MEMS-Enabled Products:

A Growing Market Segment

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Microelectromechanical Systems, now known affectionately by the MEMS acronym, have been showing up in all kinds of places: air-bag deployment, automobile suspensions, mountain-bike altimeters, cell phones, video cameras, even computer games. The canonical MEMS component is a silicon chip with some micromechanical parts designed to respond to some physical variable – pressure, acceleration, flow, sound, radiant energy. Depending on the particular device architecture, the sensing electronics may be on the same chip as the MEMS, or the MEMS may be co-packaged with a separate CMOS chip. Product volumes for such MEMS components are measured in millions of units per year. The emphasis is on achieving a low cost at acceptable levels of performance, interchangeability and reliability. Customers buy these MEMS for incorporation into larger systems, such as automobiles or video games.

There is another type of MEMS product, the *MEMS-Enabled Product*, for which market volumes are measured in thousands of units per year instead of millions of units per year. This is too small a market to permit a successful business based on the manufacture and sale of the MEMS component alone. MEMS of this type can only be sold in combination with the full product into which it is incorporated.

The canonical example of a MEMS-enabled product is a measurement instrument with a unique MEMS chip embedded in its core. One can think of the MEMS-enabled product as a large inverted pyramid (the instrument) supported by a very tiny but very strong base (the MEMS). The MEMS has functionality that is unique and special. This functionality supports a novel way of doing something useful (the tip region of the inverted pyramid), which supports the next broader level: a new instrument architecture that has some important advantage over extant technology. The new instrument competes successfully, ultimately, because of the capability of the MEMS. But it doesn’t compete in the MEMS market; it competes in the instrument market as an instrument, judged by its performance as an instrument. The MEMS disappears inside, but it is essential: it is enabling.

There are significant challenges to creating successful MEMS-enabled products. The first is the necessity of co-design of the MEMS with the system into which the MEMS will be embedded. This is most easily understood with an example, the PHAZIR^{TM} hand-held near-infrared spectrometer for materials analysis developed by Polychromix. The architecture of this spectrometer is based on the modulation capabilities of an electrically-programmable diffraction grating built as a MEMS chip. Figure 1 shows a schematic version of the operation of this chip along with a microphotograph of a fully packaged part, complete with optical window. Think of it as a set of long parallel piano keys that can be positioned up and down with electric signals. In the all-up position, the chip is a mirror. With alternate keys depressed, light impinging on the chip is diffracted away at an angle that depends on the ratio of the wavelength of light to the width of the piano key. The change from all-up to alternate down states can be achieved in less than one millisecond. This is the enabling technology.

To take advantage of this technology, an instrument architecture (starting up the inverted pyramid) was developed around the high-speed modulation capability of the MEMS (see the inset in Figure 2). Incoming light is dispersed by wavelength using a fixed grating so that each wavelength range of interest hits a different set of piano keys, called a pixel. The MEMS has 100 pixels. Light reflected from the chip is sent to a detector. If a pixel is set in diffraction mode, the light hitting that pixel is diffracted away and does not reach the detector. The way this is used to acquire an optical spectrum is discussed later. For now, the critical MEMS co-design requirements are three: the length of the piano key must match the spot size produced by the overall optical design; the voltage required to drive the piano key from up to down must be within the voltage range of available low-power electronics chips; and the mechanical structure of the MEMS must create a diffraction angle large enough to permit exclusion of the unwanted light from the optical path to the detector. Thus, this MEMS chip has design details that are tightly linked to both the optical and electronic design of the spectrometer as a whole. It is not a separate commodity.

This architecture, based on the MEMS chip, supports a very sophisticated form of Digital Transform Spectroscopy (the next tier of the inverted pyramid), in which the chip is driven through a coded sequence of 100 different up-and-down pixel combinations, creating a unique time signature at the detector. This time signature is then analyzed by a computer to create the full spectrum. Because of the intrinsic speed of the MEMS chip, the entire operation of collecting and displaying the spectrum takes less than one second. Further, because of the particular architecture, the operation of the spectrometer is insensitive to stray light and drifts in the detector, creating a wide dynamic range of sensitivity, fully competitive with conventional detector-array spectrometers.

