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Field emission studies at Saclay

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Introduction

Field emission is known to be the major limitation to the obtention of high gradients in superconducting cavities. This motivated an important effort at Saclay to understand the phenomenon and —hopefully —to cure it. The main results of this study have been or are being published in reviews (refs. 1–4). We shall give here a summary with the appropriate references.

The instruments

We developed three dedicated facilities for the experimental study of field emission. These instruments are complementary, and cover a wide spectrum of possible experiments.

1. "Global DC apparatus"(ref. 1, fig. 1). This is a high vacuum chamber housing a plane parallel gap which can be polarized in DC, with electric fields limited to 50 MV/m. The

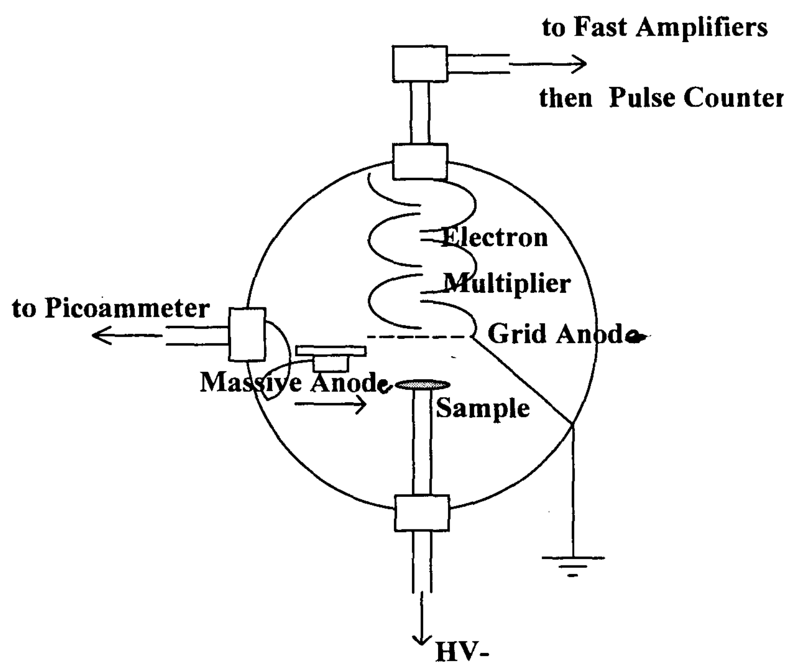

Figure 1 Global DC apparatus

cathode-anode distance is of the order of 1mm. Electrodes as large as 1 cm^2 can be used. A side chamber with a separate vacuum enables the introduction of the samples without breaking the vacuum in the main chamber. The current measurement can be made either with a picoamperemeter on a massive stainless steel anode, or with an electron multiplier able to measure individual electrons. This last feature gives access to the very low field, low current part of the gap I(E) curve. This apparatus measures the field emission from the whole sample surface, and is suited to the qualification of various surface treatments.

2. "Modified SEM" (ref. 2, fig. 2). This device is inspired from Niedermann's pioneering work (ref. 3) , and consists of a large area cathode (1 cm^2) and a small area anode (in fact, a needle) scanning above the cathode surface, at a distance of 50 μm. The available electric field

