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Theory of metal/metal multi-contact interfaces: implications of the coupling between the electrical and thermal transfer processes

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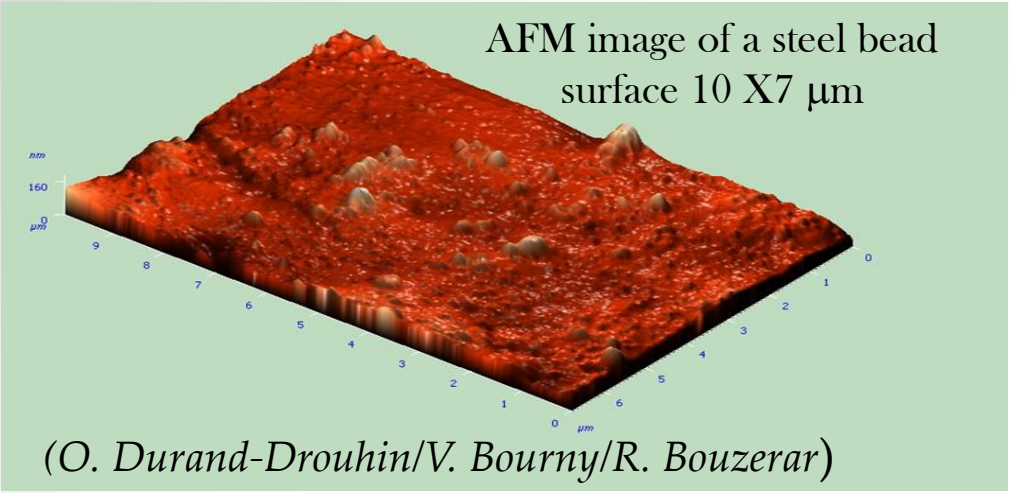
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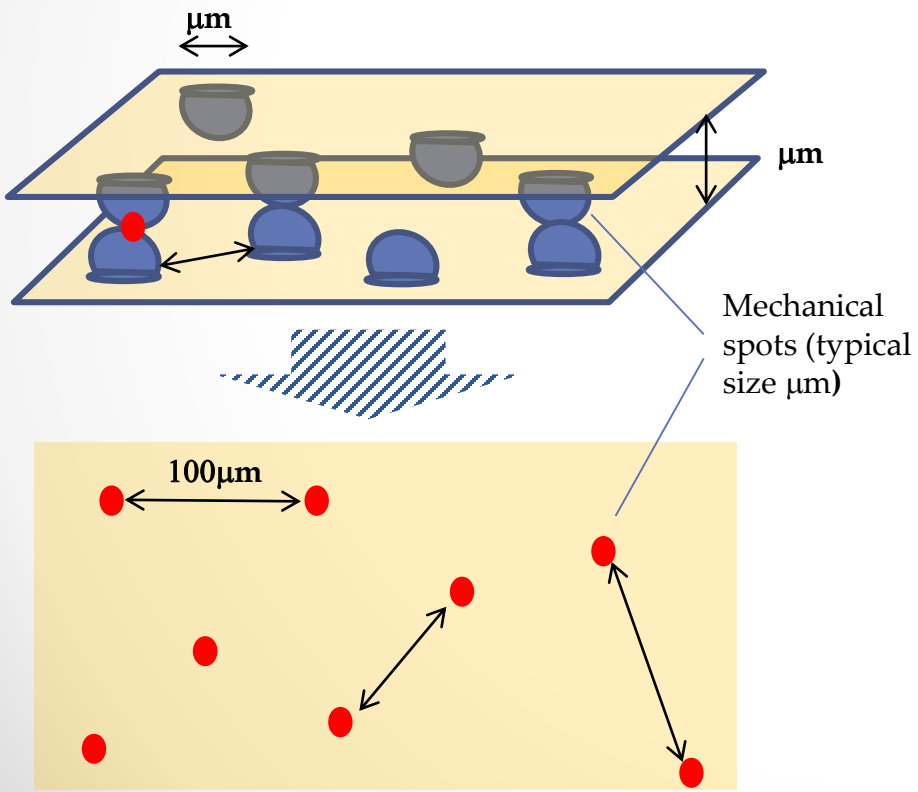
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Outline

