (Arai et al., 1998 ; Dargahi et al., 2000) or a strain-gauge sensor (Thompson and Fearing, 2001), have also been reported.

However, most tweezer-type grippers not only have difficulties in coping with sticking effect in micromechanics, but also have a limitation in sensing the gripping and contact forces in the range of nanonewton resolution (Burnham and Kulik, 1999 ; Fearing, 1995). The resolution of piezoresistive force sensors or strain-gauge sensors, for example, is in the range of several micronewtons at best. The reliable and damage-free handling of fragile micro objects requires the capability of sensing gripping and contact forces in the range of 0.1 uN up to 200 uN with nanonewton resolution. A survey of force sensing tec-

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hniques implemented so far shows that no suitable solution for integrated micro force sensors with nanonewton resolution is available today, and therefore a sensor-based reliable manipulation was not fulfilled yet.

As illustrated in Fig. 1, applications of an atomic force microscope (AFM) probe for nano manipulation such as nanoindenting/lithography (Requicha, 1999), bio-material detection (Baselt et al., 1996), characterizations of nano-materials and devices (Sitti, 2001; Guthold, 1999) and nano-asssembly (Requicha, 2001), to name but a few, have been reported. Only a few results can be found in the literature about the applications of AFM-based force sensors in other fields than AFM as a topology sensor. However, an AFM-like cantilever probe is advantageous to be used as the nanomanipulator as well as a force- and topology- sensor (Sitti, 2000). In addition, piezoresistive measurement of the deflection of an AFM-like cantilever is a promising method to implement high resolution force measurements in microrobotic applications.

In this paper, the "self-sensing" piezoresistive MEMS cantilever is implemented for nanoscale force measurements and a sensor-based manipulation. The calibration of a piezoresistive MEMS cantilever is experimentally carried out. In addition, as part of the work on a cantilever probe-based manipulation, the interaction force between a tip and a material is analyzed and the manipulation strategy associated with interaction force is investigated. Since the gripping force is achieved in the form of an interaction force, it is very important to understand the underlying force mechanics between a cantilever tip and a material surface. For example, a thorough investigation of the tip-sample interaction mechanism can establish an efficient and reliable handling strategy for nanoparticles such as carbon nanotube, photonic crystal, and biological molecule.

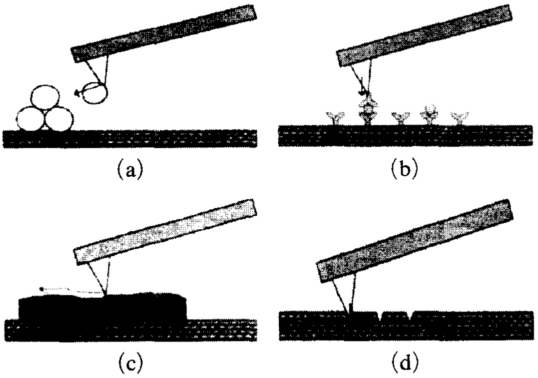


Fig. 1 Possible applications using an Atomic Force Microscope (AFM) cantilever as a nanomanipulator: (a) Nanoassembly, (b) Biosensor, (c) Nanotribological characterization, (d) Nano-indenting/lithography

The paper is structured as follows: In Section 2, modeling of the tip-sample interaction forces in a cantilever probe-based manipulation is described. In Section 3, the piezoresistive MEMS cantilever for nanoscale force measurements is described. In Section 4, the experiment and simulation results are described. Conclusions are given in Section 5.

2. Interactive Forces in Cantilever Probe-Based Manipulation

2.1 Interactive forces

Figure 2 shows a typical curve of tip-sample-distance and cantilever-deflection, when the tip approaches and retreats to and from the surface. During the approach period of the tip to the surface, i.e., the region 1 in Fig. 2, there is no tip-sample contact and also no cantilever deflection. The tip-sample contact occurs at point 2, where the tip jumps into the sample surface due

