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Near-field Photodetection Optical Microscopy (NPOM): a novel probe for optical characterization on a sub-wavelength spatial scale

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ABSTRACT

Near-field Photodetection Optical Microscopy (NPOM) is a new approach to optical surface characterization with sub-wavelength spatial resolution. The technique is based upon the direct detection of local variations in optical intensity near a surface with a photodetector of nanometer size. The ultra-small photodetector probe is raster scanned in close proximity to an optically illuminated surface and the photoresponse of the probe is measured at each point. The local optical information is electronically stored and displayed by computer in a manner similar to all Scanning Probe Microscopies. The resultant image represents the local optical intensity at each point on the illuminated surface. The probe fabrication and a recent experimental demonstration of the probe capabilities will be described.

1. INTRODUCTION

A significant amount of effort has been directed toward the goal of establishing techniques capable of optical characterization on a sub-wavelength scale. See reviews by Betzig [1] and Pohl [2]. Here we present a novel approach which differs significantly from previous approaches. The new concept Near-field Photodetection Optical Microscopy (NPOM) is based upon the construction of an optical photodetector of nanometer dimension at the end of a scanning probe tip. The photodetector is brought close to the optically illuminated surface and is scanned laterally. The local photodetector measures the variation in the local optical intensity that may be caused by sub-wavelength sized optical inhomogeneities near the surface of an optically illuminated sample. See Figure 1.

As in the case of all scanning probe measurements, the NPOM probe is rastered over a region of the sample and a map of the photodetector probe signal is acquired and displayed by computer. Because the detector is in the "near-field" of the surface scatterers, the spatial resolution achieved in the mapping is not limited by the optical wavelength, but rather is limited only by the "effective" size of the probe and the gap between the tip and surface.

The motivation for considering this approach includes the following. Firstly, the scattered fields drop off rapidly with distance when the scatterer is small compared to the wavelength of light [3]. When a sub-wavelength particle is illuminated with a plane wave, large evanescent fields are created by the optical polarization of the particle. These large fields reactively oscillate near the particle with little power transfer to the far field. If an optical absorber is placed in the region of these evanescent fields, power can be extracted. The detection of scattered light can be very efficient in this near-field regime when compared with far-field detection of the scattered light.

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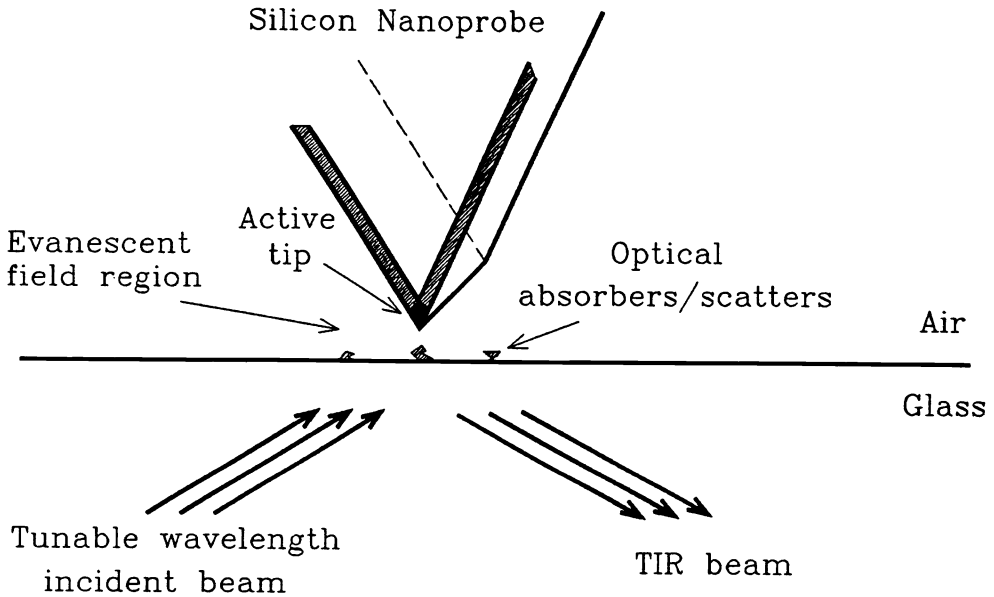

Fig. 1. Illustration of the near-field photodetection concept.

