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PHOTON SCANNING TUNNELING MICROSCOPY *

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ABSTRACT

The Photon Scanning Tunneling Microscope (PSTM) is the photon analogue of the electron Scanning Tunneling Microscope (STM). It uses the evanescent field due to the total internal reflection of a light beam in a Total Internal Reflection (TIR) prism. The sample, mounted on the base of the prism, modulates the evanescent field. A sharpened optical fiber probes this field, and the collected light is processed to generate an image of the topography and the chemical composition of the surface. We give, in this paper, a description of the microscope and discuss the influence of several parameters such as - polarization of light, angle of incidence, shape of the end of the fiber - on the resolution. Images of various samples - glass samples, teflon spheres - are presented.

I. INTRODUCTION

Photon Scanning Tunneling Microscopy (PSTM) belongs to the family of SXM microscopies [1,2] which exploit a distance dependent interaction for guidance of a probe tip and local information about this interaction. One of these new microscope - Scanning Tunneling Microscope [3] - demonstrated its capability to map atomic and molecular shapes, overcoming the fundamental limitation of any conventional microscope : diffraction obscures details smaller than about one half the wavelength of

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the radiation. The STM has been considerably described in the recent years and has imaged surface structure on a host of substance. However, the STM is restricted to imaging electrical conductors.

In 1988, at Oak Ridge National Laboratory, R.C. REDDICK, R.J. WARMACK and T.L. FERRELL [4] invented the PSTM which is a similar instrument to the STM but one which uses the tunneling of photons across the gap between the sample and a sharpened optical fiber probe tip. The PSTM uses a sample and a tip that are conductors for photons and is restricted to imaging transparent samples. If the sample is opaque it is possible to change the light source and switch to a wavelength at which the sample is not absorbing.

In chapter II a general description of the PSTM's operation is given and images of several samples is shown. A discussion of the optimization of the resolution of the microscope by acting on the important parameters is presented in chapter III. Application of PSTM - probing of optical waveguides, testing of optical surfaces are discussed in the last chapter.

II. PRINCIPLES AND OPERATION OF THE PSTM :

1) Imaging

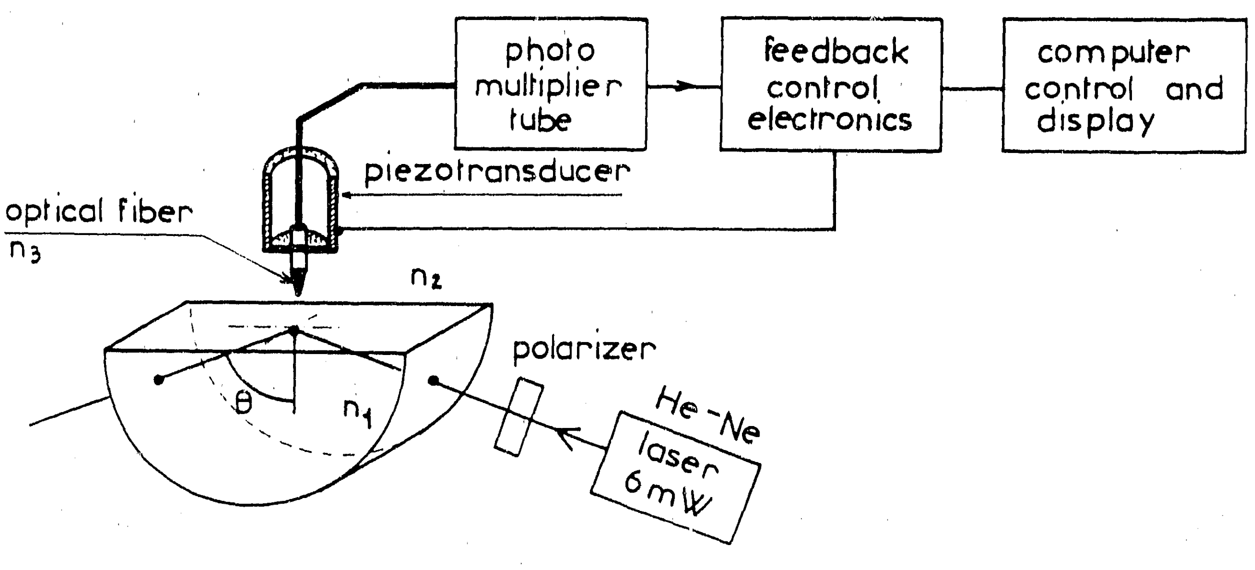

Figure 1 : Schematic of experimental set up.

An evanescent field is formed by total internal reflection at the interface between two semi-infinite media of different indexes of refraction n_1 et n_2 ($n_2 < n_1$). The light is totally reflected if the angle of incidence is larger than the critical angle $\theta_c = \sin^{-1} n_2/n_1$. This condition provides an exponentially decaying probability of photons tunneling from the sample surface to a fiber optic probe. The light is conducted by the fiber to a photomultiplier tube and converted to an electrical signal. The subsequent imaging process is identical to that of the STM.

