Mechanical suppression of tunneling between metallic beads

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Introduction

The electrical instability in a metallic powder evidenced by Branly's works [1] at the end of the 19th century is still an active research field that involves electrical and mechanical effects of granular matter and illustrates the extreme complexity of conductive grains assemblies due to the interplay between different phenomena acting at different scales.

In the present study, we focus on the electrical behavior of linear assemblies of steel beads under compression. The oxide film at the surface of the beads generates an insulating barrier resulting in electron tunneling between neighboring beads[2]. The quantum tunneling alone generates a high resistance in the upwards characteristic, which is opposed to a fundamental phenomenon taking place at the mesoscopic level, the microcontacts nucleation acting as short-cuts. These microcontacts flatten the characteristic at high current and induce a transition to a conductive state. Retaining only the mechanical and electrical contact between adjacent balls, we explore numerically and theoretically the consequences of compressive forces on the electrical behavior and evidence a progressive suppression of the tunnel coupling between adjacent beads.

1 Experimental study of a linear chain of metallic beads

In accordance with the mechanical conditions imposed to the beads assembly, we describe the theoretical and numerical system as an homologous of the experimental one: a one dimension stainless steel beads assembly (the system may be eventually reduced to a couple of beads) under compression from forces acting along the chain axis. We can notice that even if the system seems to be easy to tackle, especially for spherical beads, it is impossible to bypass the natural disorder, inducing a certain complexity, due to random variations of the surface state. Indeed, this kind of disorder inevitably influences the electrical properties of the beads since the electron transfer between two adjacent beads is actually sensitive to the surface state. Nevertheless, this disorder also presents an obvious advantage : shaking the assembly of beads prior to any measurement, we explore a large number of surface state configurations, ensuring thus the reproducibility of our measurements (cf figure 1) with respect to the surface states.

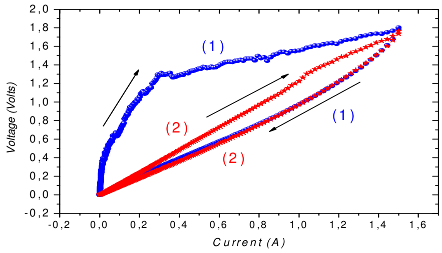

Figure 1: 2 beads typical V-I characteristics

On figure 1 is shown the current-voltage characteristic of a chain of metallic beads submitted to a static compression force (here F=41 N). This typical shape of the I-V curves known as the Branly effect, is characterized by a transition between an insulating state to a conducting state first observed at the end of the nineteenth century. If we analyze the figure 1 and restrict ourselves to the first hysteretic loop, we notice that at low currents, the I-V characteristic is ohmic with a very high resistance R_L. When increasing the current, non linear effects appear leading to a flattening of the upwards characteristic which in some cases seems to reach a saturation value V_{sat} at high current. When decreasing the applied current from this 'saturated' voltage state, the backwards characteristic is approximately linear with a strongly reduced resistance.

2 Theoretical and numerical modeling of the electrical contact

It is usually believed that the non linearity of the I-V characteristic and especially the hysteresis loop arises from thermal effects leading to a local melting of the beads material at the level of the mechanical contact area [3]. A theoretical account for such features requires the addition of more elaborated ingredients, such as electron tunneling, as suggested by de Gennes [4]. Indeed, the natural barrier erected by the insulating oxide layer (cf figure 2) leads to a likely electron tunneling process. We built up a theoretical model of the electrical transport at the level of the contact between adjacent beads, based on the competition between both processes that is, the electron tunneling through the oxide layer dominating at low currents and the micro-contacts' nucleation through local melting responsible for the decrease of the resistance (trend to saturation of the upper branch) at higher currents. The hysteretic behaviour follows from the microbridges welding process which is irreversible.

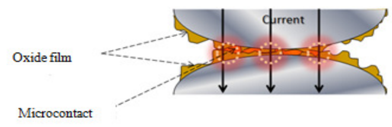

Figure 2: Insulating oxide layer crossed by electrons

In our model, each individual contact is treated as a simple RC circuit with a capacitive element accounting for the dielectric properties of the insulating oxide layer. Accounting for all the processes involved in the electrical transport at the contact between adjacent beads, we get the evolution equation of the voltage (1):

$$C\frac{dV}{dt}+G_L\frac{K_BT}{e}e^{\alpha V}\left(e^{\beta eV}-1\right)+S\left(VI\right)=I\left(t\right) \qquad (1)$$

The first term in the left-hand side (capacitive element) accounts for the dielectric properties of the oxide layer, the second one represents electron tunneling through the insulating barrier and the last one, the micro-contacts' nucleation term. This is a phenomenological term which is very difficult to compute from first principles due to the complexity of the thermal, mechanical and electrical processes holding in the contact area. For practical reasons, we handle only the nondimensional form of the equation 1,

$$\frac{du}{d\theta}+e^{\xi u}\left(e^{u}-1\right)+\overline{S}=i \qquad (2)$$

This amounts to express the variables of our system in natural units built from the model's parameters. Accordingly, the parameter ξ depends on the temperature, the surface barrier height and its thickness, θ is redefined time variable and u the rescaled voltage. By solving equation (2) with a homemade numerical code developed in the Matlab software, we can model the I-V characteristics and reproduce their typical shape shown on figure 3. We can notice that the model predicts both the non linear nature of the characteristic as well as the hysteretic loop. These predictions can be compared to the experimental data in order to yield the values of the model parameters.

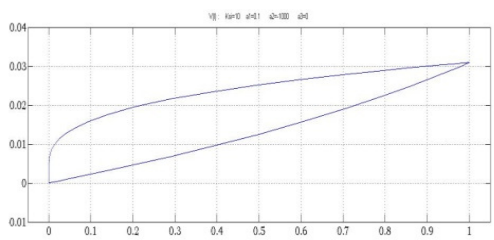

Figure 3: Numerical modeling of the V-I characteristic

3 Effect of the applied force on the electrical resistance

To account for the effect of a compression force, we incorporate the mechanical properties of the beads into the model with a perfect contact (vanishing resistance of the contact). Usual models of the effect of an applied force on the beads resistance [5] show a large mismatch with experimental data mainly due to inappropriate calculation of the beads' electrical resistance. Our approach consists partly in incorporating the Hertz theory of deformation and deriving from Ohm's law the resistance of spherical beads (in fact for any shape in our theory) between two electrodes with known relative positions (angle θ) and areas (S). We are led to a resistance (3) obeying the law :

$$G_b=\frac{\gamma S^2}{2V_b}\left(1-\cos\theta\right) \qquad (3)$$

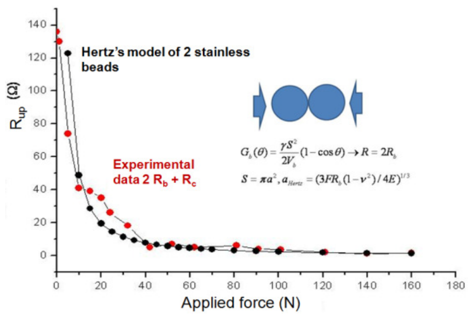

Figure 4:Effect of the applied force on the beads resistance

As we can notice on figure 4 the computed values of the resistance model (black) are in good agreement with the experimental data (red). This agreement is more important beyond 50 N. Just below, the discrepancy is due to the tunneling process in the contact zone. Considering the difference between both curves allows to extract the tunneling contribution which decreases upon increasing the force until it vanishes at about 50 N.

References

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