The next tier of the inverted pyramid derives from the fact that the optical package is small enough, light enough, and requires sufficiently low power to permit the entire spectrometer to be built as a hand-held portable battery-operated instrument, a capability simply not available from laboratory-scale instrumentation. Figure 2 shows the PHAZIR^{TM} materials analyzer along with an exploded view. The MEMS chip is buried in the small optics module that is the heart of the instrument. But the PHAZIR^{TM} also includes a light source, a sampling head that directs light onto the sample and collects reflected light for analysis, a battery pack, a display, control electronics for the MEMS, and a microcomputer that performs not only instrument control but also analysis of the resulting spectrum to identify materials. Industry-specific applications can be uploaded to the instrument without any change in hardware. Thus, the MEMS-enabled hardware of the PHAZIR^{TM} is really a product platform. Multiple products can be implemented on this platform entirely by software changes. This is the top level of the pyramid – multiple products directed at different markets, all based on the capabilities of a single custom MEMS chip. Two specific products are described below:

The fact that PHAZIR^{TM} is hand-held and battery operated means that measurements of the kind only possible in a laboratory setting can now be done in the field. Consider, for example, the problem of carpet recycling. When carpet is removed from a building site, the fiber can be recycled, but only if the fiber type can be correctly identified. The PHAZIR^{TM} can be used in the field to make this identification so that carpet samples are directed to the correct recycler, depending on fiber type, without requiring the costly step of first transporting the carpet to a laboratory-equipped warehouse.

Similar measurement efficiencies can be achieved for incoming raw-material inspection in the pharmaceutical industry. Present practice, when receiving a large drum of chemical reagent, is to quarantine the container until confirming identification can be made by taking a sample to an analytical laboratory, a procedure that may take hours and could allow transcription errors. The PHAZIR^{TM} can make the confirming measurement in one second without even requiring the package liner to be opened, thereby streamlining the time required for incoming materials inspection and improving the integrity of the process.

Of course, in order for a MEMS-enabled product to be competitive, it must pass all the same tests of calibration, stability, and reliability of the instruments in its market segment. In the case of the PHAZIR^{TM}, this means that the instrument must correct for variations in light source intensity, adapt to the varying conditions of reflected-light collection from different types of samples, and must implement a wavelength calibration standard to prevent any drift-induced errors.

At the core of these various calibrations is the intrinsic repeatability and ruggedness of the MEMS itself along with the accuracy of the voltages applied to the chip to effect the modulation. The polysilicon technology used for the MEMS is similar to what Analog Devices uses for its accelerometer products, with a long history of mechanical reliability. And the MEMS are rugged: unpackaged MEMS chips have been subjected to shocks as high as 30,000 g's without failure. So, here is another pyramid: as long as the voltage applied to the MEMS is repeatable, the displacement of the piano keys is repeatable, which means that the depth of modulation is repeatable, which means that the scaling inherent in the Digital Transform Spectroscopy algorithm to convert the time signature into the spectrum is repeatable. Therefore, the final calibration of the wavelength assigned to each pixel can be achieved with confidence.

The PHAZIR^{TM} is just one example of this very important class of MEMS-enabled products. The ability to manufacture such products depends indirectly on the health of the MEMS commodity market, which supports the vendor chain needed to manufacture the specialty MEMS in low volume. But with the MEMS commodity market now growing at a healthy pace, the MEMS-enabled products can thrive, and are beginning to do so.

Author Bio

Stephen Senturia is a graduate of Harvard ('61) and MIT (Ph.D. '66). He spent 36 years as Professor of Electrical Engineering at the Massachusetts Institute of Technology. In 2001, he led the founding team at Polychromix, which he now serves as Chairman and Chief Technology Officer. Dr. Senturia is a member of the National Academy of Engineering and a Fellow of the IEEE.