- **What is an MCI? (Multi-Contact Interface)**
  - > Academic situations (experimental issues) and industrial applications
  - > Complexity of MCIs
- **Theory of static metallic MCIs**
  - > Approximations
  - > One spot model: solutions of the electro-thermal problem and consequences (critical current…)
  - > Two spots model: Matrix formalism
- **Conclusion: Extension to many spots interfaces**
  - > Experimental evidence for the critical current
  - > Constriction vs tunneling, Branly effect





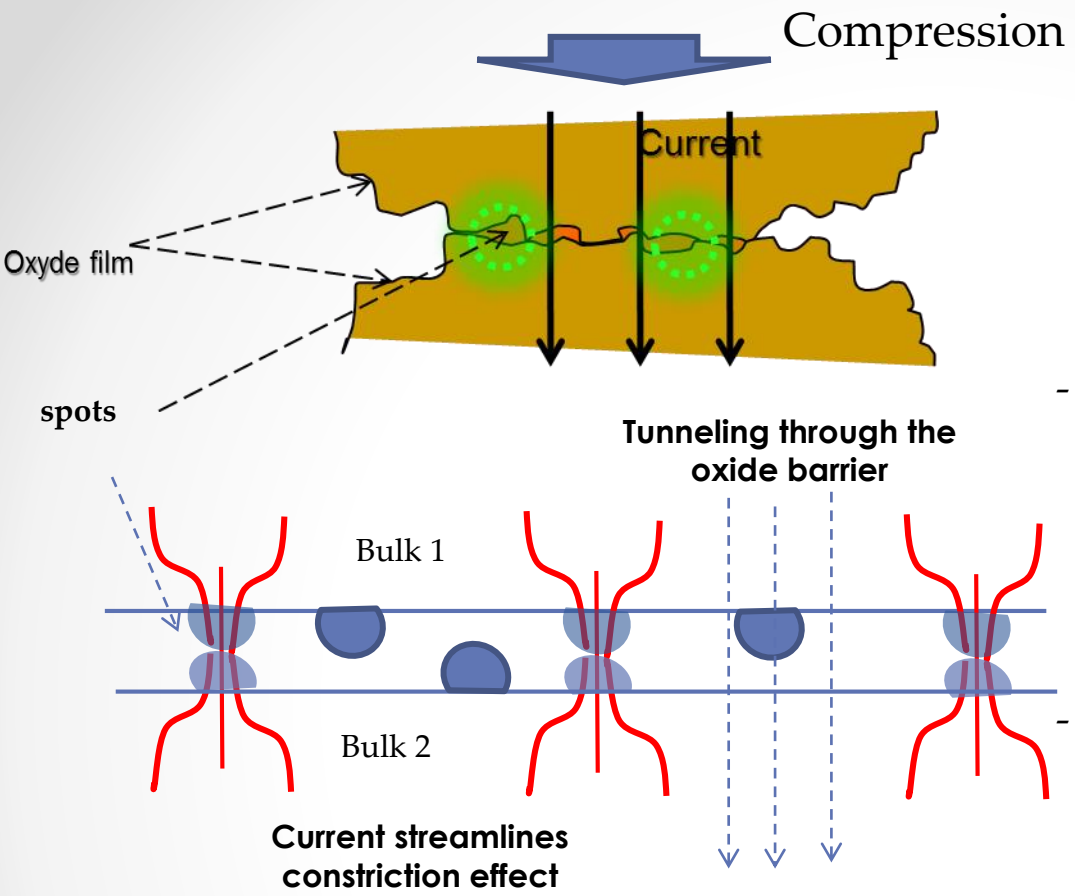
What is an MCI?

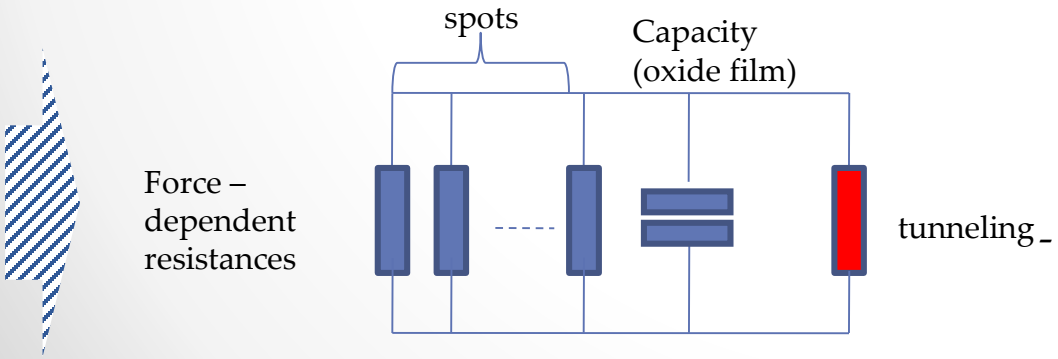
- Random surfaces (roughness) exhibit asperities with randomly distributed heights and diameters.

