

MEASURING the CONDUCTANCE
of GOLD ATOMIC WIRES:
QUANTIZED CONDUCTANCE
of a BREAK JUNCTION

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ABSTRACT

We will discuss the electronic conductance properties of junctions formed at the contact between a Au wire and a Au film. These ‘break junctions’ provide a simple experimental realization of a nanowire.

We will describe a simple apparatus based on a piezoelectric tube that permits a repetitive formation and breakage of these junctions. By applying a constant voltage of $\sim 25\text{mV}$, a current is made to flow through the junction. Using a digital oscilloscope and a homemade I-V converter the current can be measured as a function of time as the junction is broken. Measurements made at room temperature reveal steps in the current. The oscilloscope is interfaced with a computer in order to perform a statistical analysis of the current features.

Our data will be presented and analyzed in terms of the Landauer formalism for current flow through small constrictions. The features of the conductance histograms we have measured are consistent with the quantization of the conductance in units of $\frac{2e^2}{h}$.

1. INTRODUCTION

During the past decade the interest of the scientific community in the field of nanotechnology has grown tremendously, both from a theoretical and an experimental point of view. The main reason is the great number of possible applications for nanoscale devices. Since the invention of the transistor in 1948, physicists, electrical engineers and chemical engineers have been working together to meet the challenge of continuously reducing the size of solid-state devices. By 1965 the channel length of commercial Field Effect Transistor (FET) was of the order of 10 μm . Nowadays commercial FETs have typically 1 μm long channels while laboratory FET channels are as small as 100 nm [1]. However, the downscaling of electronic devices has progressed so rapidly that it has reached a level which is very difficult to exceed. This new limit, which arises on the scale of hundreds of nanometers and under, is fundamentally different from those encountered previously. This new limit involves fundamental properties of matter rather than technological innovation. Indeed, the diffusive conduction model used for conventional devices is no longer valid when dealing with dimensions of the order of or lower than the mean free path of the electron because it does not take into account the quantum nature of matter.

Since wires are the simplest components of an electrical circuit, the first step to understanding transport through nanostructures is to study current flow through nanometer or sub-nanometer diameter wires called “nanowires”. Nanowires can be categorized into 4 different types as described in Fig. 1. The study of such structures is not straightforward. The main issues are their synthesis and making electrical contacts, not to mention the interpretation of the measurements. One system however, the break junction, is significantly easier to study than the three others and this has made it possible for me to study it in the short amount of time I had for my research project. This nanostructure which is only a few atoms wide spontaneously forms at the last stages of the breakage of a contact between two macroscopic objects. What are the advantages of the break junction? First of all the electrical contacts are already built in due to the fabrication method. Secondly, the conduction mechanism in this case is fairly well understood. The drawbacks include the requirement for high

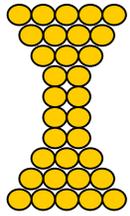
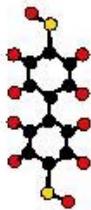
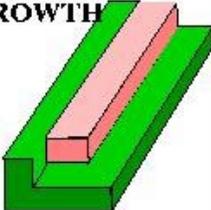
	BREAKJUNCTION 	NANOTUBE 	MOLECULAR WIRE 	ANISOTROPIC EPITAXIAL GROWTH 
Composition	Cu, Ag, Au . .	C	C,N,H,S	Pb, Sn, Rare Earths on Si
Geometry	Wires (1D)	Tubular	Fixed by Q.M.	Step Edges (1D)
Width	atomic	1-50nm	~ 1 nm	atomic
Length	few atoms	1-50 μ m	few nanometers	few μ m
External Connections	Built In	Problematic	Challenging	Problematic
Fabrication	Contact Mechanics	Carbon Arc	Test Tube	UHV Atom Deposition
Conduction Mechanism	Quasi-ballistic	Ballistic ?	?	?

Fig. 1 Characteristics of Nanowires

mechanical stability. In addition, although break junctions provide useful insights for understanding conduction mechanisms in nanostructures, these very short and unstable nanowires have no potential practical applications.

The purpose of my work is to find evidence for the quantization of conductance in gold break junctions. I will first describe the experimental setup used for my study, then I will discuss the study of a single breakage, followed by a statistical analysis of the break junction data. Finally I will present a theoretical model to explain my results.

2. EXPERIMENTAL SETUP

2.1 Air-STM

To carry out our experiment we used a homebuilt air Scanning Tunneling Microscope (built by Elton Graugnard) which enables us to do the following:

- Control the tip-sample separation by applying an offset voltage to the piezo tube
- Apply a constant voltage between the tip and the sample
- Measure the current flowing through the junction
- Periodically form and break the junction by applying a periodic voltage to the piezo tube

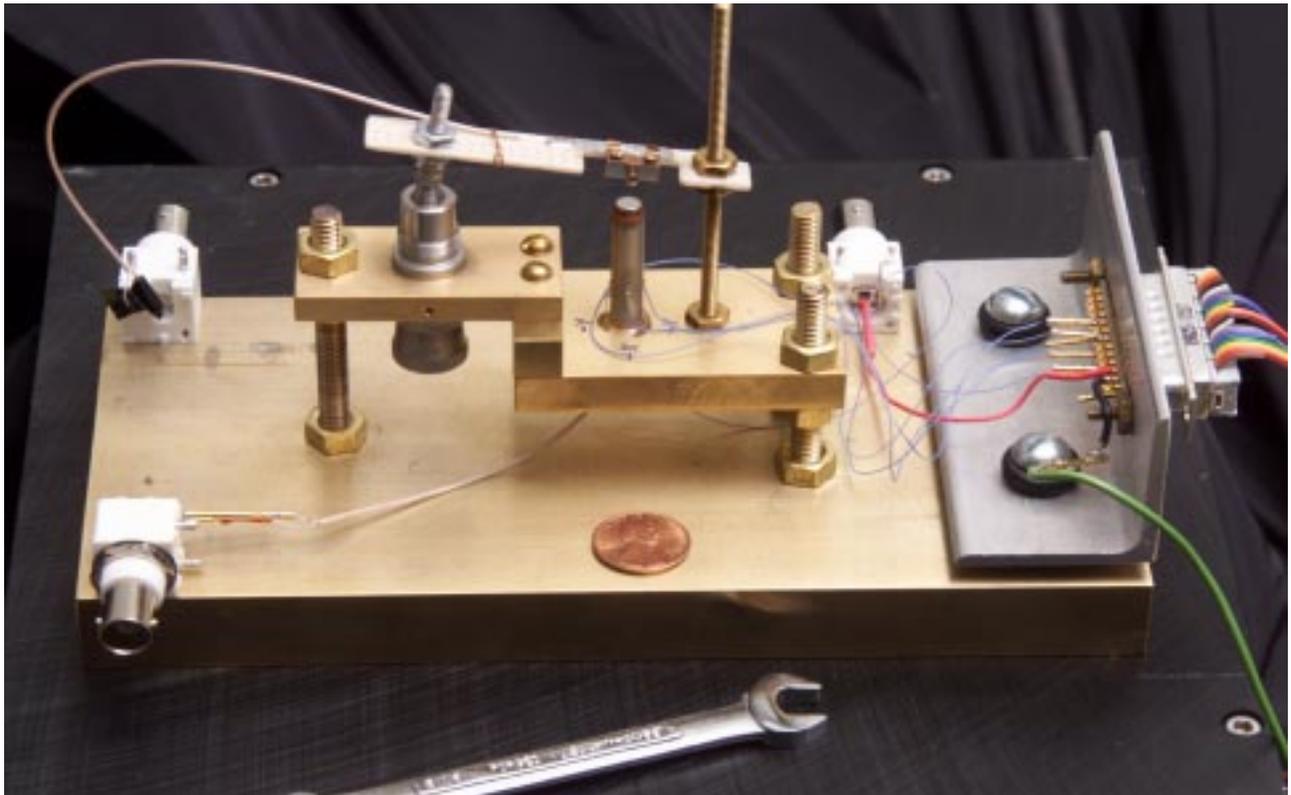


Fig. 2.1.a Homebuilt Air-STM

A photo of our instrument is displayed in Fig 2.1.a. A precision micrometer (manufactured by Newport: differential micrometer BD17.04) controls the prepositioning of the tip. The sample is mounted on the piezo tube using a magnet where the electrical connection is made through the inside of the tube. In order to minimize

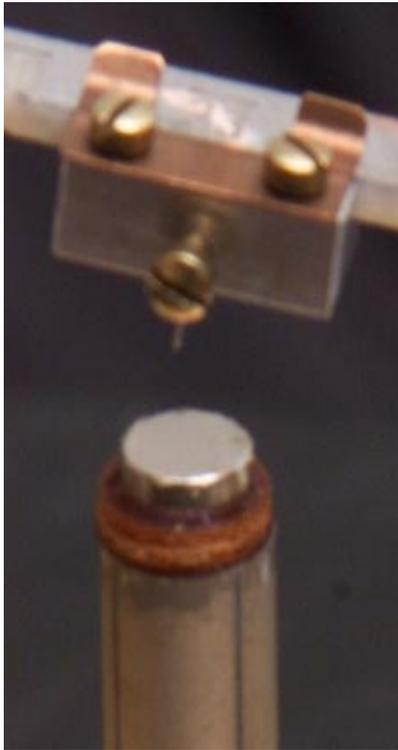


Fig 2.1.b Tip and piezo

crudeness this homebuilt STM was able to image HOPG (see appendix A). However it is sensitive to perturbations and does not provide a clean environment as a UHV STM would.

