# Switchable cantilever for a time-of-flight scanning force microscope

DongWeon Lee[a]
*IBM Research, Zurich Research Laboratory, 8803 Rüschlikon, Switzerland and NCCR (National Center for Competence for Nanoscience), Department of Physics and Astronomy, University of Basel, 4056 Basel, Switzerland*

Adrian Wetzel, Roland Bennewitz, and Ernst Meyer
*NCCR (National Center of Competence for Nanoscience), Department of Physics and Astronomy, University of Basel, 4056 Basel, Switzerland*

Michel Despont
*IBM Research, Zurich Research Laboratory, 8803 Rüschlikon, Switzerland*

Peter Vettiger
*IBM Research, Zurich Research Laboratory, 8803 Rüschlikon, Switzerland*

Christoph Gerber
*IBM Research, Zurich Research Laboratory, 8803 Rüschlikon, Switzerland and NCCR (National Center for Competence for Nanoscience), Department of Physics and Astronomy, University of Basel, 4056 Basel, Switzerland*

We have developed a cantilever device for applying a time-of-flight scanning force microscope (TOF–SFM) system. The cantilever device consists of a switchable cantilever with an integrated bimorph actuator, an integrated extraction electrode to minimize the ion extraction voltage, and an interlocking structure for precise tip–EE alignment. The TOF–SFM with the cantilever device allows quasisimultaneous topographical and chemical analyses of solid surfaces to be performed in the same way as with the conventional scanning probe technique. The switching properties of the bimorph actuator are demonstrated for use in two operating systems. Field emission measurements and a TOF analysis of a Pt-coated tip are conducted with the TOF–SFM. © *2004 American Institute of Physics.* [DOI: 10.1063/1.1651641]

A scanning probe microscope (SPM) has become an essential instrument for studying the structure and dynamics of individual molecules and atoms on a sample surface.[1,2] The current state of SPM techniques can map topography, temperature, electric and magnetic fields, and more.[3–8] Some researchers have also succeeded in moving single atoms to desired locations.[9] Vertical resolutions of less than 1 Å are routinely achieved when imaging on a well-defined sample surface. Using SPM techniques has opened entirely new capabilities in surface science, biophysics, and the semiconductor industry in the past 20 years. Simply put, there has been a steady stream of innovations. In spite of the striking achievements it has made possible, the drawback of the SPM technique is that it does not have the capability for chemical analysis of solid surfaces. To circumvent this restriction, a number of researchers have tried to combine the atom probe (AP) with the scanning tunneling microscope (STM) technique.

In early 1990, Nishikawa proposed a scanning atom probe (SAP) that uses a miniature extraction electrode (EE) that can be positioned or scanned across a planar specimen sample to analyze the chemical property of a single atom on a selected area.[10] Although this method clearly avoids the drawbacks of the conventional atom-probe technique, it still requires arrays of microtips on a planar sample for performing field evaporation at a tip apex. Another issue to be considered with the SAP method is the way the scanning electrode is aligned with the tips on the sample. A scanning electron microscope (SEM) may be employed in the SAP chamber for viewing the electrode and sample tips during a fine alignment process. A different approach proposed by Spence is the scanning tunneling atom probe (STAP) method, which combines the functions of the STM and the time-of-flight mass spectroscope (TOF–MS).[11] The basic configuration of the STAP is similar to that of the conventional STM except that it employs a removable sample stage. To analyze the chemical properties of a sample surface with the TOF–MS, the sample stage is moved away with a wobble stick, and a field evaporation pulse of up to 4 kV is added to a tip while a dc high voltage of 14 kV is biased between the tip and a channel plate. Unfortunately, all these methods have their drawbacks, which precludes them being the final design of an ultimate microscope with chemical sensitivity. Moreover, they are not practical for the chemically sensitive scanning force microscope (SFM) applications.

