Field emission for cantilever sensors

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(Received 5 September 2007; accepted 14 March 2008; published 22 April 2008)

Field emission provides an alternative sensing solution in scaled electromechanical systems and devices, when typical displacement detection techniques fail in submicron and nanodimenions. Apart from its independency from device dimension, it has also a high response, integration and high compatibility benefits. In this work, we propose using two modes of detection (fixed current and fixed bias) on two sensing methods: static sensing and dynamic resonance sensing. We measured the characteristic of the two modes and proved that field emission is a viable cantilever displacement detection technique. Customized tip on a fixed substrate has been fabricated and loaded to a UHV atomic force microscopy scanning tunneling microscopy system providing us a field emission environment with precise distance controls without the effects of cantilever bending. Thus, we are able to measure and determine the relationship of emission electric field to the electrode distance, as well as the relationship of the emission current to the electrode distance. The sensitivity obtained in our work for the static mode is 0.5 V/nm. In dynamic mode, we successfully measured a resonance of a piezoactuated cantilever at 162.2 kHz. Characterizing these relations enabled us to propose the possibility of using field emission as a cantilever displacement sensing technique. © *2008 American Vacuum Society.* [DOI: 10.1116/1.2906314]

I. INTRODUCTION

With the advance of nanoelectromechanical systems (NEMS), there is a considerable interest in the sensor community to scale resonators, such as cantilever beams, from micron down to submicron and nanometer regime. The scaled resonators are advantageous in giving faster response and higher sensitivity. However, detection of the resonance becomes challenging as the dimensions scale down; detection techniques commonly used in microelectromechanical systems (MEMS) devices are geometrical dependant and therefore suffer from scaling effects. Whereas emerging NEMS detection techniques lack integration capability.[1] In this article, we use field emission as detection method for cantilever sensors. The advantages are several: it is scalable without loss of signal, it has high bandwidth, and it can be integrated in the future using standard fabrication processes. Furthermore, field emission is tolerable to radiation and temperature effect to a great extend,[2] enabling the sensor to operate under harsh environments.

Field emission sensing has been used in previous studies in pressure sensors,[3] data storage distance control,[4] and rf MEMS switches.[5] Based on similar principles, we use the exponential relation of the emission current to the electric field to sense electrode distance changes.

This article aims to broaden the use of field emission in electromechanical sensors but not targeting specific applications; therefore, both sensing in static mode and in dynamic resonating mode are characterized and discussed.

II. THEORY AND PRINCIPLE

A. Field emission

Field emission is a cold emission of electrons from solids. The field emission theory is often referred to as the Fowler-Nordheim (FN) theory, which treats the electron emission of metal into vacuum as tunneling of solid-vacuum barrier. The generalized form of the original FN equation is given as[6]

$$I = \lambda A a E^2 \phi^{-1} e^{-\mu b \phi^{3/2}/E}, \qquad (1)$$

where A is the emission area, a and b are universal constants, ϕ is the local work function of the emitting surface material, and E is the external electric field. Both λ and μ are generalized correction factors which can be function of other quantities depending on emission conditions.

For a stable tip emitter in ultra high vacuum (UHV) condition, the correction factors λ and μ, the emission area A,

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and the work function are constant; the emission current is then related only to the electric field. Forbes *et al.*[7] defined the field and its enhancement factor as[7]

$$E = \gamma E_M = \gamma \frac{V}{h}, \tag{2}$$

where E is the local field at the emission site, γ is the enhancement factor, h is the tip-anode distance and E_M is the parallel plate electric field strength in macroscopic point of view. The factor γ is strongly related to the tip geometry and its separation with the anode. However, under certain conditions, which will be discussed later, it can be considered as a constant. By substituting Eq. (2) into Eq. (1), we obtain a FN equation in voltage form,

$$I = \lambda A a \phi^{-1}\left(\gamma \frac{V}{h}\right)^2 e^{-\mu b \phi^{3/2}(1/\gamma)(h/V)}, \tag{3}$$

and we can conclude that (1) field emission current I is exponentially related to the distance h, under fixed bias voltage, and (2) bias voltage V is linearly related to the distance h under fixed emission current.

