Ultra-Compact Multitip Scanning Probe Microscope with an Outer Diameter of 50 mm

Vasily Cherepanov, Evgeny Zubkov, Hubertus Junker, Stefan Korte, Marcus Blab, Peter Coenen and Bert Voigtländer

Abstract We present a multitip scanning tunneling microscope (STM) where four independent STM units are integrated on a diameter of 50 mm. The coarse positioning of the tips is done under the control of an optical microscope or an SEM in vacuum. The heart of this STM is a new type of piezoelectric coarse approach called Koala Drive which can have a diameter greater than 2.5 mm and a length smaller than 10 mm. Alternating movements of springs move a central tube which holds the STM tip or AFM sensor. This new operating principle provides a smooth travel sequence and avoids shaking which is intrinsically present for nanopositioners based on inertial motion with saw tooth driving signals. Inserting the Koala Drive in a piezo tube for *xyz*-scanning integrates a complete STM inside a 4 mm outer diameter piezo tube of <10 mm length. The use of the Koala Drive makes the scanning probe microscopy design ultra-compact and accordingly leads to a high mechanical stability. The drive is UHV, low temperature, and magnetic field compatible. The compactness of the Koala Drive allows building a four-tip STM as small as a single-tip STM with a drift of <0.2 nm/min and lowest resonance frequencies of 2.5 (*xy*) and 5.5 kHz (*z*). We present examples of the performance of the multitip STM designed using the Koala Drive.

1 Introduction

The controlled fabrication of self-organized nanostructures with dimensions in the single digit nanometer range is becoming possible [1]. However, the measurement of charge transport through such nanostructures is still a challenge.

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One problem is to provide electrical contacts to individual nanostructures. One approach is to establish such contacts by a multitip STM in order to enable charge transport and scanning potentiometry measurements at self-assembled nanostructures. Key requirements for multitip scanning probe instruments are that (a) all tips are independently positionable from the millimeter range down to the nanometer or atomic scale; (b) optical microscopy imaging or better scanning electron microscopy (SEM) imaging is necessary in order to navigate the tips close to each other without tip–tip crashes and in order to find specific structures on the surface in case of lithographically structured samples; (c) the final electric measurements (e.g. four point measurements) should be performed at one specific position on the nanometer/atomic scale and destruction free, i.e. without indenting the tip in an uncontrolled way into the surface or a nanostrucure. In order to meet the last requirement an instrument with currently unsurpassed stability has to be constructed. The construction of single tip instruments has shown over the last decades that the smaller an instrument is, the less drift results and the lower is the vibrational noise. This was the starting point for us to develop an ultra-compact multitip scanning probe instrument with a drift of <0.2 nm/min at room temperature.

A limit for the size of a scanning probe microscope is the size of the scanner tube, since tube scanners are used in virtually every modern scanning probe instrument. On top of the size of the scanner there comes the size of the tip-sample coarse approach. This is usually the largest part of a scanning probe microscopy instrument. We developed an ultra-compact Koala Drive which can be used for the tip-approach. It is so small that it can be even integrated inside the tube scanner, leading to an ultimate minimum size scanning probe instrument only limited by the size of the scanner tube. Apart from its small size the Koala Drive has several other advantages like a smooth travel, different from the saw tooth signal driven inertial nanopositioners [2–5] which utilizes large accelerations and correspondingly induces vibrations and undesirable power dissipations in the system. Moreover, the Koala Drive is low temperature, magnetic field and ultrahigh vacuum compatible.

In the current context the Koala Drive will be the heart of our multitip scanning probe microscope and allows to construct it with the ultra-compact size of 50 mm outer diameter. Apart from the low drift and low vibrational noise, the small size facilitates the use of such an instrument in environments where the space is limited, such as inside a cryostat or inside an electron microscope.

We will first introduce the working principle of the Koala Drive and demonstrate its operation characteristics. Then we demonstrate how the Koala Drive can be used to construct ultra-compact scanning probe instruments, specifically multitip instruments. We will present the specifications and some initial applications of our ultra-compact multitip scanning probe microscope.

