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Nanowire formation in macroscopic metallic contacts: quantum mechanical conductance tapping a table top

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Abstract

In this letter we show that quantum mechanical conductance is observed in nanowires formed by placing two wires of macroscopic dimensions in contact, making them vibrate so they get in and out of contact, and measuring the conductance response of such a system with an oscilloscope. We do this by tapping the table top on which the loose contact formed by the macroscopic wires is placed. The formation of these nanowires and the associated quantized conductance is a universal phenomenon that occurs when any two metals get in and out of contact independently of the metal sizes. This should have strong technological implications in studying contact formation, friction, tribology, forming and breaking bonds, mechanics, etc., at the nanoscopic level. Results and simple specifications needed for the formation of nanowires are presented for Au, Cu, Pt and metallic glass wires.

Keywords: Conductivity; Contacts; Quantum effects

The study of metallic nanowires and nanocontacts should enhance the understanding of structures of nanometric size. The interest on these nano-objects arises not only from the basic point of view, but also, from technological applications in future communication and information processing technologies, in integrated systems of nanometric and submicron sizes [1]. Theory, studying their electric conductance (quantization and localization) [2–7], as well as their mechanical properties [8], have been presented. Experimental production of these nanowires has been performed recently [9–13] and is a very active field of research at present.

The production of nanocontacts has been done so far by driving a scanning tunnelling microscopy (STM) tip into a metallic sample and then pulling it out. During this process a nanowire is formed, similarly to what happens when a finger is introduced in chewing gum and then is pulled out. During the tip retraction process, electrical [9–13] and mechanical properties [12] can be measured. To obtain such a wire, it has been argued whether or not a voltage pulse has to be applied when the tip is in tunnel current mode, although computer simulations have shown that just by putting in contact tip and sample and pulling the nanowire is formed [8]. We have followed this concept and stretched it further, i.e., if just by putting in contact a metallic tip and a metal and then pulling a nanowire is obtained, then, it should also be possible to produce them by placing in contact two

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metals of *any size* and then separating them. The original motivation of this work is then the suspicion that at the last stages of the breakage of a macroscopic contact, this contact should be of nanometric size. Furthermore, the nanowires produced this way should also exhibit quantized conductance. In other words, nanowires will form and have a universal behaviour for any metallic contact! The size of the metallic objects brought together is irrelevant at the last stages of the breakage of the contact.

In this work we present results that indicate that the above reasoning is correct. The experiments (the setup is shown in the photographs in Fig. 1) can be carried out at ambient conditions without recurring to STM, sophisticated equipment or special software as follows: take two wire ends, place them together or near each other (see Figs. 1a and 1b for the wire ends disposition). These wire ends should be loose. Then, connect the other ends to an I–V converter working in the microampere regime (10^5 gain) and apply some tens of mV. Place this on a table and hit the table with the hand; the wires will vibrate, getting in and out of contact. During this process, measure in an oscilloscope the current signal. It will show nanowire quantized conductance as depicted in the oscilloscope trace (in Fig. 1a, notice the steps in conductance perfectly quantized to $G_0 = 2e^2/h$, the quantum is in fact the distance between the two parallel thick lines in the oscilloscope screen). The oscilloscope used in this work was a Lecroy 9360; it captured 25 ksamples, triggered shortly after the current signal decreased from the saturation value (saturation current is about 140 μA, i.e., a resistance $< 31\ \Omega$ for a 44 mV voltage difference between the wire ends).

Experiments for many metals and their combinations have been performed. As an example we present representative results for Au, Cu, Pt and metallic glass wires. Fig. 2a describes an illustrative experiment for Pt: first the wires are out of contact; after hitting the table, they snap into contact (around $t = 0$) and break apart (descendent curve up to approximately 0.012 s where the contact breaks and the current is zero). The cables continue vibrating and the wires snap in and out of contact again, and so on, as seen in Fig. 2a. For the last and initial stages of the contact (very thin contact area), and for both approaching and departing wires, the current is quantized having a stepped behaviour. Fig. 2b is a magnification of one of the ending contacts in Fig. 2a. In Fig. 2c a histogram made with 122 different conductance experiments with Pt wires is presented. Notice quite well defined peaks at 1, 2 and 3 G_0 quantum conductance values. To make the histogram each quantum conductance unit is divided in 22 equally spaced

