Invited Review Article: A review of techniques for attaching micro- and nanoparticles to a probe's tip for surface force and near-field optical measurements

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Cantilevers with single micro- or nanoparticle probes have been widely used for atomic force microscopy surface force measurements and apertureless scanning near-field optical microscopy applications. In this article, I critically review the particle attachment and modification techniques currently available, to help researchers choose the appropriate techniques for specific applications. © *2007 American Institute of Physics.* [DOI: 10.1063/1.2754076]

I. INTRODUCTION

Scanning probe microscopy (SPM) plays an essential role in nanotechnology. Atomic force microscopy (AFM) was initially developed to obtain surface topography at nanoscale or even atomic scale[1,2] to complement scanning tunneling microscope (STM).[3] Gradually, the application of AFM has been greatly expanded to realize functional characterization; this is made possible through modifications of the probe tip (the forearm of AFM) that change or augment the interaction mechanism of the tip with the target surface. Using AFM with a modified probe, researchers are able to explore a range of surface physical and chemical properties, again at nanoscale or even at the atomic scale. Almost in parallel development with AFM, scanning near-field optical microscopy (SNOM or NSOM) was developed to achieve nanoscale optical resolution[4,5] and perform functional characterization similar to the AFM. This larger family of microscopy derived from STM, AFM, and SNOM is known as SPM.

Among probe modification techniques, attaching a particle, a single object, to the probe tip is favorable because the geometry and composition of the particle can be well controlled. Attaching a microparticle, especially a microsized sphere, to an AFM cantilever for force measurements has become routine in AFM labs since the technique was introduced in two pioneering articles published in 1991: one by Ducker *et al.*[6] and the other by Butt.[7]

In the past fifteen years, techniques have been developed for attaching even smaller objects such as single nanoparticles and nanotubes to tips used for AFM and SNOM applications. Tips modified with a submicron or even nanosized particle have been used extensively in apertureless SNOM. A metal (usually Ag or Au) nanoparticle acts as a "nanoantenna" to achieve surface-enhanced Raman spectroscopy (SERS) and evanescent photon spectroscopy. A glass fiber tip with an attached single metallic particle, compared with a fully metallized tip, can achieve higher signal-to-noise ratio because the attached metallic particle scatters light strongly whereas the glass fiber scatters light only weakly (thus reducing the background signal) due to its lower index of refraction.

Despite the development of a wide variety of techniques for attaching particles to SPM tips, a comprehensive review has yet to be written on this topic, though some review articles have touched on attachment techniques for force measurements,[8] chemistry and biochemistry applications,[9] and near-field optics applications in nanotechnology.[10] In this article, I will critically review the techniques available in the literature, hoping to aid researchers in choosing the appropriate technique for their application. Because the methods to fabricate carbon nanotube (CNT) probes have been reviewed recently,[11] that topic will not be included here.

This article consists of three sections: Sec. II reviews techniques for attaching micron sized particles; Sec. III reviews nanoparticle techniques; and Sec. IV provides perspective and includes a summary table that highlights the main features of each of the techniques discussed in the first two sections. Details of each technique are provided, along with appropriate figures and discussions of advantages and disadvantages of the techniques.

II. TECHNIQUES FOR ATTACHING A MICROPARTICLE

Probes with attached microparticles have been extensively used for interfacial force measurements. A tip modified with a sphere which has a smooth surface and diameter larger than 1 μm yields advantages over a bare tip. The sphere has a well-defined geometry and gives higher signal-noise-ratio in force measurements so more accurate information can thus be derived from force curves.[6,7]

Since a particle bigger than 1 μm can easily be observed with an optical microscope, an optical microscope and a three-dimensional (3D) micromanipulator are the standard tools for attaching a microparticle in the following techniques.

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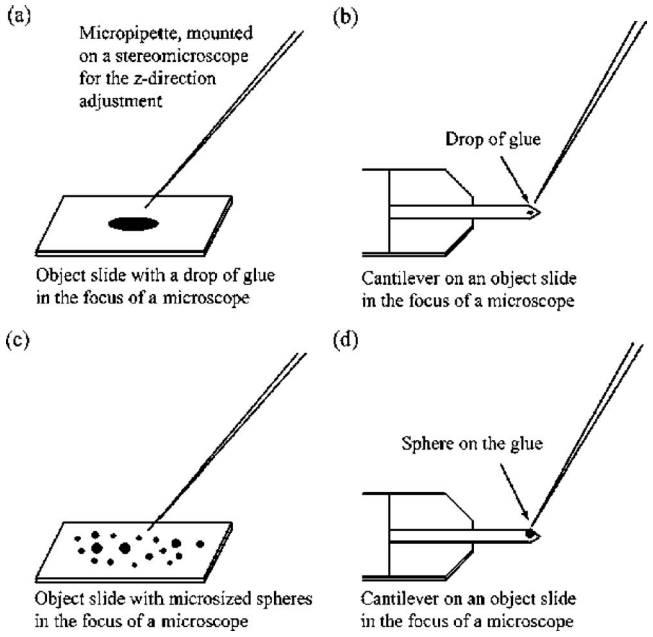

FIG. 1. Schematic of the procedure of the dual-wire technique for attaching a particle to the tip of an AFM cantilever. (a) One wire (a micropipette here) picks up a small drop of glue. (b) The glue is applied to the cantilever. (c) The other wire picks up a colloidal particle. (d) The particle is positioned on the glue spot on the cantilever. Copied with permission from Mak *et al.* (Ref. 13). Copyright 2006 American Institute of Physics.

