THERMAL CONTACT RESISTANCE OF A PARTICLE ON A SUBSTRATE

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Abstract :

It has been formerly established that field emission in RF cavities is mainly due to contamination by small micron size particles lying on the surface. When applying the RF field, these particles can melt and stick to the surface making it harder to get rid of them. In order to understand the thermal process involved, a crucial physical quantity is needed : the thermal contact resistance between the particle and the substrate. In the present paper, an experimental method is described to measure this quantity, with the use of a scanning electron microscope. By defocusing the beam of the SEM, one can get enough power deposited in one particle to melt it. The power level at which the particle melts gives the thermal contact resistance. Therefore, using the measured value, thermal calculations yield some hints for understanding the violent thermal processes observed in RF fields.

Introduction

Particles are the main source of field emission in RF cavities [1,2,3]. When applying the field, these can either be thrown away from the surface [4] or melt and stick to the substrate [5]. The thermal analysis of a particle lying on a substrate suffers from the lack of knowledge of its thermal contact resistance R_c with the substrate. R_c is expected to be much higher than the thermal resistance of the particle itself (which amounts to about a few 10^3K/W). In that case, the whole particle can be assumed to be at a fairly uniform temperature T as compared to the substrate temperature T_0.

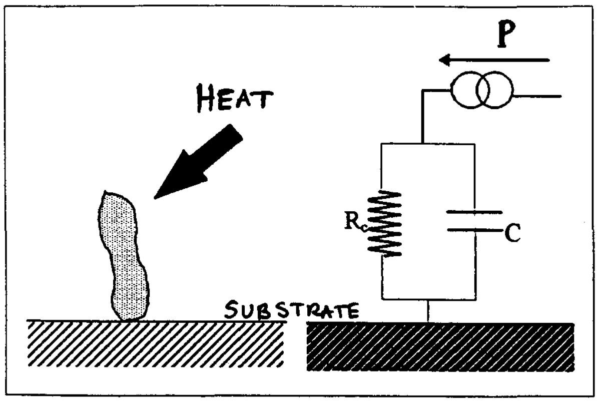


Figure 1– The equivalent thermal circuit of a particle on a substrate. The thermal resistance of the particle has been neglected.

Therefore, if the heat power deposited in the particle is P, the equilibrium temperatute T_{eq} will be only determined by the unknown quantity R_c by

$$(T - T_0) = R_c\, P$$

The knowledge of R_c is crucial for determining at which power level melting can occur, and, more generally, to put realistic numbers on thermal model calculations describing the thermal behaviour of a particle under high RF field. In particular, this might induce some hints for the physical origin of violent thermal effects observed after application of RF power in cavities.

Another information directly deduced from R_c is the time constant τ of the system. If (CV) is the total heat capacity of the particle (in J/K), equilibrium will be reached with the time constant

$$\tau = R_c\ (CV)$$

This, of course, is of major importance in pulsed field conditions where the pulse length has to be compared to τ. Notice that the higher the contact resistance, the longer the time to reach equilibrium. There, large differences in the thermal behaviour of particles are to be expected between the continuous regime and the pulsed mode.

Principle of experiment

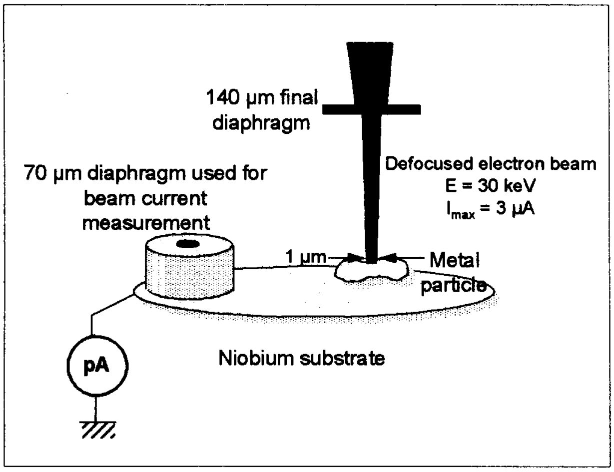


Figure 2– Each particle is heated by a defocused SEM beam. A Faraday cup is used for current calibration.

The aim is to measure the thermal resistance R_c on different particles. The idea is to use the beam of a scanning electron microscope (SEM) to deposit a controlled amount of power into one particle. Raising the power P until the particle melts will give the experimental value of R_c :

$$R_c = \left(\frac{T_f - T_0}{P}\right)$$

where T_f is the melting temperature of the particle and T_0 the (ambient) temperature of the substrate.

