Light absorption by an atomic force microscope probe

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Abstract. In this paper a probe of an atomic force microscope (AFM) served as a detector of optical radiation. We investigated absorption of optical radiation in the visible range by commercially available Si and Si_3N_4 probes. It has been shown that the radiation in the far field is mainly absorbed in the probe tip. By scanning a laser beam with a diameter of ~ 0.7 microns by the AFM probe, a lateral resolution of ~ 1.5 microns was demonstrated. Numerical modeling of evanescent wave absorption by AFM probes showed enhancement of the absorption in the probes as compared with a flat surface. A Si_3N_4 probe more effectively absorbs the evanescent radiation.

1. Introduction

Development of semiconductor lasers, optical waveguides and other structures for photonics and optoelectronics requires information about optical radiation distribution in them. Conventionally, scanning near-field optical microscopy (SNOM) is used for experimental studies of optical radiation distribution in the near field at the interface of two media, such as laser/air or optical fiber/air [1]. In this method, the sharpened optical fiber probe collects near-field radiation. An AFM probe with a subwavelength-diameter aperture is also used for collecting of near-field radiation [2]. These well-known techniques are limited in spectral range by transparence of the SNOM optical system.

Recently, we demonstrated the detection of optical radiation in the near [3, 4] and the far field [5] by conventional apertureless AFM probes. In our method, an oscillating probe absorbs optical radiation. Absorbed radiation heats the probe and shifts its oscillation frequency and phase. The frequency shift is proportional to the absorbed optical radiation. The method allows the detection of optical radiation in the near field in the visible and infrared ranges with subwavelength resolution.

The resolution of the method in the far field has not been studied. In addition, commercially available probes can be made from Si or Si_3N_4, which are transparent in the visible range and can be coated by various metal layers. At small distances between the probe and the surface, the probe is capable to capture evanescent waves emerging at the surface/air interface [6]. Effects of the probe shape, material and metal coating on the absorption of the optical radiation in the far field and evanescent waves are unstudied. The aim of this work was to experimentally and theoretically examine the characteristics of the visible light absorption by Si and Si_3N_4 probes in the near and the far fields.

2. Methods

In this study, we investigated a Si probe PPP-FMR (Nanosensors) and a Si_3N_4 probe with a metal coating (60 nm Au / 15 nm Cr) NPG10 (Bruker). The probes consist of a cantilever beam and a sharp pyramid mounted on it. Optical absorption measurements in the far field were carried out for Si_3N_4 probes using a Ntegra Spectra (NT-MDT) microscope. This microscope combines the functionality of confocal optical and atomic force microscopes. Figure 1 (a) shows a scheme of the experiment. A pyramid of the oscillating probe was illuminated by a laser beam with a wavelength λ = 527 nm. Investigations were carried out by varying the focused laser beam diameter on the probe tip. Additionally, the scanning system moved the probe with respect to the laser beam in the XY plane, i.e. the laser beam scanned the probe. During the scanning, the phase signal of the probe oscillations was recorded. Thus, a series of images of the laser radiation absorption in the probe was obtained at different diameters of the laser beam.
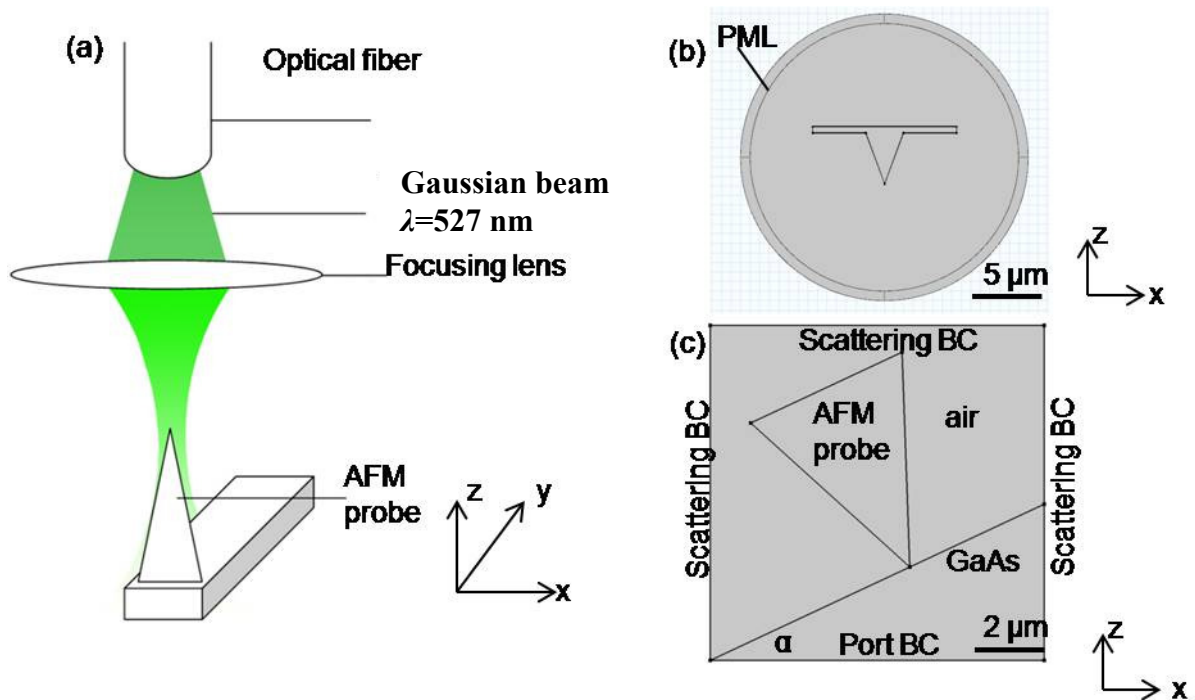