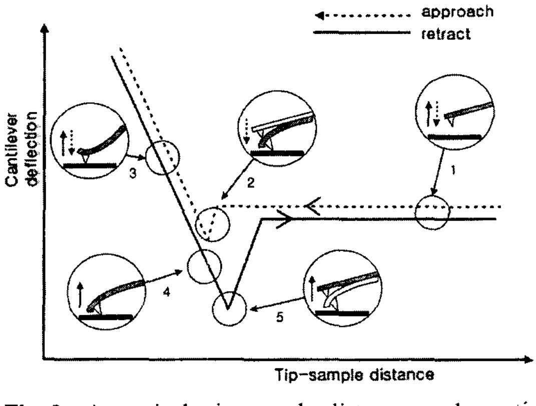


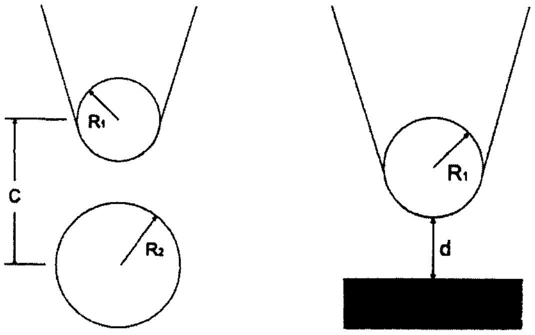
Fig. 2 A typical tip-sample-distance and cantilever-deflection curve

to the van der Waals and electrostactic forces. When the tip approaches the surface further, the cantilever begins to deflect linearly in contact with the surface, as shown in region 3 in Fig. 2.

On the other hand, when the tip pulls out from the surface, i.e., the piezo-scanner moves up in the z-direction, the force exerted on the cantilever decreases along the line 3 of the retraction curve. But the adhesive force between the tip and the sample keeps the tip in contact with the sample beyond the previous first contact point. This leads to a negative deflection of the cantilever like region 4 in Fig. 2. The cantilever then breaks freely at point 5 from the surface (pull-out) and returns to its neutral position.

2.2 Modeling

The interactive force between a cantilever tip and a sample involves various forces such as electric, magnetic, and atomic forces in a non-contact region and the indentation, adhesion, and capillary forces in a contact region. In this section, we describe mathematical models for the dominant interactive force i.e. van der Waals force that occurs in the cantilever probe-based nano manipulations. Also, for the sake of simplicity, all other forces, i.e., the electrostatic force and surface tension are not considered in this work. Hence, it is assumed that 1) the particles to be manipulated are clear and are free of electrostatic charges and 2) The humidity is so low that the surface tension can be neglected.



(a) (b)

Fig. 3 Notation for modeling van der Waals forces between (a) A spherical probe tip and a sphere-shaped sample and between (b) A spherical probe tip and a flat surface

Van der Waals force is caused by a momentary dipole moment between atoms resulting from interaction between electrons in the outermost bands rotating around the nucleus. Several overviews of van der Waals force are given in the literature (Hamaker, 1937 ; Visser, 1972). In this paper, we assume that the very sharp end-tip of MEMS cantilevers is spherical-shaped. Fig. 3 illustrates notation for modeling interactive forces in cantilever probe-based manipulation. The interactive force between a spherical probe tip and sphere-shaped sample (see Fig. 3(a)) can be estimated from the interaction force due to van der Waals between two spheres (Hamaker, 1937).

$$F_s=\frac{HCR_1R_2}{3}\left[\frac{8R_1^2R_2^2-[C^2-(R_1-R_2)^2][C^2-(R_1+R_2)^2]}{[C^2-(R_1+R_2)^2]^2[C^2-(R_1+R_2)^2]^2}\right] \quad (1)$$

where R_1 is the curvature of the spherical probe tip and R_2 is the radius of the sphere-shaped sample, C is the distance between centers and H is the Hamaker constant. The equivalent Hamaker constant for two different materials is given by

$$H_{12}=\sqrt{H_1H_2} \quad (2)$$

which H_1 and H_2 are Hamaker constants for individual materials. Table 1 shows Hamaker constants for selected materials (Visser, 1972).

By letting R_2 go to infinity, van der Waals force between a spherical probe tip and a flat space (see Fig. 3(b)) is approximated as follows.

$$F_w=\frac{2HR_1^3}{3d^2(d+2R_1)^2} \quad (3)$$

Table 1 Hamaker constants for selected materials (Note that all values are given in Joules × 10^{-20})

Material	Hamaker constant	Material	Hamaker constant
Au	45.5	SiO_2	8.55-50
Ag	40.0	Quartz	5.5-41.3
Cu	28.4	Carbon	21.7
Si	25.6	Diamond	28.4
Fe	21.2	PMMA	6.3

where d is the distance from the flat surface to the spherical probe tip.