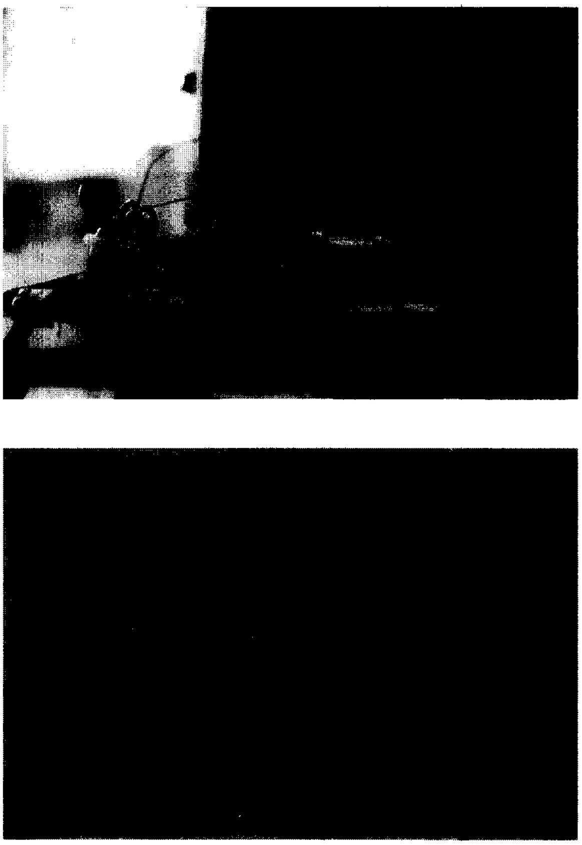

Fig. 1. Photographs of the experimental setup: (a) two copper wires, about 0.6 mm diameter, are touching loosely with a potential difference between them of a few tens of mV. The other ends are connected to the input leads of an I–V converter (10^5 gain for these experiments, about 100 mV per μA) used normally in a STM unit which is also visible. Notice in the background the oscilloscope trace of the conductance of such a system during the wires vibration. The distance between the two dashed horizontal lines corresponds to a $2e^2/h$ conductance step. (b) Detail of the wire ends.

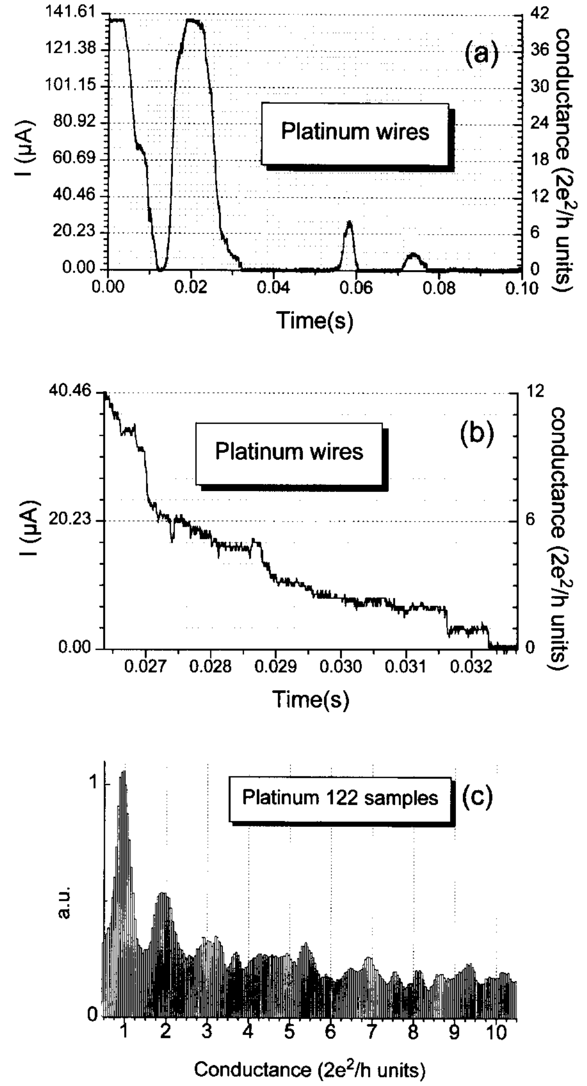

Fig. 2. Conductance experiment for two platinum wires, 0.25 mm diameter. (a) Full current evolution when the wires vibrate around the equilibrium (slightly separated wires) position. Notice evidence of the decreasing vibrational amplitude as less pronounced excursions to the full contact (resistance <310 Ω for 44 mV voltage difference) position. (b) Detail of the last stages of a contact breakage. (c) Histogram of conductance values made with 122 different curves (a.u. = arbitrary units).

