# Field Emission for Cantilever Sensing

C.K. Yang, A.J. le Fèbre, G. Pandraud, E. Van der Drift and P.J. French

*Abstract*—**Field emission as displacement transducer was investigated in this work. Tips on fixed substrates are fabricated and approched towards an electrode with precise distance control. This work shows the possibility of using field emission for high-sensitivity, integrated and scaled cantilever sensors.**

***Index Terms*—Field electron emission, Transducers, Microelectromechanical devices**

## 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 sub-micron and nanometre regime. The scaled resonators are advantageous in giving faster response and higher sensitivity. However, detection of the displacement 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 paper we use field emission as the detection method. The advantages are several: it is scalable without loss of signal, it has high bandwidth and can be integrated in the future using standard fabrication processes.

Field emission sensing has been used in previous studies in pressure sensors [2], data storage distance control [3] and RF MEMS switches [4]. Based on similar principles, we use the exponential relation of the emission current to the electric field, to sense electrode distance changes.

## 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 tunnelling of solid-vacuum barrier. The generalized form of the original FN equation is given as [5]:

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

Where $A$ is the emission area, $a$ and $b$ are universal constant, $\phi$ is the local work-function of the emitting surface material and $E$ is the external electric field. Both $\lambda$ and $\mu$ are generalized correction factors which can be function of other quantities depending on emission conditions.

For a stable tip emitter in UHV condition, the correction factors $\lambda$ and $\mu$, the emission area $A$ and the work-function are constant; the emission current is then related only to the electric field, which is a function of bias voltage $V$, distance between the tip and the counter-electrode (anode) $h$, and a tip enhancement factor $\gamma$. Forbes *et al.* have studied and defined the field enhancement factor as [6]

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

Where $E$ is the local field at the emission site and $E_M$ is the parallel plate electric field strength in macroscopic point of view. The factor $\gamma$ is strongly related to the tip geometry, which is defined in Forbes paper as the apex enhancement factor. Substituting Eq. 2 into Eq. 1 we obtain

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

and we 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. Principle of Field Emission for Cantilever Sensing

Force sensing in static mode require a method to detect the bending, or the displacement of the free-end of the cantilever. The force translates directly to the deformation 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. The mechanical displacement of the cantilever changes the $h$ in Eq. 2 and consequentially changes the emission. When emission current is fixed, $E$ is fixed, therefore the applied bias voltage $V$ is approximately a linear function of the distance $h$ and the tip-related constant $E/\gamma$ is the sensitivity of this field emission read-out technique.

The major advantage of using field emission as

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Manuscript received October 1, 2007. This work is partly supported by the NanoNed Project Code TQVB46.

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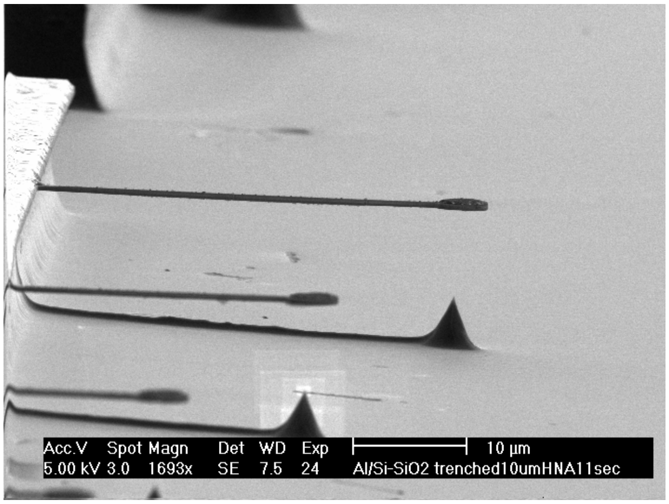


Fig. 1. Example of an integrated, self-aligned field emitter under a free-standing cantilever. The process is compatible to current MEMS and NEMS technologies.

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 the possibility of fabricating a tip under a free-standing cantilever using simple processes [7]. This allows possible integrated sensing for sub-micron and nano electromechanical sensors.

## III. EXPERIMENT SETUP AND TIP FABRICATION

### *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 (UHV) condition is needed. For this, an UHV atomic force microscopy / scanning tunneling microscopy (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 custom made silicon tip 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 piezo element with feedback controls, and its displacement can be accurately defined. More detailed description of the setup is mentioned in prior work by Le Fèbre *et al.* [3].