2.2 Electronics

The circuit design was closely modeled on that described in reference [2]. Two functions need to be performed by the electronic equipment: constant voltage source and current-to-voltage converter and amplifier. These two circuits are built together in a metal box to minimize noise. The voltage source is a 9V battery connected to a voltage divider with a variable resistor to adjust the desired value of the voltage (see Fig. 2.2). The available range is 0 to 70 mV and a typical bias voltage used for measurements is 25.8 mV.

The main component of the I-V converter is an operational amplifier (OA) OP-27 (National Instruments) powered by two 9V batteries. Using batteries both for the voltage source and the OA isolates the circuit from the building's 60 Hz outlets that could otherwise be a major source of noise. Using this configuration our average noise was below 2mV. Since the OA is in negative feedback mode (see Fig. 2.2) the

electrical noise the wires used for the connections to the tip and the sample are subminiature coaxial cables SM75 manufactured by Axon Cable. The piezo tube is hollow and its inside surface is metallized. The outside of the tube is covered with four separate metallic sectors. This is to enable lateral displacements of the sample during scanning but is not useful in our experiment. Indeed the tip needs to be at a fixed horizontal position over the sample so these four plates are connected together and the voltage is applied between the inner plate and the outer ones. Thus the piezo can extend vertically with a sensitivity of the order of 1 nm/V.

The advantages of this apparatus are twofold: it is very easy to build and low cost. Despite its

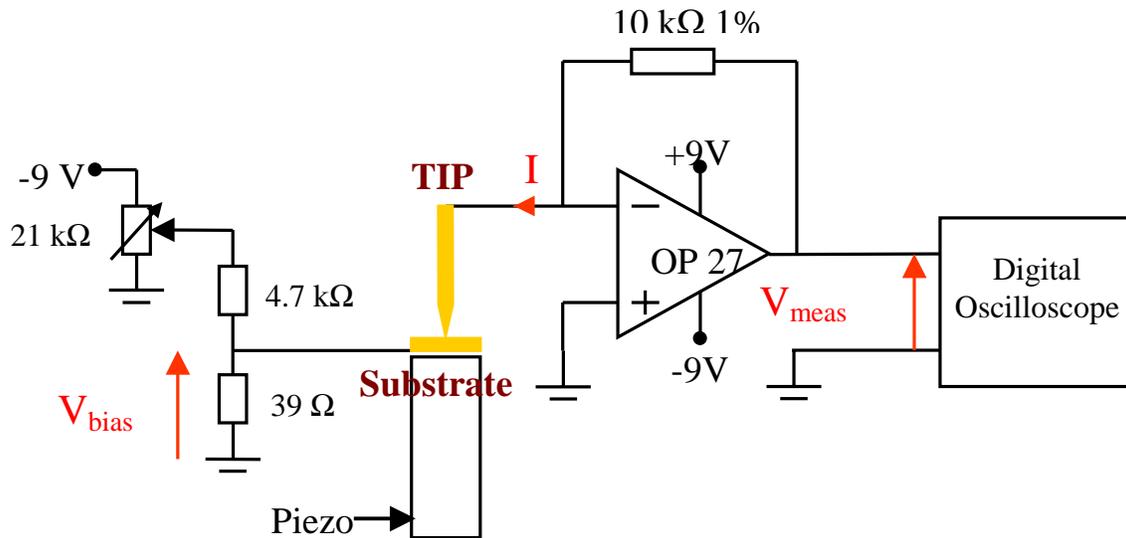


Fig. 2.2 Diagram of electrical circuit

differential input voltage is maintained at 0 and the tip is virtually connected to ground. The current flowing into the inverting input of the OA is 0 so the current I flows entirely through the feedback resistor. Therefore the relationship between the current I and the output voltage V_{meas} is:

$$V_{\text{meas}} = R I \quad (2.2)$$

where R is the feedback resistor ($R=10 \text{ k}\Omega$). The output voltage is proportional to the current flowing through the junction and is measured with a Tektronix TDS 360 digital oscilloscope. The gain of the I-V converter is 10^4 V/A

2.3 Vibration Isolation

Mechanical stability is a key issue in this experiment since the nanostructures are only a few atoms high. A photo of the system we developed is shown in Fig. 2.3. The STM is suspended by elastic cords. Two lead bricks are added to increase inertia. The entire system is put into a box to limit air circulation and sudden temperature changes. The box rests on a heavy granite block. Sorbothane vibration mounts (distributed by MacMaster-Carr, part #5965K83) are used to dampen low-amplitude vibrations.

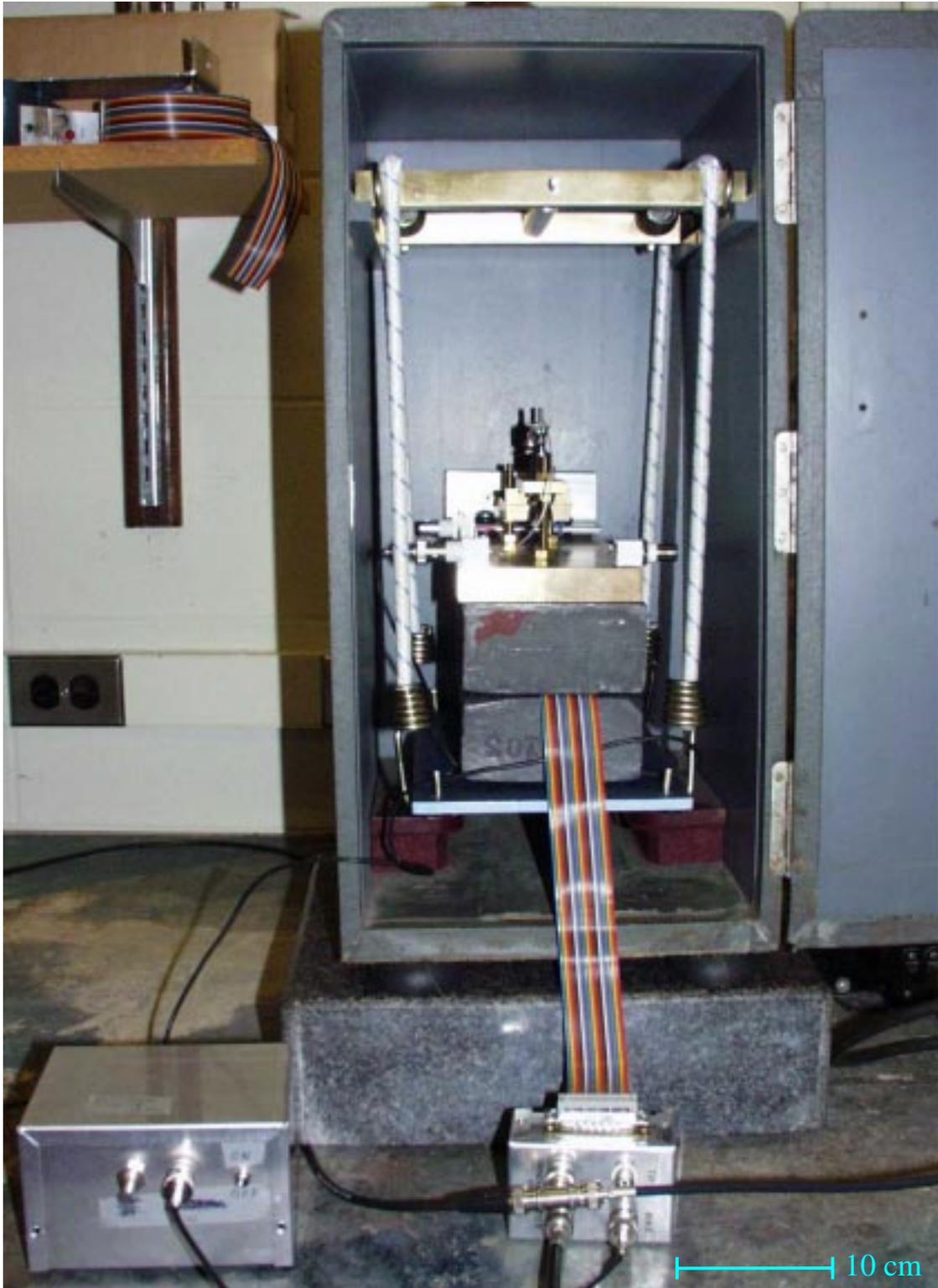


Fig. 2.3 Apparatus used for mechanical stabilization of the STM

3. STUDY OF A SINGLE BREAKAGE

3.1 Preliminary Observations and Concepts

What would you expect if you look at the current I flowing through a breaking junction? If it behaved like a macroscopic conductor it would follow Ohm's law:

$$I = G V_{\text{bias}}, \quad (3.1.a)$$

where G is the conductance of the junction and V_{bias} is the applied bias voltage.