3. Piezoresistive MEMS Cantilever

3.1 Piezoresistive ("self-sensing") cantilever

Several methods can be used in micro/nano force sensing in a micro/nanorobotic system. Zhou and Nelson (2000) proposed the use of an AFM cantilever deflection to measure interaction forces in nanonewton level. In their work, an optical beam deflection sensor was used. However, the optical beam deflection sensor has to be externally located, restricting the AFM cantilever movement. So, the entire system of the optical beam deflection sensor is not compact for the use in integrated micro/nanorobotic systems. On the other hand, Arai et al. (1998) and Dargahi et al. (2000) have proposed the use of a piezoelectric material for "self-sensing" effect. They fabricated a micromachined piezoelectric thin film with monolithic flexible structures for micro force sensing. By using self-sensing piezoelectric effect, a change in the mechanical load on piezoelectric thin film or PZT ceramics can be detected at the electrical transducer input as a sensor.

In this work, the self-sensing piezoresistive MEMS cantilever is implemented for nanoscale force sensing and manipulation. Fig. 4 shows SEM images of a MEMS cantilever tip with approximately 20 nm radius of curvature, provided by Seiko Instruments Inc. The piezoresistive cantilever enables a sensing of the gripping and contact forces by the measurement of the stress-induced electrical resistance. Fig. 5 shows microscopic images of a piezoresistive MEMS cantilever. Table 2 shows electro-mechanical characteristics of the piezoresistive MEMS cantilever used in this work.

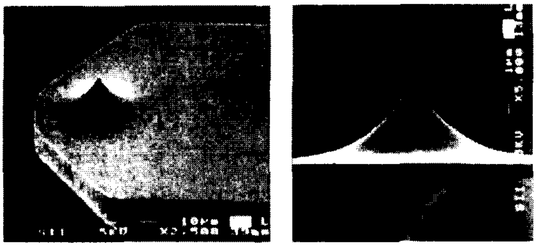


Fig. 4 SEM images of a MEMS cantilever tip with radius approximately 20 nm (Seiko Instruments Inc.)

3.2 Microrobotic manipulation system

Figure 6 shows the system configuration for a

Table 2 Electro-mechanical characteristics of a piezoresistive MEMS cantilever

Items	Characteristics
Spring constant	3 N/m
Resonant frequency	38 KHz
Resistance	550±150 Ω
Sensitivity	$2.6\times10^{-5}(\triangle R/R/nm)$
Total cantilever length	400 um
Width	50 um
Thickness	5 um
Tip radius	<20 nm

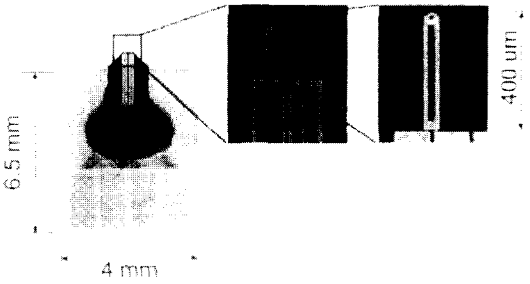


Fig. 5 Microscopic images of a self-sensing piezoresistive MEMS cantilever

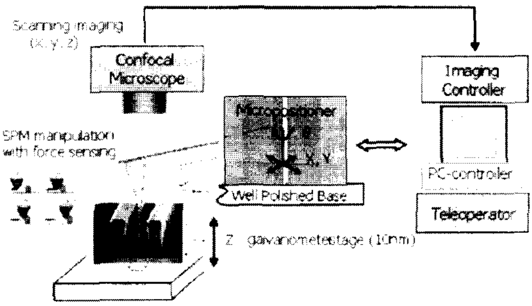


Fig. 6 The system configuration for a cantilever probe-based manipulations consisting of a confocal laser scanning microscope and a 3-DOF microrobot with a piezoresistive MEMS cantilever

cantilever probe-based nanomanipulation presented in our previous work (Kim et al., 2002). It consists of a self-sensing MEMS cantilever and a 3-DOF microrobot (positioner) under a confocal laser scanning microscope (model: Zeiss LSM5 Pascal). The developed mobile microrobot (micropositioner) on a well-polished base is used as a subsystem which provides 3-DOF motion with sub-micron resolution in small working space under the confocal laser scanning microscope (Park et al., 2003). In order to observe the microscopic environment, the system is equipped with two kinds of sensors: a confocal laser scanning microscope as a visual sensor for macro movements and a piezoresistive cantilever as a force and topology sensor for nano movements. The confocal laser scanning microscope as a visual sensor has a lateral resolution of about 200 nm and a vertical resolution of about 100 nm. We are currently in the progress of integrating a piezoresistive MEMS cantilever as an end-effector with a force sensor into the 3-DOF mobile microrobot system.

