Field-Emission Nano-tip for Microresonator Detections

C.K. Yang, G. Pandraud, E. van der Drift, and P.J. French

Abstract—**Field emission is a quantum phenomenon in which electrons tunnel through the solid-vacuum/air potential barrier under an applied electric field. Such effect is strongly dependent on cathode-to-anode distance and can be used as a distance detection mechanism. By fabricating a sharp nano-tip under a cantilever and apply a potential difference between the two components, any displacement of the cantilever will induce a change in potential field, which in turns will affect the electron emission rate, and hence change the current flow in the cantilever. In this paper, the device concept will be introduced and preliminary fabrication results will be presented. Finally, the feasibility of such concept as well as its challenges will also be discussed.**

Index Terms—**electron emission, microresonators, sensors, fabrications.**

I. INTRODUCTION

DUE to the increasing needs for faster response and higher sensitivity, microresonators have been developed with shrinking dimensions. One resonator structure that is especially interesting when scaled down in size is the cantilever. However, the detection of such devices poses a big challenge when the dimension decreases. Common techniques such as optical, and capacitive, detections etc. are not effective when scaled down [1] and new methods are needed in order to accommodate sub-micron or even nano cantilevers.

The new scheme proposed is as shown in figure 1: when a negative voltage is applied on the tip, electron emission takes place from the tip to the gap; the electrons are then accelerated towards the cantilever where they are collected and measured. The field emission in this case follows the Fowler-Nordheim theory and the emission current is a function of the gap distance.

Fabrication of such tip device is done through anisotropic and isotropic etchings of the bulk silicon. Similar process has been applied on field-emission arrays [2], however in our design, we were able to self-align the tip and the cantilever, as well as obtain tip radius of less than 30nm without oxidisation sharpening.

Research on field emission tips has been conducted for many years, applications on displays, vacuum triodes, power amplifiers and pressure sensors etc. have already been presented. However, application of field emission tips on high frequency microresonator detections have not yet been studied. In this paper, we will present the fundamental principle of the concept and its fabrication, we will discuss its feasibility and challenges, and finally we will illustrate that such scheme may provide needed scalability and response for the future NEMS resonators.

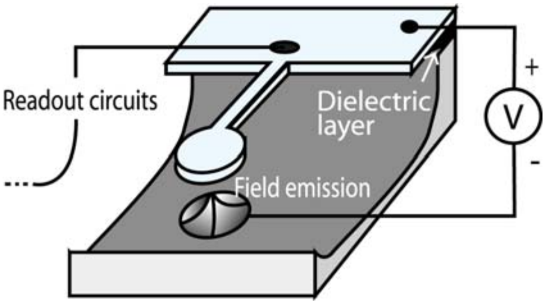

Fig. 1. Concept of the field emission nano-tip applied on microresonator detections.

II. PRINCIPLE OF OPERATION

A. Field Emission and Tunnelling

Electron field emission is a type of quantum tunnelling effect where electrons tunnelling through a potential barrier created by the solid-vacuum (or solid-air) interface. Shown in figure 2 is a schematic diagram of two types of tunnelling; in figure 2a two electrodes are brought closely together such that the electrons are able to tunnel through the narrow gap typically a few angstroms wide. In figure 2b, electrodes are separated by larger gap and tunnelling between electrodes no longer exists. However if the electrodes are operated at a greater potential difference, the probability for an electron to tunnel through the solid-vacuum/air barrier increases. Furthermore, if the cathode electrode is geometrically enhanced to distort the field, creating an intensive field around the barrier, electrons will tunnel through the interface and travel through the free space. Figure 2b illustrates the case where the applied voltage on the electrodes is larger than ϕ /q and the shape of the potential barrier is distorted by making the cathode into a tip. In this case, electrons will tunnel into the vacuum/air space even if the distance to the anode is more than a few microns.