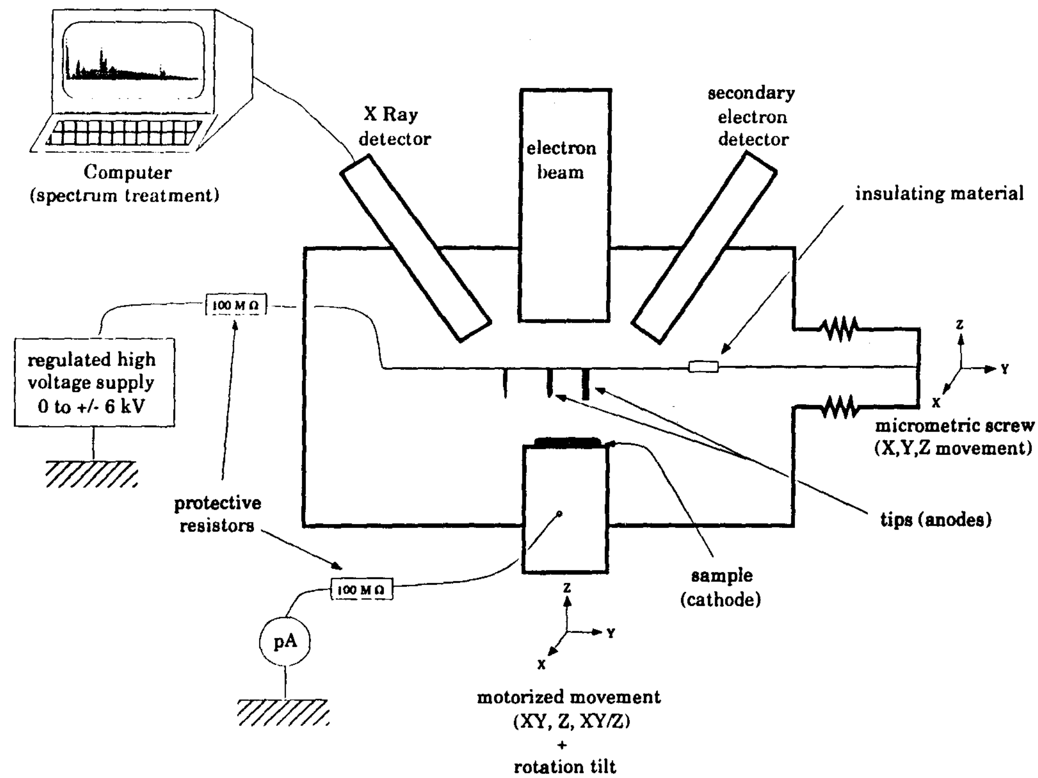

Figure 2 Scanning electron microscope modified for the study of field emission

domain is 0–200 MV/m. A picoamperemeter monitors the field emission current. This device permits the location of emitting sites on the cathode surface. The whole gap is contained in a Cambridge scanning electron microscope (SEM) equipped with an EDX facility, which enables in situ studies of the morphology and chemical composition of the emitter. This apparatus opens up possibilities of investigation on field emission at the microscopic level, and is useful for the understanding of the fundamental mechanism underlying field emission on large area surfaces.

3. "Warm cavity" (ref. 4, fig. 3). This RF cavity is inspired from the work of U. Klein, from Wuppertal university (ref. 5). It is designed so as to have a strong electric field

enhancement at the surface of a dismountable sample. Electrons originating from the sample

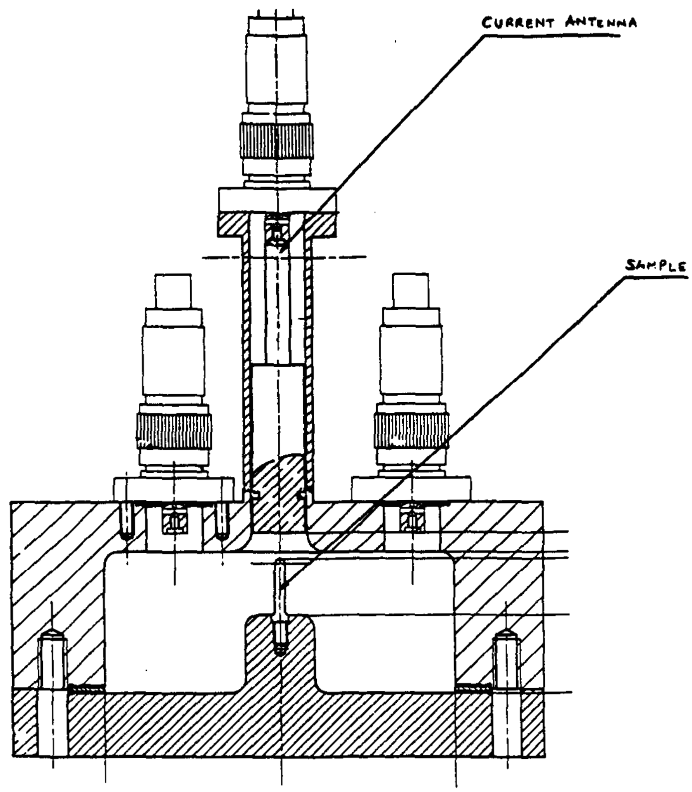

Figure 3 RF cavity dedicated to the study of field emission

surface are collected by an antenna, and the corresponding current is recorded by means of a current amplifier. Thanks to its special geometry, the electron trajectories are very simple and the travel time between sample and antenna is short compared to the RF period. This prevents secondary electrons to contribute to the current in the cavity. In order to avoid difficulties due to the study of field emission at cryogenic temperature, the cavity operates at room temperature and is made of copper plated stainless steel. Despite the small power of the klystron used (5 kW), RF fields as high as 70 MV/m can be achieved on the sample surface. These samples are hemispherically capped cylinders, of diameter 3 mm, which can readily be moved and tested in the "modified SEM" or the "global DC" apparatus to compare their emission in DC and RF regimes. This cavity is also a valuable tool to investigate the consequences of high power pulsed processing, without the constraints brought by superconductivity.

Summary of the results

1. Natural emitters

Using the "modified SEM" (ref. 2), we confirm that all emitters coincide with previously identified surface defects. When examined with the "modified SEM" facility, emitting sites were always found to be correlated with some kind of defect. This result, at variance with Niedemann's findings (ref. 6), might be explained by the poor resolution of the electron microscope he used for his study. The defects seem to enter into two main categories:

geometrical defects, revealing no foreign element under EDX analysis, and defects from particulate contamination.

