Compact large-range cryogenic scanner

Jeffrey Siegel, Jeff Witt, Naia Venturi, and Stuart Field
Department of Physics, The University of Michigan, Ann Arbor, Michigan 48109

(Received 16 September 1994; accepted for publication 18 November 1994)

We describe the construction and operation of a large-range piezoelectric scanner, suitable for various scanning probe microscopies such as magnetic force, atomic force, and Hall probe microscopies. The instrument is compact and inherently thermally compensated. At room temperature, it has a range of over 2 mm; this range is reduced to 275 μm at 4.2 K. © *1995 American Institute of Physics.*

I. INTRODUCTION

Because of its subangstrom resolution, scanning tunneling microscopy (STM) places extreme requirements of stability and resonant frequency on its scanning stage. Binnig and Smith[1] developed an elegant piezoelectric tube scanner which compactly satisfies these requirements. The scan range of tube scanners tends to be small, usually much less than a micron, ideally suited for the small fields of view needed for STM. More recently, there have been developed a great variety of novel scanning probe microscopies, such as atomic force,[2] magnetic force,[3] near-field optical,[4] and Hall probe microscopies.[5] Often, these probes image spatial variations in a parameter—magnetic field, for instance—on a scale much larger than the angstrom scale typically encountered with STM. Further, many of these microscopies have been adapted to cryogenic temperatures, where the response of the piezoelectric elements commonly used for stage motion is even further reduced. Thus there is a need for scanning stages which can reliably scan over ranges of many microns.

There have been several approaches to designing scanners with x-y ranges in the ten to hundred micron range. Several groups have simply used very long piezo elements.[6,7] Other designs use piezoelectric benders[8–13] and other types of electromechanical devices[14,15] in various geometries to improve upon the inherent limited range of tubes. Purely mechanical scanning techniques have also been used.[16,17] All these designs suffer from either a complex design scheme, or from being large and unwieldy. We describe here a scanning stage which uses piezo benders to scan over a range of 2 mm at room temperature and 275 μm at 4.2 K. It is compact, with a length of 2.5 in., and will easily fit inside a 1.25 in. diameter tube.

II. INSTRUMENT DESIGN

As shown in Fig. 1(a), the scanner consists of four piezo benders connected by three Macor ceramic pieces: a base, a secondary stage, and a scanning head. Macor is used because it is easy to machine and it has a coefficient of thermal expansion similar to that of piezoelectric material.[12] We find that this thermal match allows the piezos to be directly glued to the Macor pieces using cyanoacrylate ("super") glue, which allows for easy disassembly for repairs or modifications. We have found such joints to be reliable upon thermal cycling to cryogenic temperatures. The base, which remains fixed, has a rectangular hole large enough to fit the scanning head and give enough room for the head's x and y translation. The ends of two of the benders are glued to opposite sides of the inside of this hole, and the secondary stage is glued to the other ends of these benders. With such an arrangement, the secondary stage moves in what we call the x direction when voltage is applied to these benders. In a similar fashion, the other two benders join the secondary stage to the scanning head, allowing y motion of the scanning head relative to the secondary stage.

The benders must have their electrodes segmented in a particular way, as shown in Fig. 1(b). With this segmentation, the lower half of the bender curves in one direction upon application of a voltage, and the upper half in the opposite direction. In this way, both ends of each bender remain at all times perpendicular to the direction of motion, as required by the boundary conditions imposed by the Macor pieces to which they are glued. A stage made with unsegmented benders will not move at all. Also shown in Fig. 1(b) is the method in which our benders were wired. The lower segment on one face of the bender is connected to the upper face of the other side, and the two remaining segments are connected to each other. Thus there are two electrically independent electrodes.

