Two linear beetle-type scanning tunneling microscopes


Department of Physics, Queen’s University,
Kingston, Ontario, Canada, K7L 3N6

(Dated: October 27, 2002)

Abstract

Two beetle-type scanning tunneling microscopes are described. Both designs have the thermal stability of the Besocke beetle and the simplicity of the Wilms beetle. Moreover, sample holders were designed that also allow both semiconductor wafers and metal single crystals to be studied. The coarse approach is a linear motion of the beetle towards the sample using inertial slip-stick motion. Ten wires are required to control the position of the beetle and scanner and measure the tunneling current. The two beetles were built with different sized piezo-legs, and the vibrational properties of both beetles were studied in detail. It was found, in agreement with previous work, that the beetle bending mode is the lowest principal eigenmode. However, in contrast to previous vibrational studies of beetle-type scanning tunneling microscopes, we found that the beetles did not have the ‘rattling’ modes that are thought to arise from the beetle sliding or rocking between surface asperities on the raceway. The mass of our beetles is 3-4 times larger than the mass of beetles where rattling modes have been observed. We conjecture that the mass of our beetles is above a ‘critical beetle mass’. This is defined to be the beetle mass that attenuates the rattling modes by elastically deforming the contact region to the extent that the rattling modes can’t be identified as distinct modes in cross-coupling measurements.

PACS numbers: 07.79.C, 07.10, 07.10.F, 46.40
I. INTRODUCTION

The scanning tunneling microscope (STM) not only allows the surfaces of metals and semiconductors to be imaged at the atomic level, it provides a means for manipulating single atoms and molecules and for studying their dynamics. Since the discovery of the instrument, many different design approaches have been explored. For variable temperature applications, the beetle-type STM is particularly appropriate because it has low thermal drift. The size of the vacuum gap is relatively insensitive to temperature; thermal expansion or contraction of the scanner is compensated by a similar change in the legs.

In this paper, two beetle-type STMs are described, a tall (Fig.1a) and a short (Fig.1b) beetle, that will ultimately be used on a variable temperature sample stage that is similar to one that has been described previously. We used the Wilms design as a starting point for both STMs. In many respects, the Wilms beetle is similar to the Besocke beetle. However, the rotational coarse approach is replaced by a linear approach. The sample is displaced from the horizontal by 6° and the scanner is displaced from the vertical by the same angle, to keep the tip orthogonal to the surface of the sample. We also describe the transferable sample holders that were designed to be used with the linear beetles.

II. BEETLE DESIGN

A. The linear beetle

The differences between our beetles, the Wilms beetle and the Besocke beetle are illustrated in Fig.2 where the position of the legs, the orientation of the piezo-sectors and the location of the sample (shaded region) are shown. In both (a) and (b), coarse approach is achieved by moving the beetle towards the sample in the $x$ direction. Moving the beetle in the $y$ direction allows the tip to explore other regions of the surface and, to first order, this can be done without changing the tip-sample spacing. Because only $x$ and $y$ motions are required for course approach and beetle displacement, the piezo-sectors on each leg can be wired in parallel. Consequently, the spatial control of the beetle requires only 4 wires plus a ground connection to the inner electrodes. An additional 4 wires are required to control the scanner and 1 wire is required for the tunneling current. This means that a total of 10...
wires are connected to the beetle.

The Wilms configuration is illustrated in Fig. 2b. The major difference between our design and the Wilms design is the position of the legs relative to the sample. The Wilms beetle has mirror symmetry in the $xz$ plane. To save space and also to allow our beetles unhindered access to the top of the sample, they have two legs positioned on one side of the sample and one on the other. Because of the asymmetry in the leg position, we thought that our beetles may not move exactly parallel and perpendicular to the sample without a guide rail\textsuperscript{22,23}. However, we found that this concern was unjustified in practice.