2 The Koala Drive

The Koala Drive consists of two tube piezo elements mounted in series (one after another) as shown in Fig. 1a. At the ends and between the two tube piezos three springs are mounted, which can be moved by an extension or compression of the tube piezos along their axes. A central tube is held by these three springs. The working principle of the Koala Drive relies on concerted consecutive motions in which the frictional surfaces between a spring and the tube are alternating between static friction and sliding friction. Whenever only one spring moves, the other two will hold the tube (by static friction) and only at the single moving spring the frictional engagement will be lifted and sliding friction will occur.

One cycle of motion is shown in Fig. 1a. In step 1 of the cycle the upper piezo element contracts and the upper spring goes into sliding friction. The central tube is held stationary by the lower two springs which stay in static friction with the tube. Subsequently, in step 2 the middle spring is moving downwards while the upper and the lower spring stay at their positions. For the upper spring this is realized by a simultaneous contraction of the lower piezo element and a corresponding expansion of the upper one, leaving the upper spring unmoved. Also here a single spring (middle one) is moving, while the other two holds the tube fixed. Finally, in step 3 the lower piezo extends and moves the two upper springs up simultaneously. In this case the lower spring goes into sliding friction and the upper two springs move the tube up (static friction). Simplified, the working principle follows the rule: “Two are stronger than one”. If two springs move simultaneously, the central tube moves with them. If only one spring moves, the tube is held stationary by the other two. In Fig. 1b a photo of a Koala Drive is shown. The ultra-compact Koala Drive can have a diameter <2.5 mm and length smaller than 10 mm.

In Fig. 2 the principle of a voltage pattern at the piezo tubes (piezo 1 and piezo 2) and the resulting motion of the tube during one cycle are shown as function of time. One single cycle can induce a motion in the range between several μm and 100 nm which is ideally suited for coarse approach in scanning probe microscopy. A long stroke, only limited by the length of the tube, and speeds up to ~1 mm/s are possible.

Most other nanopositioners used for tip-sample approach in scanning probe microscopy use the inertial motion with sawtooth like signals inducing large accelerations causing vibrations in the system. The operation mode of the Koala Drive is quasi static (one cycle can even last several seconds) avoiding large accelerations which lead to a continuous motion without shaking. Avoiding steep slope signals means also less demands for the power supply (no high slew rate needed) and for the cabling (no high currents flow).

Movies of the motion of the Koala Drive measured using an SEM during one cycle of motion are available in the web under www.fz-juelich.de/pgi/pgi-3/koala. These real time movies show the motion of a STM tip attached to the central tube.

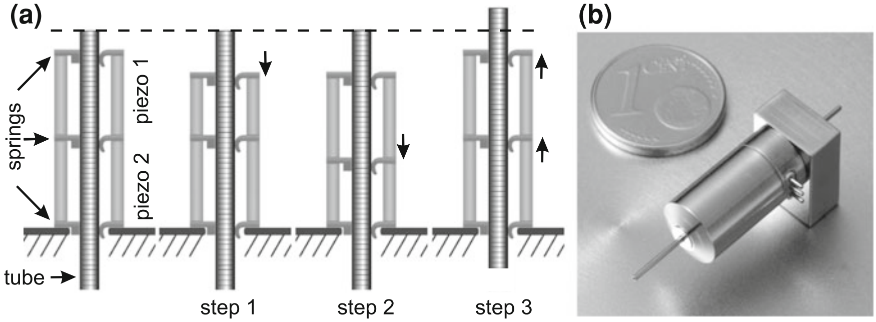
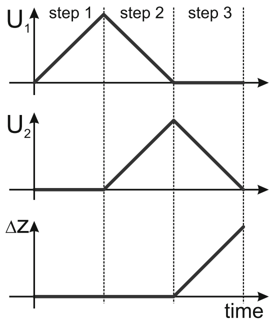