B. Cantilever mechanics

It is common to use single clamped cantilever beam as force and mass sensors. When subjected to external force or mass influences, the cantilever directly responds either by changing its beam deflection in static or quasistatic mode or by shifting its resonance frequency when resonating. In static mode, the deflection of a rectangular cantilever, with rectangular cross section and an applied force at the free end, is

$$z = \frac{4L^3}{Ewt^3} F_z \equiv \frac{1}{K} F_z, \tag{4}$$

with Young's modulus E, length L, width w, and thickness t. The applied force F_z directly translates to deflection. In resonance mode, the cantilever is excited by external force on its natural resonance frequency. The first mode resonance is governed by

$$\omega = \frac{3.515}{2\pi} \sqrt{\frac{E}{12\rho}} \frac{t}{L^2}, \tag{5}$$

where ρ is density of the cantilever. Any additional force or mass added on the cantilever will cause changes in mechanical properties, therefore shifts the resonance.[8] By counting the periodicity of the signal caused by the cantilever amplitude the resonant frequency shift can be tracked, and hence, the exerted force can be calculated.

By scaling down cantilever dimensions in Eqs. (4) and (5), sensors with higher force sensitivity and higher mechanical response can be attained. However, the smaller the device scales, the harder it is to detect it; therefore, more sensitive transducers are needed.[9]

C. Principle of field emission for cantilever sensing

Both force sensing in static mode and in dynamic resonant mode require a method to detect the bending or the displacement of the free end of the cantilever. Since field emission current and its bias voltage are strong functions of tip-anode distance, it can be applied to measure the displacement of the cantilever free end. In static bending mode, when emission current is fixed, E is fixed in Eq. (2), therefore, the applied bias voltage V is a function of the distance h and the tip-related constant E/γ is the sensitivity of this field emission readout technique. In resonant mode, emission current changes as the cantilever moves close and away from the tip; when fixing the bias voltage V, the emission current is exponentially related to the change in distance caused by the amplitude of resonance, this creates periodic exponential peaks of current every time the cantilever approaches the tip; the peaks are then counted and transform to the frequency domain. This exponential nonlinearity simplifies the detection of resonance and increases the signal to noise ratio.

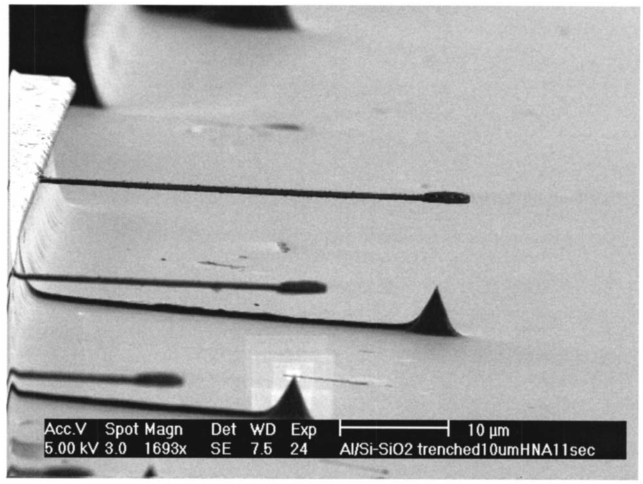

FIG. 1. Example of an integrated, self-aligned field emitter under a freestanding cantilever. The process is compatible with current MEMS and NEMS technologies.

The major advantage of using field emission as displacement transducer is that it is scalable; the emission of the electron is not dependent on the geometrical size of the cantilever. Furthermore, the fabrication of the tip emitter is compatible to MEMS and NEMS technologies. Fig. 1 shows an example of field emission sensing and the possibility of fabricating a tip under a freestanding cantilever.[10] This allows possible integrated sensing for submicron and nanoelectromechemical sensors.