All defects do not emit: only 5% emit at field levels of the order of 100 MV/m. For naturally occurring particulate contamination, we could identify no clear criterium saying why a given defect becomes an emitter. The chemical composition of the particles (emitting and non emitting) is given in fig. 4.

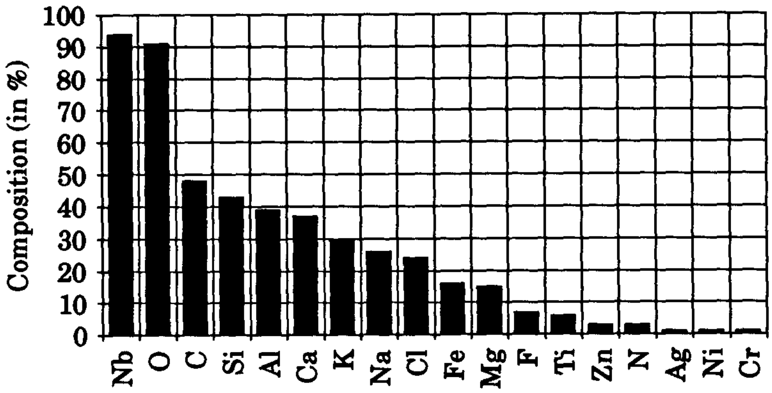

Figure 4 Elemental composition of the natural emitters, measured by EDX.

Study of these natural emitters is difficult because their emission is unstable (especially in DC regime), and because they tend to be blown away if too much field is applied.

Systematic experiments have been made with the "global DC" apparatus (ref. 1) in the low field, low current regime (fig. 5). They indicate that below 0.1 pA, the I(E) characteristics of the emission is strongly hysteretic and cannot be extrapolated from the I(E) behaviour observed at higher current. This emission is affected by adsorbed gases, and its mechanism is still unclear. It is not even clear that the emission is located at the same sites as those active in the high field, high current regime.

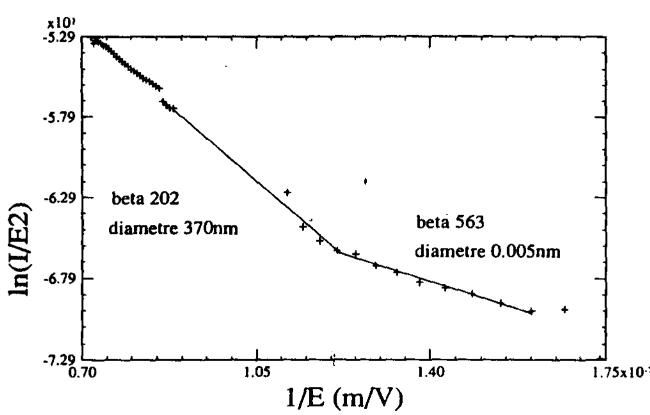

Figure 5 Typical emission characteristics of a "natural" Nb sample in the low field, low current regime.

2. Artificial sites

For the reasons mentioned above (difficult study, no clear cut "zoology" of natural emitters), we focussed the forthcoming studies on emission from well known, well controlled artificial emitters: either metallic or insulating particles of known size and morphology, or artificial geometrical defects produced by scratches.

2.1 Artificial particulate contamination

Powders of conducting or insulating materials were sprayed in controlled amounts on Nb and Au substrates. Very clear results emerged: most of the conducting particles (Fe, Ni, Au, Ag, Nb, Ti) behave as emitters at low field levels, whereas most insulating ones (Al_2O_3, SiO_2) do not emit, even at high fields (fig. 6).

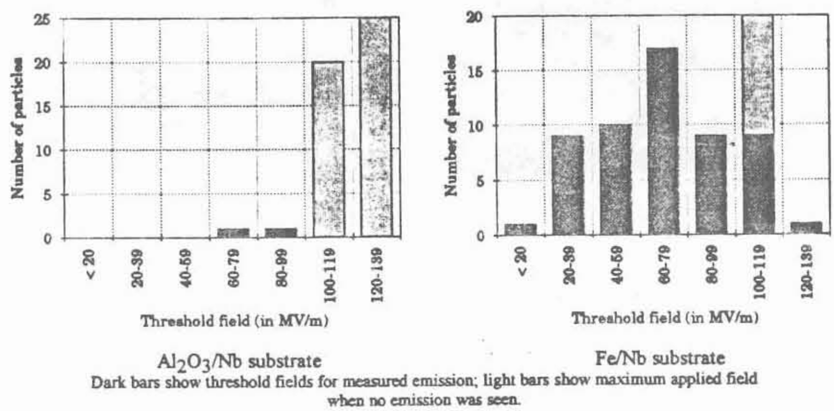

Figure 6 Field emission threshold of alumina and iron particles.