The probe tip is mounted in a piezoelectric tube similar to those used in scanning tunneling microscopy [3]. Voltages applied to the tube allow detailed control of the motion of the tip in three dimensions. Depending on the characteristics of the tube different scanning area are possible ranging from (1μm x 1μm) up to (100 μm x 100 μm) tangential to the sample.

The probe tip is formed by etching one end of a multimode graded-index optical fiber (50/125 CGE) in a solution of hydrofluoric acid.

The decay length of the exponentialy decreasing light intensity in medium n_2 can be calculated for p and s polarization by using the expression of the electric fields in the different media. These calculations show [5] that the decay length for a PSTM is a function of the shape of the tip, the angle of incidence θ, the polarization of the light, and the values of the three refractive indexes n_1, n_2, n_3. It is shown, also, that a decrease in decay length induces an increase in image resolution.

Figure 2 is an example of the exponential decay of the field intensity as a function of the increasing tip-sample distance, measured for several angles of incidence. In terms of decay lengths (or depth of penetration depending on different authors) it can be seen in Fig. 3 that a very small decay length (40 nm) can be reached by using a λ_2 = 2500 Å wavelength illumination and a near-grazing incidence. Since TIR may be observed for an enormous range of electromagnetic radiation, including X rays, we expect to endow the PSTM with resolution of the same order of scanning electron microscopy.

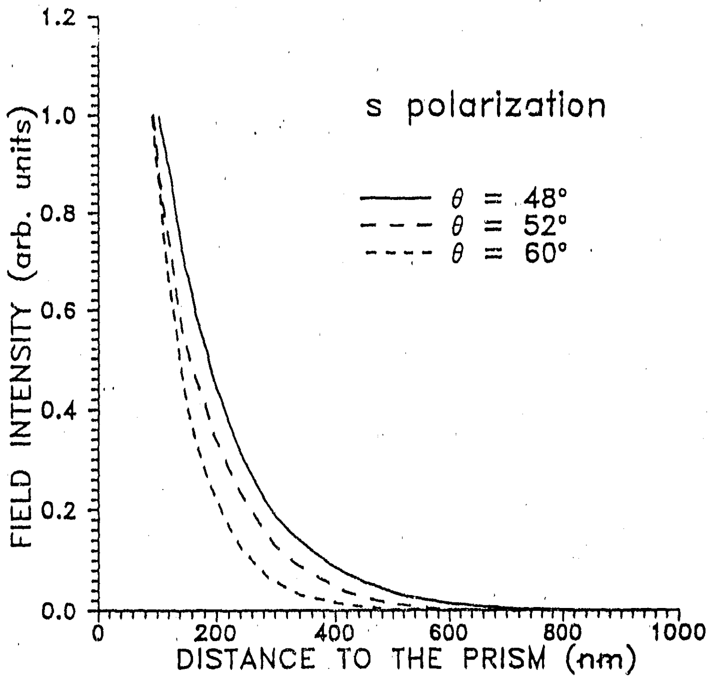

Figure 2 : Field intensity (Photomultiplier current) as a function of increasing distance d from the interface measured for s polarization and several angles of incidence at $\lambda = 6328$ Å.

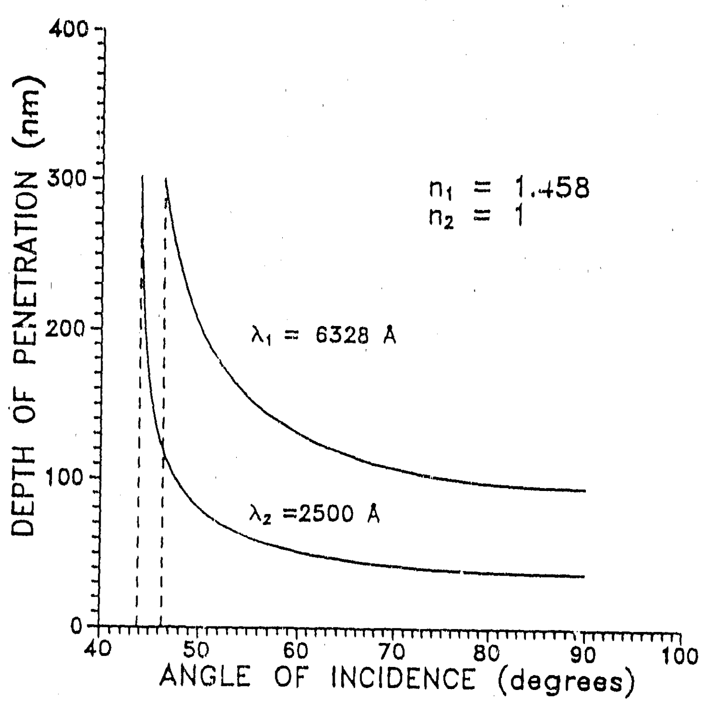

Figure 3 : Depth of penetration (or decay length) as a function of increasing angle of incidence for two wavelengths $\lambda_1 = 6328$ Å and $\lambda_2 = 2500$ Å. A glass-air interface has been considered.

