HIGH PEAK POWER PROCESSING UP TO 100 MV/M ON VARIOUS METALLIC SAMPLES

M. LUONG, B. BONIN, H. SAFA,
CEA-DAPNIA-SEA-GECS, 91191 GIF-SUR-YVETTE cedex, France,
A. LE GOFF
IPN (CNRS-IN2P3), 91406 ORSAY cedex, France

ABSTRACT

The high peak power processing (HPPP) is a well established way to reduce electronic field emission from radiofrequency (RF) metallic surfaces. The processing occurs because of some kind of instability destroys the emitter, but the basic physical mechanism at work has not yet been clearly identified. The present study describes RF processing experiments on samples of restricted area, with well localized artificial emitting sites (protrusions from scratches on the sample surface). In order to disentangle the role of thermal and mechanical effects in the processing, the samples were made from metals with different melting temperatures and tensile strengths.

INTRODUCTION

Field emission sets a limitation to the electric field that can be reached on RF surfaces. High peak power processing is a well established way to reduce this emission. It has been employed for a long time in normal conducting cavities ; its application to superconducting cavities is more recent, but already very successful [1,2]. Despite this success, the physical mechanisms at work have not yet been clearly identified. Recent studies have shown that, at least for a wide class of emitters, i.e. scratches and conducting particles lying on the surfaces, the field emission is mainly due to a geometrical enhancement of the electric field at the apex of a nanometric protrusion of the surface [3,4]. Thermal effects certainly play an important role, evidenced by the presence of molten material and craters on the RF surfaces. One can also expect mechanical instabilities of the emitting sites. Because of the large field at the emitter apex, the electrostatic pressure $p = \varepsilon_0 E^2_{\text{microscopic}}$ gets close to the yield stress of usual metals. Necking or even breaking of the apex can thus occur, and the subsequent modification of the surface geometry results in changes in its field emission characteristics.

The present study tries to gain insight in the HPPP phenomenology by processing experiments on samples of restricted area, with well localized artificial emitting sites (protrusions from scratches on the sample surface). In order to disentangle the role of thermal and mechanical effects in the processing, the samples were made from metals with different melting temperatures and tensile strengths.

EXPERIMENTAL SET-UP

Previously, a handy facility has been developed for the study of RF field emission. A detailed description was given in [5]. This facility mainly consists of 1.5 GHz stainless steel reentrant cavity working at room temperature and supplied by a 5 KW klystron (Fig. 1a). A quality factor around 6000 has been obtained by covering the inside of the cavity with an electrolytic copper layer. A new shape is given to the dismountable sample in order to reach a maximum field of 110 MV/m on the small surface (2 mm^2) at the top (Fig. 1b). The electronic current is collected on an antenna aligned with the symmetry axis of the cavity. A vacuum better than 10^{-6} Torr is provided by an ionic pump. RF pulses of 10 µs to 8 ms can be used with a repetition period of 1 to 4 Hz.

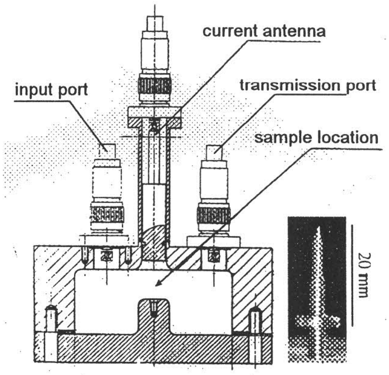

Fig. 1. The reentrant cavity and its new sample

EXPERIMENT PROCEDURE AND RESULTS

A possible substrate influence on the processing of "scratch emitters" is investigated with different metallic samples. Material properties are summarized in the table 1.

	Mo	Nb	Cu	Al
Melting point (°K)	2610	2468	1083	643
Tensile strength (Mpa) at 250°C*	400	250	300	90

* due to the sample heating by the RF surface loss

Table 1. Sample properties

The stages of the preparation of different samples are described as followed :

1) cleaning in ultrasonically agitated alcohol,

2) niobium samples / acid solution (HF, HNO_3, H_3PO_4) etching for 30 minutes (≈ 30 µm removal),

2') other samples / polishing with emery paper up to grade 4/0, optic microscope examination, cleaning in ultrasonically agitated alcohol,

3) rinsing with high purity water (resistivity > 10 MΩ),

4) drying under class 10000 laminar flow,

5) scratching with diamond tip to obtain geometrical emitting sites,

6) mounting in the cavity under laminar flow.

The sample mounting is followed by a 10 hours pumping to reach a vacuum of 10^{-7} Torr. Then a HPPP experiment can begin. The incident RF power is modulated by a pulsed periodic signal with duration τ and period T, in order to avoid breakdown in coaxial cable and N-type feed through. We use τ = 1 ms and 100 ms < T < 400 ms. The general procedure is listed below :

1/ the incident power is slowly increased for 10 min. At the same time, current values and dissipated power are read ;

2/ once $E_{peak\ max}$ is reached, a conditioning period begins and will last 30 minutes ;

3/ afterwards, the incident power is decreased and current values are read again. They will be plotted in a Fowler-Nordheim plan ($Y = \log(<I_{RF}>/E_{peak}^{2.5})$, $X=1/E_{peak}$, see Appendix) from which parameters β and A_e will be extracted.

