Looking for the Origin of Power Laws in Electric Field Assisted Tunneling

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Introduction: A sharp tip approached perpendicular to a conducting surface at subnanometer distances and biased with a small voltage builds a junction across which electrons can be transferred from the tip apex to the nearest surface atom by direct quantum mechanical tunneling. Such a junction is used e.g. in Scanning Tunneling Microscopy (STM).

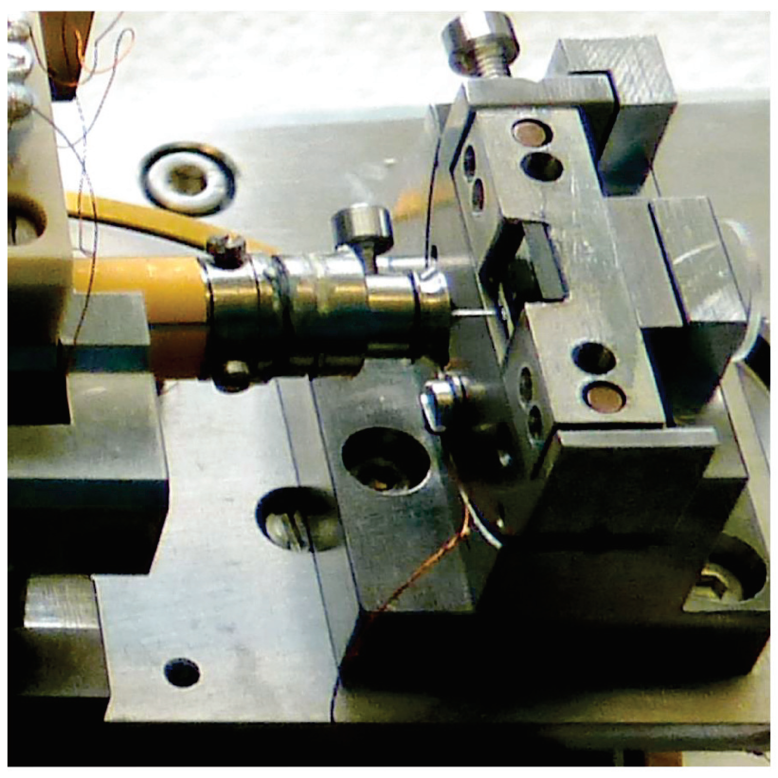

Figure 1. The experimental Setup: a nanoelectronic device

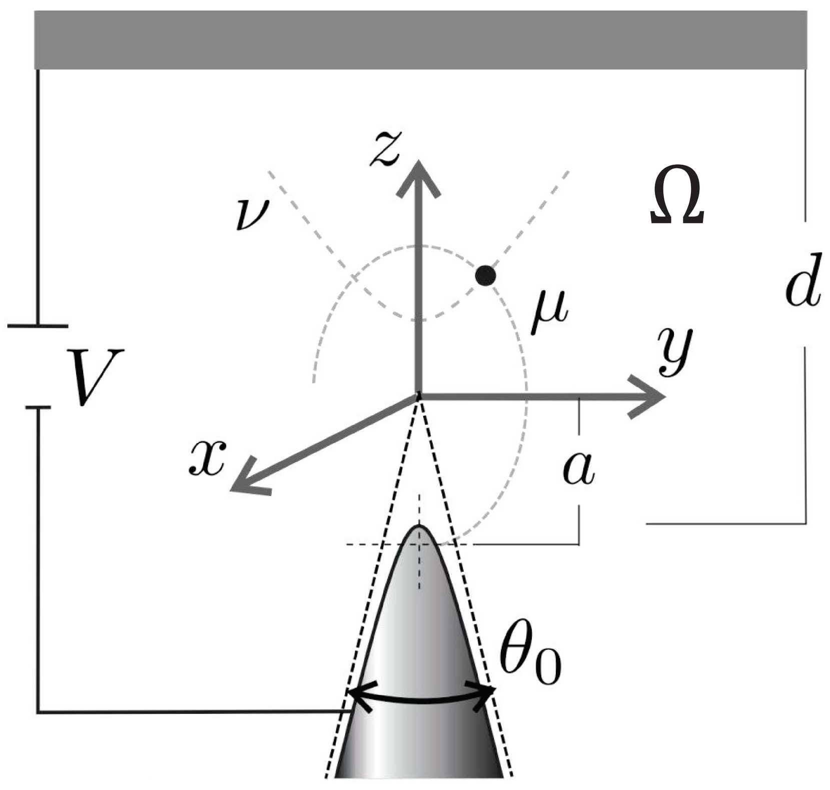

Figure 2. The electrostatic problem, tip modeled with a hyperboloid of revolution

When the distance d between tip and collector is increased beyond some nanometers, the junction enters the electric field assisted regime, the one underlying the topografiner technology –an imaging technique widely used in micro- and nano-electronics. Recent experiments[1] in this regime suggest a scaling law which can be tested numerically by verifying the collapsing of a family of $\Phi(z,d)$-curves, computed at different d, onto one single curve ($\Phi(z,d)$ being the electric potential).