In an ohmic conductor the conductance is independent of the applied bias and can be expressed as:

$$G = \sigma \frac{S}{\ell}, \quad (3.1.b)$$

where σ is the conductivity of the conductor, S is the cross-section of the conductor and ℓ is the length of the conductor.

The conductivity is an intensive quantity that describes the ability of a material to conduct electricity. For an ohmic conductor σ is independent of the applied voltage. If we assume that the length of the Au break junction is constant as it breaks, then the conductance should decrease in a smooth manner as the cross-section decreases monotonically.

In our experiment the bias applied across the junction is kept constant so that the current is proportional to the conductance (see equation 3.1.a). Therefore our measurements are first expressed in terms of current, which is the actual measured quantity, and later converted into conductance. Fig. 3.1.a is a schematic representation of the expected current versus time curve as the junction breaks in this simplistic macroscopic ohmic conductor model. For reasons that will be clear later in the next section, let us bring in a new representation of Fig. 3.1.a: the histogram plot. In this representation the current axis is divided into segments of equal current increments called bins. The data points are sorted into these bins according to their current value and the cumulative number of data points in each bin is plotted at the center of the bin versus the current value. In Fig. 3.1.a the expected current decreases in a smooth manner so each value of the current has roughly the same probability of being attained

as the junction breaks. Fig. 3.1.b is the histogram plot correlated to Fig. 3.1.a. The idea conveyed by Fig. 3.1.b is that the number of data points in each bin, which is proportional to the probability of obtaining a specific current, is independent of the value of the current.

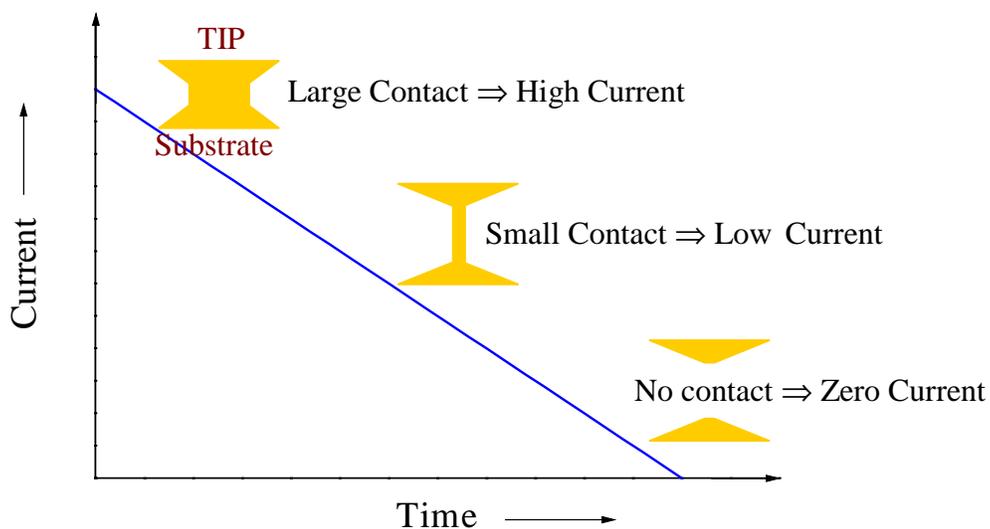


Fig. 3.1.a Expected Evolution of Current as Junction Breaks (schematic representation)

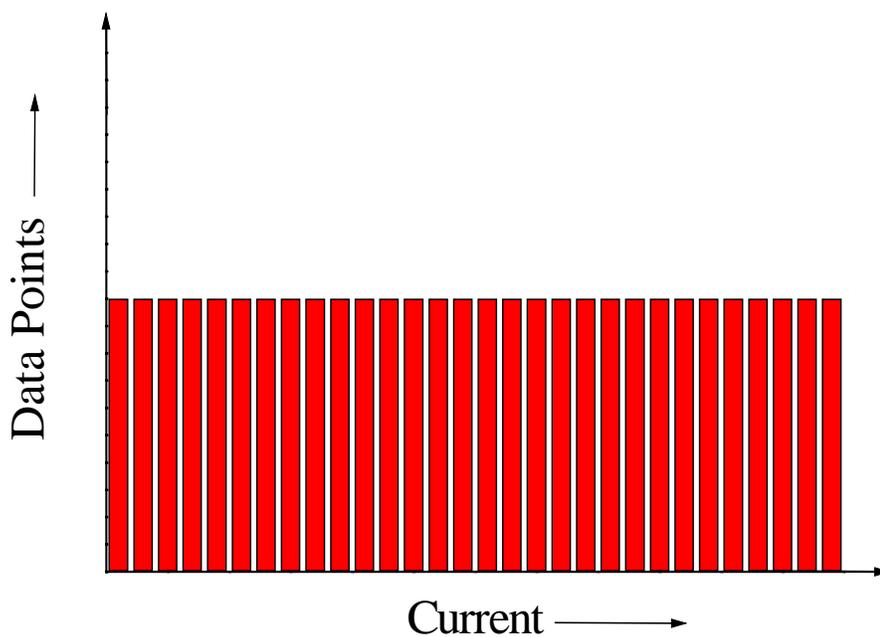


Fig. 3.1.b Histogram Plot of Fig. 3.1.a

3.2 Experimental Results

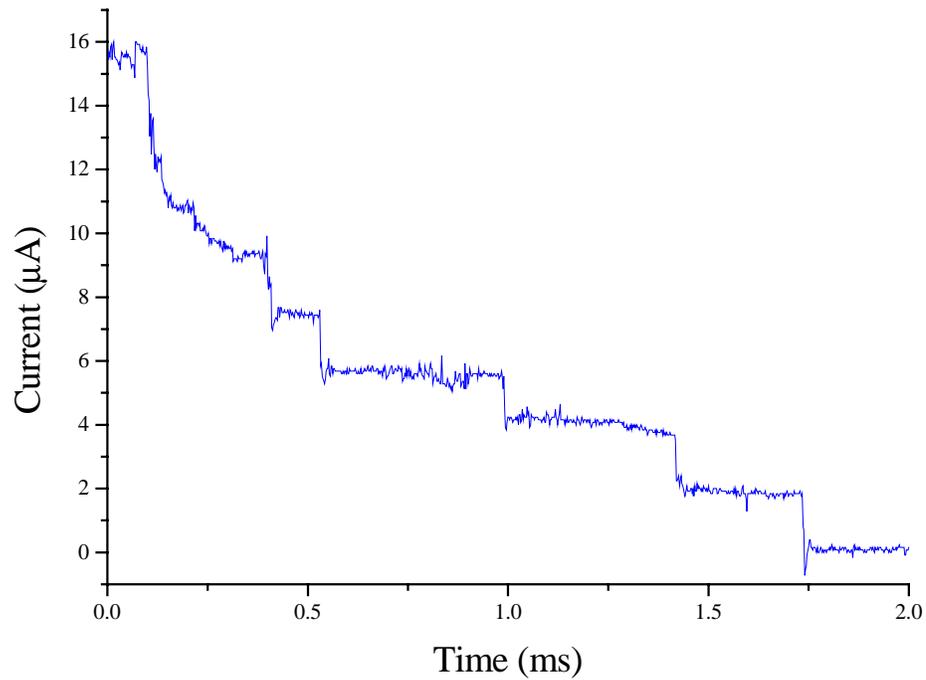


Fig. 3.2.a Experimental Evolution of the Current as the Junction Breaks

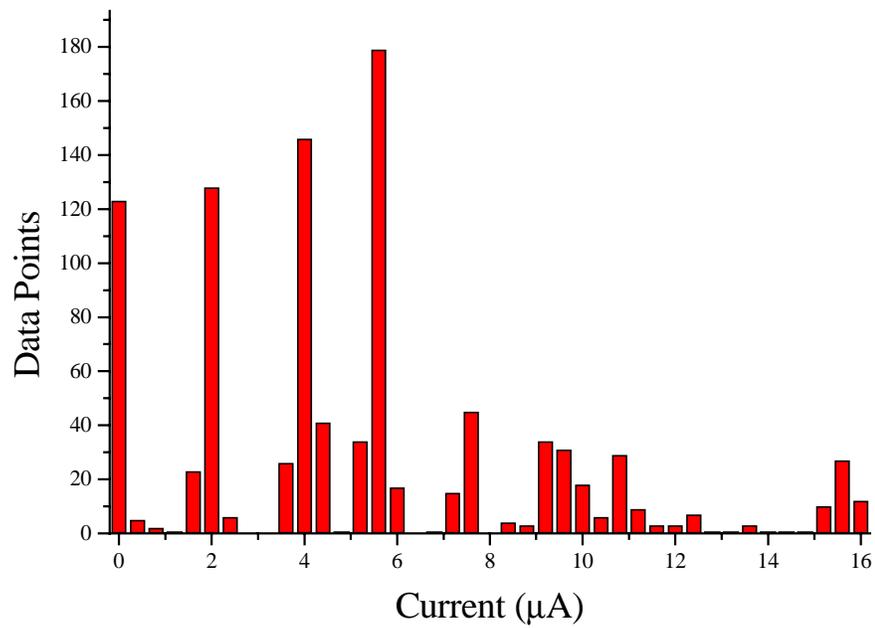


Fig. 3.2.b Histogram Plot of Fig. 3.2.a

In contrast to these expectations, actual data taken with an applied bias of 25.8 mV is shown in Fig. 3.2.a. The experimental curve has one significant and striking difference: *the current does not decrease smoothly but exhibits step-like features for the lower values of the current*. This data strongly suggests that the current flowing through the junction is quantized at the last stages of its breakage, that is to say that only a finite number of values can be attained. It also seems that the height of the steps could be constant. This is best visible in the histogram representation (Fig. 3.2.b), where each peak corresponds to a current plateau in Fig. 3.2.a.