- The mechanical contact between 'hard' solids under moderate loads consist of an MCI **[1]**: A set of **contacting asperities** (spot size typically a few µm) with density controlled by the compression force (typically a few 100 µm apart). For higher loading conditions, molecular contact (nanometric scale) should be considered. Such discrete interfaces are involved in **many processes** and applications: tribological, electrical and /or thermal transfer, sliding contact,…

- Complexity arising from the strong coupling between different processes with different length/time scales.

Complexity of MCIs under mechanical sollicitations: electrical and thermal transport features



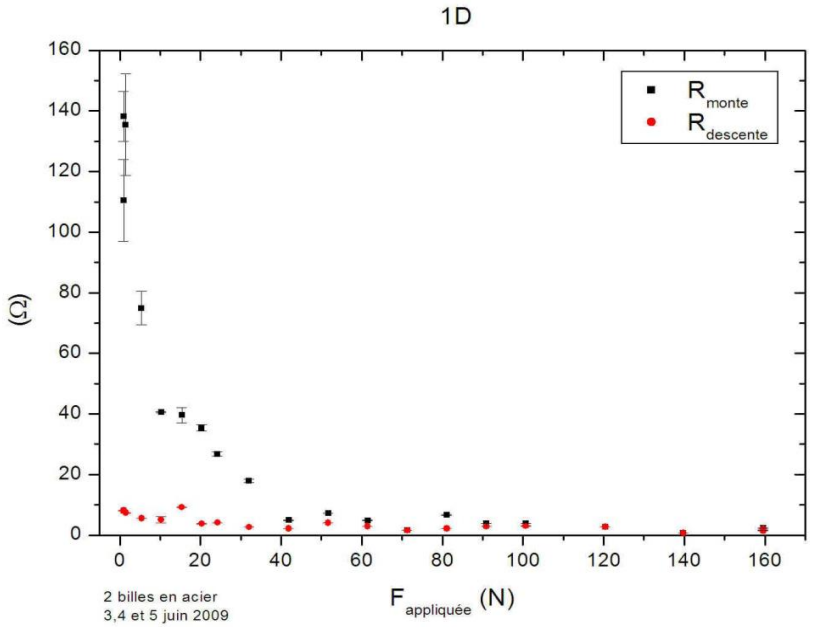


- Spot induced **constriction effect** of current/heat streamlines, resulting in electrical/thermal singular resistances **located at the contact zones** (Holm's constriction resistance **[2]**).
- **Electro-thermal coupling** due to interdependent thermal and electrical transfer (Wiedemann-Franz law **[3]**): temperature dependent **constriction resistance** (Joule heating) and interface temperature controlled by the resistance.
- Competition with **electron tunneling** through the interface: reduction of the overall electrical/thermal resistances.

