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New form of scanning optical microscopy

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The exponential decay of the evanescent field due to the total internal reflection (TIR) of a light beam in a prism is used to advantage in a new form of scanning optical microscope, the photon scanning tunneling microscope (PSTM). The PSTM is the photon analogue of the electron scanning tunneling microscope. The sample is placed on or forms the TIR surface and spatially modulates the evanescent field. Changes in intensity are monitored by a probe tip scanned over the surface, and the data are processed to generate an image of the sample. Subwavelength resolution in three dimensions is obtained because of the exponential nature of the evanescent field intensity. Images produced by a prototype instrument using 633-nm light and a 1-μm probe tip are shown to have a lateral resolution of about 200 nm.

The exponential nature of a waveform in a tunneling barrier provides the opportunity for a uniquely sensitive form of microscopy. Exploitation of this simple aspect of a finite barrier began in the present decade with the development of the scanning tunneling microscope (STM) by Binnig and Rohrer.[1] This paper reports on a new form of scanning optical microscopy which is analogous to the electron STM. The use of near-field scanning optical microscopy (NFSOM) has already been reported.[2-4] The basic concept involves the use of light emitted from or collected by a subwavelength-sized aperture scanned laterally above a sample at an aperture-sample separation of less than one wavelength of the light being used (referred to as the near-field region). The instrument reported here uses the sample-modulated tunneling of photons to a sharpened optical-fiber probe tip, the source being the evanescent field produced by total internal reflection (TIR) of a light beam. This provides an exponentially decaying waveform normal to the sample surface. As in the case of the STM, a feedback circuit is employed to regulate the intensity of the signal by varying the tip to sample distance. Thus, the feedback prevents the tip from contacting the sample. This technique is particularly suited to the study of dielectric surfaces, which are impossible to directly profile with an electron STM due to charging effects. Also, the resolution afforded by the photon scanning tunneling microscope (PSTM) is better than that of standard optical microscopes, and the data may be assimilated and readily processed by a computer. Optical absorbance or other spectroscopic information can also be obtained from the internally reflected beam. We describe below a prototype instrument which demonstrates subwavelength resolution.

The foundation for the operation of the PSTM is the total internal reflection of light incident on an interface between materials of different refractive indices (n_i and n_t) when the incident beam lies in the medium of higher index (n_i). TIR takes place when the angle of incidence θ_i (relative to the normal) exceeds the critical angle given by $\theta_c = \arcsin(n_t/n_i)$. For $\theta_i > \theta_c$, an evanescent field is produced in the medium of lesser index. The intensity of this field decreases exponentially with increasing distance from the interface according to

$$I \sim \exp\{-2kz[\sin^2\theta_i - (n_t/n_i)^2]^{1/2}\}, \quad (1)$$

where k is the magnitude of the wave vector of the incident light and z is the distance from the interface.[5] If another medium of index greater than n_t is brought within the evanescent field, such as the tip of a sharpened optical fiber, a situation arises analogous to that of a finite tunneling barrier in quantum mechanics. That is, a potential barrier for particles of energy below the barrier height is perfectly analogous to the present case, although the wave functions vary in character depending upon the type of particle.

Photons from the incident beam tunnel through the region between the tip and sample and can be collected by a suitable detection system. The presence of a sample on the TIR surface will modulate the waveform of the evanescent field, and this modulation will manifest itself as spatial variations in the field intensity at a given height above the sample surface (Fig. 1). These changes in intensity provide topographical information about the sample surface as well as information about the optical properties of the sample (for example, spatial variations in the index of refraction). The spatial resolution is affected by

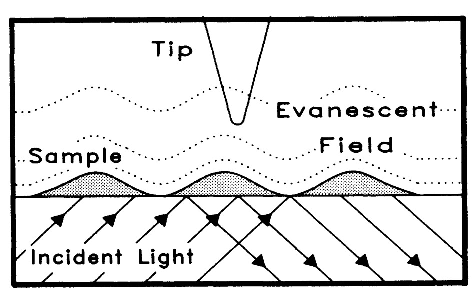

FIG. 1. Schematic of the PSTM principle. The tip probes the sample-modulated evanescent field produced by an internally reflected light beam.

the decay length of the evanescent field and by the size and shape of the tip. Further, structures of subwavelength size which are highly absorbing in the wavelength region being used may cause difficulties with resolution normal to the surface. This is due to the fact that a reduction in intensity can be due equally well to absorption or to a variation in topology of the sample. Monitoring the absorbance with the internally reflected beam may, therefore, be particularly useful for samples with poorly known optical properties. In this case, the instrument includes the qualities of the well-known Kretschmann configuration for attenuated total reflection.[6]