4. Experiments and Simulations

4.1 Signal processing and calibration

The piezoresistive cantilever-based force sensing system consists of a cantilever structure with a probe tip and a detection system: the implanted piezo resistors and Wheatstone bridge connected to pre amplifier. Figure 7 shows the experimental setup for calibrating a piezoresistive MEMS cantilever. The goal of the calibration is to acquire the force sensing signal from the voltage change provided by the Wheatstone bridge. Force measurement is performed by determining the deflection of the free end of the piezoresistive cantilever. A cantilever structure converts the force acting on the tip into its deflection, and then its deflection can be measured by the resistance change of the implanted piezo resistors shown in Fig. 5. The measurement of the resistance change induced by mechanical stress applied to the cantilever structure is performed by an integrated Wheatstone bridge that supplies a voltage change as output signal. This signal is amplified and provided to the PC for further processing by an A/D converter.

The force is then given by the force-deflection model of the cantilever, and thus the spring constant has to be known precisely for an exact determination of the force. Denoting the deflections and forces along the x, y, and z axes as shown in Fig. 8, the force-deflection model of the cantilever is then given by

$$\Delta F_z = k_c \Delta z \tag{4}$$

where k_c is the normal spring constant of the cantilever in bending with an α angle ofalong the x-axis and Δz is the deflection of the cantilever in z-direction perpendicular to the sample surface.

Figure 9 shows the experimental result of calibrating a piezoresistive MEMS cantilever as a force sensor. The measured output voltage in

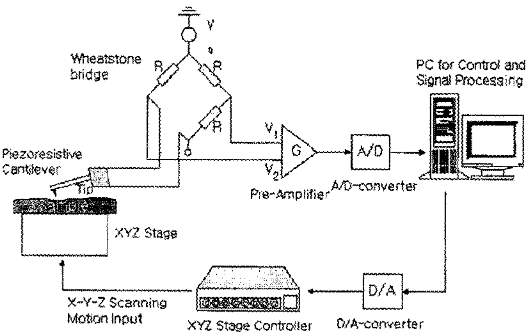


Fig. 7 Experimental system setup for calibrating a piezoresistive MEMS cantilever

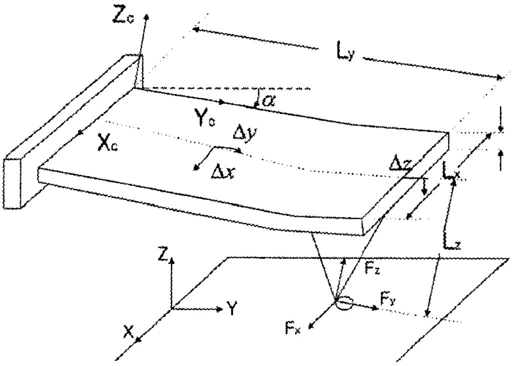


Fig. 8 Notation for modeling bending of a micro cantilever along x-y-z axes

Fig. 9 corresponds to the interactive force between a cantilever tip and a sample surface (silicon substrate) when the cantilever tip approaches and retreats to and from the surface. For calibration, the piezo-scanner moves in the z-direction, downward and upward. By obtaining exact force-distance relationships, a piezoresistive cantilever with the normal stiffness was well-calibrated. The output voltage caused by the deflection of the piezoresistive cantilever varies linearly with the distance between a cantilever tip and a surface. The measured sensitivity of a piezoresistive cantilever-based sensor is about 50 nm/V.

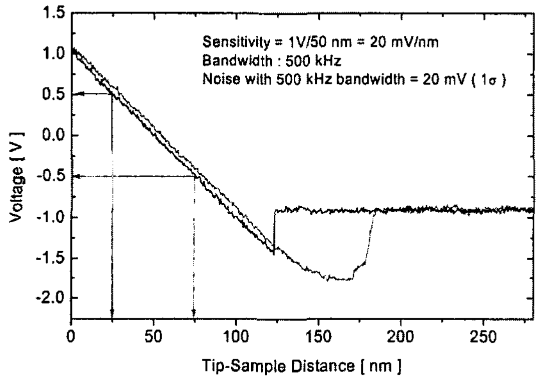


Fig. 9 Experimental result of calibrating a piezoresistive MEMS cantilever as a force sensor

