Roadmap to a $Trillion MEMS Market

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Introduction

Transistor and MEMS technologies originated from the pioneering Bell Labs work in the late 1940s and early 1950s. While the resulting semiconductor market grew to approximately $300B by 2011, the MEMS component market experienced much slower growth to an estimated $10 billion in 2011.

Recent dramatic acceleration of the consumer MEMS market growth resulted from Steve Jobs' conversion of a cell phone into a powerful computer. Computing power enabled the creative user interfaces, such as touch sensitive screens and auto landscape-portrait rotation, opening a Tornado for MEMS adoption. Acceleration sensors, gyros, magnetic sensors, microphones, pressure sensors and RF filters grew by 2011 to a multibillion units/year total market.

Based on currently forecasted growth of MEMS component market by Yole and iSupply, MEMS market is on path to reach $20B in 2016 (see Fig.1).

Visibility of an even larger MEMS market is emerging from several sources. Some MEMS visionaries, including the author, foresee a dramatic acceleration of MEMS market growth with potential to (finally) catch up and exceed the $300B semiconductor market size.

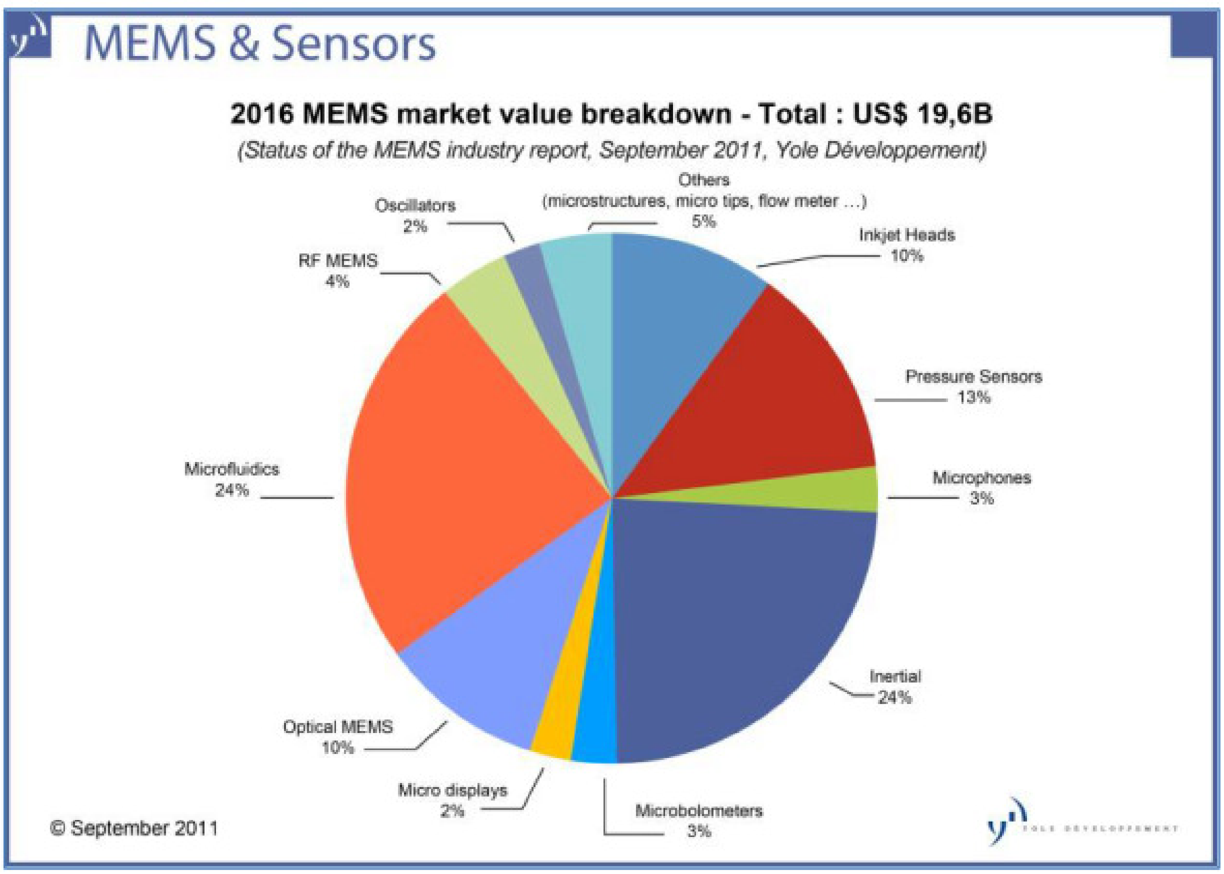

Figure 1. Yole's forecast of MEMS market (December 2011),

Pointers to Accelerated MEMS Market Growth

Several sources outlined MEMS forecast at least an order of magnitude larger than Yole's and iSupply's.

Central Nervous System for the Earth

In 2010, in multiple presentations around the world Hewlett-Packard outlined a vision for CeNSE, a Central Nervous System for the Earth, which will deploy a trillion nano sensors and actuators for the following markets:

- Climate monitoring
- Oil exploration and production
- Assets and supply chain tracking
- Smart highway infrastructure
- Tsunami and earthquake warning
- Smart grid and homes
- Structural health monitoring

Processing the sensor information would require increasing the size of Internet 1000 times, creating huge demand for computing and generating along the way a $70B global market for sensing systems, and $290B market for value added sensing services by 2013.