A. Dual-wire technique

The dual-wire technique, originally reported by Ducker *et al.* in their classic papers,[6,12] is the most popular method for the attachment of microparticles. Figure 1 illustrates the technique.[13] While observed under an optical microscope, a probe is fixed on a glass slide with cantilevers facing up. A 3D manipulator is used to first move one sharpened wire (or fiber, micropipette) to pick up a tiny amount of glue, then to deposit the glue on the tip of the cantilever. The other wire is then used to pick up a particle via capillary force and attach it to the glue spot on the cantilever. Figure 2 shows a beautifully attached 9 μm titanium sphere on a tipless cantilever.

This technique is especially suitable for dealing with tipless (flat-ended) cantilevers because the flat end facilitates applying glue and setting the particle in place. This technique has some disadvantages. First, due to the weak capillary force between the wire and particle, it is sometimes difficult to pick up a particle. Increasing the local humidity, e.g., putting an open pan of warm water nearby, may help increase the capillary force. Second, the wires must be kept clean to avoid surface contamination of the particle. Most importantly, particularly for triangular cantilevers, a defective cantilever with a leg broken can escape notice using this technique until the cantilever is subsequently used for measurements. Replacing a defective cantilever is annoying, particularly when measurements are carried out in a liquid, because one has to dissemble, reclean, and reassemble the liquid cell to continue the measurements.

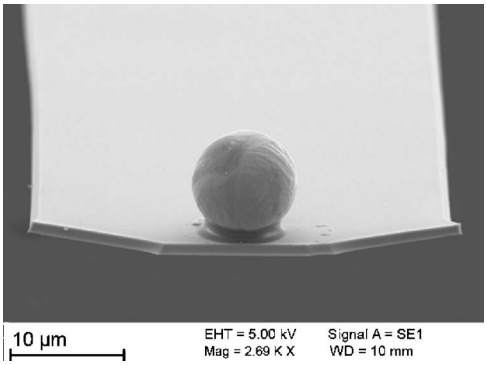

FIG. 2. SEM image of a 9 μm titanium sphere attached to the end of a tipless rectangular AFM cantilever. Copied with permission from Mak *et al.* (Ref. 13). Copyright 2006 American Institute of Physics.

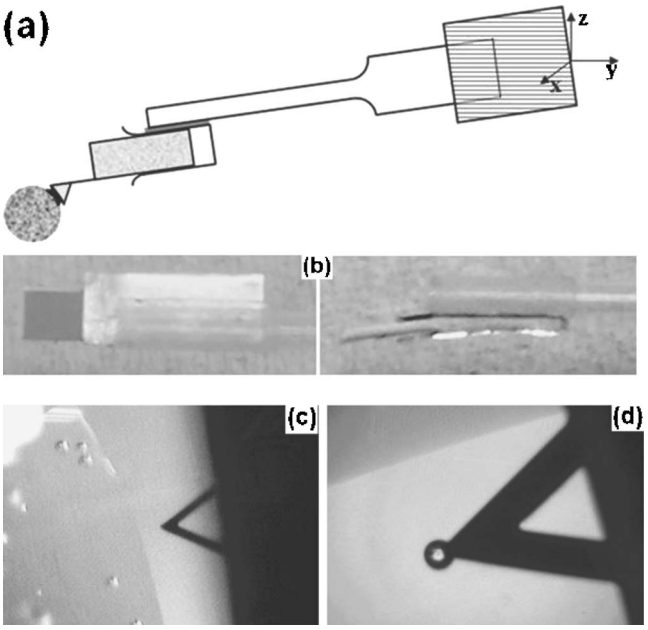

FIG. 3. The setup and the procedure of the cantilever-moving technique. (a) The setup of the probe holder. The U-shaped clip holding an AFM probe is glued to a glass pipette that is inserted into the arm of a 3D manipulator. (b) The top (left) and the side (right) view of the clip holding the probe. (c) When monitored through an optical microscope, the probe is positioned close to the edge of a small puddle of glue, lowered to press slightly against the glass slide, and pushed into the glue so that only the tip touches the glue; the probe is then pulled out to drag off the excess glue along the glass slide. (d) The tip is positioned on the top of a sphere (a 20 μm glass sphere here), lowered vertically to touch the sphere, and then lifted up. For a pyramid-shaped tip, ideally the sphere can be attached to the foreside of the tip, as illustrated in (a).