PSTM images of two samples are shown in Fig. 4, and 5. Fig. 4 is the image of the surface of a quartz slide which was coupled to the prism base by an index-matching fluid. The subwavelength-sized roughness is seen with corrugations on the order of 10 - 20 nm deep. Fig. 5 is a PSTM image of teflon spheres (ø = 225 nm) deposited on the base of the prism.

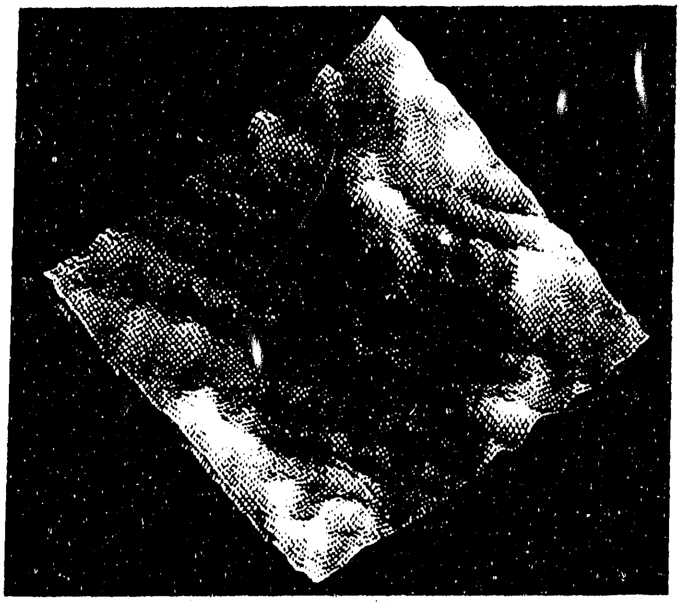

Figure 4 : Image of the surface of a quartz slide taken with a PSTM. The scan area is 3 x 3 μ^2.

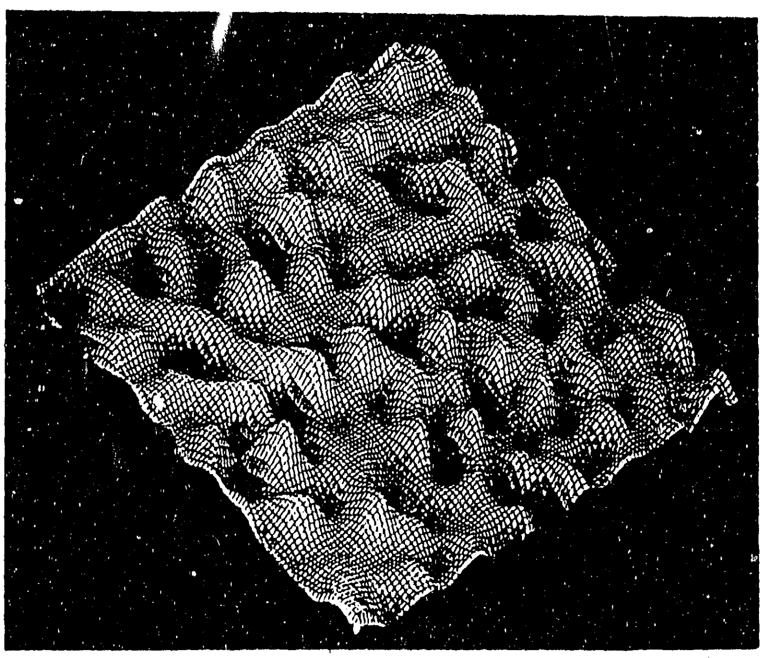

Figure 5 : Image of teflon spheres on the base of the prism

III. RESOLUTION OF THE MICROSCOPE OPTIMIZATION

High spectral resolution being required, we have conducted a serie of theoretical and experimental studies in order to optimize the parameters responsible of the variations of the penetration depth d_p - shape of the tip, polarization, angle of incidence [5].

These studies show that for both s and p polarizations the decay length decreases as the angle of incidence increases. The smallest values of d_p are obtained for the largest values of the angle of incidence and for s polarization (Fig. 6). In the PSTM the shape of the tip could be thought to be critical for the coupling between the evanescent field and the third medium. As a matter of fact it is not. The reason is that the strong dependence of energy flux on tip-to-surface distance makes only a fraction of the tip subtend any significant energy flux. This permits better tangential resolution than might be expected. The demonstration of this statement is easily made by assuming that the end of the fiber is a paraboloid (Fig. 7). It can be seen, that the variation of the intensity calculated for two models of paraboloid (a "needle" a = 4.10^7 and an "infinite plane" a = 0) are both similar to those of the experiments.

