Nano-positioning of a slender body using thermal actuator

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Abstract

Current rapid development in MEMS area has opened up many possibilities in nano-technology such as nano-fabrication. Among them is nano-scale wiring by both AFM (Atomic Force Microscope) tip and laser beam. Being able to make a relatively small deflection, a micro thermal actuator can be used to control the near field optics of the beam minutely and accurately. In this project, we will investigate the thermal actuator design that makes possible the thermal control of nano-positioning.

1. Introduction

Near-field optics has demonstrated its ability to break the diffraction barrier in terms of resolution [1]. This can be technically realized by the combination of a femtosecond-pulse laser with a near-field scanning optical microscope in the area of nano-machining [2]. Figure 1 shows a suggested schematic diagram for femtosecond laser coupling into AFM tip. The collimated light delivered by an optical fiber transmits through the cavity of the tip. Assuming uniform profile of the laser beam at the input plane, the near field intensity in the proximity of the tip (typically 5-10 nm away from it) was estimated [3]. The coupling of the incoming laser with the tip is in fact very crucial parameter for nano-machining and affected by the misalignment of the optical fiber. To increase the coupling efficiency, this error should be minimized. The possibility to meet this need is being opened by recent rapid improvement in MEMS technology that is thermal actuator. Simple voltage control can be used to expand the MEMS structure to the order up to the order of 1 micrometer if material has a relatively large thermal expansion coefficient. However, in order to obtain a fast response time for its expansion according to voltage variation, important is the choice of the material, since currently used silicon-based materials have needed huge temperature difference to get a meaningful amount of expansion. If a device can be made using metallic material with a relatively large expansion coefficient, nano-positioning is possible. Possible MEMS process for the realization of this idea is LIGA process. Moreover, to overcome the high fabrication cost in LIGA, a novel process so called "LIGA-like" has been developed [4] which takes the advantages of LIGA and MUMPS. Hence, in this project, we propose a LIGA-like process to fabricate a positioning platform. A new position control system using thermal actuator is suggested since the amount of movement by this actuator is in truly nano-scale. The detailed description of the design process will be presented and the related thermal issues will be addressed.

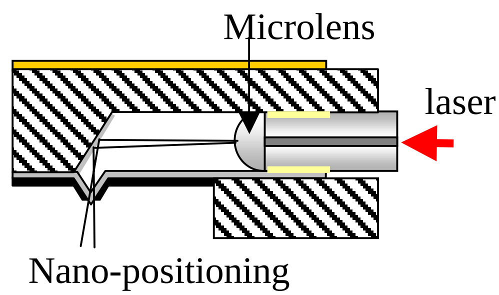

Fig. 1 Schematic of nano-positioning

2. Concept of nano-positioning

2.1 An optical fiber as a slender body

Fiber optics (optical fibers) are long, thin strands of very pure glass about the diameter of a human hair. Optical fiber is composed of core, fiber and buffer coating. For use in nano-positioning, normally the buffer coating will be stripped off. The cladding and core diameters are 127 μm, and 3~5 μm, respectively depending on applications. In this project, we use only the part comprising the cladding and core of optical fiber. Thermal conductivity of fiber is very low (typically, $0.043\,W/m\cdot K$) so that it could effectively resist heat transfer from the 'hot' thermal actuator and function as an insulating material.

2.2 Nano-positioning of an optical fiber

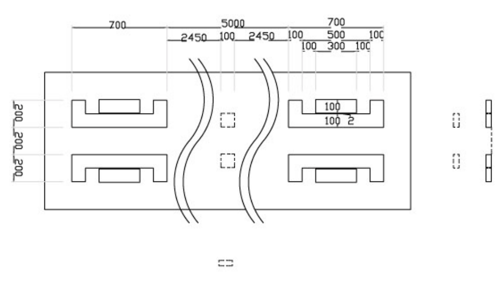

Fig. 2 Floor plan of thermal actuator (μm)

Optical fiber is placed upon the thermal actuator as shown in Fig. 2. The expansion of the thermal actuator makes it apparent that the actuating structure must be a precisely controlled one due to the capability of nano-displacement of the structure. Steering the beam coming off the fiber through the AFM tip is quite challenging because the transmission efficiency is proportional to the fourth power of the diameter of the tip. Therefore, slight misalignment caused by external disturbance such as vibration will be harmful for the beam transmission. Theoretically, the transmission efficiency is 10^{-4} assuming a hundred-nanometer tip opening, and 1 µm-wavelength light source. Many researchers have tried to increase the efficiency using various methods [2,3]. In addition to these methods, nano-positioning of the optical fiber is very important in terms of transmission efficiency.