The translational response of a bender with segmented electrodes as described above is $x = d_{31}VL^2/T^2$ (half the response of an unsegmented bender[18]), where V is the voltage difference applied between the outer electrodes, L is the length of the bender, T its thickness, and d_{31} the piezoelectric constant (strain per applied electric field). For a tube, the response is $x = 2\sqrt{2}d_{31}VL^2/(\pi DT)$, with D the diameter of the tube and T its wall thickness.[19] Thus for identical materials and equal thicknesses, the response of the bender is larger than that of a tube by a factor of $\pi D/(2\sqrt{2}T)$, which is about 14 for a typical diameter-to-thickness ratio of 12.5 (0.25 in. diameter, 0.020 in. thick). Conversely, a tube would have to be 3.7 times as long as a bender to achieve an equivalent motion.

Having such a large scanning range introduces some problems not encountered with shorter range scanners. In particular the resonant frequency in the directions of x and y motion can be very low. The resonant frequency of two flat plates constrained to be parallel to each other is $0.262(T/L^2)\sqrt{Y_{11}/\rho}$,[20] where Y_{11} is the bulk modulus of the piezo material and ρ its density. For our benders, this value comes out to be 97 Hz. However, the actual resonant frequency is lowered due to additional mass on the free ends,

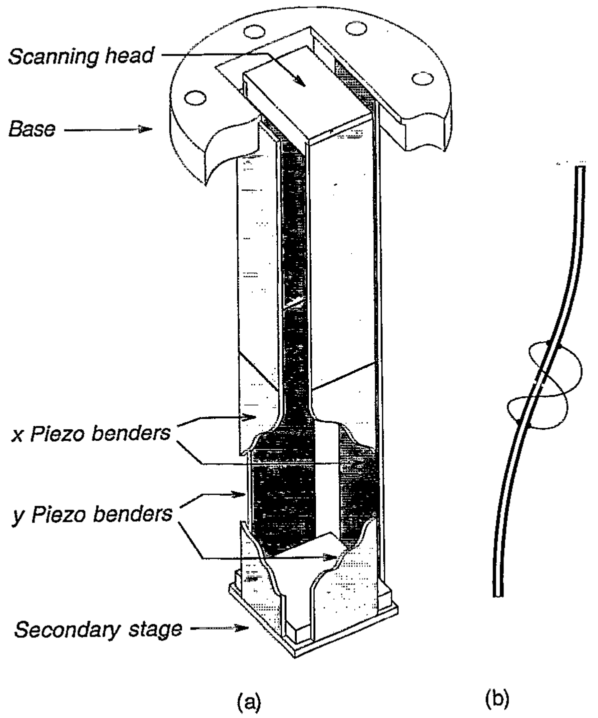

FIG. 1. (a) Schematic of the scanner, showing the four bender piezos connected via Macor stages, and (b) the electrode sectioning scheme and wiring for one bender.

which for the x translation stage is the entire mass of the y stage. In comparison, the resonant frequency of a thin-walled tube is $0.199(D/L^2)\sqrt{Y_{11}/\rho}$.[21] In terms of translational sensitivity s $(=x/V)$, the resonant frequency of a tube is $0.0895d_{31}\sqrt{Y_{11}/\rho}/(sT)$, compared to $0.262d_{31}\sqrt{Y_{11}/\rho}/(sT)$ for the benders. So the resonant frequency *for a given translational sensitivity* is actually greater for benders than for a tube. Another consideration for a large scanning range is z motion of the scanning head. As the benders bend away from their equilibrium position $x=0$, they must move in the z direction a distance $\Delta z=2x^2/(3L)$ to lowest order. With a large scan range, this z motion can be significant—13 μm for our scanner with a 2.2 mm range.

III. EXPERIMENTAL RESULTS

The benders we used on our scanning stage are 2.5 in. long, 0.25 in. wide, and 020 in. thick and have a measured small-signal d_{31} of 2.0 Å/V. The voltage to control the motion comes from a high-voltage amplifier that can provide up to ±150 V. To achieve maximum motion we apply a voltage to one electrode and the opposite voltage to the opposite electrode. The voltage difference between the electrodes can therefore swing between +300 V and −300 V. These voltages produce the maximum electric field which may be applied across the benders without risk of depoling them. Figure 2 shows a room temperature image of a microfabricated test structure, made using a commercial atomic force microscope (AFM) tip. Here the applied voltage is ±55 V, about one third the maximum voltage. The scan suffers from some nonlinearity, so that the true area scanned is not quite square.