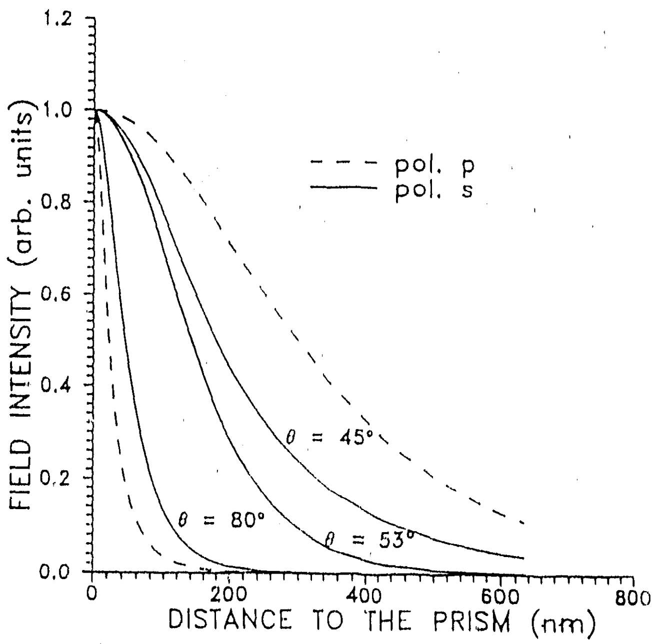

Figure 6 : Field intensity in medium 3 (optical fiber) calculated as a function of the distance to the prism and p (solid line) and s (dashed line) polarizations. For $\theta = \theta_l = 53°$ the intensity is the same for both polarizations. For the calculations the following values of the parameters have been used : $n_1 = n_3 = 1.458$, $n_2 = 1$, $\theta_c = 43°30$, $\theta_l = 53°$.

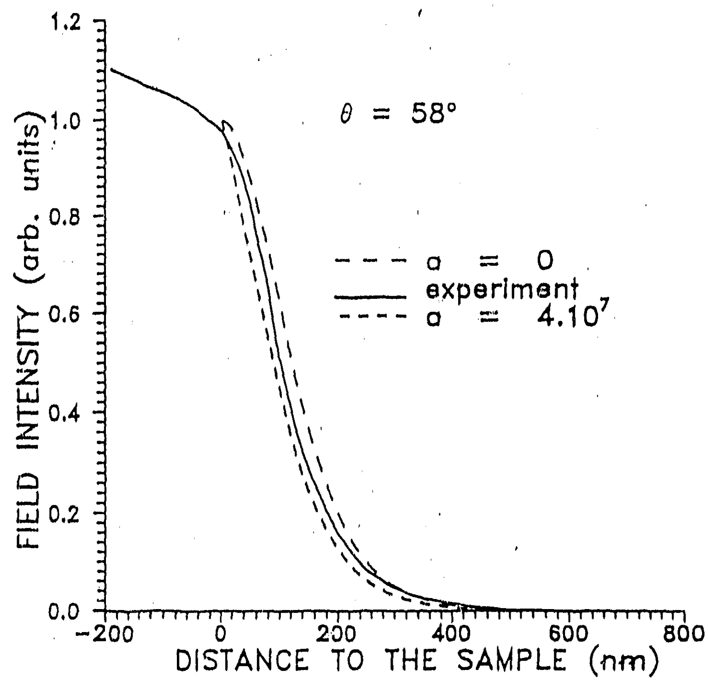

Figure 7 : Field intensity as a function of the tip-sample distance.

experiment
calculated with a flattered paraboloid model
calculated with a sharp paraboloid model.

If a sample to be studied has a spatially varying chemical composition, spectroscopy can be carried out simultaneously with the PSTM microscopy and a chemical map can be superimposed on the topology. The specific compound in a given region can be distinguished in the image by absorption or Raman spectroscopy. Results of these procedures will be published elsewhere [(6)].

The photoluminescence spectrum from a sample of ruby taken with a PSTM has been localy determined and the stress features present in the sample monitored in the region probed [(7)]. The PSTM technique has been shown [(8)] to probe directly the evanescent field outside a planar and a channel waveguide. Surface scanning images in either constant height or constant intensity mode have been obtained and have the potential to reveal both local topographic and dielectric fluctuations.

CONCLUSION

PSTM offers many exciting possibilities for surface science research. A variety of applications are forthcoming, microlithography, spectroscopies. Biological work could benefit from high resolution chemical mapping of samples in a more natural environment than that demanded by other probes.

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