Fig. 1 **a** Principle of the design of the Koala Drive. **a** Working principle of the Koala Drive: concerted interplay between static friction and sliding friction. If only one spring moves, the tube is held stationary by the other two. The motion of the springs during the different steps of a *cycle* is indicated by *arrows*. If two springs move simultaneously, the central tube moves together with them. **b** Photo of the Koala Drive

Fig. 2 Voltage pattern applied to both piezo tubes and the resulting motion of the central tube as function of time



The performance of the Koala Drive can also be seen in graphs showing the motion of the tube induced by a single cycle (step) as function of the amplitude of the excitation voltage shown in Fig. 3. Starting from low amplitudes, there is a threshold voltage above which the motion of the Koala Drive starts. For lower voltages the extension of the piezo tubes results in a buildup of stress in the system, but only beyond the threshold voltage a transition to sliding friction occurs. For amplitudes larger than this threshold voltage the single step displacement increases linearly with the signal voltage. Due to the smaller piezo constant at low temperatures, the threshold and the slope of the curves decrease for operation at low temperatures. This shows that the Koala Drive works at cryogenic temperatures (down to liquid helium temperatures) and moreover it is also ultra-high vacuum compatible and works in magnetic fields.

Depending on the particular application the design of the Koala Drive can be modified. If, for instance, the length of the drive should be small, the two tubes can alternatively be coaxially placed into each other instead of one after the other as can be seen in Fig. 4.

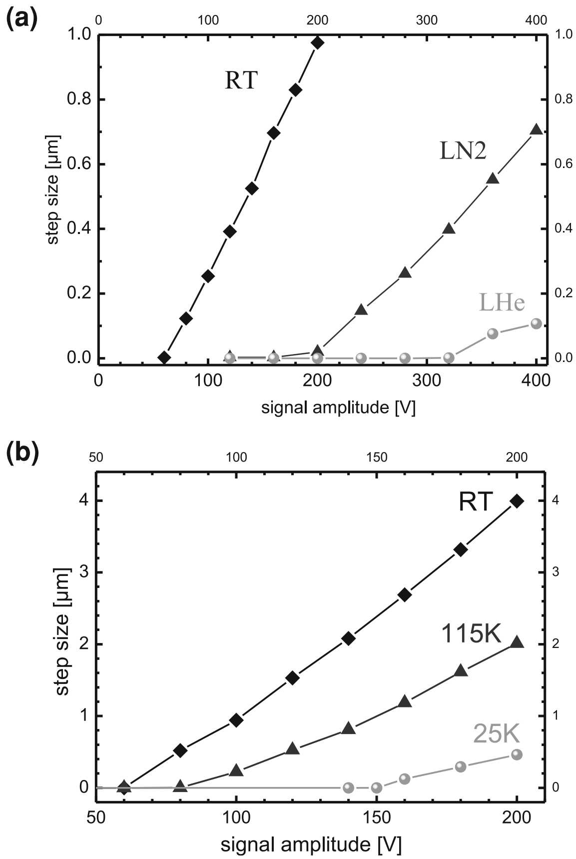


Fig. 3 Koala Drive performance: single step displacement as function of signal amplitude. **a** The data are shown for a 12 mm long Koala Drive at room temperature, liquid nitrogen temperature and at 10 K. **b** Data for a 20 mm long Koala Drive

3 The Koala Drive STM

In the next step the Koala Drive can be used to build an ultra-compact STM. The Koala Drive is used for the tip-sample coarse approach and is integrated into a segmented (scanning) tube piezo element used for the *xyz*-scanning fine motion as shown in Fig. 5a. The STM is completed by attaching a tip (plus tip holder) to the central tube and an outer frame, which holds the sample Fig. 5a. Since the coarse approach mechanism is integrated into the piezoelectric tube scanner, no extra space for the coarse approach is required. Thus this design leads to a minimal size STM. In this way a complete STM scanner can be integrated inside a 4 mm outer diameter piezo tube of <10 mm length. The use of the Koala Drive makes the scanning probe microscopy design ultra-compact and leads accordingly to a high mechanical stability. An STM image of the Si(111)-(7 × 7) surface taken with a Koala Drive STM is shown in Fig. 5b.