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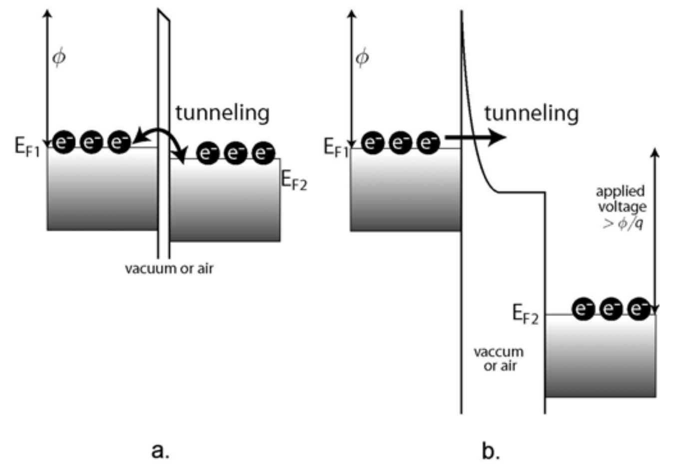

Fig. 2a. Illustrates the tunnelling of a small gap between electrodes. Typical gap distances are a few angstroms. Fig. 2b. illustrates the tunnelling of solid-vacuum/air barrier, also often referred as field emission or cold emission. The vacuum/air energy level at the tip surface (on the left of the barrier) is distorted resulting in a very narrow surface barrier. Figures redrawn from [13].

The tunnelling case in figure 2b is called field emission. Such extraction of electron from cold metal under intensive potential field is well known; Fowler and Nordheim [3] were the first people to present a theoretical study and establish the relationship of emission current density as a function of the applied potential field (F-N theory). The F-N relationship is given as [4]:

$$J = \frac{AE^2}{\phi t^2(y)} \exp\left(-B\frac{\phi^{3/2}}{E}\upsilon(y)\right) \qquad (1)$$

where

$A = 1.54 \times 10^{-6}$,

$B = 6.87 \times 10^{7}$,

$y = 3.79 \times 10^{-4} \cdot E^{1/2} / \phi$,

$E = \beta V$.

β is the field enhancement factor (cm^{-1}) at the emitting surface, whereas y is the Schottky lowering of the work-function barrier. Also in most of tip cathode cases,

$t^2(y) \simeq 1$,

$\upsilon(y) = 0.95 - y^2$.

Together, the F-N equation can be re-written as:

$$J = \frac{A(\beta V)^2}{\phi} \exp\left(-B\frac{\phi^{3/2}\upsilon(y)}{\beta V}\right). \qquad (2)$$

or as:

$$\ln\left(\frac{J}{V^2}\right) = \ln\left(A\frac{\beta^2}{\phi}\right) - B\frac{\phi^{3/2}\upsilon(y)}{\beta V} \qquad (3)$$

For a constant work function ϕ and Schottky factor y, the logarithmic F-N relation in the form of $\ln(J/V^2)$ versus $1/V$ plots a straight line with a slope proportional to $\phi^{3/2}\upsilon(y)/\beta$ and an intercept to β^2/ϕ. Following the relationship in (3), the field enhancement factor can then be obtained experimentally.

Now consider the original equation (1) which predicts that changes in potential field will induce changes in emission current density J, then if the anode is made in the form of a cantilever, the vibration of the cantilever should ultimately change the emission density, and hence modulates the current signal through the device. Figure 3 shows the F-N relation of the emission current versus the cathode-to-anode distances.

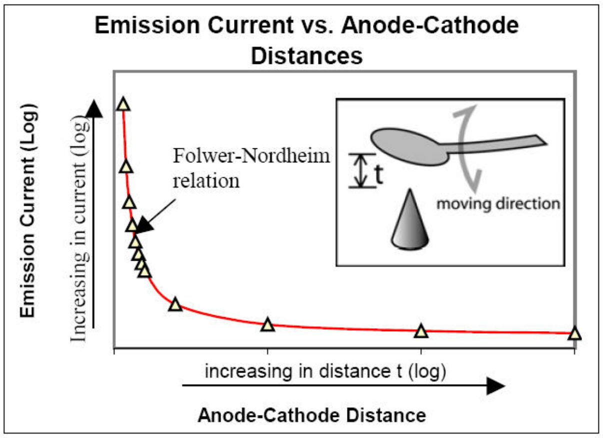

Fig. 3. F-N relationship of the emission current vs. the cathode-to-anode distances

B. Resonator Sensors Based On Frequency Measurements.

Applying field emission for sensor detection is not without problems, one of the biggest obstacles is the stability of the emission and the low current signal. Due to these reasons, we propose field emission mechanism be used on the detection of resonant sensors. Resonator sensors are devices with an element vibrating at resonance that changes its output frequency or phase [5]; such sensors are based on time measurements, and have the advantages over conventional analogue sensors in that they output signals in pulses rather than continuous measurements.

