

## Atomic Force Microscope

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The scanning tunneling microscope is proposed as a method to measure forces as small as  $10^{-18}$  N. As one application for this concept, we introduce a new type of microscope capable of investigating surfaces of insulators on an atomic scale. The atomic force microscope is a combination of the principles of the scanning tunneling microscope and the stylus profilometer. It incorporates a probe that does not damage the surface. Our preliminary results *in air* demonstrate a lateral resolution of 30 Å and a vertical resolution less than 1 Å.

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We are concerned in this paper with the measurement of ultrasmall forces on particles as small as single atoms. We propose to do this by monitoring the elastic deformation of various types of springs with the scanning tunneling microscope (STM).<sup>1</sup> It has been a common practice to use the displacement of springs as a measure of force, and previous methods have relied on electrostatic fields, magnetostatic fields, optical waves, and x rays. Jones<sup>2</sup> has reviewed the devices that use variable capacitances and he reports that displacements of  $10^{-4}$  Å can be measured. SQUIDS<sup>3</sup> are superconducting elements that measure the expulsion of magnetic fields in variable-inductance devices. They are used in gravity gradiometers to measure displacements of  $10^{-6}$  Å. Tabor and co-workers<sup>4</sup> in their work with van der Waals forces have used optical interference methods to measure displacements of 1 Å. With an x-ray interferometer constructed from a single crystal of silicon, Deslattes<sup>5</sup> has also measured displacements of  $10^{-6}$  Å which is about 1% of the nuclear diameter.

We are proposing a new system wherein the STM is used to measure the motion of a cantilever beam with an ultrasmall mass. The force required to move this beam through measurable distances ( $10^{-4}$  Å) can be as small as  $10^{-18}$  N. The masses involved in the other techniques are too large to reach this value. This level of sensitivity clearly penetrates the regime of interatomic forces between *single atoms* and opens the door to a variety of applications. The atomic force microscope (AFM) is a new tool designed to exploit this level of sensitivity. It will be used to investigate both conductors and insulators on an atomic scale. We envision a general-purpose device that will measure any type of force; not only the interatomic forces, but electromagnetic forces as well.

With the STM,<sup>6</sup> the atomic surface structure of conductors is well resolved. For bulk insulators<sup>7</sup> an equivalent method is missing although the stylus profilometer (SP)<sup>8,9</sup> has been developed into a powerful microscopic technique. Teague *et al.*<sup>10</sup> have used the SP to record three-dimensional images of surfaces with a lateral resolution of 1000 Å and a vertical resolution of 10 Å. A related technique is the scanning capacitance microscope described by Matey and Blanc.<sup>11</sup> They report a lateral resolution of 5000 Å and a vertical resolution of 2 Å.

The SP has much in common with the STM. The tip in the STM and the stylus in the SP are both used to scan the surface, sense the variations of the sample, and generate three-dimensional images. The stylus in the profilometer is carried by a cantilever beam and it rides on the sample surface. This means that a rough surface can be plastically deformed.<sup>12</sup> The radius of this stylus is about 1 μm, and the loading force extends from  $10^{-2}$  to  $10^{-5}$  N.<sup>13</sup>

The spring in the AFM is a critical component. We need the maximum deflection for a given force. This requires a spring that is as soft as possible. At the same time a stiff spring with high resonant frequency is necessary in order to minimize the sensitivity to vibrational noise from the building near 100 Hz. The resonant frequency,  $f_0$ , of the spring system is given by  $f_0 = (1/2\pi)(k/m_0)^{1/2}$ , where  $k$  is the spring constant and  $m_0$  is the effective mass that loads the spring. This relation suggests a simple way out of our dilemma. As we decrease  $k$  to soften the spring we must also decrease  $m_0$  to keep the ratio  $k/m_0$  large. The limiting case, illustrated in Fig. 1, is but a single atom adsorbed at site *A* in the gap of an STM. It has its own mass and an effective  $k$  that comes from the coupling to neighboring atoms.

