AIP Review of Scientific Instruments

A nanopositioner for scanning probe microscopy: The KoalaDrive

Vasily Cherepanov, Peter Coenen, and Bert Voigtländer

Citation: Rev. Sci. Instrum. **83**, 023703 (2012); doi: 10.1063/1.3681444
View online: http://dx.doi.org/10.1063/1.3681444
View Table of Contents: http://rsi.aip.org/resource/1/RSINAK/v83/i2
Published by the AIP Publishing LLC.

A nanopositioner for scanning probe microscopy: The KoalaDrive

Vasily Cherepanov, Peter Coenen, and Bert Voigtländer[a)]
Peter Grünberg Institut (PGI-3), Forschungszentrum Jülich, 52425 Jülich, Germany and JARA-Fundamentals of Future Information Technology

(Received 5 December 2011; accepted 13 January 2012; published online 7 February 2012)

We present a new type of piezoelectric nanopositioner called KoalaDrive which can have a diameter less than 2.5 mm and a length smaller than 10 mm. The new operating principle provides a smooth travel sequence and avoids shaking which is intrinsic to nanopositioners based on inertial motion with sawtooth driving signals. In scanning probe microscopy, the KoalaDrive can be used for the coarse approach of the tip or sensor towards the sample. Inserting the KoalaDrive in a piezo tube for *xyz*-scanning integrates a complete scanning tunneling microscope (STM) inside a 4 mm outer diameter piezo tube of <10 mm length. The use of the KoalaDrive makes the scanning probe microscopy design ultracompact and accordingly leads to a high mechanical stability. The drive is UHV, low temperature, and magnetic field compatible. The compactness of the KoalaDrive allows building a multi-tip STM as small as a single tip STM. © *2012 American Institute of Physics*. [doi:10.1063/1.3681444]

INTRODUCTION

Key requirements in scanning probe microscopy are the insensitivity to mechanical vibrations and a small (thermal) drift of the instrument. In order to fulfill these figures of merit, the design of scanning probe instruments has seen an evolution over three decades from initially quite large instruments[1,2] to contemporary pocket size scanning probe microscopes (SPMs).[3–5,7] The KoalaDrive nanopositioner which we present here (Fig. 1(b)) was developed in an effort to push the design of SPMs further towards ultracompact instruments. Here, the minimal size is not a value on its own, but leads directly to improvements for the key figures of merit. A smaller size leads directly to a smaller thermal drift which scales linearly with the size. Also, a smaller size increases the eigenfrequencies often more stronger than linearly, leading to a better damping of (unavoidable) external vibrations.

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, i.e., the mechanism which brings tip and sample form an initial mm separation into the μm extension range of the piezoelectric scanner tube. This coarse approach is usually a quite large part of a scanning probe microscope. The ultracompact KoalaDrive (which is now also commercially available) can be used for this tip-sample approach. It is so small that it can be 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 KoalaDrive has the advantage of a smooth travel, different from the sawtooth signal driven inertial nanopositioners[6,8–10] which utilize large accelerations and correspondingly induce vibrations and undesirable power dissipations in the system. Moreover, the KoalaDrive is low temperature, magnetic field, and ultrahigh vacuum compatible.

We will first introduce the working principle of the KoalaDrive and demonstrate its operation characteristics. Then, we demonstrate how the KoalaDrive can be used to construct ultracompact scanning probe instruments. The KoalaDrive can tap its full potential for the miniaturization of scanning probe instruments for the case of multi-tip scanning probe instruments.

THE KOALADRIVE

The KoalaDrive consists of two tube piezo elements mounted in series, for instance (one after the other), as shown in Fig. 1(a). 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 KoalaDrive 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. 1(a). 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 ones hold 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

a)Corresponding author; b.voigtlaender@fz-juelich.de.