Figure 1. (a) Scheme of the experiment (the AFM probe scanning the laser beam of different diameters). Geometrical models for numerical simulations of light absorption by the AFM probe (b) – in the far field, (c) absorption of an evanescent wave.

For numerical simulation of the electromagnetic waves absorption by the AFM probe, the *Electromagnetic waves, frequency domain* module in the Comsol Multiphysics software was used. To calculate the absorption of radiation in the far field, the model was set as a two-dimensional region bounded by a circle with a perfectly matched layer (PML) on the boundary (figure 2(b)). In the center of the circle there was a probe that can be approximated by a triangle and was parameterized by the real and imaginary parts of the refractive index of the material of which it was made. It is assumed that all the fields have a harmonic dependence on time and that all material properties are linear with respect to the field strength. The solution of the Maxwell's equations is searched in the form:

$$E = E_{relative} + E_{background},$$

where the background field is known, and the relative field is the field, after the addition of which to the background one, it turns out that the field satisfies Maxwell's equations. In the simulation, the field of the Gaussian beam is used as the far field ($E_{background}$) (built-in function in the used module). The width of the beam ω depends on the distance z from the beam waist ω_0 as follows:

$$\omega(z) = \omega_0 \sqrt{1 + \left(\frac{\lambda z}{\pi \omega_0^2}\right)^2}$$

By using this dependence, one can simulate different diameters of the laser beam by changing the coordinate of its waist.

To simulate the evanescent wave field, the model was set as a two-dimensional square area bounded at the top and sides by the scattering boundary condition (BC), and for the lower boundary condition the Port BC was used, which is a planar electromagnetic wave (figure 1(c)). For the evanescent field, the border GaAs /air was introduced in the model, inclined at an angle α to the lower boundary of the model. At angles α greater than the angle of total internal reflection at the GaAs/air interface, the evanescent wave appeared and its absorption in the probe was calculated. GaAs Refractive index at $\lambda = 527$ nm was equal to $n = 4.058$, GaAs was chosen as a classical material for semiconductor lasers.

The standard function *ewfd.Qe* (hereinafter referred to simply as Q) of the Comsol Multiphysics package was used as an indicator of the absorbed energy. This function corresponds to the electromagnetic power transformed to the heat (averaged over the time period of the wave). From the Poynting's theorem, this function is equal to:

$$Q = \int J \cdot E \, dV$$

3. Results and discussion

3.1. Far field light absorption

Figures 2 (a), (b), and (c) show a series of phase images of the Si_3N_4 probe by a scanning laser beam with different degrees of focusing (with a beam diameter of 0.7 μm, 3 μm and 5 μm, respectively). Since the phase shift is proportional to absorbed radiation, it follows from figure 2(a) that the light is absorbed mainly in the pyramid of the probe (a bright spot on the image). Moreover, the pyramid edges are also visible in the figure. Defocusing of the laser beam blurs the image of the pyramid and the cantilever of the probe. Figure 2(d) shows cross sectional profiles corresponding to figures 2 (a), (b) and (c), built along the dotted lines in figure 2 (b). Interestingly, in a particular probe, the pyramid was shifted by 2 μm to the right from the center of the cantilever, it was taken into account in the numerical simulation. Figure 2 (e) shows the experimental and calculated profiles of absorbed optical radiation and they are in good agreement with each other.