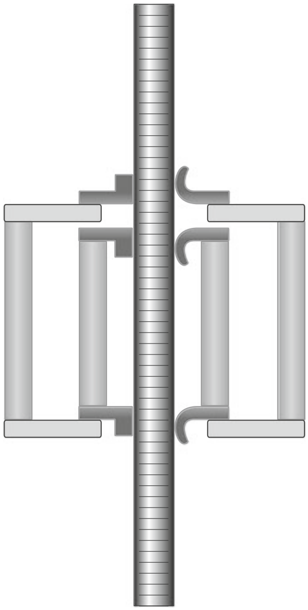


Fig. 4 Another variant of the Koala Drive design where the two piezoelectric tubes are coaxially stacked into each other

4 The Koala Drive Multitip STM

The advantage of the Koala Drive is utilized fully in the design of an ultra-compact four-tip STM using the Koala Drive. The modular design consists of four identical units. Each unit consists of a Koala Drive used for the coarse tip-approach toward the sample. The tip is mounted under 45° relative to the vertical direction in order to allow for the positioning of the tip apex to the same region as the ends of the other tips. The Koala Drive is fixed to a plate which is moved according to the design of the beetle STM [4].

Four of these units can be integrated inside a housing of 50 mm outer diameter. A photo of this ultra-compact four-tip STM is shown in Fig. 6a. The whole instrument is built ultrahigh vacuum compatible. With the sample holder placed on top, the housing is closed completely leading to a good shielding from outer electric disturbances. The sample holder can be moved in *xy* directions over several mm in coarse motion by shear piezo elements on top of the housing. The coarse motion of the four tips and the sample can be observed by an optical microscope from below, or in future by a scanning electron microscope. The view onto the four tips brought within couple of μm together on a lithographically structured test sample is shown in Fig. 6b. The working distance of the optical microscope is 50 mm. Videos showing tip positioning and sample positioning under the control of the optical microscope can be found in the web under www.fz-juelich.de/pgi/pgi-3/koala.

STM images of a Pt(111) single crystal were taken under ambient conditions with all four tips [6]. An example which shows one atomic layer high steps is

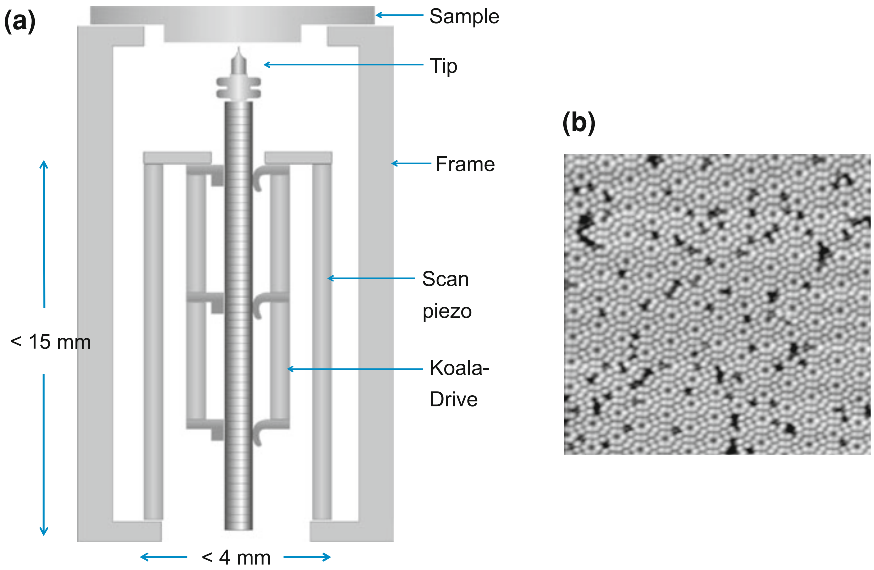


Fig. 5 **a** Design of a single tip STM using the Koala Drive leading to a minimal size STM. **b** Atomically resolved STM image of the (7 × 7) structure on a Si(111) sample (lateral scan size 30 × 30 nm)

shown in Fig. 7. The drift of the system was measured by taking continuously many scans over a time of several hours and identifying same features (defects) in those images. The *xy*-drift was measured in this way to <0.2 nm/min and the *z*-drift to <0.1 nm/min under ambient conditions at room temperature in an ordinary lab which was not specifically temperature stabilized.

