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Fabrication and mechanical properties of an organo-mineral cantilever-based probe for near-field optical microscopy

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ABSTRACT

We present the design, batch fabrication sequences and mechanical characterization of an optical near-field probe. The probe structure is made of a hybrid organo-mineral material synthesized using a sol–gel process. The cantilever-type probe was designed for Scanning Near-field Optical Microscopy (SNOM) in collection mode and its design was optimized by simulations. The mechanical properties of the probes were measured and topographical images of a standard surface obtained with the fabricated probes are presented.

1. Introduction

In the last decades, increasingly sophisticated optical characterization methods have been developed to obtain resolution beyond the Rayleigh limit. Many of these methods are based on the processing of optical signals related to propagating waves, thus giving information concerning objects or details of objects the size of which is bigger than half wavelength. On the other hand, Scanning Near-field Optical Microscopy (SNOM) makes use of evanescent waves that carry information about sub-wavelength-sized objects or details. Near-field optic probes also offer the possibility to acquire simultaneously topographical and optical images and to mechanically interact with the object, although investigations and interactions are limited to the object surface. This can be either an advantage, for example when studying the cell membrane, or a drawback, for instance when focusing on the cell cytoplasm or nucleus.

Presently, SNOM use is rather limited because it requires experienced operators for optical adjustments and due to the difficulties to reproducibly fabricate high performance probes at low cost. There are two kinds of SNOM probes: tapered optical fibers and cantilevers. Cantilever-type probes have three main advantages compared to tapered optical fibers: better mechanical resistance, batch fabrication and possibility of integrating passive or active optical functions and signal processing on the probe holder.

Many studies on the development of cantilever-type SNOM probes have focused on improving the probe sensitivity and resolution. Some of these probes show remarkable sensitivity and resolution [1–3]; however, the used fabrication method generally allows the fabrication of a single probe at a time and is hardly reproducible. Others studies concentrated on decreasing the manufacturing costs by developing/optimizing parallel fabrication procedures for producing the probe cantilever, tip and tip aperture.

The proposed techniques are based on classical micromachining approaches (photo-lithography, layer deposition, wet and dry etching) using silicon substrates. The cantilever is usually made of silicon nitride or oxide [4–7], polymers [8], silicon [9], or III–V compounds. The material used for the tip is not necessarily the same [6]. The control and sharpening of the tip aperture to sub-wavelength values is of great importance for the probes optical resolution and the parallel production of the tip aperture is the most critical stage of the fabrication process. Various procedures

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have been proposed based on strategies that associate different etching techniques [4,5,9–11], including sequential oxidation and etching methods [7,12,13]. Except in [8], the tip and the cantilever are finally released from the mold by elimination of the mold (generally the silicon substrate).

In this paper we present the design (Section 2), the parallel fabrication (Section 3) and the mechanical characterization (Section 4) of a near-field optical probe made of a hybrid organo-mineral material. The mechanical and optical properties of this material allow releasing the cantilever and tip by unmolding and to use the cantilever as an optical guide. This hybrid material also allows to plan the monolithic or hybrid integration of optical functions on the support and consequently the suppression of some optical adjustments and improved probe efficiency.

In addition, the tip of our probe is solid, differently from the tips of commercially available cantilever-based SNOM probes that are hollow due to the used fabrication methods. Hollow tips can be used only in emission mode because they are not appropriate for signal collection. Conversely, our probe allows working also in collection mode, thus enlarging the investigation field, particularly to objects that are sources of light.

2. Design

2.1. Material

We chose a hybrid organo-mineral material made of two interlocked mineral and organic three-dimensional networks because it has the properties of both polymers (ease and simplicity of layer deposition and structure definition by photo-polymerization) and bulk glasses (optical characteristics and a better mechanical strength than polymers). The mechanical and optical features of the material are adjustable based on the degree of polymerization of the two networks. The sol–gel synthesis of the hybrid material is simple and is performed at moderate temperature (120 °C max). Polymerization of the mineral part is enhanced by annealing. Polymerization of the organic part is obtained by ultra-violet (UV) activation of a photo-initiator The fabrication process of the hybrid material is compatible with standard microelectronic techniques and this material has already been used for photonic circuits [14,15].