Conducting particles tend to orient themselves along the electric field lines (fig. 7). This behaviour maximizes the microscopic electric field at the particle apex. After emission,

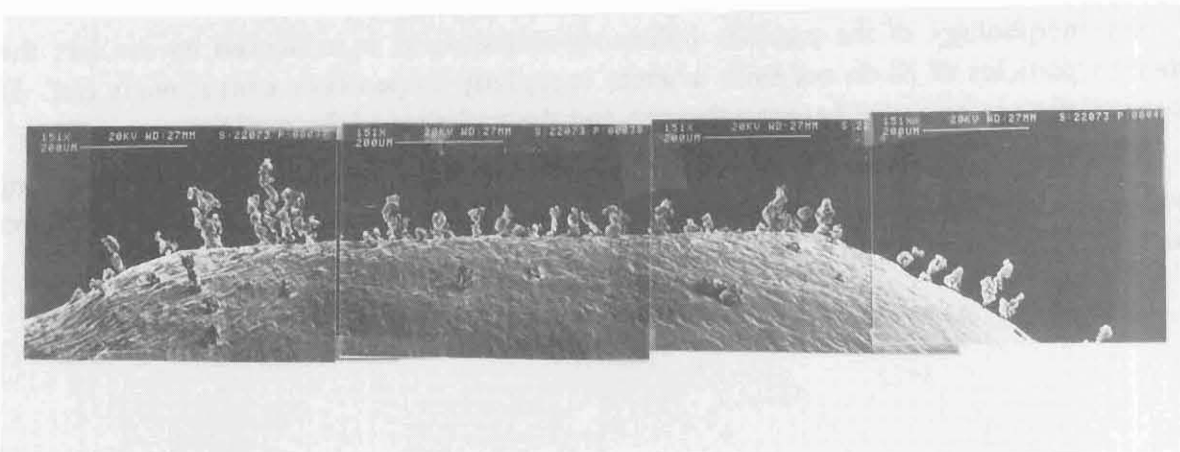

Figure 7 Orientation of iron particles along electric field lines in the "warm" cavity.

particles are in electrical contact with the substrate, and are welded to the substrate (fig. 8).

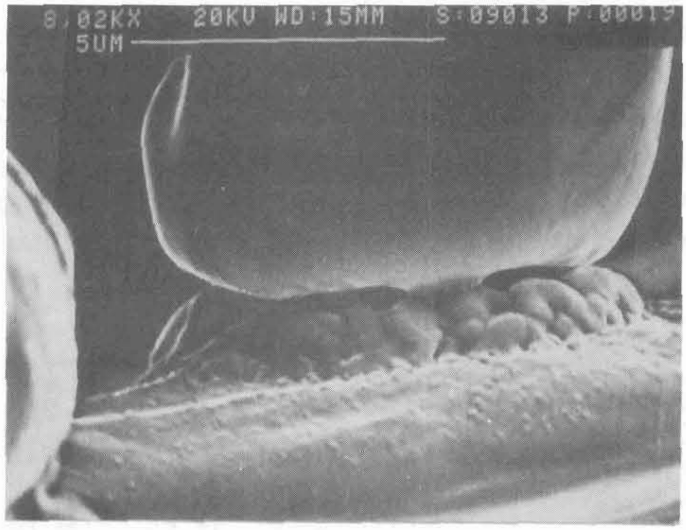

Figure 8 View of an iron particle after emission. The roll at the base of the particle is molten iron, welding the particle to the substrate.

The oxide on the substrate does not seem to play a very significant role: no difference of behaviour was observed between naturally oxidized and anodized Nb substrates, or between Au and Nb substrates. This finding results from experiments in the "modified SEM", and in the "Global DC" apparati.

The morphology of the particles influences emission, as is evidenced by the fact that spherical particles of Ni do not emit, whereas irregularly shaped ones emit strongly (ref. 3). No correlation is observed between the size and the emission of the particles.

Pulsed RF can remove dust particles. Shorter pulses seem to be more effective than long ones (Fig. 9). This might (partly) explain the well known success of "high peak power processing" for reducing field emission in RF cavities.

