The Multimeter at the Nanoscale

Charge transport measured at the nanoscale by a multi-tip scanning probe microscope

Bert Voigtländer, Vasily Cherepanov, Peter Coenen

PGI-3 Forschungszentrum Jülich, 52425 Jülich

A multi-tip scanning tunneling microscope (STM) specifically designed for charge transport measurements at the nanoscale is described. Complementing the instrument with a versatile measurement electronics creates a powerful tool to give insight into fundamental transport properties at the nanoscale. We demonstrate the capabilities of the instrument by measuring resistance profiles along freestanding GaAs nanowires, by the acquisition of nanoscale potential maps, and by the identification of an anisotropy in the surface conductivity at a silicon surface.

1 Introduction

Since microelectronics evolves into nanoelectronics, it is essential to perform electronic transport measurements at the nanoscale. The standard approach to this is to use lithographic methods for contacting nanostructures. In a final nanoelectronic device, this method will be used. However, in research and development stages other methods to contact nanoelectronic devices may be more suitable. An alternative approach for the contacting of nanostructures is to use the tips of a multi-tip scanning tunneling microscope (STM) [1], in analogy to the test leads of a multimeter used at the macroscale. The advantages of this approach are: (a) *in situ* contacting of “as grown” nanostructures still under vacuum allows to keep delicate nanostructures free from contaminations which can be induced by lithography steps performed for contacting. (b) Flexible positioning of contact tips and different contact configurations are easy to realize, while lithographic contacts are permanent. (c) Probing with sharp tips can be non-invasive (high ohmic), while lithographic contacts are invasive (low ohmic).

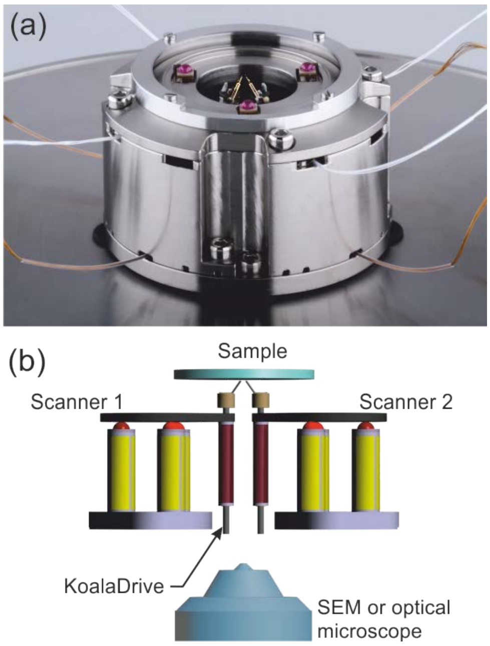

Fig. 1 (a) Photo of the TetraProbe multi-tip scanning probe microscope *with an outer diameter of only 50 mm, leading to highest stability. (b) Schematic side view of the internal structure of the TetraProbe instrument.*

In order to use the scanning tunneling microscopy (STM) for electrical measurements at nanostructures, more than one tip is required. Thus, we developed an ultra-compact and ultra-stable multi-tip scanning tunneling microscope (STM) which gives access to the above outlined advantages in nanoprobing [2]. This is in accord with the recent paradigm shift in scanning probe microscopy which transforms from “just imaging” to detailed measurements at the nanoscale.

2 TetraProbe multi-tip microscope

A photo of our instrument is shown in Fig. 1(a) and Fig. 1(b) shows the side view of the internal structure of two of the four modular scanning units. Each unit comprises a KoalaDrive, a nanomotor particularly developed in order to make scanning probe microscopes ultimately small. The KoalaDrive, which is described in detail in Ref. [3], is used for the coarse tip-approach towards the sample. The tip is mounted under 45° relative to the vertical direction in order to allow the positioning of all tips at one region on the sample. The KoalaDrive is fixed to a horizontal plate (black in Fig. 1(b)) which is moved in the horizontal directions via slip-stick motion [1]. The plate rests on three balls fixed to three tube piezo elements. Saw-tooth signals on these piezo elements allow an inertial slip-stick motion (coarse motion) of the plate in the horizontal xy-directions. The fine xyz-scanning of the tips is performed by these three piezo elements, as well.

