THE ROLE OF GEOMETRIC FIELD ENHANCEMENT FOR THE ENHANCED FIELD EMISSION OF NIOBIUM

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Abstract

We have systematically investigated the 'natural' emission sites of two cm² sized samples, which were wet chemical prepared and heated in UHV at 400°C. The changes of the emission parameters due to a deposition of a 16 nm gold layer on one sample were evaluated with respect to the current models for the enhanced field emission process. Comparison of the Fowler-Nordheim parameters β_{FN} and S_{FN} of the emitters with their geometrical field enhancement factors β_{geo}, which were estimated from high resolution scanning electron microscope analysis, revealed that the observed emitting structures are sharp enough to explain the measured β_{FN}, while the values of S_{FN} do not agree with the geometry.

1. INTRODUCTION

The performance of superconducting Nb accelerating cavities is affected by thermal breakdown and enhanced field emission (EFE), which are caused by bulk and surface imperfections. Besides its local occurrence, the physical mechanisms leading to EFE are still unknown. DC field emission (FE) scanning microscopy of cm² sized samples with high spatial resolution [1] combined with *in situ* scanning microscopy (SEM) and auger electron spectroscopy (AES) is well suited for the identification and analysis of single emitters. As a result of such studies [2 ,3], much progress has been achieved in the surface preparation technique of Nb cavities [4]. Since scratches or particulate contamination have mostly been found at the FE sites, it was suggested that geometric field enhancement plays a major role for EFE [5]. Moreover, heating [2,3] and gas exposure [6] have changed the strength of FE sites significantly. Therefore, detailed studies on the role of the geometry and adsorbates for the EFE of typical emitters on Nb samples will be presented in this paper.

2. EXPERIMENTAL

Two non-heat-treated Nb samples (PK1, PK4, ∅ = 15 mm), which were involved in prior FE experiments [2,7], were recovered by a buffered chemical polishing (BCP 1:1:1) of 10 µm. The samples were rinsed in a container and by a water jet with deionized, filtered water, and dried in unfiltered air. Additional emitters were activated by UHV-heat treatment at 400°C for 15 (PK4) or 30 minutes (PK1), respectively. After the first FE analysis a gold layer of about 16 nm thickness was deposited on one sample (PK4) by means of a special evaporation apparatus. As can be seen in the SEM picture (fig. 1), small particles and even submicron sized substructures of the particles were uniformly covered with gold. It is remarkable that regions with formerly varying secondary electron emission showed uniform brightness after the gold deposition. No charging was observed in the SEM after the deposition, i.e. the gold layer was not insulated from the cathode. Besides Nb a lot of foreign elements (Si, Mg, Fe, Al, Ti, Ca, W, Cr, K, Ni, Mo, Mn) were detected in the particles by energy dispersive x-ray (EDX) analysis ($Z \geq 11$), which was performed *ex situ* in combination with SEM, but at about 50% of the FE sites only Nb was detected.

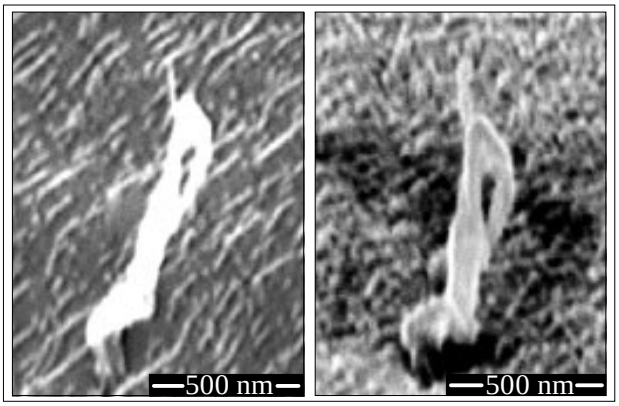

Fig. 1: SEM micrograph of an emitting particle on a Nb surface before (left) and after gold deposition (right).

