Single-tube three-dimensional scanner for scanning tunneling microscopy

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We report a new type of three-dimensional mechanical scanner fabricated from a single piezoelectric tube. It has a typical response of 5 nm/V in each orthogonal direction and mechanical resonances at 8 kHz (bending perpendicular to the tube axis) and 40 kHz (motion parallel to the tube axis). When used in a scanning tunneling microscope it is the higher frequency mode which is most critical since it corresponds to motion perpendicular to the sample surface. We show an image of the atomic surface of graphite taken in air using a tube scanner incorporated into a scanning tunneling microscope. The tube scanner allows the development of smaller, simpler, and faster scanning tunneling microscopes.

Most mechanical scanners used for scanning tunneling microscopy (STM) have until now been constructed along the same basic design. Separate piezoelectric transducers are fixed in orthogonal directions and give a combined *x-y-z* range of motion. Often three transducers are fixed in a tripod arrangement in which the three meet at a common vertex.[1] A typical tripod scanner fabricated from PZT-5H (Ref. 2), where each leg is a rectangular bar 13 mm long and 2 mm thick, has a response of 1.5 nm/V in each direction, and a lowest mechanical resonance at 5 kHz. Some have used combinations of bimorphs to give higher resonance frequencies.[3] We have invented a new kind of three-dimensional scanner fabricated from a single piezoelectric tube which gives significantly improved performance compared to the conventional tripod scanner and proves to be easier than all other scanners to fabricate and incorporate into an STM. Our single-tube scanner fabricated from PZT-5H and measuring 12.7 mm long, 6.35 mm in diameter, and 0.51 mm thick has a response of 5 nm/V in each direction. The lowest mechanical resonance at 8 kHz corresponds to a bending mode perpendicular to the tube axis. When incorporated into an STM this corresponds to a deflection parallel to the surface of a sample. The resonance mode corresponding to motion parallel to the tube axis occurs at 40 kHz. This very high-frequency mode proves to be the more crucial one for STM operation since it corresponds to motion perpendicular to the sample surface.

In order to get three orthogonal displacements from a single tube we section the electrodes coating the piezoelectric. Figure 1 shows one possible configuration where the outside electrode is split into four areas of equal area. By applying a voltage (whose sign depends upon the polarization of the piezoelectric material) to a single outside electrode, that segment of the tube is made to expand perpendicular to the electric field. This causes the whole tube to bend perpendicular to its axis. Orthogonal *x-y* motion is obtained by controlling the voltages on two of the electrodes spaced 90° apart. The other two electrodes can be grounded or used as large amplitude offsets by applying a high dc voltage. Motion in the *z* direction is obtained by applying voltage to the single inside electrode which causes a uniform expansion of the tube. The *x-y* motion is not entirely orthogonal to *z*, but the coupling is small. The effective coupling is minimized by placing the electrically isolated STM probe tip on one of the dc motion electrodes. To ensure the highest possible orthogonality a precision machined tube must be used.[4]

After the development of our tube scanner we discovered that a similar design has been used as a transducer for a stereo phonograph cartridge.[5] In that application *x-y* motion