The minimum measurable value of R_c is given by the maximum power available from the beam. In a SEM, there is a relationship between the beam size d and the beam current I connected through the brillance β of the gun

$$I = \frac{\pi^2 \alpha^2 d^2 \beta}{4}$$

where α is the opening angle of the beam.

d (nm)	5	30	200	900	2000
I (A)	10^{-12}	10^{-10}	10^{-8}	10^{-6}	10^{-5}
P_b (W)	3.10^{-8}	3.10^{-6}	3.10^{-4}	3.10^{-2}	0.3

Thus, a high resolution requires a highly focused beam (low d) and consequently a low current I. A standard use will stay at I=1nA giving a beam diameter d=60 nm. Of course, the deposited power will also depend linearly on the beam energy. The highest possible electron energy was chosen (E=30 keV) in order to maximize the available power. It was possible to do so because the electron mean range at that energy is a few microns (depending on the particle material) but anyhow still smaller than the particle sizes chosen. As high powers are needed, the beam has been defocused while keeping it well inside the particle (d=1μm). The previous table shows that the maximum available power beam will then be around 120mW. The real beam current has been experimentally measured using a Faraday cup with a 70μm diameter hole (see fig. 2)

It should be noted that the real deposited power P in the particle is lower than the incoming beam power P_b even though the beam is not spreading out of the particle and with the assumption that all electrons are stopped in the particle. First, one has to correct for the reflected primary electrons (approximately 20% depending on the Z value of the material) and secondary electrons (but these carry very low energies). Secondly, radiation losses (when the particle heats up) may contribute to lower the amount of real heat flowing through the basis to the substrate.

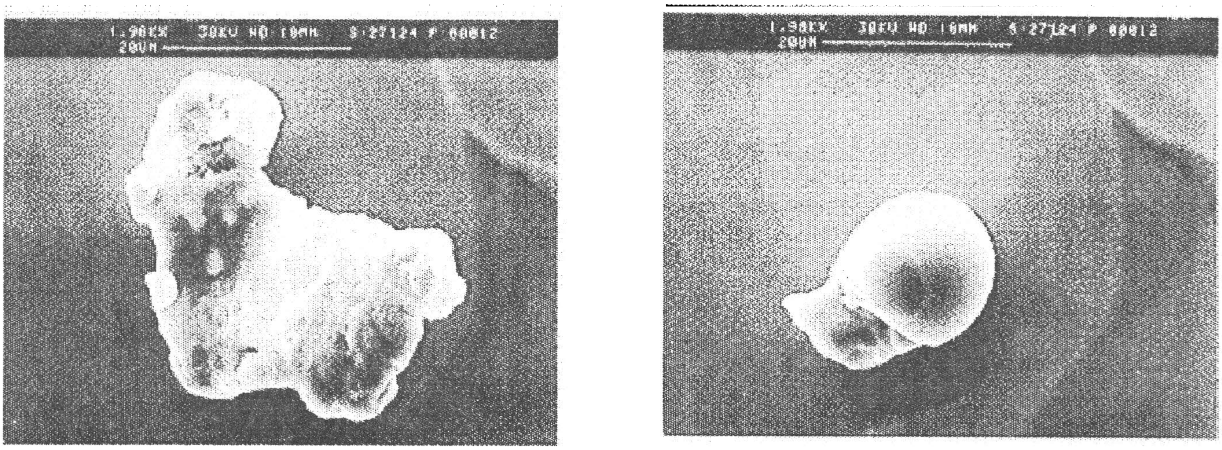
Taking into account all the above mentioned items, the lowest value for the thermal contact resistance one can measure with this method will be for example for an iron particle (T_f=1810K)