The reason to combine field emission and resonator sensors is that resonator sensors are less sensitive to some of the problems that may be significant in the field emission applications. More detailed discussions on challenges of field emission scheme and its feasibility on sensor detection will be given in later sections.

III. FABRICATION

A. Self-aligned Process Steps

Fabrication of emission tips has been well studied and presented in the past few decades [6][7]. However in this paper, the fabrication process is greatly simplified where the cathode tip formation and the releasing of the anode cantilever are combined together, resulting to a self-aligned process. Figure 4 illustrates the process steps:

1) Insulating sacrificial layer deposition: Deposition of dielectric layer acting both as sacrificial layer and as insulating layer. SiO_2 was applied due to its good electrical insulation, and that it can be easily removed in HF solutions in later phases.

2) Conducting mechanical layer deposition: Deposition of the mechanical layer for the resonant cantilever. The layer has to be conductive in order to act as an anode that collects electrons emitted from the tip. The layer also acts as the etch mask for the tip formation in later phases. Aluminium layer was used in this work.

3) Patterning: RIE anisotropic etch of the deposited layers was performed. Trenching into the silicon substrate is also performed in order to assist formation of sharper tip profile in later isotropic etchings.

4) Tip formation: Tip formation through isotropic etching of the silicon substrate. Wet etchings using mixtures of HNO_3 and HF have been tried while dry etchings using SF_6 has also been tested. Both wet and dry etchings are able to produce good results with tip radius of roughly 30nm, provided that good etching and timing controls are available. The choice between wet and dry depends on material selectivity, yet dry etching generally produces better yields. Further sharpening of the tip down to atomic size has been reported using oxidation method [7], however due to the existence of the metallic Al layer, the thermal oxidation process was not performed in this work.

5) Sacrificial layer removal: An underetching of the sacrificial layer in order to remove residue dielectric layer on the anode cantilever. Residue of sacrificial layer on the anode will not only affect the collection of the emitted electrons, but also the mechanical characteristic of the resonating cantilever.

The advantage of the process mentioned is that only one mask is needed to pattern both the mechanical device and the tip mask. Furthermore, anode and the cathode tip are self-aligned in the same process, which greatly simplified the fabrication of both the sensor and its transducer in an integrated manner.

B. Fabrication limitations

In conventional processes, the tip would be fabricated first and protected by either by photoresists or silicon oxide re-flows. The mechanical anode would be later added on top and an etching of the protective layer is performed to release the tip. In the self-aligned process described above, we ruled out the complex steps to simplify the fabrication. Yet in return, this will limit the materials available for making the resonant anode.

In the process point of view, the limiting factor of material for resonant anode lies in its etching selectivity. The resonant anode has to be highly selective to both the isotropic tip etching and the isotropic sacrificial back etching. In the process, we opted for SF_6 dry etching for the tip formation and concentrated HF (73%) wet etching for the sacrificial back etching. Concentrated HF, in contrast to BHF or 40% HF solutions, provides a much higher selectivity between SiO_2 and Al [8].

Furthermore, the resonant anode also needs to fulfil several requirements:

-- Good resonant properties such as high Young's Modulus,
-- High electrical conductivity,
-- Low stress profile, and
-- Silicon process compatibility.

Although aluminium does not have good mechanical properties for a microresonator, it still fulfilled the later three requirements. In our first fabrication results, we were able to fabricate freestanding cantilevers 20µm long and 500nm thick.

