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Progress on scanning field emission microscope development for surface observation

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ABSTRACT

Fabrication technologies for X-band high gradient accelerating structures have been studied at KEK with SLAC, INFN and CERN. A scanning field emission microscope has been developed at KEK for the observation of the microscopic surface defects which may be related to the rf breakdown trigger. We present the progress on the experimental results of studying field emission characteristics by scanning an arbitrary area of 0.5 mm × 0.5 mm on OFHC copper surface using a newly developed scanning field emission microscope.

1. Introduction

Since 1990, KEK has been studying X-band accelerating structure fabrication technologies and has been strongly collaborating with SLAC. So far high gradient and wake field performance tests have been carried out at both laboratories. Currently parameters such as various materials, surface preparation and assembly technologies are being studied in order to understand what influences rf breakdown performance and pulse heating damage [1,2]. Especially important are the microscopic study of materials and surface preparations techniques. After constructing a successful prototype high gradient accelerating structure, an order of a few ten thousand structure sections must be manufactured for the collider in a cost effective manner to construct a TeV energy range accelerator. We conjecture that measurements of field emission current at each point on the surface and the field emission distribution on the surface area are very important because the field emission enhancement may be caused by surface defects. Thus the scanning field emission measurement can be one of the important tools for identifying regions with enhanced field emission. Copper is obviously interesting for rf applications due to its high electric and thermal conductivity, as well as its aptitude for precision machining.

2. Experimental setup of scanning field emission microscope

Fig. 1 shows a schematic of the scanning field emission microscope setup. A tungsten tip is used as a point anode. Electro polished OFHC (oxygen free high conductivity) copper was used as the planar cathode. Two types of cathode surfaces were tested: one is a diamond turned surface and the other is a chemical etched surface. The cathodes are kept in an ultra vacuum chamber at a typical pressure of 10^{-7} Pa. The anode tip is less than 1 μm in diameter, and the cathode (sample) is a 10 mm × 40 mm rectangular plane. The sample is treated at 600 °C for 2 h in vacuum. The tip is positioned vertically using a precise screw and PIEZO actuator, which can measure as small as 0.1 μm gaps. The two-axis linear stages are installed and pulse motors are mounted outside the chamber. The stages are moved via the feed through axis, which has 0.1 μm positioning accuracy. The zero distance is found by bringing the electrodes into contact by PIEZO actuator. The gap distance is set to 1 μm. It is necessary to reach a field of 200 MV/m with the available 200 V power supply. At first we attempt to measure field emission at arbitrary points while maintaining the 1 μm gap and change the applied voltage from 0 to 200 V in 10 V steps. Then we make one-dimensional scans while maintaining the 1 μm gap and travel 1 mm each on both the mirror and chemically etched surface. Finally we make a 2 mm × 2 mm area scan with the same gap as in the previous measurement, by applying a voltage of 200 V. Fig. 2 shows the newly developed scanning field emission microscope. The drive motors for the scanning were mounted on the outside of the vacuum vessel to preserve the high quality vacuum environment.

3. Tentative results and discussion

3.1. Reproducibility

Fig. 3 shows the reproducibility of the field emission current measurements vs. bias voltage. We repeated the measurement

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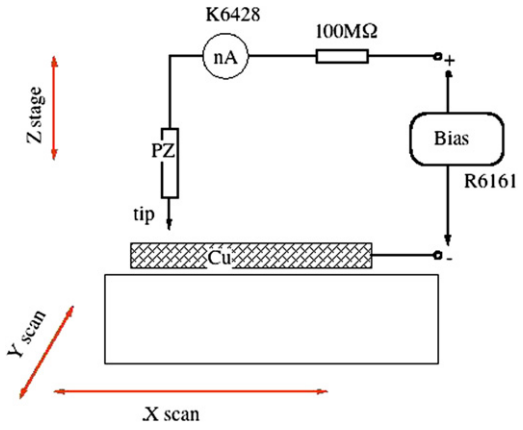

Fig. 1. Schematic drawing of the experimental setup.

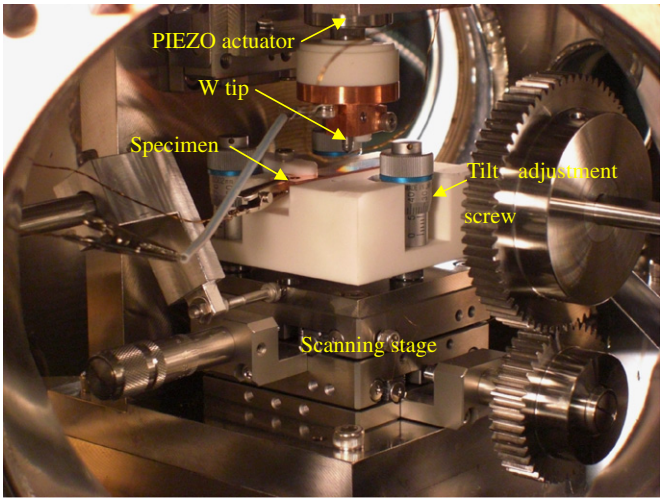

Fig. 2. Photograph of the newly developed scanning field emission microscope.