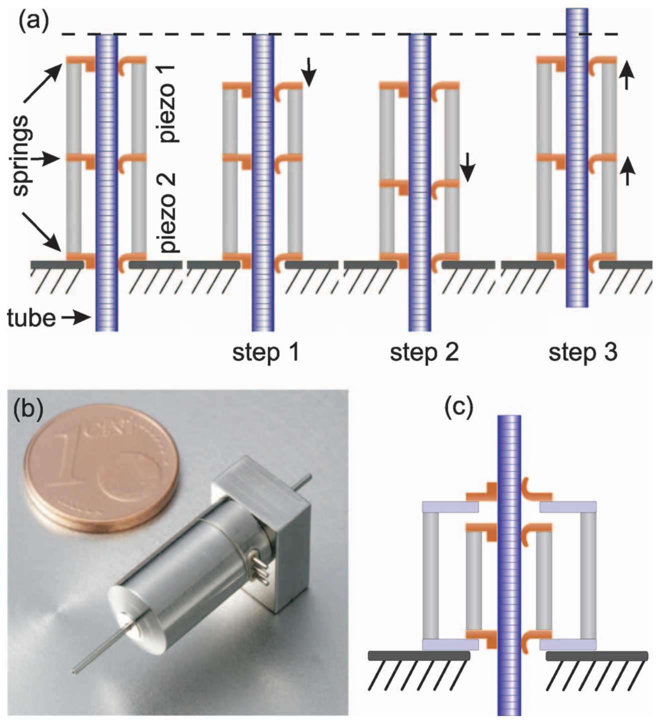

FIG. 1. (Color online) (a) Principle of the design of the KoalaDrive. (a) Working principle of the KoalaDrive: concerted interplay between static friction and sliding friction. If only one spring moves, the tube is hold stationary by the other two. The motion of the springs during the different steps of a cycle is indicated by arrows. If two springs move simultaneously, the central tube moves together with them. (b) Photo of the KoalaDrive. (c) Another variant of the KoalaDrive design where the two piezoelectric tubes are coaxially stacked into each other.

simultaneously, the central tube moves with them. If only one spring moves, the tube is hold stationary by the other two. In Fig. 1(b) a photo of a KoalaDrive is shown. The ultracompact KoalaDrive can have a diameter less than 2.5 mm and length smaller than 10 mm. Depending on the particular application, the design of the KoalaDrive can be modified. If, for instance, the length of the drive is small, the two tubes can alternatively be coaxially placed into each other instead of one after the other as can be seen in Fig. 1(c).

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 $\sim$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 KoalaDrive 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 KoalaDrive measured using an SEM during one cycle of motion are available in

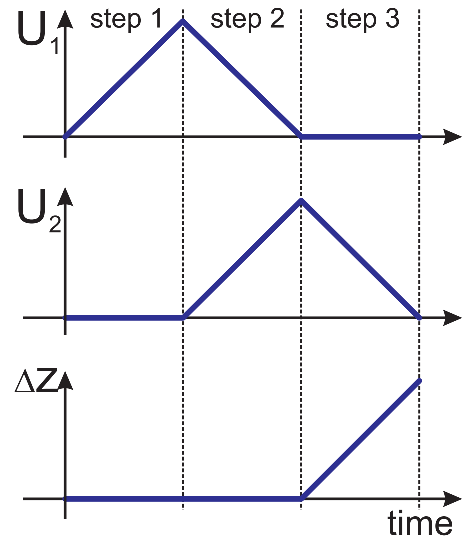

FIG. 2. (Color online) Voltage pattern applied to both piezo tubes and the resulting motion of the central tube as function of time.