III. FABRICATION AND MEASUREMENTS

A. Emission measurements setup

In order to understand and measure the relationship between field emission, bias voltage and tip-electrode distances, an accurate displacement control in ultra-high vacuum condition is needed. An ultrahigh vacuum atomic force, microscopy/scanning tunneling microscopy (UHV AFM/STM) system from RHK Technology was used to characterize the tip and measure the emission versus distance relationship. The measurements were done by mounting cus-

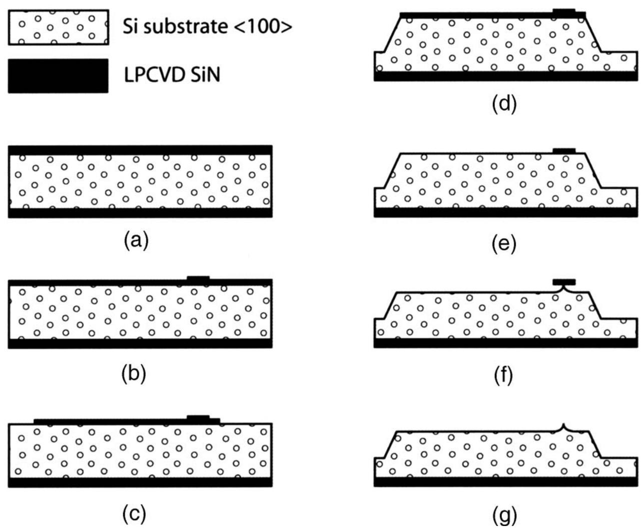

FIG. 2. Process steps for fixed tip fabrication. (a) Deposition of 300 nm silicon nitride by LPCVD. (b) Patterning of tip mask and 150 nm deep etching. (c) Patterning of base mask and etching to land on silicon. (d) Silicon etching by KOH. (e) Silicon nitride etch (maskless) landing on silicon. (f) Isotropic silicon etching by SF_6 plasma. (g) Silicon nitride pad removed in phosphoric acid.

tom made silicon tips onto the AFM z-scanner stage and approach it to a flat 86 nm TiW coated silicon sample on the sample stage. When applying a bias voltage, the TiW coated sample will act as the counter electrode for our tip measurement. The z-direction approach is controlled by a calibrated piezoelectric crystal with feedback controls, and its displacement can be accurately defined. The system is operated in open-loop and in closed-loop (feedback) modes: In open-loop mode, the emission tip is connected to a Keithley 6487 picoammeter for direct current measurements; tip-anode distance is controlled independently; in feedback mode, the emission tip is connected via a low noise amplifier to the Z piezocontroller. A voltage source is connected independently to the tip for biasing, and the TiW sample electrode is kept grounded.

B. Emission tip fabrication

A great interest has been focused on carbon nanotubes (CNTs) as emitter material in recent years.[11] The CNT has the advantages of high emission rate and stability, but currently it still lack a reliable process of integrating with MEMS, NEMS, and complementary metal-oxide semiconductor technologies for mass production. We therefore based our experiments and characterizations on silicon tips.

We fabricated AFM-mountable silicon tips but without cantilevers; the tips are protruding from the fixed substrate to ease the measurements presented in this work. Figure 2 shows the fabrication steps of such a tip; firstly, a low-stress LPCVD silicon nitride mask layer was deposited on a silicon substrate; a tip mask was patterned by plasma etching half of the nitride layer. A second mask defining the AFM base was then applied and etched down to silicon. The sample was put in KOH solution to form a platform for the tip and the nitride was removed to leave the first nitride mask on. Finally, the silicon sample was isotropically etched to form the tip and dipped in phosphoric acid to remove the fallen tip mask. The technique mentioned above uses one mask layer to house multiple mask designs; this allows us to fabricate tip very close to platform edges, which is otherwise challenging in resist spinning and lithography exposures. Having tips close to edges of elevated platform enable AFM approaching with relaxed tilting restriction; this allows the tip to be nearest to the counter-electrode when mounted on the AFM scanner stage. The tips fabricated by this process are typically 2–3 μm high and with 10–25 nm tip radius. Figure 3 shows the fabrication results. The fabricated tips were further coated with 10 nm Cr and 40 nm Au for conduction and emission.