The second motivation is that the resolution achieved by the near-field photodetection approach is not limited by the opacity condition that limits the resolution of the aperture approaches [1,2]. The NPOM detection scheme does not require an aperture to perform the near-field measurement. A sharp tip of arbitrarily small radius can in principle be used as the photodetector. The third motivation is that local optical spectroscopy can be performed if the photodetector is fabricated with semiconducting materials, since photodetection can occur over a range of wavelengths. Semiconductor fabrication techniques should also provide a means for batch fabrication of these nanoprobes at a relatively low cost.

2. PROBE FABRICATION

The first attempts to demonstrate this new concept have been based upon the construction of a silicon photodiode detector at the tip of a cleaved silicon substrate as shown below in figures 2a and 2b. A silicon wafer (100) with a thermal oxide of thickness typically 200 nanometers is cleaved along two of its crystallographic cleavage planes (111), leaving a rectangularly shaped corner as shown in figure 2a. This corner has a radius of curvature typically below 10 nanometers, as shown by a Scanning Electron Microscope (SEM). After the cleavage, the sample is dipped into an HF etch, and approximately 100 nanometers of oxide is removed. The etch has two effects. It reduces the vertical thickness of the oxide from 200 to 100 nanometers, and it etches the oxide layer laterally near the cleaved edges of the wafer. In this region, a bare v-shaped channel of silicon is exposed by the removal of the oxide. The result is shown in Figure 2b. At this point, a photodiode can be created by evaporating a thin film of aluminum over the silicon/silicon dioxide structure at such an angle so that the aluminum makes contact to the silicon in the channel regions, but makes no contact to the cleaved silicon faces. A photoresist mask is painted on to limit the metal-semiconductor contact area to a region within 25 micrometers of the tip. An anneal is then performed to assure that an adequate contact is made between the aluminum film and the exposed silicon in the channel. The result of this process is to create a Schottky diode at the tip of the cleaved wafer. This diode can be used as a nanometer scale photodetector. The built-in depletion of the diode typically has a depth on the order of 20 nanometers, the width typically is approximately 100 nanometers and the length of the diode is approximately 25 micrometers.

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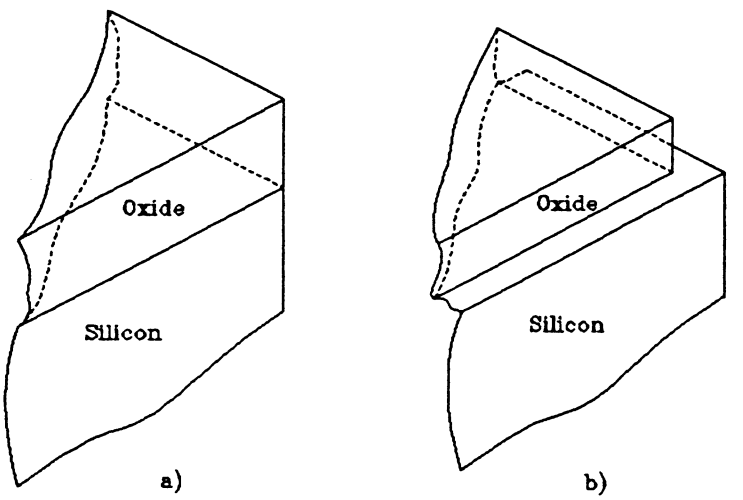

Fig. 2. a) Oxidized silicon (100) wafer after cleavage along two (111) planes. b) Silicon tip structure after removal of half of the silicon dioxide layer by an isotropic etch in hydrofluoric acid.

The electronic and optical properties of the small photodiode detectors were characterized by measuring current-voltage (I-V) relation for the devices with and without optical illumination. Figure 3 shows the typical response of the photodetector tips as a function of illumination. The figures indicate that there is a strong modulation of the reverse leakage current under optical illumination as is expected.