Four of these scanning units are integrated inside a housing of 50 mm outer diameter, allowing for a completely independent motion of all four tips. The whole instrument is built ultrahigh vacuum compatible. The tips and the sample can be changed without breaking the vacuum. With the sample holder placed on top of the housing, it is closed completely leading to a good electric shielding from outer disturbances. The sample holder can be moved in xy-directions over several mm by shear piezo elements on top of the housing. In order to bring the tips to a desired position for the subsequent electrical measurements, it is important that the motion of the four tips and the sample can be observed, either by an optical microscope, or by a scanning electron microscope as shown in the bottom of Fig. 1(b). A scanning electron microscope (SEM) image of the four tips brought close to the sample under study is shown in Fig. 2. Imaging with the secondary electrons leads to a shadow effect (dark shadow image of the tip apex) giving access to the tip sample distance, as seen best for the lower left tip in Fig. 2. With the KoalaDrive as key element, it was possible to develop an ultra-compact multi-tip scanning tunneling microscopy (STM) instrument with a drift of less than 0.2 nm/minute at room temperature and with atomic resolution for all four tips. Recently, a startup company named mProbes [4] has been founded by the authors which offers this instrument and others.

Fig. 2 SEM image of four tips (diameter 250 µm) close to the surface. Imaging with the secondary electrons leads to a shadow effect giving access to the tip sample distance. The dark shadow of the tip is seen best for the lower left tip.

Performing electrical measurements with a four-tip microscope demands more than to have four tips and to be able to position them to desired places. Concerted measurements of currents and voltages with all four tips have to be performed on a real time basis. Our electronics allows operating each tip either as (biased) current probe, or as voltage probe as shown in Fig. 3. Before an electrical measurement, all four tips are positioned to the desired positions on the sample. Subsequently, the tips are approached towards the sample by a desired distance, and different I/V ramps are applied between different tips (and/or the sample. In the simplest case a current is injected between the two outer tips and a potential difference is measured between the inner tips (classical four-point measurement). However, also various kinds of other measurements can be performed.

3 Nanoscale transport

In the following, we demonstrate the capabilities of the instrument for nanoscale charge transport measurements by presenting some examples.

3.1 Resistance profiling along nanowires

As a first example, we present nanoscale resistance mapping along freestanding GaAs nanowires with a diameter of ~100 nm. The structure of these nanowires grown by a method known as vapor-liquid-solid growth, involving vertical growth of the nanowires on a substrate via a catalytic gold particle, was studied in detail. However, not much is known about the dopant incorporation and the resulting electrical properties of such freestanding nanowires. This is the case, as the nanowires are still “as grown” upright and attached to the substrate, thus it is not possible to contact nanowires by lithographic techniques. In the measurement configuration shown in Fig. 4(a), the sample is tilted by 45° in order to facilitate optimal SEM imaging of the nanowires, as shown in Fig. 4(b). The schematics in Fig. 4(a), and in an SEM image in Fig. 4(b) shows three tips brought into contact with a nanowire, realizing a four-point resistance measurement (with the sample as fourth contact). Tip 1 injects the current to the nanowire with the sample acting as current drain, while tip 2 and tip 3 act as voltage probes. In this way a four-point measurement is realized.

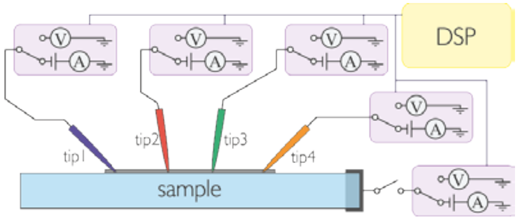

Fig. 3 Schematic of the capabilities for concerted spectroscopic measurements. Each tip can be configured as current probe or as voltage probe. Patterns of injected currents (and tip heights) can be performed and the resulting voltages are recorded. The simplest example of a pattern is a classical four-point resistance measurement.

The configuration of the (green) voltage probing tips is analogous to the test leads of a multimeter with the important difference that now the electrical measurements are performed at the nanoscale. Another technical difference is that resistance measurements with a multimeter are usually performed with two test leads only. In a two probe measurement, the total measured resistance is the sum of the resistance of the resistor to be tested plus the contact resistances of the two leads. At the nanoscale these contact resistance can be as large as, or even larger than the resistance of the nano-device under study. Due to this, a four-point measurement has to be used. While in the two point method the current injection I and the voltage probing V are performed in one single loop, these are separated in two loops in the four-point method. While the injected current still depends on the contact resistances, the actual value I is measured (Fig. 4(a)). The voltage between the two other probes (green in Fig. 4(a)) is measured with a voltmeter having an inner resistance much larger than the contact resistances. Thus, a resistance measurement with the four-probe method (R = V/I) is independent of the contact resistances.