IV. MEASUREMENTS

A. Fixed tip characterization

Loaded silicon tip was first biased at 1 V and approached to the anode until 1 nA direct tunneling current was measured. We set this distance as our zero working distance and retract the tip via a calibrated piezo. In order to stabilize the tip emission, we retracted the tip to 400 nm, apply a bias voltage, and maintain the emission current at 100 nA for 5 min. We then repeat the stabilization again at 100 nm distance with 200 nA emission current.

After stabilization, *I-V* curves of the field emission are obtained at several tip-anode distances and its FN plot are shown in Fig. 4. The straight lines in the FN plot indicate field emission from our tip.

B. Characterization for static mode sensing: Bias voltage versus tip-anode distance under fixed emission current

In static cantilever sensing, the amount of bending in the cantilever is the information of interest; For a constant emission current, the electric field must be constant assuming enhancement factor γ stays constant; this will lead to a linear relationship between the bias voltage and the tip-anode distance, allowing a linear plot. Measurements are performed on fixed tips because this allows accurate control of tip-anode distance without the effect of cantilever bending; we first approach the fixed tip to the TiW flat sample with 0.6 V bias until 3 nA field emission current is reached. We presume the tip at this state is either touching or very near to the anode; therefore, the extension of the calibrated z-direction piezo is recorded and set as the zero distance. Then the bias voltage is increased slowly while a feedback loop controller retracts the piezo in order to maintain a fixed 3 nA emission current.

Figure 5 shows the measurement of the voltage versus tip-anode distance experiment. The bias voltage applied is slowly ramped up to 30 V and back down to 0.6 V three times. The extension and retraction of the piezo is recorded and plotted against the bias voltage. By line fitting the measurements, we obtain, in average, a linear slope of about 2×10^{-9} m/V, which is tip-shape related and corresponds to

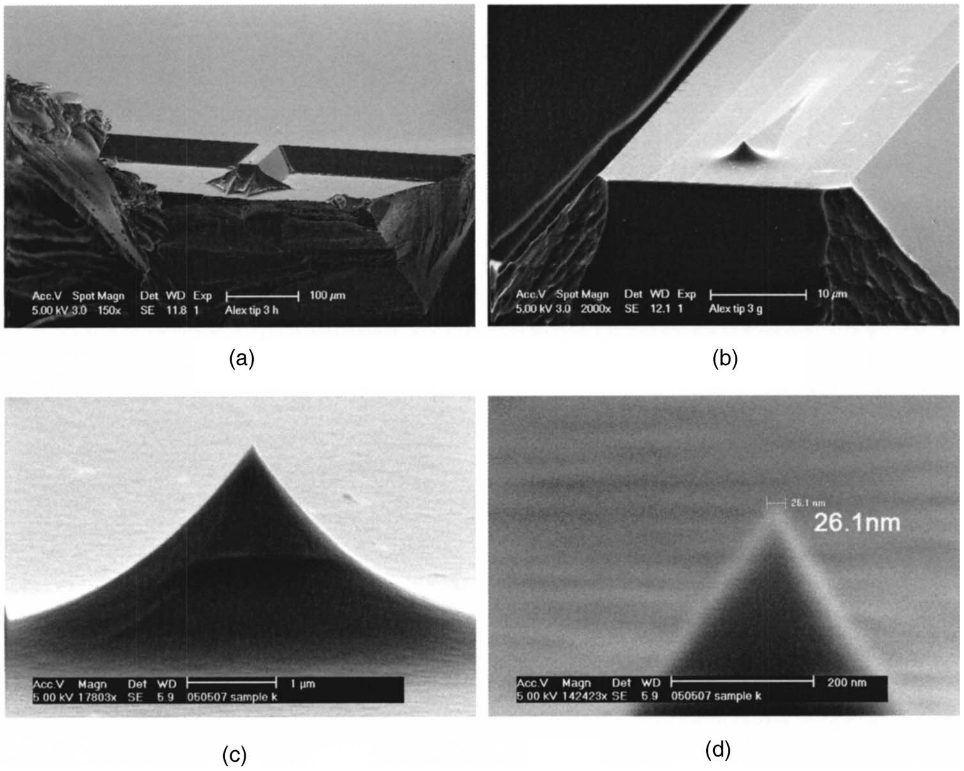

FIG. 3. [(a) and (b)] Silicon AFM tip on fixed substrate platform. This platform design allows AFM approaching with relaxed tilting considerations. The tip are fabricated as close to the platform edge as possible. (c) Typical tip structure after isotropic silicon etching. (d) Zoom in of Fig. 4(c), tip radius can be as small as 13 nm and is reproducible.