4. STATISTICAL ANALYSIS

4.1 Motivation

If we repeat our measurement a large number of times, the curves we obtain

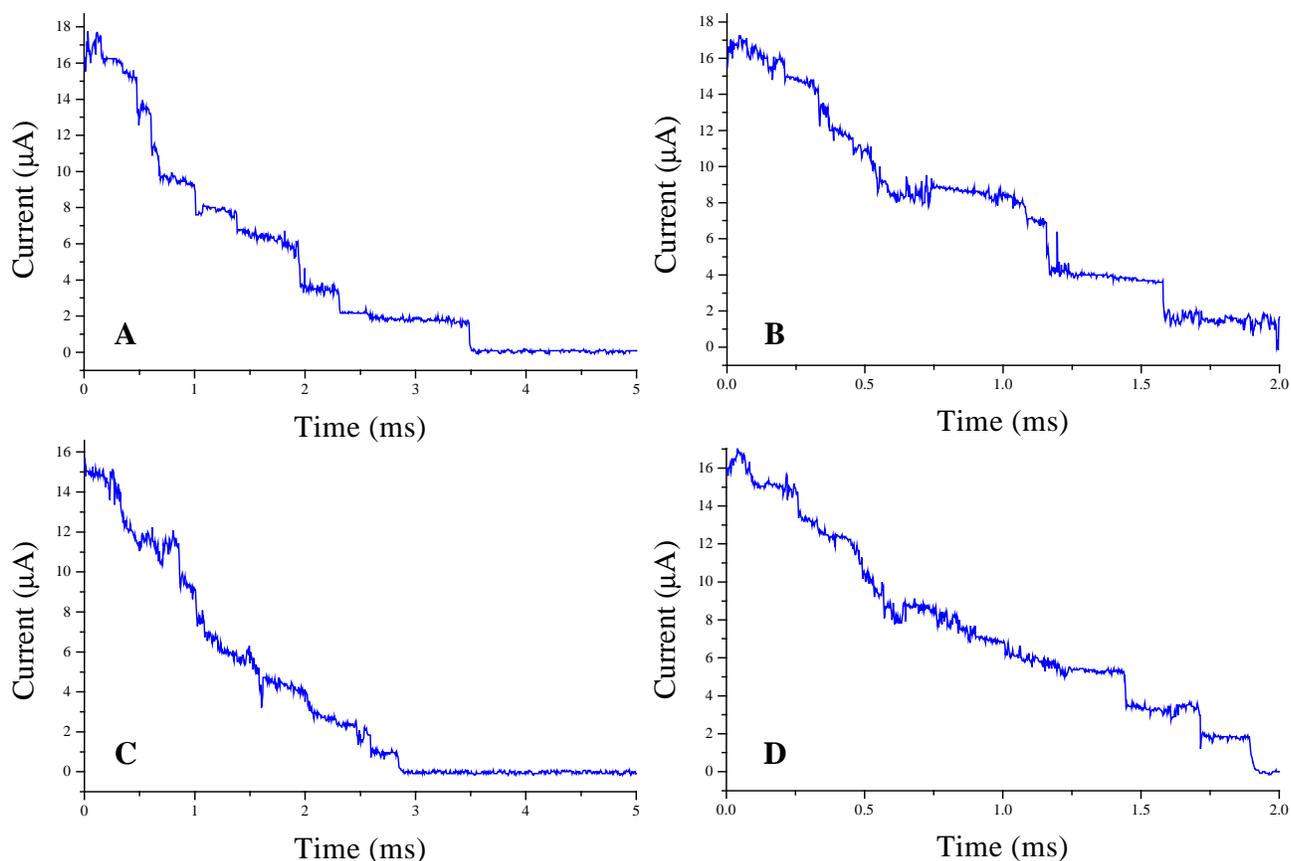


Fig. 4.1 Set of Four Different Data Curves

show significant differences. Fig. 4.1 shows a set of four data curves that display typical behaviors. Curve A exhibits well-defined steps (up to five) and can be considered as a reference curve. Curve B shows 2 well-defined steps but the second one (for a time of ~ 0.75 ms) seems to be twice as high as the first. In curve A, the steps are roughly the same height. Curve C is a case where, except for the first step, we can hardly see any steps at all. In curve D we can see three steps which last roughly the same time whereas in curve A the first step lasts about three times longer than the second one. Obviously these differences make it difficult to draw any solid conclusions by studying a single curve. Nevertheless we can try to bring out an average behavior by doing a statistical study, which is the object of the next section.

4.2 Acquiring Statistical Data

In order to solve the problems discussed above, we need to obtain repetitive measurements from a break junction. In this study, this was accomplished by forming and breaking the junction many times by applying a sine wave voltage to the piezo tube. An offset voltage can be used to bring the tip within the range of the sine wave oscillations. When mechanical stability is sufficient, the current response of the

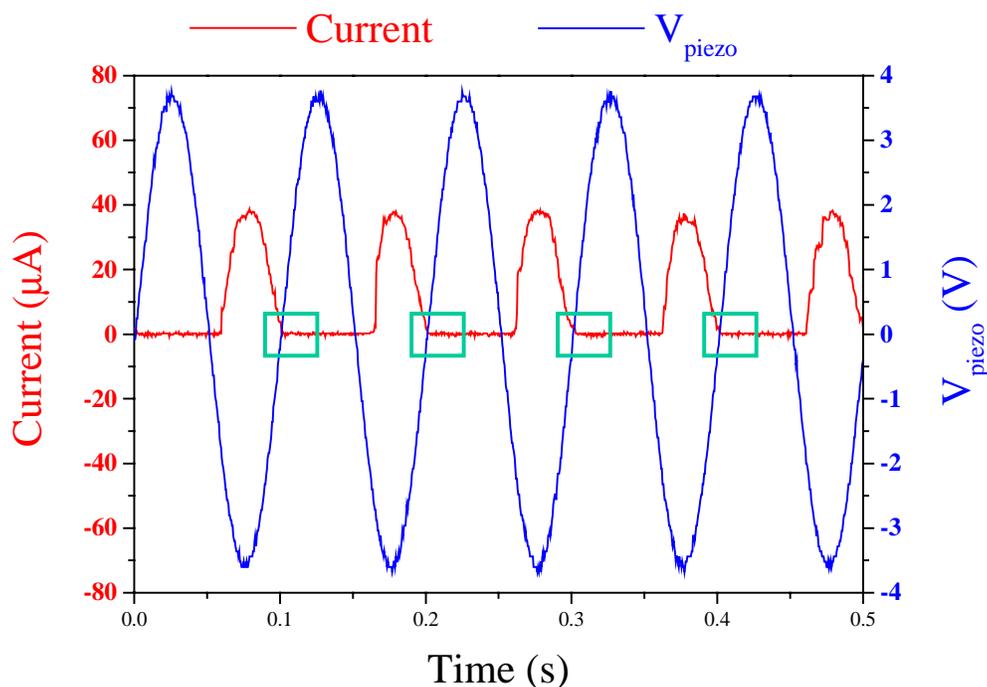


Fig. 4.2.a. Repetitive Formation and Breakage of the Contact

4.3 Results

A representative histogram is given in Fig. 4.3. It was acquired with an applied bias of 25.8 mV. The sine wave voltage applied to the piezo had a 10 V peak-to-peak amplitude and a 10 Hz frequency. The histogram exhibits three well-defined peaks at approximately 2, 4 and 6 μA . The quantization of the current is not merely a statistical fluctuation but since it appears as an average phenomenon it can be considered as an intrinsic feature of the break junction.