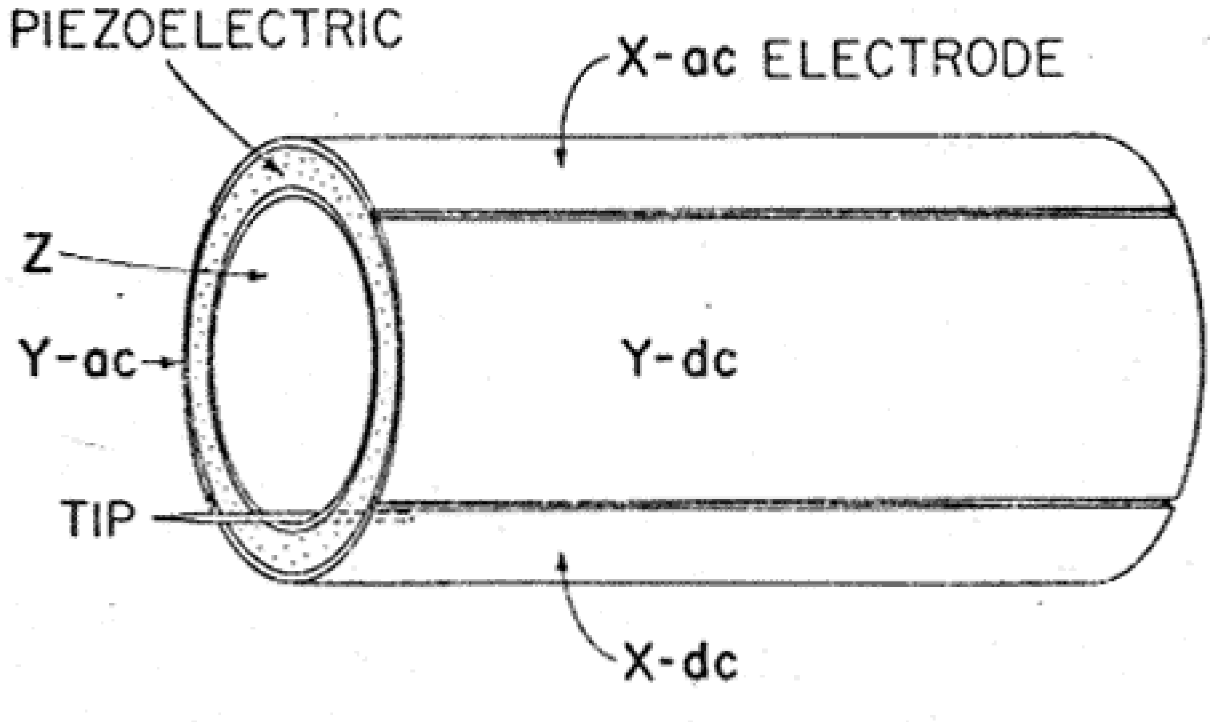

FIG. 1. Drawing of a tube scanner showing the outside electrode sectioned into four equal areas parallel to the axis of the tube. As voltage is applied to a single outside electrode the tube bends away from that electrode. Voltage applied to the inside electrode causes a uniform elongation. A small ac signal and a large dc offset can be separated on electrodes 180° apart. A probe tip is shown mounted for an STM.