2.3 Motion control and calibration

Fig. 2 shows two micro-electromechanical structures: a thermal actuator and a capacitor. The capacitor acts as a positioning sensor measuring the gap between the actuator and the capacitor block. The measurement of the gap that directly relays to the voltage of the power supply can be expressed in the following expression.

$$\frac{dC}{C} = -\frac{dx}{x} \qquad (1)$$

where C and x are electrical capacitance and gap, respectively. Once the actuator gets to the desired position, we can control the further amount of expansion by modulating additional voltage.

2.4 Manufacturability

The specification of the thermal actuator should meet the requirement of relatively high thermal expansion coefficient while retaining uniform shape of the structure at high temperature near 200 °C. Paraffin has been used for low temperature thermal actuator [8]. But copper is our target material for the structure because it has reasonably high expansion coefficient and cannot be damaged at the operating temperature. Additionally, high aspect ratio structure is desired in order to lift up the optical fiber by the amount of hundreds of nanometers at ΔT = 200 K. LIGA process seems to be the best for this purpose. However, due to the high cost of the process, LIGA process will be replaced with LIGA-like process utilizing UV light source.

3. Electrothermal analysis

3.1 Expansion amount

Thermal actuator considering in this project makes use of thermal expansion to give a nano-scale movement of a slender body, or an optical fiber. Neglecting mechanical one, isotropic strain due to thermal expansion is expressed as

$$\varepsilon = \frac{\Delta l}{l} = \alpha \Delta T \qquad (2)$$

where α is thermal expansion coefficient, 17ppm for copper, and characteristic length l is 100 µm. Therefore, in case of copper with temperature difference of 200K, expansion amount of the actuator is estimated to be 340 nm. This is within the value needed to the nano-positioning in the present project.

Thermal stress is not important in this application because only the bottom part of optical fiber contacts thermal actuator allowing free movement of top part. Mechanical stress due to the weight of a slender body is also negligible because it does not vary with time once it is applied to the actuator.

3.2 Equivalent circuit for thermal actuator

There are four actuators exactly the same as one another (Fig. 2). If we make parallel circuits each of which is composed of a pair of actuators such as (1,2), (1,3) and so on, then we can control the temperature simultaneously by applying the same voltage. In this case, proportional to the square of it is the amount of heat generated in an actuator.

$$\dot{q}''' = \frac{1}{\mathrm{v}}\frac{\mathrm{V}^2}{\mathrm{R}} \quad [\mathrm{W/m^3}] \qquad (3)$$

where v, V and R is the volume, voltage and resistance of an actuator, respectively. Volume (v) and resistance (R) can be expressed as

$$\mathrm{v} = 9l^3 \quad [\mathrm{m^3}], \qquad \mathrm{R} = 9\frac{\rho}{l} \quad [\Omega] \qquad (4)$$

where ρ is the electrical resistivity of copper, $1.673\times10^{-8}\ \Omega\cdot\mathrm{m}$.

3.3 Response time

As mentioned in section 3.2, heat generation is proportional to the voltage squared [eq. (3)]. Other important heat transfer mode can be either conduction to wire bonding or that to ambient air, i.e. convection. In case that there exist anchors in a traditional thermal actuator, researchers [6,7] have argued conduction to the solid anchor is dominant over convection. In the present project, however, there is no anchor structure and gold wire bonding is expected to have slightly different temperature from the actuator, which means that natural convection by ambient air can be dominant without heat generation.