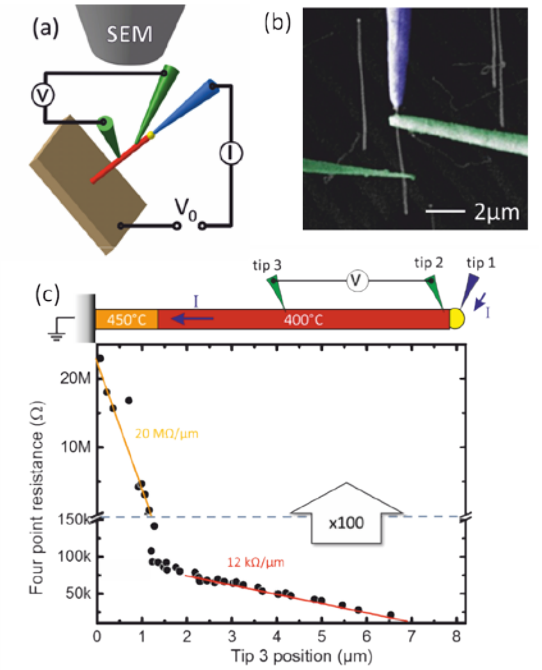

Fig. 4 (a) Schematic of a four-point measurement on a nanowire with three tips contacting the nanowire. (b) SEM image of a freestanding nanowire contacted by three tips. The STM tips act like the test leads of a multimeter, however, contacting objects like the nanowire at the nanoscale. (c) Resistance profile along a nanowire measured at many different points along the nanowire. On the top in (c) the two step growth process is indicated with the nanowire base grown at high temperature (orange), leading to an undesired high resistance at the nanowire base (as shown in the lower part of (c)). The upper part of the nanowire (red) has the desired low resistance (12 kΩ/µm).

In the STM based approach of nano-contacting, four-point measurements can be performed not only in one single configuration, as it is the case for the lithographic approach, but many configurations can be measured by moving the tips along the nanowire (a movie of this can be accessed in the web [4]). In this way we can measure a resistance profile along the nanowire with 40 or 50 data points. Figure 4(c) shows a resistance profile along a nanowire, which shows a small resistance in the upper part of the wire, while at the nanowire base the resistance becomes very high [5]. This can be correlated to the two-step growth process of the nanowires: An initial high temperature growth step was used in order to nucleate straight vertically growing nanowires, while a lower growth temperature leads to a more efficient incorporation of the doping species. The identification of the undesired very low doping of the base of the nanowires is a very valuable information triggering subsequent efforts towards improving the electrical properties of the nanowires (increasing the doping) by using different growth conditions.

3.2 Potential maps

Another method giving valuable insight into the charge transport properties of nanostructures is the scanning tunneling potentiometry (STP) [6]. STP can be performed with a multi-tip STM and allows to map the potential landscape while a current flows through the film/nanostructure under study. Potentiometry maps give insight into fundamental transport properties, such as the influence of defects on the local electric transport.

The implementation is shown in Fig. 5(a), with tips 1 and 2 injecting a current into the nanostructure or surface to be studied, while tip 3 simultaneously measures the topography and also records the electric potential at each image point which is induced by the flowing current. Figure 5(b) shows an example of a potential map measured on a silicon surface, showing that the largest potential drop occurs at the atomic step edges. Implementing scanning tunneling potentiometry into a multi-tip STM setup has several advantages: (a) The direction of the injected current can be changed quickly. (b) The local current density can be high by positioning the injecting tips close to each other. (c) No external contacts have to be provided to the sample. The potential resolution is a couple of µV. We have applied the STP technique on Si surfaces and could determine the surface conductivity on the terraces as well as the step resistivity [6].