E/γ in Eq. (2). In terms of sensors, this slope is the reciprocal of the sensitivity of a sensor, which corresponds to 0.5 V/nm.

Plotted in the inset of Fig. 5 is the residuals calculated from the linear fit of each measurement. Most of the data points reside within 2 nm from the fit and stays so throughout the whole range of bias; this exclude the possibility of a higher order fitting, suggesting a constant field enhancement factor γ, for the tips we fabricated and with tip-anode separation less than 80 nm. The drift in slope for each ramping cycle (up and down) range from 0.066 to 0.23 nm/V; between the first measurement (up1) and the last measurement (down3), the total drift is about 0.58 nm/V. The difference in slope for each measurement may be due to the emission characteristic change of the tip, but also possible hysteresis of the piezocrystal.

For the static mode sensing, relationship between the enhancement factor γ, tip-anode distance and tip geometry need to be defined; Smith *et al.*[12] investigated on relationship of emission field threshold versus tip-anode distance; they experimentally measured a nonlinear relationship and de-

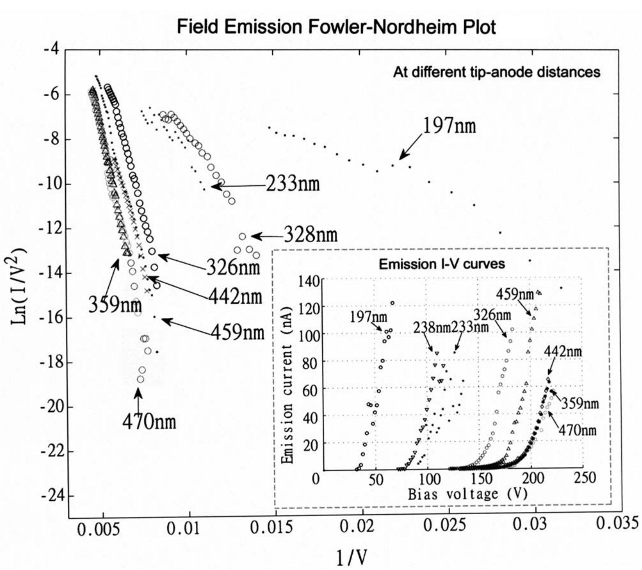

FIG. 4. Fowler-Nordheim plot of silicon tip coated with CrAu. Several *I-V* curves are obtained at different tip-anode distances. The inset plots the original *I-V* measurement data.

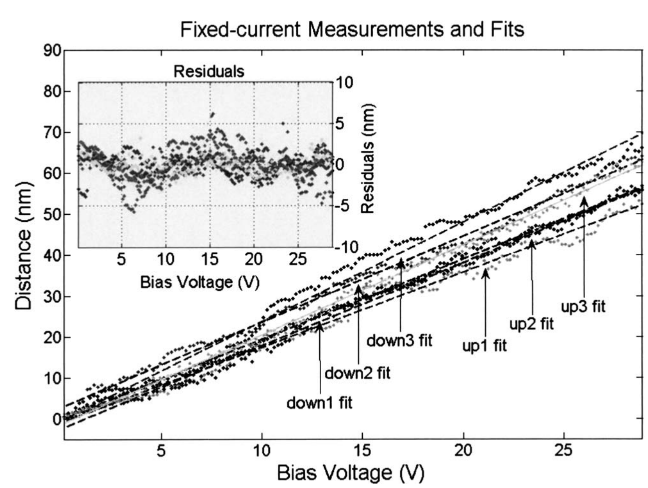

FIG. 5. Bias voltage vs tip-anode distance under fixed 3 nA emission current. Measurements are taken by ramping bias voltage up and down three times, starting from up1 and end by down3.

TABLE I. Linear fittings on the data of fixed current measurement in Fig. 5.