During step 1/, high current values are observed. Their behavior as a function of E_{peak} do not obey the Fowler-Nordheim theory. This is not really surprising, since emitter sites are being processed during the field increase.

Furthermore, desorbing species may be ionized by high energy electrons and then induce resonant secondary electron emission between the current collecting antenna and the surrounding cavity wall.

These perturbations can lead to spurious field emission current values. Only the conditioning at high field guarantees a substantial elimination of adsorbed gas layers.

Several sudden drops of the current (reduction by a factor 2 to 100) occur in step 2/. Many of these are preceded by a short period (~ 2 s) current fluctuation.

Measurements are always reproducible in step 3/.

A total of 14 different samples were tested : 2 non scratched samples (1 Nb, 1 Mo), 12 scratched samples (3 Mo, 3 Nb, 2 Cu, and 4 Al). Main results are reported below.

a) Scratched samples emit higher current than non scratched ones during the processing ; this recalls that scratches form strong emitters.

b) Since samples have different thermal and mechanical properties, a different "processability" is expected for each metal. However, results show no clear dependence of emitter characteristics after processing (β, A_e) on the sample metal (Fig. 2). The dispersion of those characteristics probably comes from the initial geometry of emitter sites, and is not wider than the dispersion observed on Nb samples. Hence the field emission on all four investigated metals seems to be reducible by HPPP.

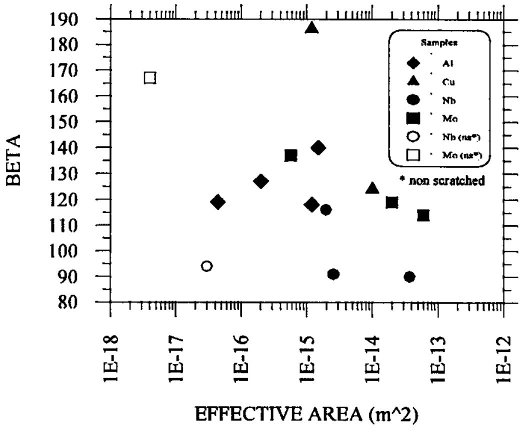

Fig. 2. Effective area and Bêta distribution after HPPP

c) After the RF processing, the examination with a scanning electronic microscope shows metal droplets on all samples (Fig. 3). This proves that violent transformations occur during the processing.

d) A statistic limitation of the current density ($j = <I_{RF}>/A_e$) arises around 10^{11} A/m². No value above 10^{12} A/m² is found on any tested samples even at maximum electric field (Fig. 4).

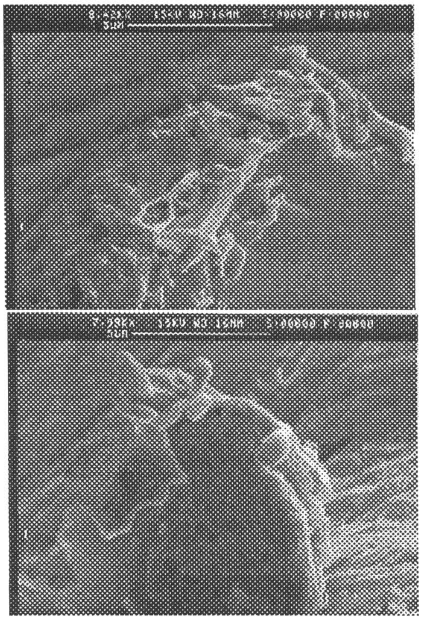

Fig. 3. Traces of explosive transformations

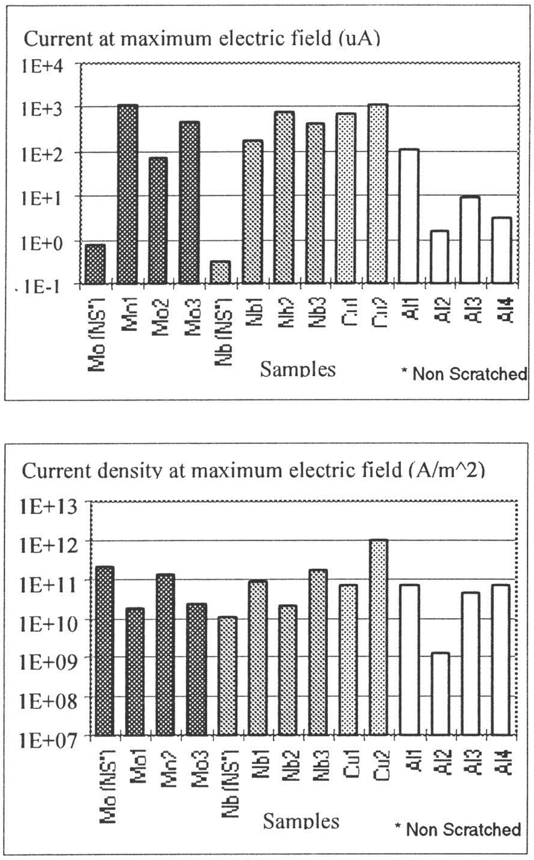

Fig. 4. Current and current density

The high current density induced processing is clearly shown on a scratched molybdenum sample (Fig. 5).

