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Thermo-mechanical transduction suitable for high-speed scanning probe imaging and lithography

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ABSTRACT

Microelectromechanical systems (MEMS) with integrated read-out and actuation are very useful tools for a wide variation of applications, especially in scanning probe microscopy (SPM) and lithography (SPL). They avoid the use of conventional optical beam deflection techniques or external excitation and are suitable for massively parallel scanning probe solutions and biochemical sensors. Such arrays of beams offer an increased throughput to scan large areas in SPM and SPL. However, the fabrication technology of such complex MEMS requires careful design of all components. This paper presents a comparison between analytical, numerical and experimental data of a cantilever with integrated thermal actuator and piezoresistive sensor, suitable for fast SPM and SPL. The focus of this work lies on the efficiency of the actuator, to achieve a high static displacement, which is required for an array operation. To maximize this displacement, two material compositions for a varying geometry of the beam's layers are analyzed. With a scanning electron microscope and a laser vibrometer an increased displacement of the beam about 10 μm can be presented, which is in a good agreement with our theoretical predictions.

1. Introduction

Micro-cantilevers are one of the most popular resonators; they make excellent scanning probes and transducers for a broad field of applications in micro- and nanotechnology today. The simplicity of their structure and fabrication processes, as well as the ease of excitation and response measurements are the reasons of their popularity. One of the most common applications of micro-cantilevers is the atomic force microscope (AFM), which is a very high-resolution type of scanning probe microscopy (SPM) technology. The AFM has a variety of possible imaging modes (contact mode, non-contact mode, intermittent-contact mode, etc.) and is well suited for different measuring tasks at the nanoscale [1]. Another area of application is the scanning probe lithography (SPL), which is a promising tool for future desktop nanofabrication [2]. Despite their high potential for inspection and fabrication, AFM and SPL are serial processes and thus have a limited throughput.

One approach to overcome those challenges is to implement massively parallel arrays. This concept generates a high throughput by using multiple cantilevers in parallel to perform an AFM or SPL operation. To realize this concept, the actual setups for AFM and SPL need to be reassessed. Today, one of the most popular deflection read-out techniques providing good sensitivity is the optical read-out. This method uses a laser and a photodetector to detect the movement of a beam. Considering arrays of cantilevers, each cantilever requires an individual light source and photo detector. This requires precise mechanical alignment as well as an additional mass to carry, in case of a top scanner. Thus, the realization of optical measurement is challenging and limited.

An additional approach to improve speed and sensitivity is to reduce the dimensions of each cantilever of an array. With current microfabrication technology, extremely small and soft cantilevers are viable, where opto-mechanical alignment is difficult, due to the required small size laser spot. The challenge is to maintain the resolution while scanning at speeds needed for high-throughput imaging and lithography. This requires precise and fast detection of the interaction between the sample and the tip. As such, cantilevers are needed to be extremely small and soft with high signal-to-noise ratios (SNR).

For these and other reasons efforts were undertaken to integrate deflection sensors into micro-cantilever structure in contrast to expensive and large optical based readout. The read-out of deflection is realized by a two-dimensional electron gas (2-DEG) piezoresistive sensors integrated into the base of the cantilever beam [3–6]. Four piezoresistors are arranged in an integrated Wheatstone bridge configuration to reduce the influence of temperature variations. The advantage of piezoresistive cantilevers is not only the electrical readout but also the capability for an integrated actuation.

Many different techniques for actuation in micro-electromechanical systems (MEMS) have been established, for instance: capacitive, electromagnetic, piezoelectric, and thermal; each one has its own advantages and disadvantages [7–10]. Well-known and well used is the

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piezoelectric actuation to excite cantilevers at their eigenfrequency. In this case the cantilever is driven to oscillate near its resonance frequency by a small piezoelectric element mounted at the base (at the AFM holder). Advantages of piezoelectric excitation are a very low power consumption and a high operational frequency. A drawback is that the response of cantilevers using piezoelectric actuation is notably distorted even in air, as it drives mechanical resonances of the whole AFM setup. Additionally, the use of piezoelectric actuator for cantilever arrays is difficult, since each beam needs to be excited near its own resonance, as well as each beam needs an individual static displacement in order to be aligned and to be able to follow the topography of a sample surface.

To overcome the drawbacks of a piezoelectric actuation a thermal actuator can be used instead. This actuation principle can be easily integrated "on the chip", and is suitable for an array operation. In such a way each cantilever can be excited individually with a static displacement and at its resonance frequency, without interference to the mechanical AFM setup. Thermal actuation is based on bi-layer structures composed of thin films, wherein a volumetric heat generation causes a thermal expansion of cantilever layers [11–12]. Different coefficients of thermal expansion between the layers result in bending of the cantilever by means of differential extension of composite layers, whereby the displacement of the cantilever tip can be precisely controlled by the dissipated electrical power in the embedded metallic resistor [11–12]. The dissipated power in its turn is proportional to the square of the applied voltage, therefore the cantilever deflection changes quadratically with the input voltage [13–14]. The main advantages of this approach are the precise excitation of the cantilever at its resonance and the fast deflection of the cantilever at lower frequencies (off-resonance from 1 Hz to 13 kHz). These low frequencies can be used for z-positioning instead of an additional positioning stage. Thus, the probe can precisely follow a steep curvature of a sample without crashing or sticking to the surface, enabling real non-contact imaging.