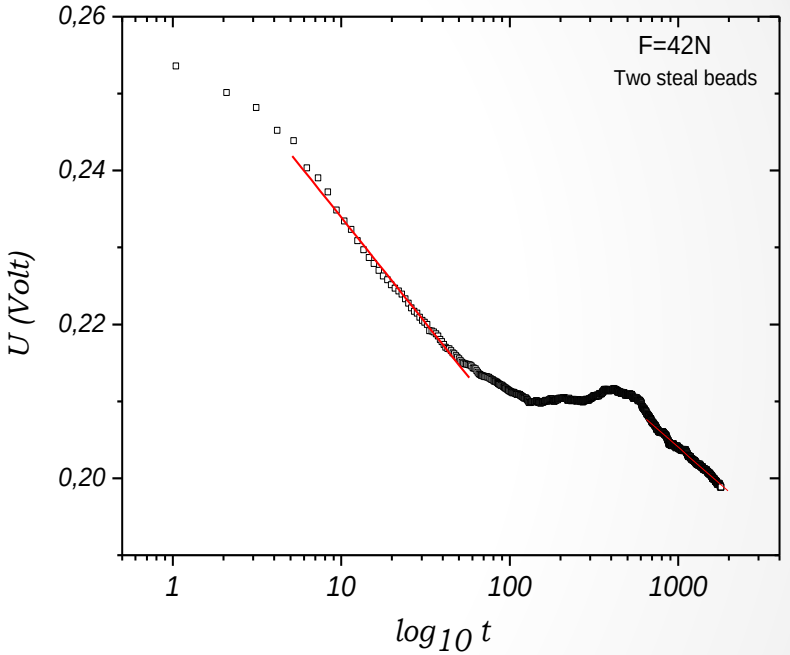
Approximations

Theory of static metallic MCIs

- **Neglecting shear stress** component within the interface: normal load conditions (no creep of the contact area **[4]**) – see opposite
- **Compression force** treated as a **control parameter**: mechanical conditions influence thermal/ electrical transfer with no feedback (separation of the mechanical degrees of freedom) – see figure below
- **Low spot density** (low compression force): independent spots condition and focus on constriction effect with a posteriori evaluation of the tunneling contribution

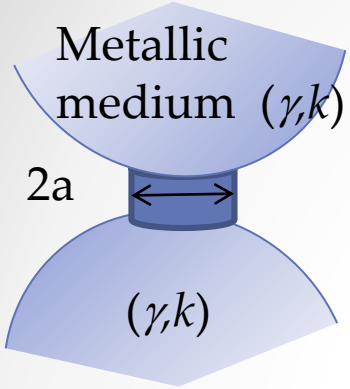


Voltage creep effect for a contact between two steel beads (V. Bourny/R. Bouzerar)

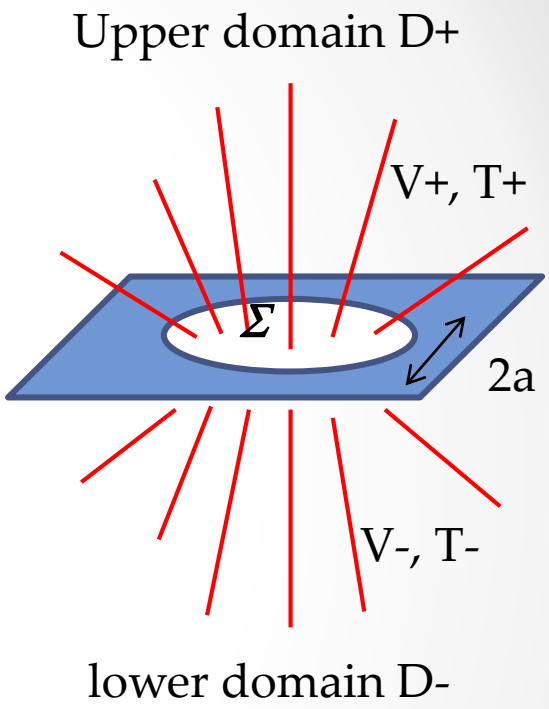


Dependence of the linear resistance upon the compression force at increasing/decreasing current (V. Bourny/R. Bouzerar)

Theory of static metallic MCIs



- Single spot idealized to a **disk** (Σ) with radius a, the upper and lower metallic pieces (electrical/thermal conductivity γ/k) corresponding to domains D+/D-



- The current flowing through (Σ) being set to I, the potential and temperature distributions in D+/D- are solutions to the equations (resistance of interface R_Σ)

$$\begin{cases} \operatorname{div}(\gamma\ \nabla V_\pm) = \pm I\theta_\Sigma(\vec{x}) \\ k\Delta T_\pm + \gamma\left|\nabla V_\pm\right|^2 = -R_\Sigma I^2\theta_\Sigma(\vec{x}) \end{cases}$$

where the distribution

$$\theta_\Sigma(\vec{x}) = \begin{cases} 0, \vec{x} \notin \Sigma \\ \neq 0, \vec{x} \in \Sigma \end{cases}, \forall D \supset \Sigma : \int_D \theta_\Sigma(\vec{x}) d^3\vec{x} = 1$$