A detailed description of a prototype apparatus and its operation will be reported elsewhere.[7] Briefly, the arrangement is as follows: A 7-mW helium-neon laser beam is directed onto the internal face of a prism at an angle beyond the critical angle so that it experiences TIR. The laser was found to produce an evanescent field intensity which offered more than sufficient signal for the optical fiber probe tip. The geometry of our PSTM follows that of most conventional STM's in that the probe tip is mounted on a piezoelectric translator and scanned over a stationary sample. Our instrument employs piezoelectric bimorphs to achieve tip motion along three orthogonal axes.[8] The scanner is made from PZT-5H piezoelectric ceramic bimorphs and has a minimum resonant frequency of 1.75 kHz. The scanner has a range of 10 μm tangential to the sample and 6 μm normal to it. Initial calibration of the scanner's motion was performed by using an electromechanical deflection meter with a resolution of 0.01 μm. The tip end of the optical fiber is attached to the piezoelectric scanner while the other end extends to an RCA 1P28 photomultiplier tube.

Motion of the scanner is monitored and controlled by a personal computer, which also serves to collect and process the scan data. As the tip is rastered laterally above the sample, a feedback circuit senses the current from the photomultiplier tube and adjusts the tip to sample separation so as to maintain a constant photomultiplier current. The tip height at each scan point is monitored and stored by the computer and forms the coordinates for constructing a three-dimensional image replica of the sample surface. The computer is subsequently used to process the data and form a crude gray-scale rendering of the sample. Further image processing is accomplished with a Silicon Graphics image-processing work station.

A critical component of the PSTM is the probe tip. An ideal high-resolution tip is formed by sharpening the tip to a small radius termination with a narrow divergence. Tips were formed by chemically etching one end of a 30-cm long, 200-μm diam quartz optical fiber in a 49% solution of hydrofluoric acid. To date we have achieved tips with diameters down to 150 nm using this method. Some of these tips were thereafter coated by evaporating 200 nm of silicon normal to the length of the fiber as the fiber is rotated axially in order to leave an aperture on the very end of the tip. Images were taken which were obtained using both coated (aperture) and uncoated tips. The results were similar, but this was likely due to the small thickness of the coating. We have also established a method whereby tips may be further sharpened beyond the HF acid etch by using CHF_3 in a dc-biased, rf plasma-etching system to etch directionally, through a mask of submicrometer sized metal particles, a layer of SiO_2 evaporated onto the tip. This produces several needlelike protrusions a few tens of nanometers in diameter on the end of the tip. These needles may further be coated with silicon and then plasma-etched to reveal even smaller apertures on the ends of the needles. Results of this procedure will be published elsewhere.[9]

To demonstrate the exponential decay of the evanescent field, measurements were made of the photomultiplier current as a function of the probe tip's distance from the interface. The laser beam was internally reflected with an incident angle of $45° \pm 0.3°$ in a quartz medium ($\theta_c = 43.34°$). Data were taken for both coated and uncoated tips; the results are shown in Fig. 2. The decay length d for the evanescent field intensity, as given by the relation

$$(1/d) = 2k[\sin^2\theta_i - (n_t/n_i)^2]^{1/2}, \quad (2)$$

was calculated to be 296.0 nm at 45°. This varies by ± 27.4 nm with the uncertainty in angle. Our experimental results yielded average values of 265 nm for the coated tip and 269 nm for the uncoated tip. There was very little difference between the decay lengths measured with the coated (aperture) tip and those measured with the uncoated tip. The major difference between the coated (aperture) tip and the uncoated tip was the reduced overall signal strength for the coated tip. A thicker coating would be needed to produce aperture-limited higher resolution.

Once evanescent coupling and feedback control of the tip position was established, imaging by rastering over the surface became possible. The PSTM was calibrated in operation by looking at a holographic grating sample with a known line spacing of 1.17 μm. The grating structure was formed in a layer of transparent photoresist on a quartz substrate. This sample was coupled to the prism base by an index-matching gel. A PSTM image of this sample taken with an uncoated tip is shown in Fig. 3(a). The corrugations are approximately 160 nm high and some smaller structure can also be seen. Using a coated tip resulted in a nearly identical image. For comparison, a

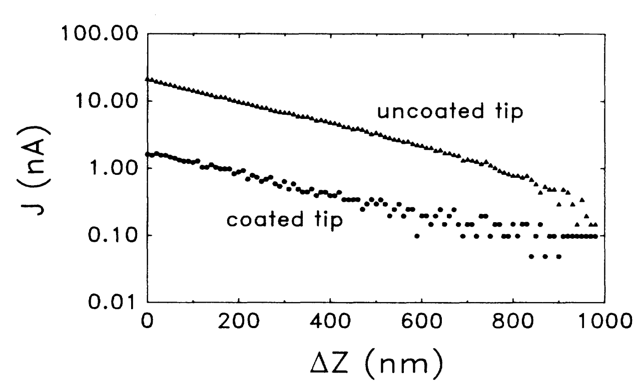

FIG. 2. Photomultiplier current J as a function of increasing distance ΔZ from the interface using both a coated (aperture) and uncoated tip.

portion of the grating was coated with a 30-nm gold layer and imaged with both an electron STM and a conventional scanning electron microscope. These images are shown in Figs. 3(b) and 3(c), respectively.