The specifications of the ultra-compact four-tip STM are summarized in the following:

- Coarse tip *xy*-positioning: type: inertial slider, range: ±2 mm (each unit).
- Coarse tip *z*-positioning: type: Koala Drive range: ±5 mm (each unit).
- Coarse sample *xy*-positioning: type: inertial slider, range: ±2 mm.
- Scanning: *xy*-range: 10 µm (each unit at RT), *z*-range: 1 µm (each unit at RT).
- Measured lowest resonance frequencies: *xy*: 2.5, *z*: 5.5 kHz.

A multitip STM has the disadvantage that only conducting samples can be studied. However, many interesting samples important in nanoelectronics consist of conducting structures on insulating substrates. In order to perform electrical measurements on insulating substrates (e.g. SiO_2) a multitip scanning force microscope (AFM) is required. In the future we would like to extend our multitip STM to a multitip AFM (atomic force microscope). However, AFM detection method most widely used (the beam deflection detection) is not suitable for this, since four optical systems would have to be adjusted and interference between the four laser beams is likely to occur. For this reason a completely electrical

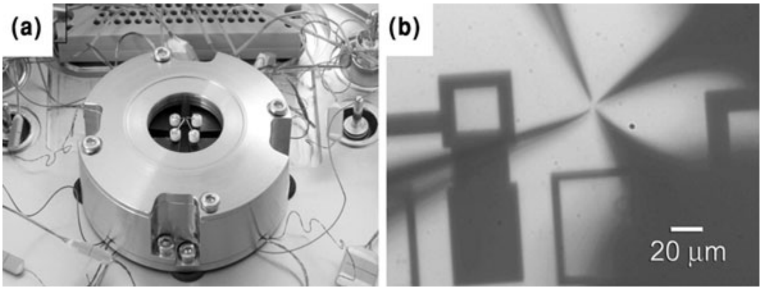


Fig. 6 **a** Photo of an ultra-compact four-tip STM with an outer diameter of 50 mm. **b** Optical microscope image of the four tips of the ultra-compact four-tip STM brought within a couple of µm together. The optical microscope views to the tips and sample from below

excitation and detection is desirable. This can be achieved by quartz crystal sensors like the tuning fork sensor [7] or the needle sensor. We have chosen the needle sensor, because of its small footprint which is advantageous in the context of multitip instruments. We have performed tests which showed that the needle sensor can be used to upgrade an STM in an easy way to an AFM [8, 9].

5 Measurements Performed with a Multitip STM

In the following we report on some measurements performed with one of our multitip STM instruments. These results were obtained with the multitip STM shown in Fig. 8a. These results demonstrate a proof of principle for electrical measurements with a four-tip STM.

Making electrical measurements with a four-tip STM is more than to have four tips and to be able to scan with them. Concerted measurements of currents and voltages with all four tips have to be performed on a real time basis. A typical measurement is performed as follows. Initially all four tips are scanning in STM mode and positioned to the desired positions at which the electrical measurement will be performed. Then the feedback (e.g. for all four tips) is disabled and the tips are approached toward the sample by a desired distance (or remain in the original position). Subsequently, 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 probe measurement). However, also various kinds of other measurements can be performed, for instance I/V measurements of every tip to the sample in order to measure the resistance of the contact which has been established by approaching the tip. We usually perform such kind of calibration measurements before and after the actual measurement in order to test the stability of the contacts formed. These different I/V ramps can last altogether 10–20 s and we observe a change in the measured currents of $<10\%$ for the same measurements performed at the