Various kinds of FE measurements were performed on the samples by means of a field emission scanning microscope, which is incorporated in a commercial UHV analysis chamber [1]. After recording the emitter distribution (FE maps), selected emission sites were analyzed. The onset field strength E_{on} was determined by measuring voltage U versus electrode distance z at constant current I = 0.5 nA, and Fowler-Nordheim (FN) analysis without image force correction and assuming a fixed work function Φ was performed by recording $I(U)$. The chamber contains a SEM and AES. The heat treatments of the samples were carried out by electron bombardment in a preparation chamber, from where the samples are transfered without breaking the vacuum.

3. RESULTS

Measurement of the FE behavior before and after the gold deposition led to the following results. With one exception the E_{on} of 25 investigated emitters increased, the average value of before 49 MV/m went up to 94 MV/m after the deposition. As can be seen in fig. 2, the FN parameter β_{FN} tended to smaller values by the

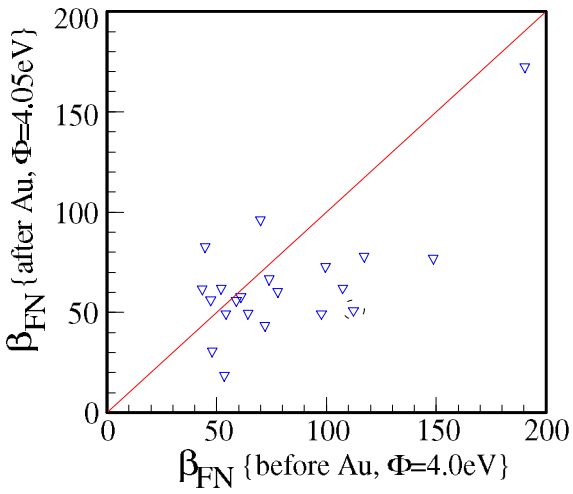

Fig. 2: Change of the FN parameter β_{FN} by the gold deposition.

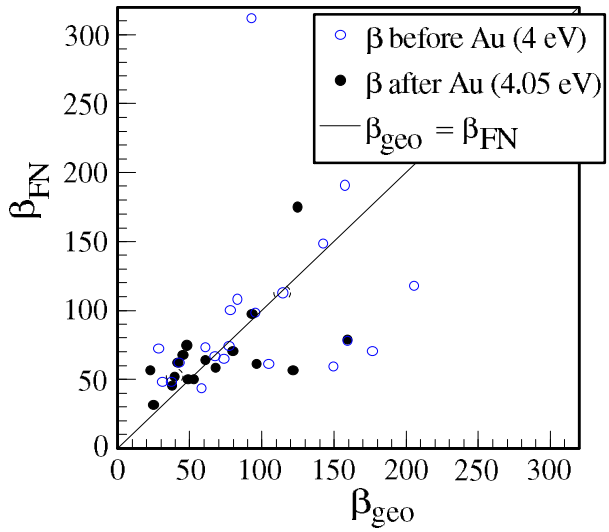

Fig. 3: Dependence of the FN parameter β_{FN} on the geometrical field enhancement of the emitting structures.

gold deposition. For the determination of β_{FN} and S_{FN} a Φ of 4.0 eV or 4.05 eV was assumed for emitter analysis on the 'pure' Nb or on the gold covered sample, respectively. For an optimum fit of measured field enhancement factors to the protrusion model, the Φ of gold was chosen slightly different from the literature values ($\Phi \geq 4.3$ eV). As a further result, 68% of the FN parameter S_{FN} decreased by the gold deposition.

The geometrical field enhancement factor β_{FN} was estimated considering the substructure of the emitting particles. According to [5] the additional field enhancement β_2 of a substructure (radius r_2, height h_2) inside the enhanced field (β_1) of the particle (r_1, h_1) leads to a resulting field enhancement factor $\beta_{geo} < \beta_1 \cdot \beta_2$. Taking data of [5] and of own numerical field calculations leads to

$$\beta_{geo} = \beta_2 \cdot \left(2 + (\beta_1 - 2) \cdot \exp\left(-\left(\frac{\beta_1 \cdot h_2}{h_1}\right)^{(1.2367 - 0.0285\beta_1)}\right)\right).$$

The factors β_1 and β_2 were estimated according to [8]. As shown in fig. 3, the resulting β_{geo} values before as well as after the gold deposition are of the same order of magnitude and in most cases almost of the same size as the measured FN parameters β_{FN}.

