IN-SITU EXPERIMENTS OF VACUUM DISCHARGE USING SCANNING ELECTRON MICROSCOPES *

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Abstract

The fundamental understanding of vacuum discharge mechanisms and induced surface damage is indispensable for the CLIC feasibility study. We have been conducting dc sparc experiments inside a Scanning Electron Microscope (SEM) at Uppsala university in order to investigate localized breakdown phenomena. By using a SEM, we achieve the resolution of the electron probe in the few-nm range, which is of great advantage as the surface roughness of the polished accelerating structures is in the same scale. The high accelerating field of 1 GV/m is realized by biasing an electrode with 1 kV set above the sample with a gap of sub μm. Furthermore, a second SEM equipped with a Focused Ion Beam (FIB) is used to modify the topography of sample surfaces thus the geometrical dependence of field emissions and vacuum discharges can be studied. The FIB can be used for the surface damage analysis as well. We have demonstrated subsurface damage observations by using FIB to sputter a rectangular recess into the sample in the breakdown region. Those powerful surface analysis techniques can be productively applied to the study of fatigue in prototype accelerating structures as well.

INTRODUCTION

The high accelerating field of 100 MV/m in CLIC (the Compact Linear Collider) is generated by sending radio-frequency (rf) waves through specially designed accelerating structures. The high electrical fields tend to cause surface degradation of the accelerating structures [1], increasing the probability for an electrical breakdown due to the increased surface roughness. One of the key conditions for the reliable operation of CLIC is limiting the breakdown probability to the order of 10^{-7}. In order to reach that regime, we have been working on a fundamental study of the breakdown phenomena using Scanning Electron Microscopes (SEMs). Direct current (dc) experiments inside a SEM provide an opportunity to investigate localized breakdown phenomena and the induced surface damage. Furthermore, we investigate surface characterizations after breakdowns which can provide key clues about the mechanism of breakdown.

Studies of fatigue of the surface under rf condition with prototype accelerating structures [2, 3] and macroscopic dc breakdown experiments for example [4, 5, 6] are also under way at CERN, SLAC and KEK. In addition, plasma modeling and simulations are in well progress at Helsinki University.

PRE BREAKDOWN STUDY

In order to explore source of electrical discharges, we have measured field emissions and sought surface evolution under high electrical field gradient condition. A detailed experimental setup is written in Ref. [7]. The dc experimental setup (Fig. 1) is installed in the vacuum chamber of an SEM (FEI ESEM xl30). Taking advantage of in-situ measurements, one can observe surface conditions of both anode and cathode before and after experiments. In the present work, a copper sample is mounted on an inclined holder which permits to move the tungsten tip at 90 degrees with respect to the sample surface. Field emission currents between the sample surface and the tip are measured with a Keithley 6430 electrometer that can also be used as a source-meter to apply external voltages to the gap. The voltage range of the Keithely is limited to 200 V and we normally use a commercial high-voltage power supply that permits us to reach voltages up to a few kV. During the field emission measurement, the high voltage applied on the tungsten tip is turned off once the measured current exceeds a certain threshold in order to prevent a discharge. The leakage current level of the experimental setup is approximately 20 fA if we use an electron beam blanker in order to prevent depositing the electron current on the sample. Using the setup described in Ref. [7] we investigate the reproducibility of the field emission current while ramping the voltage up and down repeatedly. We start by approaching the tungsten tip to the copper sample, which we can observe in the SEM. We identify the subject area and record SEM images. Once we know the site, we turn off the electrons in the microscope with the beam blanker

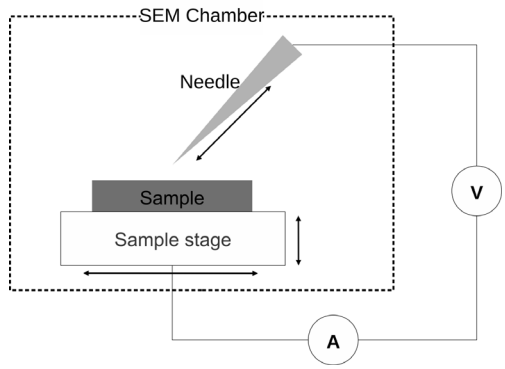

Figure 1: Schematic of experimental setup for field emission measurements and breakdown study.