B. Cantilever-moving technique

With this technique, instead of moving wires, the cantilever is moved around either by a 3D manipulator or on an AFM head.[14–17] Figure 3 shows the setup and the procedure.[17] The cantilever is first moved to pick up a tiny amount of glue from a glass slide and then moved to a particle to pick it up. Compared with the dual-wire technique, the advantages of this method are as follows: First, no wires are needed, one can thus bypass time-consuming steps such as wire sharpening, glass pulling, and wire cleaning. Second, a defective cantilever can be noticed more easily, because when a cantilever is tapping the glass slide to pick up glue, the broken leg of a defective cantilever deflects light in a different direction which is easily observed.

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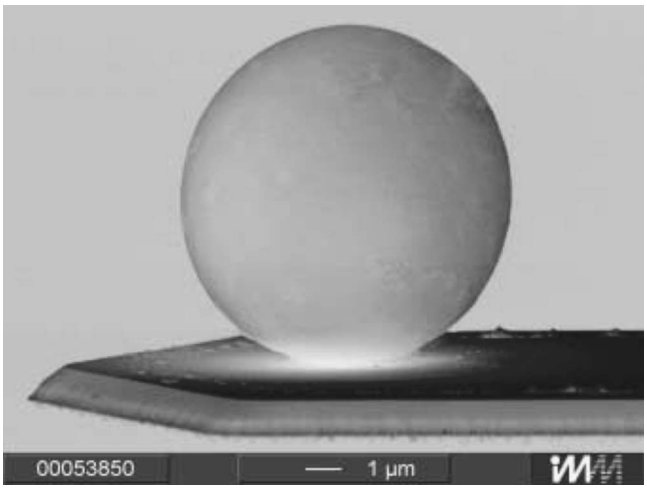

FIG. 4. A borosilicate glass sphere (about 9.2 μm in diameter) sintered to a tipless silicon cantilever at 780 °C for 2 h. Image courtesy of Bonaccurso (Ref. 18).

C. High temperature sintering technique

With the two former techniques, an adhesive (usually epoxy resin) is used to glue a particle to the tip. Under certain circumstances, for example, when the probe is used in liquid, dissolution of the adhesive might be a potential contamination concern, particularly for measurements demanding stringent cleanliness. In order to eliminate potential contamination from the adhesive, Bonaccurso[18] and Bonaccurso *et al.*[19] developed an elegant sintering technique to attach borosilicate glass particles. Borosilicate glass was chosen because of its relatively low melting temperature (1250 °C) and softening point (820 °C). With this technique, a cantilever is moved by a 3D manipulator to touch a drop of glycerol and then to pick up a glass sphere using capillary adhesion. The cantilever with the attached particle is then heated in an oven to a temperature slightly below the softening point of the glass. Note that the glycerol between the sphere and cantilever evaporates when heated. Figure 4 shows a sphere sintered to a cantilever. Unfortunately, the sintering step of this technique limits its application to materials like borosilicate glass with rather low melting temperature.

III. TECHNIQUES FOR ATTACHING A NANOPARTICLE

For submicron particles or nanoparticles, it is not feasible to accurately position a single particle on a tip using the techniques described in the first section due to the intrinsic resolution limitations of optical microscopes. For instance, as shown in Fig. 5, only nanoparticle clusters, instead of a single nanoparticle, can be attached to the tip using the conventional cantilever-moving technique, as demonstrated by Ong *et al.*[20] To my knowledge, the smallest single particle to be successfully attached using the cantilever-moving technique is around 1 μm, as demonstrated by Okamoto and Yamaguchi.[21] Recently, some more sophisticated techniques have been developed to modify a tip with a single nanoparticle. These techniques utilize state-of-the-art knowledge of surface chemistry, optics, and photocatalysis.

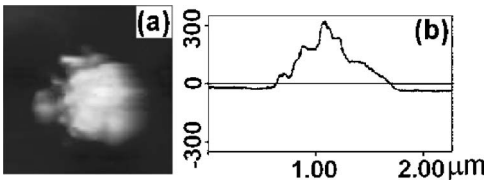

FIG. 5. Clusters of ceria nanoparticles (size of individual particles: 50–100 nm) have been attached to the tip of an AFM cantilever using the cantilever-moving technique. (a) Topography of the clusters obtained by scanning (reverse imaging) a grating with spikes sharper than the cluster, showing that the cluster is composed of multiple individual nanoparticles. Image size: 2×2 μm^2. (b) The cross-sectional profile. Image courtesy of Sokolov (Ref. 20).