The region, where the enhanced field stays within its maximum or a few percent less, is the emitting area S_{geo}, which should be about $r_2^2 \cdot \pi$. In contrast to the field enhancement factors, the majority of the S_{FN} show unrealistic high values and a wide spread on the pure Nb sample, but the gold deposition lets the S_{FN} tend to more realistic values (fig. 4). Sample PK1 compared with the uncovered PK4 shows similar results in FN- and geometrical parameters.

Taking β_{geo} and S_{geo} of the emitters of PK4 and assuming Φ = 4.0 or 4.05 eV the 'geometrical onset field strength' $E_{on,geo}$ can be obtained from the FN formula. The comparison with the measured E_{on} is shown in fig. 5. Surprisingly, there is a rather good agreement between the geometrically deduced and the measured E_{on} for most FE sites. For sample PK1 there's a higher percentage of exceptions from this correlation.

It has to be mentioned that because of their complex shape it was often equivocal to determine the emitting substructure of the particles. At particles like the one in fig. 1, where the sharpest geometry is evident, we observed in general the best agreement between geometrical estimation of the FE parameters and measurement as indicated by the dotted circles in figs. 2-5.

4. DISCUSSION AND CONCLUSIONS

The current models for the explanation of the EFE are geometrical field enhancement, metal-insulator-vacuum- (MIV) model, and metal-insulator-metal- (MIM) model. Compared to a flat surface, sharp metallic structures cause local geometrical field enhancement

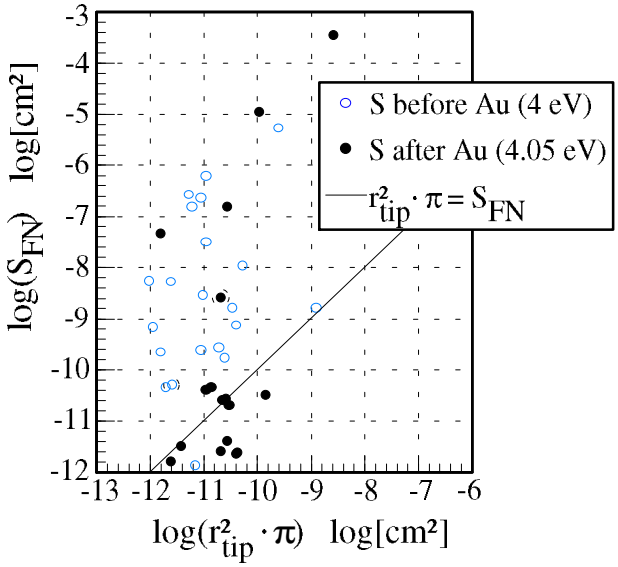

Fig. 4: Plot of the FN parameter S_{FN} versus tip surface of the emitting structures.

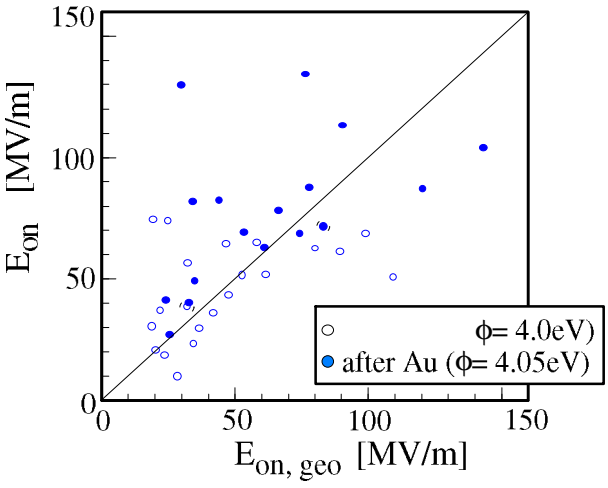

Fig. 5: Correlation between measured E_{on} and $E_{on,geo}$, which was calculated by means of the FN-formula for estimated β_{geo} and S_{geo} of the emitting structures.

