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A compact method for optical induction of proximal probe heating and elongation

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Compact method for optical induction of proximal probe heating and elongation

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A tapered, metal-coated, optical fiber probe will elongate when heated by light input through a fiber. The induced motion can be used for data storage or nanostructuring of a surface. The elongation produced by this alignment-free system is measured with force feedback in a near-field scanning optical microscope (NSOM). The input light intensity controls the elongation magnitude, which ranges from a few nanometers to more than 100 nm. A 0.5-mW input energy yields ~20 nm of probe elongation. The elongation quantified here can create artifacts in any experiment using pulsed laser light with a NSOM or an atomic force microscope. © 2002 Optical Society of America

1. Introduction

Scanning proximal probes enable many types of nanoscale fabrication. Atoms can be moved one at a time to build surface structures with a scanning tunneling microscope (STM).1–3 Current bursts with a STM can create surface structures.4 Electrons injected from a STM into a metal thin film can produce terraces on the buried surface.5,6 The STM can be used as an electron source for electron-beam lithography,7 for electron-assisted chemical vapor deposition,8 or to remove a surface layer.9 Near-field scanning optical microscopes (NSOMs) have been used to write magnetic bits;10 to expose resists;11 to oxidize conjugated-polymer thin films;12 and, in combination with a current from the metal NSOM aperture, to locally modify the properties of high-temperature superconductor YBa2Cu3O7-δ (yttrium, barium, copper, oxygen).13 Atomic force microscopes (AFMs) have been used as dip pens for direct-write lithography14 and for writing bits into a substrate.15 A thermomechanical writing technique,16 by which optical pulses are coupled to a metallized tip of a tapered optical fiber, has been used in data-storage applications, yielding areal densities greater than 10 Gbits/in². In this paper we highlight that the thermomechanical technique can be extended to most scanning probe platforms and should be usable without head-stage modification in fiber-based NSOM systems. No special alignments will be required at the microscope head. The probe can be constructed so that none of the light reaches the sample17 when light absorption might alter the experiment. The thermal process at the probe is not characterized by a single time constant (in the 10-ms regime and associated mainly to the glass shank expansion)18,19 but includes those rapid time constants that result from expansion of the metal coating. This ensures reasonable speed performance of the elongation device.20 At the heart of a NSOM thermomechanical method is the probe axial elongation, which we analyze and quantify in this paper.

2. Experiment

The probe is similar to that used in the NSOM. It is constructed by heating and pulling of an optical fiber in a commercial apparatus and is then coated with aluminum. Metal coating is required, since the primary coupling of the light to heat the probe is by means of multiple imperfect reflections that occur when the light coupled into the core of the fiber reaches the tapered region of the probe. The absorption of light in the metal coating occurs mainly in the ~100-μm proximity of the probe apex, as predicted by ray-tracing-based models,21 and establishes a non-uniform axial temperature distribution.22 The probes used in this research had open apertures at the end, as NSOM probes do, but this is not required and makes little difference in the operation, since

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such a small fraction of the input light leaves the aperture. We studied the response of two different probe geometrical classes to illustrate the robustness of the probe response to probe morphology. Electron microscope (SEM) images of the two classes of probes are shown in Fig. 1. The chubby tip has a large aperture and a cone angle of 40 deg. The skinny tip has a smaller aperture and a 20-deg cone angle near the apex. Both types of tip have similar structure far from the apex. The fiber tapers over a length of approximately 1 mm.

The experimental layout is shown in Fig. 2. An acousto-optic modulator switches light from a laser, which is then coupled into the probe fiber. Several modulations were used, from blocking the beam manually to square-wave modulation between 1 and 10 Hz. We used visible (512-nm green from an argon-ion laser) and infrared (1.15 μm from a He–Ne laser) light, with ON powers of ~0.5 mW. The probe is mounted in a NSOM. The microscope holds the tip in a fixed position of ~10 nm over a flat sapphire or silicon sample, without scanning the tip. The lateral force feedback maintains a constant tip–sample separation. Thus the motion of the sample reflects the compensation for the probe elongation. Optical lever-arm amplification of the probe motion, measured by a properly placed edge of a photodiode detector, provides the signal for lateral force detection.23 The bandwidth of the lateral force detection scheme limited the temporal range over which probe elongation could be measured. When the time scale of the probe elongation is too small for the feedback to follow, the probe deviates from its ~10-nm fixed distance from the surface. If the probe motion is fast and large enough, the probe will crash into the surface. This is the primary reason for using low-frequency modulation and only 0.5 mW of power, which gives approximately 20 nm of probe motion, although we expect elongation dependence on the quality of the aluminum coating. For square-wave light motion, inducing square-wave probe elongation, the feedback will slew at its bandwidth of >1 kHz to return the probe–sample separation to its nominal value. Some transient error in positioning may result after the light switches.

