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100×100 Thermo-Piezoelectric Cantilever Array for SPM Nano-Data-Storage Application

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A PZT cantilever array with integrated heaters and piezoelectric sensors, termed a thermo piezoelectric cantilever has been fabricated and studied for application to a high-speed and low-power scanning probe microscopy (SPM)-based nano-data-storage system. In this system, the data are written using a heater and read using a piezoelectric sensor integrated with the cantilever. By the use of a piezoelectric readback method, power consumption during the read/write process can be lowered considerably. With the thermo-piezoelectric cantilever we can successfully write 40 nm data bits on the polymer media, polymethylmethacrylate (PMMA). The sensitivity of the PZT piezoelectric sensor was 0.55 fC/nm. The charge readback signal of the cantilever was obtained using a patterned SiO_2 sample. To improve the data rate, we developed a (100×100) 2D thermo-piezoelectric cantilever array for parallel operation.

1. Introduction

Scanning probe microscopy (SPM) has been powerful tool in the fields of science and technology due to its high resolution. Recently, there has been interest in increasing the throughput of SPM to implement SPM technology in industrial applications, such as a semiconductor production line, scanning probe lithography and high-density data storage. SPM-based data storage has been studied extensively to overcome the storage density limitation of HDD and optical storage systems. Vettiger *et al*. pioneered and proved the feasibility of using an atomic force microscope (AFM) tip in data-storage systems. They used a thermomechanical data storage concept in which a resistively heated AFM tip reads

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*Corresponding author, e-mail address: ysrevol@lge.com and writes data bits while being scanned over a polymer substrate.(1)

In this data-storage system, power consumption is a considerable problem because the AFM tip is heated to over 300°C to read and write data bits.(2) Furthermore, since the thermal sensing method is based on measuring differences in thermal resistance, good cantilever resistance uniformity across the array is crucial.

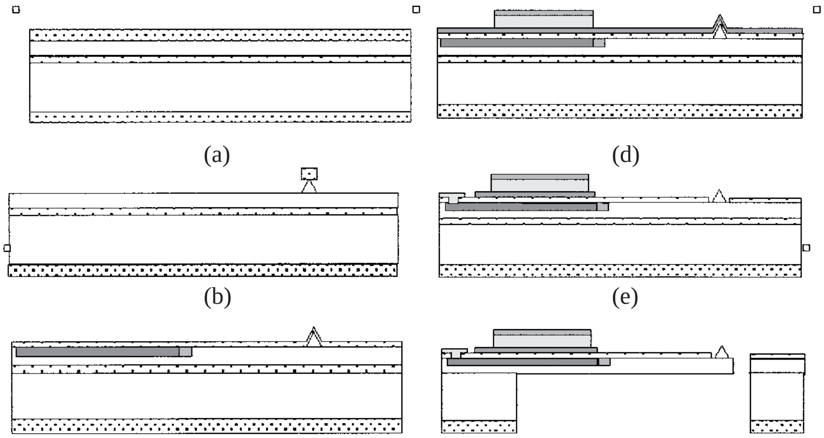
In our research, we use a new reading system to address these issues. Instead of the thermal sensing method, a piezoelectric sensing method is employed to read data by collecting piezoelectric charge. The cantilever used to do this is called a thermo-piezoelectric cantilever.(3) For the fabrication of the piezoelectric sensor, lead zirconate titanate (PZT) thin film has been chosen over zinc oxide (ZnO) film for several reasons, such as its higher piezoelectric constant and lower leakage current. However, there are some problems incorporating PZT thin films into the micro-fabrication process, such as adhesion and difficulties in etching the film. Nam *et al.* developed a cantilever structure integrated with a PZT actuator with a ruthenium oxide (RuO_2) top electrode, which showed excellent electrical and adhesion properties.(4)

In this study, thermo-piezoelectric cantilevers integrated with heaters and piezoelectric PZT sensors, have been fabricated to study thermomechanical writing and piezoelectric readback on a polymer film for a low-power SPM data-storage system. To enhance the data rate we fabricated a 100×100 thermo-piezoelectric cantilever array.

