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Anurag Garg  
*Birck Nanotechnology Center, Purdue University, garg@purdue.edu*

Venkattraman Ayyaswamy  
*Birck Nanotechnology Center, Purdue University, venkatt@purdue.edu*

Andrew Kovacs  
*Birck Nanotechnology Center, Purdue University, akovacs@purdue.edu*

Alina A. Alexeenko  
*Birck Nanotechnology Center, Purdue University, alexeenk@purdue.edu*

Dimitrios Peroulis  
*Birck Nanotechnology Center, Purdue University, dperouli@purdue.edu*

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DIRECT MEASUREMENT OF FIELD EMISSION CURRENT IN E-STATIC MEMS STRUCTURES

Anurag Garg\textsuperscript{1}, Venkattraman Ayyaswamy\textsuperscript{2}, Andrew Kovacs\textsuperscript{1}, Alina Alexeenko\textsuperscript{2} and Dimitrios Peroulis\textsuperscript{1}

\textsuperscript{1}School of Electrical Engineering - Birck Nanotechnology Center, Purdue University, USA
\textsuperscript{2}School of Aeronautics and Astronautics, Purdue University, USA

ABSTRACT

Direct experimental evidence of field emission currents in metallic MEMS devices is presented. For the first time, high resolution I-V curves have been demonstrated for micro-gaps in MEMS-based capacitor/switch-like geometries. The I-V dependence shows a good agreement with the Fowler-Nordheim theory, supporting the hypothesis that field emission plays a significant role in charging phenomena in MEMS switches. The data has been used to extract effective values of the field enhancement factor, $\beta$, for the metallic structures fabricated under typical MEMS processes.

INTRODUCTION

Micro-Electro-Mechanical-Systems (MEMS) have emerged as a promising enabling technology for the development of miniaturized low-cost and low-power switches, actuators, and sensors. Applications include RF components for high frequency systems [1] [2] [3], mechanical sensors [4], and environmental sensors [5] to name a few. The design of these sensors involves micron-level gaps between various surfaces, and in the case of electrostatically actuated MEMS, also the creation of strong electric fields in these gaps. The reliability of these devices however remains to be a hurdle on the road to widespread commercial adaptation of MEMS-based switches and actuators. Improved understanding of failure mechanisms of electrostatic MEMS is key to the development of reliable design practices for such systems.

As device dimensions and gap sizes are reduced, the electric field strength in these gaps is proportionally increased, subjecting the devices to an increased threat of performance loss due to field emission currents or complete failure due to electrostatic discharge. The process essentially involves the transfer of charge between two closely-spaced surfaces on the devices. This is typically initiated by one of two processes: avalanche ionization and vapor arc. Avalanche ionization is caused by free electrons accelerating in the electric field towards ionizing collisions that cascade into an exponential increase of free charges. A vapor arc occurs when there is high field emission current density that heats up small surface features until they explosively vaporize, spreading a conductive vapor path between the electrodes and initiating a breakdown [6].

In the past, measurements of breakdown voltage in micro-gaps have resulted in broad evidence of deviation from the classical Paschen law due to field emissions [7] [8] [9]. Figure 1 shows a summary of these works along with the traditional Paschen curve. These attempts, however, have been in most cases limited to measuring breakdown voltages based on visual observations of a spark or glow in the gap.

![Figure 1: Breakdown voltages for microgaps at 1-atm air. Data for this figure was taken from [7] [8] [9] [10] [11].](image)

This paper presents direct high-resolution measurements of electric current through the air gap as a function of voltage and compares the data with the Fowler-Nordheim theory for field emissions. The measurements under increasing voltage show an I-V behavior that is consistent with surface erosion during transient field emission driven gas discharges.

THEORY

Field emission is the phenomenon by which electrons are extracted from metals by the application of very high electric fields. The process is described by the Fowler-Nordheim theory [12] which relates the current density to the electric field using the following equation

$$j_{fe} = \frac{A\beta^2E^2}{\phi^2(y)} \exp\left(-\frac{B\phi^{3/2}v(y)}{\beta E}\right)$$

(1)

where $j_{fe}$ is the current density, $\phi$ is the work function,
β is the field enhancement factor and constants A and B are Fowler-Nordheim constants given by

\[
A = 6.2 \times 10^{-6} \text{ A/eV} \\
B = 6.85 \times 10^{7} \text{ V/cm/eV}^{3/2}
\]

Note that \(v(y)\) and \(t^2(y)\) were not part of the original Fowler-Nordheim equation and were corrections included in [13]. The correction terms are given by

\[
v(y) \approx 0.95 - y^2 \\
t^2(y) \approx 1.1
\]

where \(y \approx 3.79 \times 10^{-4} \sqrt{\beta E} \) is a function of the electric field, work function of the metal and the field enhancement factor.