We propose a TOF–SFM with a switchable cantilever (SC) that has significant advantages for chemically sensitive SFM applications. One of them is that a local EE with a tip-electrode distance as small as a few micrometers significantly reduces the field-desorption voltage needed. A second important advantage is that the switching time between SFM and TOF–MS modes is reduced by orders of magnitude

[a]Author to whom correspondence should be addressed; electronic mail: dle@zurich.ibm.com

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FIG. 2. Topographic image of a standard sample for atomic force micros-copy calibration imaged by a switchable cantilever with piezoresistive strain sensor.
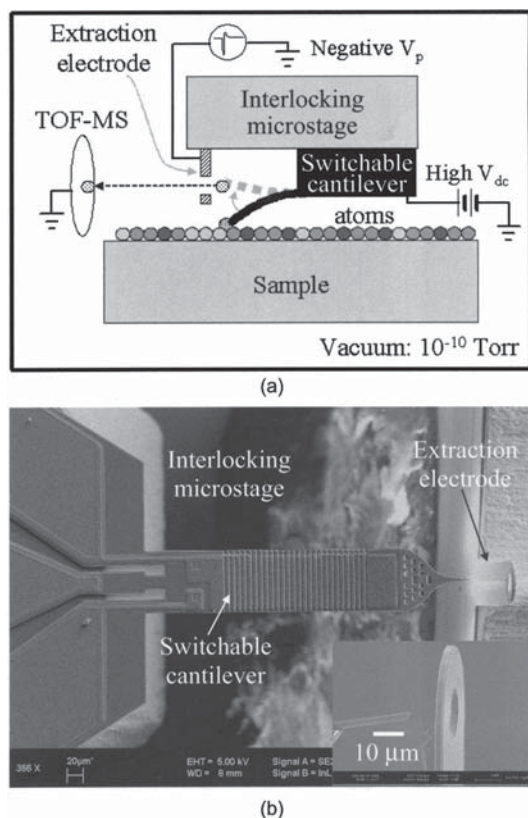
FIG. 1. (a) TOF–SFM basic concept and (b) a SEM image of a fully as-sembled cantilever device. Inset: Close-up of tip region when the tip is switched in front of extraction electrode.

thanks to a bimorph microactuator integrated in the cantile-ver. The result is a very compact device with the capability of quasisimultaneous topographical imaging and chemical analysis.

Figure 1(a) shows the configuration of the TOF–SFM system housed in an ultrahigh vacuum chamber. The TOF–SFM is based on a conventional SFM system for surface imaging with atomic resolution and a TOF–MS system for chemical analysis of single ions. The SC combines the two operating systems. The design of the SC based on the bi-morph effect is such that it maximizes its efficiency to limit the switching temperature. In addition, V grooves were etched into the Si cantilever surface along the bimorph pad to soften the cantilever in this area and to improve the actua-tion efficiency because of the larger bimorph area of the V-groove structure. An integrated piezoresistive strain sensor (PSS) to measure cantilever deflection is also integrated on the SC, eliminating the need for an external optical system. The PSS is placed right next to the edge of the SC to enhance its piezoresistive sensitivity. To prevent undesirable diffusion of chemical compounds at the in-plane tip when the SC is switched from the SFM to TOF–MS mode, a large gap is fabricated between the tip and the heater area. The SC is prebent by controlling the deposition conditions of the dif-ferent films on it, which provides the desired in-plane tip-approaching angle of 20°. While the SC tip is scanned in contact with the sample, it grabs chemical compounds on the surface, and is then switched in front of the EE. By applying a potential pulse between tip and EE, the chemical com-
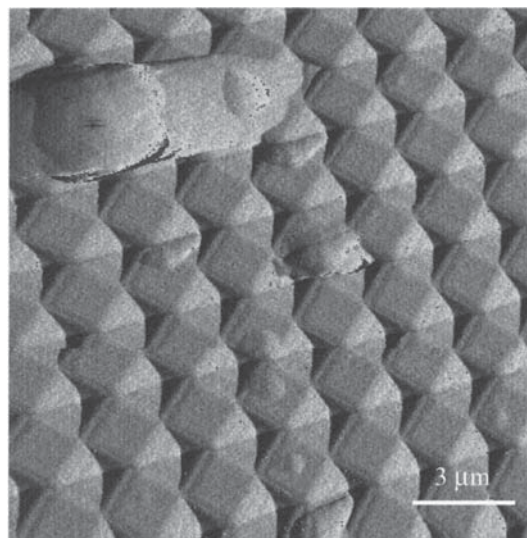
pounds are ionized, extracted, and accelerated towards the TOF–MS for analysis.