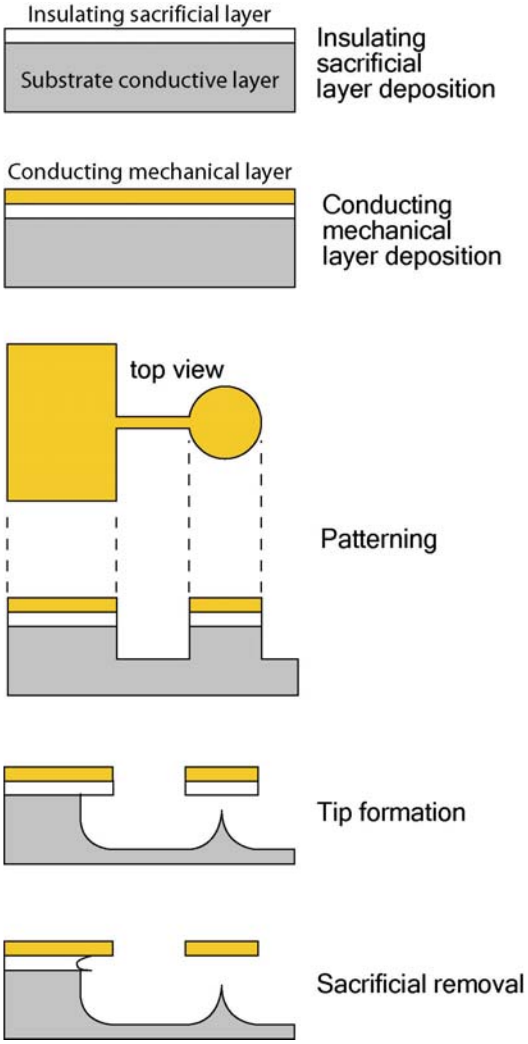

Fig. 4. Process steps.

C. Process Results

Figure 5 presents as few processing results from the steps aforementioned.

IV. CHALLENGES

A. Modelling concerns

The F-N plot of linear relationship between $log(J/V^2)$ and $log(1/V)$ was introduced in previous sections for characterizing field emission from tips. This approach however is not fully correct and is sometimes inadequate. First of all, the F-N $log(J/V^2)$ vs. $log(1/V)$ should not be treated as linear, but rather as a non-linear relationship. Conventional linear treatment of the F-N plot will ultimately results to a mathematically correct but physically contradicting scenario, in this case, devices differing in only one parameter would still give the same F-N plot. This is mainly due to the fact that both J and E of the emission are position sensitive whereas V and I are not [9].

Secondly, the F-N theory was based on planar model with a classical image correction to characterize tip geometries.

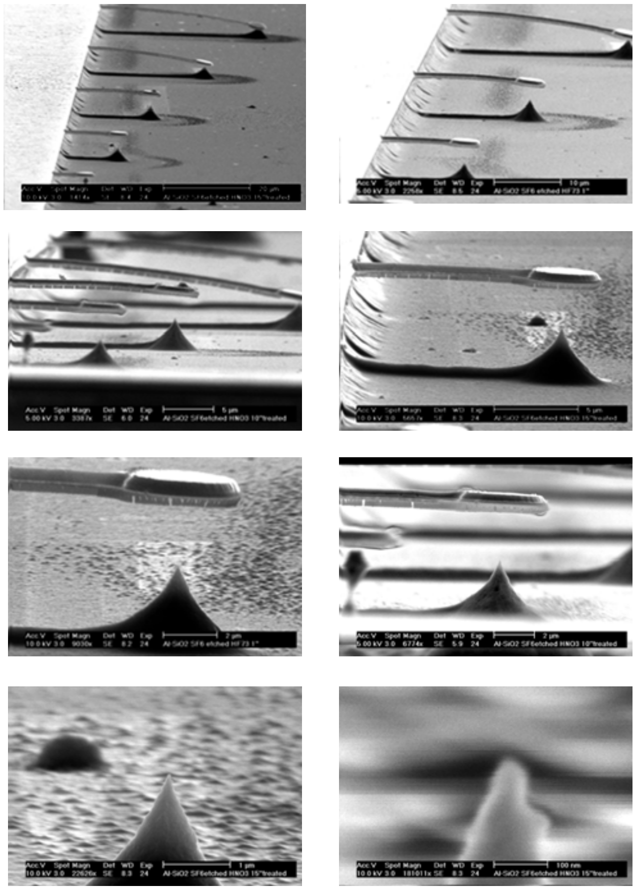

Fig. 5. Process results.

However this method is only limited to relatively blunt tips (tip radius ≥ 50nm). The deviation of F-N theory of sharp tips will result erroneous characterizations of underestimated emission areas and overestimated electric fields [10].

