Microfabrication of MEMS Electro-Thermal Actuators for Problem-Based Learning

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Abstract

Microelectromechanical systems (MEMS) is a multidiscipline area requiring knowledge in various STEM disciplines such as: mechanics, material science, chemistry, physics, and electronics etc.….A graduate course at the University of New Mexico focuses on learning theory of microfabrication and applying this knowledge through a hands-on problem-based learning project. The problem-based learning project focused on developing a MEMS electro-thermal actuator and the challenges associated with microfabrication. The hands-on experience was performed during the lab section of the course in a cleanroom environment. The course was designed to give students theoretical knowledge while giving them hands-on experience as a MEMS process engineer thus giving them experience in MEMS microfabrication.

The present work focused on fabricating an aluminum electro-thermal MEMS actuator on a silicon wafer using photoresist as the sacrificial layer and measuring the displacement as a function of the applied voltage, which was performed as laboratory work supplementing the graduate course. Actuators with varying dimensions were developed. Stresses in the aluminum cantilever structure were reduced by controlling sputtering deposition parameters such as thickness and power. Removal of the sacrificial photoresist layer proved to be a limiting factor because a liquid etchant was used, which lead to issues with stiction. Care was taken to optimize the process of the electro-thermal actuators and reduce the amount of stiction and overall intrinsic stress present of the device. The results of this project were working devices and knowledge of process improvements to increase the efficacy of future work in this field.

Introduction

Theory, Fabrication, and Characterization of Nano and Microelectromechanical Systems (NEMS-MEMS), a graduate course at the University of New Mexico, is taught via a series of lectures and six hands-on laboratory experiments in a Class 1000 cleanroom. The objective of the course is to provide a foundational knowledge of MEMS theory and applications and to provide students with hands-on experience in microfabrication by developing an electro-thermal actuator. The electro-thermal actuators were made of aluminum deposited on silicon wafers using a photoresist sacrificial layer. Many designs, which comprised the same features but differed in dimensions, were developed. The devices work by applying an AC or pulsed DC voltage to the bond pads. As current passes through the aluminum, resistance is present and subsequently thermal energy in the form of heat propagates throughout the structure. Resistance R is modeled in Equation 1 as a function of a material's resistivity ρ and the structure's dimensions in the form of surface area A and length L.

$$R = \frac{\rho L}{A} \tag{1}$$

Because the actuator comprises two arms of the same material and length, differences in resistance between the two should arise from their cross-section area, with varying widths. Greater resistances in a material correspond to an increase in thermal energy and thus the smaller arm, which has a smaller surface area, will heat up faster than the wider (cold) arm. Heating a material up causes it to experience an expansion, therefore applying a voltage to the contacts results in the thinner (hot) arm heating up faster than the wide (cold) arm and expanding at a different rate, resulting in a net displacement. This relatively simple MEMS device requires knowledge in electronics, heat transfer, structural mechanics, material science, and chemistry. The multi-discipline nature of the project allows students to apply theoretical knowledge in these areas to an applied technology, which has potential to allow the students to retain the knowledge and skills.

This project was working towards developing electro-thermal MEMS actuators that could be controlled via a specific amount of input voltage. As such, the largest objective is the fabrication of the MEMS devices. Over the course of three sessions in a cleanroom setting, the electro-thermal actuators needed to be monolithically integrated onto silicon wafers with precise handling so as to align all the thin film layers with minimal resolution error (<5 μm).

The design for the electro-thermal actuator and its corresponding finite element modeling (FEM) simulation images are shown in Figure 1. The simulations evaluate displacement, where blue regions are those that do not experience displacement and red regions (and regions transitioning to red) are those that experience greater displacement. Besides fabricating fully working devices, another objective was to observe and record the output of the actuators.

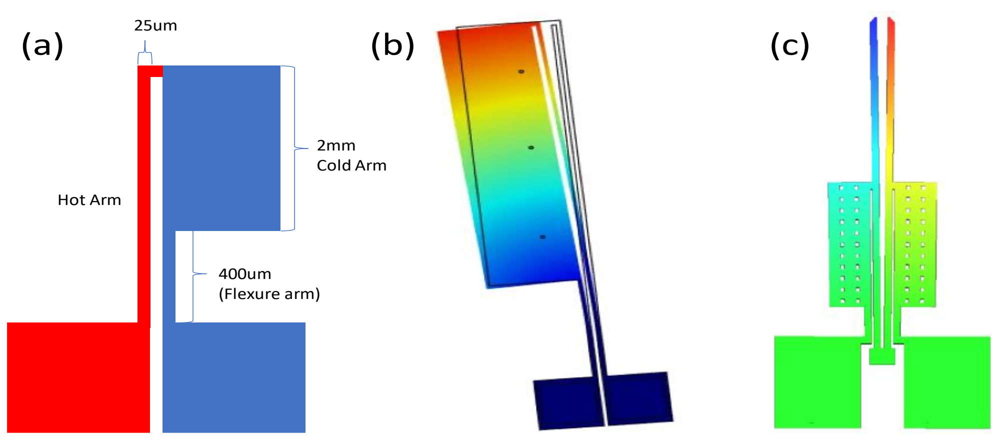

Figure 1: The electro-thermal actuator (a) design, (b) FEM displacement simulation, and (c) FEM displacement simulation for a gripping application

Materials and Methods

The electro-thermal actuators were developed via surface micromachining. The fabrication process is shown in Figure 2. The process consisted of two different photoresist layers and a thin film Al layer. The materials and chemicals that were used in this process include AZ 1518 photoresist, AZ 400K Developer, acetone, methanol, isopropyl alcohol (IPA), and PAN (phosphoric, acetic, and nitric acid), while the tools that were used consist of a spin coater, hot plates, an exposure/aligner machine, a sputtering machine, and supercritical dyer. A surface profilometer, probe station, and SEM were also used to aid in characterizing the devices.