The Besocke-beetle sector configuration is shown in Fig. 2c\textsuperscript{15,16}. The beetle is rotated azimuthally on a 3-sector annular ramp (the raceway) that surrounds the sample. This rotation is achieved by applying appropriate vectorial voltages to the sectors of the 3 piezo-legs. The beetle can also be moved laterally ($x$, $y$ and vector combinations) to probe new areas of the sample. Because both lateral and azimuthal rotation of the beetle are required, the piezo-leg sectors can’t be wired in parallel. Twelve wires have to be threaded from the sample manipulator to the leg sectors. The 4 wires controlling the scanner, plus the ground and tunneling connections make a total of 18. In some implementations of the Besocke-beetle design, the 90° sectors are rotated so that the sectors are tangential and perpendicular to the mounting circle of the piezo-legs\textsuperscript{24}. This eliminates 4 wires and reduces the total number to 14. In others, the four 90° sectors on the piezo-legs are replaced by three 120° sectors\textsuperscript{25}. The latter configuration reduces the total number of wires from 18 to 15.

Our design retains all the advantages of the Besocke-beetle design\textsuperscript{15,16} while reducing the number of wires that have to be threaded from the manipulator to the beetle to 10. This increases the vibrational isolation between the beetle and the manipulator, and it also reduces the chance of beetle failure as a result of accidental wire breakage or shorting. Moreover, because the beetle is moved in two orthogonal directions ($x$ and $y$), the scan directions can be aligned with the crystalline axes of the sample and the $y$ and $z$ movements, are to first order, decoupled. Furthermore, as the raceway is flat, it is straightforward to both machine and polish.
### B. Scanner

An exploded view of the scanner is reproduced in Fig.4. The EBL#2 piezoelectric tube was manufactured by Staveley Sensors Inc. Four 90° metal segment electrodes and a wrap-around ground electrode were added to the piezoceramic tube. To avoid having fine 0.003” wires attached directly to the electrodes, we glued 0.010”, AWG-30, gold-plated copper wires (California Fine Wire, CFW-156-010) to the electrodes. The wires were then guided through polytetrafluoroethylene (PTFE) tubes (Omega Engineering Inc., TF-W-30) that were press fit into holes in the tip pin. The thicker wires were less fragile and consequently much easier to handle. The PTFE tubes provide support for the control wires and mechanically damp them. They also provide electrical isolation from the beetle chassis. This arrangement produces very little stress on the glue joints and is very stable. The 0.010” wires fit into pin terminal with carrier assembly (PTCA) sockets (SPC Technology, PTCA-16-01-L1) that extend out from the ring component of the beetle chassis. Each socket is electrically isolated using PTFE tubing (Alpha Wire Company, TFT 200-14 NA Q1 6B) and press fit into guide holes in the ring. This ensures maximum spacing between the control wires as they pass up from the beetle to the PTFE connector plate on the beetle manipulator (Fig.5). Kapton-coated copper wires (0.003”, California Fine Wire, CFW-156-0031-HML) are attached by PTCA sockets that fit onto the protruding sockets of the ring. The fine wires are then threaded up to the top of the manipulator where they plug onto 2.5” long stainless steel tubes that are supported by an insulating contact plate. The other end of the metallic tubes are connected to PTFE insulated jumper wires that feed up to the 10-pin connector. The advantage of this design is that a break in a fine wire means that only the fine wire has to be replaced. It is not necessary to replace any of ‘internal’ wiring on the beetle.

To reduce cross-talk between the scanner and the Kapton coated 0.003” tunneling wire, the tip wire and the scanner control wires were electrically separated from one another. The scanner control wires were located outside the thin wall stainless steel tube in the beetle manipulator whereas the tunneling wire was passed through the center. Between the top of the steel tube and the BNC feedthrough, the PTFE covered tunneling wire was shielded with silver braid. Moreover, between the bottom of the puller tube and the tip, the tunneling wire threads through the hollow lifting post. Consequently, the tip wire was electrostatically shielded all the way from the feedthrough to the tip. The tip assembly is made entirely from
pre-fabricated parts. To allow tips to be exchanged easily the tip is located in a PTCA socket. The tip and socket fit into another PTCA socket that is secured inside a ceramic bead (Omega). The bead is mounted onto two ceramic spacers (Kimball Physics, Al₂O₃-SP-C-025 and Al₂O₃-SP-C-050). At the bottom of the assembly, the 0.050” spacer sits flush with the end of the scanner piezo, and it is attached to the inside wall of the tube. All the glue points are made with non-conducting epoxy to electrically isolate the tunneling wire from the inner ground electrode of the piezo. A funnel is made from an aluminum washer, using a pipe flaring tool, and glued with conducting epoxy (Epoxy Technology Inc. EPO-TEK H21D) to the wrap-around ground electrode of the scanner. The funnel provides additional electrostatic shielding for the tip.