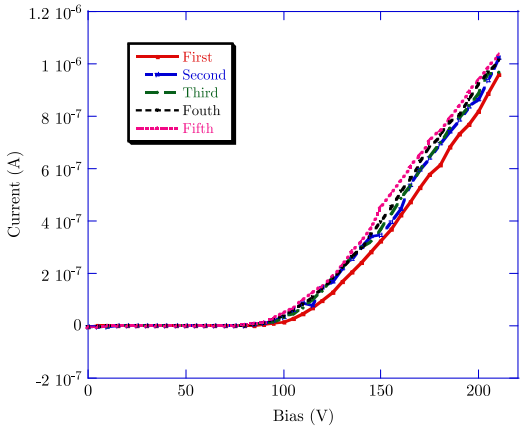

Fig. 3. Reproducibility of the measurements of the field emission current vs. bias voltage.

five times to confirm the reliability of the experimental setup. The measurement conditions and procedure are as follows: bring the anode tip up to 50 μm to the sample surface with a threaded rod, soft touch the surface using the PIEZO actuator and then place the tip at 1 μm from the surface. The bias voltage is varied from 0 to 210 V with 10 V steps. After reaching the maximum voltage, the bias voltage is reduced to zero immediately. This procedure is repeated five times. The measurements have good reproducibility, with 4.3% error. We think this confirms the usability of the field emission measuring system.

3.2. Comparison of the Fowler–Nordheim plots at any random points on the copper surface

Fig. 4 shows **Fowler–Nordheim** (F–N) plots at any random point on the sample of the copper surface. We used oxygen free high conductivity copper material (HITACHI class 1: purity 99.996%). Then the sample was turned by a single crystal diamond tool resulting in a final Peak-to-Valley (P-V) roughness of 20 nm. Finally copper was heat-treated at 600 °C in the vacuum furnace. The distance between the anode tip and surface was set to 1 μm and the same procedure as described at the end of Section 3.1 above was applied. Thirty five arbitrary points were measured and the results are shown in Fig. 3. Each frame in Fig. 3 shows the measurements at 5 of the 35 points. This data shows that the F–N plots have deviated from a linear function. We calculated I/E^2 to be approximately -52 for an applied bias of 210 V. The E value is calculated using the Poisson equation. It is difficult to understand the bump near 1×10^{-8} $(1/E)$ observed on all seven frames. The standard F–N equation does not explain this bump. Fig. 3 plots demonstrated that the field emission may depend on surface conditions such as: contamination, crystal defects, grain boundaries, copper oxide layer, surface roughness and so on. In future tests we propose to use a reference surface, which is made from a single crystal with a confirmed crystal orientation, an atomic level of surface roughness and without a copper oxide layer.

3.3. One and two-dimensional scans

A one-dimensional scanning field emission measurement has been carried out. The anode tip scanned the mirror surface and chemical etched surface separately. The roughness of the mirror surface and chemical etched surfaces are 20 nm P-V and 50 nm P-V, respectively. The traveling distance is 2 mm for each. The data sampling pitch is 2.5 μm and 0.1 mm/sec scanning speed is selected. Fig. 5 shows the field emission profile of each surface. The characteristics of both data profiles are very similar, with several field enhanced positions. The saturated regions on the graph indicate the limit of the data acquisition device. We calculate an electric field variation below the anode tip because the surface roughness of 20, 50 nm P-V are 2%, 5%, respectively. Therefore we speculated that the measured field enhancement may be caused by surface contamination or crystal defects.

Fig. 5 shows that the emission current is saturated at 2 nA, which means that the anode tip and the cathode plate are in electrical contact. Following microscopic inspections, which reveal no surface damage on the cathode plate we conclude that the cathode was not in direct contact with the anode. We speculate that the presence of foreign particles on the cathodes surface shorted it to the anode tip, thus causing the saturation regions in Fig. 5. In future experiments we plan to improve cathode surface cleanliness to achieve better reproducibility of the measurements.