Process flows for fabrication of an in-plane tip and the SC are detailed in Ref. 12. A 4 in. silicon-on-insulator wafer is used as starting material for the fabrication of SCs, EEs, and interlocking stages. All of them are batch-fabricated on the same wafer. The cantilever with the in-plane tip is de-fined by photolithography and $SF_6$-based reactive ion etching (RIE). Afterwards the tips are sharpened by a low-temperature oxidation at 950 °C for 2 h. The expected thick-ness of the oxide layer at the top of the surface is ~400 nm, which has experimentally been confirmed to be the best thickness for the in-plane tip sharpening. A SEM photograph of a tip obtained with the low-temperature oxidation tech-nique is shown in Fig. 2(a). A tip apex radius of 10 nm can be realized using this process. Two piezoresistors for the strain sensor and the integrated heater are defined by boron-ion implantation at a density of $5 \times 10^{15}$ atoms/cm$^2$ and sub-sequent thermal annealing at 1050 °C for 45 s. Then a stress-free SiN thin film is deposited by plasma chemical vapor deposition as electrical insulation between the Al layers and the piezoresistors. After defining the contact area by photo-lithography and the $CHF_3$-based RIE, the Al pad for the bi-morph structure and the metal wires for electrical connec-tions are formed on the SC by a lift-off process. A deep RIE process is used to pattern the backside Si and to define the SC thickness. Finally, the SC levers are released by remov-ing the topside protection photoresist with acetone. Figure 1(b) shows SEM views of the assembled SC/EE where the ''interlocking-type'' alignment structure is employed to fa-cilitate and improve the alignment precision of the assembly.

We have characterized the switching properties of the SC. The SC tip deflections have been measured as a function of actuation power for SC with V grooves, and the obtained deflection of the SC is about 60 $\mu$m when 25 mW, corre-sponding to a temperature of 150 °C, is applied to the inte-grated heater. To calibrate the temperature versus power, the Al melting point (660 °C) is used as reference. Al melting on
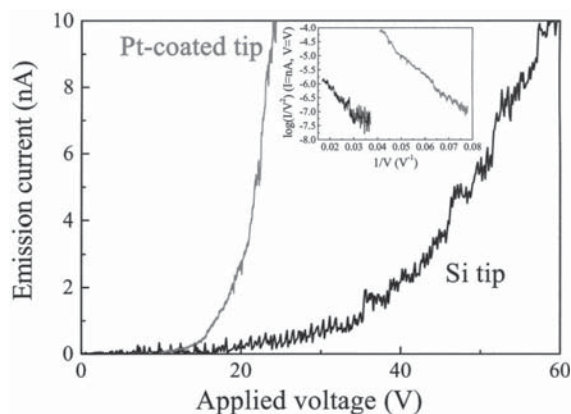
FIG. 3. Emission current vs voltage characteristics of Pt-coated tip and Si tip. Inset: Fowler–Nordheim plot.



FIG. 4. Mass spectrum of the switchable cantilever with a Pt-coated tip.

the SC was observed at 110 mW. The measured resonance frequency of the SC is 27.6 kHz, and the sensitivity $\Delta R/R$ of the PSS is $6.7 \times 10^{-7}$/nm. This is very close to the predicted value of $\sim 28$ kHz. The frequency response of the bimorph actuator upon application of 25 mW actuation power is measured using a function generator and an optical microscope. The resulting switching speed of $\sim 10$ ms is very attractive for fast TOF–SFM applications.

