PERSPECTIVES ON MEMS, PAST AND FUTURE: THE TORTUOUS PATHWAY FROM BRIGHT IDEAS TO REAL PRODUCTS

Stephen D. Senturia
Department of Electrical Engineering,
Massachusetts Institute of Technology, Cambridge, MA, 02139, USA
Tel: (617) 253-6869, Fax: (617) 253-9606, e-mail: sds@mit.edu

ABSTRACT

There has been no shortage of bright ideas in the area of microsensors, microactuators, and microelectromechanical devices of all sorts. However, the track record on converting those ideas into commercially successful products has seemed uneven to some, both inside and outside the field. It has taken as much as 15 to 20 years (or more) between early research prototypes and full commercialization for such devices as silicon pressure sensors, accelerometers, ion sensors, and optical displays, somewhat less for some of the passive components such as microfluidic cells for biological application. This paper looks back to the gathering at the Materials Research Society in Boston in 1981 out of which the sequence of Transducers conferences was born, illustrates how far the field has progressed since, and then examines some of the real hurdles that must be overcome during the process of creating products from ideas.

AUTHOR'S PREAMBLE

The invitation to present a Plenary paper on as daunting a subject as "Perspectives on MEMS, Past and Future" opens the door to almost any type of rambling discourse. Since its purview is the entire history of the field and a projection of the future, it is not possible for this paper to follow the usual scholarly model, with citations of relevant work and detailed discussions of individual accomplishments. And the risk of, by omission, seriously offending one's colleagues, is daunting in its own right. Therefore, the perspective adopted here is a very high-level one, looking only at major trends, and drawing from rather well-known commercialization examples from well-known companies. Since the message is that "products matter," this seems an appropriate way to proceed.

Table I. Selected Titles from the 1981 MRS Symposium on Solid-State Transducers

"Signal Conversion in Solid-State Transducers," S. Middelhoek and D. J. M. Noorlag
"Integrated Silicon Sensors: Interfacing Electronics to a Non-electronic World," K. D. Wise
"VLSI and Intelligent Transducers," W. H. Ko and C. D. Fung
"Microdielectrometry," N. F. Sheppard, D. R. Day, H. L. Lee, and S. D. Senturia
"Hall-effect Devices as Strain and Pressure Sensors," Y. Kanda
"An Integrated Pressure Transducer for Biomedical Applications," X.-P. Wu, M.-H. Bao, and W.-X. Ding
"Semiconductor Gas Sensors," S. R. Morrison
"Prototype Sodium and Potassium Sensitive Micro-ISFETs", Y. Ohta, S. Shoji, M. Esashi, and T. Matsuo
"pH-Sensitive sputtered Iridum Oxide Films," T. Katsube, I. Lauks, and J. Zemel

REVISITING THE PAST

At the November, 1981 Materials Research Society (MRS) meeting in Boston, a group of about eighty researchers in the field of "Solid-State Transducers" gathered from around the world to share their experiences, both technical and organizational. The symposium, which was co-organized by Wen Ko and Scott Chang, was a two-day affair. Table I shows some of the papers that were presented there. Among the most dramatic was Prof. Matsuo's presentation of an ion-sensitive field-effect transistor

0-7803-7731-1/03/$17.00 ©2003 IEEE

built, literally, at the tip of a needle, a tour-de-force of microfabrication. The only "physical sensors" discussed during the symposium, in addition to pressure sensors, were magnetic sensors, the microdielectrometer for low-frequency dielectric analysis of resins, a temperature sensor, and a dew-point sensor. Chemical sensors, including both gas sensors and ion-sensitive devices, were prominent. Accelerometers, flow sensors, gyros, switches, relays, and actuators of any type were nowhere in sight.

During the discussion after the evening panel session, the group spontaneously came up with the idea of holding an extra evening session to discuss the field as a whole, and what it needed. That meeting proved seminal.

The researchers who gathered on the evening of November 19 had lots of complaints. Everyone was tired of trying to present papers at meetings in which microfabricated sensors were always placed into a catch-all session at the edge of the main program. First and foremost, the group wanted a meeting exclusively devoted to microsensors and microactuators. Second, the group wanted a dedicated journal, with editors and reviewers who understood the field, a place where investigators could concentrate the relevant literature effectively. (At that time, papers on solid-state sensors and actuators would turn up scattered among a host of journals: *IEEE Transactions on Electron Devices*, *J. Electrochemical Society*, *Solid-State Electronics*, *Thin Solid Films*, *J. Applied Physics*, *Applied Physics Letters*, and many more.) Third, the group held the first of many discussions on infrastructure – the problem of building and maintaining fabrication facilities required for this type of research and product development. (A fourth area, one that only became important as the field matured, namely, design tools, was not even on anyone's radar screen at that time.)