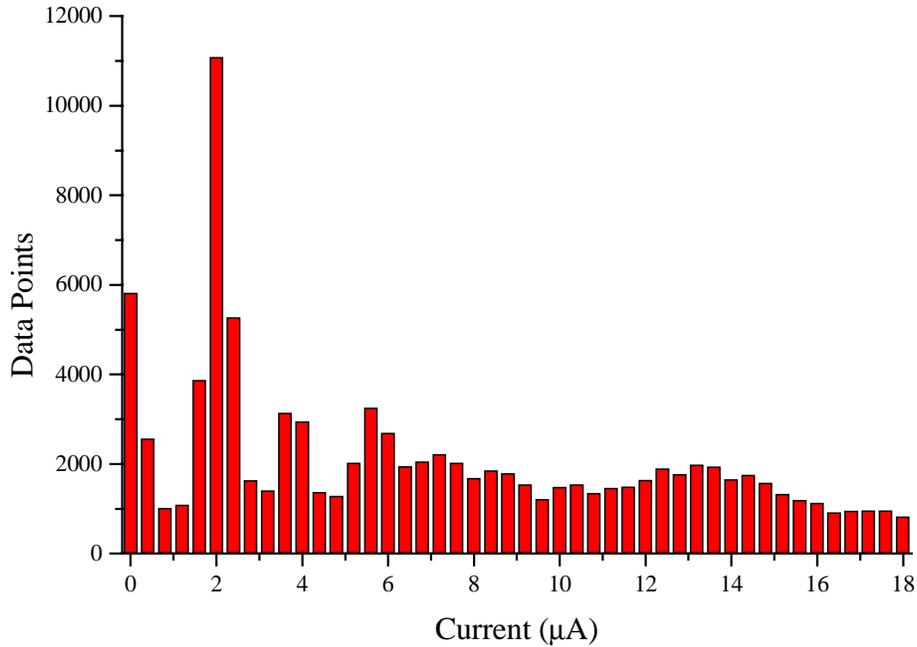


Fig. 4.3 Histogram Plot of 100 Breakage Curves

5. THEORETICAL INTERPRETATION

5.1 Conductance of a One Dimensional Metal

The aim of this section is to present the concept of the quantum of conductance, $G_0 = 2e^2/h$. This constant characterizes ballistic conduction, i.e. conduction where scattering is not a significant factor in the transport mechanism. This is the case when the length of the conductor is small compared to the mean free path of the electron. Consider a one dimensional metal in contact with two reservoirs

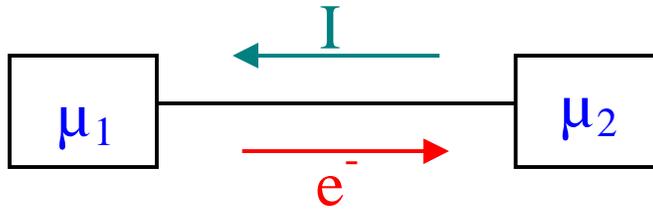


Fig 5.1.a Diagram of a One Dimensional Conductor

having chemical potentials μ_1 and μ_2 (see Fig. 5.1.a). Assuming μ_1 greater than μ_2 , the electrons are flowing from the first reservoir to the second and the conventional current flow is in the opposite direction.

Fig. 5.1.b represents a first approximation dispersion relation for electrons in the conduction band of a metal. The fundamental assumption in this model is that all the electrons flowing from the first reservoir to the second (i.e. with $k > 0$) are in equilibrium with μ_1 and that all the electrons flowing from the second reservoir to the first (i.e. with $k < 0$) are in equilibrium with μ_2 . Therefore at temperature $T=0$ the $k > 0$ branch of the energy diagram is filled up to μ_1 and the $k < 0$ branch is filled up to μ_2 . If the dispersion relation is symmetric the current created by the electrons with energy E lower than μ_2 is zero because the current created by an electron with e.g. $k > 0$ will be compensated by an electron of the same energy with $k < 0$. Thus only electrons with an energy E between μ_1 and μ_2 actually contribute to the current. Since the $k < 0$ branch of the diagram is only filled up to μ_2 all these electrons have a positive k (see Fig. 5.1.b.).

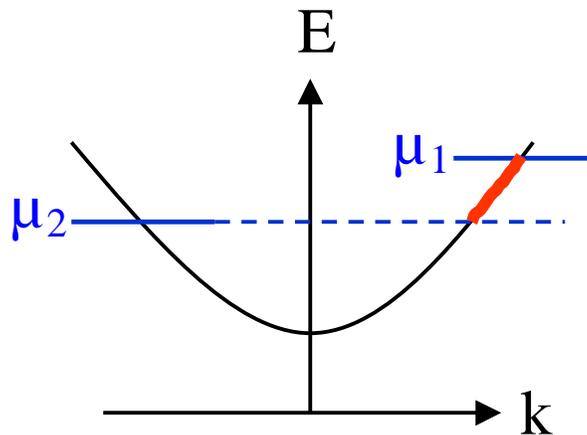


Fig. 5.1.b Conduction Band of the Metal

The current contribution dI of a small number dn of these electrons with an energy E between E and $E+dE$ is

$$dI = -e dn v(E), \quad (5.1.a)$$

where e is the absolute value of the electron charge and $v(E)$ is the velocity of an electron of energy E . The number of electrons within a certain energy window is determined by the one dimensional Density Of States (DOS):

$$dn = \text{DOS}_{1D}(E) dE. \quad (5.1.b)$$

Assuming spin degeneracy, the usual expression for the DOS in one dimension is

$$\text{DOS}_{1D}(E) = \frac{2}{\pi \hbar v(E)}. \quad (5.1.c)$$

However in this case the electrons that contribute to the current only occupy one side of the conduction band. Since the band is assumed to be symmetric the DOS in our case is simply half of the usual one:

$$\text{DOS}_{1D}(E) = \frac{1}{\pi \hbar v(E)}. \quad (5.1.d)$$

Therefore

$$dn = \frac{dE}{\pi \hbar v(E)}. \quad (5.1.e)$$

From Eq. 5.1.b it follows that:

$$dI = -\frac{e}{\pi \hbar} dE = -\frac{2e}{h} dE. \quad (5.1.f)$$

To calculate the total current we must sum over all the energies that contribute to the current flow:

$$I = -\frac{2e}{h} \int_{\mu_2}^{\mu_1} dE = -\frac{2e}{h} (\mu_1 - \mu_2). \quad (5.1.g)$$

The difference in chemical potential is maintained by applying a bias voltage V_{bias} such that:

$$(\mu_1 - \mu_2) = -e V_{\text{bias}}. \quad (5.1.h)$$

Thus

$$I = \frac{2e^2}{h} V_{\text{bias}}. \quad (5.1.i)$$

By definition, the conductance is

$$G_0 \equiv \frac{I}{V_{\text{bias}}}. \quad (5.1.j)$$

Finally, we have

$$G_0 = \frac{2e^2}{h}. \quad (5.1.k)$$

The numerical value of G_0 is $G_0 = 77.48 \mu\text{S}$ and $\frac{1}{G_0} = 12.91 \text{ k}\Omega$.

5.2 Landauer Formalism

A more general description of current flow through narrow constrictions takes into account the width of the conductor. The simplest way to do this is to model the electrons as laterally confined by a two-dimensional infinite potential in the x and y directions (see Fig. 5.2.a). This is the typical particle in a box problem of elementary quantum mechanics. By solving the Schrödinger equation it can be shown that there is a discrete number of eigenstates (or ‘modes’) for this two-dimensional system [3]. The total energy of the conductor is the sum of the lateral mode energy and of the

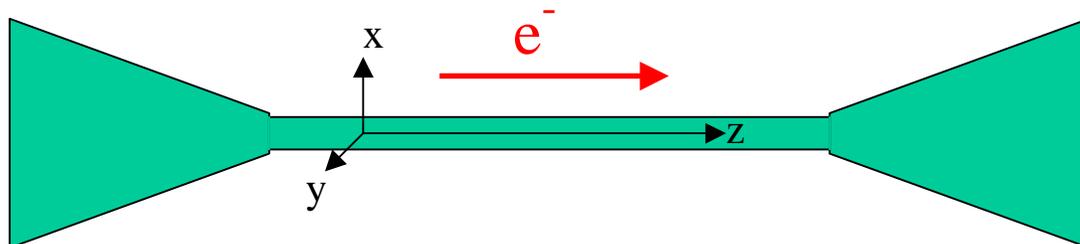


Fig. 5.2.a Lateral confinement in the conductor

energy of the one-dimensional solution in the z-direction. Therefore the dispersion relation for the conduction band represented in Fig. 5.1.b must be replaced by the one in Fig. 5.2.b. Modes are also called channels when considering conduction.