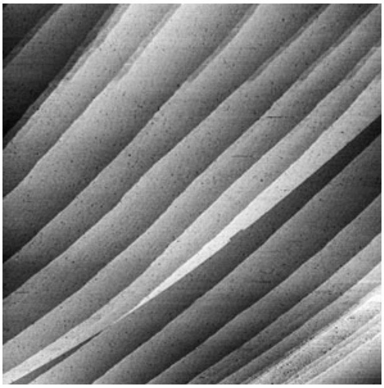


Fig. 7 STM image of atomically high steps on a Pt(111) crystal under ambient conditions (lateral scan size 500 × 500 nm). Corresponding images were acquired with all four tips

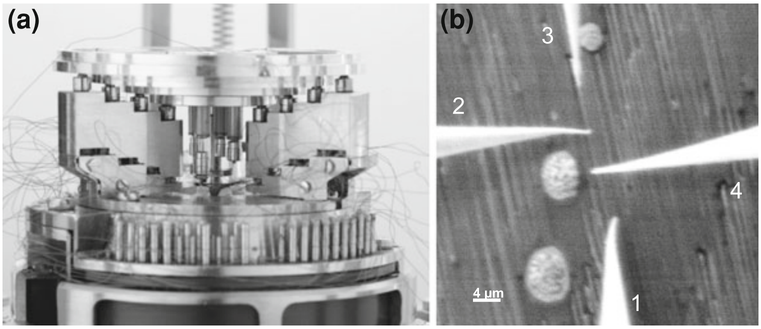


Fig. 8 **a** Photo of our multitip STM with which the results presented in the following were obtained. **b** SEM image of Y-silicide nanowires grown on Si(110). Due to the crystal symmetry of the Si(110) substrate the silicide nanowires are aligned in the vertical direction. The four STM tips are positioned in a line in order to contact one nanowire

beginning or the end of this time frame. The stability of the electric tip-sample contacts established over a measurement period is important in order to obtain reliable results. If all desired voltage ramps are finished the tips are moved back to the original tunneling tip-sample distance and the feedback is resumed.

In order to perform such concerted measurements the control electronics of all for tips have to communicate to each other.

5.1 Four Point Measurements at an Yttrium Silicide Nanowire

As a first example we show a four-tip measurement at an yttrium silicide nanowire. The yttrium silicide nanowires were grown by depositing 0.6 nm yttrium at 1070 K sample temperature. Due to the crystal structure of the Si(110) substrate the silicide nanowires are aligned along one direction which is vertically in the SEM image shown in Fig. 8b. The silicide nanowires have a height of 5–30 nm, a width between 30 and 50 nm and length of several μm. The four tips of the STM are positioned in a line in order to contact one nanowire as shown in Fig. 8b.

Unlike in a conventional four probe measurement where the two outer probes inject the current and the two inner probes act as voltage probes, here we used only current probes. The principle of the measurement setup is shown in Fig. 9a and consists of four current probes which are biased to a certain potential. Technically they are built by biased STM preamplifiers. The difference between the bias potentials of the outer probes drives a current through the nanowire which is measured by the two (outer) current probes. Before we come to the measurement of the potential by the two inner probes, we consider a possible leakage of the injected current to the substrate.

In principle the current injected by one of the outer probes can run not only through the nanowire as desired, but can also leak to the substrate. In this context it is important to keep in mind that the interface between silicide nanowire to the silicon substrate forms a Schottky barrier. If this Schottky barrier is reverse biased, no current will flow to the substrate. We confirmed this by measuring the current to the substrate by a fifth current preamplifier Fig. 9a. If the Schottky barrier was reverse biased, only a negligible current was detected proving that the current runs almost only through the silicide nanowire.