The mass of the spring in manmade structures can be quite small but eventually microfabrication<sup>14</sup> will be employed to fabricate a spring with a mass less than  $10^{-10}$  kg and a resonant frequency greater than 2 kHz. Displacements of  $10^{-4}$  Å can be measured with the STM when the tunneling gap is modulated. The force

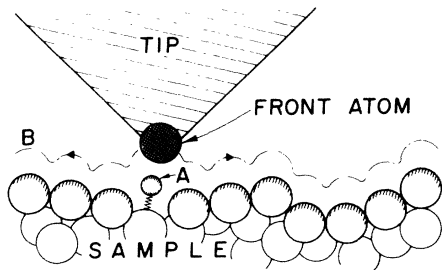


FIG. 1. Description of the principle operation of an STM as well as that of an AFM. The tip follows contour *B*, in one case to keep the tunneling current constant (STM) and in the other to maintain constant force between tip and sample (AFM, sample, and tip either insulating or conducting). The STM itself may probe forces when a periodic force on the adatom *A* varies its position in the gap and modulates the tunneling current in the STM. The force can come from an ac voltage on the tip, or from an externally applied magnetic field for adatoms with a magnetic moment.

required to produce these displacements is  $2 \times 10^{-16}$  N and this is reduced by 2 orders of magnitude when a cantilever with a *Q* of 100 is driven at its resonant frequency.

AFM images are obtained by measurement of the force on a sharp tip (insulating or not) created by the proximity to the surface of the sample. This force is kept small and at a constant level with a feedback mechanism. When the tip is moved sideways it will follow the surface contours such as the trace *B* in Fig. 1.

The experimental setup is shown in Fig. 2. The cantilever with the attached stylus is sandwiched between the AFM sample and the tunneling tip. It is fixed to a small piezoelectric element called the modulating piezo which is used to drive the cantilever beam at its resonant frequency.

The STM tip is also mounted on a piezoelectric element and this serves to maintain the tunneling current at a constant level. The AFM sample is connected to a three-dimensional piezoelectric drive, i.e., the *x, y, z* scanner. A feedback loop is used to keep the force acting on the stylus at a constant level. Viton spacers are used to damp the mechanical vibrations at high frequencies and to decouple the lever, the STM tip, and the AFM sample. The tip is brought in close proximity to the sample by mechanical squeezing of the Viton layers. High-frequency ( $> 100$  Hz) filtering of building vibrations is done as in the pocket-size STM<sup>15</sup> with a stack of metal plates separated by Viton.

We have operated the AFM in four different modes which relate to the connections of the two feedback circuits, one on the STM and the other on the tip. All four of these modes worked in principle. They each served to maintain a constant force,  $f_0$ , between the sample and the diamond stylus while the stylus followed the contours of the surface.

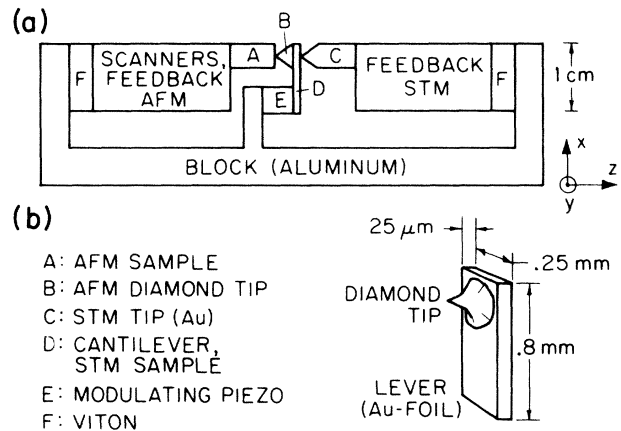


FIG. 2. Experimental setup. The lever is not to scale in (a). Its dimensions are given in (b). The STM and AFM piezoelectric drives are facing each other, sandwiching the diamond tip that is glued to the lever.

In the first mode we modulated the sample in the *z* direction at its resonant frequency (5.8 kHz). The force between the sample and the diamond stylus—the small force that we want to measure—deflects the lever holding the stylus. In turn, this modulates the tunneling current which is used to control the AFM-feedback circuit and maintain the force  $f_0$  at a constant level.