C. Legs

Instead of gluing the three piezo-legs directly to the beetle disk [20], we glued them to aluminum pins. The aluminum pins were then press fit into holes in the aluminum disk and then tightly secured using stainless steel set screws. The outer diameter of the pins, for both beetles, was larger than the outer diameter of the piezos to provide room to thread the control wires through holes in the pins. This allowed each leg to be manufactured independently and then located in the disk during final assembly. It also gave us the freedom to change a piezo-leg after fracture or depolarization without modifying the disk.

As with the central scanner, we avoided connecting the fine 0.003” copper wires directly to the piezo-sectors. Instead, 0.010” wires were glued to the piezo-sectors and threaded through PTFE tubes that were recessed in the pins. The PTFE tube provided both electrical isolation and support for the wire. Finally, sapphire balls were glued into the base of the leg units with non-conductive epoxy (Epoxy Technology Inc. EPO-TEK-H77).

III. CALCULATION OF EIGENFREQUENCIES

We start with the eigenmodes of a massless tube of length \( L \), inner diameter \( d \) and outer diameter \( D \) (Fig.6) with one end rigidly fixed. We define bending (\( \perp \)), torsional (\( \phi \)) and flexing (\( \parallel \)) modes with respect to the high symmetry axis of the tube. The eigenfrequencies of the tube, associated with these three modes, are: \( \omega_\perp = \sqrt{\kappa_\perp/m} \), \( \omega_\phi = \sqrt{\kappa_\phi/I} \) and
\[ \omega_\parallel = \sqrt{\kappa_\parallel/m}. \] The corresponding spring constants\[11,26,27,28] are:

\[ \kappa_\perp = \frac{3\pi}{64} E \frac{d^4 - d^4}{L^3}, \tag{1} \]

\[ \kappa_\phi = \frac{\pi}{32} G \frac{d^4 - d^4}{L}, \tag{2} \]

and

\[ \kappa_\parallel = \frac{\pi}{4} E \frac{d^2 - d^2}{L}, \tag{3} \]

where \( E \) is the Young’s modulus, \( G = E/(1+\nu) \) is the shear modulus, \( \nu = 0.31 \) is Poisson’s ratio for the piezo-ceramic and \( \omega = 2\pi f \). These expressions can be used to calculate the eigenfrequencies of the scanner and the legs. The ‘internal’ eigenfrequencies of the disk can be ignored\[25,29\]. They are much higher than any of the other frequencies that are calculated below.

The eigenfrequencies of the scanner are tube eigenmodes. Because the top end of the scanner is glued to the aluminum pin, only the bottom end of the scanner can bend, twist and flex. The corresponding eigenfrequencies can be calculated by using the mass and the moment of inertia of the tip assembly in the equations given above.

The eigenmodes of the legs are slightly more complicated. The piezo-tubes are once again glued into aluminum pins and the top of the leg piezos do not move relative to the disk. The leg flexing mode produces a vertical displacement of the disk and the leg bending mode produces a horizontal displacement. The eigenfrequencies of both modes can be calculated using the mass that loads each leg \( m_L \). Another important mode is the torsional mode of the disk and the eigenfrequency of this mode can be calculated from the bending eigenfrequency of the legs\[29\], \( \omega_\phi^{\text{beetle}} \approx \sqrt{2} \omega_\perp^{\text{leg}} \). Because the (unidirectional and circumferential) bending and flexing modes of the legs induce motion of the disk we often refer to these modes as the bending (\( \perp \)), torsional (\( \phi \)) and flexing (\( \parallel \)) modes of the beetle, respectively. Note that torsional motion of the legs is only possible if the bottom of the legs twist because the top is rigidly fixed.
IV. MEASUREMENT OF EIGENFREQUENCIES

We have calculated the principal eigenfrequencies for both beetle designs and the location of the eigenfrequencies is indicated on the measured vibrational spectra (Fig.7 and Fig.8). The spectra are measured by exciting the bending mode of the scanner with a 10V pp sinusoidal voltage and measuring the in-phase pickup voltage on the leg piezos with a lock-in amplifier. In Fig.7 there are a number of strong resonance peaks extending from just below 2.0kHz to 4.5kHz. The lowest two correspond very well with our estimates of the bending and torsional modes of the beetle. The beetle flexing mode lies at \( \approx 11.5kHz \) and there is a resonance peak close to this frequency. Additionally, we have calculated that the bending, the torsional and the flexing modes of the lifting assembly are 3.5, 4.4 and 37.3 kHz, respectively, when the lifting bar is located 0.65” above the disk. The lifting assembly was designed for ease-of-use. We found, as expected, that lowering the lifting bar shifted the resonances associated with the lifting assembly to higher frequency (not shown).