We demonstrated a two-dimensional field emission scan measurement. We scanned an area of 0.5 mm^2 region in 2 μm steps. Fig. 5 shows field emission strength distribution in a 0.5 mm^2 region of two different locations. The field enhanced regions are shown in blue. The maximum field enhancement is a factor of seven. As seen in Fig. 6, the field enhanced regions appear to be approximately linear from top to down. We speculate that this linearity is due to the diamond cutter tool marks. For example, the tool mark might contain a copper oxide layer, some gas and/or have an altered crystal formation compared to an

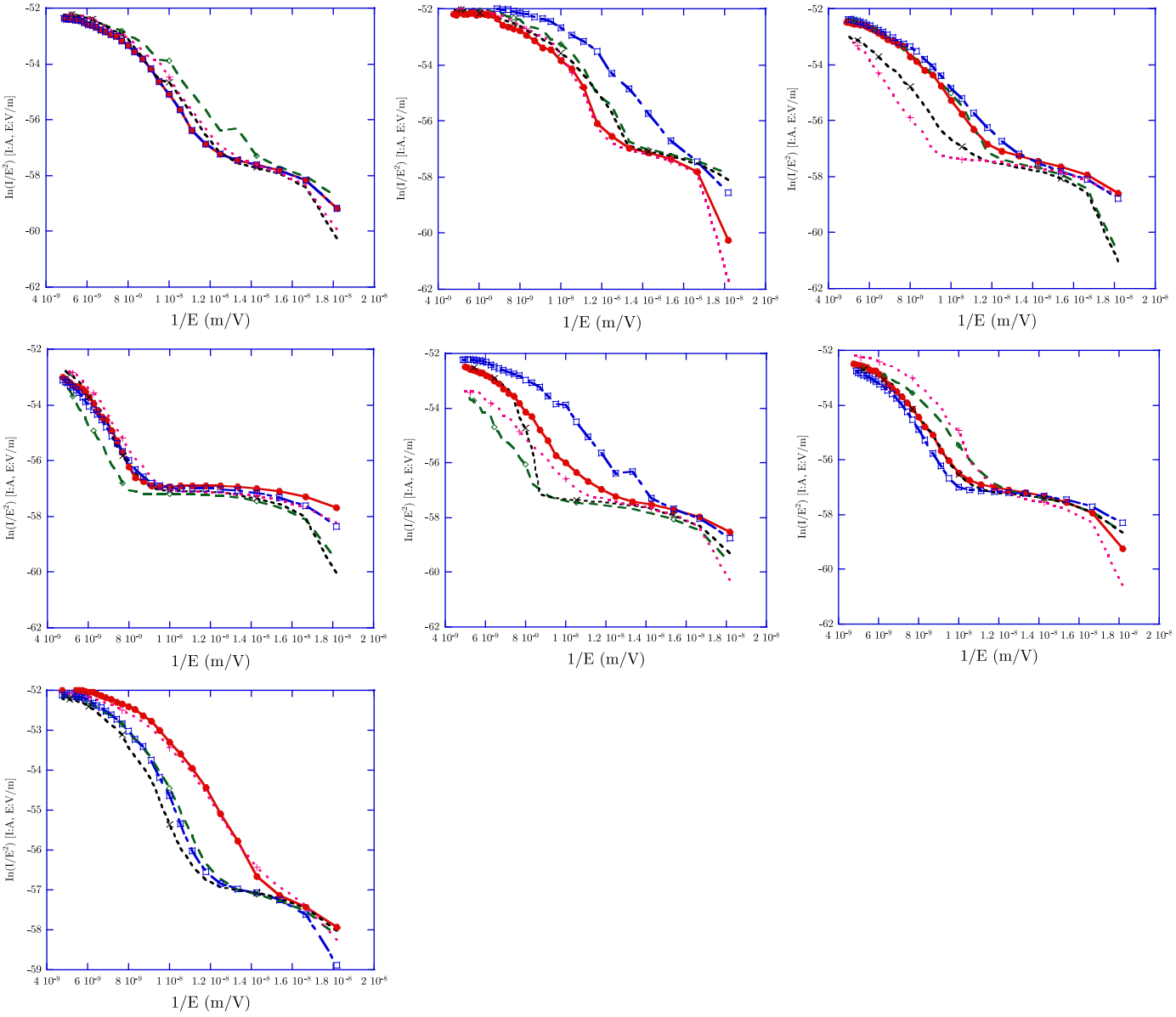

Fig. 4. Fowler–Nordheim plots at 35 arbitrary points. Each frame includes data for five locations.

