Crater Formation and Transition of Gas Breakdown Mechanism at Nanoscale

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ABSTRACT

Gas breakdown is a common phenomenon in electronics devices and in plasma formation for multiple applications. Increasing device miniaturization motivates better characterization of this behavior to ensure device reliability. Gas breakdown is either driven by avalanche or, as device sizes are reduced to microscale, field emission, which depends strongly upon the electrode surface roughness and sharpness. However, repeated breakdown events or further reductions in gap size may further alter the breakdown mechanism. For instance, submicroscale gaps may cause the dominant electron emission mechanism to transition from field emission to space-charge limited emission. Repeated breakdown mechanisms can change the effective gap distance, electrode surface roughness, or gap distance. This study aims to characterize this behavior. We first measure current under different applied voltages to examine atmospheric gas breakdown for gap distance between 60 nm to 500 nm for cathodes with different aspect ratios. Second, we assess crater formation using a pin anode and plate cathode with gap distances at 1±0.5 μm and 5±0.5μm for multiple breakdown events on different areas of the plate using scanning electron microscopy (SEM). Field emission generally occurs at higher electric fields for smaller gap distances and larger aspect ratios. The current vs. voltage curve shows a general pattern of a rapid rise in current followed by a plateau. This result contributes to better understanding on the transition between gas breakdown and electron emission mechanism at microscale and smaller gaps to ensure reliability of microelectromechanical systems (MEMS) and nanoelectromechanical systems (NEMS).

I.INTRODUCTION

The gas breakdown has been described by Paschen's law for over a century.[1] It formulated the relationship between the breakdown voltage V_b to the product of gas pressure, p, and anode-cathode gap distance. However, Paschen's law fails for microscale gap distances under 10 microns [2]. Recent progress on electronic device miniaturization necessitates better characterization of micro- and nanoscale gas breakdown. One important application is micro electrical propulsion systems for small satellites. These systems require high voltage for producing plasma while protecting the circuit from being damaged by breakdowns[3,4].

Ideally, the electrical breakdown should be avoided in electronic devices since it can damage the device or be a safety hazard[4]. MEMS like electrostatic switches[5] are widely used in communications and biotechnology[6]. With the increasing maturity of nanofabrication technology NEMS are being used for sensing and scanning in electronic displays, printers, and airbags[6]. Electrical breakdown in these systems can cause damage to the circuit and lead to malfunction. This motivates studies on the gas breakdown at microscale and nanoscale. Over the past two decades, numerous studies have examined the deviation from Paschen's law at microscale gaps[7]. At larger scales (tens of microns and larger), the gas breakdown is driven

by Townsend avalanche[1]; however, field emission dominates breakdown at microscale gaps due to the insufficient amount of distance for gas collinsion[8]. The breakdown voltage, V_b, exhibits either an extended plateau or a continued decrease with decreasing distance d at a constant pressure[10]. As distance transitions from the PL to the field emission regime, a limit is reached and then begins to fall[2]. Many factors are involved in this process, including the cathode surface roughness and the background gas used in the experiment[11-13]. Multiple breakdowns may also change the surface properties of the cathode, such as creating craters or altering surface roughness [11].

According to existing studies, as the gap distance shifted to the nanoscale, the breakdown is dominated by space charge limited emission[12]. Under this regime, the gap is too small such that an electrical barricade is formed between the cathode and anode which limit the current flow. In vacuum, the breakdown follows the Child-Langmuir's law while on the contrary condition it is described by Mott-Gurney law which takes into account of particle collision[9]. Sudeep Bhattacharjee and Tathagata Chowdhury have shown the relationship between voltage the current in vacuum and confirmed the space charge limit[13]. Experiments have been done on submicron scale breakdown at atmosphere pressure, but the distance of the gap is too big and didn't seem to reach the space charge limit regime[14].

It is essential to characterize how will breakdown-induced change in cathode surface for other gas conditions and in between breakdown events. Recent breakdown experiments in the air at atmospheric pressure show that multiple breakdown events for 1 μm gaps create 3–50μm deep craters[11]. However, only considered 1, 5, and 10 breakdown events did not characterize each individual breakdown event. This stimulated our study to explore the variation in crater formation for each individual breakdown event, which has important considerations for microscale devices with high voltages that may suffer from breakdown and then subsequent electrode damage since these craters change the effective gap distance and subsequent breakdown voltage[11].