Since Si_3N_4 does not absorb optical radiation with $\lambda = 527$ nm, it should be absorbed by a Au / Cr coating which is covering the pyramid and the cantilever. Since the thickness of the coating is the same everywhere, the absorption should also be uniform. However, in figure 2 the absorption is non-uniform. A possible explanation for this inhomogeneity is the enhancement of the optical radiation absorption in the probe tip, connected with its geometry [7] and a bilayer metal coating. Moreover, one should consider various optical radiation reflection coefficients from the surface of the probe cantilever and pyramid edges. Increased absorption of optical radiation in the probe tip opens up the possibility of its use for mapping of the optical radiation distribution in the far field. Indeed, according to the Rayleigh criterion [8] the Si_3N_4 probe can resolve two laser beams with diameters of 0.7 μm at a distance of 1.5 μm from each other (figure 2 (f)).

3.2. Absorption of the evanescent wave

Figure 3(a) shows the dependence of the light absorption by Si and Si_3N_4 probes from the distance between the probe tip and the surface (z- dependence). The angle of light incidence α was 25° (figure 1). Note that the angle of total reflection for our model was ~14°. For comparison, the same dependence was calculated for the Si plane of rectangular shape. The figure shows that both the nitride and silicon probes increase the absorption of evanescent waves in comparison with the flat Si plane of rectangular shape. The same behaviour was observed in the absorption of the optical radiation in the far field. It is interesting to note that the z-dependence for the Si_3N_4 probe decays more slowly than for the Si probe, indicating that the nitride probe is more effective in detecting evanescent radiation.
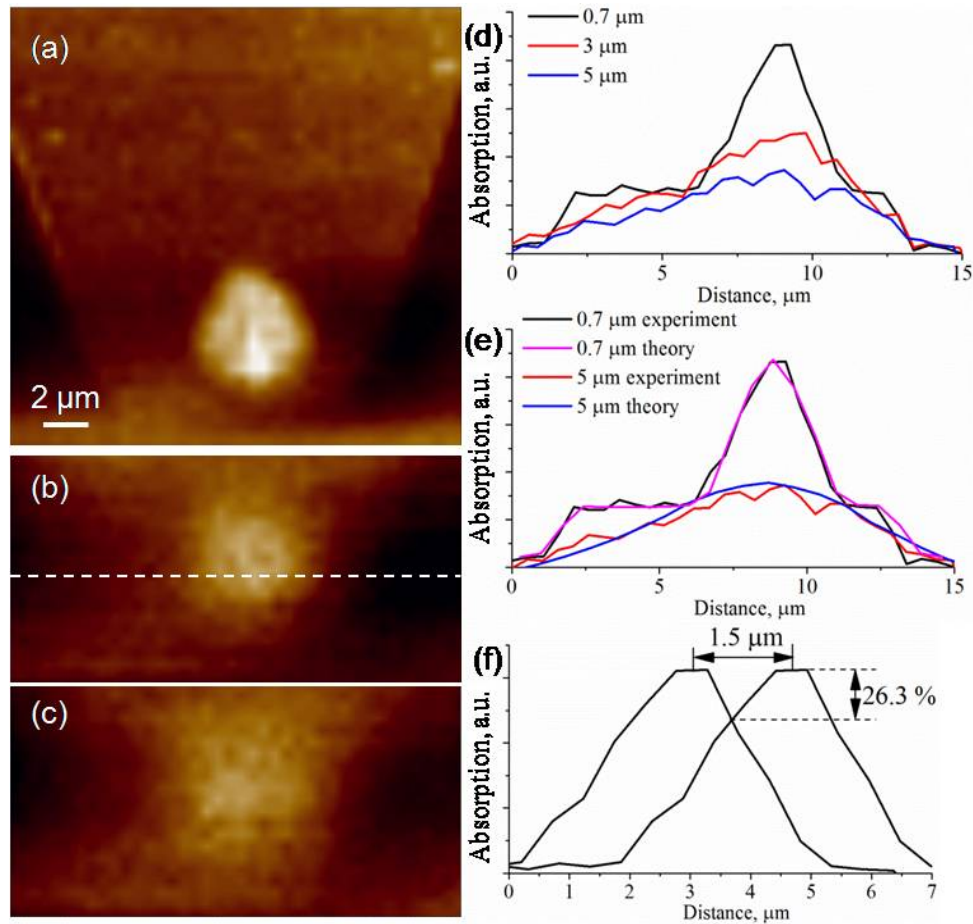