A. Inversed self-assembly grafting technique

Sqalli *et al.* developed an inversed self-assembly grafting technique to attach a single nanoparticle or multiple nanoparticles to the tip of a SNOM fiber probe.[22] The essence of this technique is that a layer of propylthiol groups on the tip is used as an adhesive to graft a nanoparticle to the tip. The pretreatment of the SNOM optical fiber tips is also critical: the tip is first etched in HF solution, followed by aluminum evaporation to cover the sides of tips. The tip is then silanized in a heated chamber. Adsorbed molecular water on the tip is removed by heating. Under ethanol production 3-ercaptopropyl-triethoxysilane is introduced into the chamber to react with the remaining hydroxyl (OH) groups on the tip to form a layer of propylthiol groups. The tip is then taken out and rinsed in distilled water to remove the silicon propylthiol groups on the Al coated part of the tip.

The tip is then dipped into a Au nanoparticle suspension to allow Au nanoparticles to graft onto the tip with the thiol groups. This is the reason why the process was named as "inversed self-assembly process." It is found that a single Au nanoparticle [see Fig. 6(a)] attaches to the tip after being immersed in the suspension for 5 min. Longer immersion leads to multiple nanoparticle attachments [see Fig. 6(b)].

B. Wet-chemistry surface assembly

Vakarelski and Higashitani developed a full wet chemical technique to covalently attach gold nanoparticles to the tip of an AFM cantilever.[23] They demonstrated the technique

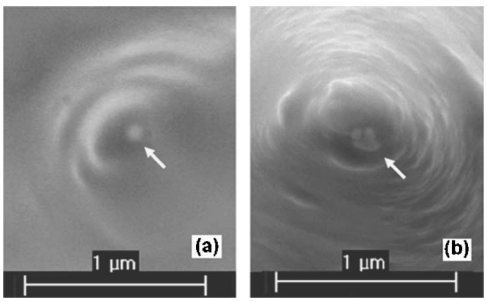

FIG. 6. SEM pictures of Au nanoparticles attached to the tip of a silica SNOM tip with the "inverse self-assembly" technique. (a) Top view of an attached single Au particle (indicated by the arrow) of around 60 nm in diameter. (b) Top view when multiple Au particles have been attached. Note that in the original paper the two images were mistakenly transposed. Copied with permission from Sqalli *et al.* (Ref. 22). Copyright 2006 American Institute of Physics.

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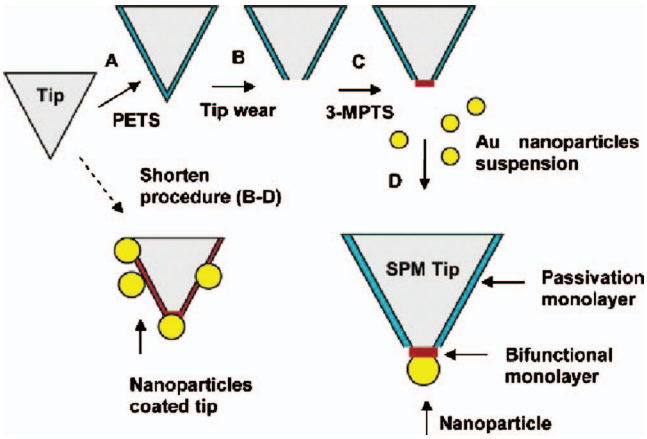

FIG. 7. (Color) The procedure of the wet surface-assembly technique. There are four steps for attaching a single nanoparticle. (A) The surface of the tip was made chemically passive by silanization with a monolayer of phenethyltrichlorosilane. (B) The passivation layer at the end of the tip was removed to expose a fresh native oxide surface by scanning the tip against a clean silica wafer surface. (C) The exposed surface reacts with 3– methacryloxypropyltrimethoxysilane (3-MPTS) silane to form a monolayer. (D) The tip is dipped into the Au nanoparticle suspension to allow a single nanoparticle to covalently bond to the tip. In the shortened procedure, as indicated by the dashed arrow, the phenethyltrichlorosilane (PETS) silanization step is omitted; however, multiple nanoparticles deposit on all sides instead of only at the end of the tip. Copied with permission from Vakarelski and Higashitani (Ref. 23). Copyright 2006 American Chemical Society.

by using a silicon nitride probe with sharp tips. The main steps of the attachment procedure are shown schematically in Fig. 7. A single Au nanoparticle terminated tip [Fig. 8(c)] can be realized by following the four step procedure; whereas multiple nanoparticles deposit on all sides of the tip following the shortened procedure, although a single nanoparticle is often found attached at the end of the tip [Figs. 8(b) and 8(d)]. The authors claimed that after optimizing the parameters in each step, a successful attachment rate of 30%–50% was achieved.