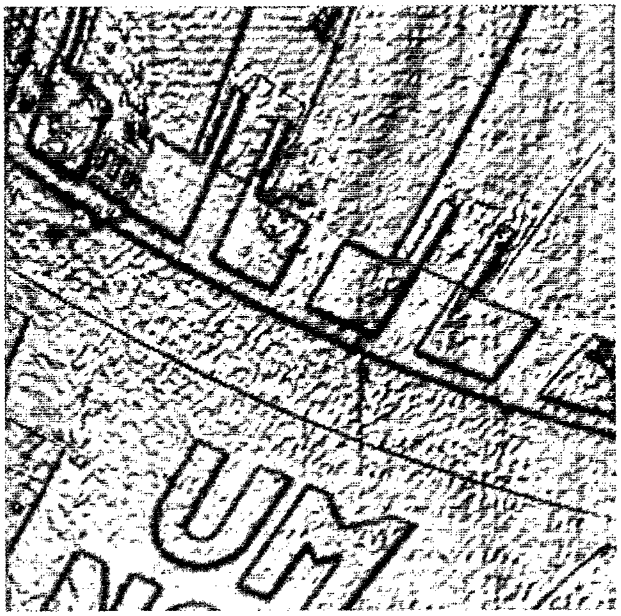

FIG. 2. An 800 μm square room temperature image of a microfabricated test structure, taken using a commercial AFM tip. Only one-third the maximum possible range was used for this image, so that the full room temperature range is expected to be about 2.2 mm.

Measurements of this structure with an optical microscope show that the scan range is about 800 μm. The resolution is clearly limited only by the 3.1 μm pixel size of the 256×256 pixel scan. We apply only ±55 V for this room temperature scan because the scan head was designed mainly for cryogenic use, where the bender motion is less, and at room temperature the scan head hits the base at applied voltages of greater than ±55 V. Making a linear extrapolation to ±150 V would yield a room temperature range of around 2.2 mm.

We have also measured the room temperature resonant frequencies and vibrational motion of the stage in the x and y directions using an optical interferometer. All measurements were performed in air with the stage mounted on a floating optical table. Figure 3 shows the amplitude response of the scanner to a small sinusoidal voltage. The scanner has a resonance at about 45 Hz in the x direction, and at about 73 Hz in the y direction. The x resonance is lower since the x benders carry the extra mass of the y piezos. Although these frequencies are low compared to small tube scanners (which have a much smaller range), they appear entirely adequate for the kinds of scans typically made with these large ranges. Also of interest is the fluctuation of the scan head when no voltage is applied, due to mechanical noise coupling into the system. The amount of noise is difficult to measure, but the scanner mounted in air on an optical table is a typical operating regime. With the voltage leads to the piezos grounded, we measured rms deviations of the scanner head of 4.5 nm in the x direction and 5.7 nm in y. These values are far below the size of any pixel one might expect in operation of such a large-range scanner. Indeed, when the high voltage amplifier was attached but kept at nominally zero volts, the rms displacement noise went up by a factor of about 5, showing that