levels. For every interval the number of points of a digitized conductance curve is counted and summed for several experiments (100 at least) to produce a final histogram. It is worth mentioning that this statistic is not directly comparable with others made with STM experiments, in which the tip retraction speed is controlled. This is not obviously the case in our experiments, i.e., the vibrational amplitude decays naturally while in the STM experiments the tip retraction speed is usually held constant. In addition, our two electrodes are identical pieces of wire.

Typical conductance curves for Cu and Au are presented in Figs. 3a and 4a. Notice that while for Cu there are up to six quantized steps for Au all the curve is quantized, up to the 40 quanta level! A histogram corresponding to just this curve is displayed in Fig. 4b. Of the 30 peaks shown 20 are at integer values of the conductance within 15%. There is no curve in the literature with this characteristic. This agrees well with simulations performed for Au nanowires where the disorder predicted is small [8]. Notice that disorder in the wire will destroy the quantization to smaller values than G_0 [6,14]. The histograms for Cu and Au (Figs. 3b and 4c) somehow reflect the behaviour

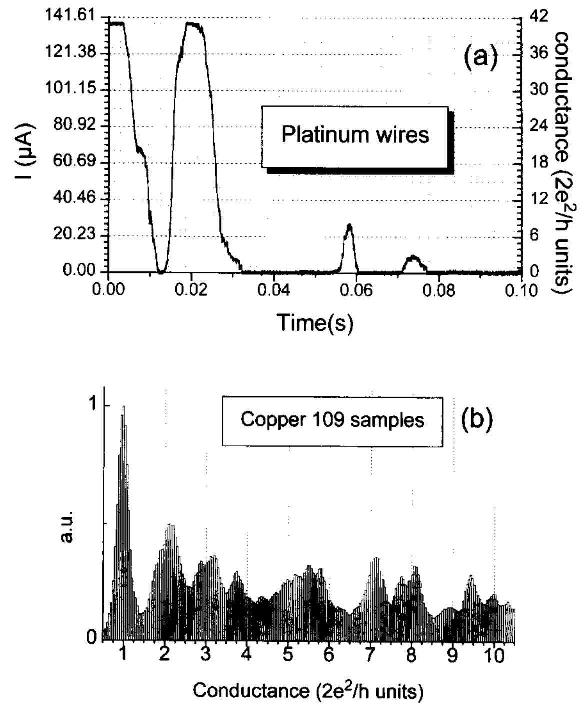

Fig. 3. (a) Conductance experiment for copper wires, 0.6 mm diameter. (b) Histogram of 109 individual curves.