$$R_{c\,min} \geq 2.\,10^4 \quad K/W$$

Experimental results

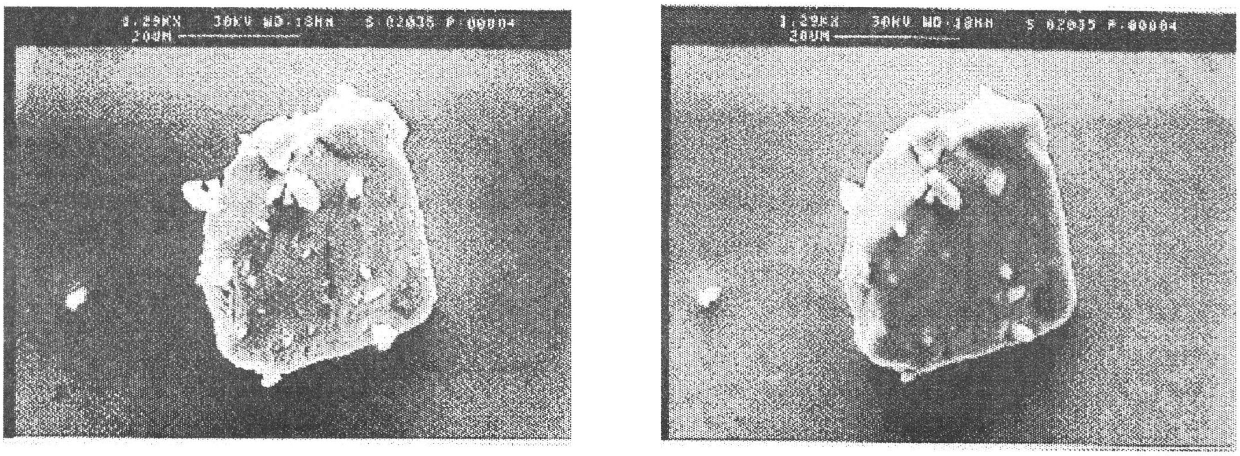
a– On metallic particles

Iron particles (T_f=1810K) and niobium particles (T_f=2688K) with different sizes (20μm to 50μm) have been sprinkled on a niobium substrate. Each particle is individually observed in the SEM. Then, the beam is defocused on it, and the corresponding power is gradually raised until the particle is seen to be modified. At that point, going back to a low power beam, a picture of the particle is taken. Melting the particle under the SEM beam can sometimes induce big changes, the shape beeing completely modified. Other times, it results in a surface smoothing, the overall shape remaining approximately identical. In any case, after melting, no modification is anymore observed up to the highest beam power available (120mW). This might suggest that the particle contact with the substrate changed while melting. A better contact would result in a lower contact resistance R_c by at least an order of magnitude.



Fe particle : before firing.

Fe particle : after firing at 14.9 mW.



Nb particle : before firing.

Nb particle : after firing at 18.9 mW.

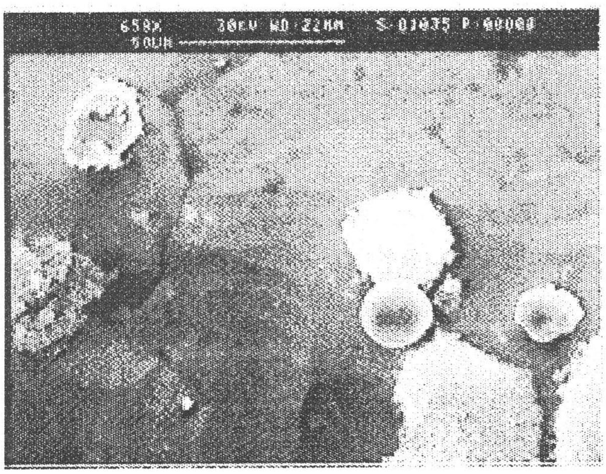
Figure 3– Examples of two particles melted under the SEM beam. Note the dramatic change in the first case (that particle was thin) whereas the second one only shows an overall surface smoothing.

Average thermal resistance values deduced from tens of metallic particles are summarized in the following table. A relatively low discrepancy is found from one particle to another. No important differences are observed neither from different sizes of particles (in the studied range) nor from their nature (iron and niobium particles have roughly the same R_c although the melting points are far different).

Nature	iron	niobium
Size [μm]	20-50	20-50
Beam power (at melting point) [mW]	20	25
Deposited power [mW]	15	19
R_c [K/W]	10^5	$1.3\ 10^5$

b– On insulating particles

The same procedure has been applied to alumina particles (T_f=2310K) on a niobium substrate. They melt for surprinsingly low beam currents indicating that they had a very bad contact with the substrate. From the measurements, thermal contact resistance above 10^7K/W were found (a power of some tenths of mW was enough to melt them) — with a high uncertainty due to the low power levels (corrections begin to be about the same level). It is thus expected that these insulating particles will immediately heat up in a radiofrequency field (the bigger the particle, the stronger the heat). This might explain why alumina particles have a peculiar behaviour in RF cavities [6].



Two alumina particles have beeen fired at 0.25 mW.

Figure 4– Alumina particles on a niobium substrate. The two molten particles are easily recognizable.

Discussion

Two important conclusions can be derived from the above measured values of R_c. First, the power needed to reach melting on a 20μm size metallic particles is of the order of P=10mW. This is at least an order of magnitude above what can be estimated from the heat deposited due to the RF losses (P_{RF}<1mW @ E=60MV/m in the specific case of the RF warm cavity designed for field emission studies at Saclay [7]). It is also orders of magnitude above other sources of heating (Joule effect due to the field emitted current, Nottingham effect etc... which are completely negligible). The only physical phenomenon that could lead to that amount of heat would be the ion bombardment provided that the local pressure above the particle exceed some 10^{-2}mbar (the global pressure in the cavity is less than 10^{-7}mbar). This hypothesis of a "microplasma" forming above an emitting site is plausible. It can be shown that atoms ionized by the emitted electrons close to the particle may be accelerated in the RF field, strike the particle with enough energy (10 eV to 300 eV) to heat it up. This unstable self growing process may lead to the melting of the particle and is worth to be analysed further or demonstrated experimentally.

The second conclusion coming up from the value of R_c is the time constant. If one considers a 20μm size iron particle, (CV)=10^{-8}J/K so

$$\tau = 2 \ ms$$

as compared to its own time (i.e. assuming a perfect contact) which is around $\tau_0 = 30 \ \mu s$. Therefore, RF pulses shorter than 2ms should not allow thermal effects on particles (except perhaps at very high fields) whereas surfaces submitted to RF pulses longer than 2ms should exhibit strong thermal effects. And this is, indeed, in agreement with what is experimentally observed [2,4,8].

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