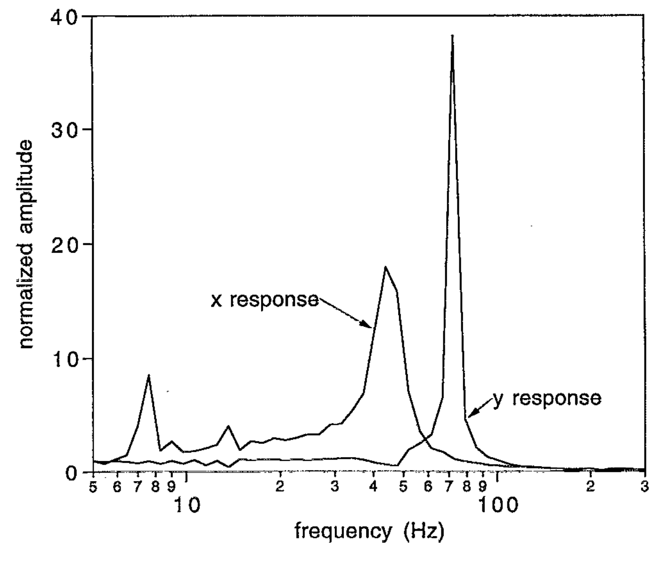

FIG. 3. The amplitude response of the scanner.

in this case amplifier noise was more important than mechanical noise.

For many applications, some form of z motion is required. In principle, a voltage proportional to the desired z motion could be added to the outer electrodes of all the benders, causing them to lengthen. The addition of such a voltage, however, will limit the maximum x-y excursion of the scanner, since the depoling field will be reached for smaller values of the x or y driving voltages. Further, the amount of z motion obtainable this way is quite small compared with the large x-y motions. Thus, we have found that it is usually easiest to add a short bender, either on the scanner head or on the fixed part of the microscope, to effect z motion. In this way, large z motions can be obtained with relatively high resonant frequencies while being completely decoupled from the x-y motion.

IV. LOW TEMPERATURE OPERATION

The main design goal of this scanner was to get large scanning ranges even at cryogenic temperatures, where d_{31} for piezoceramics decreases by roughly an order of magnitude relative to room temperature. Our design has several advantages for low temperature work. First, of course, is its large range at cryogenic temperatures. It is also quite compact, with the Macor base, the widest part of the scanner, having a diameter of only 1.125 in., making the instrument small enough to be used inside a storage Dewar or superconducting solenoid. Finally, the design is inherently temperature compensated. Even though the length of the benders changes due to thermal contraction upon cooling, the scanning head does not move relative to the base. This is because the mechanical path from the base to the secondary stage is made of the same piezo material as the path from the secondary stage to the scanning platform.

We have taken images of the same sample as in Fig. 2, but at 4.2 K. Comparison of the two images indicates a total scan range (applying now the maximum ±150 V) of 275 μm. Thus the response of our piezos decreases by a factor of 8. This scan range is much greater than that reported for a large-range piezoelectric tube scanner,[5] which scanned a 9 μm square at cryogenic temperatures. Our scanner's large range should allow for imaging a wide range of intermediate-scale physical systems at cryogenic temperatures. As an example, Fig. 4 shows the magnetic field above a 100 μm thick Pb film at 4.2 K in a magnetic field of 200 G. This image was taken using a 2×2 μm^2 microfabricated GaAs Hall probe, and shows the normal and superconducting lamenae expected in type-I superconductors with large demagnitization factors. The relatively large size of these lamenae precludes their observation with conventional small-range tube scanners.

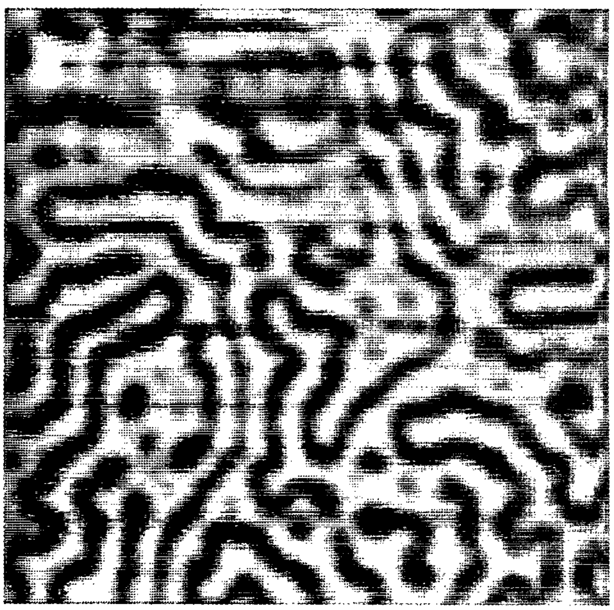

FIG. 4. A 4.2 K scanning Hall probe image of a 100 μm thick Pb film. At 200 G, this film shows the laminar normal (dark) and superconducting (bright) domains expected in type-I films with large demagnetization factors. The image is 230 μm on a side.