The vibrational spectrum of the short beetle is presented in Fig.8 as is the calculated location of the beetle bending mode. The torsional and flexing modes are calculated to be 14.1 and 21.5 kHz respectively (not shown). The vertical axis has been multiplied by a factor of 5.0 relative to that of Fig.7. Although the same excitation voltage (10V pp) was used, the amplitudes of the peaks are smaller in Fig.8 because the piezo-tubes on the short beetle are stiffer than those on the tall beetle.

V. VIBRATIONAL STUDIES IN THE RATTLING RANGE; 500 - 1700Hz

We have studied the vibrational properties of our beetles in the rattling range; 500-1700 kHz. This is an important frequency range because it is commensurate with scanning frequencies. Because we have described these studies in detail elsewhere, we will only summarize our main findings here. In contrast to previous studies, which were performed on beetles with a mass of \( \approx 3-4g \), we found that the low frequency vibrational spectrum of our beetles is dominated by ‘intrinsic’ modes. We found no evidence for ‘extrinsic’ rattling peaks due to inertial sliding or rocking of the beetle on the raceway.

For example, the following control experiments were performed. We found that lifting the beetle off the raceway, with the manipulator, and sitting it down again did not change the
vibrational spectrum as it does with lighter beetles. We measured the vibrational spectrum of the beetles on a flat surface and also on a Frohn-style raceway. We could detect no significant changes in the vibrational spectra. The Frohn-style raceway was manufactured specially for this control experiment. Both the flat surface and the Frohn-style raceway were made from stainless steel. The surfaces were left unpolished. Adding additional masses ($\Delta m \leq 20g$) to the beetle had no effect on the vibrational spectrum, indicating that the modes in the rattling range are not associated with the legs or affected by the increase in contact pressure. Consecutively removing fine wires from the beetle had no effect on the vibrational spectrum, suggesting the wires are mechanically damped by their attachment to the beetle disk. The vibrational spectrum of the beetles did not depend upon the kind of the anti-vibration system the beetle was mounted on. Coupling between beetle and stack modes has been observed when beetles are placed on plates that have a relatively small mass and moment of inertia. We used three different support systems to test this. The first was the 5-tier viton stack that we normally use when scanning. The second was a stainless steel disk supported by three viton chords and the third was a two tier viton stack supported from viton chord. Furthermore, removing the tip from the tip socket did not change the vibrational spectrum.

How do we explain the absence of rattling modes in our beetles? We note that our beetles are 3-4 times heavier than those used previously. If the rattling modes arise from a rocking motion of the beetle on surface asperities then it is possible that our beetles elastically or plastically deform asperities on the surface and suppress the rattling motion. This notion has been discussed in the literature before. Consequently, there may be a ‘critical beetle mass’ (or alternatively a critical contact pressure) that suppresses the rattling modes by attenuating them and shifting them to lower frequency. This suggestion is supported by previous experimental studies.

VI. SAMPLE HOLDERS

A sketch of our sample holder is presented in Fig.9. It has two flat molybdenum landing pads, polished to better than 1$\mu m$, to support the beetle. The pads were kept small so that the holder could be transferred through a commercial quick entry sample load lock. To prevent the beetle from inadvertently walking off the sample table, a tantalum foil was spot
welded around the edge of the pads. Below the pads the molybdenum base has a square cross section and two grooves allow the sample holder to be passed between perpendicular sample transfer forks. The grooves were milled oversize to ensure that the samples transferred easily without binding.

