Position Paper: Issues in MEMS Fabrication

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The development and use of microelectromechanical systems (MEMS) has been dynamic, with tremendous growth and a number of notable success stories. At least five factors have been key to this success: 1) the availability of a high quality material; 2) the availability of tools for fabricating, inspecting, and testing devices; 3) a knowledgeable and well trained supply of people; 4) strong, committed funding sources in both the government and private industry; and5) a demonstrable need for the technology (the subject of one of the other focus areas of this workshop). Future success and maturity of MEMS still hinges on these factors, although priorities have shifted as the field has grown. This paper will attempt to look at the next 10-20 years of MEMS development in light of the first four factors, and suggest some guidelines for future work, with emphasis on the area of MEMS fabrication. I suggest that continued growth into even more applications and markets will require the incorporation of polymers as an active material in MEMS.

MEMS fabrication has benefited greatly from the knowledge base and infrastructure of the integrated circuit industry. MEMS initially grew out of the disciplines of electrical and mechanical engineering, and has primarily remained there. However, the past ~5 years have seen a surge in application of MEMS outside these two areas, particularly in chemical and biological applications such as gas analyzers, DNA replication reactors, chemical sensors, etc. This interest has brought expertise from these nontraditional disciplines into MEMS, greatly enhancing the third and fifth factors above. However, this talent has mostly been applied to the uses of MEMS, not necessarily to the *fabrication* and *production* of MEMS. Therefore, most MEMS are still silicon based, with other materials having roles in coatings or packaging.

For precision MEMS, and for devices requiring integrated electronics, silicon has no equal. However, it is not always the best material for a given device or application. For example, silicon is brittle; it is only available in specific shapes (wafers); patterns are limited to 2-dimensions or very limited 3-dimensional structures; silicon is incompatible with many chemical and biological substances; silicon fabrication requires sophisticated, expensive equipment operated in a clean-room environment. And despite the well-known advantages of batch fabrication, it has become increasingly apparent that the low-cost potential of MEMS is difficult to achieve. This is often because 1) the cost of the device lies primarily in the application-specific packaging, not in the silicon, and 2) most MEMS markets are relatively small quantity, niche applications, which do not take advantage of the economy of scale in batch fabrication.

A potential answer to many of these problems is plastic. In general polymers will not offer the precision of silicon, and it may not be possible to make polymer structures as complex as silicon structures. But polymers are flexible, chemically and biologically compatible, available in many varieties, and can be fabricated in truly 3-D shapes. Not only is the material very low cost, but the fabrication methods are generally low cost as well. Polymer-based MEMS can be particularly advantageous in low to moderate performing devices which are low cost or even disposable. Silicon devices must be packaged inside another material (often a polymer) while polymer MEMS can be self-packaged. While integrated circuits cannot be made in polymers, electronic functions are achievable using conductive polymers or patterned metal on the polymer (e.g., circuit boards) with attached electronic components. The infrastructure of the polymer industry is much larger than that of silicon. Therefore, just as MEMS has benefited from the silicon industry, it can benefit from the polymer industry.

The list of potential uses for plastics in MEMS is almost unlimited. However, realizing this goal requires a focus, similar to that which has been applied to silicon based MEMS with great success. In the remainder of this paper, i will discuss four specific technical challenges that i believe need to be addressed.

Familiarity with Materials and Processes: To date, polymer-based MEMS devices have been fairly simple. But the complex silicon-based mechanisms of today evolved from the simple devices of two decades ago. Polymers in MEMS must, and will, undoubtedly go through a similar evolution. A large barrier to this is that the number of different polymers and different polymer processing techniques is overwhelming. For example, in my development of a polymer-based microactuator, i start with a polymer sheet that has good thermal and mechanical properties, commonly used in flexible printed circuitry. A thin polymer dielectric film, added to the surface, requires a high dielectric constant, low leakage and high breakdown strength. One or two different adhesives are needed, and the adhesive varies depending on which dielectric is used. Choosing the best material in each of these categories is difficult. Few MEMS practitioners have the strong polymer background that would be desirable for this task, although that number is growing. Likewise, there are many different ways of processing polymers, applying films, etc. Therefore, there is a critical need to foster cooperation between MEMS researchers and those in non-traditional MEMS areas. This cooperation must focus on the fabrication as well as the applications of MEMS.