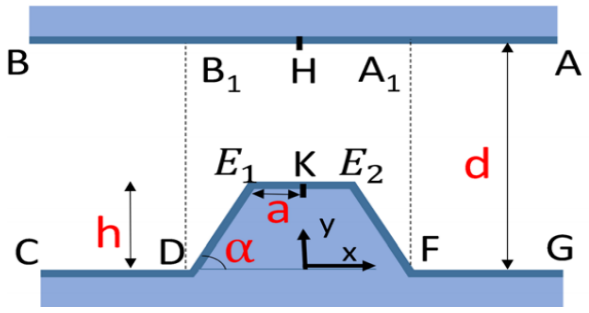

Fig. 1 Design of the device[15]

This research studies the crater formation under a nitrogen environment by placing a tungsten needle in front of the copper plate. The gap distance will be fixed at 1 ± 0.5 μm and measure the breakdown voltage and current for each breakdown events. One to ten time of breakdown will be performed on different location of the sample. This samples will be analyzed by atomic force microscopy (AFM) and light microscopy before and after the experiment to quantify cathode damage. The entire setup will be placed under a nitrogen environment to control the humidity. This research will be a further study of surface change over the multiple breakdowns.

The goal of this paper is also to show the breakdown at sub-micron gap distance which is a transitioning from field emission to space charge limit. A pre-fabricated device is made with varying gaps between 70 nm to 500 nm distance. The current vs. voltage (I-V) curve, the breakdown voltage is measured.

II.MATERIALS AND METHOD

A. MATERIAL

The submicroscale breakdown experiment uses a chip premade by Birck nanotechnology center. All devices are made of gold for the best conductivity and lay above silicon to ensure electrical isolation. The device is premade into different gap distance, *d,* from 60 nm to 1000 nm. The devices are also made with different aspect ratios (the top edge of the trapezoid, *a,* divided by the height of the trapezoid, *h*) of 1, 0.5, 0.25 and 0.125. Figure 1 shows the design of the device. Table 1 lists the varying geometry for our experiment. Both anode and cathode are made into square pads with a thickness of 4 nm and side length of 100 μm. There are five replicates for the same dimension on one chip.

The device is connected to the circuit with the probe station (). The probes we use are tungsten needles () with 1.2 μm tip diameter to avoid any device damage during operation. The circuit uses a Keithley 2410-C source meter to apply voltage and measures the current simultaneously. Figure 2 shows a schematic diagram of the device and probing setup

Table 1. Geometery of the devices on the chip

a (nm)	h (nm)	D (nm)	Gap Size (nm)	a (nm)	h (nm)	D (nm)	Gap Size (nm)
500	500	1000	500	384	384	500	116
62	250	1000	750	62	250	500	250
125	250	1000	750	125	250	500	250
250	250	1000	750	250	250	500	250
100	50	1000	950	31	125	500	375
100	100	1000	900	62	125	500	375
38	384	500	116	125	125	500	375
96	384	500	116	25	50	500	450
192	384	500	116	50	50	500	450