The field enhancement factor β is a strong function of the surface properties including roughness. The dependence on roughness makes it hard to predict the value of β whose values have been found to vary between 1.5 and 115 in various experiments in the past [14]. Previous work [15] dealing with numerical simulations of discharges in micron gaps used a value of around 50.

**FABRICATION AND MEASUREMENTS**

The MEMS devices were fabricated using a three mask process, and traditional lithography techniques. We start with an oxidized silicon wafer and deposit a 200-nm Au film that is patterned to make the electrodes and contact pads. Ti is used as an adhesion promoter. A layer of photoresist is then spun on and patterned to make the sacrificial layer for the MEMS beams. A metal seed layer is deposited and the fixed-fixed beams are formed using electroplated Ni. We target a Ni thickness of 6-8 \(\mu\)m in order to achieve a high spring constant, so that we essentially have a static gap capacitor for the voltages under question. The sacrificial layer is then removed using the PRS2000 photo-resist stripper, and critical-point drying is used to dry the samples. The structures were designed to have an electrode-overlap area of 120 \(\mu\)m \(\times\) 270 \(\mu\)m and gap of approximately 3 \(\mu\)m.

In order to measure the field emission current through the MEMS device, a low-side current sensing scheme is employed. Placing a sense resistor in the current path leads to a voltage drop proportional to the current magnitude. The resistor is placed between the DUT and the circuit ground (hence low-side), as this allows the possibility of connecting a simple op-amp to amplify the output. The value of the resistor is also carefully chosen so that it is low enough to minimize the voltage burden, but high enough to provide the sensitivity for low current values. For our case, a resistor value of 100 \(k\)Ω was selected. Current is measured using both the current sensing resistor and the source current value on the Keithley 2410 source meter. A Labview program was used to setup and automate the measurement process, and both instruments (Agilent 34410A Digital Multimeter, and Keithley 2410 Source Meter) were controlled using a GPIB interface. Figure 2 shows an SEM image of the switch, along with the test setup.

![Figure 2: SEM Image of MEMS device and test setup.](image)

**RESULTS AND DISCUSSION**

Using the above methods, high-resolution I-V curves have been measured for the first time in microgaps in MEMS-based capacitor/switch-like geometries. The results show an exponential rise in current at specific voltages, consistent with field emission behavior. The I-V dependence also shows good agreement with the Fowler-Nordheim theory. Figures 3, 4 and 5 show three of the measured curves on a log-linear scale, along with several curves from the Fowler-Nordheim equation for several values of (β). The three devices shown are identical in geometry and were picked from the same fabricated die. There was however a difference in the measured gaps, possibly due to lithography variations from one place to another on the die. Devices 1 and 2 has a measured gap of 3.3 \(\mu\)m while device 3 had a measured gap of 2.8 \(\mu\)m.

It is observed that the measured data cannot be described by a single value of (β) for the entire voltage range. However there is good agreement using different values of (β) for
different voltage ranges. We hypothesize that the field emission driven microplasma discharges are continually eroding the surface and removing sharp asperities on it. These sharp asperities are the points of maximum charge densities on the surface of the beam and electrode, and the starting points of the discharge. As they are eroded away, a higher voltage is required to initiate emission from the next largest surface asperity. A reduction in $\beta$ (as demonstrated by the comparison between measurements and field emission theory curves) is representative of a smoothening of the surface, and consistent with our hypothesis. The measurements have been repeated for multiple devices and a close agreement between measured I-V curves and those predicted by the Fowler-Nordheim theory have been observed.

**CONCLUSION**

Direct experimental evidence of field emission currents in metallic MEMS has been presented through the direct measurement of high-resolution I-V curves in the micro-gaps. The results have been compared to the Fowler-Nordheim theory for field emissions and shown to have good agreement. The data has also been used to extract effective values for the field enhancement factor, $\beta$, for the metallic structures fabricated under typical MEMS process. The fitted results show a decrease in $\beta$ over the voltage range, suggest a continual eroding of surface asperities and smoothening of the metal surface.

The direct current measurements in electrostatic MEMS structures support earlier indirect observations of a significant role of gas discharges on the lifetime of MEMS capacitive switches. In particular, the earlier observations that switch lifetime depends on the composition of gas, frequency and voltage polarity are consistent with the field-emission driven bulk ionization of gas in the microgaps of such capacitive devices.

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