Data set	Slope	Intercept	R square	RMSE
Ramp up 1	1.837×10^{-9}	-1.03×10^{-9}	0.9861	1.8295×10^{-9}
Ramp down 1	1.955×10^{-9}	-2.03×10^{-9}	0.9976	8.0153×10^{-9}
Ramp up 2	2.022×10^{-9}	-2.454×10^{-9}	0.9942	1.3007×10^{-9}
Ramp down 2	2.088×10^{-9}	2.114×10^{-9}	0.9939	1.3699×10^{-9}
Ramp up 3	2.185×10^{-9}	-1.431×10^{-9}	0.9969	1.0117×10^{-9}
Ramp down 3	2.418×10^{-9}	-4.729×10^{-9}	0.9848	2.5243×10^{-9}

duced that the field-enhancement factor is a strong high order function of the distance; this is different from what we observed. We believe it is because the distances measured by Smith *et al.* are from a few microns up to 400 μm, which is in the orders of magnitude larger than ours (0–30 nm). Axelsson *et al.*,[13] on the other hand, observed differences in the dependency of the enhancement factor on separation distance: when the separation is within a few nanometers, the enhancement factor remained at unity, and when the separation is larger, the enhancement factor becomes nonlinear with respect to the distance. Finally, Le Fèbre *et al.*[14] derived a model for the relation using finite element analysis and successfully fitted to their measurements. Further investigation and more experiments, however, are needed to understand the differences between Smith *et al.*, Axelsson *et al.*, Le Fèbre, *et al.* and our new results.

Finally, from Fig. 5 and Table I, we observed RMSE as high as 2.5 nm, and spike of current that correspond to 6 nm displacement error: this suggests considerable degradation in sensitivity and reliability of the fixed-current sensing mode in application. The errors are caused mainly by the instability of the emission tip and the feedback electronic noises: both can be minimized by better process and fine-tuned measurements. Nevertheless, our measurements show the potential and the possibility of achieving high linear displacement sensitivity for cantilever sensing.

C. Characterization for dynamic cantilever mode sensing: Emission current versus tip-anode distance under fixed bias voltage

Emission current is exponentially related to the electric field; therefore, sensing emission current in resonance mode will generate peak signals at each cycle when the cantilever is at the nearest point to the emission tip. In this case, the periodicity of the cantilever vibration is the desired information, not the exact value of the amplitude; therefore, measurement of the precise amplitude is not needed.

To understand the relationship of emission current and the tip-anode distance, emission current was measured while a fixed tip was slowly displaced by a z-direction piezo, simulating amplitude of a cantilever. We first fix a bias voltage and approach the tip to anode until 3 nA emission current is reached. Extension of the calibrated z piezo is recorded and slowly retracted. Current is constantly measured until it reaches our measurable limit, which is around 3 pA. Figure 6

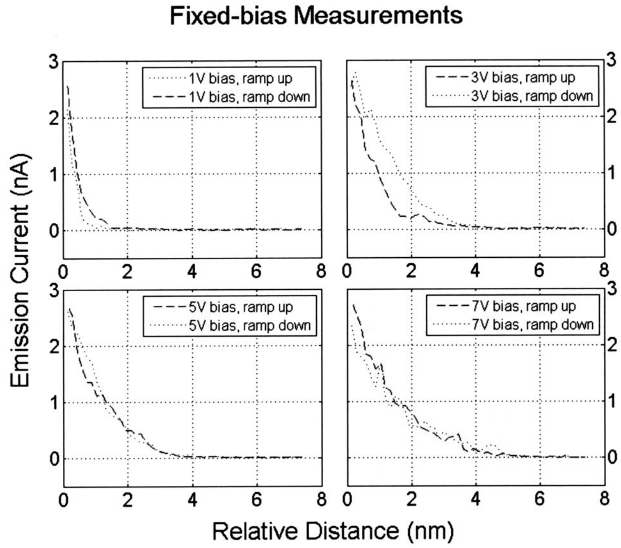

FIG. 6. Emission current vs relative tip-anode distances under fixed bias voltages. Measurements taken with different voltages.