Small Size: MEMS devices are small, with features ranging from sub-micron to millimeter scale on die ranging from millimeter to centimeter scale. While some features can be small (e.g., features on circuit boards) typical plastic components are larger - millimeter scale and up. In fact, individual polymer molecules (e.g., teflon) can be several microns long! Therefore, achieving smoothness and precision in a polymer comparable to that in silicon is challenging. Since the dimensions of plastic components are typically large, the tools used to fabricate them usually are not designed for micron-scale precision. And there are few applications, outside of MEMS, that demand these properties from polymers. Finally, the environment in which polymers are processed is usually quite different from the MEMS fabrication cleanroom. Micron-sized particles can adversely affect micron-sized devices, whether they are silicon or plastic. Therefore, to achieve mico-scale devices there must be an increased focus on precision, smoothness and cleanliness in polymer-based MEMS materials and fabrication tools.

Integration of Polymers, Electronics and Mechanics: Electronics are the driving force in nearly all silicon-based MEMS. The structure transforms an input (mechanical, thermal, chemical, etc.) into an electronic output. Electronics also will be dominant in polymer-based MEMS, both in powering a device or system, and in doing any required sensing and analysis. For maximum effect, it is important to integrate the electronics with the polymers as intimately as possible. Examples include burying electronic or photonic devices into plastic, or mounting them onto 3-d structures (instead of onto a simple 2-D circuit board). In addition, advantage can be taken of the inherent conducting and semiconducting properties of many polymers, or of polymer/conductor composites. However, an additional advantage of polymer-based MEMS is that, along with electronic operation, they are amenable to pneumatic and hydraulic driving. That is, the output of the device can be *mechanical* rather than electronic. This can be a strong plus in fluid handling applications such as liquid and gas analysis systems. Therefore, there must be a focus on maximizing the integration of electronics and mechanics – both input and output - with polymers.

Multifunction and multimaterial systems: In polymer-based MEMS, the polymer(s) should actively participate in the device function. If the polymer is merely passive - for example as a protective coating or as a substrate for mechanical support, electrical interconnection or power distribution - it is simply a package for the real device. Active polymer components take advantage of polymer properties to increase the functionality. For example, conductive or piezoelectric polymers can be used in actuators, pumps and valves; transparent or colored polymers can act as lenses, waveguides, filters and other optical components; hard polymers can be molded into mechanical components such as gears, springs, etc. The functionality is even greater if multiple polymer materials with different properties are used in a single, multifunctional device. Plants and animals are very efficient because they do this. For example, nerve cells sense both pressure and temperature, and conduct signals. Polymers, because of their great variety, are able to do this better than silicon. Therefore, a multifunction and multimaterial mindset must be encouraged.

Strategic direction and funding - naturally, new development requires funding. MEMS has advanced greatly in the past decade, due to a strong commitment from the government, particularly darpa, and private investment. Traditionally, funding has covered basic and applied fundamental work, and initial demonstrations of devices. Often, there have been insufficient resources to demonstrate reliability, manufacturability, and operation in real application environments. An increased focus on these issues is important for future growth. Equally important is the need for strategic direction. Just as MEMS developers need polymer expertise to know how to incorporate polymers into devices, they also need application and user expertise to know what to make. DARPA and NSF cannot, by themselves, provide all of the direction that is needed. But they can foster stronger ties between the MEMS developers and the users within the government. Therefore, continued strong funding is needed to strengthen the role of polymers in MEMS. That funding should include strong interaction between the MEMS and application communities, and the funding agencies should play a strong role in initiating that interaction. This is true whether MEMS are silicon-based, polymer-based or, preferably, both.