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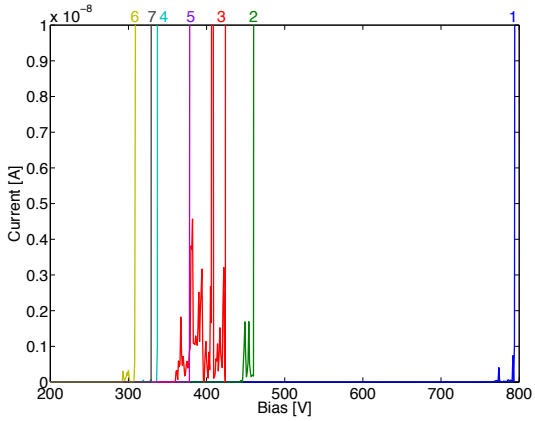

Figure 2: Measured current as a function of voltage. Each run number is indicated on the top of its line.

and increase the voltage on the tungsten tip from zero up to 1 kV with 1 V step. During the ramp we measure the field emission current and stop the ramp once the current exceeds 100 nA in order to avoid breakdown. We then ramp the voltage down and repeat the ramp 7 times in total. The resulting curves showing the current as a function of voltage are depicted in Fig. 2. The first I-V curve is the blue one and successive ramps move the onset of field emission to lower voltages, indicating that the surface was modified in the process.

POST BREAKDOWN STUDY

In a different experimental period we actually increased the voltage across the tip in order to create a discharge and we subsequentially investigated the surface by several means such as electron dispersive Xray spectroscopy (EDX). The investigations reported here were done on a diamond turned copper sample.

EDX

We analyzed two different locations on a copper sample that was subjected to a discharge using EDX. Both locations are within the breakdown area. The instrument used for the evaluation was a LEO 1550 scanning electron microscope operated at an acceleration voltage of 7 kV and a working distance of 12.5 mm. The first measurement was performed on a location 1 in Fig. 3 with only copper present and where no bright particles are observed. The other measurement was performed at location 2 in Fig. 3 on top of a bright particle found within the breakdown area.

In Fig. 4 we show the EDX spectrum from location 1 which exhibits peaks around 0.94 keV which agree within a few eV with those of CuL. Moreover, there are no visible tungsten peaks in the spectrum. We conclude that at location 1 there is predominantly copper present. Repeating the same investigation on location 2, resulting in the EDX spectrum shown in Fig. 5 where we, apart from the copper

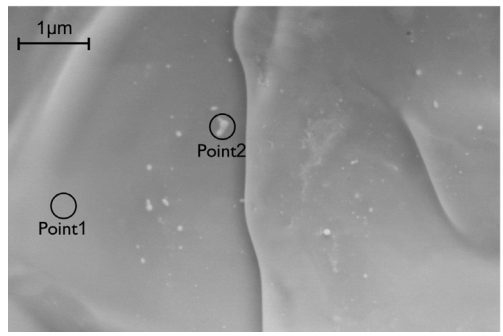

Figure 3: SEM with marked area where the EDX analysis was performed.

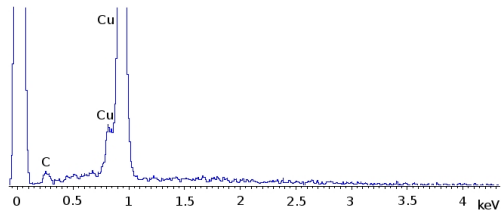

Figure 4: EDX spectra acquired from the point 1 in Fig. 3. Only Cu peaks are visible.

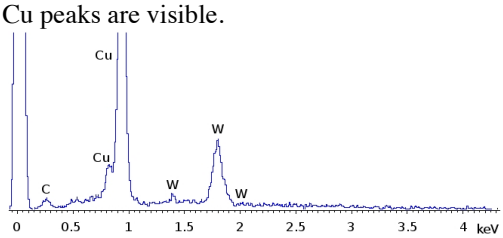

Figure 5: EDX spectrum acquired from the point 2 in Fig. 3. Cu and W peaks are visible.

peaks, also found peaks around 1.8 keV which we could identify as WM. All peaks in the above spectra are in good agreement with literature values of where they should appear, indicating that tungsten has been transferred from the tungsten tip to the copper sample during the breakdown.

We also performed the converse measurement and looked for copper on the tip, but were not able to identify measurable quantities, despite the fact that the tungsten tip was very distinctly affected by the breakdown.

Cross section

The analysis described in the previous section was confined to the surface of the sample. In order to expand the investigation under the surface we use the focused ion beam machine FEI Strata DB235 available in Uppsala University to use the cut and slice method to create a hole in the sample by sputtering with 30 keV Gallium ions and successively erode one thin 100 nm thick slice after another from one side of the hole and observe the resulting cross section through the surface with the electron microscope that is part of the same machine. In order not to damage the surface with the gallium ions during the cutting process, the