Characteristic function of Σ surface

Theory of static metallic MCIs

Complete these equations with the **Wiedemann-Franz law**,

$$k/\gamma T = L \approx 2,45.10^{-8} V^2/K^2 \quad \text{(Lorentz const.)}$$

Introducing the vector field built up from the electrical and thermal field (electrothermal coupling), we get:

$$\vec{e} = \nabla V_{\pm}/T_{\pm} \rightarrow \begin{cases} \mathrm{div}\vec{e} = \pm \dfrac{LI}{k}\theta_{\Sigma}(\vec{x}) \\ L\dfrac{\Delta T}{T} + \vec{e}^{\,2} = -L\dfrac{R_{\Sigma} I^2}{k}\theta_{\Sigma}(\vec{x}) \end{cases}$$

In the **limit of small amplitudes** of the field $\vec{e}$ - smallness of L – and high enough temperature, these equations simplify to:

$$\begin{cases} \Delta V_{\pm} \approx \pm \dfrac{LI}{k} T_{\Sigma}\theta_{\Sigma}(\vec{x}) \\ \Delta T_{\pm} \approx -\dfrac{R_{\Sigma} I^2}{k} T_{\Sigma}\theta_{\Sigma}(\vec{x}) \end{cases} , \vec{x} \in D_{\pm}$$

Charge localized on the spot (ingoing and outgoing current seen as opposit charges)

$$Q_{\Sigma} = \mp \varepsilon_0 \frac{LI}{k} T_{\Sigma}$$

Power heat source located at the spot (temp. TΣ)

Theory of static metallic MCIs

Solutions to the simplified equations (T_a: ambient temp.)

$$V_{\pm}(\vec{x}) = \mp L \frac{I T_{\Sigma}}{4\pi k} \int_{D_{\pm}} \frac{\theta_{\Sigma}(\vec{x}')}{|\vec{x}-\vec{x}'|} d^3\vec{x}'$$

$$T_{\pm}(\vec{x}) = T_a + \frac{R_{\Sigma} I^2 T_{\Sigma}}{4\pi k} \int_{D_{\pm}} \frac{\theta_{\Sigma}(\vec{x}')}{|\vec{x}-\vec{x}'|} d^3\vec{x}'$$

- potential discontinuous on the spot (singular voltage) resulting in a **'localized' resistance**, but continuity of temperature:

$$R_{\Sigma} = (V_+ - V_-)\big|_{x=0} / I = L T_{\Sigma} / \pi a k$$

Holm's constriction resistance recovered!

$$T_{\Sigma} = T_{\pm}(\vec{x}=0) = T_a / (1-(I/I_C)^2)$$

- **Critical current** (new feature!) of a single spot reads:

$$I_C = \pi k a \sqrt{2/L}$$

a	Fe	Cu	Al	Pb	Steel
1 μm	2.4 A	11.4 A	6.92 A	1.02 A	0.76 A

- Spot resistance increasing with current (thermal effect): the spot acts as a **localized phonon source** with power driven by the current.
- Infinite resistance at I_c manifesting a **transition** to an insulating state.
- **Non linear** V-I characteristic:

$$V(I) = \frac{L T_a}{\pi a k} I / (1-(I/I_C)^2)$$

Theory of static metallic MCIs

Two spots model

- Straightforward extension of the constriction model to two spots

$$\Delta V_{\pm} = \pm \frac{L}{k}\left(I_1 T_1 \theta_{\Sigma 1}(\vec{x}) + I_2 T_2 \theta_{\Sigma 2}(\vec{x})\right)$$

$$\Delta T_{\pm} = -\frac{L}{\pi k}\left(\frac{T_1 I_1^2}{a_1}\theta_{\Sigma 1}(\vec{x}) + \frac{T_2 I_2^2}{a_2}\theta_{\Sigma 2}(\vec{x})\right)$$

$$I = I_1 + I_2 ; I_2 / I_1 = R_1 / R_2$$

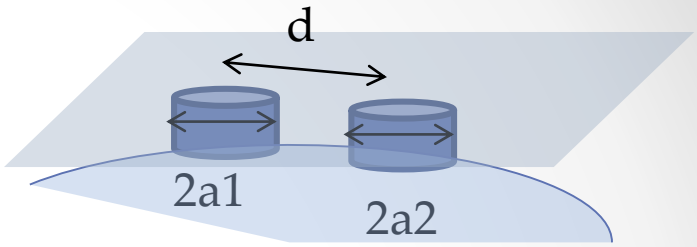
- Approach to the problem through a **matrix formalism** (2X2)