To resistively heat the sample, current is passed between two electrically isolated sample supports interior to the sample holder base. The supports were designed to hold the sample at a $6^\circ$ incline to the horizontal, such that the tip was always perpendicular to the sample plane. The higher support is held at high potential through an electrical connection made through the sample holder base. The lower support extends below the sample holder and the return current path is made through an electrical contact at the heating stage. The sample is held onto the supports with tantalum clips, and provides a conductive link between the two sections of the sample holder. The small size of the sample supports and strategically placed ceramic spacers help to minimize heat transfer from the sample to the sample holder base and the landing pads when the sample is flashed.

VII. THE VACUUM SYSTEM

The STM is located in a spherical stainless-steel vacuum chamber that was manufactured by Johnsen Ultravac (Burlington, Ontario) with a diameter of 8.0”. A room temperature sample stage can be mounted from below or a variable temperature sample stage can be mounted horizontally from the side. Additionally, there are ports for the beetle manipulator, two wobble-sticks for sample manipulation, and several windows that provide a clear view of the sample stage during sample transfer. The STM chamber is connected to a manifold chamber that is located directly over a Varian 400 L/s StarCell ion pump. The ion pump is the heaviest component in the system, and it is located close to the center of a triangular support frame. At each vertex of the triangular frame there is a Newport I-2000 Laminar Flow Isolator that allows the vacuum system to be ‘floated’.

Samples are introduced using a commercial quick-entry sample load lock (MDC MT-12-MPT) located on the manifold chamber. A Varian TV141 Navigator turbo pump is used for roughing. Samples can be transferred between the manifold and the STM chamber using a magnetic coupled transfer arm (MDC GMTM-36). The manifold chamber has a sample flashing stage. The sample temperature is measured using an infra-red pyrometer (Land
Infrared M1 600/1600C). All aspects of sample preparation and temperature monitoring are computer controlled using a data acquisition card (National Instruments Lab-PC+) and LabView (National Instruments) virtual instruments.

VIII. ELECTRONICS

Both the imaging and spatial control of the STM were performed using commercial electronics manufactured by R.H.K Technology Inc. We used two stages of pre-amplification using the IVP 200 pre-amplifier and a multi-gain pre-amp (PN 14-1104-90). For data acquisition, visualization and image analysis, we used the SPM 100 controller and the SPM 32 software package. The entire STM UHV system was run from a dedicated quiet ground line and care was taken to eliminate earth loops by using a single grounding point.

IX. TIPS

Tips were fabricated from polycrystalline W (Goodfellow W005325) and Pt-Ir (Goodfellow PT025140) wire, with a diameter of either 0.25 or 0.50 mm. The W tips were electrolytically etched in KOH\[182\] prior to insertion in the scanner and the Pt-Ir tips were prepared by mechanical cutting\[19,36\]. Once in the vacuum system, the tips were prepared by field emission using the following procedure. First, the tip was brought within tunneling range of the sample using a computer controlled close approach. The tip-sample separation was then increased to between 50 and 100 Å by moving the beetle in the $x$-direction. A positive voltage of less than 500 V was applied to the sample and the field emission current was continuously monitored through a picoammeter attached at the tunneling wire. Improved resolution could often be observed after maintaining currents of a 1-5 µA for 10-20 minutes. Following a tip crash, or in cases where satisfactory resolution could not be obtained after field emission, self-sputtering was used. The chamber was backfilled to $10^{-5}$ Torr with Ar. A negative bias of less than 500 V was applied to the tip and the sample was grounded thorough a picoammeter. Ar atoms were ionized by the field emission current and the ions were accelerated onto the tip. An abrupt decrease in the sample current indicated that the tip had restructured\[39\]. Then, the self-sputtering would be immediately discontinued by removing the bias voltage. Following field emission treatment, most self-sputtered tips
exhibited improved resolution.

X. PERFORMANCE

Highly oriented pyrolitic graphite (HOPG) surfaces were used to test the microscopes in air. We had no difficulty using either the tall or the short beetles to image graphite with atomic resolution. The microscopes were then tested in ultra-high vacuum using the Si(111)(7×7) surface reconstruction and Cu(110). To date, we have used copper surfaces primarily to test our tip preparation procedures (see above). The majority of our imaging has been done on silicon and we present silicon images at three different length scales to demonstrate the performance of the microscopes here. The silicon samples were degassed to 550°C and then flashed to 1260°C for 20 sec. using a.c. resistive heating, annealed at 850°C for ten minutes and allowed to cool at approximately 1°C/sec. A similar procedure was used for Si(100)(2×1) surfaces. Lateral piezo calibrations (xy) were performed using the 26.88 Å spacing between corner holes in the 7×7 cell and vertical piezo calibration (z) was performed using single atomic-steps on Si(100).