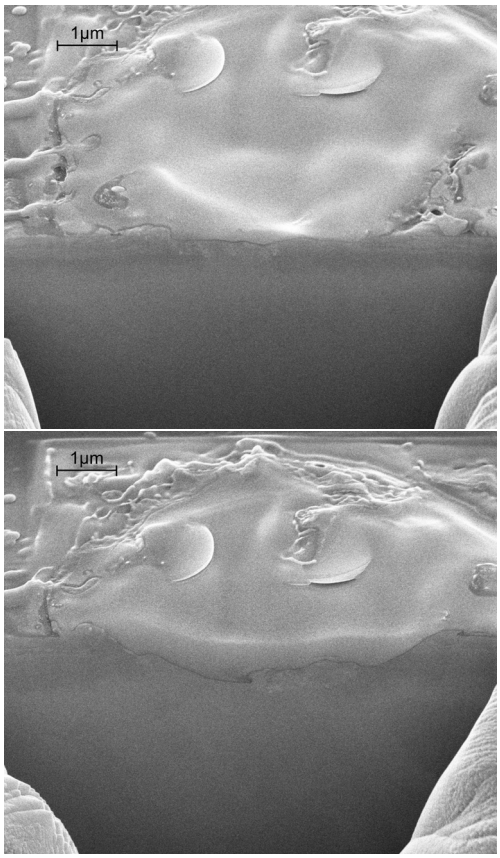

Figure 6: Two pictures of a sequence from a cut and slice analysis of a breakdown site using the FIB at Uppsala University.

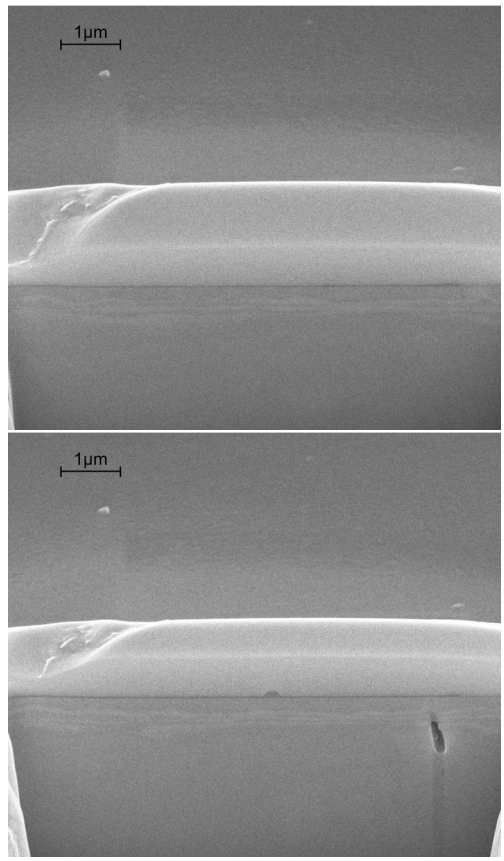

Figure 7: Two pictures of a cut and slice analysis of a pristine location of the diamond turned copper sample.

surface is covered with a thin protective layer of Platinum. The subsequent scanning procedure to generate a sequence of cross sections is very time-consuming and takes several hours.

We first analyzed the location where a breakdown had happened and show two of the slices in Fig. 6. In the right slice a few 100 nm more were eroded from the side of the hole as can be seen by comparing the features near the sides of the pictures. We can also observe the Platinum layer as a brighter layer on the top.

We then performed the same type of analysis on a location on the copper sample that was unaffected by breakdown and created a hole and cut slices from one of the sides of the hole. Two slices of the resulting set are depicted in Fig. 7 where we observe two interesting features. First there are horizontal stripes visible under the surface at a depth of less than 1 μm which we suspect to be the result of the manufacturing process and especially that the diamond turning applied stresses in the material. The second feature is the hole visible on the lower picture near the right side of the same picture, a few 100 nm below the surface. This is particular interesting in the light of the theoretical work reported in Ref. [8] which suggests that holes below the surface can become unstable under the influence of a strong electric surface field leading to the development of protrusions on the surface that later lead to field emission sites that become unstable and lead to breakdown.

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REFERENCES

[1] D.K. Davies, Journal of Vacuum Science and Technology 10 (1973) 115.

[2] M. Aicheler, J. Phys.: Conf. Ser. 240 (2010) 012051.

[3] M. Aicheler, International Journal of Fatigue Volume 33 Issue 3 (2011) 396.

[4] T. Higo et al., PAC'05, May 2005, p. 1162 (2005).

[5] T. Ramsvik et al., Phys. Rev. ST Accel. Beams 10 (2007) 042001.

[6] A. Descoeudres et al., Phys. Rev. ST Accel. Beams 12 (2009) 092001.

[7] T. Muranaka et al., Nucl. Inst. and Methods A, in press, doi:10.1016/j.nima.2011.04.044.

[8] S. Parviainen et al., Nucl. Inst. and Methods B Volume 269 Issue 14 (2011) 1748.