- Condition for thermal equilibrium of the 2-spots interface: eigenvalue problem for matrix B

$$4\pi^2 \frac{k^2}{L}\frac{T_{eq} - T_a}{T_{eq}}\vec{e} = B.\vec{e}$$

- **Same dependence** of the equilibrium temperature with total current I as for one spot but a **critical current**:

$$I_C = 2\pi k \sqrt{\frac{2d - a_2}{L(4d - a_1 - a_2)}}(a_1 + a_2)$$



-Matrix associated with two spots

$$\hat{B} = \begin{pmatrix} 2I_1^2 / a_1^2 & I_2^2 / a_2 d \\ I_1^2 / a_1 d & 2I_2^2 / a_2^2 \end{pmatrix} = I^2 \hat{\phi}(T_1, T_2)$$

- admits as an eigenvector,

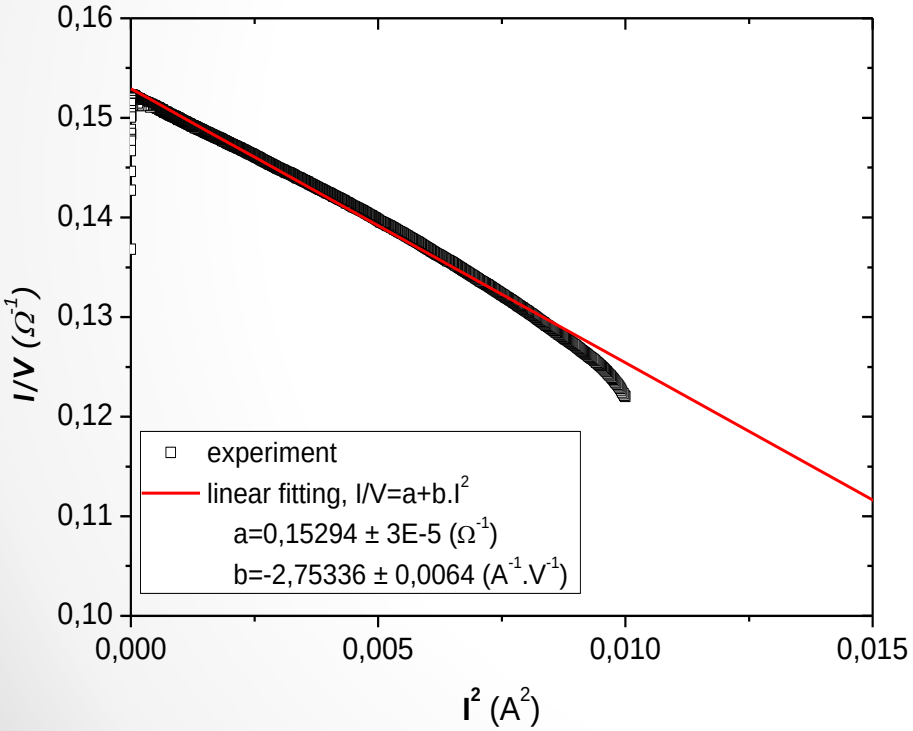
$$\vec{e} = \frac{1}{\sqrt{2}}\begin{pmatrix} 1 \\ 1 \end{pmatrix}$$

- 'Dilute' limit

$$d \gg a_1, a_2 \rightarrow I_C \approx 2\pi k \sqrt{\frac{2}{L}} a$$

Conclusion: extension to many spots interface

- We built up a model of metal/metal MCIs accounting for the electrothermal coupling within such interfaces dominated by the **constriction effect**.
- A workable 2-spots model (simplest one) evidences the influence of the **spots distribution** on the potential and temperature fields. Evidence for a specific **matrix formalism** for computation of the MCI properties such as the equilibrium temperature of the interface.
- Prediction of a **transition** from metal to insulating state driven by the current (thermal effect localized at the MCI) through a **critical current** depending on **spot radius** and **thermal conductivity** of the material.