(protrusion model). According to certain electronic properties in an insulating layer on the cathode an applied electric field leads locally to the formation of conduction channels with band bending and to a 'hot electron emission' (MIV) [9]. MIM structures cause field enhancement by the 'antenna effect', whereby the electrons are emitted because of the enhanced field or additionally by the hot electron emission.

What would in the framework of these models change in the FE behavior by the gold deposition? The radii of curvature increase in the order of the film thickness. In the protrusion model this leads to a slight decrease of β and increase of *S*. A moderate increase of E_{on} is the consequence. In the presence of a gold covered insulating layer - the gold layer is in electrical contact with the cathode - no emission should occur in the MIV model. If the insulator is on top of a field enhancing particle and the MIV-mechanism is the main emission mechanism, the emission after the gold deposition should be much weaker (strong decrease of β and increase of E_{on}). In a mainly by the antenna effect induced EFE of a MIM structure one would also expect a strong decrease of β and increase of E_{on}. The change of *S* in the two latter cases is unclear. Comparison of these considerations with the experimental data rules out a pure MIV model. Because of the moderate increase of E_{on} and the slight decrease of the majority of β_{FN} values the MIM model or MIV combined with geometrical field enhancement seems less probable than the protrusion model.

We observed a good agreement between the measured E_{on} and $E_{on,geo}$, which was calculated from the geometrically estimated parameters by means of the FN equation. The β_{FN} of the single emitters is of about the same size as their β_{geo}. Therefore the emitting particles after wet chemical preparation and heating of Nb samples are capable to produce the observed emission by geometrical field enhancement. However, as in previous studies [3], most of the measured S_{FN} are unrealistic high and the values are wide spreaded. Even using image force correction or assuming locally changed work function can not explain these values. So the protrusion model is not the whole story. Adsorbates, oxides, and other chemical compositions on the metal surface, which are in general present even after annealing in UHV, play probably a crucial role in this context. Several experimental and theoretical studies have considered the change of the work function [6,10 ,11], additional levels inside the potential barrier [12 ,13] or the change of the barrier shape [14 ,15] due to adsorbates. An influence of adsorbates on the parameter *S* is reported in [6,11,16 ,17].

In order to get more knowledge about the influence of adsorbates, oxides, and to study the role of the substructure of the particles and the contact between particles and cathode, an ion gun is installed at present.

5. ACKNOWLEDGMENTS

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6. REFERENCES

[1] E.Mahner et al., Appl. Surf. Sci. 67, 23 (1993).
[2] N.Pupeter et al., Proc. of the 4th Eur. Particle Acc. Conf. 3, ed. by V.Suller and Ch. Petit-Jean-Genaz, London, 2066 (1994).
[3] N.Pupeter et al., Proc. of the 7th Workshop on RF Superconductivity, Saclay, in press (1995).
[4] Proc. of the 7th Workshop on RF Superconductivity, Saclay, in press (1995).
[5] M.Jimenez et al., J. Phys. D: Appl. Phys. 27, 1038 (1994).
[6] G.Ehrlich, F.G.Hudda, J. Chem. Phys. 35, 1421 (1961).
[7] E.Mahner et al., Proc. of the 6th Workshop on RF Superconductivity, ed. by R.M.Sundelin, CEBAF, Newport News, 1085 (1993).
[8] T.Utsumi, IEEE Transactions on Electron Devices 38, 2276 (1991).
[9] K.H.Bayliss, R.V.Latham, Proc. Roy. Soc. London A 403, 285 (1986).
[10] L.Schmidt, R.Gomer, J. Chem. Phys. 42, 3573 (1965).
[11] L.Schmidt, R.Gomer, J. Chem. Phys. 45, 1605 (1966).
[12] C.B.Duke, M.E.Alferieff, J. Chem. Phys. 46, 923 (1967).
[13] E.W.Plummer, R.D.Young, Phys. Rev. B 1, 2088 (1970).
[14] G.Ehrlich et al., J. Chem. Phys. 28, 506 (1958).
[15] J.W.Gadzuk, E.W.Plummer, Rev. Modern Phys. 45, 487 (1973).
[16] H.E.Clark, R.D.Young, Surf. Sci. 12, 385 (1968).
[17] N.K.Allen et al., J. Phys. D: Appl. Phys. 12, 969 (1979).