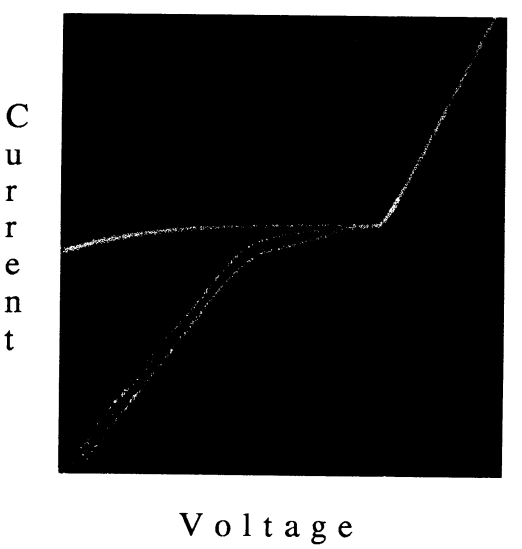

Fig. 3. Experimental I-V curves for the near-field photodetector measured with and without optical illumination. The upper curve is without illumination and the lower curves are with illumination.

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3. EXPERIMENTAL DEMONSTRATION

To demonstrate the performance of this nanoscale optical detector, the probe was used to measure the evanescent field distribution in a total internal reflection (TIR) experiment. The experimental arrangement is shown in Figure 4. A He-Ne laser is sent through a prism at an angle greater than the critical angle for TIR. The probe is piezoelectrically translated toward the surface with a small dither (10 nanometers) in the direction of travel. The resultant photodiode signal at the frequency of the dither is measured by a lock-in amplifier and displayed as a function of probe position with respect to the sample surface. Typical results are shown in Figure 5 for several different illumination angles. As is expected, the decay length of the evanescent field depends upon the illumination angle. A plot of the measured decay length as a function of illumination angle is shown in Figure 6 for many measurements. Also shown by the solid line is a theoretical curve for the predicted decay length. As can be seen in the figure, the experimental data follow the trend of the theoretical prediction, but the measured decay lengths are consistently shorter than that predicted. The most likely explanation of this discrepancy is that the presence of the nanoprobe modifies the local decay length of the optical evanescent fields. This explanation is presently being evaluated.

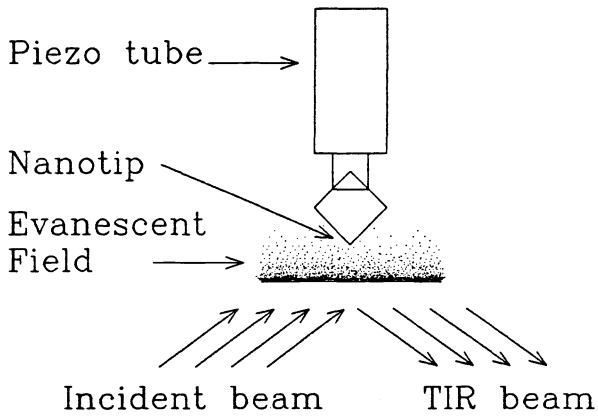

Fig. 4. Schematic illustration of the experimental setup to measure the optical decay length of the evanescent fields under illumination beyond the critical angle.

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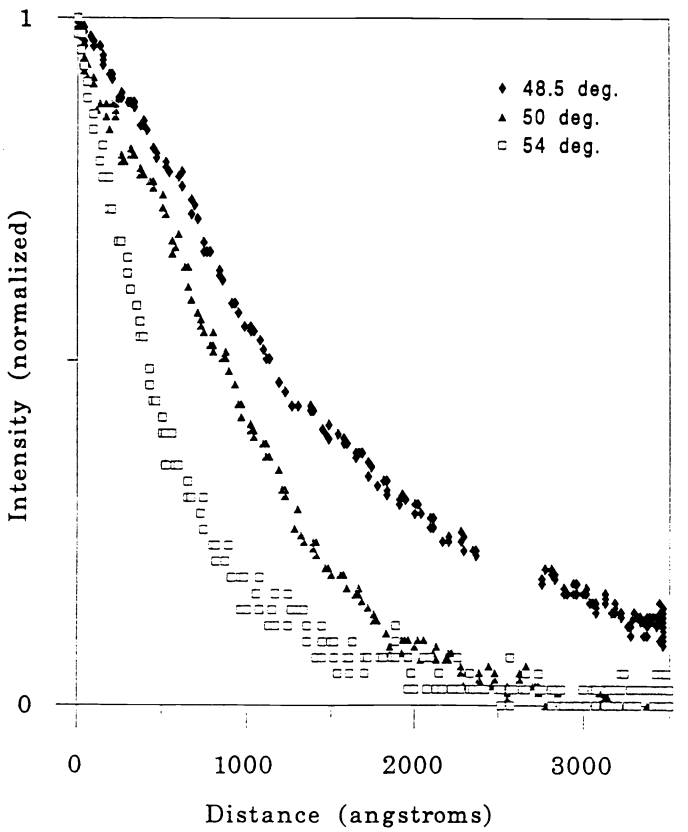