Some low magnification images of the silicon surface are presented in Fig. 10 that demonstrate that the microscopes are capable of imaging relatively large areas. Fig. 10a is approx. 900×900 nm image that was acquired with the tall beetle. The image clearly shows a regular step distribution on a Si(111) surface that was miscut by 3° towards (112). At higher magnification, the 7×7 reconstruction was present on the terraces. Fig. 10b is a 126×126 nm image, acquired with the short beetle, from a Si(001) surface miscut 7° towards (110). This miscut creates short terrace lengths.

Fig.11 is a negative-bias image of the Si(111)(7×7) surface, taken at higher magnification, showing the intersection of the 7×7 reconstruction with a kinked step edge with atomic resolution on both the upper and lower terraces. The image has an area of approx. 24×24 nm and it was acquired with the short beetle at a bias of -1.06 V.

Fig.12 is a high-magnification image of the Si(111)(7×7) surface that was obtained with the short beetle. Although this image has had a constant background subtracted to enhance contrast, it has not been smoothed or filtered. The quality of this image clearly indicates that the noise levels have been reduced to the point where they do not significantly interfere with image acquisition. The linescan, taken between corner holes of the 7×7 cell,
confirms this. The bias was -0.12V. At this voltage the tunneling is via the metallic surface state and the linescan possesses some asymmetry between the faulted and un-faulted halves of the $7 \times 7$ unit cell. At these low bias voltages, the adatoms in the faulted half of the $7 \times 7$ unit cell give rise to more tunneling current than those in the unfaulted half.

XI. DISCUSSION

We have described the design, construction and performance of two linear beetles. The linear beetles are relatively simple to construct and operate, requiring only 10 control wires and a flat polished surface to walk on. The design obviates the need to manufacture and polish a Frohn-style raceway. We have described a modular approach to the construction of the piezo-legs that allows the legs, and in the case of the short beetle also the scanner, to be removed for repair. The same systems provides very efficient vibrational damping of the fine control wires, as they are rigidly attached to the beetle disk. The fine wires can also be unplugged. This allows the beetle to be easily removed from the manipulator. We also described sample holders that were specifically designed for the linear beetles. The two beetles have quite different vibrational properties. The beetle bending mode for the tall beetle lies at $\approx 1.7\text{kHz}$. The piezo-legs of the short beetle are shorter and wider. Consequently, the beetle bending mode lies at $\approx 10\text{kHz}$. We have not yet been able to take full advantage of this substantial improvement in the low frequency vibrational spectrum, because our controller is limited to acquisition speeds slower than 1ms/line. We also summarized the results of some detailed studies we made of the low frequency vibrational spectrum in the rattling range. In contrast to previous studies, we found that there were no extrinsic rattling modes. All the modes that we could detect were intrinsic modes that could be assigned to different parts of the beetle. We estimated the eigenfrequencies of the principal eigenmodes and found good agreement with measured peaks in the vibrational spectrum. The most natural explanation for the lack of extrinsic rattling modes is that they are suppressed. Our beetles are 3-4 times heavier than those used in previous studies and consequently the contact pressure between the sapphire balls and the raceway is 3-4 times larger. This could suppress the rattling motion of the beetle on the raceway by elastically, or plastically, deforming the contact region. This may mean that there is a ‘critical beetle mass’. We define this to be the mass that suppresses the rattling modes to the extent that they can’t be detected in cross-coupling.
measurements. If a critical mass does exist, it means that having a small beetle mass is not the only design criterion that is important. The best way of testing this notion is to load a light beetle that already exhibits extrinsic rattling modes. The notion of a critical beetle mass is consistent with previous suggestions\textsuperscript{26} and previous vibrational studies\textsuperscript{26,50} of beetle-type STMs.