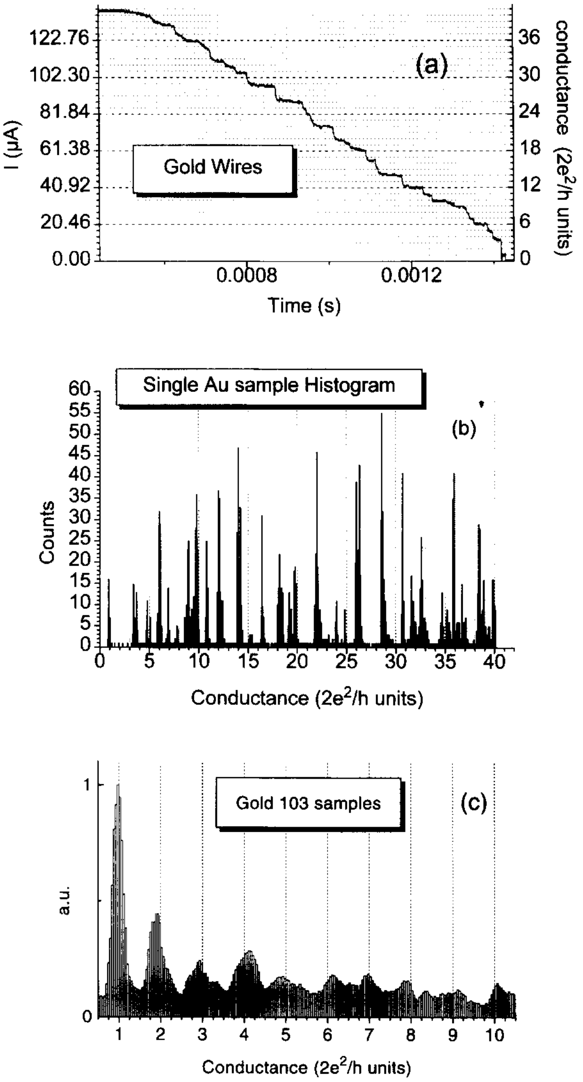

Fig. 4. (a) Conductance experiment from full contact (resistance $< 310\,\Omega$ for 44 mV voltage difference), to broken contact for gold wires, 1 mm diameter. (b) Histogram for the previous curve. (c) Histogram of 103 individual curves.

shown in the previous conductance curves. While for copper the majority (those at 1, 2, 3, 5, 7, 8 and 10 G_0) of the peaks are centered at integer conductance values, for gold this is true for *all of them*. These two materials have a strong s character, while Pt has an s-d character.

Finally, to see if the quantized steps are a consequence of the crystallinity of the wires, we have performed experiments with metallic glass wires $(Co_{94}Fe_6)_{72.5}Si_{12.5}B_{15}$. This is a ferromagnetic metal, with an amorphous structure which approaches the elasticity limit. The conductance experiment (Fig. 5a and amplification of the last stages Fig. 5b) exhibits two last steps even though the metal is amorphous, although in this case the behaviour for higher conductances is much more

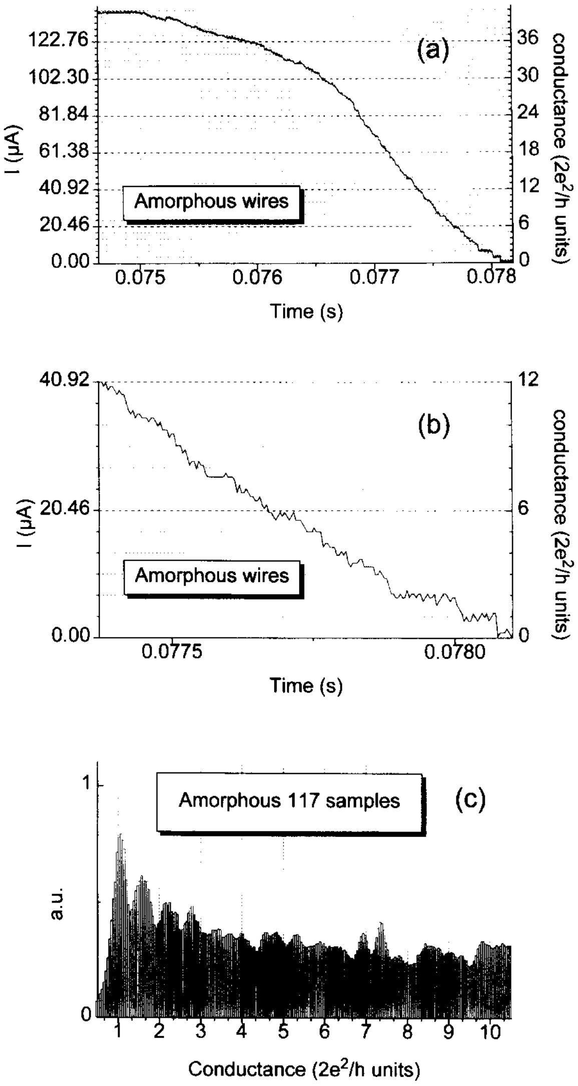

Fig. 5. Conductance experiment for amorphous $(Co_{94}Fe_6)_{72.5}Si_{12.5}B_{12.5}$ wires, 0.12 mm diameter. (a) Current evolution from full contact to broken contact. (b) Detail of the last stages before the contact breaks. (c) Histogram of conductance values made with 117 curves.

continuous than for the crystalline wires. The histogram (Fig. 5c) displays a well defined first peak at $1G_0$ conductance value followed by three peaks separated by approximately 2/3 G_0. Clearly, this is an effect of the non-crystalline structure of the metallic glass. Numeric calculations [14] show that an idealized nanowire system with atoms with their energies fixed can go from G_0 to 2/3 G_0 step in conductance if the atomic energies are taken randomly around the initial energy with a 20% width. However, it seems that some order appears when the nanocontacts start forming in these amorphous structures. This point is currently under study.