In summary, we have designed, constructed, and demonstrated the capabilities of a compact, large-range piezoelectric scanner suitable for operation at cryogenic temperatures. This scanner may find applications in a variety of novel scanning microscopies which require much larger scan ranges than are possible using standard tube scanners.

ACKNOWLEDGMENTS

This work was supported in part by the NSF under Grant No. DMR-92-22541, and was performed in part at the National Nanofabrication Facility, which is supported by the NSF under Grant No. ECS-8619049, Cornell University, and industrial affiliates.

[1] G. Binnig and D. P. E. Smith, Rev. Sci. Instrum. **57**, 1688 (1986).
[2] G. Binnig, C. F. Quate, and C. Gerber, Phys. Rev. Lett. **56**, 930 (1986).
[3] Y. Martin and H. K. Wickramasinghe, Appl. Phys. Lett. **50**, 1455 (1987).
[4] E. Betzig, J. K. Trautman, T. D. Harris, J. S. Weiner, and R. L. Kostelak, Science **251**, 1468 (1991).
[5] A. M. Chang, H. D. Hallen, L. Harriot, H. F. Hess, H. L. Kao, R. E.

Miller, R. Wolfe, J. van der Ziel, and T. Y. Chang, Appl. Phys. Lett. **61**, 1974 (1992).

[6] R. García Cantú and M. A. Huerta Garnica, J. Vac. Sci. Technol. A **8**, 354 (1990).

[7] V. K. Adamchuk, A. V. Ermakov, and S. I. Fedoseenko, Ultramicroscopy **42–44**, 1602 (1992).

[8] M. O. Wantanabe, K. Tanaka, and A. Sakai, J. Vac. Sci. Technol. A **8**, 327 (1990).

[9] M. A. McCord and R. F. W. Pease, Appl. Phys. Lett. **50**, 569 (1987).

[10] P. Muralt, D. W. Pohl, and W. Denk, IBM J. Res. Devlop. **30**, 443 (1986).

[11] B. L. Blackford, D. C. Dahn, and M. H. Jericho, Rev. Sci. Instrum. **58**, 1343 (1987).

[12] J. Burger, S. C. Meepagala, and E. L. Wolf, Rev. Sci. Instrum. **60**, 735 (1989).

[13] U. Dürig, D. Pohl, and F. Rohner, IBM J. Res. Devlop. **30**, 478 (1986).

[14] R. García Cantú and M. A. Huerta Garnica, Surf. Sci. **181**, 216 (1987).

[15] J. E. Yao, J. He, G. Y. Shang, Y. L. Kuang, J. Wei, K. Zeng, K. C. Lin, J. W. Dai, and Y. X. Su., in *International Symposium on Electron Microscopy*, edited by K. Kuo and J. Yao (World Scientific, Singapore, 1991), p. 81.

[16] D. A. Brawner and N. P. Ong, J. Appl. Phys. **73**, 3890 (1993).

[17] R. N. Goren and M. Tinkham, J. Low Temp. Phys. **5**, 465 (1971).

[18] From catalog, Vernitron Piezoelectric Division, Bedford, OH.

[19] C. J. Chen, Appl. Phys. Lett. **60**, 132 (1992).

[20] R. D. Blevins, *Formulas for Natural Frequency and Mode Shape* (Krieger, Florida, 1979), p. 221.

[21] M. E. Taylor, Rev. Sci. Instrum. **64**, 154 (1993).