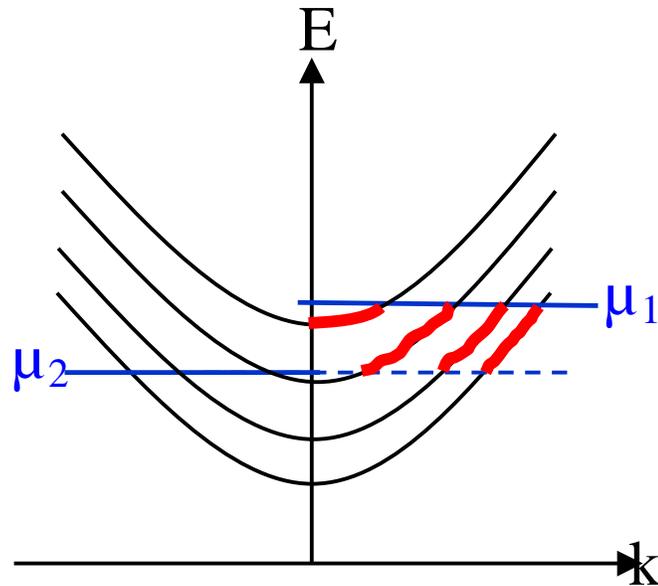


Fig. 5.2.b Conduction Band of a Confined Metal with 4 Transverse Modes

What is the effect of these channels on the conductance? The Landauer formalism for current flow through small constrictions provides the following answer [4]:

$$G = G_0 \sum_{i=1}^N T_i, \quad (5.2.a)$$

where G_0 is the quantum of conductance, N is the number of conduction channels and T_i is transmission coefficient for the i^{th} channel in the wire. The factors T_i come into play when the conductor is not ideal (i.e. non-ballistic). It represents the probability that an electron coming through one of the leads will transmit to the other side of the constriction traveling through the i^{th} channel. T_i is not equal to 1 when backscattering becomes important in the transport process. Since the length of break junctions is less than the mean free path of an electron in a metal ($\sim 100 \text{ \AA}$), it is

reasonable to assume that the conductance is ballistic and $T_i = 1$ for all channels. The Landauer formula becomes:

$$G = NG_0, \quad (5.2.b)$$

$$\frac{G}{G_0} = N. \quad (5.2.c)$$

Equation 5.2.c tells us that the conductance divided by G_0 is always equal to an integer. Following this analysis it becomes interesting to convert our current versus time data into a normalized conductance plot. Such a plot is shown in Fig. 5.3.a.

5.3 Comparison with Experimental Data

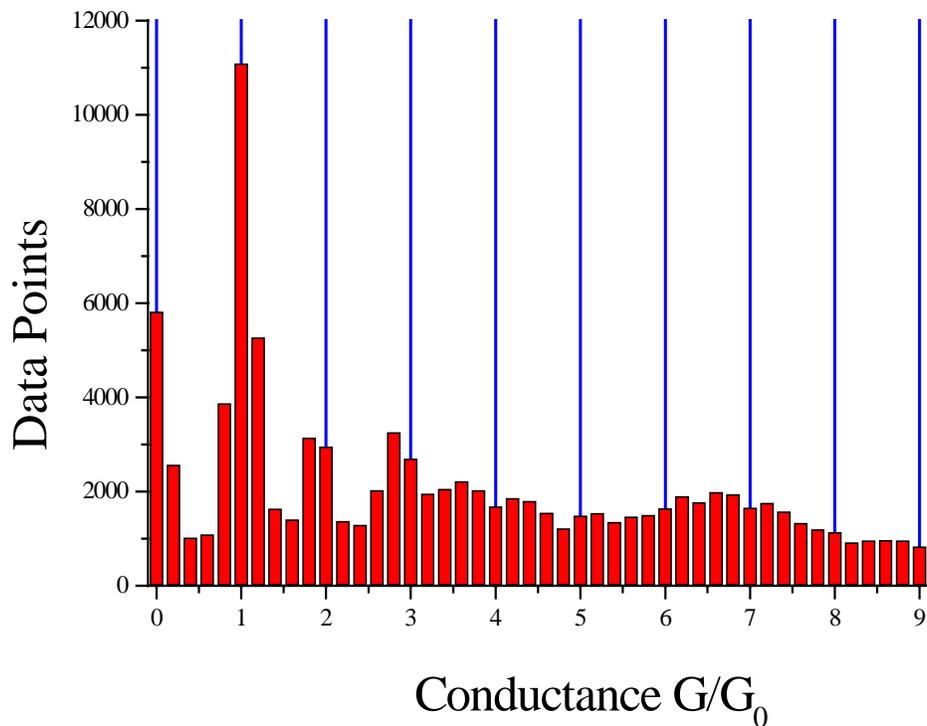


Fig. 5.3.a Conductance Histogram obtained from converting Fig. 4.3

The horizontal axis of the histogram plot in Fig. 4.2 was converted into a conductance axis and divided by the quantum of conductance G_0 to investigate the consistency with theoretical predictions (see Fig. 5.3). The conductance histogram reveals three peaks at $1.0 G_0 \pm 0.1 G_0$, $1.8 G_0 \pm 0.1 G_0$, and $2.8 G_0 \pm 0.1 G_0$. While peaks are observed, they exhibit a number of features:

- The peaks broaden for higher values of the conductance and are washed out after the third peak.
- The peaks tend to be shifted towards lower values of the conductance.

This shift in peak position can be modeled by a series resistance R_S such that

$$\frac{1}{G} = \frac{1}{G_{\text{junction}}} + R_S, \quad (5.3.a)$$

where G_{junction} is the intrinsic conductance of the break junction whereas G is the measured conductance. By plotting

$$G_{\text{junction}}/G_0 = \frac{1}{\frac{1}{G/G_0} - R_S G_0}, \quad (5.3.b)$$

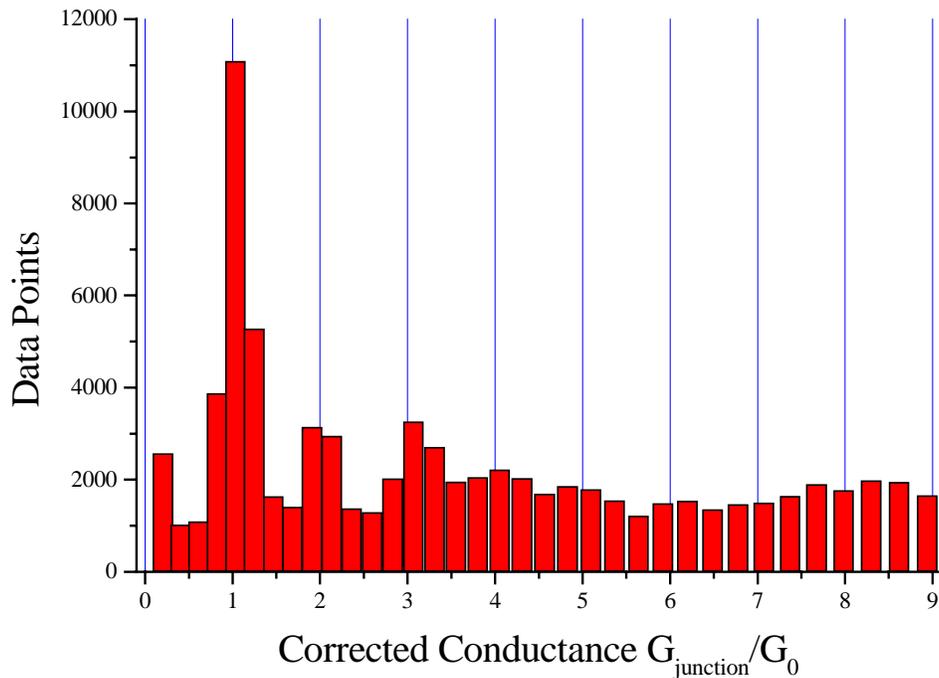


Fig. 5.3.b Conductance Histogram in Fig. 5.3.a
Corrected by a Series Resistance $R_S = 400 \Omega$

it is possible to fit the value of R_S to match the peak maximums with the integer values of the G_0 . Fig. 5.3.b is a plot of the conductance histogram in Fig. 5.3.a corrected by a series resistance of $R_S = 400 \Omega$, which is the value that fits our data best. The peaks are now located at $1.0 G_0 \pm 0.1 G_0$, $1.9 G_0 \pm 0.1 G_0$, and $3.1 G_0 \pm 0.1 G_0$. A confirmation of this fitting can be found in the fact that this corrected histogram also seems to reveal a faint peak at $4.0 G_0 \pm 0.1 G_0$. Our value of R_S falls within the range found in the literature: from 230 to 490Ω [2, 5, 6, 7]. This series resistance is due to the backscattering of the electrons [8].

The broadening and shifting of peaks are consistent with disorder in break junctions, as shown by tight-binding calculations done by Garcia-Mochales [9]. The results of these calculations are reproduced in Fig. 5.3.c. The parameter D is a disorder parameter.

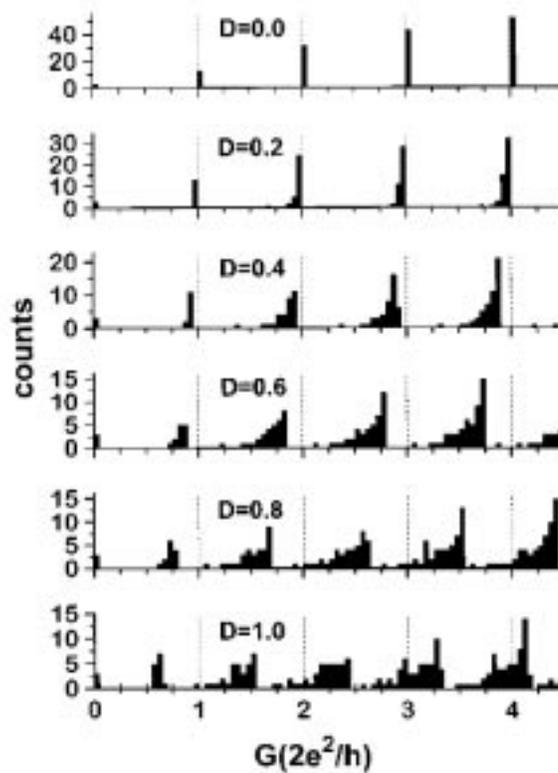


Fig. 5.3.c Theoretical histograms for nanowires with different degrees of disorder [9].