We have also made experiments combining different metals and the result is similar. It should be also added that the diameter of the wires used ranges between 0.1 and 1 mm in diameter, so the wires used are macroscopic and therefore the formation of nanowires and their characteristics has nothing to do with the small size of the tips in STM experiments.

We have performed a wide set of experiments (the data presented here is a small and representative fraction) with nanowires formed in a very simple way. From all our results it appears that the formation of nanowires and their quantized conductance are a universal property of any metallic contact, specially in the initial and final stages of the contact formation. When the conductance increases, section increases, the electric behaviour becomes that of the bulk, and each material has its own behaviour. This should be assigned to plastic and elastic regimes. Notice the differences between Au, a soft metal, and Pt, hard, and the metallic glass, hard and disordered. It is clear that much plastic information can be obtained. In addition, these experiments could be used to study tribology and friction, by measuring conductance instead of force when a metal slides over other metal. The measurement of conductance, for small nanowires, is a very precise method to measure the contact area, that can be related to the number of bonds forming and breaking in the contact. The results reported here open new ways for experiments at high and low temperatures, because there are not drift problems as in the local probes, as

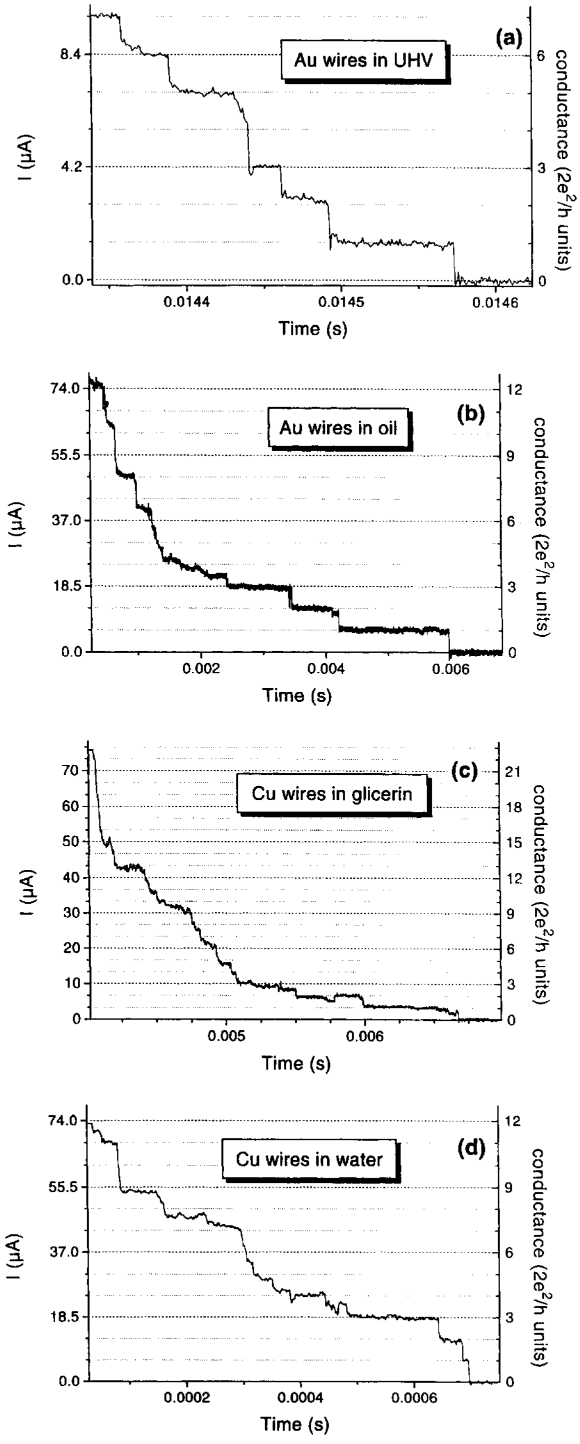

Fig. 6. Conductance experiments following the measurement method explained in this letter for: (a) two gold wires in ultra high vacuum (UHV) conditions; (b) two gold wires in oil (Cepsa Diesel 20–40); (c) two copper wires in glicerin; (d) two copper wires in water. In all cases the wire diameter was 0.25 mm.

well as for example measurements of magnetic properties at atomic- and nano-scales, etc.