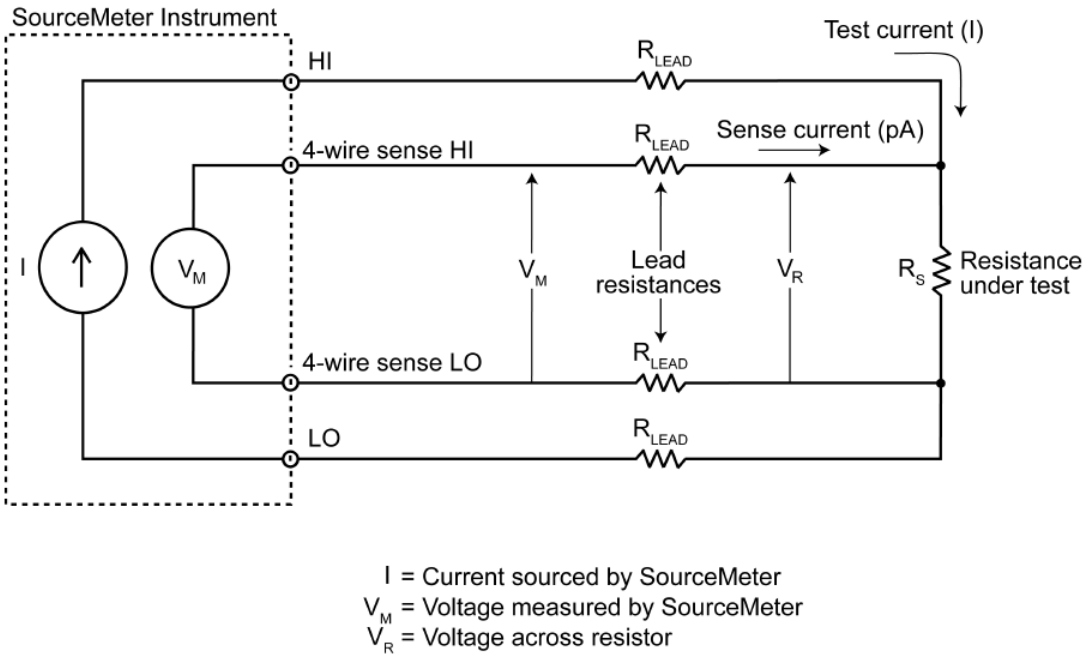

FIG. 2 Schematic of the experimental set up with the submicro scale experiment[16]

The crater formation process after multiple microscale gas breakdown experiments use a tungsten needle with a tip diameter of 1.2 μm (Roboz Surgical Instrument Co., RS-6065), and a copper plate (Fire Mountain Gems, H20–9336FX) with an area of 20 mmX20mm and thickness of 1mm. Both the needles and copper plate mounted to a 3D printed holder using Polylactic Acid (PLA) as material to assure the electrical isolation. The plate holder is installed on to a micromanipulator with an increment of 1μm. The entire setup is placed in a flush box and filled with nitrogen. Figure.3 shows the principle diagram of the micromanipulator-controlled plate setup.

To guarantee the same surface roughness, all copper plates are polished using 400 grid polishing pads (Pace Technologies) using the wet polishing station. All copper plates are cleaned using acetone to remove any contamination on the surface and flushed with purified water to remove any residuel. After the surface treatment, each copper plate is divided into 16 regions for the multiple breakdown experiment. A wire is welded to the back of the copper plate to allow the connection to the circuit. Two 1 MΩ resistors are connected to the circuit. The one before before the gap is used to limit the current, and the one after the gap to measure the current flow. The current and voltage measurements are made by two 1:100 voltage probes () from the oscilloscope. The first voltage probe connects between the copper plate and the needle to measure the voltage across the gap. The second voltage probe connects between the 1 MΩ resistors after the gap. The current can be calculated through ohms law, I = V/R. We use a high voltage power supply (Stanford Research System, PS365, 10kV) to apply a high voltage across the gap.

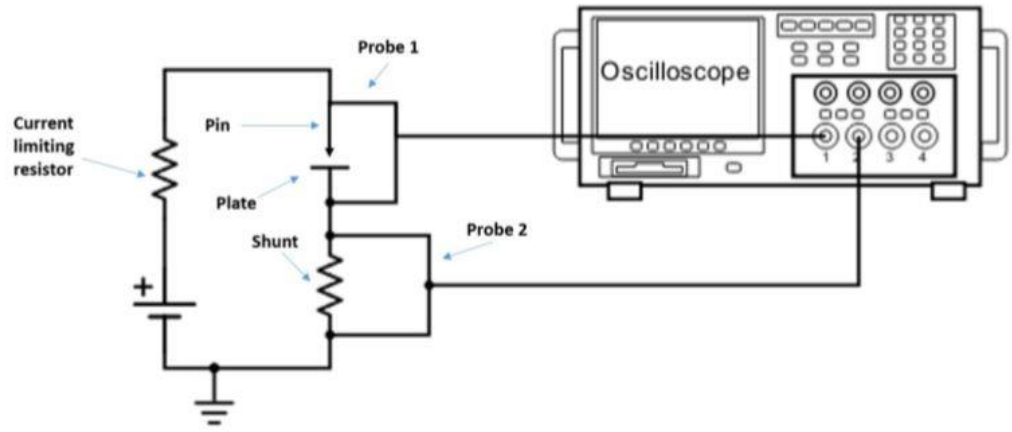

FIG. 3 Schematic of the experimental setup with a pin to plate configuration to test samples [11]