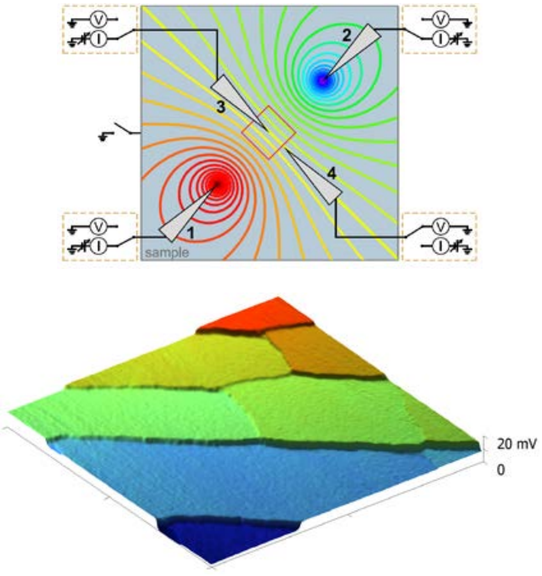

Fig. 5 (a) Schematic of the four-tip scanning tunneling potentiometry setup. Tips 1 and 2 are in contact to the sample surface and inject a lateral current represented by the colored equipotential lines. Tip 3 is in tunneling contact and is scanned *across the surface, acquiring the topography map and the potential map simultaneously. The scan area is indicated as red square (largely exaggerated). (b) Potential map measured on a Si surface with the main potential drop occurring at the atomic step edges. The current flows from the top to the bottom in this image.*

3.3 Anisotropic conductance

As nano-devices become smaller and smaller, the surface to volume ratio (i.e. the fraction of atoms located at the surface) increases constantly. The increasing importance of surface conductance compared to conductance through the bulk in modern nanoelectronic devices calls for a reliable determination of the surface conductivity in order to minimize the influence of undesired leakage currents on the device performance or to use surfaces as functional units. A model system for corresponding investigations is the Si(111)-7x7 surface.

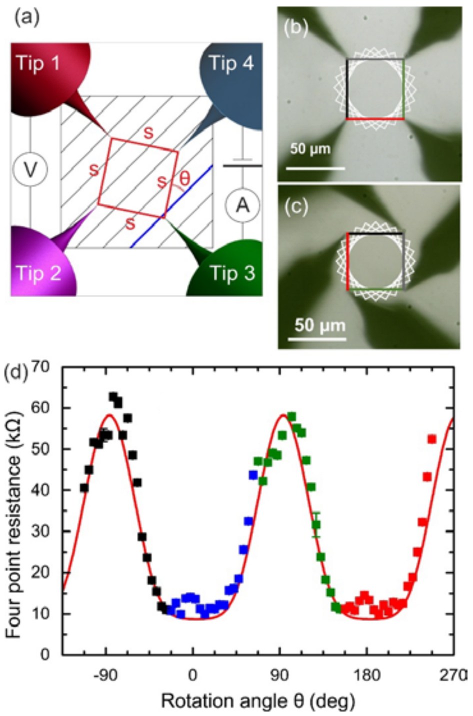

Fig. 6 Anisotropy of the surface conductivity of the Si(111)-7x7 surface. (a) Schematic of the square four-point configuration with the steps on the surface indicated by the diagonal lines. The square given by the tip positions on the sample is rotated, as also shown in the actual microscopy images (b)-(c). (d) Four-point resistance measured as function of the rotation angle. The resistance is low if the current is directed parallel to the step edges, while it is large when the current is perpendicular to the step edges.

The challenge is to disentangle the contribution due to the surface conductivity from the bulk conductivity. We have recently developed a method which uses distance dependent four-probe measurements in the linear configuration in order to determine the surface conductivity [7]. Moreover, also the anisotropy of the surface conductivity can be measured by the four-probe method, when the tips are arranged in a square arrangement and are rotated (Fig. 6(a)-(c)). In the current case the anisotropy is induced by a parallel arrangement of atomic steps on the surface. If the injected current runs parallel to the step edges, the measured four-point resistance is lower than for a current directed perpendicular to the step edges. The continuous behavior of the measured four-point resistance as function of the rotation angle is shown in Fig. 6(d). From these data the step resistivity as well as the resistivity of the terraces can be determined [7].

4 Conclusion and outlook

A multi-tip scanning tunneling microscope can be like a multimeter at the nanoscale in order to contact nanostructures by the tips and performing subsequently electrical measurements. This multi-tip based approach of nanoprobing has the advantage of a very flexible probe (re-) positioning, allowing for many different probing geometries on a single nanostructure. Moreover, contaminations of the nanostructures inherent to the lithographic approach are avoided and the probing contacts can be non-invasive. In order to implement the scanning probe based approach of nanoprobing, we designed an ultra-compact multi-tip STM with an outer diameter of 50 mm with a drift of less than 0.2 nm/min at ambient conditions. This instrument which is now also commercially available by mProbes is complemented by a versatile measurement electronics which allows virtually any electrical measurements involving the four tips and the sample.

Altogether, the SPM based nanoprobing approach and specifically our TetraProbe instrument allows to perform a large variety of nondestructive electrical measurements at the nanoscale. Currently, the TetraProbe instrument is developed further towards a multi-tip AFM/STM to allow for an improved performance on partly insulating samples.

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