Fig. 5. Intensity of the optical evanescent field versus distance as measured by the near-field photodetector. The angles are measured from the perpendicular.

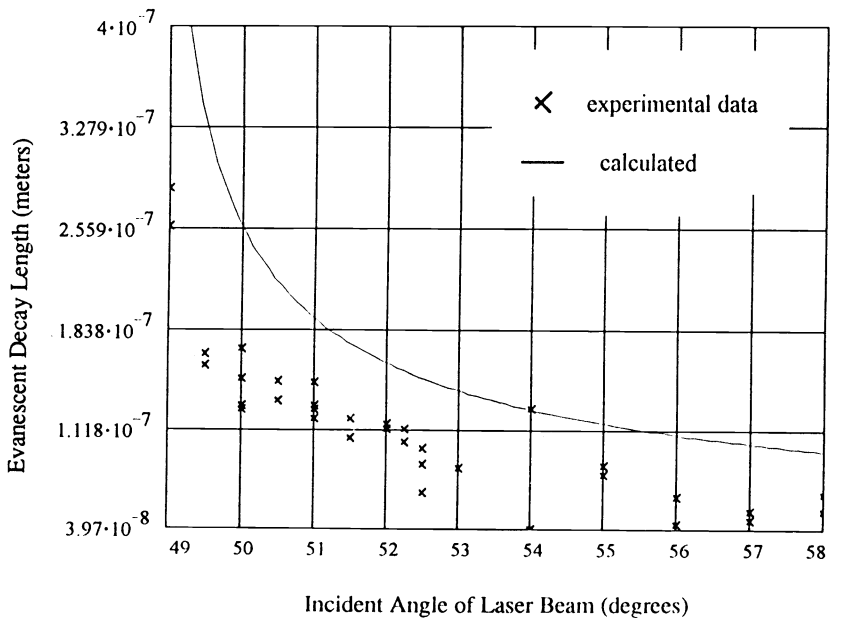

Fig. 6. Measured evanescent tail length versus the angle of the incident optical beam. The solid curve represents the theoretical prediction of the angular dependence. As can be seen the measured data are systematically shorter than that predicted by one dimensional theory.

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Several attempts have been made to image nanometer scale structure under optical illumination with the photodetector probes. Structure in the images appears on the half wavelength scale (300 nanometers) but nothing that is clearly beyond the diffraction limit. It has been determined that the electronic noise in the nanoprobe is limiting the spatial resolution achievable in the images. Currently this noise is dominated by optical noise from the laser. We believe that when this noise is reduced, smaller scale structure will be visible in the NPOM images.

It has been noted that when an AFM is used to control the height of the probe during the optical imaging, very high resolution structure (sub 10 nanometer) can be seen in the optical image. This high resolution structure, however, is not optical in nature. Rather it is due to the dependence of the optical signal on the average height of the probe above the surface. It represents a topographic coupling into the optical image. This problem is common to essentially all near-field optical approaches.

4. SUMMARY

A new approach to near-field optical microscopy has been presented. Nanometer scale semiconductor probes have been fabricated. These probes have been used to detect the evanescent optical fields that exist near an interface under conditions of total internal reflection. The optical field decay length has been measured as a function of the incident angle. Decay lengths down to 80 nanometers have been measured with the near-field photodetector. The measured decay lengths were compared with a one dimensional model. It was found that the measured decay lengths were systematically shorter than that predicted by theory.

5. REFERENCES

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