B. METHOD

For the submicron scale experiment. We first place the chip onto the probe station and use vacuum to keep it in place. A visual examination on each device is first performed to ensure the device do not have visiable damaged. Then we use the two tungsten probes connected to the cathode and anode pad to connect the device complete the circuit. The two probe leads are connected to the Multimeter. The anode lead is connected to source output and the measurement has positive bias. The cathode lead is connected to the source input and the measurement has negative bias. The sourcemeter is configurated to voltage supply mode and current sensing mode. After everything is connected, a 0.5 V is applied to the device to determine if there is any systematic error causing the device to short.

The source meter is controlled by a computer using MATLAB. Two voltage sweeps are performed with different step size and range. The sourcemeter takes a measurement of the current after every voltage increment and sends it back to the computer. The sourcemeter is set with a current compliance which is a protection mechanism to stop supply more current when the limit is reached. The compliance is set at 0.1μA to protect the sourcemeter and the entire setup from being damaged. This value is selected based on experiments showing at this current level, the device are definitely melted and shorted. Any data after the melt down would be unreliable.

This SMU sweeps at a step size of 5 mV and sweeps from 0 with speed at 0.05V/s. The power source is removed few second after the current compliance is reached to prevent further damage to the experiment set up

For the crater formation experiment, the copper plate is first evenly divided into 16 regions to identify the multiple breakdown experiment. Each ismarked on the top left corner to identify the orientation of the device. Ten of the regions are labeled one to ten which will conduct that number of breakdowns that take place. The plate is placed onto the plate holder. The entire setup is placed into the flush box and connected with the wire. The gap distance is set by applying 30 V to the gap and uses the micromanipulator to let the pin gently touch the copper plate to close the gap in order to see a voltage drop across the gap. Then we will back off the plate to the desired distance. Previous experiments have shown that this process won't have any damage to the copper surface and the needle.[15,16] The desired distance is set to be 1 μm and 5 μm. After the gap set, the flush box is closed and flushed with pure nitrogen for 5 minutes with flowrate at 2 standard cubic feet per second. We used a computer-controlled power supply which increases voltage supply at 5 V/s applied across the gap until the breakdown happens. The applied voltage is removed as soon as the oscilloscope is triggered to prevent further damage to the copper plate. The waveform from the voltage probes is saved for comparing the result to previous experiments.

After each test, a new pin is applied to ensure the quality of the experiment and to perform SEM on those needles to see if there is any copper being transferred to tip of the needle during the breakdown. The copper plate is also examined by AFM to analyze how the surface material is changed.

III. RESULT

A. Nano-scale breakdown

a. Device condition before and after the breakdown

We used a 800x microscope to take a picture of the device before and after the breakdown to examine the device change. Figure 4A shows the device before apply any voltage. And Figure 4B shows the device after the breakdown. The black shadow on the top and bottom of the gap are the probes we use to connect the device to the circuit. This picture is taken under magnification of 100 times.

As we can see the difference between the two pictures, the gap is connected with melted gold and we can also indentify the melting gold on the tope edge of the device. The device got destoried due to heat generated from field emission. At this point we are unable to affirm exactly when the meltdown happens, but the meltdown have changed the device geometry shortly after the field emission start. One hyposis on why we are seeing different pattern in the I-V curve is because the change in geometry. In this case all the date after the sudden change in current would be caused by the change in the geometry.

This experiment point out the heating problem in nanoscale experiments. This experiment uses gold to make all the device for best conductivity, but gold has very low melting point and are not accommodate for the heat generated in this experiment. In future experiment, the device should be made of materials that can tolarrate heat. Tungsten is recommended for it's high melting point and good conductivity.