**Acknowledgments**

This research was supported by the Natural Sciences and Engineering Research Council of Canada and Queen’s University at Kingston, Canada. We would like to thank the following people for their help during the design and construction of our microscopes: M. Wilms for providing a copy of his thesis and drawings of his beetle, J. Seifritz and the research group of R. Möller, B. Gompf, R. Stecher, M. F. Crommie, A. Kahn, M. Salmeron and his research group, D. F. Ogletree, P. Zeppenfeld, J. Nogami, A. J. Slavin, M. C. Robinson, G. Lengel, L. Pattison, R. Aucoin and L. Aucoin.
33 J. A. Miwa, Master’s thesis, Queen’s University (2002).
37 J. M. MacLeod, Master’s thesis, Queen’s University (2001).
Tables

Table 1

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Quantity</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D$</td>
<td>0.125</td>
<td>inches</td>
</tr>
<tr>
<td>$d$</td>
<td>0.077</td>
<td>inches</td>
</tr>
<tr>
<td>$L$</td>
<td>0.5</td>
<td>inches</td>
</tr>
<tr>
<td>$E$</td>
<td>$6.3 \times 10^{10}$</td>
<td>N/m$^2$</td>
</tr>
<tr>
<td>$\nu$</td>
<td>0.31</td>
<td></td>
</tr>
<tr>
<td>$G$</td>
<td>$2.4 \times 10^{10}$</td>
<td>N/m$^2$</td>
</tr>
<tr>
<td>$\kappa_\perp$</td>
<td>$3.93 \times 10^5$</td>
<td>N/m</td>
</tr>
<tr>
<td>$\kappa_\phi$</td>
<td>16.1</td>
<td>Nm</td>
</tr>
<tr>
<td>$\kappa_\parallel$</td>
<td>$2.44 \times 10^7$</td>
<td>N/m</td>
</tr>
<tr>
<td>$m_S$</td>
<td>0.16</td>
<td>g</td>
</tr>
<tr>
<td>$m_L$</td>
<td>4.33</td>
<td>g</td>
</tr>
<tr>
<td>$I_S$</td>
<td>$0.81 \times 10^{-10}$</td>
<td>kg m$^2$</td>
</tr>
<tr>
<td>$I_L$</td>
<td>$1.59 \times 10^{-11}$</td>
<td>kg m$^2$</td>
</tr>
</tbody>
</table>

Dimensions, material parameters and spring constants for the piezo-ceramic tube used in the tall beetle. Also listed are: the mass compressing the legs $m_L$, the mass tensioning the scanner $m_S$, the moment of inertia of the tip assembly $I_S$ and the moment inertia of the sapphire ball $I_L$.

Table 2

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Beetle</th>
<th>Scanner</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_\perp$</td>
<td>1.52</td>
<td>7.85</td>
<td>kHz</td>
</tr>
<tr>
<td>$f_\phi$</td>
<td>2.15</td>
<td>71.33</td>
<td>kHz</td>
</tr>
<tr>
<td>$f_\parallel$</td>
<td>11.94</td>
<td>61.73</td>
<td>kHz</td>
</tr>
</tbody>
</table>

Calculated eigenfrequencies for the tall beetle ($f = \omega/2\pi$).
Table 3

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Quantity</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D$</td>
<td>0.250</td>
<td>inches</td>
</tr>
<tr>
<td>$d$</td>
<td>0.202</td>
<td>inches</td>
</tr>
<tr>
<td>$L$</td>
<td>0.3</td>
<td>inches</td>
</tr>
<tr>
<td>$\kappa_\perp$</td>
<td>$1.96 \times 10^7$</td>
<td>N/m</td>
</tr>
<tr>
<td>$\kappa_\phi$</td>
<td>289</td>
<td>Nm</td>
</tr>
<tr>
<td>$\kappa_\parallel$</td>
<td>$9.09 \times 10^7$</td>
<td>N/m</td>
</tr>
<tr>
<td>$m_S$</td>
<td>0.304</td>
<td>g</td>
</tr>
<tr>
<td>$m_L$</td>
<td>4.99</td>
<td>g</td>
</tr>
<tr>
<td>$I_S$</td>
<td>$1.14 \times 10^{-9}$</td>
<td>kg m$^2$</td>
</tr>
<tr>
<td>$I_L$</td>
<td>$1.99 \times 10^{-9}$</td>
<td>kg m$^2$</td>
</tr>
</tbody>
</table>

Parameters for the short beetle that are different from those of the tall beetle.