3.3.1 With heat generation

The energy balance with a resistive heating source is estimated

$$\rho_{\mathrm{m}} c \frac{\partial T}{\partial t} \sim \dot{q}''' = \frac{\mathrm{V}^2}{81 l^2 \rho} \quad [\mathrm{W/m^3}] \qquad (5)$$

where $\rho_{\mathrm{m}} c$ is the heat capacity of copper, $3.546 \times 10^6 \,\mathrm{J/m^3 \cdot K}$. Here, we used voltage of 2mV resulting in $\dot{q}''' = 2.952 \times 10^8 \,\mathrm{W/m^3}$. Temperature variation of thermal actuator with respect to time is

$$\Delta T \sim \frac{\dot{q}'''}{\rho_{\mathrm{m}} c} t = 83.25\, t \quad [\mathrm{K}] \cdot \qquad (6)$$

Therefore, response time constant, τ, is equal to $1/83.25 = 1.201 \times 10^{-2}$ [sec].

3.3.2 Without heat generation

With natural convection by ambient air, Newton's cooling law gives the following estimation;

$$\rho_{\mathrm{m}} c \frac{\partial T}{\partial t} \mathrm{v} \sim h\mathrm{A}(T_{\infty} - T) \quad [\mathrm{J}] \qquad (7)$$

where A and T_{∞} are air-contacting area of the actuator, $27l^2$, and ambient air temperature, 293[K], respectively. Heat transfer coefficient, h, is approximately 10 [W/m^{2}K] in case of natural convection. Hence, temperature as a function of time is of the form,

$$T \sim \exp\left(-\frac{h\mathrm{A}}{\rho_{\mathrm{m}} c \mathrm{v}} t\right) = \exp\left(-\frac{t}{11.82}\right). \qquad (8)$$

Without heat generation, therefore, estimated response time constant is 11.82 sec, which is larger than that with heat generation by order of 10^3.

4. Design and Fabrication scheme

4.1 LIGA process

There is application for microstructures of relatively large (i.e. 10-100 µm) thickness. One of the most well known processes is the so-called LIGA process for structure definition and fabrication. The process consists of depositing a thick (10-500 µm) layer of an X-ray sensitive photoresist [4]. The resist is then exposed through an X-ray mask using a synchrotron source after which the resist is developed and removed. Then the deposition utilizing electroplate follows as a method of forming high aspect ratio structure.

4.2 LIGA-like process

However, X-ray inherently uses a gigantic synchrotron source unless tabletop X-ray is available. This fact limits the use of this source in the laboratory. Current project contains high aspect ratio cuts that can be accomplished by LIGA process. These are not well done by UV lithography (even with deep-UV) because of the absorption of the photoresist. Normally, the single-step maximum thicknesses are limited to about 5 µm. Using high transparency and high-viscosity photoresist systems with UV source is well suited to our application eliminating both space and cost problems. In addition, UV-exposable, negative-working, photosensitive polyimides that can have spun-on thicknesses in excess of 60 µm in a single coat are now commercially available, thus satisfying the thickness requirement.