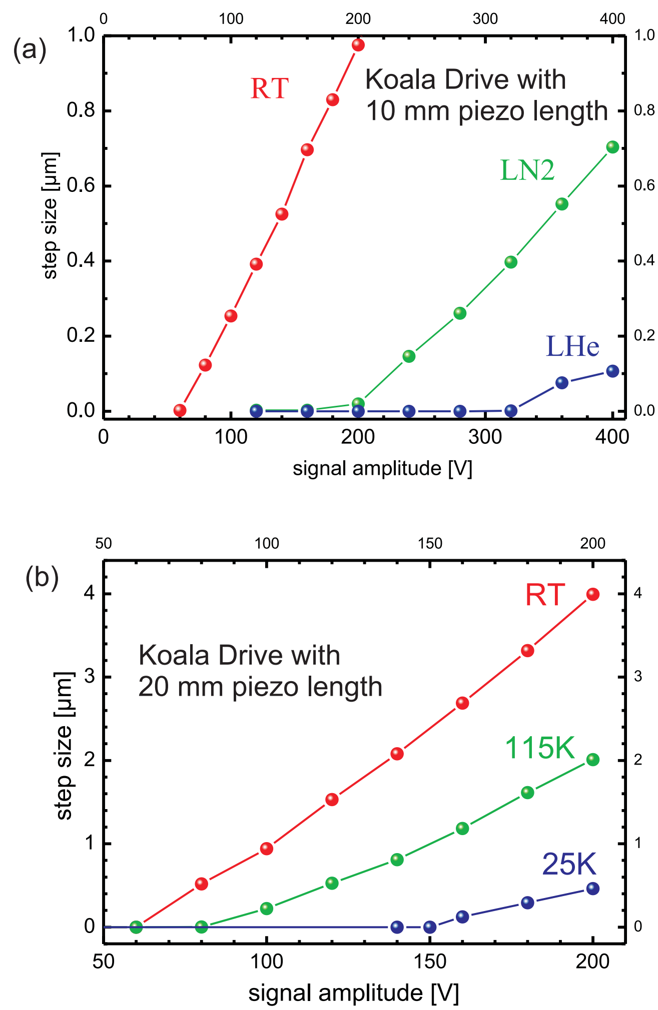

FIG. 3. (Color online) KoalaDrive performance: single step displacement as function of signal amplitude. (a) The data are shown for a KoalaDrive with a total piezo length (sum of both piezo elements) of 10 mm at room temperature, liquid nitrogen temperature, and at 10 K. (b) Data for a KoalaDrive with a total piezo length of 20 mm.

the web under www.fz-juelich.de/pgi/pgi-3/koala. These real time movies show the motion of a scanning tunneling microscope (STM) tip attached to the central tube.

The performance of the KoalaDrive 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. These data were measured by performing several hundreds of steps and simultaneously observing the total distance moved using an optical microscope. Starting from low amplitudes, there is a threshold voltage above which the motion of the KoalaDrive starts. For lower voltages, the extension of the piezo tubes results in a build up 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 KoalaDrive works at cryogenic temperatures (down to liquid helium temperatures). The step sizes range from a minimal step size of $\sim$100 nm up to several μm depending on the length of the KoalaDrive and the applied voltage. The piezo length indicated in Fig. 3 corresponds to the length of both piezo elements together.

In order to provide a reliable operation, all three springs should have the same spring constants and a careful alignment of the springs with respect to the central tube is important. The reliability of the KoalaDrive has been confirmed by using it in air during a five-day exhibition for 8 h continuously without becoming stuck. This corresponds to more tip-sample approaches that can be reasonably performed with one STM. In UHV, we operate one STM with KoalaDrive coarse approach since two years without any problem.

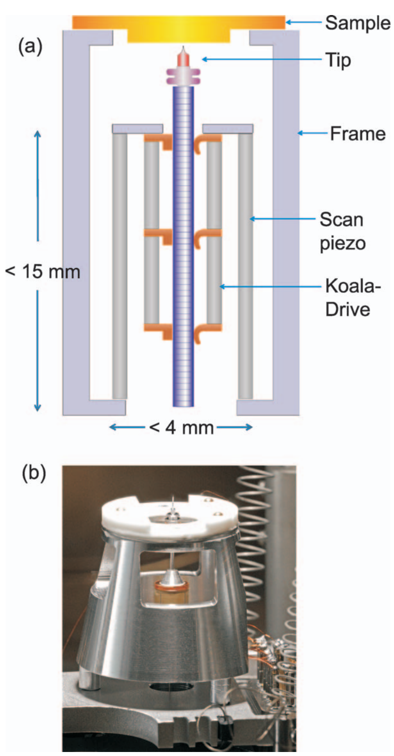

FIG. 4. (Color online) (a) Design of a single tip STM using the KoalaDrive leading to a minimal size STM. (b) Photograph of an actual KoalaDrive STM.