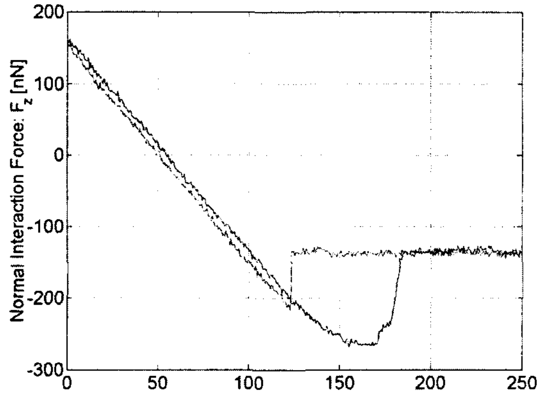


Fig. 10 Force measurement based on the cantilever force-deflection model when a cantilever tip is touched on the surface at the z-direction

Using calibration results, the interactive force between a cantilever tip and a sample surface can be calculated from equation (4). Based on the cantilever force-deflection model, Fig. 10 shows the interactive force measurement when a cantilever probe tip is touched on the surface at the z-direction. The force sensing resolution is less than 1 nN, thus allowing not only the sensing of gripping and contact forces of the fragile micro objects but also a sensor-based feedback control in cantilever probe-based manipulation with very low controlled forces.

4.2 Simulation for cantilever probe-based manipulaiton

The eventual goal in nanomanipulation with a cantilever probe tip, even though it may not be easily achieved yet, would be the realization of a feedback control of the tip-sample interaction force, for example, van der Waals force, by using a nanorobot manipulator like piezoresistive cantilever.

Simulations were carried out for the pick-up of a spherical particle (in this case copper). The pick-up process starts with the movement of the cantilever in the x-y directions and scrutinizing the target object within the range of the field of view of microscope. Then, the tip approaches a particle, grips it, moves it up, and holds. Figure 11 presents the interactive forces which are produced in gripping a spherical particle (Cu) located on the flat surface using a spherical-shaped silicon tip.

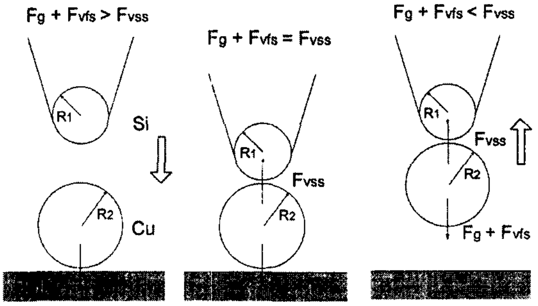
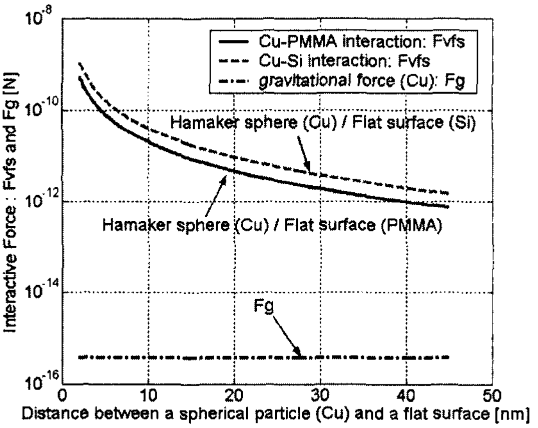
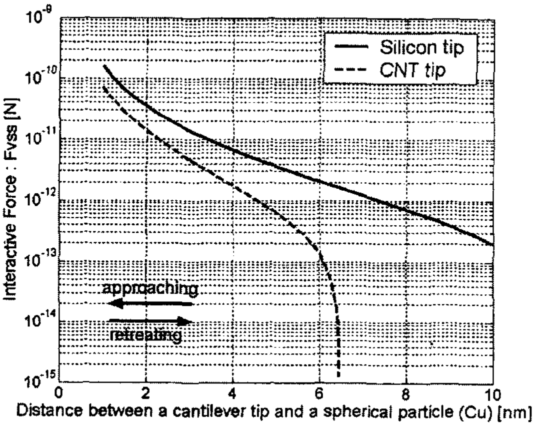


Fig. 11 Pick-up processes of a spherical particle using a cantilever probe : (a) Approach, (b) Grip, and (c) Move-up and hold

In the absence of electrostatic force and surface tension, let F_g, F_{vfs}, and F_{vss} be the gravitational force, van der Waals force between a spherical particle and the flat surface, and van der Waals force between a cantilever tip and a spherical particle, respectively. The gripping, moving-up, and holding strategies can be achieved by controlling the magnitude of these three types of forces. The distance between a cantilever tip and a spherical particle should be controlled for picking up the particle. However, it is difficult to know how far the tip is from the sample surface without sensing the interactive force. The interactive force can be estimated in real-time, based on the cantilever force-deflection model and calibration result of the implemented piezoresistive MEMS cantilever.



