Integrated micro-scanning tunneling microscope

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(Received 30 May 1995; accepted for publication 10 August 1995)

Two versions of micro-scanning tunneling microscopes (micro-STMs) have been fabricated. The integrated micro-STMs are fabricated from single crystal silicon using the high-aspect-ratio SCREAM process. Each micro-STM includes integrated \(xy\) comb drive actuators and a torsional \(z\) actuator with integrated cantilever and tip. One micro-STM measures approximately 200 \(\mu m\) on-a-side and is an example of a STM element for a STM array architecture. Another, larger micro-STM/atomic force microscope measures 2 mm on-a-side including a 1 mm long cantilever with a 20 nm diam tip. We demonstrate the operation of this larger STM by obtaining a STM image of a 200 nm metal conductor on a silicon chip. © 1995 American Institute of Physics.

Scanned-probe instruments have been used to image and manipulate single atoms, to measure force on the atomic scale, and to perform nm-scale lithography.\(^1\)\(^-\)^\(^5\) The family of scanned-probe instruments includes the atomic force microscope (AFM) and the scanning tunneling microscope (STM). Two recent reviews highlight the design, methods, and applications of STMs and AFMs.\(^6\),\(^7\) These macroscopic scanned-probe instruments, for the most part, use large piezoelectric actuators to position a tip or a probe in three dimensions \((xyz)\). Because of the mass of the tip-actuator structure and the size of these macroscopic instruments, the scanning rate is slow. More importantly, these instruments are not easily integrated into arrays of massively parallel scanned-probe devices that are required for high speed atom manipulation and information storage, and for high throughput, nm-scale lithography systems. This has motivated the development of micromachined scanning probe microscopes.\(^8\),\(^9\)

Here, we discuss two micro-scanning tunneling microscopes (micro-STMs) fabricated from single crystal silicon (SCS) using the high-aspect-ratio single crystal reactive etch and metallization (SCREAM) process.\(^10\)-\(^12\) One micro-STM measures approximately 200 \(\mu m\) on-a-side and is an example of a STM element for an array architecture (Fig. 1). Another, larger micro-STM/AFM measures 2 mm on-a-side including a 1 mm long cantilever with a 20 nm diam integrated tip on a 6 \(\mu m\) high by 1 \(\mu m\) diam support shaft (Fig. 2). This micro-STM also includes SCS specimen supports to facilitate STM imaging. We outline the design and fabrication process for both micro-STMs and demonstrate the operation of the larger STM by imaging a 200 nm wide metal conductor on a silicon chip.

Both versions of the micro-STM use released SCS comb capacitors as drives for scanning the tip in \(x\) and \(y\).\(^13\),\(^14\) The displacement, \(\Delta\), generated by a capacitive comb drive is

\[
\Delta = N \frac{\varepsilon_0 b}{2kd} V^2
\]

where \(N\) is the number of fingers or interdigitated capacitor plates, \(\varepsilon_0\) is the permittivity of free space, \(b\) is the height of the fingers, \(k\) is the spring constant of the restoring spring, \(d\) is the gap between the fingers, and \(V\) is the voltage applied across the fingers. The support beams from the anchor posts at the periphery of the micro-STMs serve as the restoring springs for the scanning stage. We chose the comb capacitor as the drive because the force it generates is independent of the distance the fingers have moved. As shown in Fig. 1, the 200 \(\mu m\) on-a-side micro-STM has four comb capacitor drives to move the center stage in the \(+x\), \(-x\), \(+y\), and \(-y\) directions. Each comb drive has 40 fingers. The stiffness, \(k\), in both \(x\) and \(y\) is about 76 N/m. Subsequently, the nominal displacement generated by each drive is about 20 nm with 25 V applied. Thus the maximum scan range is about \(\pm 50\) nm in \(x\) and \(y\) with 40 V. The frequency response in \(x\) and \(y\) is on the order of 1 MHz. For the 2 mm on-a-side micro-STM (Fig. 2), three groups of comb capacitor drives are used to move the released stage in the \(+x\), \(+y\), and \(-y\) directions. Each comb drive has 512 fingers. Under scanning electron microscope (SEM) observation we obtained the displacement versus applied voltage for this device shown in Fig. 3. With a practical voltage limit of 40 V, the total scan range available to this design is 1.7 \(\mu m\) in \(x\) and 2.9 \(\mu m\) in \(y\). Based on the calculated mass of the device and the observed reso-

![FIG. 1. SEM micrograph of the 200 \(\mu m\) by 200 \(\mu m\) micro-STM.](image-url)
nant frequencies, 5.4 and 3.1 kHz, in $x$ and $y$, respectively, the spring constants are $k_x = 5.8$ N/m and $k_y = 1.9$ N/m. The resonant frequencies are comparable to that of larger, traditional STMs because of the low $x$ and $y$ spring constants and the relatively large mass of the device. Subsequent designs will focus on increasing the actuator force and the stiffness while maintaining a reasonable scan range.