### *B. Emission Tip Fabrication*

We fabricated our AFM tip on an elevated fixed substrate. Fig. 2. shows the steps; 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 design information, 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 platform edge allows 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 to 3 µm high and with 10 to 25 nm tip radius. Fig. 3 shows the fabrication results.

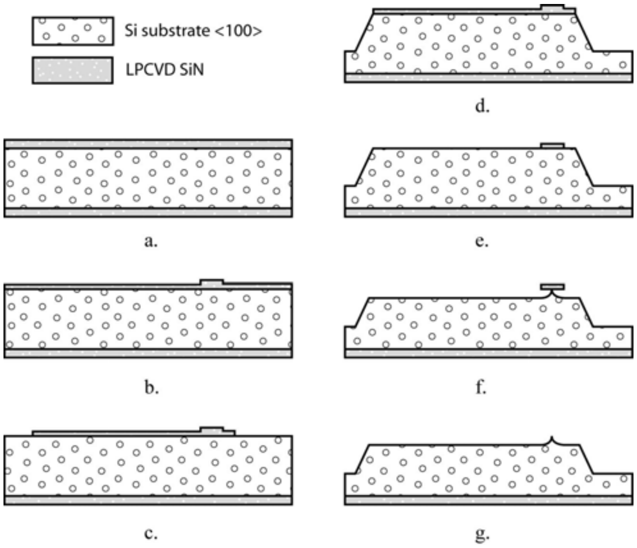


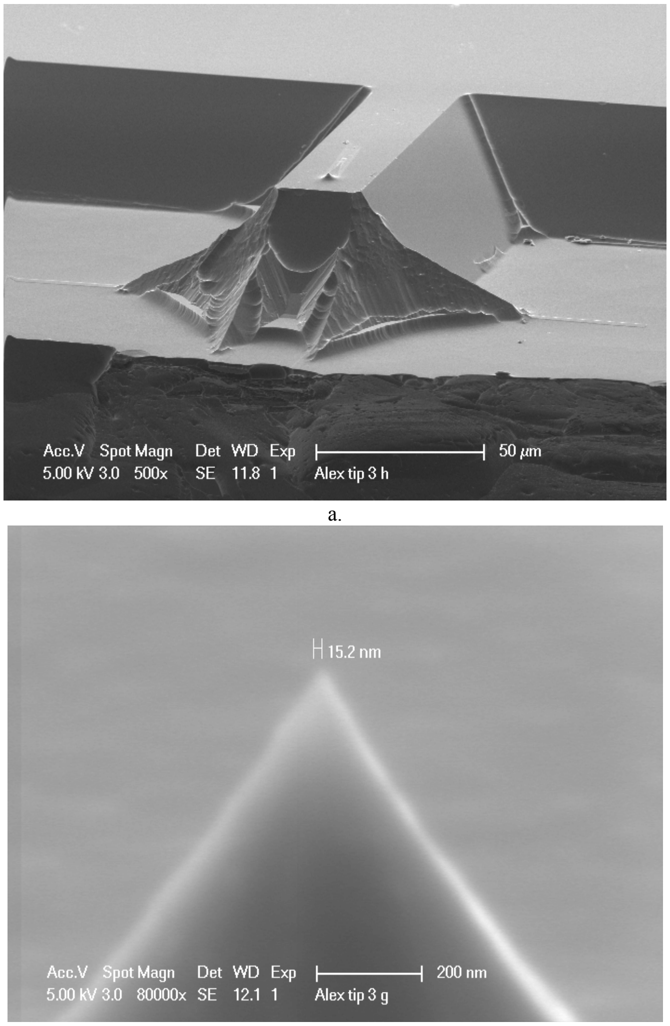
Fig. 2. Process steps for fixed tip fabrication. a). Deposition of 300 nm silicon nitride by LPCVD. b). Patterning of tip mask etched 150 nm deep. c). Patterning of base mask etched to land on silicon. d). Silicon etch by KOH. e). Silicon nitride etch (maskless) land on silicon. f). Isotropic silicon etch by SF6 plasma. g). Silicon nitride pad removed in phosphoric acid.

The fabricated tips were further coated with thin layer of metals for conduction. Layers of CrAu, TiW and TaPt have been applied to different tips for different measurements.