2. Results and Discussion

To fabricate the thermo-piezoelectric cantilever, we started with a (100) n-type silicon-on-insulator (SOI) wafer with a top silicon layer of 5 μm thickness (Fig. 1(a)). After silicon tips were formed on the top silicon layer (Fig. 1(b)), a 100-nm-thick thermal oxide layer was grown on it. Boron was implanted at 40 keV at a dose of 5×10^{14} cm^{-2} to form the heater platform and at a dose of 5×10^{15} cm^{-2} in the high-doping region under the PZT sensor to fabricate the electrical contact (Fig. 1(c)). Then, the wafer was subjected to furnace annealing in an N_2 ambient at 900°C for 30 min. After depositing a 240-nm-thick layer of low-pressure-chemical-vapor-deposited (LPCVD) oxide for passivation, a bottom electrode was formed using a sputter-deposited thin titanium (Ti) adhesion layer, followed by the subsequent deposition of a 120-nm-thick platinum (Pt) layer. Then, a PZT layer was formed by a sol-gel process. After each coating and baking step, the films were crystallized at 700°C for 1 min using the rapid thermal annealing (RTA) system (Fig. 1(d)). The final thickness of the PZT film was approximately 500 nm. On top of the PZT film, a RuO_2 film was deposited for use as a top electrode. The PZT capacitor structure was patterned using an inductively coupled plasma reactive ion etcher (ICP RIE). The Pt/Ti pad was formed by the lift-off process (Fig. 1(e)). Finally, the backside silicon was selectively removed by a deep RIE process (Fig. 1(f)).

A scanning electron microscopy (SEM) image of the fabricated thermo-piezoelectric cantilever and tip is shown in Fig. 2. The resistive heater and piezoelectric sensor of the cantilever are clearly defined in the figure. The length of the cantilever was measured to be approximately 150 μm and the height of the tip was 2 μm. The resonance frequency of this cantilever was approximately 150 kHz.



(a) (d)

(b) (e)

(c) (f)

Fig. 1. Process flow of PZT cantilever fabrication.

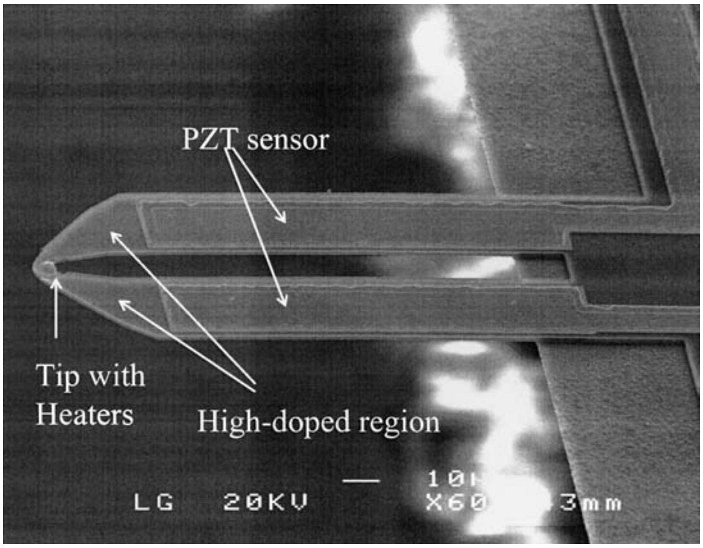


Fig. 2. SEM image of thermo-piezoelectric cantilever.

For the polymer media, a polymethylmethacrylate (PMMA) film of 40 nm thickness was used. To prevent wear of the tip during writing, a 70-nm-thick cross-linked photoresist (SU-8) layer was spin coated between the Si substrate and the PMMA film. Using the thermo-piezoelectric cantilever, we successfully wrote a series of data bits of 40 nm bit size on the PMMA media, as shown in Fig. 3. The amplitude of the applied voltage pulse was 8.5 V and the duration was a few tens of msec.

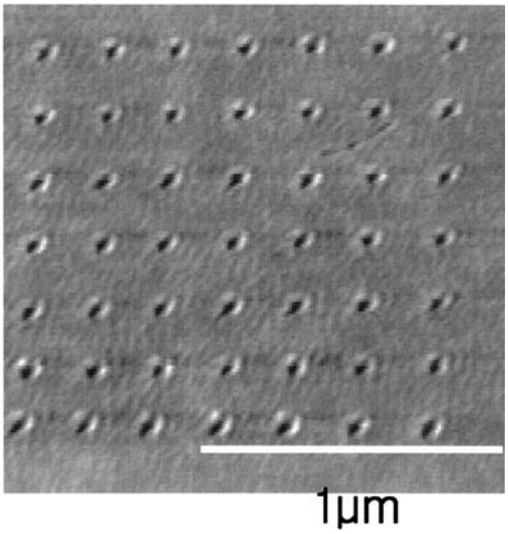


Fig. 3. AFM image of sample with recorded data.

With this cantilever, a piezoelectric sensing method was employed to read the data instead of a thermal sensing method. For a piezoelectric material, such as PZT, the mechanism of sensing is as follows: when stress is applied to the PZT sensor, charges are generated on the surface of the PZT capacitor as the electric domains of the piezoelectric material are changed by the applied stress.