2.2. Structure

The key elements of the probe are a cantilever with a solid pyramidal-shaped tip at the end. This structure allows the integration of passive or active optical functions on the chip by using classical microfabrication techniques (Fig. 1). Given the Young's modulus of the chosen material (see Section 3.1), the cantilever stiffness can be adjusted by changing its dimensions (length, width, thickness). The cantilever faces are coated with a thin metal layer in order to confine the light so that it behaves as an optical guide. This also allows the optical measurement of the cantilever deflection in order to control the tip vertical position relative to the horizontal surface and thus to realize topographical images with an atomic force microscope (AFM). The cantilever is supported on the probe chip by the continuation of the optical guide body. The optical guide is coupled to a photodetector located in the support (Fig. 1).

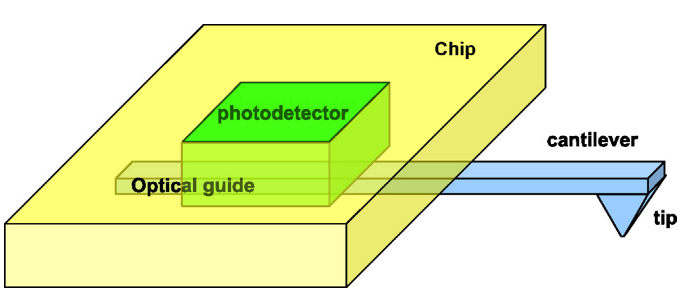

Fig. 1. Probe structure.

2.3. Simulations

Before fabrication, we simulated light propagation in the tip-cantilever structure to optimize the dimensions of the cantilever beam and particularly its thickness. Simulations were realized in two dimensions (2D) for the collection mode configuration: the sample underneath the tip emits light that is diffracted and collected at the tip aperture (Fig. 2). Light then propagates through the tip and the cantilever beam toward its end. We used the COMSOL Multiphysics (V 4.2a) (COMSOL France, Grenoble, France) finite element modeling software because it satisfies the multi-scale dimension constraints (from some tens of μm to some tens of nm) and allows taking into account the sharp angles of the probe structure. In each triangular finite element, the calculated parameter is the magnitude of the vertical electric field component $|E_z|$ and its intensity $|E_z|^2$.

For simulation (and then also for fabrication) we used probe structures in which the tip was pyramidal with a height of about 10 μm, which is the average height of commercial SNOM probes. This corresponds to a width at the bottom of the pyramid of about 14 μm. The width of the cantilever guide was also of about 14 μm. The cantilever beam length was 30 μm: this limits the surface meshing and is longer than the minimum length to obtain stabilized guided modes. The distance between the tip apex and the sample was 10 nm.

Simulations obtained for two structures in which the cantilever beam thickness was 2 μm or 6 μm, respectively, and the tip aperture diameter was 70 nm (standard aperture size of commercial SNOM probes) indicated that the number of guided modes increases with the thickness of the cantilever beam (Fig. 2).

We defined the collection coefficient C_a as the ratio of the integral of light intensity on the surface of the cantilever at its end (A

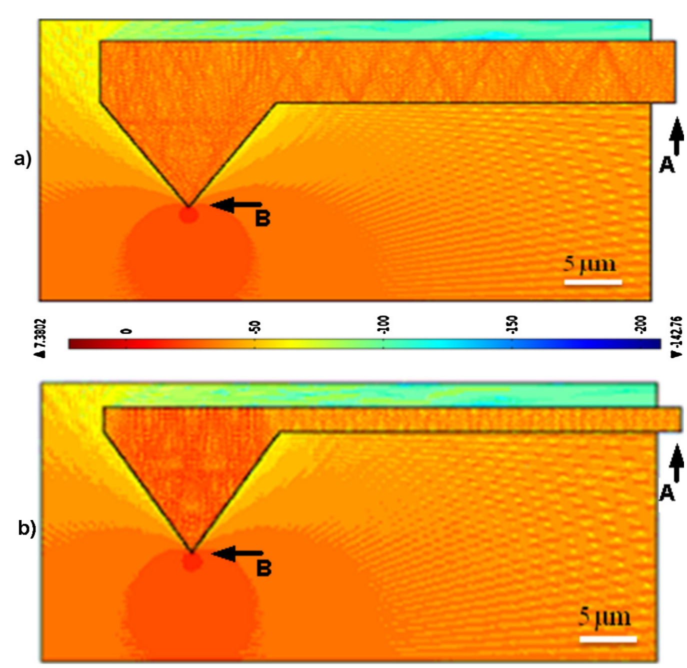

Fig. 2. 2D simulation of light propagation from the tip toward the cantilever base (a) for a 6 μm thick cantilever and (b) a 2 μm thick cantilever.