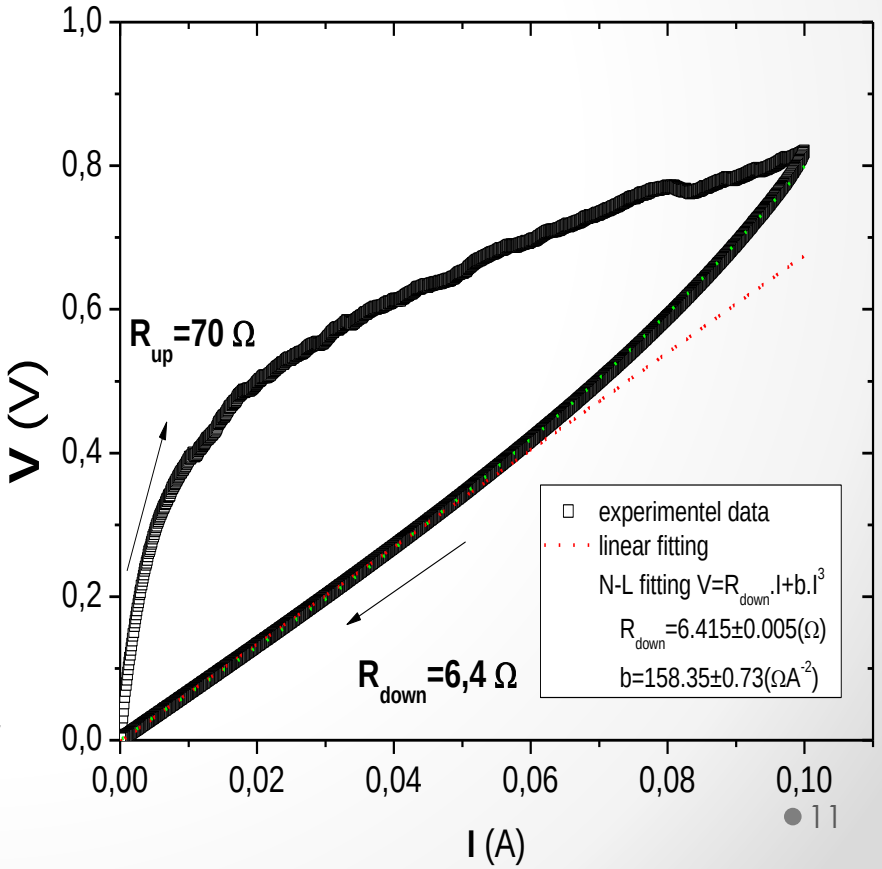


Evidence for a critical current: Plot I/V vs I2 validating the prediction of the model (V. Bourny/R. Bouzerar)

- Prediction of a **non linear I-V** characteristic of the interface: validated by experimental data (see figure)
- The **matrix formalism** allows an extension to many spots situations and especially **disordered interfaces** (more realistic) consisting of randomly distributed spots: natural connection with random matrices theory.
- Influence of the **shear component** of the stress field within the interface to be incorporated: possible correlation between **friction forces** and the electrical properties of the MCI.
- Derivation of the **continuum limit** of the model (relevant for high compression forces) to explore the transition to the smooth **Hertz contact** (real contact area close to the apparent area).

Conclusion: extension to many spots interface

- The starting model focuses on constriction effects: it gives an incomplete account for the usually observed I-V characteristic (see figure below) and especially the hysteretic behaviour (**Branly effect**) **[5]**.
- The upward branch (increasing current/decreasing resistance) requires a supplementary process : **electron tunneling** through the interface is **a likely candidate**.
- **Competition** between the compelling processes **tunneling [6]** and **constriction** might lead to new effects: interface electrical instabilities, …
- MCI endowed with these modified properties acts as an effective medium: tunneling and electron scattering by mechanical spots (phonon sources) resulting in the **renormalization** of the **thermal/electrical properties**…



Typical I-V characteristic for two steel beads under compression (V. Bourny/R. Bouzerar): Branly effect

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[6] A. Tekaya, R. Bouzerar, V.Bourny, I. Tekaya, World Journal of Engineering 8 (2) (2011)

Detailed Content

- **What is an MCI?**

> Academic situations (experimental issues) and industrial applications

> Complexity of MCIs: How to handle multiple couplings? Mechanical spots, electrical and thermal properties

- **Theory of static metallic MCIs**

> Approximations

- Characteristic scales separation
- Prevailing processes (constriction, tunneling)
- High and low spot density limits and compression forces range

> One spot model: solutions of the electro-thermal problem and consequences (critical current,…)

> Two spots model: Matrix formalism. Condition for thermal equilibrium of the interface.

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> Constriction vs tunneling. Branly effect