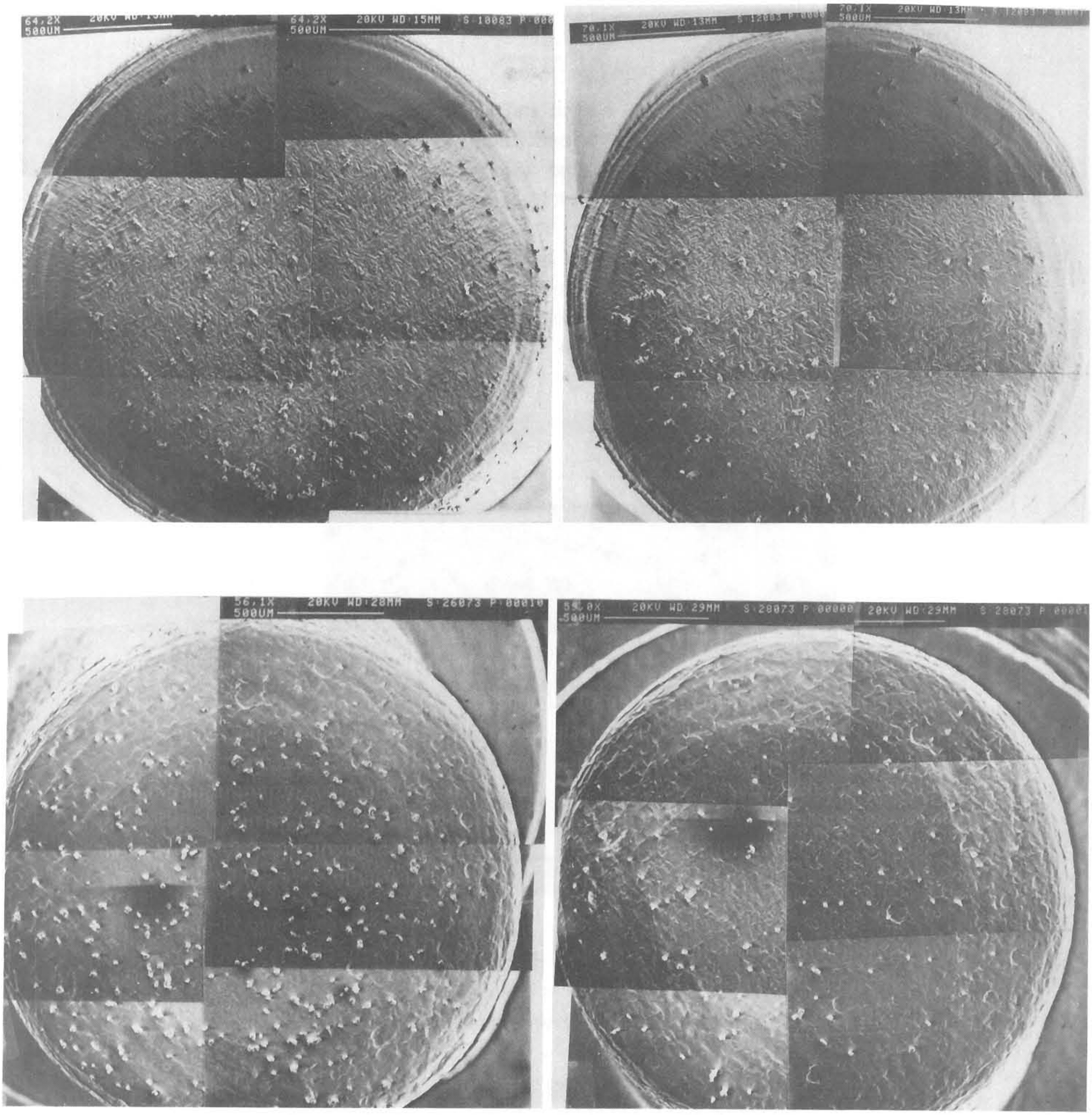

Figure 9 Effect of short vs long RF pulses on the removal of iron particle contaminants. Left column: before RF; Right column: after RF; First line: long pulses (τ = 10 ms ; 15% of the particles are removed after RF); Second line: short pulses (τ = 0.2 ms ; 70% of the particles are removed after RF)

2.2 Scratches

Geometrical defects were produced on Au and Nb substrates by scratching the surface with a needle (ref. 3). Hard needles were used (diamond, W or Nb tips). It was checked with EDX analysis that, at least for diamond and W tips, the needle keeps its integrity during the scratching, and that no material from the needle is left on the substrate (to the precision of EDX analysis). Such geometrical defects are strong and stable electron emitters on both substrates. Morphological studies of these scratches show very sharp protrusions, which might promote a large field enhancement at their apex (fig. 10). Typical height of the emitting protrusions in these experiments is of the order of 10 μm. The curvature radius at the apex is commonly found to be 100 nm, and might be even less in reality, since the resolution of the SEM is of this order.