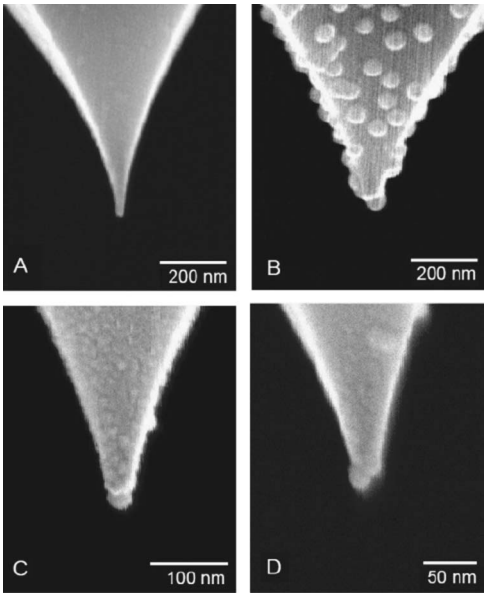

FIG. 8. Typical SEM images of a tip before and after the attachment of Au nanoparticles. (a) A fresh tip. (b) Multiple Au nanoparticles attach to the tip following the shortened procedure. (c) A single nanoparticle attaches to the end of the tip following the four step procedure. (d) A single nanoparticle might attach to the end of the tip following the shortened procedure. Copied with permission from Vakarelski and Higashitani (Ref. 23). Copyright 2006 American Chemical Society.

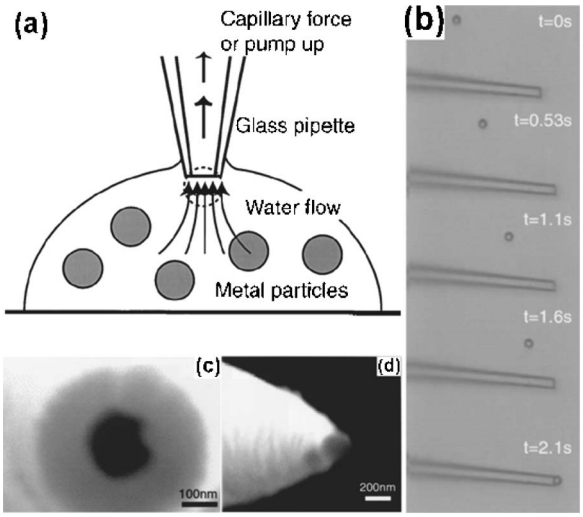

FIG. 9. The water-flow suction technique. (a) A microtube is immersed in an aqueous suspension of nanoparticles. The water flow induced by either the capillary force or pumping drives the particles towards the microtube's orifice. A particle larger than the orifice will be trapped at the orifice. (b) A series of pictures showing a particle moving towards the orifice. (c) SEM picture of the end of a microtube showing that the inner diameter of the orifice is about 150 nm. (d) SEM picture of a microtube with an attached gold nanoparticle at the end. Copied with permission from Kawata *et al.* (Ref. 24). Copyright 2003 American Institute of Physics.

Compared with the former inverse self-assembly technique, this technique has the advantage that each step of the process operates at room temperature in a wet chemical environment; thus it does not require any high temperature equipment. However, the essence of the two techniques is the same—both use a silanized monolayer as the adhesive to graft a nanoparticle to the tip.

C. Water-flow suction technique

Kawata *et al.* invented a water-flow suction technique to attach a single nanoparticle to a SNOM glass microtube.[24] The principle is simple and elegant. As shown in Fig. 9(a), a microtube is immersed in the suspension of nanoparticles, water is driven out through the microtube by the capillary action or by pumping so that particles dispersed in the water are driven towards the orifice of the microtube. The first particle larger than the orifice is thus trapped at the orifice. Figure 9(b) shows a series of pictures of the movement of a particle. Finally, the micropipette is dried out, and the particle remains attached at the orifice due to capillary adhesion between the tube and particle. Figure 9(c) shows a carefully pulled microtube with an inner diameter slightly over 100 nm, and Figure 9(d) shows an attached 180 nm Au particle.

D. *In situ* picking-up technique

Kalkbrenner *et al.* developed a technique for *in situ* attachment of a single nanoparticle at the end of an optical fiber tip[25] using a combined SNOM and scanning confocal microscope. Before being mounted in the SNOM head, the

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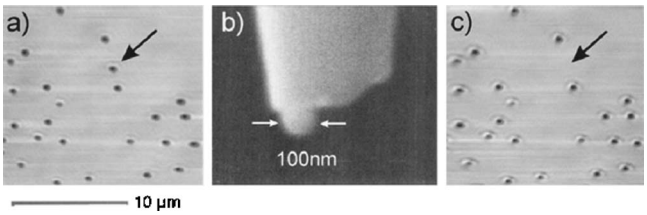

FIG. 10. The *in situ* picking-up technique. (a) A confocal image of gold particles that are spin coated on a glass slide. The particle marked with the arrow will be targeted and approached with the tip under shear-force control. (b) SEM image of a single particle that is picked up and attached to the end of the tip. The tip is coated with a monolayer of polyethylenimine as adhesive. (c) The repeated confocal scan of the same area verifies that the particle has indeed been picked up and is missing from the glass slide. Copied with permission from Kalkbrenner *et al.* (Ref. 25). Copyright 2001 Blackwell Publishing.

fiber tip is placed in polyethylenimine solution to form a monolayer on the surface. The monolayer acts as an adhesive to pick up and fix the nanoparticle. Gold particles are spin coated on a glass slide to a low coverage density [Fig. 10(a)]. Individual particles are imaged with the confocal mode; one particle is then targeted and approached with the mounted optical fiber under shear-force control. The tip contacts the particle and the particle attaches to the tip via the monolayer on the tip, as shown in Fig. 10(b). Finally a confocal scan of the same area is repeated to verify that the particle was indeed picked up [see Fig. 10(c)]. They claimed a high success rate. I believe that this technique can also be used for AFM probes if the tip can also be modified with an appropriate monolayer.