(a) Interactive force : F_{vfs} and F_g



(b) Interactive force : F_{vss} for different materials of probe tip

Fig. 12 Simulation results of the interactive forces

Figure 12 shows simulation results of the interactive forces needed for pick-up task. The pick-up task models previously described were implemented with the MATLAB simulation tool. Manipulation using a cantilever probe tip was performed for different materials combination of a flat substrate and cantilever. Hamaker's combination relationships described in equation (2) are supposed to be applicable. Table 3 shows Hamaker constants for two different materials.

The interactive forces acting between a copper sphere and each flat surface with different materials (in this case PMMA and silicon) are shown in Fig. 12(a). As can be predicted with equation (3), interactive force decreases with the distance between a spherical particle and a flat surface. Fig. 12(a) also shows that interactive force between a sphere in copper and a substrate in silicon is larger than that between a sphere in copper and a substrate in PMMA because the substrate in silicon is made of a higher Hamaker constant material.

In the aim to observe the role of the materials in interactive force, different constitutive materials of cantilever probe tip were also chosen. The cantilever probe tip in silicon and carbon nanotube (CNT) tip has been used for simulation. The cantilever probe tip in silicon is mostly used. Due to their high aspect ratio, well-defined cylindrical structure, and good mechanical robustness, however, carbon nanotubes (CNTs) have the potential to be used as the probing tips. Cantilever tips attached with a CNT tip is also commercially available. Fig 12(b) shows interactive force (to be controlled) between a cantilever tip and a copper sphere. The general behavior in the case of simulation with silicon tip is close to the one obtained with CNT tip.

Table 3 Hamaker constants for different contacts (Note that all values are given in Joules× 10^{-20})

H_{CuPMMA}	H_{CuSi}	H_{CuCNT}
13.38	26.96	24.83

Silicon and carbon possess a high Hamaker constant, but CNT tip has much lower radius of curvature. Consequently, interactive force using CNT tip dominates in smaller distance between a tip and a sphere, and should be more precisely controlled.

From these results, the optimal gripping forces can be estimated as a function of distance between a cantilever tip and a spherical particle and between a spherical particle and a flat substrate surface. Therefore, a range of displacement of a cantilever probe tip ensuring gripping by adhesion can be determined. For example, assuming a 6 nm separation of a 200 nm diameter copper sphere from a PMMA flat substrate surface, when a cantilever tip in silicon approaches to a spherical particle within 1.5 nm, a pick-up task due to $F_{vss}(=6.75\times10^{-11}\,\text{N}) > F_g + F_{vfs}$ is achieved. In the distant region rather than 2 nm, adhesion force between a cantilever probe tip and a sphere is too weak to overcome adhesion between a sphere and a substrate. It should be also noted that the gravitational force F_g acting on a 200 nm diameter sphere of copper is 3.678×10^{-16} N. So the weight is negligible compared to the attraction forces of van der Waals force at the nanoscale, and the cantilever tip will be able to pick up the spherical particle by adhesion. These observations provide an insight into an effective manipulation of particles by adhesion as well as the mechanics of nanomanipulation.

5. Conclusions

In this paper, the "self-sensing" piezoresistive cantilever was implemented for nanoscale force measurement and a sensor-based manipulation in microrobotic applications. The calibration of a piezoresistive MEMS cantilever is experimentally carried out. In addition, as part of the work on cantilever probe-based nanomanipulation, the manipulation strategies with the analysis on the interaction forces between a tip and a material are investigated. The associated forces analysis may give an insight into the mechanics of a cantilever probe-based nanomanipulation. Experiments and simulations show that the force sensing resolution is less than 1 nN. Thus, we may achieve sensor-based feedback control with very low controlled forces, and may be able to sense gripping and contact forces of the fragile micro objects.

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