## IV. MEASUREMENTS

### *A. Fixed Tip Characterisation*

Silicon tip with 10 nm Cr and 40 nm Au coating were loaded into the UHV AFM system for characterization. The tip was first biased at 1 V and approached to the anode until 1 nA was measured. We set this distance as our zero working distance and retract the tip via a calibrated piezo. The I-V curves of the field emission are obtained at several tip-anode distances and its Fowler-Nordheim (FN) plot are shown in Fig. 4. The FN plot shows that our tips are indeed field emitting and the measurements we present later are field emission properties.



a.

b.

Fig. 3. a). 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. b). Zoom-in of the tip, tip radius can be as small as 15 nm and is reproducible.

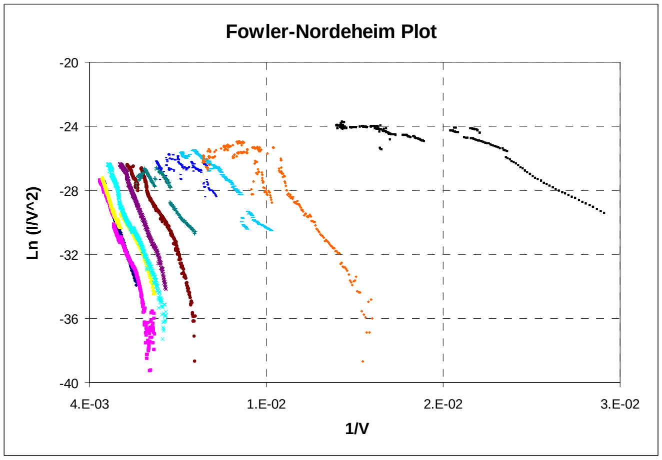


Fig. 4. Fowler-Nordheim plot of silicon tip coated with CrAu. Several I-V curves are obtained at different tip-anode distance. The emission becomes unstable as the tip-anode distance and the bias voltage increases.

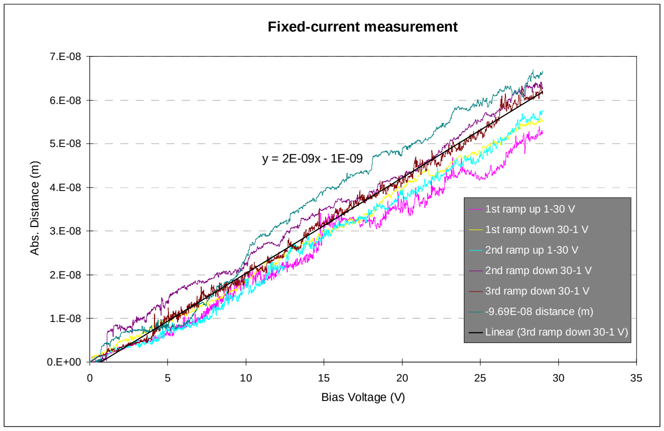


Fig. 5. Bias voltage vs. tip-anode distance, under fixed 3 nA emission current.

### *B. Bias Voltage vs. Tip-anode Distance Under fixed emission Current*

In static cantilever sensing, the amount of bending in the cantilever is the information of interest; from previous section we know that in theory under constant emission current, the electric field must be constant, this in turn will lead to a quasi linear relationship between the bias voltage and the tip-anode distance, allowing us to plot linear voltage-to-distance plot. Measurements are performed on fixed tips because this allows accurate control of tip-anode distance without the effect of cantilever bending. The procedure is similar to previous work from Le Fèbre *et al.* [3]. We first approach the fixed tip to the TiW flat sample with 0.6 mV bias until 3 nA field emission current was reached. The tip at this state is at direct tunneling regime within 1 nm of distance, therefore the extension of the calibrated, z-direction piezo is recorded and set as the 0 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.

Fig. 5 shows the measurement of the voltage vs. tip-anode distance experiment. The bias voltage applied is slowly ramped up to 30 V and back down to 1 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 a constant slope of $2\text{x}10^{-9}$ m/V, which is tip-shape related and corresponds to $E/\gamma$ in Eq. 2. In terms of sensors, this slope is equal to the sensitivity of the sensor, which is found to be 0.5 V/nm. Smith *et al.* [8] have investigated on relationship of emission field threshold vs. tip-anode distance. They experimentally measured a non-linear relationship and deduced that the field-enhancement factor is a strong function of the distance; this is different from what we observed. We believe it is because the distances measured by Smith are from a few microns up to 400 μm, which is in the orders of magnitude larger than ours (0 nm to 30 nm). Axelsson *et al.* [9] on the other hand, observed differences in the dependency of the enhancement factor on separation distance: when the separation was within a few nanometres, the enhancement