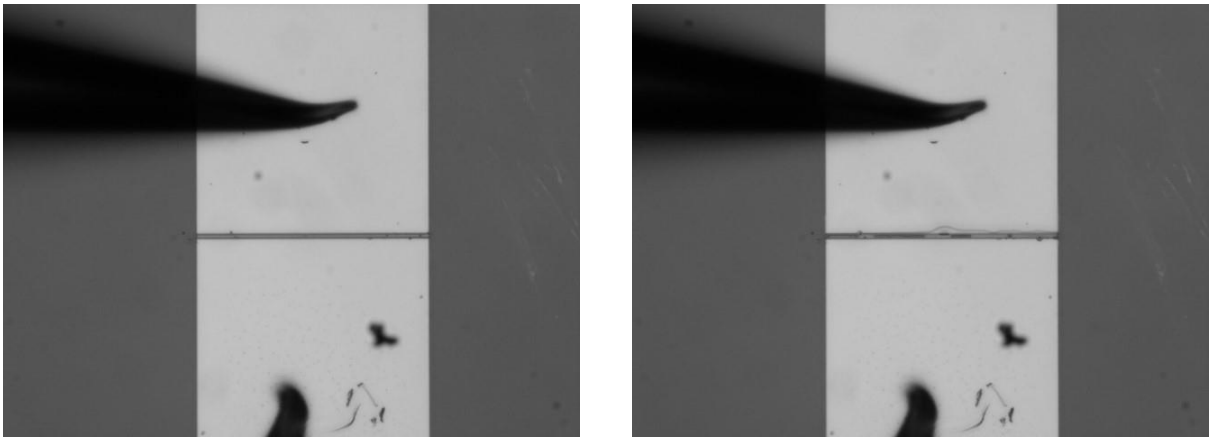

Figure 4. Device before and after the breakdown

b. Current Voltage curve (I-V curve)

Figure 5 and 6 shows some sample I-V curve with some typical curve feature we discovered during the experiment. Figure 5 is the I-V curve on device with geometry of D = 1000nm, h = 500nm, a = 50nm. Figure 5a and Figure 6a are Folwer Nordinham plots with y axis in logrismic scale. All current data are shifted up for 2 E^-10A so all the negative data points caused by sensing error would be able to be plotted on this graph. Figure 5b and Figure 6b are zoomed in I-V curve plotted on a linear scale.

We have discovered that the typical I-V curve have two general shape. As discussed in last section of the paper, the I-V curve are highly influenced by the condition of the device. According to the result, when the device get meltdown there are two possible changes in the device. The first way would be the melted gold filling the gap between the cathode and the anode. The device will short immideatly after the gold get melted and the I-V curve would be like in Figure 5. The other way of meltdown is the gap between the electrods didn't get filled right after the field emission, instead, the gap might get expanded and the I-V curve will have all kinds of wired behavior. Eventually the gap is filled with gold and the device get shorted shown in Figure 6. After the device get shorted the current will reach the sourcemeter compliance which is the flat end on the right of the graph. Since the device is shorted these data no longer contains useful information. The voltage is removed shortly after the current reach the limit to prevent further damge on the chip and the probe.

We found that almost all the devices we tested have a up curving as shown in both figures. We suppose any data point after a sudden change would be caused by a meltdown.