Figure 2. Scanning a laser beam by the Si_3N_4 probe. Phase shift images obtained during scanning the laser beam with a diameter of (a) 0.7 μm; (b) 3 μm, (c) 5 μm; (d) corresponding cross-sectional profiles; (e) experimental and numerically simulated cross-sectional profiles; (f) illustration to the Rayleigh criterion of optical resolution.

Figure 3 (b) shows the absorption of evanescent radiation by Si and Si_3N_4 probes depending on the angle of incidence α. The distance between the probe and the surface was 50 nm. The figure shows that the absorption ratio $Q_{Si3N4}/Q_{Si} > 1$ at $\alpha = 15°$; 20°; 30° and $Q_{Si3N4}/Q_{Si} < 1$ for $\alpha = 25°$ and 35°.
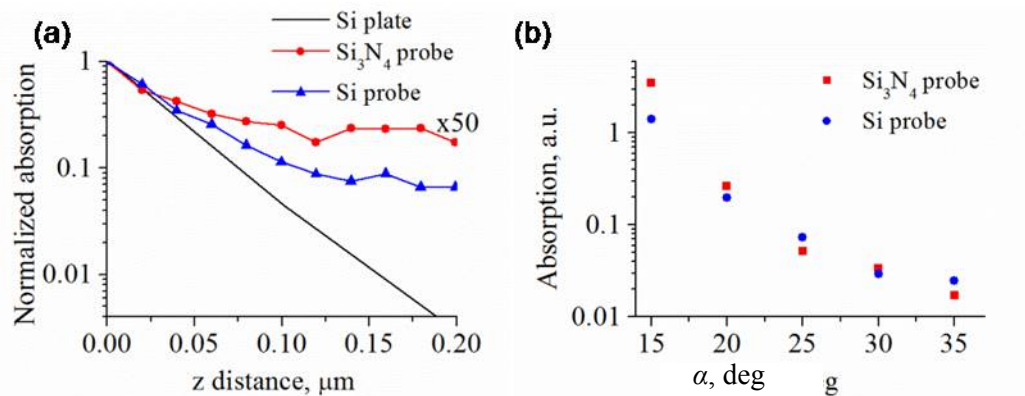
Figure 3. (a) Normalized dependence of evanescent wave absorption on the z-distance between the probe and the surface for Si_3N_4 and Si probes and for a Si plane of rectangular shape (black curve). (b) Dependence of evanescent wave absorption on light incidence angle α for Si_3N_4 and Si

This result shows that under certain α, a Si_3N_4 probe is more efficient than a Si probe and vice versa. Interestingly, this ratio Q_{Si3N4}/Q_{Si} varies non-monotonically with α.

4. Conclusions

To conclude, we investigated the absorption of optical radiation ($\lambda = 527$ nm) by Si and Si_3N_4 AFM probes. The absorption of the laser beam with varying diameters by a Si_3N_4 probe was experimentally studied. It was shown that in the far field for the laser beam with a diameter of 0.7 μm, the probe provides a resolution of ~ 1.5 microns. Such a high resolution is due to increased absorption of light in the tip of the probe.

Numerical simulation of evanescent wave absorption by Si and Si_3N_4 probes showed the enhancement of absorption, as compared with a flat absorber. The Si_3N_4 probe absorbs evanescent radiation more efficiently. The study of evanescent radiation absorption depending on the incidence angle α revealed that the dependence $Q_{Si3N4}(\alpha)/Q_{Si}(\alpha)$ is non-monotonic because of the influence of the probe material.

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