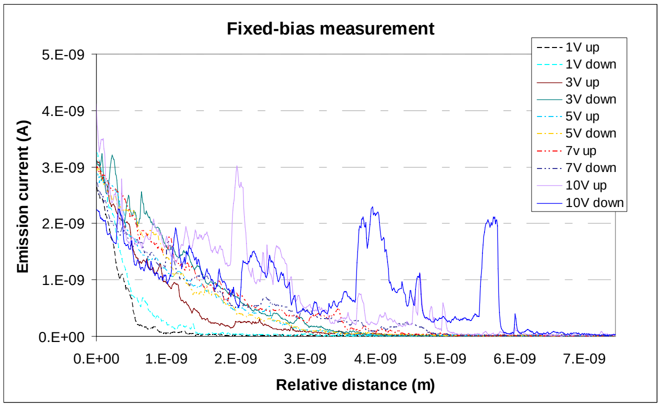


Fig. 6. Emission current vs. relative tip-anode distances, under fixed bias voltages.

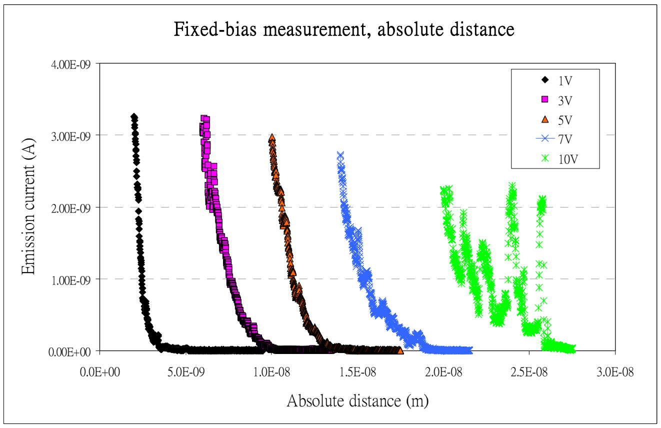


Fig. 7. Emission current vs. calculated absolute tip-anode distances, under fixed bias voltages. Only damp-down data from Fig.7 are plotted.

factor remained at unity; and when the separation was larger, the enhancement factor became nonlinear with respect to the distance. Further experiments and modelling are needed to understand the differences between Smith, Axelsson and our new results.

Also shown in Fig. 5 are the instability of the emission, and a drift of emission current after a few rampings. Both effects may reduce the sensitivity of the device, and would require constant calibration of the sensor. Nevertheless, our measurements still show the potential and the possibility of achieving high sensitivity displacement sensing for cantilever applications.

### C. *Emission Current vs. Tip-anode distance Under Fixed Bias voltage*

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 resonance 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. Fig. 6 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 measure, 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 (only the ramp down data are plotted).

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

## V. DISCUSSION

### A. *Quasi-static Cantilever Displacement Sensing*

Field emission on quasi-static displacement which simulates cantilever bending under static mode have been measured. We used the fixed-current mode to obtain linear relationship for detecting static cantilever bending.

The fixed-current mode uses a feedback loop to control the emission current in a similar way to how a STM measures surface in constant height mode (with constant current). Although this mode would be vulnerable to the instability and the drift of the field emission, our preliminary measurement still shows promising results.

The fixed-bias mode on the other hand is measured in open-loop systems; the signals obtained are non-linear, susceptible to noise and unstable at higher initial distance. Due to this reason, we believe fixed-biased mode may not be applicable to static bending measuring.

### 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 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].

### 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 a few parts:

*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. In Eq. 1 we presumed $\lambda$, $\mu$, $\phi$ and $A$ are constant, however in reality the tip emitter may change its physical characteristics and hence change its emission parameters, causing unstable emissions.

*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 for future investigations.

## VI. CONCLUSION

In conclusion, we have presented the use of field emission on electromechanical sensors, targeting the scaling cantilevers. Two modes of field emission sensing, fixed-current and fixed-bias modes, have been proposed and compared. We 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.

## ACKNOWLEDGMENT

The author would like thank H.S.J. van der Zant for useful discussions, and staff of TU Delft Nanofacility for the process supports.

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