It was out of that evening meeting that Transducers was born: an international conference on solid-state sensors and actuators to be held every two years on a regional rotation, organized by an international governing body made up of representatives from Europe, Asia, and North America. This structure has been maintained ever since, starting with the Delft meeting in 1983, then Philadelphia (1985), Tokyo (1987), Montreux (1989), San Francisco (1991), Yokohama (1993), Stockholm (1995), Chicago (1997), Sendai (1999), Munich (2001), and now back to Boston (2003). There are four individuals who have attended every Transducers meeting: Mitsuo Ai, Yozo Kanda, Simon Middelhoek, and this author.

The year 1981 was also the birth year for *Sensors and Actuators*, the first journal devoted exclusively to solid-state sensors and actuators. Its issues of July and September 1982 contained most of the papers presented at the 1981 MRS meeting.

To summarize, the state of MEMS in 1981 can be visualized as in Figure 1. Most of the activity was either in basic research or the engineering science associated with the technology and devices themselves. Relatively less effort was devoted to products.

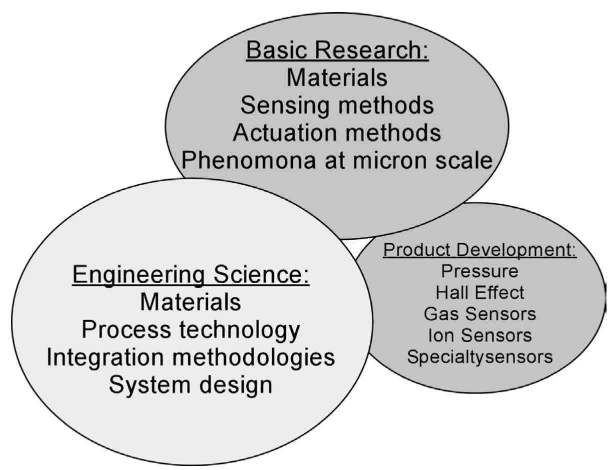

Figure 1. The State of MEMS in 1981

EXAMINING THE PRESENT

The field of solid-state sensors and actuators has now matured. Not only has the Transducers sequence of meetings grown to be the preeminent such meeting worldwide, but regional meetings such as Eurosensors and the Hilton Head Workshop on Solid-State Sensors and Actuators, and topical meetings such as Optical

MEMS and Micro-TAS have taken hold. There is even an annual conference devoted to the commercialization of MEMS. And there is now a multiplicity of topical journals: *Sensors and Actuators*, *IEEE/ASME J. Microelectromechanical Systems*, *J. Micromechanics and Microengineering*, and *Sensors and Materials*, to name a few.

As Kurt Petersen pointed out in his plenary comments at the Stockholm meeting, what started out as a field of research and development called “solid-state sensors and actuators,” which, over time, has morphed into “microelectromechanical systems,” “MEMS,” or “Microsystems,” is no longer a single discipline. Rather, it is a collection of technological capabilities that impact many disciplines. The impact is sufficient that individual disciplines are now holding their own meetings, to the point where it is now possible to go to a meeting involving MEMS or microsensors almost every week of the year. There are newsletters and trade magazines devoted to the micro-world, and a growing infrastructure of fabrication vendors and equipment suppliers to those vendors for such technologies as double-sided mask alignment, deep reactive-ion etching, aligned wafer bonding and vapor release etching.

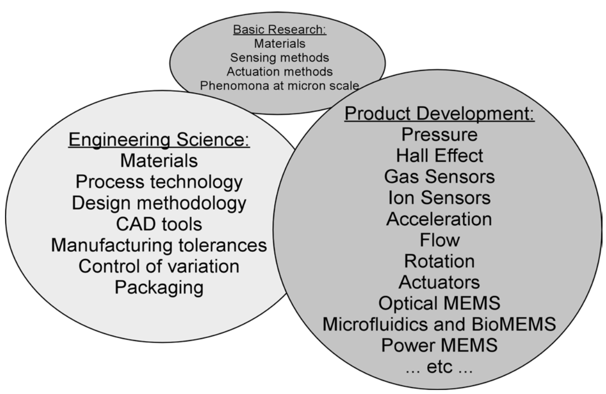

Figure 2. The State of MEMS in 2003

Perhaps the most significant change since 1981 can be visualized with the aid of Figure 2. Products now dominate the field, supported by continuing and expanding efforts in the engineering science domain, but the basic-research component has not grown to keep pace.