E. Optical tweezers technique

Optical tweezers (a laser trapping technique) have been used extensively to manipulate nanoparticles. For an extensive review on the application for chemical analysis, see the review article by Kitamura and Kitagawa.[26] Using optical tweezers, Pampaloni *et al.* successfully attached a 250 nm fluorescent bead to a grafted microtubule to study the mechanical properties of microtubules.[27] A microtubule is first fixed on a gold substrate via covalent grafting with a self-assembled monolayer [Fig. 11(a)]. Optical tweezers are then used to position the nanoparticle onto the tip of the grafted microtubule [Fig. 11(b)].

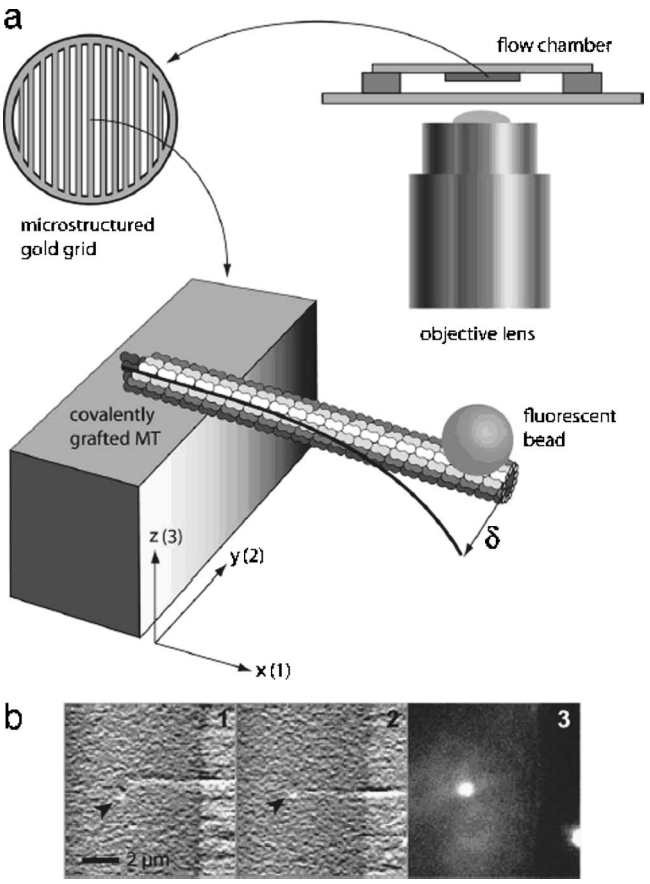

FIG. 11. Optical tweezers technique. (a) A microtubule (MT) is fixed on a gold substrate via covalently grafting with a self-assembled monolayer. The operation is carried out under an optical microscope. (b) The sequence of positioning (first frame) and attaching (second frame) of a 250 nm fluorescent bead (indicated by the arrow) to the tip of a grafted MT. Frame 3 is the fluorescence image of the bead after changing the filter. Copied with permission from Pampaloni *et al.* (Ref. 27). Copyright 2006 National Academy of Sciences, U.S.A.

F. Direct deposition techniques

With all techniques reviewed in Secs. III A–III E, particles to be attached are either used as received or prepared separately before attachment. In contrast, the following techniques start from scratch: a nanoparticle is *directly* deposited (or grown) on the tip induced by a chemical reaction or an electron beam. Here I do not include other similar techniques for the deposition of a thin film instead of a particle, for example, vacuum deposition.[28]

1. Nanopipette chemical reaction deposition

Barsegova *et al.* ingeniously utilized the principle of Tollen's reaction to fabricate a silver or gold particle on the tip of a nanopipette used in SNOM.[29] Tollen's reaction is used in carbohydrate chemistry to detect the presence of aldehyde groups—the so-called "silver mirror test." In a solution of glucose, silver nitrate ($AgNO_3$), and ammonia, Ag^+ is reduced to metallic Ag.

The technique was demonstrated by using a nanopipette with one or two channels. The nanopipette is to be used as a tapered cantilever. With a two-channel nanopipette, $AgNO_3$ solution flows in from one channel and sugar solution from the other. Tollen's reaction deposits Ag between the orifices of the two channels on the tip. With a single-channel nanopipette, $AgNO_3$ solution is injected through the channel into a sugar solution; Ag also deposits on the tip around the reaction area. The size of the deposited particle can be controlled by changing the reaction time. Figure 12 shows a 100 nm Ag particle formed between two orifices.