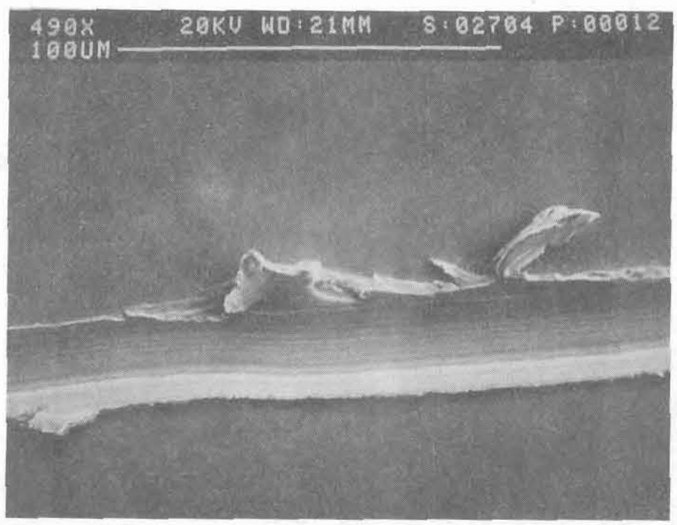

Figure 10 A typical geometrical defect produced by scratching a Nb surface with a diamond needle.

Contacts were also made with a plastic needle. Due to the difference of hardness between plastic and metal, no geometrical defects were produced on the niobium surface. No emission is observed from these contacts despite a considerable contamination of the niobium substrate by plastic particles.

2.3 For both types of emitters

Comparison of emission in DC and RF regimes.

Most of the studies on field emission are made in the DC regime, and it is generally assumed that the mechanisms of emission are the same in DC and in RF. This assumption has never been tested in detail, although this is clearly an important issue. The facilities developed at Saclay should enable us to draw some conclusions. Unfortunately, no clear results have been obtained yet, mainly because the comparative experiments are only beginning. Even with complete experiments, the comparison might be blurred for the following reasons: i) Adsorbed gases obviously affect field emission, and desorption is certainly more effective in RF than in DC; ii) Particulate contaminants which dominate the field emission behaviour on large area electrodes tend to be removed more easily in DC than in RF regime. It is thus difficult to ascertain that the studied sample is in the same state during measurements in DC and in RF.

Despite these difficulties, we could already check that after RF conditioning, the Fowler-Nordheim characteristics of a large area electrode is about the same in DC and in RF.

Thermal effects

Important thermal effects are observed on emitting sites. Like in many previous studies (ref. 7), craters of molten niobium are often found around active emitting sites (Fig. 11). (more precisely : around emitting sites which *have been* active. Craters seem to appear after some discontinuity — for example a breakdown — in the behaviour of the emitter).

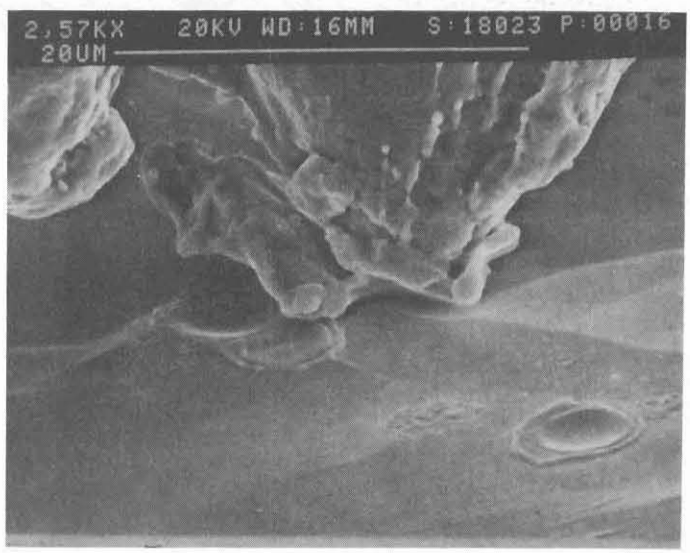

Figure 11 Typical craters (here: molten niobium).

After emission in RF, dust particle emitters, eg Fe or Ni, appear to be molten and welded to the substrate surface (Fig. 8).

"Scratch" emitters also display thermal effects : Fig. 12a shows a geometrical defect acting as a powerful emitter. The characteristics of its emission changed irreversibly above some current threshold. SEM picture of the same site after this accident reveals a molten apex (fig. 12b).