There are several advantages in using the piezoelectric sensing method. First, charge is generated by the cantilever deflection so that power consumption is negligible during the reading process. Second, there is no limit in the selection of a low-T_g polymer for writing, and thus power consumption can be significantly reduced. Third, the piezoelectric sensing method is simpler than the resistive sensing method with respect to the design of electronics, because it does not have an off-set problem due to the nonuniformity of cantilever resistance. Finally, the reading speed of the piezoelectric sensor can be faster than that of the thermal sensor, since the charge generation rate of the piezoelectric sensor is on the order of nanoseconds while that of a thermal sensor is on the order of microseconds for the heating of the cantilever.

Figure 4 shows a schematic drawing of the experimental setup, illustrating how the piezoelectric charges are collected from the PZT cantilever. As the tip travels across the indentations, piezoelectric charges generated by the PZT cantilever are collected. These generated charges are amplified with a charge amplifier (model no.: CS515-2, Clear Pulse Company) and these amplified signals are compared with these initial settings using a comparator. By means of this comparison, it is determined whether the amplified signal is 0 or 1.

We estimated the sensitivity of the PZT piezoelectric sensor by measuring the charge output when the cantilever is deflected at a frequency of 1 kHz. The sensitivity was determined to be 0.55 fC/nm, as shown in Fig. 5.

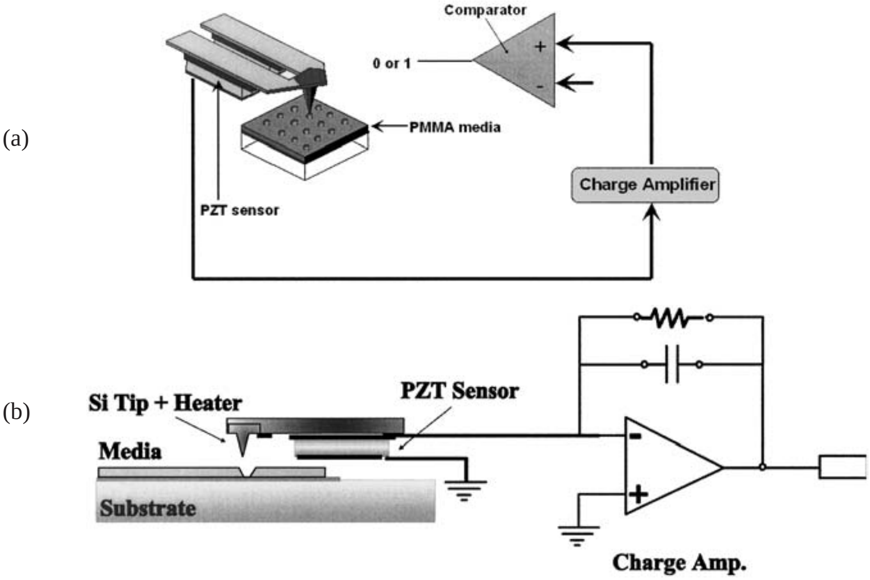


Fig. 4. Schematic diagram of experimental setup. (a) full experimental setup (b) thermo-piezoelectric cantilever and charge amplifier.

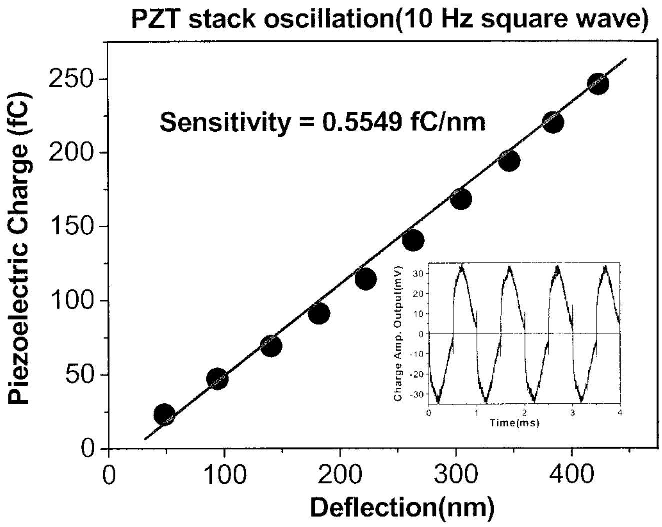


Fig. 5. Sensitivity of PZT sensor of thermo-piezoelectric cantilever.