Table 4

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Beetle</th>
<th>Scanner</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_\perp$</td>
<td>9.96</td>
<td>57.09</td>
<td>kHz</td>
</tr>
<tr>
<td>$f_\phi$</td>
<td>14.09</td>
<td>80.14</td>
<td>kHz</td>
</tr>
<tr>
<td>$f_\parallel$</td>
<td>21.48</td>
<td>87.03</td>
<td>kHz</td>
</tr>
</tbody>
</table>

Calculated eigenfrequencies for the short beetle.
Fig. 1 A side view of (a) the tall beetle and (b) the short beetle, drawn to scale. The diameter of the tall beetle disk is 1.3”. The lifting assembly comprises a vertical lifting post, a collar and two horizontal lifting bars. The piezos on the short beetle are considerably stiffer than those on the tall beetle, being three fifths the length and twice the diameter of those on the tall beetle.
Fig. 2 The sector configurations for: (a) our beetles (b) the Wilms beetle and (c) the Besocke beetle. The shaded region, in each case, represents the sample.
Fig. 3 An exploded view of the short beetle. Parts: (1) sapphire balls, (2) piezo-tubes, (3) aluminum pins, (4) scanner assembly, (5) y-plate, (6) stainless steel set screw, (7) ring, (8) PTCA sockets, (9) aluminum cover, (10) stainless steel flat head screws, (11) lifting post, (12) lifting bar, (13) stainless steel set screw and (14) collar.
**Fig. 4** An exploded view of the scanner assembly showing: (1) aluminum pin, (2) piezotube, (3) Omega ceramic bead, (4) Kimball Physics ceramic spacer, (5) Kimball Physics ceramic spacer, (6) aluminum funnel (the skirt), (7) permanent PTCA socket, (8) removable PTCA tip socket and (9) tip.
Fig. 5 A schematic drawing of beetle manipulator, the tall beetle resting on the semiconductor sample holder and the 5-tier viton stack.
Fig. 6 A schematic drawing of the piezo-ceramic tube showing inner tube diameter \((d)\), outer tube diameter \((D)\), length \((L)\), the parallel \((\parallel)\) and perpendicular \((\perp)\) directions.
Fig. 7 The vibrational spectrum of the tall beetle and the calculated eigenfrequencies. The peaks occurring at 1.7, 2.1 and 11.7kHz correspond closely to the calculated bending (⊥), torsional (φ) and flexing (∥) modes of the beetle, respectively. Two other peaks, found at 7.4 and 8.2kHz, are assigned to the bending mode of the scanner and the torsional mode of the legs, respectively. Even on this scale, the absence of peaks in the rattling range, 500-1700Hz, is very noticeable.
Fig. 8 The vibrational spectrum of the short beetle. The peak at 9.5 kHz is attributed to the beetle bending mode (⊥). The torsional and flexing modes of the beetle are located at higher frequencies. Although the short beetle does have some modes in the rattling region, they were all positively identified as intrinsic modes.
Fig. 9 The molybdenum sample holders were designed to be used with (a) semiconductor wafers and (b) metal single crystals. (a) The sample holder has two landing pads. The longer pad accommodates two of the beetle’s legs and the shorter accommodates one and it is shown with a rectangular, 7×17mm, silicon wafer mounted in the center. The wafer is cleaned by resistive heating. (b) The metal sample is recessed in the sample holder and heated using a heater that is located behind the sample (not shown).
Fig. 10 Large-scale images of silicon surfaces. (a) Image area approx. 900×900 nm, acquired at a sample bias of +1.24 V on a vicinal Si(111) surface with the tall beetle. The surface preparation algorithm was refined to create large, regular terraces. (b) A 126×126 nm image of a high-offcut Si(100) surface acquired at a sample bias of +2.00 V with the short beetle.
Fig.11 A negative-bias image of a Si(111)\((7\times7)\) surface with a kinked step taken with the short beetle. The image area was approx. 24×24 nm and the bias was -1.06 V (see the text).
**Fig. 12** A high magnification image of the Si(111)(7×7) surface reconstruction taken with the short beetle with a bias of -0.12 V. The line profile between the points labeled i and ii on the image, bisects two corner holes of the 7×7 cell. It has noticeable asymmetry.