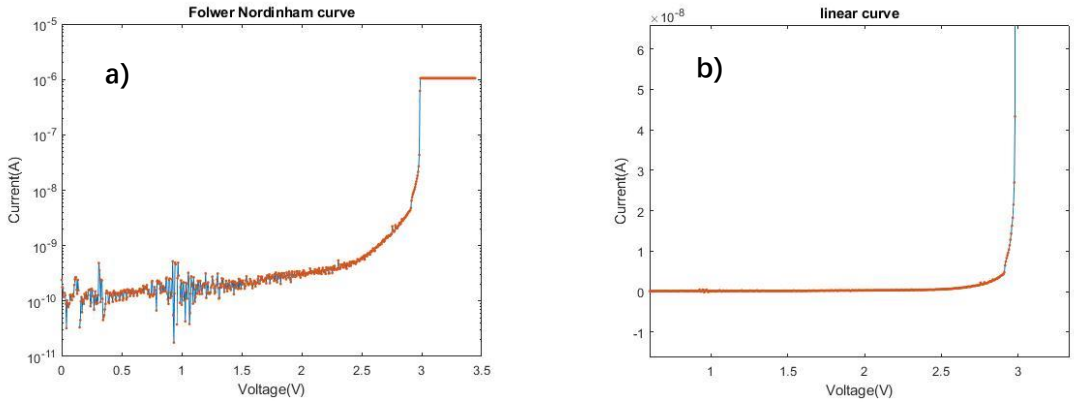

Fig. 5 current vs. voltage (I-V curve) for D = 1000nm, h = 500nm, a = 50nm a)Folwer Nordinham plotted in y axis logrismic scale b) Linear scale

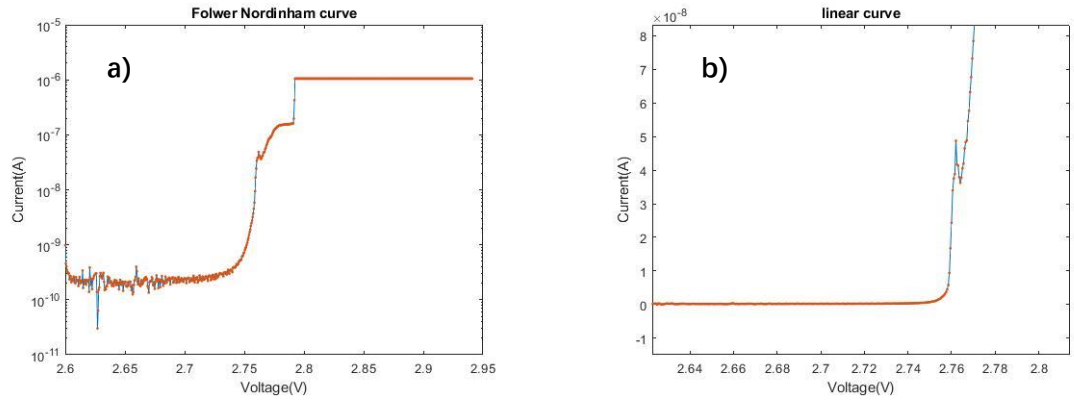

Fig. 6 current vs. voltage (I-V curve) for D = 500nm, h = 250nm, a = 250nm a)Folwer Nordinham plotted in y axis logrismic scale b) Linear scale

B. Crater formation investigation

Figure 7 shows the result of SEM on the needle before and after 10 breakdowns. To ensure that the needle doesn't capture any copper during the touching calibration process. Two controlled needles are made by touching the copper plate in standard calibration process and preform SEM on them, the result is shown in Figure 7a. Two experimental needles are analized after ten breakdowns, the result is shown in Figure 7b.

We have preformed an back scattering on the sample to identify elements. Copper for the plate and Tungsten from the needle are the only two element atoms that are expectect to be found on the sample. Since they have very different atomic mass (copper 63.54; tungsten 183.84), copper will have deeper color in the figure.