A gold particle can also be prepared using a variant of this technique, as demonstrated by the same authors.[29] After an initial seed Ag particle forms, a Au particle is grown on the Ag seed in an electronless Au enhancing solution (details not provided). This technique has been applied commercially to produce probes used in the AFM/SNOM equipment by the company Nanonics Imaging.

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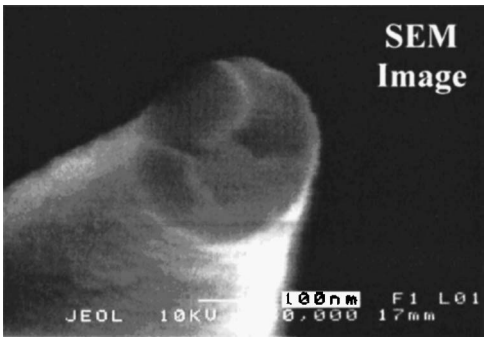

FIG. 12. SEM picture of the tip of a nanopipette with a 100 nm Ag nanoparticle deposited by the chemical reaction deposition technique. (Note that solutions come out from two orifices below the nanoparticle.) Copied with permission from Barsegova *et al.* (Ref. 29). Copyright 2002 American Institute of Physics.

2. Photocatalysis deposition

Okamoto and Yamaguchi utilized the photocatalytic effect of titanium dioxide (TiO_2) to deposit a Au nanoparticle onto the tip of an AFM cantilever.[30] The principle of the photocatalytic effect of TiO_2 is that irradiation with light of energy greater than the TiO_2 band gap creates electron/hole pairs; in a solution, the electrons in the conduction band reduce Au^{3+} ions to metallic Au; at the same time the holes in the valence band oxidize water to oxygen.

Okamoto and Yamaguchi used uncoated silicon nitride cantilevers with integrated pyramidal tips. The cantilever is sputter coated with a 20 nm Ti film and then oxidized in air to form a TiO_2 layer. Figure 13 illustrates the photocatalytic deposition process. The cantilever is put in the aqueous solution of tetrachloroauric acid ($HAuCl_4$), ultraviolet light irradiation reduces Au^{3+} ions to Au through the photocatalytic reaction so that Au deposits on the surface to form a particle. The authors found that the illuminated area had to be on the nanoscale so that the deposition only occurred at the apex of the tip. They achieved this by ingeniously using evanescent wave illumination generated by the attenuated total reflection of a laser beam through a prism. Because the penetration depth of the evanescent wave is a fraction of the wavelength, only the apex of the tip is illuminated. Figure 14 shows a tip before and after the deposition of a 150 nm Au nanoparticle. This technique can, in principle, be used for the SNOM tip as well. The shape control of the deposited particle will be a major challenge.

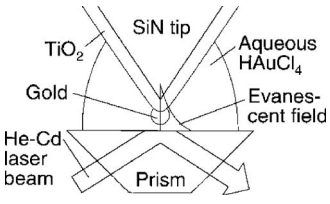

FIG. 13. Illustration of the photocatalytic deposition technique. A silicon nitride tip with an oxidized TiO_2 surface layer is irradiated by ultraviolet light to form metallic Au by reducing Au^{3+} ions by the photocatalytic effect in the aqueous solution of tetrachloroauric acid ($HAuCl_4$). To limit the reaction to the apex of the tip, the tip is illuminated with the evanescent wave that is generated by the attenuated total reflection of a He-Cd laser beam at the prism/electrolyte interface. Copied with permission from Okamoto and Yamaguchi (Ref. 30). Copyright 2001 Blackwell Publishing.

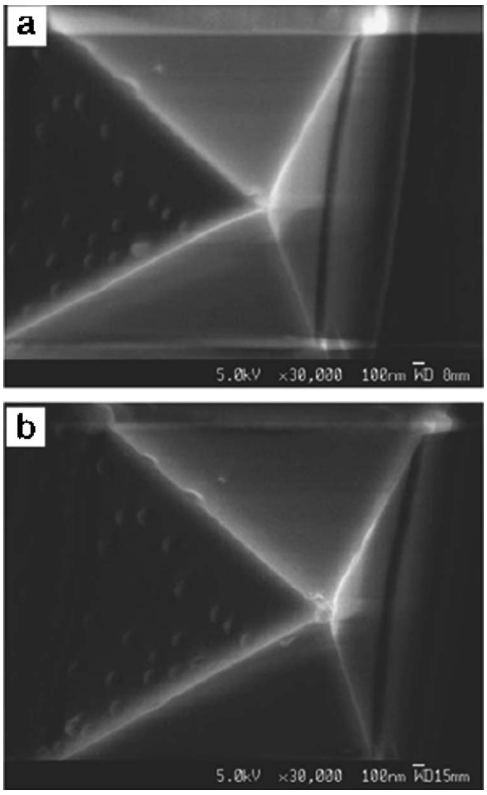

FIG. 14. SEM images of a tip before (a) and after (b) the deposition of a 150 nm Au nanoparticle (indicated by the arrow) prepared by the photocatalytic deposition technique. Copied with permission from Okamoto and Yamaguchi (Ref. 30). Copyright 2001 Blackwell Publishing.