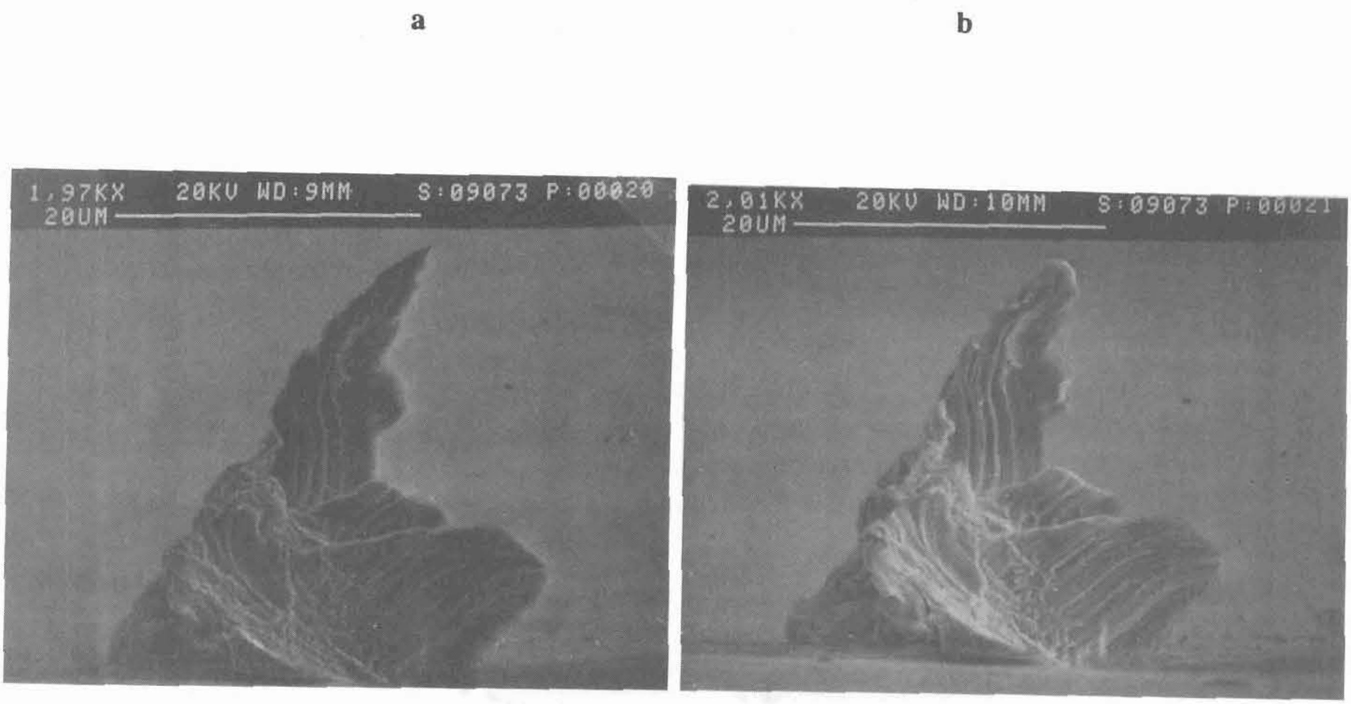

Figure 12 Morphology of a "scratch" defect (a) before and (b) after emission.

It is thus natural to assume that emission is located at the apex, but the exact cause of the heating (Joule effect, ion bombardment,....ref 8) is not yet clear. Active sites are known to emit some light (ref. 9). A modification of the "warm" cavity has been done recently at Orsay-Saclay (ref. 9) in order to permit observation of this light. Spectroscopic analysis should tell whether it is of thermal origin. This experiment, presently under way, should contribute soon to the understanding of the thermal effects associated with field emission.

Superposed protrusions ?

Most of the above mentioned experimental facts find a natural explanation if the enhanced field emission is simply due to a geometrical field enhancement at the apex of a conducting protrusion (ref. 3). This protrusion can be either a particulate contaminant, or a geometrical defect of the surface. Many electrostatic models have been published, calculating the field enhancement at the apex of variously shaped protrusions. The general outcome of these studies was that very high and sharp protrusions are needed to explain the field enhancement factors of the order of 100 required to fit experimental observations. These elusive "filaments" failed to be observed under microscopic examination, and the geometrical explanation was (too ?) soon discarded, partly for this reason. We would like to revisit this geometrical interpretation, by pointing out that field enhancements might be obtained with geometries differing from the "filamentary" ones considered so far. Evidence from many recent experiments suggests that emission might take place at the atomic scale, on aggregates of a few atoms (ref. 10). This corresponds to very sharp apex curvature radii (admitting that the concept of curvature radius keeps some meaning on this length scale), much sharper than the ones considered in the past. This can give rise to large β values, even for moderate protrusion heights. As an example, consider two superposed protrusions (fig. 13): the large one has a sharpness sufficient to produce a field enhancement factor β_1. Close to its tip, the projection surface will appear locally flat, with a uniform local field E_1 that is β_1 times greater than the field E_0 applied globally. The second, much smaller protrusion with field enhancement factor β_2 placed on its surface will itself experience a tip field E_2 enhanced over E_1 by a factor of β_2, or an overal enhancement $\beta \approx \beta_1\beta_2$.