In the second and third modes, the lever carrying the diamond stylus is driven at its resonant frequency in the *z* direction with an amplitude of 0.1 to 10 Å. The force,  $f_0$ , between sample and stylus changes the resonant frequency of the lever. This changes both the amplitude and phase of the ac modulation of the tunneling current. Either of these can be used as a signal to drive the feedback circuits.

In the fourth mode we used one feedback circuit. It was connected to the AFM and it was controlled by the tunneling current in the STM. This system maintained the tunneling gap at a constant level by changing the force on the stylus.

The fourth mode was further improved by reconnection of both feedback circuits in such a way that the AFM sample and the STM tip were driven in opposite directions with a factor  $\alpha$  less in amplitude for the STM tip. The value of  $\alpha$  ranged from 10 to 1000.

In contrast to previous methods, the absolute value of  $f_0$ , the force on the stylus, was not well defined except at the beginning of the measurement. The deformation of the spring,  $\Delta z$ , is well calibrated at the starting point, but as the measurement proceeds each component of the system moves in an unknown way because of thermal drifts. These change the initial calibration. Additionally, we know that the three-dimensional motion of the AFM sample must produce modest amounts of change in  $\Delta z$  so as to compensate for the simultaneous motion of the stylus as it follows

the topography of the surface. Therefore, even in the absence of thermal drifts the force  $f_0$  will vary over a certain range that is dependent on both the roughness of the surface and the value of  $\alpha$ .

The fourth mode proved to be the most reproducible. We used it to record the results shown in Figs. 3 and 4, where we show the topography for two different areas of a ceramic ( $\text{Al}_2\text{O}_3$ ) surface. The successive traces along the  $x$  axis are displaced from each other by the small, undefined thermal drift along the  $y$  axis. The vertical dashed lines of Fig. 3 indicate the smooth variation in the  $y$  direction of topographic features that can be followed from trace to trace. From these results and from the noise amplitude on the traces we can estimate that it should be possible to resolve a periodic corrugation on the sample with an amplitude below  $1 \text{ \AA}$  when the period of the corrugation is between  $1$  and  $100 \text{ \AA}$ .

The results from the other three modes were inferior to these. We encountered a threshold of force in these measurements which might be related to water films covering the surfaces of the AFM. The fine structure on the right of the curves of Fig. 4 could only be observed when the applied force exceeded the threshold. For smaller forces the structure was

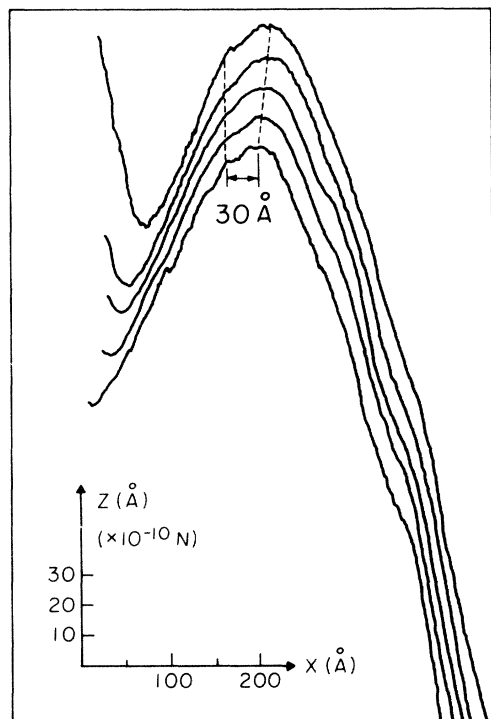


FIG. 3. The AFM traces on a ceramic ( $\text{Al}_2\text{O}_3$ ) sample. The vertical scale translates to a force between sample and tip of  $10^{-10} \text{ N/\AA}$ . For the lower trace the force is near  $3 \times 10^{-8} \text{ N}$ . The stability of the regulated force is better than  $10^{-10} \text{ N}$ . The successive traces are displaced by a small drift along the  $y$  axis.

smearred out. We suspect that this level is determined by the force that is necessary to penetrate the film. In the first three methods we used small forces well below the threshold and there we lose the fine structure.