After establishing a current through the nanowire by the outer probes (probes 1 and 3 in Fig. 8b), the potential of the inner probes was determined by recording successively I/V curves of tip 2 and tip 4. The potential at which no current flows corresponds to the potential at the position of tip 2 and tip 4, respectively. Technically tip 2 and tip 4 are contacted one after the other to the nanowire, and the bias voltage of each tip (2 and 4) was ramped and the current flowing through the corresponding preamplifier was recorded. The voltage for which no current flows corresponds to the potential present on the nanowire at the position of the tip. The two I/V curves recorded for tip 2 and tip 4 while a current of 200 μA was flowing through the nanowire are shown in Fig. 9b. As can be seen from this image, the voltage difference between tip 2 and tip 4 is 167 mV, which results in a resistance of 935 Ω. Taking into account the distance between tips 2 and 4 (2.4 μm), as well as the height ($\sim$15 nm) and the average width ($\sim$50 nm), results in a resistivity of 26 μΩ cm. This value can be compared to a resistivity of about 50 μΩ cm measured on thin yttrium silicide thin films [10, 11].

5.2 Four Point Measurements on Graphene

In the following we present four probe measurements performed on graphene exfoliated on SiO_2. The fact that the graphene is located on top of an insulating SiO_2 layer without any outer contacts to the graphene flake makes it difficult to contact such graphene flakes by a multitip STM. Using an SEM the tip can be

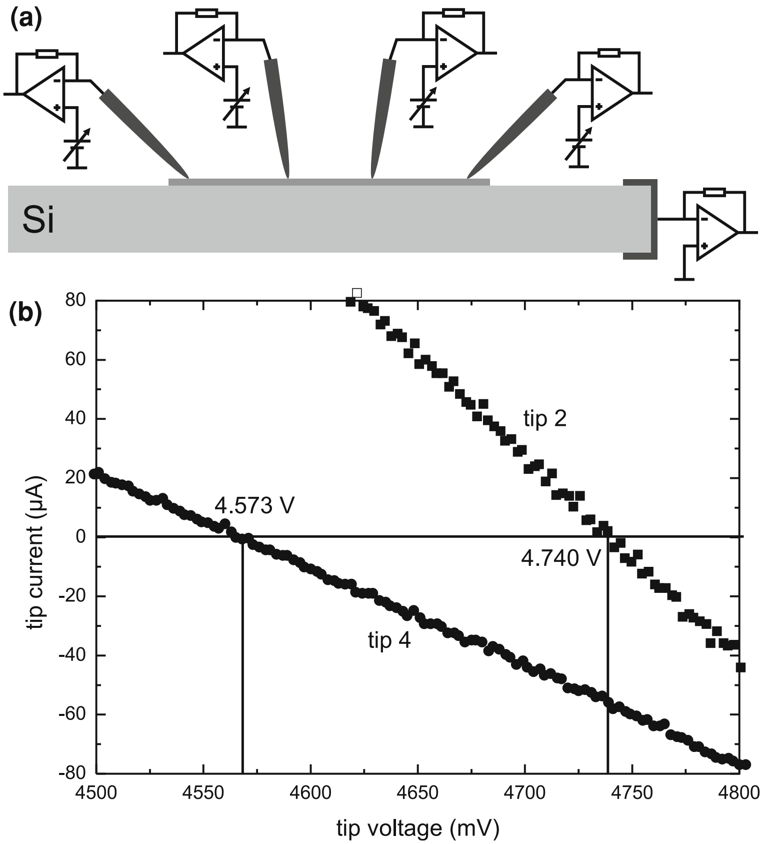


Fig. 9 **a** Principle of a four point measurement using biased preamplifiers as current probes. **b** I/V measurements of tip 2 and tip 4 in Fig. 8b. The voltage at which the current vanishes corresponds to the potential of the tip

positioned above the graphene flake, but the distance between tip and sample is difficult to estimate from the SEM images.

Here we present a method to detect the point of contact between tip and graphene flake using SEM images and a biased tip. Figure 10a shows a SEM image in which a graphene flake is imaged with dark contrast on the silicon dioxide substrate. The tip approaching the surface is still not in contact with the flake. If the tip is negatively biased at -10 V, the SEM contrast of the graphene flake reverses to a bright contrast if the biased tip comes into contact with the graphene flake, as seen in Fig. 10b. The negative potential of the graphene flake relative to the sample leads to an enhanced emission of secondary electrons. Vice versa a positive tip voltage leads to a darker contrast in the SEM image at the