We also used the PSTM to image the surface of a clean quartz microscope slide. Figure 4 shows a $9 \times 9\ \mu m^2$ region of the surface. The subwavelength-sized roughness is seen with corrugations on the order of 100–200 nm deep. A total of 28 scans taken over a period of two days exhibited reproducible structure at a lateral resolution of 200 nm. Structures with dimensions on the order of 80 nm normal to the surface were found to be readily resolvable. Noise in the feedback electronics gave rise to 16-nm peak-to-peak fluctuations.

In conclusion, we have reported on a new optical microscope, the photon scanning tunneling microscope (PSTM). The principle and method of operation is directly analogous to the electron STM—the exponential nature of a waveform inside a tunneling barrier is exploited to make an imaging instrument capable of subwavelength resolution. One novelty of the PSTM lies in the use of a feedback system driven solely by optical processes to regulate the probe tip's distance from the sample. Although many techniques have been reported in the NFSOM literature for making very small apertures,[3,10] the effective sharpening of the tip due to the exponential nature of the evanescent field is the primary mechanism for achieving subwavelength resolution with this instrument (as is the case with the electron STM). In fact, increasing the angle of incidence of the internally reflected beam and decreasing the wavelength of the light dramatically decreases the decay length of the evanescent field. The effective sharpness of the tip improves and results in better resolution. Of course, while subwavelength apertures are not necessary for achieving subwavelength resolution, their use should improve resolution.

As in the electron STM, ultimate resolution of the PSTM depends upon the effective sharpness of the tip.

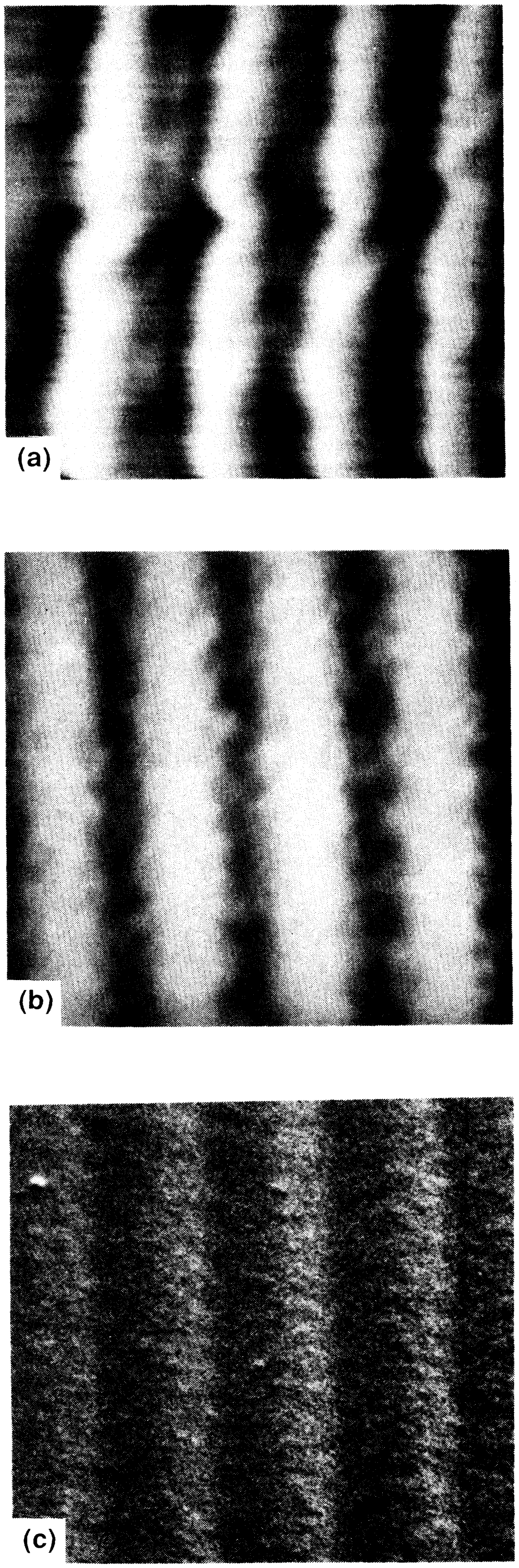

FIG. 3. Images of a holographic grating structure taken with (a) PSTM, (b) electron STM, and (c) scanning electron microscope. Actual line spacing is 1.17 μm.