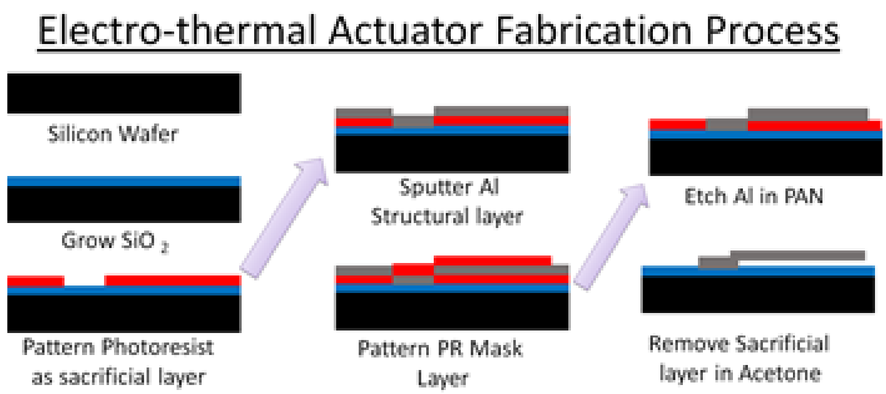

Figure 2: The fabrication process flow for the electro-thermal actuators

Results

Several actuators were successfully micromachined with complete hot arms, cold arms, contact pads, and flexures as shown in Figure 3. Unfortunately, removing the sacrificial layer in acetone resulted in some of the cantilevers adhering to the substrate, a process known as stiction. Supercritical CO_2 drying was used to reduce the chances of stiction. Nevertheless, voltage was applied to the actuators by a probe station to explore the deflection. Of the devices that did not experience significant stiction, successful deflection was observed. Excessive voltage applied lead to excessive heat which caused the Al layers to melt and the device to fail.

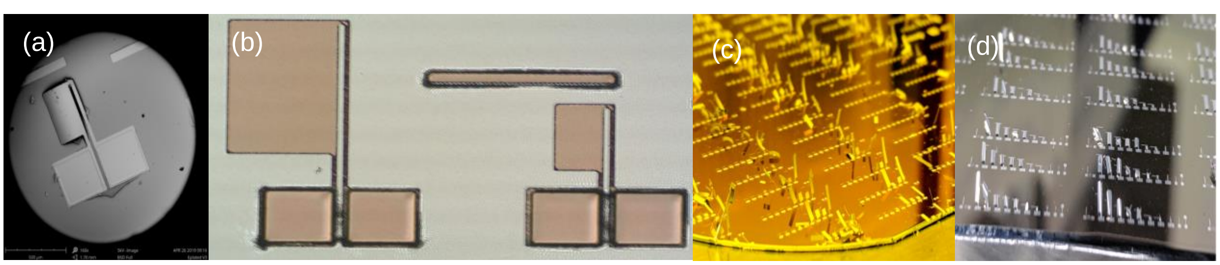

Figure 3: Images of an electro-thermal actuator (a) under SEM, (b) an optical microscope, and (c), (d) with high and low stressed devices

Discussion and Challenges

Previous work on developing electro-thermal actuators resulted in devices that had high intrinsic stress, due to the thin film Al deposition process as shown in Figure 3 (c). The process used in this project overcame that issue by reducing the Al thickness and optimizing the sputtering parameters as shown in Figure 3. Stiction was still a major issue for larger scaled devices, which needs to be further investigated in future courses.

This obstacle can be solved with further process improvements that precludes stiction by using a supercritical dryer. The supercritical dryer introduces liquid CO_2, which has an easily accessible supercritical state, thus eliminating stiction issues. This supercritical dryer prevents stiction by eliminating surface tension effects due to evaporated liquids, thus improving the release of MEMS devices.

This project allowed the students to gain practical experience and to learn how to apply microfabrication theory to real-life problems. The students felt that the hands-on experience in the lab section of the course helped them to retain the theoretical information, and to learn how theory can be applied to solve real-life challenges.

Conclusions

Electro-thermal MEMS actuators were designed, modeled, fabricated, characterized, and tested during this project. The concepts, techniques, and skills necessary for the development of the devices were taught in the MEMS course as foundational knowledge necessary for research and commercial progress. Previous work in the laboratory section was improved upon via altering process parameters; specifically, the devices exhibited much less stress and were able to experience motion when a voltage was applied. New issues, primarily in the form of stiction, became prevalent and solutions were presented so as to further optimize fabricating electro-thermal actuators for the future work of students participating in the MEMS course. This was an introduction course for many students into the world of microfabrication and MEMS and consisted of students from a wide range of backgrounds who had to work together to develop and solve a real-life challenge. This allowed students to combine their previous experience in STEM disciplines to develop a functional MEMS actuator.

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References

1. Tas, N., Sonnenberg, T., Jansen, H., Legtenberg, R., & Elwenspoek, M. (1996). Stiction in surface micromachining. *Journal of Micromechanics and Microengineering, 6*(4), 385-397. doi:10.1088/0960-1317/6/4/005

2. Cauchi, M., Grech, I., Mallia, B., Mollicone, P., & Sammut, N. (2018). Analytical, Numerical and Experimental Study of a Horizontal Electrothermal MEMS Microgripper for the Deformability Characterisation of Human Red Blood Cells. *Micromachines, 9*(3), 108. doi:10.3390/mi9030108

3. Adams, T. M., & Layton, R. A. (2010). *Introductory MEMS: Fabrication and applications*. New York: Springer.

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