To obtain a surface image in noncontact mode, the SC with integrated PSS has been installed into the conventional SFM system. Two electrical wires from the PSS are connected to an external Wheatstone bridge circuit, which senses the cantilever deflection by measuring the change of resistance value. Figure 3 shows a topographic image of a standard sample used for SFM calibration imaged by the SC.

For the field emission experiments, the tip is switched to a position of TOF mode by using the bimorph actuator and is grounded by a picoamperemeter. A positive dc voltage on the EE is slowly increased to measure emission behaviors. The measured emission current that flows from the tip to the EE in vacuum is plotted as a function of applied voltage. Figure 3 shows the field emission characteristics of two different types of tip, a Pt-coated Si tip and a pure Si tip. The inset shows a Fowler–Nordheim plot of the $I$–$V$ curves. The Pt-coated tip turns on at only 15 $V_{dc}$ thanks to the low Pt work function, the field enhancement due to the sub-20-nm tip radius, and the small tip-EE distance of less than 10 $\mu$m. The turn-on voltage of the SC with integrated EE is less than 50 times that of the SC with a funnel-shaped Al electrode. The tip-EE distance for the funnel-shaped Al electrode was approximately 1 mm. This field emission experiment is of particular interest because tips start to field evaporate at approximately the inverse tenfold electric field used for the field emission.

To measure the flight time of evaporated ions from the tip apex the SC with Pt-coated tip is placed into the TOF–SFM chamber. A negative pulse is applied to the EE using a Blümlein-type ns kV pulser while a positive dc high voltage of 800 V is biased to the tip. The negative pulse amplitude is kept at 20%–30% of the positive dc voltage value, which is constantly and slowly increased until the first ion impact is
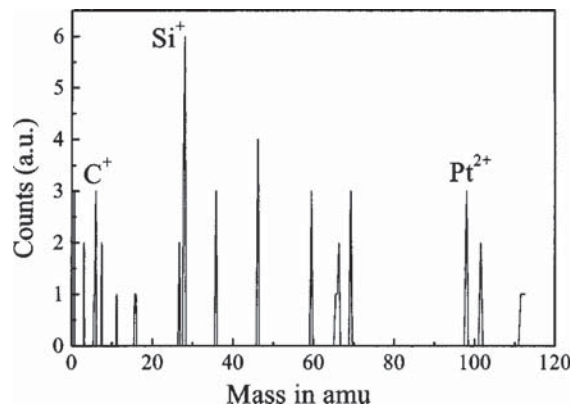
detected on a multichannel plate (MCP). The pulser defines the departure time $t_0$ of ions, and the MCP defines the arrival time $t$ of the evaporated ions. Masses and chemical properties of the ions can be calculated using a computer system with labview control. The capability of single-ion detection in our TOF–SFM system is about 60%. The vacuum in the chamber during the TOF measurements was $\sim 3 - 10^{-8}$ Pa. A TOF spectrum of the Pt-coated tip consisting of 30 pulses at $V_{dc} = 800$ V and $V_{pulse} = -204$ is shown in Fig. 4. $C^+$ (12), $Si^+$ (28), and $Pt^{2+}$ (97.5) ions evaporated from the Pt-coated tip are observed in the mass spectrum when a negative pulse voltage is applied to the EE. Sufficient electric field for ion evaporation is achieved only at the moment of the negative pulse on the EE.

We have reported a cantilever device for a TOF–SFM that promises quasisimultaneous chemical and topographical analyses of solid surfaces. The cantilever device consisted of a SC and an EE to combine two functions: TOF–MS and SFM. The SC based on the bimorph effect exhibits a switching speed as low as 10 ms, and turn-on field emissions have been demonstrated with an extraction voltage as low as 15 V. The emission current and the TOF analysis have also been performed using two different types of cantilever devices with a Si tip and a Pt-coated Si tip.

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