（this part will be added after the backscatter result come out）

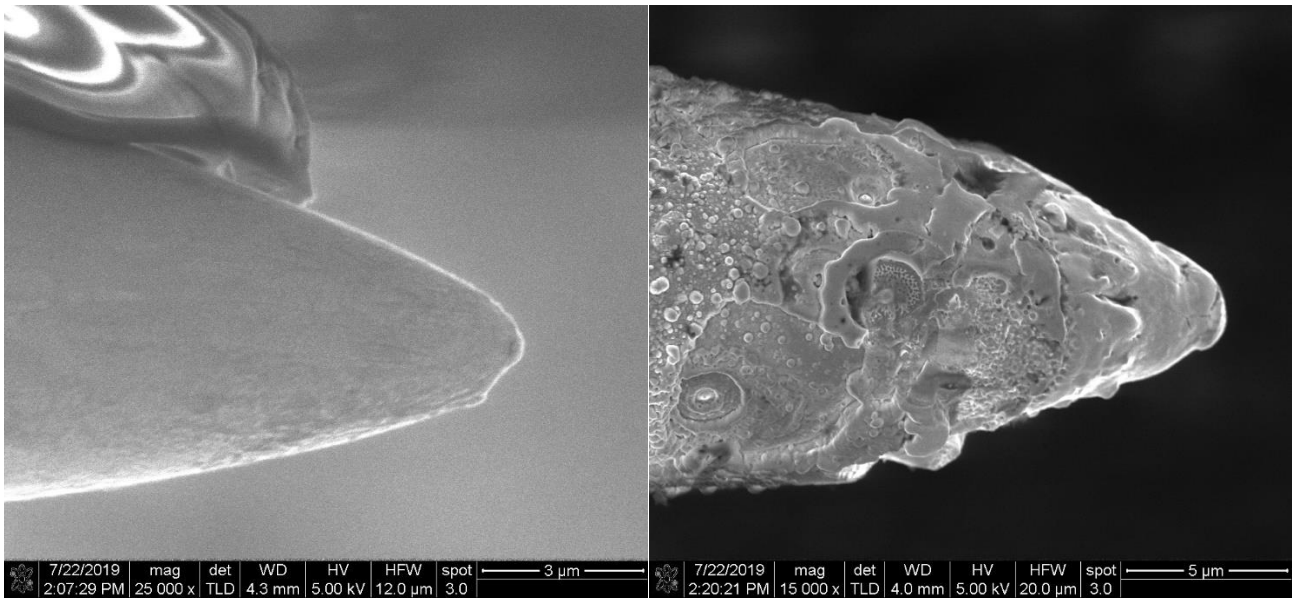

Fig 7. The SEM result on the needle a) control group before the breakdown b)experimental group after the breakdown

Figure 8-9 shows the result of the AFM for the copper plate after 2 and 3 breakdowns. We can see the dent being crated by the breakdown. The material are removed in the center and forms a crater. On the edge of the crater, there are upheaval formed. This is the place we found the majority of the removed material. (I am unfinished here, waiting for the actual result)