Computational Methods: The tip, kept at ground potential, is placed in front of a conducting plane set at voltage $+V$ (see Fig. 2). Denoting with Ω the region of space excluding the tip and the plane, the electrostatic problem is a well defined Dirichlet problem for the electric potential Φ:

$$\begin{cases} \nabla^2\Phi & = & 0 & \text{in } \Omega, \\ \Phi & = & 0 & \text{on the surface of the tip,} \\ \Phi & = & +V & \text{on the plane,} \\ |\Phi|(x) & \leq & V & \forall \vec{r} = (x,y,z) \in \Omega. \end{cases}$$

Results: To the leading order, the potential depends on d differently in the "near" $(d \ll a)$ or "distant" $(d \gg a)$ regime

$$\begin{cases} \Phi(z) & \sim & V \cdot \frac{z}{d} & \text{for } d \ll a, \\ \Phi(z) & \sim & V \cdot \left(\frac{a}{d}\right)^{\lambda} \cdot \frac{z}{a} & \text{for } d \gg a, \end{cases}$$

with the geometry-factor λ determined by the aperture angle of the tip θ_0 (see Fig. 2).

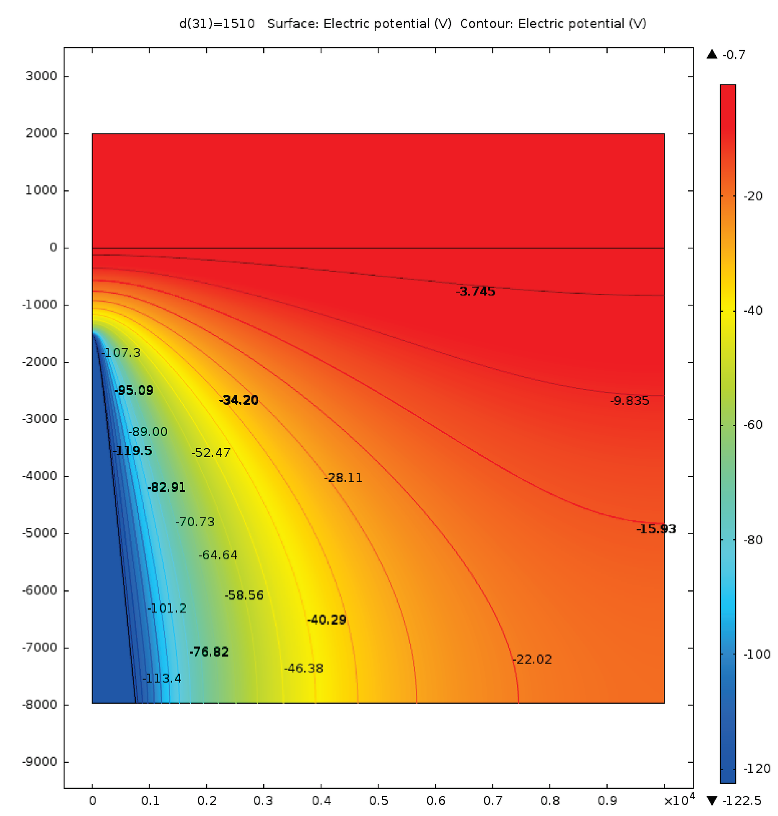

Figure 3. COMSOL simulation of the diodelike junction

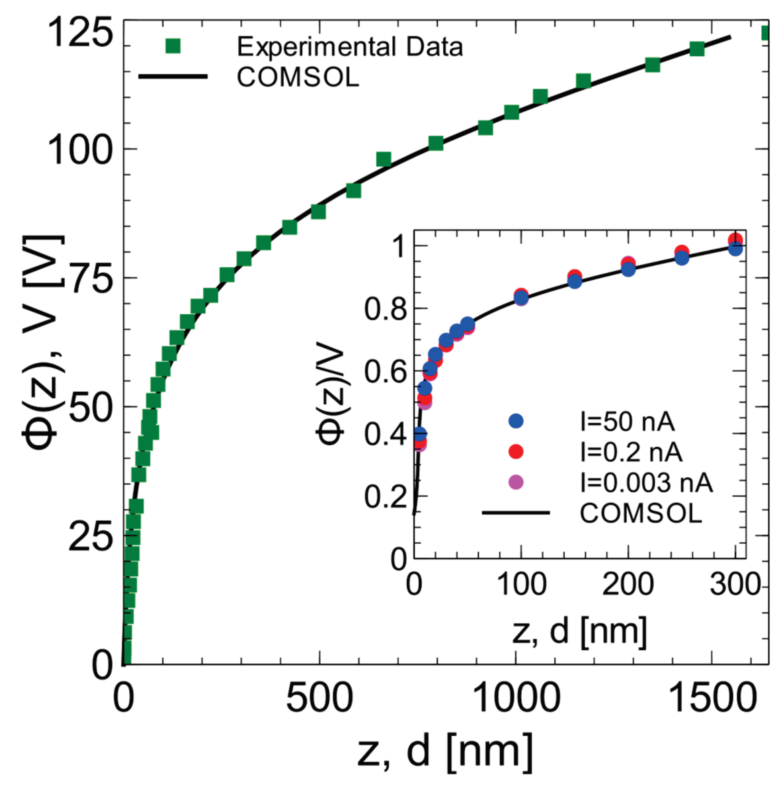

Figure 4. Examples of Φ/V-d curves for constant current

Conclusions: In the range $d \gg 10$ nm, the experimental data follow a power law $\propto d^{\lambda}$, with $\lambda = 0.21 \pm 0.02$. For smaller values of d the dependence becomes almost linear, indicating that the junction behaves as a plane capacitor at short distances: Direct tunneling typically occurs in this geometry. The essential features observed experimentally are captured by introducing the potential Φ computed for "realistic" tips into standard equations for electric field assisted tunneling. This highlights the potential of COMSOL-simulation in the context of field-emitted electron microscopy.

References:

1. H. Cabrera *et al.*, Phys. Rev. B 87, 115436 (2013)
2. D.A. Zanin *et al.*, Advances in Imaging and Electron Physics bf 170, 227 (2012)