Summarizing, *we demonstrate here that nanowires can be formed by driving two metals of macroscopic dimensions and any size in and out of contact.* Notably, we have argued here about metal–metal contacts but probably, any contact between materials should be similar. This is difficult to measure for insulators because the electronic conductivity is too low, although it can be increased by doping. We also think that the fact that quantization exists could be a signal to drive functional operations of many systems when they approach each other, in particular this could happen in biological systems, although this is speculative.

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Addendum

Conductance measurements on metallic contacts formed between two macroscopic wires show well defined quantization. Although initial "on top of a table" experiments were carried out at ambient conditions, we have found that the conductance steps not only appear in air but also in many kinds of environmental conditions and situations; i.e. the quantum conductance observed is a very robust phenomenon. As examples, in Fig. 6 we show the conductance steps when the two macroscopic wires are immersed in water, oil, glycerin, or in ultra high vacuum. These experimental results reflect the fact that conductance quantization is a universal phenomenon.

References

[1] Workshop on Nanoscience: Transport in Nanoscale Structures, Sponsored by the Army Research Office, Seattle, Washington, May 1993. TCN No 93–018, see Summary on Properties and Characterization of Nanowires by G.M. Whitesides, N. García and R.P. Andres.

[2] R. Landauer, J. Phys. Condens. Matter 1 (1989) 8099.

[3] P.W. Anderson, Phys. Rev. 109, (1958) 1492.

[4] C.W.J. Beenaker and H. Van Houten, Solid State Physics 44 (1991) 1.

[5] N. García and L. Escapa, Appl. Phys. Lett. 54, (1989) 1418;
N. García, paper presented at the STM Workshop, International Center for Theoretical Physics, 1987.

[6] E. Kander, Y. Imry and U. Sivan, Phys. Rev. B 41 (1990) 12941.

[7] E.N. Bogachek, A.N. Zagoskin and I.O. Kulik, Sov. J. Low Temp. Phys. 18, (1990) 796;
J. Torres, J.I. Pascual and J.J. Sáenz, Phys. Rev. B 49 (1994) 16581.

[8] U. Landman, W.D. Luedtke, N.A. Burnham and R.J. Colton, Science 248 (1990) 454;
U. Landman and D. Luedtke, J. Vac. Sci. Technol. 9 (1991) 414.

[9] J.I. Pascual, J. Méndez, J. Gómez-Herrero, A.M. Baró, N. García, U. Landman, W.D. Luedtke, E.N. Bogachek and H.-P. Cheng, Science 267 (1995) 1793.

[10] J.I. Pascual, J. Méndez, J. Gómez-Herrero, A.M. Baró, N. García and V.T. Binh, Phys. Rev. Lett. 71 (1993) 1852.

[11] L. Olesen, E. Lægsgaard, I. Stensgaard, F. Besenbacher, J. Schiøtz, P. Stolze, K.W. Jacobsen and J.K. Nørskov, Phys. Rev. Lett. 72 (1994) 2251.

[12] N. Agrait, G. Rubio and S. Vieira, Phys. Rev. Lett. 74 (1995) 3995.

[13] J.M. Krans, J.M. van Ruitenbeek, V.V. Flsun, I.K. Yanson and L.J. de Jongh, nature 375 (1995) 767;
J.M. Krans, C.J. Muller, I.K. Yanson, Th.C.M. Govaert, R. Hesper and J.M. Ruitenbeek, Phys. Rev. B48 (1993) 14721.

[14] P. García-Mochales, P.A. Serena, N. García and J.L. Costa-Krämer, to be published. We have performed extensive tight binding calculations that indicate that disorder creates minima in the steps and reduction of quantization. These effects are larger for larger disorder.