Development of Surface Micromachining Technologies for Microfluidics and BioMEMS

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ABSTRACT

In the last decade, examples of devices manufactured with SUMMiT^{TM} technology have demonstrated the capabilities of polysilicon surface micromachining [1]. Currently we are working on enhancements to this technology that utilize additional structural layers of silicon nitride to enable Microfluidics and BioMEMS applications. The addition of the silicon nitride layers allows the fabrication of microfluidic flow channels that are transparent (allowing observation of cellular motion) and insulating (allowing the placement of polysilicon electrodes at arbitrary locations in the flow channels). The goal of this technology development effort is to ultimately provide functionality that is not feasible with other microfabrication technologies. The enhancements build on the key features of surface micromachining: manufacturability and compatibility with CMOS processing, which allow us to leverage the investment already made in the microelectronics processing technology. In this paper we will present examples of devices fabricated using this new enhanced surface micromachining technology. These devices include pumps, valves, and a cell manipulator.

Keywords: Surface micromachining, silicon nitride, BioMEMS, microfluidics

INTRODUCTION

Microsystems are expected to play a major role in the global technology revolution in the next several decades that is going to involve biology, medical sciences, information technology and many other disciplines which are quite possibly not very obvious [2]. This revolution is going to provide scientists with the capability to manipulate the very basic building blocks of life at a scale that has never been possible before – the molecular scale on which the basic processes of biology occur. One of the main drivers for this revolution from the technology side is going to be cost, another will be the size of devices. Some of the most significant effects and issues to emerge will be due to the increased life span and improved quality of human life and the possibility of genetic manipulation, as well as the incorporation of technology into the human body (biomedical implants) and improved individually tailored drugs and drug delivery systems.

There are many different micromachining technologies available which can be harnessed to address the needs of this impending revolution. Silicon surface micromachining technology in particular builds on the incredible investment that has been made in the microelectronics industry and leverages all the advantages of batch fabrication and established processing technologies. As a microsystem is going to be a complete system, not just a device, the hybrid integration of devices – microelectronics, optics, surface and/or bulk micromachined components – in a package that is suitable for the specific application will provide the required system solution. Our technology development is aimed at providing the ultimate level of integration and functionality that would not be possible or feasible with other micromachining technologies. The technology that we will describe in this paper has the potential to integrate micromechanical systems, microfluidic systems, BioMEMS and electronics onto a single substrate to create a true microsystem on a chip that can potentially be used to address the needs of the ongoing biomedical revolution.

SUMMiT™ TECHNOLOGY

SUMMiT™ technology uses polysilicon as the mechanical material and silicon dioxide as the sacrificial material (Fig.1b). In this technology, considering each polysilicon layer as a potential microfluidic channel top or bottom, there are 4!=24 different configurations possible. A critical component of this process flow is the chemical-mechanical polishing which allows the integration of multiple mechanical layers without having to worry about topography issues. We have used SUMMiT™ technology to fabricate a variety of microfluidic systems; such as a drop ejector (Fig. 2, 2pl drops ejected at 10 m/s [3]) and a peristaltic pump (Fig. 3, 60 nl/s calculated maximum pumping rate for a 0.4 nl volume device [4]). These microfluidic devices highlight an advantage of surface micromachining, the electrostatic actuation system is built directly into the MEMS structure to produce a highly integrated microsystem.