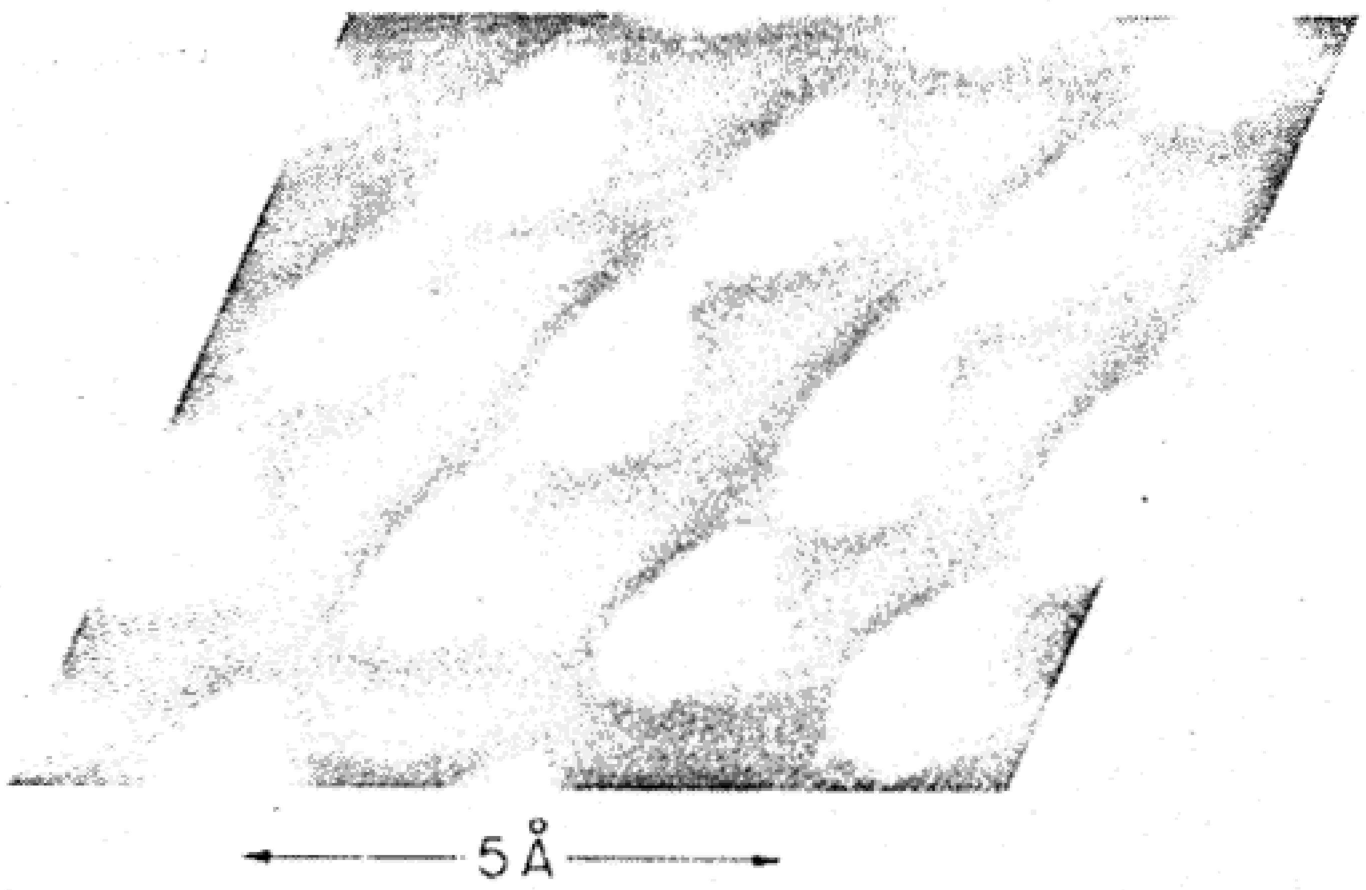

FIG. 2. An STM image of the surface of graphite taken in air using a single-tube scanner. The experimental technique and interpretation of the image are given in Ref. 6.

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of a stylus in a record groove produced voltages corresponding to two audio channels. The z motion was not used.

Figure 2 shows an STM image of the surface of graphite taken in air using the tube scanner described above. The experimental technique used to take this image is described elsewhere.[6] We have found that for STM work the tube scanner has several important advantages over the typical tripod scanner. The tube scanner has greater range and higher resonance frequencies. The high resonance frequencies allow faster scanning speeds and provide greater rejection of ambient vibration. The low mass of the tube gives a larger acoustic impedance mismatch to the rest of the system and so prevents propagation of scanner noise. The smallness and simplicity of the tube scanner means that the whole STM becomes more compact, more resistant to vibration, and easier to construct. Moreover, while drift caused by thermal expansion is a problem which distorts many STM images because of the cylindrical symmetry of the tube scanner there is no thermal distortion in the x-y plane if the tip is mounted symmetrically.

We have found that the single-tube scanner has allowed us to make smaller, simpler, and more reliable scanning tunneling microsopes that can operate faster and with less distortion.

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Longitudinal CO_2 laser operating directly at line voltage with hollow cathode discharge

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A different type of longitudinal CO_2 laser is developed with multisegment hollow cathode discharge that sustains at low voltages. Operation of this laser is investigated with a 400-V peak ac source obtained directly from a three-phase line using inductive ballasts. Output laser pulses of 2 ms FWHM, 3-W peak power and repetition frequency of 100 Hz are obtained from an active length of about 45 cm at an operating pressure of 12 mbar (CO_2:N_2:He $= 1:1:10$). The specific output power can be increased by improving cooling of the active medium.

Part of the current technological trend in enhancing versatility of the CO_2 lasers has been directed towards the development of more reliable, compact, safe, and inexpensive systems. A single factor that can help in achieving these is the low-voltage operation of the laser. But at low excitation voltages, the interelectrode spacing has to be reduced in a conventional CO_2 laser. Under these conditions, the negative glow and the associated Faraday dark space fill the entire discharge volume.[1] These discharge regions are not suitable for pumping the CO_2 laser.[1,2] Sedwick and Seguin have overcome this problem by using an inverted brush cathode screened with a grid to operate a low-pressure transverse discharge CO_2 laser with abnormal glow at low voltage.[2] We have developed a simple longitudinal low-voltage CO_2 laser with segmented discharge mainly constituted by the hollow cathode discharge. This type of discharge has the inherent characteristic of sustaining at low voltage while producing a relatively large number of low-energy electrons in the range of 0–4 eV which are the most suited for the excitation in a CO_2 laser medium.[3] This experimental laser has been operated directly at about 400 V from a three-phase line, eliminating the requirements of a transformer and other high-voltage components for the power supply of a usual longitudinal CO_2 laser. As a result, the overall system is very compact, light, reliable, and of the least possible cost. This scheme is particularly attractive for a medical laser system where high voltage poses a serious problem of fire hazard due to the presence of highly combustible vapors of anaesthesia, etc. in the operating theater.[4] Compared to a transverse discharge CO_2 laser, a longitudinal low-voltage system would be preferred because of its superior beam quality for focusability and mode filling of the gain medium. Although the main aim of developing the experimental laser described in this note was to achieve laser action in CO_2 with low-voltage longitudinal discharge, this device is useful for a number of experiments in photochemistry[5] and spectroscopy[6] at its present power level of about 3-W peak.

The schematic of the laser assembly and the experimental setup are shown in Fig. 1. An enlarged view of the electrode design is also shown in the inset of this figure. The laser

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