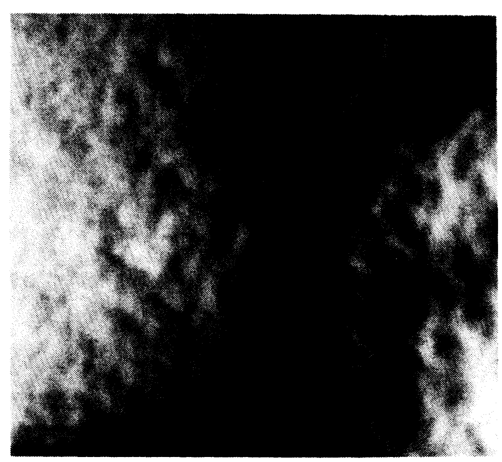

FIG. 4. Image of the surface of a quartz microscope slide taken with the PSTM. The scan area is $9 \times 9\ \mu m^2$. The gray scale ranges 340 nm.

We expect optimization of tip fabrication techniques together with the generation of more strongly decaying evanescent fields to endow the PSTM with lateral resolutions of the same order of scanning electron microscopy. Since TIR may be observed for an enormous range of electromagnetic radiation, including x rays, the use of an optical fiber and TIR arrangement is potentially very versatile. Frequencies which are high enough to be absorbed by the optical fiber will need to be converted to visible light before being channeled to a photomultiplier.

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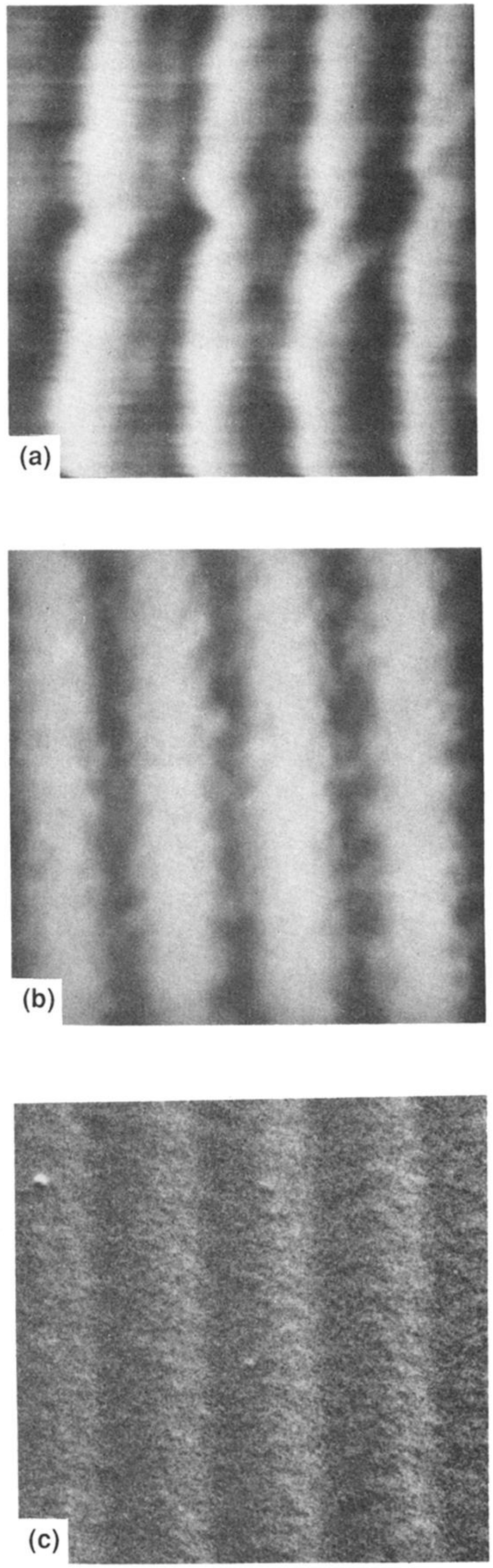

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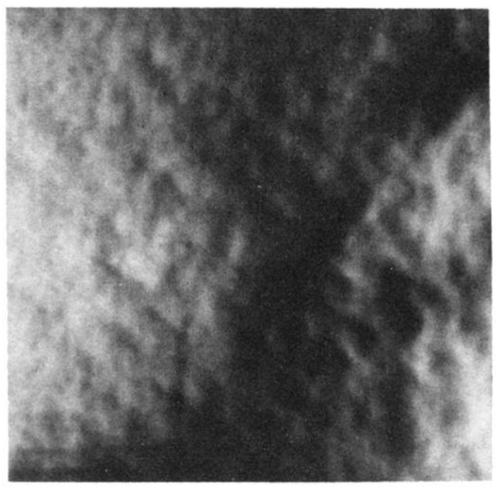

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