PREDICTING THE FUTURE

What, indeed, does the future hold? First and foremost, much of the “basic research” resources and energy are shifting into the “nano” world. “Nano,” of course, means different things to different people. To some, it is simply the sub-micron world as an extension of the micron-scale world, fabricating nano-scale tunneling tips, cantilevers, resonators and similar devices with ever-decreasing dimensional scales. This part of the nano-world is just a scaled-down version of the micro-world. To others, “nano” takes on the special meaning of manipulation or assembly at the atomic or molecular level. Molecular self-assembly, artificial assembly using scanning probe tips or other mechanical devices, and devices for physically interacting with individual molecules all fall in this category.

Because of this dramatic shift of basic research toward “nano,” and recognizing that it may be 15-20 years before there are viable products based on bottoms-up nanotechnology, *it is this author’s opinion that the future of the micro-scale world and MEMS depends on creating a steady flow of more and new types of successful products.* That is, MEMS in the future will be judged less by what is learned and more by what is or can be accomplished in the practical world.

MEMS researchers continue to produce bright ideas at an astonishing rate. Power MEMS, micro-chemical reactors, integrated heat-management and heat-recovery systems, microsystems for genomics and proteomics, and microresonators for signal processing are just some of the areas where new ideas bubble forth. But will they ever become products? Unless the answer is “yes” at least some of the time, much of the energy and dynamism that has characterized the MEMS field for the past twenty-plus years may flag and fail. Therefore, it is worth looking, at a high level, at some of the issues governing that tortuous pathway to commercialization success.

There are at least three major barriers to commercialization of MEMS-based devices: product leverage (or lack of it), market dynamics and infrastructure. Depending on how these interact, the commercialization pathway can look very different.

PRODUCT LEVERAGE

Virtually every successful MEMS or microsensor product has had some significant product leverage. That is, the MEMS or microsensor component has permitted some new or improved functionality of a valuable system. In some cases, the MEMS device represents a complete paradigm shift in how devices or systems are built. An example is the quartz or silicon Coriolis-based rate gyroscope. These devices do not work well in macro versions, but are quite successful in micro versions and enable the anti-skid protection system in high-end automobiles. Also in the case of the automobile, the pressure sensor together with the zirconia oxygen sensor enabled a new type of engine control system, with improved efficiency and exhaust emissions, while minimizing the burden of added weight and cost. The silicon accelerometer now dominates the market for automotive air-bag deployment. The Texas Instruments digital mirror array chip enables a compact and bright image projector, and the microfluidic devices from such companies as Caliper Technologies and Aclara enable microchemical analysis systems to function with greater speed and higher throughput than their bulkier predecessors.

Note that the successful products must perform at least as well as the competitive products they are replacing in order to realize the value of the product leverage. An interesting case-in-point is the status of MEMS RF switches, which have not quite reached the performance levels necessary to replace conventional relays. Once those performance levels, measured in terms of both specifications and lifetime, is reached, the small size and low inertia of the MEMS devices will present formidable competition to relays – provided, of course, that they can be manufactured cheaply enough.

It is also worth noting in passing that the low inertia and high resonant frequencies of many MEMS devices make them intrinsically less susceptible to shock and vibration than their larger-scale cousins. This alone, in some cases, could provide significant product leverage.

MARKET DYNAMICS

The term “market dynamics” incorporates two aspects: market size, and market timing. Both are subjects of countless marketing studies.

A good rule of thumb is never to trust a marketing study. Nevertheless, there are some very basic things one can say about market size and timing that have significant implications for a successful commercialization pathway.

If the product potentially fits into an established huge market, such as the automotive examples mentioned earlier, with markets of 50 million components per year or more, the whole issue boils down to one of manufactured cost. He who manufactures a product that meets specifications at the lowest cost will win. Cost, in this case, must include the total cost required to use the product. As an example, consider a passive automotive pressure sensor (without the electronics) compared to a fully integrated version, such as the devices produced by Motorola. We recall that as early as 1981 there were issues of integration: “To integrate or to dis-integrate? That is the question.” Motorola argues that the integration, which is, at first glance, very costly, actually saves the customer from having to include a circuit board, thereby lowering the overall cost to the customer even though the pressure sensor itself might be more expensive than its passive counterpart.

But many MEMS products address much smaller markets, not necessarily in dollar volume, but in part count. For example, many companies were started within the past five years with the goal of building large optical cross-connect switches, and several of the legacy telecommunications companies also invested heavily in their own internal solutions.

Some of them actually work quite well. But the unit market size for such switches is measured in hundreds or thousands, not millions. Further, the optical networks are not yet ready to deploy such switches in any quantity (an example of unfortunate market timing). The result has been something of a bloodbath among optical MEMS startups, and even the highly heralded Lambda-router from Lucent is presently on the shelf.