Out of plane motion is achieved with an integrated torsional $z$ drive. In Fig. 1, the torsional $z$ drive is comprised of a torsion bar across the center of the rectangular stage. Two metal pads underneath the torsional stage form parallel-plate capacitor drives with the SCS beams of the stage. When a voltage is applied to an electrode on one side of the stage, that side of the stage is pulled downward and the opposite side moves upward, similar to the motion of a teeter-totter. The high aspect ratio tunneling tip is the bright spot located at the center of the lower outermost beam of the rectangular stage. In Fig. 2, the torsional $z$ drive consists of a released square truss or plate on the right of the torsion bar, and a 1 mm long cantilever on the left of the torsion bar. The electrodes patterned underneath the square plate and the cantilever form two parallel-plate capacitor drives to generate motions in the $+z$ and $-z$ directions, respectively. The high-aspect-ratio tunneling tip is located on the far left end of the cantilever. The torsional rigidity of a beam with a rectangular cross section can be expressed as

$$k_u = \beta G \frac{a^3 b}{L_T^2}, \tag{2}$$

where $G$ is the shear modulus of rigidity ($\approx 66.3$ GPa for single crystal silicon), $b$ is the height of the beam, $a$ is the width, $L_T$ is the length, and $\beta$ is a constant of order one which depends on the aspect ratio, $ba$. For the 200 $\mu$m on-a-side micro-STM, $L_T$ is 58 $\mu$m which gives $k_u = 4.6 \times 10^{-9}$ N m. For 2 mm on-a-side micro-STM, $L_T$ is 50 $\mu$m and $k_u = 4 \times 10^{-8}$ N m. This torsional cantilever design can also be used for the measurement of very small forces.

Figure 2 also shows specimen support posts on both sides of the tunneling tip. Six support posts like these were fabricated as an integrated part of micro-STM fabrication. These support posts are 200 $\mu$m by 200 $\mu$m in area, and they are about 2 $\mu$m to 3 $\mu$m above the top of the tunneling tip. With these support posts, we are able to place the test specimen (a silicon chip) directly onto the micro-STM chip. No external components are needed to accomplish tip-sample approach.

The fabrication process for the single crystal silicon micro-STM is illustrated in Fig. 4. In Fig. 4(a), the high-aspect-ratio SCS tip is made by the thermal oxidation of silicon. Many examples of the tip formation process are found in literature. After thermal oxidation, a cap similar to that in Ref. 18 remains on the tip to protect the tip during

![Fig. 2. SEM micrograph of the larger 2 mm by 2 mm micro-STM.](image1)

![Fig. 3. The measured displacement vs applied voltage squared for the micro-STM shown in Fig. 2.](image2)

![Fig. 4. Schematic drawing of fabrication process flow.](image3)
subsequent processing. Also, the specimen support posts are fabricated at this time. During the steps shown in Figs. 4(b) and 4(c), the \( xyz \) stage with its torsional \( z \) drive and comb capacitor drives is fabricated using the SCREAM process.\(^{10-12}\) Two electrical isolations for interconnections are accomplished in this step using thermal oxidation. Figure 5 shows the integration of the high-aspect-ratio tip with the torsional \( z \) drive. After the steps shown in Figs. 4(b) and 4(c), a plasma enhanced chemical vapor deposition (PECVD) silicon dioxide layer is deposited. A partial exposing process is used to strip the silicon dioxide from the top of the high-aspect-ratio SCS tip. In Fig. 4(d), a 50 nm gold film is deposited onto the SCS tip with a 5 nm chromium film serving as the adhesion layer. A 150 nm aluminum film is then deposited to make the drive electrodes, as well as the interconnects.

During image acquisition a test sample was placed onto the micro-STM chip and supported by the specimen support posts. The test sample consisted of a 2 mm by 2 mm silicon chip with 300 nm wide lines and trenches defined by electron beam lithography and coated with a gold/palladium alloy to form a conductive surface. By ramping a dc voltage on the \( +z \)-drive electrode, the micro-STM tip approached the sample until a tunneling current was observed. We connected the electrode underneath the tunneling tip to a feedback control circuit. A commercial STM control unit\(^{19} \) performed the feedback control of the tunneling tip, providing the \( xy \) scan signals, and recorded the image. A square-rooting circuit was added to compensate for the voltage dependence of the displacement generated by the comb capacitor [Eq. (1)] to linearize the scan in the \( x \) and \( y \) directions.

Figure 6 shows the STM image obtained with the micro-STM. This picture shows an area about 200 nm by 200 nm near the edge of a groove on the test sample. The scale was approximated from the known dimensions of the test sample and the displacement versus applied voltage relations shown in Fig. 3.

We have fabricated and tested two micro-scanning tunneling microscopes with integrated \( xyz \) actuators. The two micro-STMs are fabricated from single crystal silicon using the high-aspect-ratio SCREAM process. Each micro-STM includes \( xy \) comb drive actuators and a torsional \( z \) actuator with an integrated tip. One micro-STM measures approximately 200 \( \mu m \) on-a-side and is an example of a STM element for an array architecture. Another, larger micro-STM measures 2 mm on-a-side. We demonstrated the operation of this larger STM by acquiring a STM image of a 200 nm metal conductor on a silicon chip.

This work is supported by ARPA and the National Science Foundation. All fabrication was performed at the Cornell Nanofabrication Facility at Cornell University which is supported by the NSF, Cornell University, and Industrial Affiliates.

15 S. A. Miller, Y. Xu, and N. C. MacDonald (unpublished).
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