The following improvements over the handmade version used here should increase the resolution to the point where we will be able to resolve the atomic features. Available microfabrication techniques<sup>14</sup> will allow us to reduce the mass of the stylus-cantilever unit by several orders of magnitude. When the instrument is mounted in an ultrahigh-vacuum chamber where clean surfaces can be well characterized we know from our STM experience that the stability will be improved by at least 2 orders of magnitude. With these optimum conditions the thermally induced vibrations of the cantilever at room temperature will limit the force sensitivity to  $10^{-15} \text{ N}$ . If the system is cooled below  $300 \text{ mK}$  we estimate that the lower limit will be  $10^{-18} \text{ N}$ .

This level becomes interesting when we compare it to the interatomic forces.<sup>15</sup> In the strongest materials with ionic bonds the binding energy is  $10 \text{ eV}$ . It is  $10 \text{ meV}$  for those materials that are held together with the weak forces of van der Waals. If we arbitrarily equate the energy to a force acting through a distance of  $0.16 \text{ \AA}$  we find that a binding energy of  $1 \text{ eV}$  is equivalent to a force of  $10^{-8} \text{ N}$ . The interatomic forces therefore range from  $10^{-7} \text{ N}$  for ionic bonds to  $10^{-11} \text{ N}$  for van der Waals bonds<sup>16</sup> and down to perhaps  $10^{-12} \text{ N}$  for some of the weaker forces of surface reconstruction. The limiting sensitivity of our instrument is far less

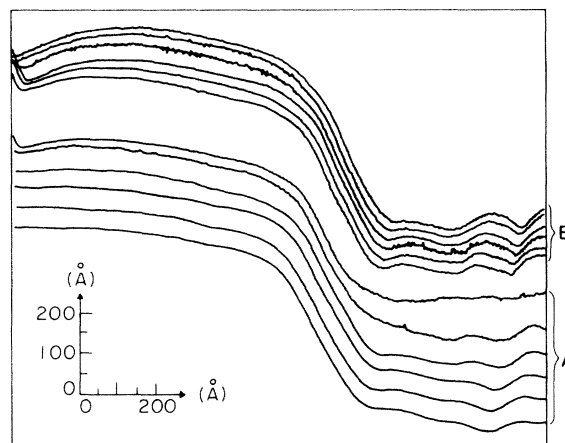


FIG. 4. The AFM traces for another area of the ceramic sample. The curves grouped under *A* were recorded with additional low-pass filtering. For this set the stabilizing force,  $f_0$ , was reduced by thermal drifts as we moved from the lowest to the highest traces of set *A*. The force  $f_0$  is near  $10^{-8} \text{ N}$  for the highest curve. We note that the structure vanishes on the traces when the sample-to-tip force is reduced below this level. The force  $f_0$  was reset to a higher value near  $5 \times 10^{-8} \text{ N}$  for the traces marked *B*.

than these values. Therefore, we should be able to measure all of the important forces that exist between the sample and adatoms on the stylus.

Finally, we want to point out that these forces also exist in the tunneling microscope itself and that they can have a strong influence on the data collected with the STM.<sup>17,18</sup> The STM could be used as a force microscope in the mode described here by simply mounting the STM tip on a cantilever beam.

We are pleased to thank J. Pethica for his inspiring talk on the problems of the tip at the STM workshop in Oberlech, Austria, which—although some months later—probably triggered the idea for the AFM. We also want to express our appreciation to H. Rohrer and D. Pohl for those stimulating discussions. This work was supported in part by a grant from the IBM Corporation and in part by the Defense Advanced Research Projects Agency.

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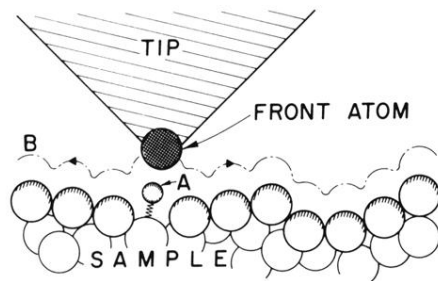


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