INFRASTRUCTURE

Manufacturing is difficult. The experience of companies such as Motorola and Analog Devices, who invested heavily in their own manufacturing infrastructure over many years to develop pressure and acceleration sensors with integrated electronics, precisely to be able to offer their customers the advantage of a complete and compact measurement solution, is that it takes deep pockets, iron-willed commitment, and the courage to invest for the long haul. Another example is the long internal development pathway undertaken by Texas Instruments to bring their digital mirror array products to market.

But what about the other products, for which the total world market is measured in thousands of units rather than millions of units per year? Almost of necessity, manufacturing at this scale requires working with vendors, which, even though there are some highly professional and effective vendors out in the world, is a quick way to grow old. The MEMS Exchange (with financial support from the U.S. Government) is attempting to create a useful brokerage function for designers who may need access to multiple vendors in order to get a device built. Alternatively, companies who outsource their fabrication must develop their own private (and often closely guarded) network of vendors. In either case, the vendor supply chain requires constant nurturing and managing, a taxing burden at best.

The critical question for the entire MEMS enterprise is whether there is enough business to make a set of vendors profitable. If not, a critical vendor may have to leave the business, and the MEMS product builder has no pathway to getting manufactured product. Optical telecommunications provides an example: many of the optical switch companies needed to get mirror arrays built. Some, like Lucent, built them, at least initially, in house. Others went to outsourced manufacturing companies for vendor services. Still others created their own in-house fabs, at a huge cost in precious venture capital money. All such organizations, including the manufacturing vendors, are now in some degree of disarray because the business volume, anticipated on the basis of market surveys, hasn't developed.

Another critical infrastructural issue is packaging. If the wafer-fab vendor supply is thin, the supply of skilled MEMS packaging houses is even thinner. Part of the difficulty here is that there are few opportunities for standardization, meaning that many (perhaps most) MEMS packages are custom-designed and custom-fabricated. Nevertheless, there is a modest network of vendors in the post-processing and packaging arena such that low-to-moderate-volume products can get built in appropriate quantities.

THE DEVELOPMENT HURDLE

As a final subject, we consider development pathways, prior to product manufacturing. Universities, research institutes, and industrial R&D labs can do very interesting prototype fabrication. But if a device is to be manufactured in a facility other than where it was prototyped, a very painful and difficult transfer process to a vendor or set of vendors who can manufacture must take place. Because each vendor supports its own strict set of process flows, it is possible for a well-developed prototype to fail to match the capability of any vendor. Therefore, if one is to work with the R&D side of the MEMS world for testing out ideas, it should be done with one eye on the capabilities of a specific set of vendors so that "un-manufacturable" products are not the end result.

The alternative strategy is to work directly with manufacturers as vendors even when developing prototypes. In order for this to work, the manufacturers need to believe that if they invest some processing time in a prototype device, product volume will eventually result. Because manufacturers have only a limited capacity for prototype building and process development, they may charge a development customer a heavy surcharge for the privilege of working with them. But the advantage of paying this charge and then doing the development work within a manufacturing-qualified vendor is that no subsequent process transfer is required when one is fortunate enough to hit a market that is both real, in terms of product volumes, and ready, in terms of market timing.

Design tools customized for the multi-physics problems that frequently arise in MEMS are now commercially available. These tools permit a level of computational prototyping that was impossible a decade ago and support the kind of rigorous design process that permits a product developer to test whether a given performance can or cannot be achieved with constraints imposed by the process steps supported by a particular vendor. It is often strategically wise to work with more than one vendor for a particular device, especially if one is concerned whether either vendor can successfully build the product. In such cases, it is usually necessary to customize the product design for the quirks of each vendor's process flow. The MEMS CAD tool sets greatly ease this task.

CONCLUSION

This has been a very high-level look at some history of the early days of MEMS and at some of the challenges facing the MEMS field in the future. The assertion here is that the vitality of MEMS in the future, if it is to mirror that of the past, requires a continuous flow of commercial successes. The new ideas are coming, but transferring new ideas to successful products may require following a tortuous path, full of pitfalls. It is good to keep these hazards mind. They breed humility among the MEMS community and respect for the difficulty of doing anything right, ever. When something is done right, the entire community can and should applaud the success.

ACKNOWLEDGEMENT

The author is indebted to Stephen Bart, formerly of Coventor, Michael Judy of Analog Devices, David Amm, formerly of Silicon Light Machines, and David Monks of Motorola for detailed discussions of product development experiences that provided case-study information for the author's textbook, *Microsystem Design*. This paper draws on that same set of insights, leavened by the author's own recent experiences in the commercial world as Chairman and CTO of Polychromix.