6. CONCLUSION

Our measurements show that the room temperature conductance of a Au break junction is quantized in units of the quantum of conductance $G_0 = \frac{2e^2}{h} = (12.91 \text{ k}\Omega)^{-1}$. As the junction breaks its width decreases reducing the number of channels available for conduction. Fig. 6 shows a geometry for the break junction that can be inferred from this study: the junction is formed of multiple strands of single-atom wires and when the strain increases the atoms rearrange to form fewer but longer wires. These rearrangements coincide with shifts in the conductance. Proof of this has actually been provided by High Resolution Electron Microscopy combined with simultaneous conductance measurements [10]. The images are reproduced in appendix C.

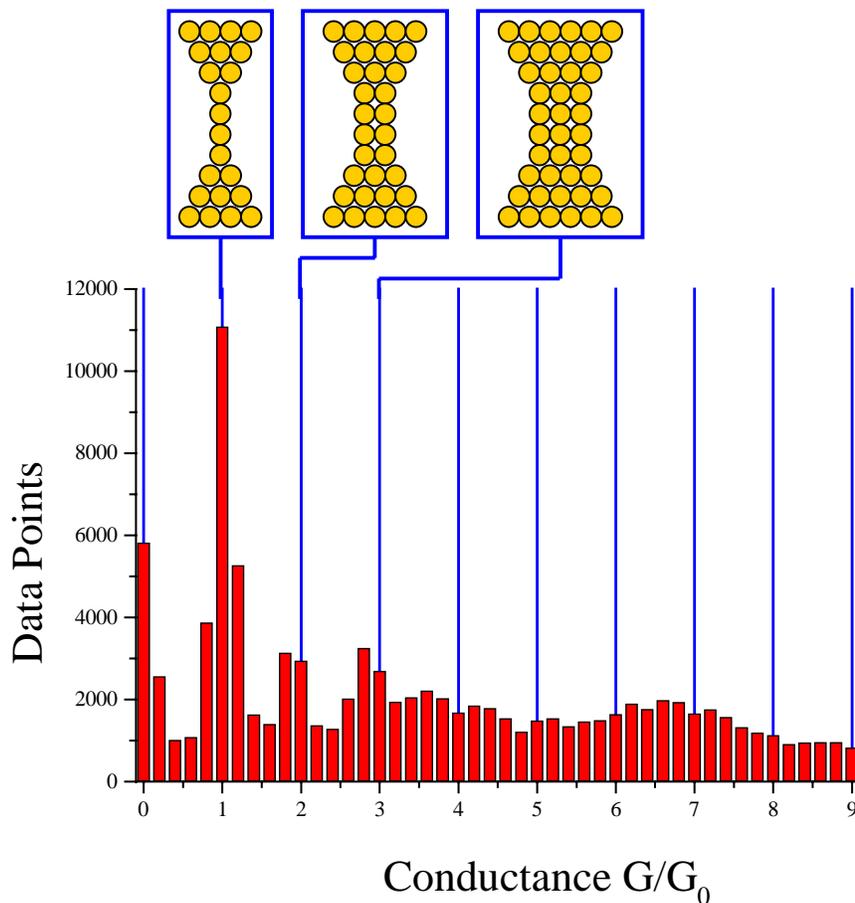


Fig. 6 Inferred Break Junction Geometry

The main difficulty encountered during this work was obtaining sufficient mechanical stability. Surprisingly the best stability we were able to obtain was well above our expectations: the junction remained at one quantum of conductance for several minutes. However this turned out to be very difficult to reproduce and subsequent measurements became difficult. Another problem we were confronted with was the presence of fictitious peaks in our histogram data. These peaks were most likely due to the difference in the vertical resolution of the current window and the number of bins in the histogram as suggested in reference [5]. This limited the number of bins that we could use to acquire our data and made for a resolution of only $\pm 0.1 G_0$.

Whereas the geometrical properties and conductance statistics of gold break junctions are now well understood, their I-V properties remain unexplained. Few studies have been made, but surprisingly I-V curves all reveal that at constant tip-sample separation (and therefore at constant conductance) I-V curves exhibit a non-linear behavior. A possible explanation could be Luttinger-Liquid transport properties due to the strong one-dimensional character of the break junctions [5].

The system we have built is designed to do I-V measurements, but if sufficient mechanical stability must be attained. This system could be used to perform statistical studies of other nanoscale systems such as carbon nanotubes and nanowires formed from molecule-coated nanometer-diameter gold clusters.

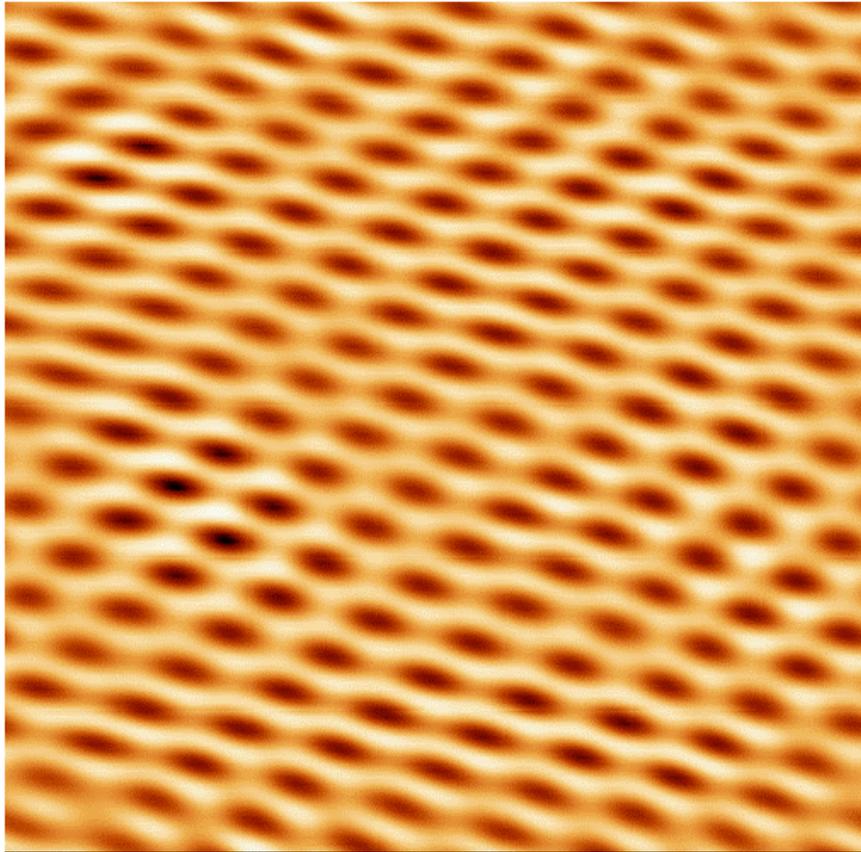
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APPENDIX

A. HOPG Image

HOPG (3% Boron doped) taken with a Pt tip
with the homebuilt air STM.



Data processed with a 2D-FFT.

B. Code for Histogram Acquisition Program

Large Sections of this code are taken from Tektronix QuickC programs.

```
#include <stdio.h>
#include <math.h>
#include <stdlib.h>
#include <string.h>
#include <conio.h>
#include <time.h>
#include "decl.h"
```

```

#define Np    1000 /*number of points*/
#define Ns    10   /*number of steps*/
#define Nb    5    /*number of bins per step*/
#define R     1e4  /*resistor value*/
#define G0    7.748092e-5
#define Vb    25.8e-3 /*bias*/

int scope;      /* address of scope */
int brd;        /* handle for gpib board: GPIB0 */

/*****
*
* gpibWrite - send the contents of the string to the device and wait
* for the write to finish.
*****/
int gpibWrite( int dev, char *cmd)
{
    int cmd_len;

    cmd_len = strlen(cmd);

    /*
    * set the timeout for 10 seconds, send the command
    * wait for the scope to finish processing the command.
    */
    ibtmo(dev,13);
    ibwrt (dev,cmd,cmd_len);

    /*
    * If ibwrt was successful, wait for scope completion.
    */
    if(ibsta >=0)
        ibwait(dev,STOPend);

    return(ibsta);
}

/*****
* gpibRead - read into the string from the device and wait for the
* read to finish.
*****/
int gpibRead( int dev, char *resp, int cnt )
{
    /*
    * set the timeout for 10 seconds, send the command, and
    * wait for the scope to finish processing the command.
    */
    ibtmo(dev,13);