Combining the deflection sensor and actuator in the micro-cantilever structure simplifies the overall mechanical design of the whole setup as well as the electronic circuitry necessary for signal conditioning and acquisition. Moreover, it reduces the dimensions and costs of each cantilever. These and other benefits led to the design of the cantilever with integrated piezoresistive read-out and highly effective, thermally driven bi-morph actuator, presented in this article. This approach sets the foundation for high speed cantilever arrays [15]. To achieve a high performance in speed and sensitivity, a comprehensive understanding of the actuation process and the relation between dissipated heat and displacement is necessary.

Tamayo's research group (2007, [16]) presented an analytical model for predicting the deflection of a bi-material cantilever. In 2010 Jian Yu Fu published a study of thermally actuated cantilever arrays for nanolithography. This study includes analytical models for temperature distribution and deflection of a cantilever array [17]. Several other projects significantly contributed to the development of large two-dimensional (2D) cantilever arrays. In the frame of the IBM project "Millipede", headed by P. Vettiger and G. Binnig, large arrays of up to 64×64 electrostatically actuated piezoresistive cantilevers for data storage were demonstrated [18–20]. Calvin Quate's group made 1D arrays of piezoelectrically actuated piezoresistive cantilevers for fast imaging [21]. Later on, arrays with up to 8×64 thermally actuated piezoresistive cantilevers were realized within the European Project PRONANO [22].

The present work includes analytical and numerical models for describing the maximum deflection and temperature distribution along the cantilever based on Joule heating through the actuator. To maximize the beam's displacement, two different materials for the actuator have been studied, together with a variation of the beam's thickness. The theoretical results have been validated by means of an experimental setup in a scanning electron microscope (SEM) and a scanning laser vibrometer. The experiments are focused on the maximal displacement, but also illustrate the shape of the beam's displacement along its length.

2. Thermomechanical cantilever and model

The micro-beam considered in this article is shown in Figs. 1 and 2 and has a piezoresistive sensor close to its fixed end as well as a thermal actuator towards its free end. This actuator is formed by a meander shape aluminum (Al) layer, which is located at the bottom side of the silicon (Si) beam. A silicon oxide/nitride (SiO_2/Si_3N_4) isolation layer is located in between the aluminum and the silicon layer. This composite structure sets the basis for the thermal actuation by means of different layers with varying coefficients of thermal expansion.

The fabrication process is based on a double-sided silicon micromachining procedure, which is developed for manufacturing piezoresistive AFM microprobes [23,24]. Double-side polished, (1 0 0)-oriented, 3–5 cm silicon wafers were used as a starting material. First, by using a silicon nitride mask, a 12 μm high sharp tip was formed by anisotropic etching of the {3 3 8} and {4 1 1} fast-etching planes in a TMAH solution at 60 °C (the shape of the tip depends on the etching conditions and the type of alkali etchant). Next, the following steps were applied: sequentially applied oxidation, phosphorus and boron diffusion, ion implantation, dry and wet etching, insulator and aluminum film deposition, and photolithography. By applying these processes sequentially in the order given above, the piezoresistors, p+ diffusion formed connecting paths, contact windows and metallic connections were formed at the front side of the wafer. In the back-side processing sequence a corner-compensated membrane pattern was created by a two-side photolithography process [10]. The wafers were then placed in a chuck for anisotropic etching of silicon in a hot TMAH solution. During the etching, a nitride mask was used. This etching creates a 20 μm thick silicon membrane in the future beam area. Next, both the cantilever and the microprobe shapes were defined in the membrane by the most critical, final photolithography step on the topside of the wafer. Silicon dry etching based on gas chopping etching techniques is used. With this approach, first an isotropic etching step with SF6-plasma is carried out for duration of a few seconds to a few minutes (depending on the equipment used), creating an isotropic etch profile with depth of a few hundreds of nanometers. The second step is a deposition step to form the passivation layers using CHF_3/Ar plasma. These two steps are repeated continuously during the complete etching process. A 20 μm thick AZ4562 photoresist is used to mask the circuit and to protect the tip. The cantilever sensors fabricated this way routinely offer atomic resolution at ambient room conditions. Recent work demonstrated an AFM image obtained on highly ordered pyrolytic graphite (HOPG) by an active probe, demonstrating atomic resolution [2] and capability of high imaging speed [25]. This article also reports about the development of piezoresistive scanning probes, revealing a progress

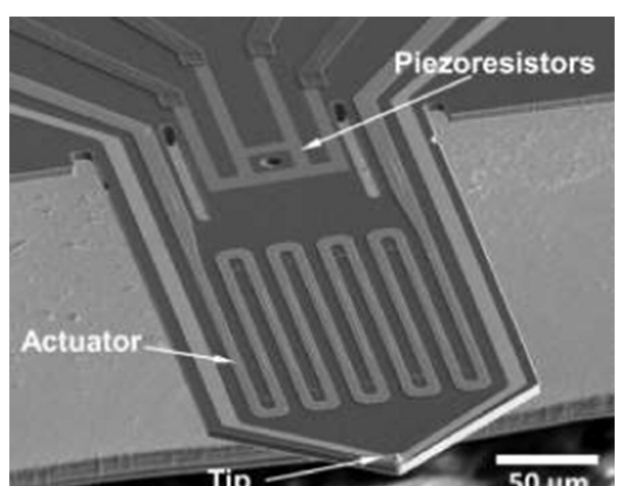

Fig. 1. Thermomechanically transduced piezoresistive cantilever.