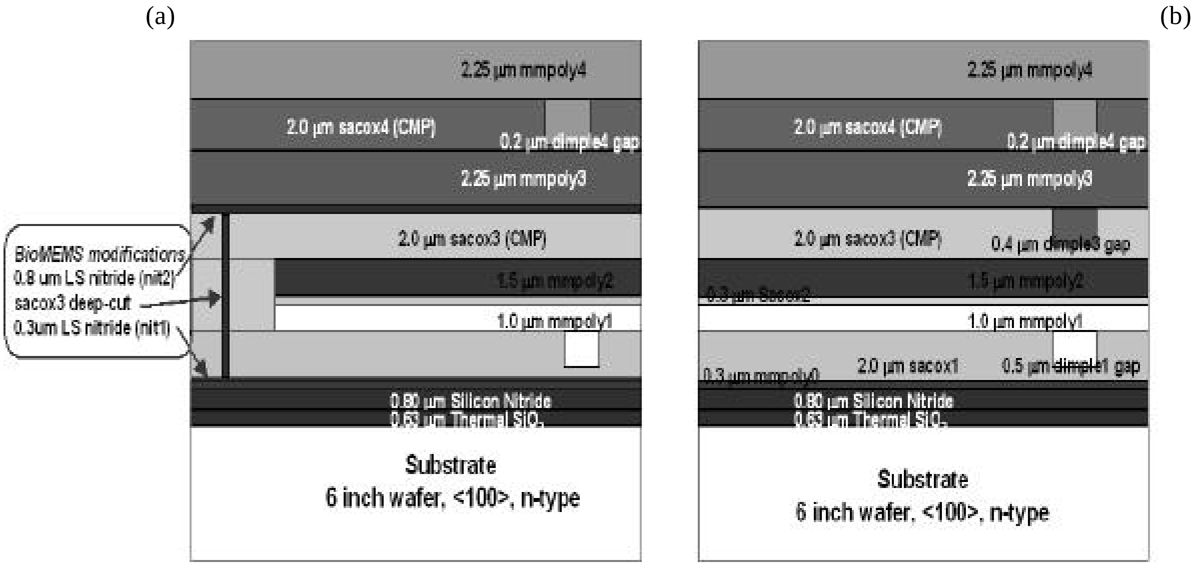


Figure 1. (a) Modified flow and (b) standard SUMMiT™ layers. The incorporation of the low stress silicon nitride layers allows the creation of complex microfluidic structures and enclosed cavities with optical access and the ability to create almost any arbitrary field inside these structures.

Figure 2. Electrostatic ejectors designed and fabricated using SUMMiT$^{\text{TM}}$ technology. Precise drop volume control without any satellite drop formation was achieved.

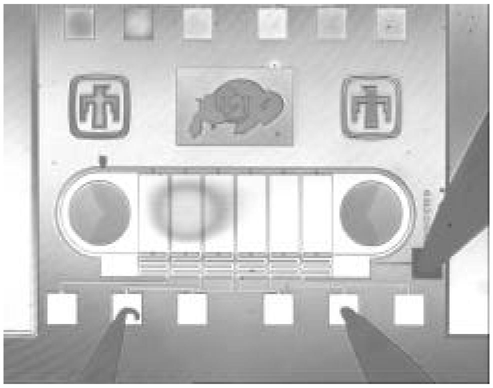


Figure 3. SUMMiT$^{\text{TM}}$ peristaltic pump [4].

Nitride Layer Modifications

To further enhance the capabilities of our technology, we have developed a new process flow (Fig.1a). In this technology, additional layers of insulating material (low stress silicon nitride) and a deep oxide cut allow the creation of microfluidic channels, pumps, valves and other enclosures that can be readily interfaced with the extensive library of mechanical components available in the standard technology. These silicon nitride layers also provide optical access into the structures and allow the incorporation of regions of electrical isolation and/or conduction to produce truly integrated electromechanical microfluidic and BioMEMS devices on a chip. By positioning electrodes for creating electric fields and mechanical actuation around the insulated channel the troublesome issue of electrolysis is circumvented. In addition, using these devices for in-channel reactions and synthesis opens up a large range of possibilities for accessing the nano-scale physics and chemistry. The inclusion of the additional silicon nitride layers also makes possible the fabrication of on-chip parallel plate electrokinetic pumps [6]. The strengths of the modified SUMMiT$^{\text{TM}}$ process are the tremendous flexibility that in enables – many different types of devices can be fabricated – and the ease with which all of these devices can be integrated.

A wafer lot containing designs using the nitride modification was run to test the functionality of both the standard parts and new microfluidic “core-components”, such as valves (Fig.4), pumps (Fig.5), mixing/reaction chambers and separation/detection systems. We are currently testing different valve configurations for obtaining the pertinent performance parameters such as leak rates, maximum pressure and flow rates. We also have included simple silicon nitride flow channels in this wafer lot that will allow us to generate pressure versus flow rate data. This type of basic data is key to the characterization of both our new fabrication process and the validation of our device geometry. By comparing these types of measurements with analytical and numerical predictions of flow within these devices we can gain a high degree of confidence in both our design and fabrication methodologies.