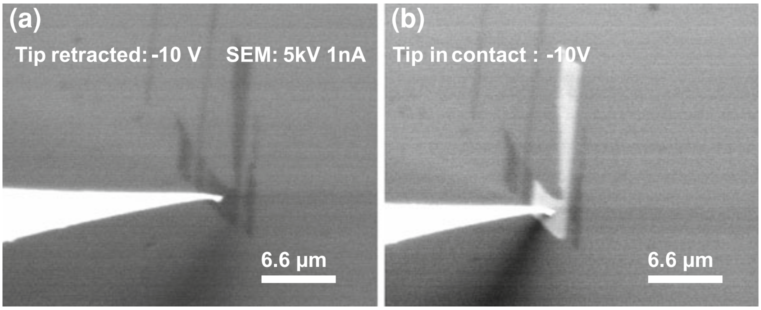


Fig. 10 Contacting of a graphene flake under SEM control using a biased tip. **a** The tip is not in contact with the flake: the flake appears to be darker than substrate. **b** The flake, when contacted with a biased tip, appears to be brighter than the substrate

point of contact. The method described above allows to contact graphene flakes on an insulating oxide substrate nondestructively by an STM tip.

After the first tip has been brought nondestructively into contact to the graphene flake a bias voltage can be applied to the flake and the other tips can be contacted using the ordinary STM mode approaching the tip to a biased flake. This has been done on a several layers thick graphene (graphite) flake shown in the SEM image in Fig. 11a. Tip 3 and especially tip 4 are bent quite much (from previous experiments) but can be still used to drive a current into the graphene sheet. The potential present at the positions of tip 1and tip 4 is measured using these tips as voltage probes, disconnected from the current preamplifiers during the concerted measurement. This conventional four probe measurement with the inner tips used as voltage probes results in a I/V curve which is shown in Fig. 11b. A linear dependence between the measured voltage difference and the injected current is measured. The slope corresponds to a resistance of 9.43 Ω which results in a sheet resistance of 60 Ω/□ taking into account an infinite flake model and the actual distances between the tips. After the measurement of the I/V curve is finished, tip 1 and tip 4 return to the tunneling position.

6 Conclusions

We have shown that the development of a new type of piezoelectric motor serves as the basis for ultra-compact scanning probe microscopes. The Koala Drive is the heart of our ultra-miniature STMs. The Koala Drive can tap its full potential for the miniaturization for the case of multitip scanning probe instruments. We constructed an ultra-compact multitip STM with an outer diameter of 50 mm with a drift of <0.2 nm/min at ambient conditions. This instrument can be combined with an optical microscope or a SEM in order to navigate the positioning of the tips.

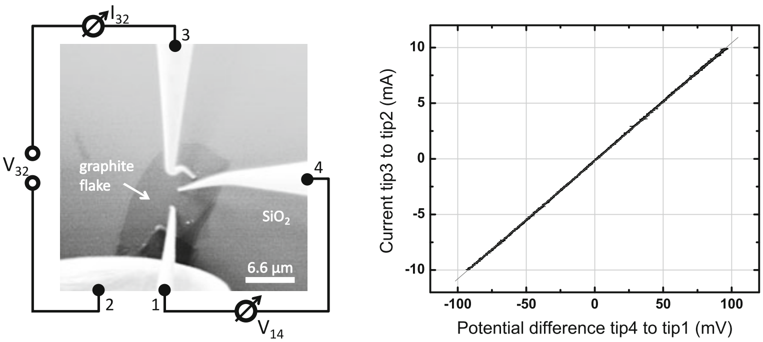


Fig. 11 **a** SEM image of four tips positioned on a multi-layer graphene flake in order to perform a four probe measurement. Tip 2 (at the lower left edge of the image) is very much bent. **b** Measured I/V curve during a four probe measurement resulting in a sheet conductance of 60 Ω/□

We demonstrate the capabilities of the instrument by four point measurements at a yttrium silicide nanowire and on a graphene flake. Here concerted measurement processes starting and ending with the tips in tunneling conditions are essential in order to perform nondestructive electrical measurements at the nanoscale.

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