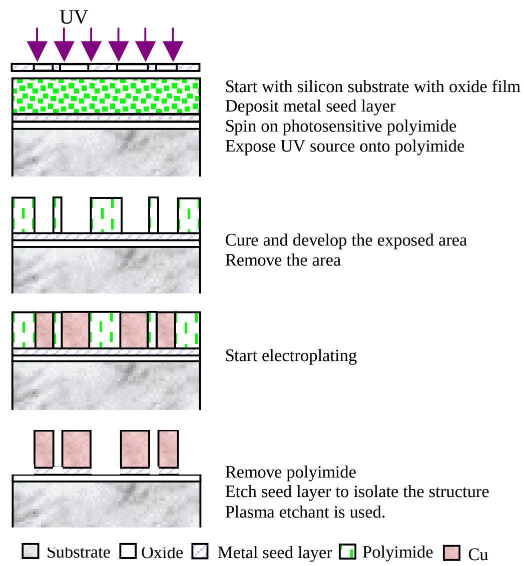

Fig.3 Process Flow of LIGA-like process

4.3 Fabrication flow

A process flow is described in Fig. 3 and details are well explained in the reference [4]. Oxidized silicon wafers are used as the initial substrate (oxide thickness 0.3-1.3 µm), and a suitable electroplating seed layer of metal is deposited on the substrate. The metals, in order of deposition, are 25 A chromium (as an adhesion layer), 1500 A copper, and 1000 A chromium. The copper seed layer was of sufficient thickness to ensure uniform plating across the waver with minimal resistivity effects. Photosensitive polyimide (Ciba-Geigy robimide 348 or 349, a photoimageable, thermally imidizable material) is then spun on the wafer which, then, is exposed to UV. The patterns in the polyimide are then developed in which ultrasonic development is needed for films with thicknesses greater than approximately 25 µm. To electroplate the microstructures, electrical contact is made to the activated seed layer, and the wafers are immersed in the suitable electroplating solution. Then, electroplating is carried out in the normal fashion, with the wafer at the cathode of the electroplating cell. When the electroplating is complete, the polyimide is removed. Once the polyimide is removed, electrical isolation of the metal structures can be achieved by using plasma etching (Fig. 3).

5. Numerical Simulation

We argued in section 3 that, if we can give temperature difference of 200 K, we can obtain nano-positioning of a slender body (optical fiber) as large as 340 nm. In addition to that, we estimated the response time with and without heat generation. This section will compare those theoretical estimations with the simulation results and see if and how the thermal actuator under consideration works.

5.1 Method of simulation

The heat equation considering transient energy storage, diffusion by conduction, and generation by a volumetric heat source is as follows;

$$\rho_{\mathrm{m}} c \frac{\partial T}{\partial t} = k \nabla^2 T + \frac{\mathrm{V}^2}{81 l^2 \rho} \tag{9}$$

where k is the thermal conductivity of copper, 393 $\mathrm{W/m \cdot K}$ at 400 K, and all the other parameters are the same as shown in section 3.

Computation has been implemented only for heat equation using *StarCD*. To isolate thermal effect, zero-deflection boundary condition was applied resulting in no deflection in the system. Transient analysis was carried out with implicit Euler method.

5.2 Results and discussion

Voltage of 2 mV was imposed in the source term [eq.(9)] from beginning to 2.5 sec. Then, no heat source was applied for 0.0155 sec before reapplying the same source for 0.0055 sec. In a real system, capacitance should take a role of measuring the expansion of the actuator and controlling time during which the voltage of 2 mV is applied. Fig. 4 shows the temperature history of thermal actuator. The increasing temperature slope is 82.7 K/sec which is very close to the estimated value, eq. (6). Within 2.5 sec temperature difference goes up to 180 K allowing 306 nm positioning. Then 0.0155 sec release and 0.0055 sec reheating is repeated to retain the temperature difference. Fig. 4 shows we can retain the amount of expansion by means of electrical capacitance control.

6. Conclusion

Nano-positioning of a slender body, or optical fiber using thermal actuator is investigated to see if and how it works. With electrical heat source, about 300 nm positioning is obtained. We showed we can retain this expansion by capacitance-indicating voltage control. Simulation result also showed that this positioning method is viable.

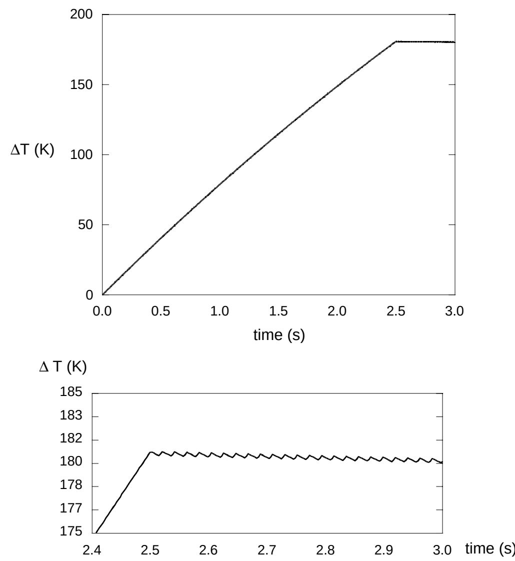

Fig. 4. Temperature history of thermal actuator

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