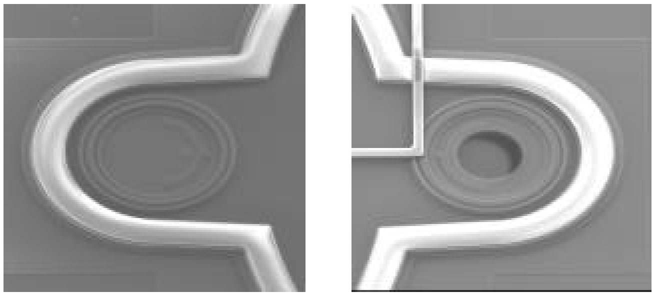


Figure 4. Inlet and outlet valves constructed using polysilicon layers. Polysilicon springs provide the restoring force for the valves. The silicon nitride membrane is transparent to the electron beam used for imaging. The outer diameter of the valve structure is 135um, and the valve height is 3um.

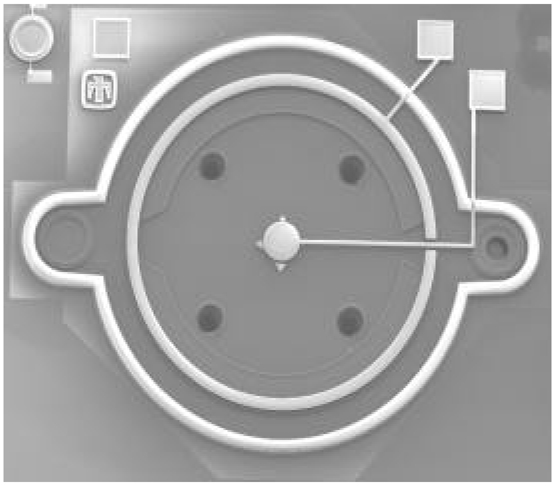


Figure 5. A membrane pump realized using the modified flow. There are inlet/outlet valves inside the cavity and actuation electrodes are placed above the silicon nitride layer which is 1mm in diameter and located 6um above the surface.

An example of an integrated device is shown in Fig. 6, which is a cellular manipulation device. Fig. 7 shows red blood cells flowing through the cellular manipulator. The manipulator is designed to disrupt the cell membrane to allow delivery of large molecules into the cell. A third chemical entry/extraction port is also connected to the channel to make this device into a continuous flow system. Such a device would enable injection of genetic material, proteins, fluorescent tags into the cells and in a massively parallel setup large numbers of cells can be processed. A second generation of this device will have hollow structures for allowing direct injection/withdrawal of materials into/from cells. Polysilicon electrodes are also incorporated into this device to allow additional manipulations and measurements such as electroporation [5], extracellular recordings and field assisted vesicle fusion.

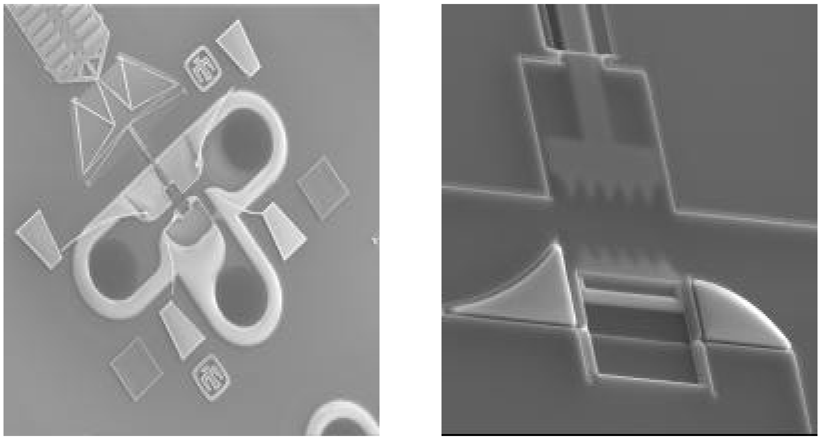


Figure 6. Cellular manipulation device which shows the integration of microfluidic channels and mechanical structures. The width of the channel is 12.5 um at the narrowest point for this design variation.