shows the measurement of the current in relation to the relative distance traveled by the z piezo at different fixed bias voltage. The measurements at each bias voltage are taken twice by retracting (ramping up) the piezo until no current is measured, and then extending back (ramping down) until 3 nA is reached. In order to translate the relative distance into absolute distance, we used the result obtained in the previous section; we assume that the properties of the tip used during the fix-current measurement did not change, and its enhancement factor stayed to be 0.5 V/nm. Therefore, for a 5 V bias voltage measurement, the initial tip-anode distance would be 10 nm apart with 3 nA emission current. The absolute tip-anode distance is calculated via this method and plotted against emission current, as shown in Fig. 7.

The stability of the tip decreased as the bias voltage increased. We suspect this is caused by the increased initial

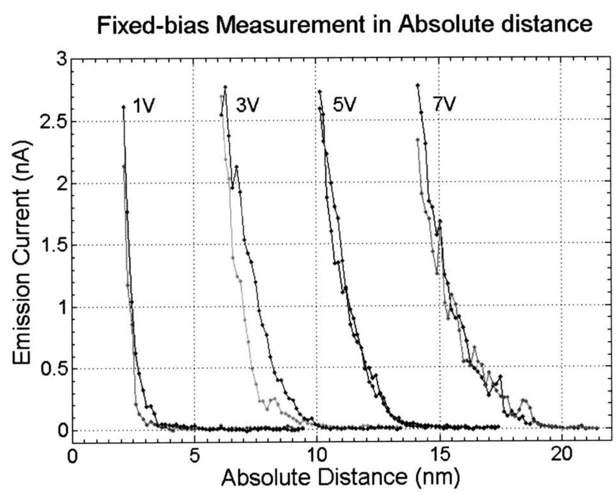

FIG. 7. Emission current vs calculated absolute tip-anode distances under fixed bias voltages. Calculation by applying results from Fig. 5 on the data of Fig. 6.

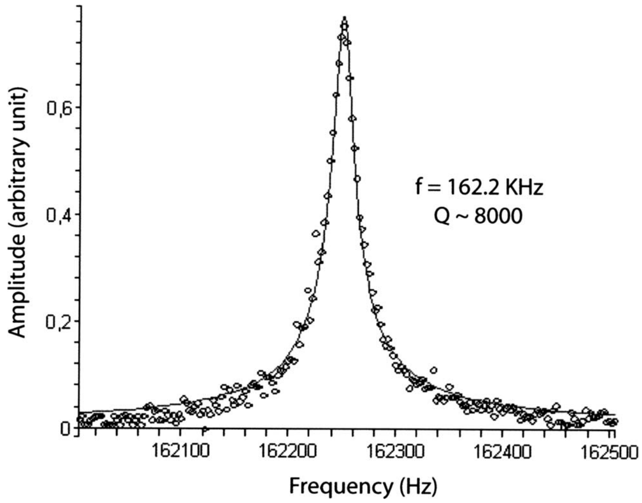

FIG. 8. Resonance curve obtained by field emission current measurement on a highly doped AFM probe. Resonance frequency measured is 162.2 kHz, which is typical resonance frequency of this type of cantilever.

distance. Nevertheless, for a resonance measurement, only the periodicity of maximum peak current is important.

D. Resonance detection

To test our theory of field emission sensing, we loaded a commercially available AFM tip cantilever. The cantilever is highly doped ($<0.01\ \Omega\,\mathrm{cm}$) with high spring constant ($48\ \mathrm{N/m}$) to minimize the effect of electrostatic bending. The tip cantilever was actuated by piezo and biased at 80 V and 150 nm above the anode. We successfully measured the resonance curve of the cantilever via field emission current sensing under fixed bias voltage. Figure 8 shows the curve with resonant frequency at 162.2 kHz and a quality factor of ~8000. Cantilevers of the same type were measured in an optical AFM setup for comparison and have typical resonant frequency of 158 kHz in air.

V. DISCUSSION

A. Error analysis

Emission stability has long been a challenge for field emission applications. We observed fluctuations in out tip emission, which translates to fluctuations in distance measurement. In resonant mode applications, random fluctuations in emission current do not affect the mechanical resonance frequency, therefore, the sensitivity of this mode is independent from the fluctuation error.

