

Emerging MEMS & Sensor Technologies to Watch - 2015

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As the year draws to a close, people naturally start to think about what the next year, and the future, will bring. With growing anxiety over continuing price erosion in high volume MEMS and frenetic M & A activity, the question on many people's minds is:

What will be the next big thing in MEMS and sensors?

We don't have a crystal ball, but we do know from history that most of today's blockbuster MEMS technologies originated in academic laboratories. We expect more to emerge over time.

This brief report highlights important new topics and papers presented at this year's academic conferences. Criteria for noteworthiness were *commercial relevance, offers a solution to a known or anticipated problem, and technology game-changers*. Nearly all of the technologies mentioned here will need many more years of intensive development and probably more than \$100M in investment to bring them all the way to market. Nevertheless, they each hold potential to create new waves of commercial activity in the MEMS industry.

The emerging MEMS and sensor technologies to watch are:

- Navigation-grade gyroscopes
- Zero quiescent power devices
- GaN resonators
- Graphene FET gas sensors
- Biodegradable sensors
- Flexible energy harvesters
- Paper-based devices

An executive summary of each technology is provided below. For more technical details, please consult the list of References at the end of this document.

Navigation-grade gyroscopes

Several research groups are developing new MEMS gyro architectures which depart from conventional design. NTHU in Taiwan is pursuing mode-matching in ring-coupled structures, while Georgia Tech is focusing on bulk acoustic wave structures to achieve improved bias stability and lower noise [1, 2]. Politecnico di Milano is leveraging the CEA-Leti M&NEMS piezoresistive nano-wire architecture for its ability to reject external vibration and shock [3]. The target application for these next generation gyros will be navigating small vehicles without GPS assistance for minutes to hours. When GPS is

temporarily unavailable, such as indoors, in narrow urban streets, or in a tunnel, inertial sensors would provide essential vehicle tracking data until the next GPS fix. Amazon hopes to land packages on lawns and rooftops via drone, but this feat cannot be accomplished in all conditions without navigation-grade MEMS inertial sensors.

Zero quiescent power devices

Everyone is excited about the possibilities for the Internet of Things (IoT), but that excitement will fade rapidly if a sensor network will demand continual replacement of drained batteries. Development of ultra-low power electronics will be critical to IoT's future success. To that end, at least two groups are working on innovative communication electronics which draw no power until some threshold event is detected by a sensor. Both cleverly employ tuned mechanical resonators to create electronic amplification under specifically sought conditions. UC Berkeley's device uses no power while waiting to receive VLF transmissions [4], and the Chinese Academy of Sciences' device consumes no power until it is triggered by a threshold vibration amplitude. The latter device uses kinetic energy harvested during the vibration event to drive an RF transmitter. The transmitted message contains only the location code of the sensor module, but no sensor data, since the transmission itself indicates that a threshold was exceeded. [5]

GaN resonators

After silicon MEMS, came quartz, silicon carbide, and diamond MEMS. Now gallium nitride MEMS are coming, too. [6] The material's wide band gap, high piezoelectric coefficients and ability to handle high temperature enables the wafer-level integration of high performance RF MEMS resonators with high power and high frequency electronics. Two groups, at MIT [7], and Univ. of Michigan [8], recently presented different approaches for achieving optimized GaN resonators. These devices could be used as high GHz resonators for channel-select filtering in RF receiver front ends.

Graphene FET gas sensors

While it is relatively easy to create a gas sensor, far harder is creating a sensor selective to different species. A group at UC Berkeley has developed a sensor based on a single graphene field effect transistor (FET) which does not need elevated temperatures to operate and can discriminate between NH_3 , NO_2 , H_2O , CH_3OH . This group has validated a novel transduction mechanism in which the shift in FET conductance versus gate voltage indicates the presence of different gases. [9]

Biodegradable sensors

Detecting pressure changes in the body is useful for diagnosis and monitoring of many medical conditions. A pressure sensor made of biologically-compatible materials which could harmlessly degrade over time after implantation or swallowing would be enormously

useful. Researchers at Georgia Tech and University of Pennsylvania have been developing a pressure sensor having a membrane made from biodegradable polymers with electrodes and inductor coils made of zinc. [10] The sensor transmits data in a manner similar to RFID, when energized by an external reader. The same group is also working on biodegradable chemical batteries, which use the body's own fluids as the battery's electrolyte, and having magnesium and iron electrodes which dissolve harmlessly over time. [11] A similar approach for power generation is currently being commercialized in the Proteus ingestible sensor. [12]

Flexible energy harvesters

The challenge with MEMS-scale energy harvesters is that the small mass of the device inherently limits the kinetic energy which can be harvested. However, small energy harvesters arrayed into large-format, flexible substrates (centimeters to meters) could potentially generate useful quantities of power. Sogang University is pursuing polymer thread-based harvesters which could then be woven into large area textiles such as clothing, curtains, flags or sails. [13] Researchers at CEA are focusing on plastic-based harvesters which could be screen-printed onto large sheets, such as for building or vehicle wrappers [14]. Both groups' technologies leverage piezoelectric polymer materials and the much larger mechanical strains that can be developed in polymer materials versus metals or silicon.

Paper devices

Paper is emerging as a potential substrate for ultra-low cost sensors (< \$0.01 per sensor). It is a low cost material, and can be fabricated on high-throughput, large format roll-to-roll equipment, in uncontrolled environments. Academic groups are developing surprising capabilities on this humble material, focusing primarily on medical diagnostic functions in low-resource settings. [15] The Whitesides group at Harvard has been leading the way on paper-based electronics. [16] A research group at SUNY Binghamton recently demonstrated a folded paper-based battery, using bacteria as the electron source, that could generate 0.5 V. [17] You read that right: bacteria found in a droplet of dirty water can attach themselves to electrodes and generate electrons as they metabolize. Paper sensors, which to date have been relying on external batteries, could eventually be powered by paper batteries. In a low resource setting, after use, the sensor system could be simply incinerated with a match.

Looking forward: a trend away from silicon?

In recent history, market demands for lower cost (and lower performance) devices eventually pushed some technologies onto cheaper substrates. LEDs migrated from sapphire to silicon, and microfluidics migrated from silicon, to glass, and are now on plastic and paper. While not all sensors will be able to move to paper due to physics limitations, with time (> 10 years), we may start to see simpler sensors, where ultra-low cost is key to

the market opportunity, migrating to paper. Manufacturing infrastructure for high volume production of paper-based electronic devices still needs to be built. However, building this infrastructure could happen quickly under the right market conditions, given that paper handling machinery is already well-known from the centuries-old printing industry.

A key realization from this year's study is that much academic research on MEMS and sensors is currently focused on materials *other than silicon*. Since the blockbusters of the next decade are likely to come from this current academic research, we need to keep a collective eye on this trend away from silicon.

The semiconductor industry has been very bullish about IoT because it assumes that trillions of future IoT sensors will be made on silicon. What happens to that dream if price pressure and new technology eventually push many of those sensors to lower cost materials like paper and plastic?

For more in-depth analysis of the technologies discussed here, please contact Alissa Fitzgerald at amf@amfitzgerald.com or +1 650 347 6367 x101.

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