3. Results and Discussion

Examples of the measurements for a slender probe are shown in Fig. 3. The nominal input power level of infrared and visible light is 0.5 mW in both cases. Note the correlation between input power and the probe elongation, regardless of the wavelength. Although the data shown in Fig. 3(a) would suggest that elongations produced by the infrared light are greater than the ones produced by the visible light, in Fig. 3(b) the opposite occurs. This is attributable to the fact that the actual power reaching the probe depends on many factors such as losses along the fiber and different coupling efficiency for infrared and for visible light. The probe fiber is few mode for the visible light, so the probe transmission is a strong function of the mode traveling in the fiber, i.e., the coupling into and the positioning of the fiber. We understand that the probe elongation will be more sensitive to the energy input rather than to the particular wavelength chosen because the probe elongation relies on heating and because the large number of reflections within the probe21 ensures that a significant fraction of any wavelength light is absorbed by imperfect reflections from the metal coating on the probe taper. The shape of the taper resembles a small version of a witch’s hat beam dump.

To determine whether significant thermal energy is transferred to the sample when it is in close proximity to the sample, the elongation was measured as a function of probe–sample distance, shown in Fig. 4. On the length scales of interest here, thermal con-
Measurements, including those on cells, have not been ligible. This result is expected, since most NSOM probe elongation to decrease when the infrared beam is turned on.

The modulation level is determined by the input power. We are somewhat limited in the range of powers that we can study with force feedback to measure the probe elongation, since the probe may transiently crash into the sample. Alternatively, one can use the Fabry–Perot cavity formed by a flat surface and the NSOM-probe flat termination to estimate the probe elongation and thus avoid the limited bandwidth feedback response, which is described in more detail elsewhere. A probe coated with aluminum will degrade if the temperature reaches half the melting temperature of aluminum, or ~470 K, when multiple internal reflections, diffusion, and surface energy combine to make the aluminum ball up. Using this as a limit, we estimate the maximum elongation of the probe to be ~200 nm, at 4.5-mW input power.

We previously studied the temporal optical throughput response of the classes of probes used here, both before and after probe damage. Those results indicate a response independent of frequency to ~20 Hz. At higher frequencies, the response falls logarithmically. The process cannot be modeled as a single-time-constant response, which would fall as 1/f. This is common to many thermal problems. It means that the probe elongation is still present at higher frequencies and that this probe elongation method is applicable for fast probe motion. The amplitude will be 1/5 its low-frequency value at 10 kHz.

The fast variation of the optical throughput implies that a significant fraction of the taper is heated within the 15-nm window is shown for comparison. Typically, the feedback stability in our system is 1 nm. Data outside the 15-nm window result from instabilities of the input power laser.
According to this temperature profile, we have estimated the contribution to the total probe elongation from the NSOM probe, we have estimated the contribution to the total probe elongation from the apex of 0.5 °C at the tip end is expected for a 0.5-mW input power. The temperature profile is used to calculate the thermal expansion of a 1-mm-long bare fiber (circles) and a full metal probe (squares). The aluminum coating is taken into account by considering a position-dependent thermal coefficient that equals \( \alpha_{\text{Al}} \) at the tip end and \( \alpha_{\text{quartz}} \) at the shank. The corresponding probe expansion (diamonds) provides a better fit to the observed probe thermal expansion in our experiment. Note that the region closer to the tip end contributes more to the elongation.

In conclusion, we have demonstrated that probe elongation can be driven by optical power input to an NSOM-like probe. The elongation is independent of the wavelength used and the distance from the sample. The frequency response and properties suggesting its use for delivery of heat or mechanical impulses to a surface have been described. We note that the process quantified here should be taken into account whenever pulsed light is used in NSOM or AFM experiments.

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