Headshot

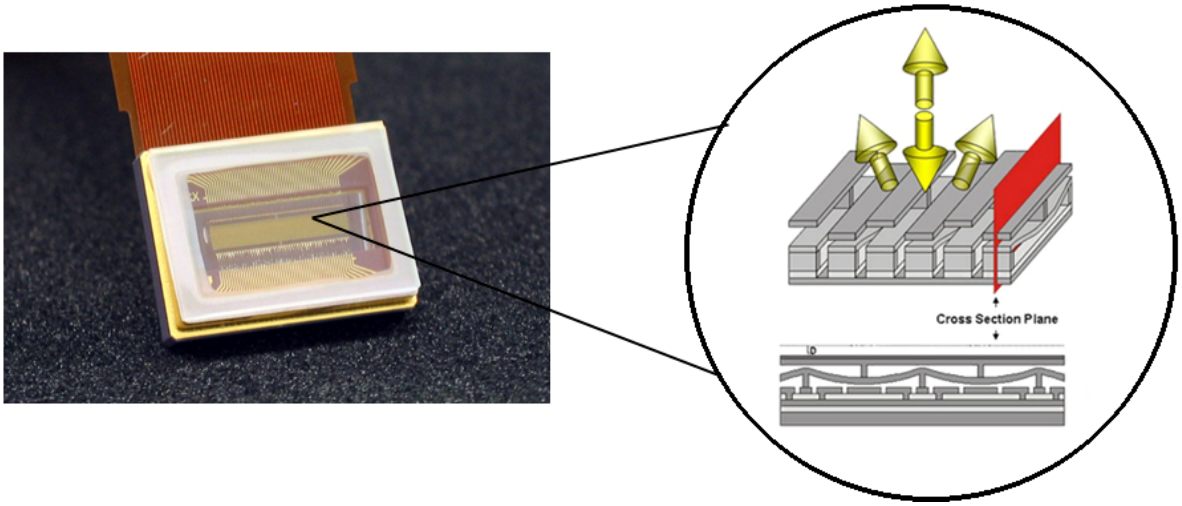

Figure 1: A packaged MEMS chip with a schematic illustration of its operation as an electrically programmable diffraction grating.

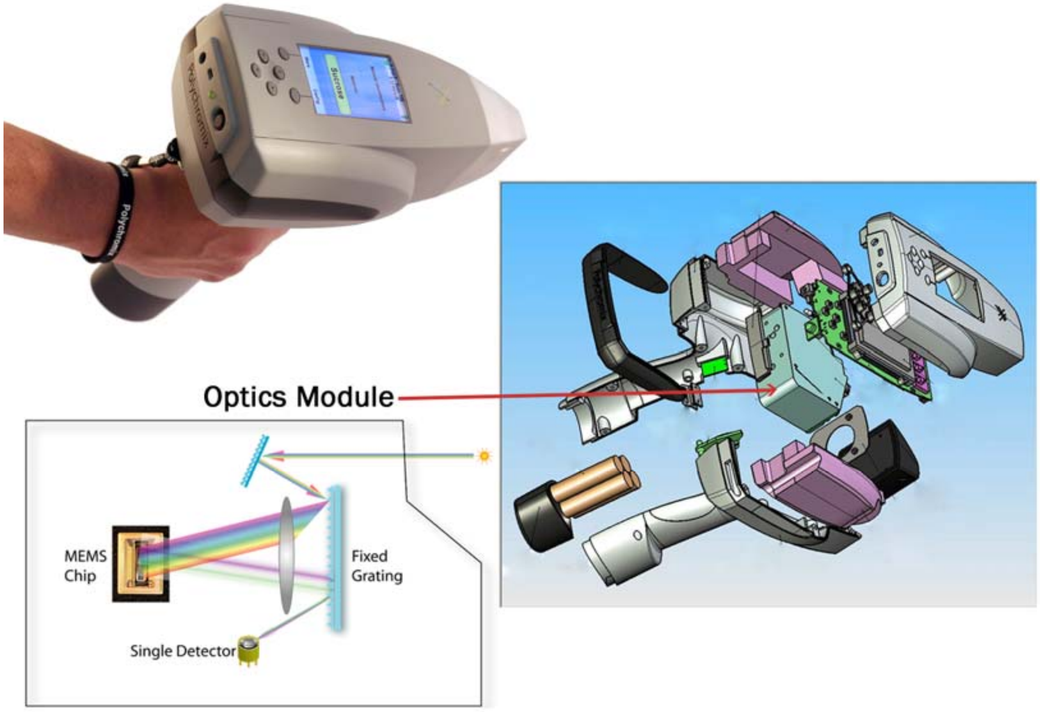

Figure 2: The PHAZIR^{TM} along with an exploded view revealing the optics module with the MEMS chip inside. The optical architecture is shown in the inset.