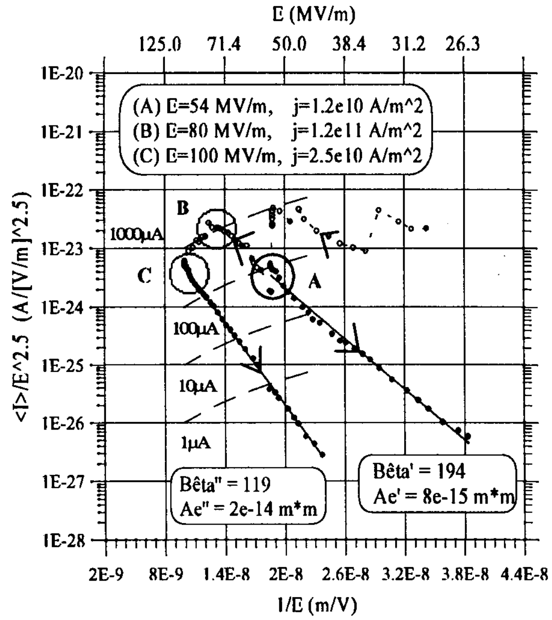

Fig. 5. A scratched Mo sample processing

DISCUSSION

Melting traces, sudden drops of current, and the limitation of current density observed in this study provide a further evidence for the explosive nature of events acting in HPPP.

The statistic limit value of the current density lies in the order of which that can promote explosive emission by means of micro plasmas in DC field emission experiments [6]. In DC regime, several calculations based on models taking into account energy exchange processes like thermoionic emission, Joule effect, or Nottingham effect lead to the conclusion that a local temperature around 1000-2000 K is reached for current densities beyond 10^{12} A/m^2 [7,8]. In RF field emission, the ionic bombing must bring an important additional contribution to the energy exchange.

Since the current density only depends on the microscopic enhanced electric field, the value of 10^{11} A/m^2 corresponds to $E_{micros} = \beta \cdot E_{appl} = 1.5\ 10^{10}$ V/m. Thus surface defect emitters like scratches with β less than 150 can statistically survive a HPPP at 100 MV/m. This could explain why HPPP sometimes fail on accelerator cavities, when a more important contamination occurs during the cavity mounting. A higher field HPPP would leave weaker β emitters. This assertion is consistent with E. Tanabe's results, who found β around 60 after RF processing at 230 MV/m on metallic samples [9]. But such a high field is not available in super conducting cavities because of the magnetic quench limitation.

The present work suggests that the HPPP effectiveness is possibly limited to strong surface metallic defect emitters.

APPENDIX

For a continuous electric field E, locally enhanced by a factor, Fowler-Nordheim theory provides the current density, when the image force potential is neglected :

$$j_{DC}(E) = \frac{1.54\ 10^{-6}\ \beta^2 E^2}{\phi} \exp\left(-\frac{6.83\ 10^9\ \phi^{1.5}}{\beta E}\right),$$

with j_{DC} in A/m^2, E in V/m, the work function in eV. Since electron emission is localized on very small sites, one usually sets the measured current, as $I = j\ A_e$, where A_e (m^2) is called the effective area.

For a GigaHertz RF field , the current I takes the form of a very short pulsed periodic positive signal with the RF period. Since current/voltage converters bandwidths are limited to a few hundred Kilohertz (typically 100 KHz for Keithley Model 428), only the continuous component $<I_{RF}>$ is measured. We have :

$$< I_{RF} > = \frac{A_e}{T_{RF}} \int_0^{T_{RF}} j_{DC}[E(t)]\,dt, \text{ with}$$

$$E(t) = E_{peak} \sin\left(\frac{2\pi t}{T_{RF}}\right) \text{ at the tip.}$$

For $\beta \in [50;1000]$ and $E_{peak} < 130$ MV / m,

an analytical approximation of $< I_{RF} >$ is found :

$$< I_{RF} > \cong A_e \, \frac{5.59\ 10^{-12}\ \beta^{2.5}\ E^{2.5}}{\phi^{7/4}} \exp\left(-\frac{6.83\ 10^{9}\ \phi^{1.5}}{\beta\ E_{peak}}\right).$$

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