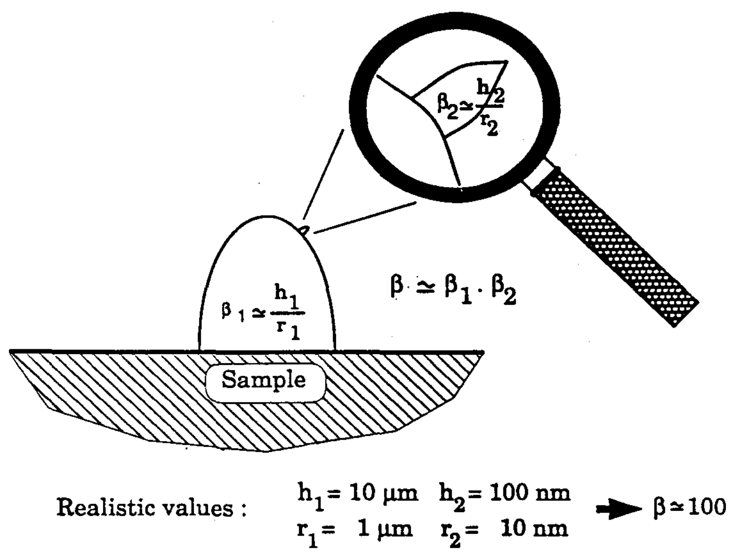

Figure 13 Superposed protrusions.

For the two considered projections, the enhancement factor $\beta_{1,2}$ equals roughly the ratio of the height of the projection to its apex curvature radius. It appears entirely plausible that a projection-on-a-projection model can account for both the observed geometry and the measured β. A beta value of the order of 100 can readily be achieved with two superposed protrusions of realistic dimensions, for example with respective heights $h_1 = 10\ \mu$m, $h_2 = 100$ nm, and curvature radii $r_1 = 1\ \mu$m, $r_2 = 10$ nm. Such protrusions are within the range of observation of a good scanning electron microscope, and have indeed been observed by us on some geometrical defects produced by the above mentioned method. A typical example is shown in fig. 14.

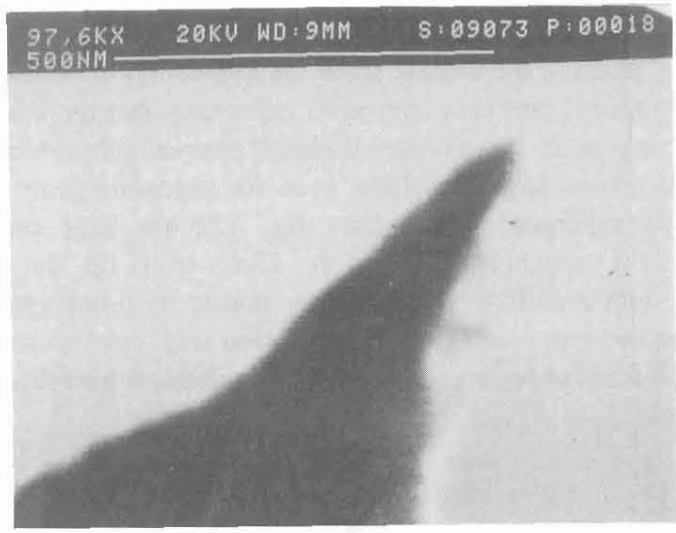

Figure 14 Same emitter as in fig. 12, seen here with a larger magnification. The apex radius is of the order of tens of nm.

All the above arguments in favor of the geometrical model must of course be taken with a large "grain of salt". We cannot ignore that field emission from protrusions is affected by adsorption or oxidation (refs. 11,12), and that these effects are not described by the simple geometrical model.

Conclusion

By a series of dedicated experiments, we have found strong evidence in favor of the projection model as the main explanation for the emission of at least two kinds of sites: conducting particulate contaminants and regions of mechanical damage. It remains to be seen to what extent the sites studied here are similar to the ones actually met in practical applications. We do feel, however, that this study has some degree of generality, because all the "natural" emitters we met so far entered into one of these two categories: conducting particles or geometrical defects. In particular, we never met evidence for more complicated emitters, like MIM structures (ref. 13).

Till now, the effort from Saclay was directed mainly towards the *understanding* of the mechanisms of enhanced field emission. Despite some progress in this direction, we propose no miracle remedy to cure emission. The enemy, however, has been clearly identified: we confirm that dust contamination must be avoided to minimize field emission. Geometrical defects are less of a problem: their occurrence can probably be reduced by means of appropriate chemical treatments, and by elementary precautions to avoid mechanical contacts with the surface after the treatment. Further investigations at Saclay will be directed more specifically towards the research of surface treatments reducing the activity of existing emitters. Such treatments, like firing (refs. 14,15), or high peak power processing (ref. 16) already exist. We feel, however, that an indispensable prerequisite to eradicate field emission is an improved surface cleanliness.

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