Finally, the F-N theory assumed clean metallic electrodes when it was first derived. In real applications however, semiconductors are sometimes used as the cathode tip. In this case, emission is strongly influenced by the complex electron states of the semiconductors [11].

B. *Emission concerns*

One of the biggest challenges in applying field emission on microresonator detections is the electron extraction from the cathode tip. Before any field emission can occur, high voltage differences are needed to set-up the required field potential. Typical voltages for non-gated semiconductor emission tips are 10^3~10^4 V [11]. Furthermore, even under high voltage circumstances, the emission from a single tip is still very low, in the orders of a few μA down to less than 1 nA, depending on the tip geometric shape, material used and tip-to-tip distances (for array measurements).

Finally, a major concern over the emission of the tips is their stability in providing emission currents. It has been discovered that field emission tips can produce short-term fluctuations; such fluctuation is most obvious in single tip measurements (50% fluctuation has been reported) and average out when in arrays of tips [2][4]. The nature of the fluctuation is still unproven.

C. *Operation concerns*

Due to the requirement of high potential between the electrodes, a large electrostatic force will be created and apply on the resonating anode. The induced force will not only affect the vibration of the resonator sensor, but most of all, if the exerted force is too large, the cantilever will be pulled down hence breaking the tip and remain stuck onto the substrate.

Another concern on the operation is that field emission can only work under vacuum condition. Emission current decreases as the air pressure increases, this is not only due to the increase of electron-air molecule collision, but also due to the fact that gas absorption to the tip will alter its work function and decrease emission rate. In a practical point of view, field emission should be operated to pressure no more that 10^{-5} Torr [2].

The vacuum restriction will not only limit the application of such device, but also impose difficulties in fabrication involving micro- or macro-encapsulations.

Finally, for cantilevers under resonance, parasitic capacitance between the anode layer and the cathode substrate may cause current signal leakage. Field emission itself however, is in principle not frequency limited.

D. *Fabrication concerns*

As stated in the fabrication section, material selectivity is essential to the production of self-aligned tips. Nonetheless, careful control of the etching process is also important. Currently there are no etch stops for forming tips, most of the etching process is done by precise time control, hence the yield of tip can be low.

Moreover, smooth and clean tip surface are also vital for reliable and stable tip emissions. Especially when using semiconductor tips, surface condition greatly affects the work function of the solid-vacuum/air interface, which in turn is related directly to the emission rate. In most cases, the emission rate decreases when the surface is not well processed.

V. FEASIBILITY

In the previous section, challenges and concerns over the application were introduced, here we would like to assess whether the challenges can be overcame and determine if the field emission scheme is applicable in resonator detections. Apart from modelling and fabrication concerns, the feasibility of such implementation dwells mainly on increasing both emission efficiency and the emission stability of the tip:

1) *Increasing emission efficiency:* This means that same signal current can be obtained at lower cathode-to-anode voltage. The implication is such that the integration of the device with IC electronics becomes much easier, and most of all, less electrostatic force is induced. Field emission tip operating at low turn-on voltage (10V) has been reported [12]; it is obtained by forming atomically sharp tip, and by adding a small aperture gate around the tip.

By adding a gate structure around the tip means more processing steps, however the gate structure can not only lower the emission voltage, but also provide electrostatic shielding of anode from cathode, and physically protect the tip from deflecting cantilever.

2) *Emission stability:* The high fluctuation of single field emission tip will be a major problem when measuring the variation frequency of the current signal. The fluctuations will simply induce peaks to the current measurement and falsify the frequency measurement. Up until now the nature of the fluctuation is yet to be understood. However we know that the fluctuation are usually short-termed that comes in groups and each peak lasts from 0.1 sec to a few sec [4], hence eventually it may be possible to use digital signal filtering to filter out the fluctuations at the digital circuits end.

VI. CONCLUSIONS

Implementation of field emission tip on microresonator detection is proposed in this paper. A fundamental introduction to the field emission as well as resonator sensor is also given. The fabrication results were only recently obtained and testing of the device will be done in the near future. Finally, discussion of the challenges and possible solutions were presented.

Essentially, the real feasibility of field emission scheme is only clear after extensive tests of actual devices. The goal of this paper is to provide an overview of such kind of device and arise interests as well as possibility for further investigations.

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