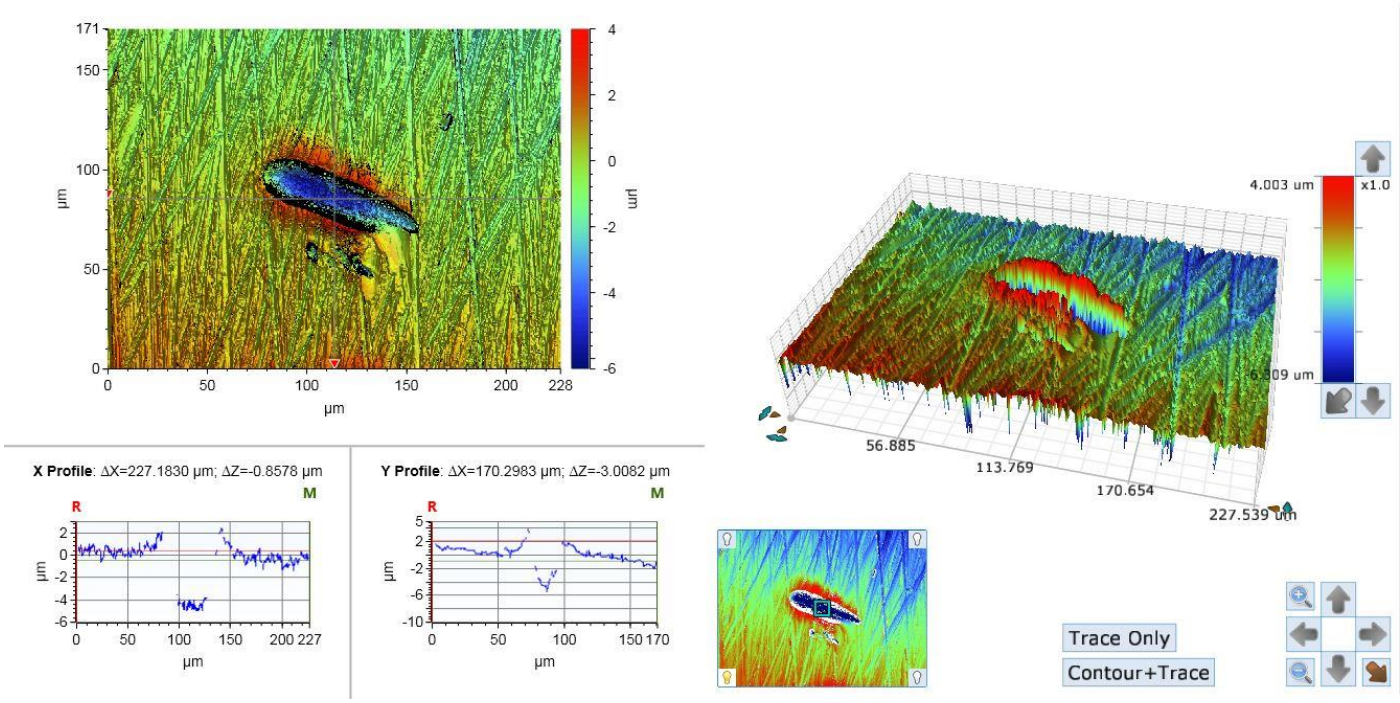

Fig 8. AFM result of the crater after 2 breakdowns

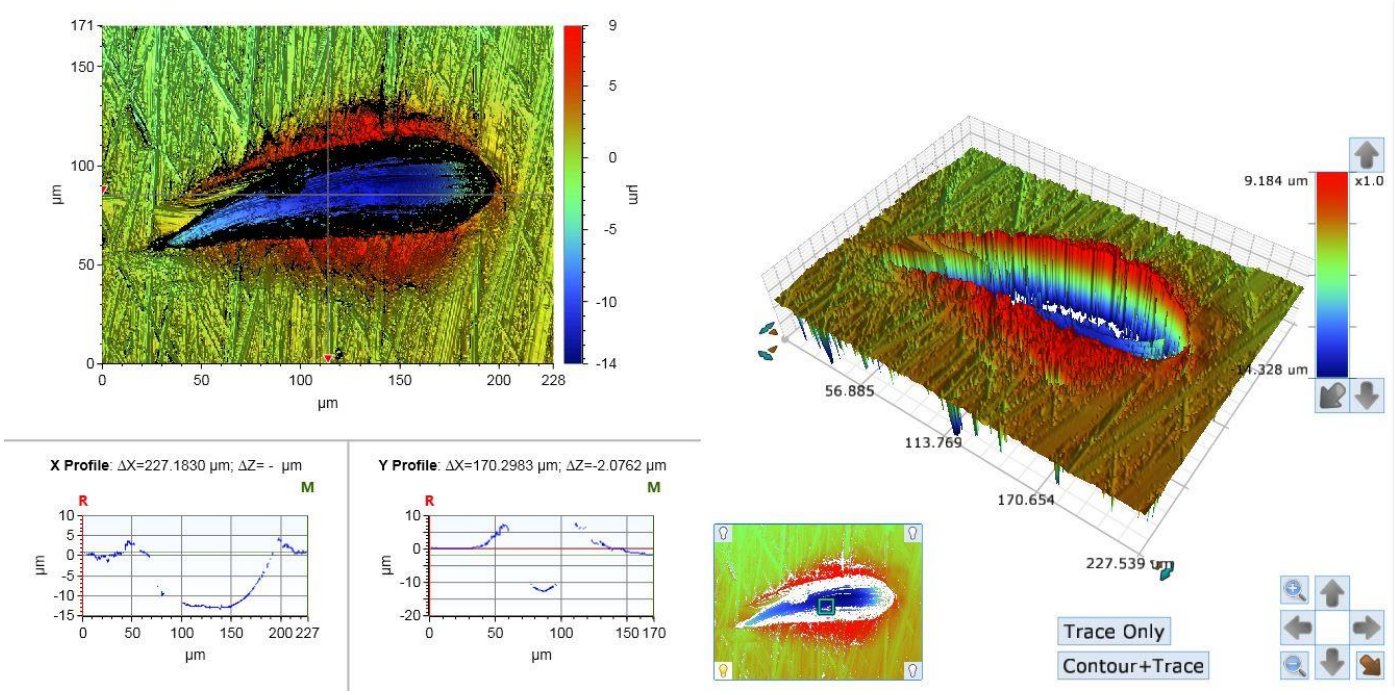

Fig 8. AFM result of the crater after 3 breakdowns

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