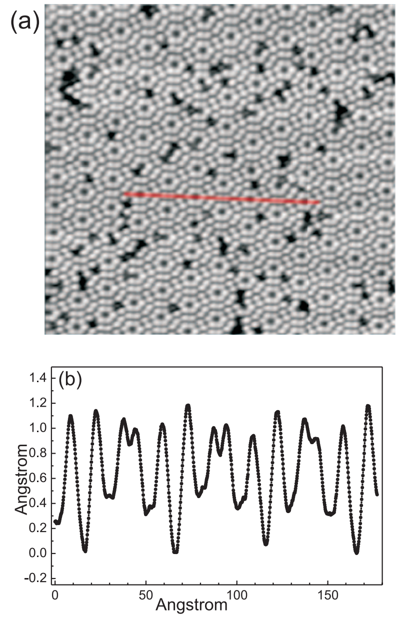

FIG. 5. (Color online) (a) Atomically resolved unfiltered STM image of the (7×7) structure on a Si(111) sample (lateral scan size 30 nm × 30 nm). (b) Line scan (not averaged) through the red line in (a).

THE KOALADRIVE STM

In the next step, the KoalaDrive can be used to build an ultracompact STM. The KoalaDrive 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. 4(a). The STM is completed by attaching a tip (plus tip holder) to the central tube and an outer frame, which holds the sample in Fig. 4(a). 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. In Fig. 4(b), a photograph of an actual KoalaDrive STM is shown. The use of the KoalaDrive makes the scanning probe microscopy design ultracompact and leads accordingly to a high mechanical stability. An unfiltered STM image of the Si(111)-(7×7) surface taken with a KoalaDrive STM is shown in Fig. 5(a) and a corresponding line scan through the line in Fig. 5(a) is shown in Fig. 4(b). The advantages of the KoalaDrive are utilized fully in the design of an ultracompact four-tip STM using the KoalaDrive with an outer diameter of 50 mm which we test currently.

CONCLUSIONS

We have shown that the development of a new type of piezoelectric motor serves as the basis for ultracompact scanning probe microscopes. The KoalaDrive is the heart of our ultraminiature STMs enabling coarse positioning steps between 100 nm and 4 μm at room temperature. The KoalaDrive can tap its full potential for the miniaturization for the case of multi-tip scanning probe instruments. Apart from the size, the unique features of the Koaladrive are the smooth travel without sawtooth signal also in combination with the low temperature, vacuum, and magnetic field compatibility.

[1] G. Binnig and H. Rohrer, Helv. Phys. Acta **55**, 726 (1982).
[2] J. E. Demuth, R. J. Hamers, R. M. Tromp, and M. E. Welland, J. Vac. Sci. Technol. A **4**, 1320 (1986).
[3] J. W. Lyding, S. Skala, J. S. Hubacek, R. Brockenbrough, and G. Gammie, Rev. Sci. Instrum. **59**, 1897 (1988).
[4] Th. Michely, M. Kaiser, and M. J. Rost, Rev. Sci. Instrum. **71**, 4461 (2000).
[5] L. Petersen, M. Schunack, B. Schaefer, T. R. Linderoth, P. B. Rasmussen, P. T. Sprunger, E. Laegsgaard, I. Stensgaard, and F. Besenbacher, Rev. Sci. Instrum. **72**, 1438 (2001).
[6] S. H. Pan, International patent publication WO 93/19494 (1993).
[7] S. H. Pan, E. W. Hudson, and J. C. Davis, Rev. Sci. Instrum. **70**, 1459 (1999).
[8] D. W. Pohl, Rev. Sci. Instrum. **58**, 54 (1987).
[9] K. Besocke, Surf. Sci. **181**, 145 (1987).
[10] J. Frohn, J. F. Wolf, K. Besocke, and M. Teske, Rev. Sci. Instrum. **60**, 1200 (1989).