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Nanowire formation at metal–metal contacts

E. Tosatti[a,b,*]

[a]International School for Advanced Studies (SISSA), INFM Democritos National Simulation Center, Via Beirut 2-4, I-34014 Trieste, Italy
[b]International Centre for Theoretical Physics (ICTP), P.O. Box 586, I-34014 Trieste, Italy

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Abstract

The thinnest nanocontacts between two metal bodies take sometimes the shape of regular ultra-thin suspended nanowires. I will qualitatively review here some of the theory work done in our group in connection with this phenomenon. I will discuss why nanowires arise, their stability, and their evolution with time. I will touch on the formation mechanism of 'magic' long lived nanowires endowed with especially stable structures, on their spontaneous thinning, and on the helical and the monatomic magic nanowires observed mostly in gold.

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1. Introduction

When at night we turn the lights off to go to sleep or otherwise, with that simple flicking of a switch we carry out (most probably unawares) a very delicate physics experiment. We move in that moment two metal blocks apart, suddenly straining and mechanically rupturing a myriad of metal–metal nanocontacts, each carrying a fraction of the total current in the circuit.

What are the nature, the geometry and shape, the electronic structure, the ultimate conductance of these atomic sized contacts? And what is the connection between these, the structure and the electronic and may be magnetic properties, and all of them and the electrical properties? Trying to answer some of these questions has been the theme of some research in our theory group, which I shall review in this short paper in honor of Eli Burstein. While this is not an area, where Eli himself contributed, the curiosity that inspired me to enter this area is very much in the spirit of Eli's own ever curious approach to physics and to life, a spirit which he has been spreading contagiously throughout his long career.

This paper covers in part material presented in a special Lundquist conference that was held honoring Eli Burstein at the International Centre for Theoretical Physics (ICTP) in Trieste in May 2004. The association of Eli with ICTP has been long and important, dating back to the 1970s. In close contact with Abdus Salam, who established ICTP, but especially with Franco Bassani and Stig Lundquist, each of them in different ways founding fathers of Condensed Matter theory at ICTP, and later with Bob Schrieffer, Praveen Chaudhari, Phil Anderson, and Yu Lu, Eli powerfully helped pulling together our international community and shaping our future along the lines that continue through different people today. I cannot resist showing at this point a nice picture of Eli among these and other main actors, taken at a meeting in ICTP in the early 90s, in Fig. 1.

Now to business. What about nanocontacts, their geometry and structure, first of all? A generally acceptable notion seems that, uncontrolled as they are, metal–metal

* Address: International School for Advanced Studies (SISSA), INFM Democritos National Simulation Center, Via Beirut 2-4, I-34014 Trieste, Italy. Tel.: +39 40 3787 443; fax: +39 40 3787 528.

E-mail address: tosatti@sissa.it.

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Fig. 1. Eli Burstein (center, between P. Chaudhari and E. Tosatti) at a meeting in ICTP, Trieste in the early 1990s. I recognize among others A. Salam, Yu Lu, F. G. Bassani, P. W. Anderson, K. S. Singwi, H. Singwi, A. Sjolander, F. Garcia Moliner, H. Rohrer, H. Stoermer, K. Schoenhammer, B. A. Huberman, L. P. Gorkov, R. Fieschi, G. Srinivasan, H. R. Ott, V. Sa-yakanit, C. W. Lung. X. G. Gong, S. M. Girvin, O. M. Gunnarsson, B. I. Lundquist, and S. O. Lundquist (whose anniversary was being celebrated) wearing two ties.

nanocontacts will as a rule differ from one another, all of them probably wildly irregular in shape and properties. As such, it would seem impossible for a theorist to give anything better than some kind of statistical discussion of their properties, along perhaps with simulations [1,2,23] of the way the rupture may occur from a plausible starting geometry of the nanocontact.

The last few years nevertheless brought several direct pieces of experimental evidence offering a less discouraging view, and moving the focus to some specific microscopic geometries that are definitely non-random.

The first kind of evidence comes from break junction conductance jump histograms [3], demonstrating contact a drop of conductance taking just before contact breaking the form of sharp steps, as shown for example in Fig. 2.

The majority of steps are clearly—if approximately—quantized close to multiples of the ballistic conductance quantum $G_0 = 2e^2/h$ [3]. In fact metal nanocontacts are a notable instance, where quantized ballistic conductance can be observed even at room temperature. Besides that, this kind of conductance evidence also proves that the thinnest contact neck must really have atomically small dimensions, both lengthwise (otherwise conductance would not be ballistic) and across (otherwise the smallest steps would not be of order G_0). From the conductance point of view the nanocontacts, far from being random, come in some kind of preferential forms, such as to produce well defined abundance maxima and minima as reflected by the conductance histogram peaks.

A second evidence came as a an additional and wonderful surprise when Takayanagi and his Tokyo group

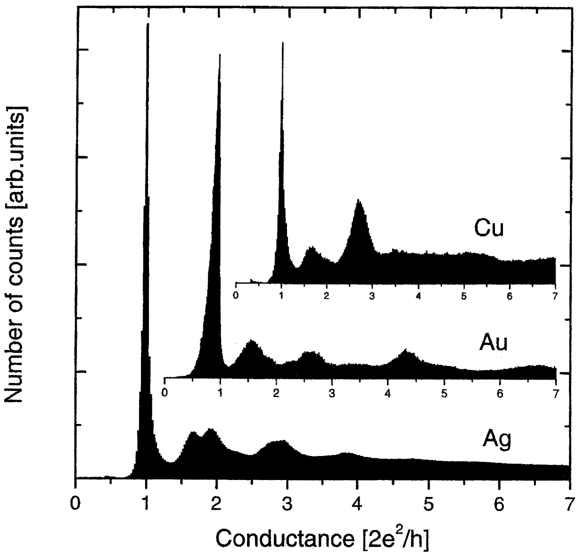

Fig. 2. Break junction conductance histograms for Au, Ag and Cu. Sharp peaks, particularly the first, indicate quantization in units of $G_0 = 2e^2/h$. After Ref. [3].