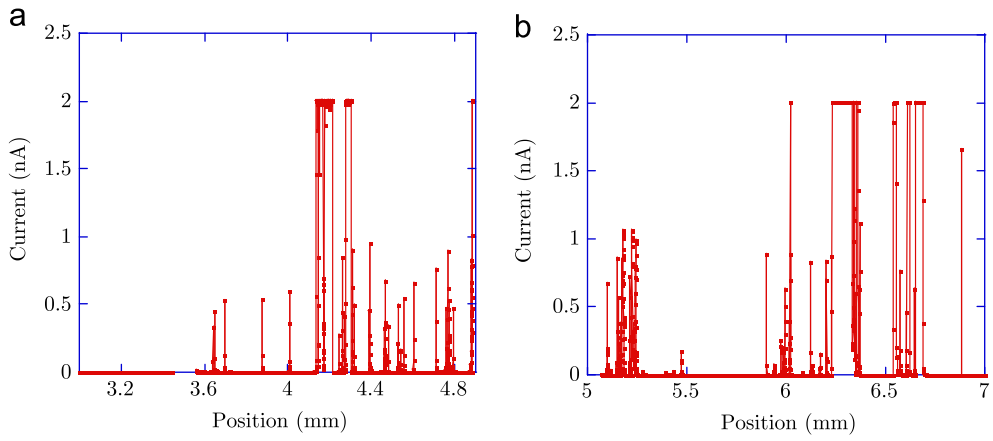

Fig. 5. One-dimensional field emission scans: (a) mirror surface, (b) chemically etched surface.

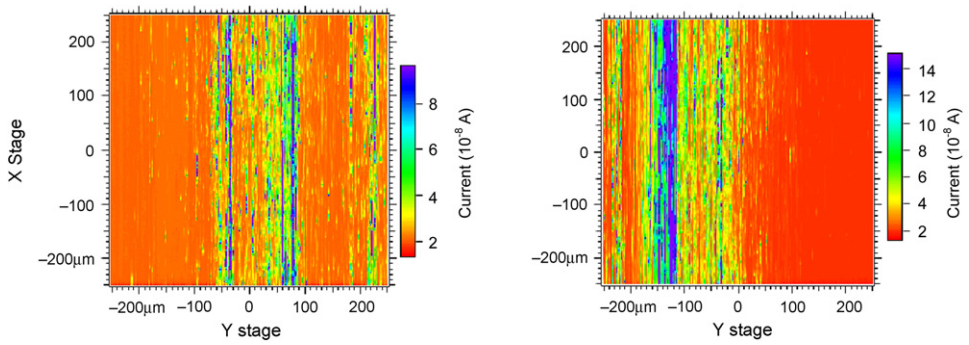

Fig. 6. Two-dimensional field emission scan results. The graphs are for arbitrarily selected regions. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

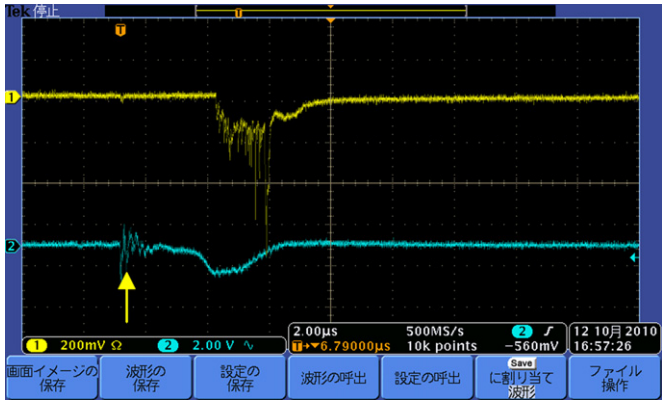

Fig. 7. Observation of photo emission (yellow) and field emission enhancement (blue) in a breakdown event. The arrow indicates the possible occurrence of a breakdown trigger signal. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

unperturbed crystal surface. In order to differentiate between these features we need to measure the surfaces with X-ray photoelectron spectroscopy (XPS), Scanning Electron Microscope (SEM) and X-ray diffraction methods.

Fig. 7 shows one of the Photo Multiplayer Tube (PMT) signals when scanning a field enhanced point on the surface. The signal strength of PMT is not yet calibrated. We believe the signal represents a breakdown site. On the scope picture in Fig. 6, the yellow trace corresponds to the PMT signal and the blue to the current in the field emission microscope. The small oscillation in the field emission current prior to the onset of the PMT signal might be related to the breakdown trigger. Precise observation of the surface characteristics are needed in order to further understand breakdown and breakdown trigger physics.

4. Summary

The field emission scanning microscope can easily provide measurements of field enhanced regions. Even if these results depend on specific features of the metal surface and its treatment, they can help to select proper surface preparation procedures for high gradient structures.

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