```

```

    ibrd(dev,resp,cnt);
    /*
    * If ibrd was successful, wait for scope completion.
    */
    if(ibsta >=0)
        ibwait(dev,STOPend);

    return(ibsta);
}

/*****
* gpibWait - wait for a gpib command to finish by doing a query
* and reading its results; wait only as long as the delay value
*****/
int gpibWaitCom(int dev, int delay)
{
    char rd[6];

    delay = delay+0;
    gpibWrite(dev,"*OPC?");

    if(ibsta >= 0)
        gpibRead(dev,rd, strlen(rd));

    return(ibsta);
}

/*****
* gpiberr - display error from defined error codes based on what
* is contained in ibsta. This routine would notify you that an IB
* call failed.
*****/
void gpiberr(char *msg)
{
    printf ("%s\n", msg);
    printf ( "ibsta=&H%x <", ibsta);

    if (ibsta & ERR ) printf (" ERR");
    if (ibsta & TIMO) printf (" TIMO");
    if (ibsta & END ) printf (" END");
    if (ibsta & SRQI) printf (" SRQI");
    if (ibsta & RQS ) printf (" RQS");
    if (ibsta & CMPL) printf (" CMPL");
    if (ibsta & LOK ) printf (" LOK");
    if (ibsta & REM ) printf (" REM");
    if (ibsta & CIC ) printf (" CIC");
    if (ibsta & ATN ) printf (" ATN");
    if (ibsta & TACS) printf (" TACS");
    if (ibsta & LACS) printf (" LACS");
}

```

```

if (ibsta & DTAS) printf (" DTAS");
if (ibsta & DCAS) printf (" DCAS");
printf (" >\n");

printf ("iberr= %d", iberr);
if (iberr == EDVR) printf (" EDVR <DOS Error>\n");
if (iberr == ECIC) printf (" ECIC <Not CIC>\n");
if (iberr == ENOL) printf (" ENOL <No Listener>\n");
if (iberr == EADR) printf (" EADR <Address error>\n");
if (iberr == EARG) printf (" EARG <Invalid argument>\n");
if (iberr == ESAC) printf (" ESAC <Not Sys Ctrlr>\n");
if (iberr == EABO) printf (" EABO <Op. aborted>\n");

if (iberr == ENEB) printf (" ENEB <No GPIB board>\n");
if (iberr == EOIP) printf (" EOIP <Async I/O in prg>\n");
if (iberr == ECAP) printf (" ECAP <No capability>\n");
if (iberr == EFSO) printf (" EFSO <File sys. error>\n");
if (iberr == EBUS) printf (" EBUS <Command error>\n");
if (iberr == ESTB) printf (" ESTB <Status byte lost>\n");
if (iberr == ESRQ) printf (" ESRQ <SRQ stuck on>\n");
if (iberr == ETAB) printf (" ETAB <Table Overflow>\n");
}

/*Function getwfm*/
void getwfm(float *voltptr)
{
int rslt;           /* error return variable */
char wfm[2040];    /* array for raw scope input */
FILE *outfile;    /* output file handle */
int i;             /* loop index */
int nr_pt, pt_off;
char cmd[80];
char c;
char *ptr;
float yoff, ymult, xincr, xzero;
char xunit[12], yunit[12];

printf("\nTransferring waveform....");

memset( cmd, 0, 80 ); /* initialize command string to all nulls */

/* Prepare to read waveform data */
sprintf( cmd, "DATA:SOURCE CH1");
if((gpibWrite( scope, cmd ) < 0) ||
   (gpibWrite( scope, "DATA:ENCDG RIBINARY;WIDTH 1") < 0)||
   (gpibWrite( scope, "HORIZONTAL:RECORDLENGTH 1000") < 0) ||
   (gpibWrite( scope, "DATA:START 1") < 0)||
   (gpibWrite( scope, "DATA:STOP 1000") < 0)||
   (gpibWrite( scope, "HEADER OFF") < 0))
{

```

```

        gpiberr("ibwrt Error: Unable to Setup waveform parameters");
        exit(1);
    }

    ibwrt (scope,"TRIG:MAI:MOD NORM",17);
    ibwrt (scope,"ACQ:STOPA SEQ",14);

    /* Make sure setup changes have taken effect and a new waveform is acquired
*/
    if (gpibWrite( scope, "ACQUIRE:STATE RUN") < 0)
        {
            gpiberr("Error: GPIB error or timeout waiting to acquire waveform");
            exit(1);
        }

    printf ("\nWaiting for Single Acquisition to Finish...");
    ibwrt(scope,"*WAI",4);

    printf ("\nTransferring Curve....");
    /* Read screen image data */
    if (gpibWrite( scope, "CURVE?") < 0)
        {
            gpiberr("ibwrt Error: CURVE?");
            exit(1);
        }
    /* printf("\nIssued CURVE?"); */
    /* Read in the header information. The header includes #<x><yyy> */
    ibrd( scope, &c, 1 ); /* read in the '#' symbol */
    ibrd( scope, &c, 1 ); /* read in string length of num bytes to transfer */
    rslt = atoi(&c); /* convert string to integer */
    ibrd( scope, cmd, rslt ); /* read in string containing num bytes to transfer */
    cmd[rslt]='\0'; /* force a null terminated string */
    rslt = atoi(cmd); /* num bytes to transfer */
    /* printf("\n About to read waveform."); */
    /* Read the raw waveform data including the linefeed at the end */
    if((ibrd( scope, wfm, rslt ) < 0) || (ibrd( scope, &c, 1 ) < 0))
        {
            gpiberr("ibrd Error: WAVEFORM");
        }
    /* printf("\nAbout to read preamble."); */
    /* Read the waveform preamble */
    sprintf( cmd,
"WFMPRE:CH1:NR_PT?;YOFF?;YMULT?;XINCR?;PT_OFF?;XUNIT?;YUNIT?"
);
    if(gpibWrite( scope, cmd ) < 0)
        {
            gpiberr("ibwrt Error: WFMPRE?");
            exit(1);
        }
    memset( cmd, 0, 80 ); /* initialize the string buffer */

```

```

if(ibrd( scope, cmd, 80 ) < 0)
    {
        gpiberr("ibrd Error: WFMPRE");
        exit(1);
    }
sscanf( cmd, "%d;%e;%e;%e;%d;%[^;];%s", &nr_pt, &yoff, &ymult,
        &xincr, &pt_off, xunit, yunit );

/* Process waveform data*/

/* Output scaled x, y values in (Sec, Volts)
* Time[i] = (i - PTOFF) * XINCR
* Volts[i] = (point value - YOFF) * YMULT
*/
for(i=0;i<nr_pt;i++){
    voltptr[i]=(float)(((float)wfm[i] - (float)yoff) * ymult);
    /* printf("\nvoltptr[%d] = %f",i,voltptr[i]); */
}

/*Histogram Function*/
void hist(float *voltptr,unsigned long *freqptr)
{
    int i,j;
    float cond[Np]={{0}};
    float data[Np]={{0}};

    printf ("\nAdding data to histogram....");

    for (i=0;i<Np;i++)
        {
            cond[i]=voltptr[i]/(R*G0*Vb); /*Conversion into units of G0*/
            data[i] = floor(Nb*cond[i]+0.5); /*Rounding into a bin*/
            /* printf ("\n cond[%d] = %f ",i,cond[i]); */
            /* printf (" data[%d] = %f",i,data[i]); */
            freqptr[(int)data[i]]++; /*Incrementation of bin*/
        }
}

main()
{
    int i,j,k,n;
    float volt[Np]={{0}};
    unsigned long freq[Nb*Ns+1]={{0}};
    FILE *outfile;

/*Function prototype*/
void getwfm(float *);
void hist(float *, unsigned long *);

```

```

/* Assign unique identifiers to the device DEV1 store it in the
 * variable "scope" and check for errors. If DEV1 is not defined,
 * ibfind returns -1 */
if( ((scope = ibfind("DEV1")) < 0) ||
    ((brd = ibfind("GPIB0")) < 0))
    {
        gpiberr("ibfind Error: Unable to find device/board!");
        exit(0);
    }

/* Clear the device and check for errors */
if ((ibclr(scope) < 0) || (ibsre(brd,0) < 0))
    {
        gpiberr("ibclr/ibsre Error: Unable to clear device/board!");
        exit(0);
    }

/*Reset counter*/
n=1;

/*Acquire and process data*/
while(kbhit()==0)
    {
        clrscr();
        gotoxy(0,0);
        printf ("\nCurve: %d",n);
        getwfm(volt);

        if(volt[0]>volt[Np-1])
            {
                n++;
                hist(volt,freq);
            }
    }

/*Print number of curves put in histogram*/
clrscr();
gotoxy(0,0);
printf("\nA total of %d curves processed.\n", n);

/*Save histogram in file*/
outfile=fopen("hist.dat","w");
fprintf(outfile,"%s \t %s\n","G","Freq");
for(i=0;i<=Nb*Ns;i++)
    fprintf(outfile,"%f \t %lu\n",(float)i/Nb,freq[i]);
fclose(outfile);

}

```

C. High-Resolution Electron Microscopy Images [10]

These images are reproduced from H. Ohnishi et al. The sequence a, b, c, d, e, f is chronological and represents different stages of the breaking of the junction. The arrows point out the number of gold atom strands. The images show that the junction is successively formed of 5, 4, 3, 2, and 1 strands before it is broken.