3. Focused electron beam (FEB) induced deposition

Sqalli *et al.* used a focused electron beam (FEB) to deposit a single particle on the tip of a silica SNOM probe.[31] A volatile Au precursor is put into the vacuum chamber of a scanning electron microscope (SEM). Electron beam irradiation decomposes the precursor to deposit metallic gold onto the probe tip. The particle shape and size can be controlled by scanning the electron beam and changing the irradiation

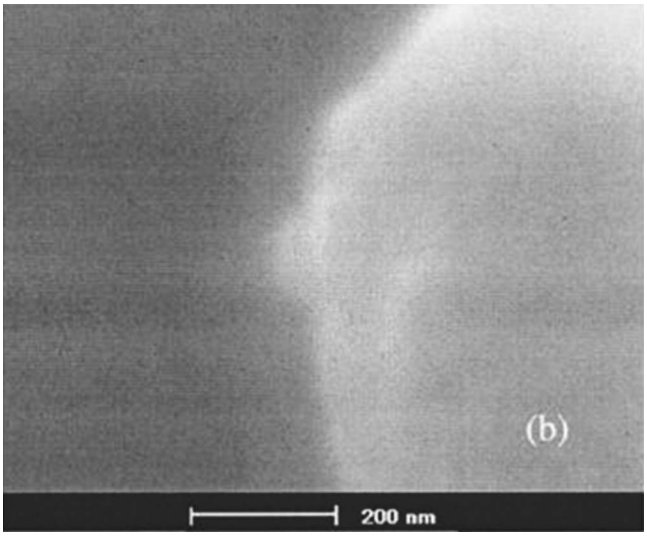

FIG. 15. SEM image of a 60 nm elliptical Au nanoparticle fabricated by the FEB induced deposition technique. Copied with permission from Sqalli *et al.* (Ref. 31). Copyright 2002 American Institute of Physics.

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TABLE I. Comparison between techniques for attaching a single microparticle and nanoparticle to the tip of an AFM or SNOM probe.

Techniques	AFM or SNOM probe suitability	Nature of the particle	Operation environment	Adhesives used	Special equipments required	Reference
Dual-wire technique	AFM	Not limited	Dry	Glue	Micromanipulator; sharpened wires	6, 12, and 13
Cantilever-moving technique	AFM	Not limited	Dry	Glue	Micromanipulator	14–17
High temperature sintering technique	AFM	Borosilicate Glass	Dry	Glycerol	Heatable chamber	18
Wet-chemical surface assembly	AFM (SNOM)[a]	Au	Wet	Self-assembled silane layer	None	23
Photocatalytic deposition	AFM (SNOM)	Au	Dry+wet	No	Sputter coating; evanescent wave illumination	31
Inverse self-assembly	SNOM optical glass fiber (AFM)	Au	Dry+wet	Self-assembled propylthiol groups	Heatable chamber	22
Water-flow suction	SNOM glass microtube (AFM)	Not limited	Wet	Water	None	24
Tip picking up	SNOM optical fiber (AFM)	Au	Dry	Polyethylenimine monolayer	Confocal microscopy	25
Optical tweezers	Microtube (AFM, SNOM)	Au	Wet	Self-assembled monolayer	Optical tweezers	27
Nanopipette chemical deposition	SNOM glass nanopipette with channels	Ag	Wet	No	None	29
Focused electron beam deposition	SNOM silica fiber (AFM)	Au	Dry	No	Focused electron beam equipment	31

[a]The probe(s) in the parentheses may also be potentially produced with the technique.

time. Figure 15 shows a tip deposited with a 60 nm Au nanoparticle with elliptical shape. The ability to control the shape of the deposited particle is an advantage of this technique.

G. A comparison of various particle-attachment techniques

Table I summarizes the techniques we have discussed and provides a comparison of the techniques in terms of their suitability for AFM or SNOM, *in situ* or *ex situ* operation, operation environment, adhesive used, and any special equipment requirements. I hope this table can be a starting point for researchers who wish to choose the most appropriate technique for their specific purposes.

IV. PERSPECTIVE

These methods for attaching a single particle to probe tip of AFM and SNOM instruments are the result of the creativity of many scientists who have developed clever techniques for the manipulation of particles by application of mechanical force, interfacial self-assembly, optical tweezers, photochemical reaction, and wet or dry deposition. Looking towards the future, I anticipate that methods for the batch production of particle-attached probes will emerge by transplanting the "top-down" protocols used in the semiconductor industry; at the same time, I also anticipate that exciting new discoveries in nanochemistry—the revolutionary "bottom-up" methods—will provide a continuing impetus for inventing new particle-attaching techniques.

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