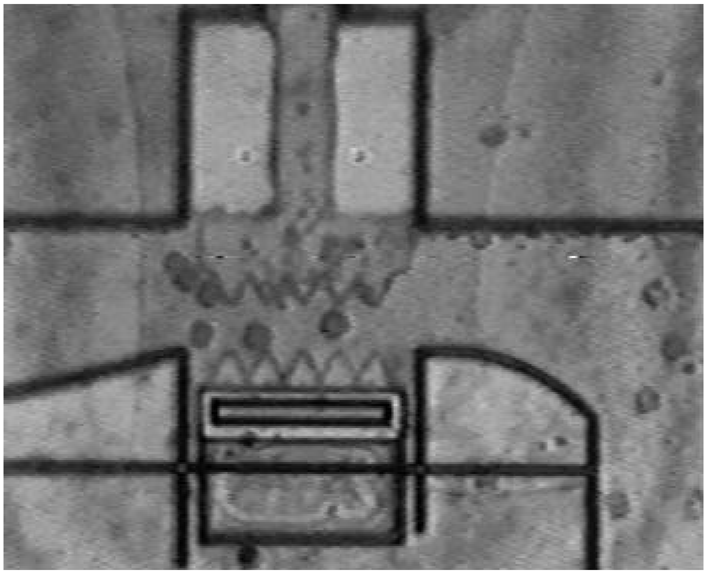
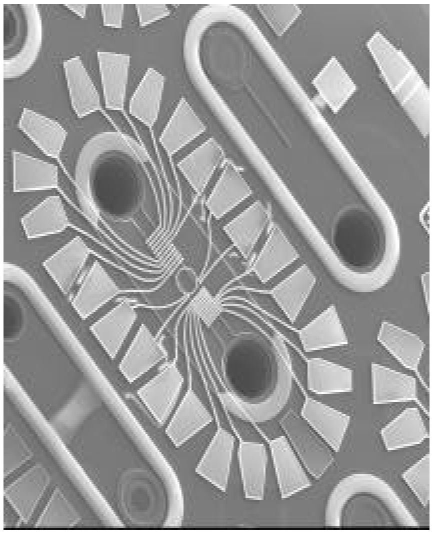


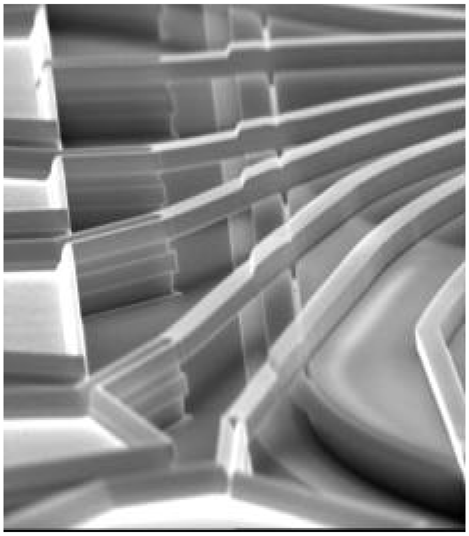
Figure 7. Red blood cells flowing through the cellular manipulation device.

Other devices fabricated using the additional silicon nitride layers (Fig. 1b) include flow channels with electrodes arranged around the channel to create and sense electric and magnetic fields (Fig.8). These devices are ideal candidates for carrying out separations, in-channel synthesis and manipulation of materials utilizing the electrokinetic phenomena. Parallel plate electrokinetic pumps were also included in this first wafer lot.



(a)

Figure 8. (a) A flow channel with electrodes for creating/sensing electric and magnetic fields. Electrodes with varying shapes and spacing allow creation of almost any arbitrary field inside the channel for driving separations and in-channel synthesis. (b) Close-up SEM of polysilicon electrodes formed around the silicon nitride channel structure.



(b)

CONCLUSIONS

In a system view, integration of MEMS components similar to the ones shown here will allow multiple complex functions to be performed on a chip. This capability will generate a new level of system integration and enhance the manufacturability and applicability of microsystems utilizing microfluidics, especially in biological and medical applications. The devices shown in this paper are all from the first wafer lot to incorporate the extra layers of silicon nitride into the SUMMiT^{TM} fabrication process. Based on the results of the characterization and fabrication details of this lot, new designs and further experiments are being conducted.

Acknowledgements

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