In static mode applications, however, emission current is directly measured and interpreted as distance. The inset of Fig. 5 shows an error in distance caused by emission current instability; most of data lay withing 2 nm error range. Also observed are a common deviation at bias voltages less than 5 V, and a wavelike error in the residual plot. The former deviation is due to the transitions between direct tunneling and field emission under low bias, close tip-sample distances, and it is the cause for the nonzero intercept of the fits. The later periodic error is suspected to be systematic errors caused by the feedback electronics together with the piezoelectric crystal. Shown in Table I are the data of all six linear fits, with R-square values around 0.99.

B. Field emission, spring constant, frequency, and sensitivity

Field emission requires intense electric field to extract electrons from solids. In the mechanical point of view, this means high electrostatic force will be applied to the cantilever.

For a static cantilever, spring constant K determines not only how sensitive it is to the force of interests but also how much the electrostatic force can influence it. Therefore, a trade-off has to be considered in order to have a cantilever with low spring constant to sense the target but also enough spring constant to endure the bending caused by the field emission bias. Bending of cantilever under field emission biasing, and its effect on distance sensing has been studied in previous work by Le Fèbre *et al.*[3]

For dynamic cantilever sensing, the force resolution is not only dependent on the spring[1] constant but also strongly on its Q factor and its resonance frequency. According to Eqs. (4) and (5), we believe that by changing the aspect ratio of the cantilevers, it is possible to increase the spring constant of the cantilever, while increasing its resonant frequency; this would minimize the increase in the minimum detectable force F_{min}.

C. Future work

In this work, we have presented the concept of field emission sensing, and its prove of concept. However, more intensive researches are still needed to quantify and characterize the sensitivity and applicability of field emission sensor. Future research in field emission should focus on the following parts.

Broadbandwidth, high gain current amplifiers, and high frequency actuators. The emission current emitted by a single metal coated silicon tip, under reasonable voltage bias, is in the nanoampere range. For cantilever sensing in dynamic mode, this would require a high-gain and high-bandwidth amplifier. Furthermore, for submicron cantilevers, typical actuation in high frequency, such as electrostatic actuation cannot be applied due to its disturbance to the emission extraction field. Piezoactuation and most of the mechanical actuations, on the other hand, has an upper limit in the megahertz range.

The emission instability and the emission extraction field. Although field emission sensing is a highly displacement sensitive method, its instability reduces its sensitivity in static mode. Resonance mode on the other hand is less affected by the instability of the emission, but, the electrostatic force caused by the extraction field will have a pronounced effect on the cantilever mechanics and changing its resonance characteristics.

The vacuum operation condition. Working in UHV condition posses a great obstacle to package the device and can be a disturbing issue for sensor applications that need direct contact with their sensing environment. Therefore, operation of field emission in low vacuum or even atmospheric environment is of interest.

More research is therefore needed to further investigate the issues and break through the limitations of field emission sensing in true application devices.

VI. CONCLUSION

In conclusion, we have presented the use of field emission on electromechanical sensors, specifically the cantilevers. Two modes of field emission sensing have been proposed: fixed-current for static or quasistatic cantilever bending sensing and fixed-bias for resonant sensing. We showed, for the first time, the measurement of the cantilever resonance by field emission. We also used fixed silicon tip on AFM system for the fixed-current sensing and obtained a linear relationship for voltage as a function of cantilever displacement. Finally, based on our measurements we proved the feasibility and the possibility of this alternative sensing solution for the future scaled sensors devices.

ACKNOWLEDGMENTS

The author would like thank Herre van der Zant, Bob, van Someren, and Eduardo Margallo for the useful discussions, and staff of TU Delft Nanofacility for the process supports. This work is partly supported by the NanoNed Project Code TQVB46.

The paper was presented at the 20th International Vacuum Nanoelectronics Conference (IVNC 2007), 8–12 July 2007, Holiday Inn Chicago Mart Plaza Hotel, Chicago, Illinois, USA.

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