Furthermore, the output voltage of a patterned SiO_2 standard sample of 100 nm depth and 10 μm pitch, as shown in Fig. 6, was obtained by measuring the readback signal of the charge amplifier at various scanning speeds, as shown in Fig. 5. We can obtain a positive output voltage when the cantilever tip travels down the patterned area and over the flat area, then the output voltage is discharged to zero through the feedback resistance and when the

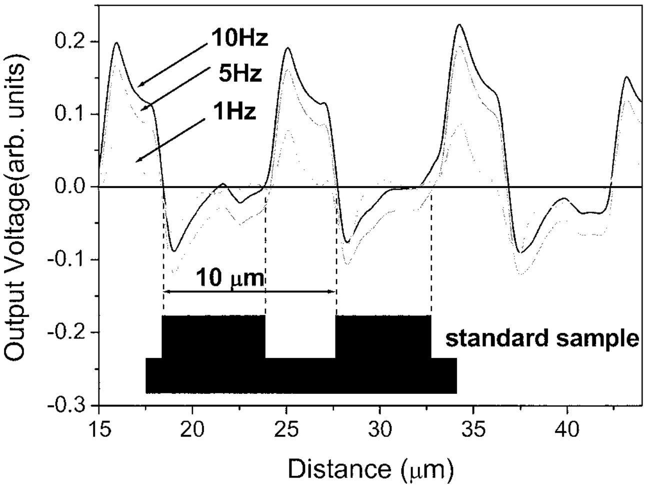


Fig. 6. Output voltage when reading standard grating of 100 nm depth and 10 μs pitch.

tip travels up a patterned area the negative output voltage is obtained. It is noted that the amplitude of the output voltage at a 10 Hz scan speed is higher than that at a 1 Hz scan speed. In general, a high-pass filter exhibits lower voltage gain during low-frequency operation than during high-frequency operation. This means that the system utilizing a thermo-piezoelectric cantilever and a charge amplifier operates as a high-pass filter (see Fig. 4(b)). Therefore, this system exhibits no dc offset voltage. It enables the output system of our data storage system to be designed as a simple electronic circuit.

To improve the data rates, we developed and fabricated a (100×100) 2D thermo-piezoelectric cantilever array for parallel operation. Figure 7(a) shows an SEM image of the (100×100) cantilever array with a spacing of 100 μm and Fig. 7(b) shows a magnified view of Fig. 7(a).

3. Conclusions

In this research, a thermo-piezoelectric cantilever was fabricated and studied for thermomechanical writing and piezoelectric readback on a polymer film for use in a high-speed low-power SPM-based nano-data-storage system. We successfully read and wrote data bits using the thermo-piezoelectric cantilever. The thermo-piezoelectric cantilever utilizing a piezoelectric sensor was used to obtain readback signals using a patterned sample of 100 nm depth. A sensitivity of 0.55 fC/nm was obtained. To improve the data rate, we fabricated a (100×100) 2D thermo-piezoelectric cantilever array for parallel operation. Finally, it was confirmed from simulation using a simple circuit model that the thermo-piezoelectric cantilever array is capable of high-speed operation.

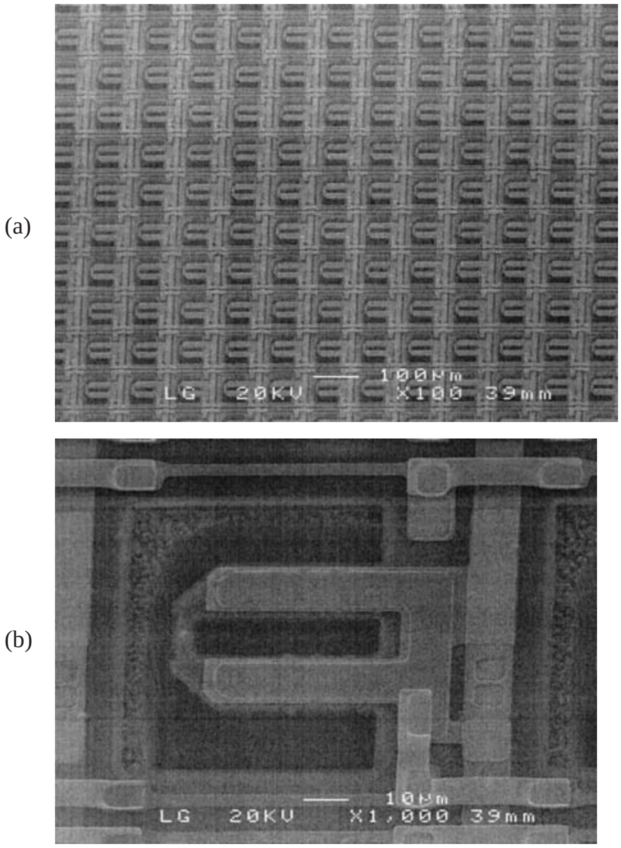


Fig. 7. (a) SEM image of 100×100 thermo-piezoelectric cantilever array (b) magnified view of (a).

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