With a trillion nodes, the MEMS market would be large. Assuming a smart Internet sensor node priced at just $1 would result in $1T market…

Sensory Swarms

At the MEMS Technology Summit conference at Stanford University (co-organized by the author in October 2010), Horst Muenzel, Regional President of Robert Bosch LLC, presented a vision for 7 trillion devices consisting of Sensory Swarms connected to the Internet to serve 7 billion people in 2017 (in 2010 there were already 5 billion mobile phone subscribers). This vision followed a presentation by Jan Rabaey, Co-Director of Berkeley Wireless Research Center "A Brand New Wireless Day" at Bears Conference in February 2009.

All devices would be part of mobile internet servicing "Internet of People" (social people networking) and "Internet of Things" ("social" machine networking).

This vision translates to 1000 sensors per average person in 2017. While it sounds somewhat big, we are already seeing high end applications supported by large number of sensors, for example:

- Advanced cars have close to 100 sensors.
- Smart homes use 10s and 100s of sensors.
- Smart phones use 6 sensors.
- Medical diagnostics uses 100s of different sensors, which will be migrating to personal devices.

It is thus not too big of a stretch of imagination to foresee the growth outlined by Bosch. With a 7 trillion nodes, the market at $1 sensor node would be $7T…

Smart Business

Harbor Research introduced a concept of Smart Systems in the era of Pervasive Internet, where people, devices, sensors and businesses are connected and able to interact with each other. Smart business practices will enable a truly connected converged physical and virtual world.

Some of the leading markets for smart sensing systems include cell phones, health monitoring devices, smart grid infrastructure, automotive, IT and industrial systems.

This will enable collective awareness, creativity and better decision making capabilities, driving (per Harbor Research) the largest growth opportunity in the history of business.

Third Industrial Revolution

Looking back, all major technologies coming to market were changing world's productivity and balance of power. At the BSAC meeting on 9/22/11, Vijay Ullal, VP of Maxim, referenced three major technology based revolutions:

- 1st revolution increased productivity by bringing steam, electricity, internal combustion, radio and aeronautics.
- 2nd revolution further increased productivity through transistors, computers and Internet, propelling the semiconductor market to $300B.
- 3rd emerging revolution based on fusion of computing, communication and sensing, freeing humans for creative work and enabling MEMS market size to catch-up with semiconductor market.

Vijay stated that growth could be significantly accelerated if MEMS R&D speed would be increased to 15 cycles/year, and standard MEMS processes become available for the fastest growing products.

Making this feasible would require significant funding exceeding capability of a single company.

The attractiveness of competing in a $1T market by design only using standard MEMS processes, as opposed to competing in a $10B market using both design and process, should entice competitors to cooperate, thus creating coo-petition (cooperating competitors).

The $10B 2011 MEMS component market is estimated by Yole to grow at 14%/year. At this rate, the MEMS market would reach $1T after 35 years (2046). To accelerate growth to $1T to 10 years, the growth rate would have to increase to 54%/year.

Bryzek's Mobile Vision

Market pull for MEMS products created by mobile devices is unprecedented and disruptive on a global scale. Within just 4 years from iPhone introduction, mobile devices absorbed several billion MEMS/sensor components.

As mobile devices provide open architecture for software development and enable data processing (with powerful processor), include high resolution graphic display and enable global wireless communication, they eliminate multiple cost and infrastructure barriers for the emerging MEMS based personal medical devices, thus enabling massive adoption.

Due to aging population, increasing lifespan and continuously increasing complexity of medical technologies, health cost is dramatically increasing. In the US, it reached $2.5 trillion in 2009, representing 18% of the GDP (EE Times 12/9/09).

Remote home care emerges as a Tornado-in-making in the US, promising to reduce health care cost and provide care to those who currently don't have it. Global healthcare issues are even more complex, with developing countries struggling with lack of equipment and diseases eliminated in the US.

Deployment of low cost (in large volume) medical devices integrated or plugging into mobile devices has already started. Wearable (wireless) devices market (ABI Research) is forecasted to grow from 12M devices (almost all of them for sports and fitness) in 2010, to 420 million wearable health monitors in 2014, with 59 million projected to be used used at home.

In 2011, the first mobile products have received FDA clearance: blood pressure monitoring cuff and CT-scan viewer. The cost and approval time should shrink in 2012, as FDA is expected to issue detailed guidelines about which mobile health devices and apps fall under its jurisdiction, and how it will regulate them.

By 2015, 30 percent of the world's smart phone users are forecasted to use mobile health product. By 2020 most smart phones may have integrated or will be connected to a variety of health devices, such as activity sensors, bio-sensors, chemical sensors, spectrometers, microfluidic diagnostics and drug delivery devices, ultrasound scanners, proteomic analysis, gene analyzers, etc.

With a forecasted 7 billion mobile users by 2020, assuming 14 different medical MEMS based devices per average mobile user would bring TAM to 100 billion devices. With an average ASP of $10, it could represent a trillion dollar market.

Sensor data processing will represent another large market. It is feasible in this time frame to envision an integrated "doctor on a chip" ("app"), providing medical interpretation of results and, for example:

- Detecting diseases based on analysis of body fluids in few minutes, implemented with disposable microfluidic cartridges and spectrometers embedded into a cell phone.
- Monitoring blood sugar level and controlling continuous insulin delivery for diabetics, implemented with wireless spectrometric glucose sensors and insulin pumps.
- Detecting diseases based on personal ultrasound scanner output.
- Processing personal ultrasound scanner output to display 3D optical images of baby in the womb.

Impact of Accelerated MEMS Market Growth

The byproducts of dramatic market growth are new jobs and formation of new companies and industries.

Job Creation

Forecasted MEMS market growth will be reflected in the massive creation of new jobs. These high tech jobs may follow the iPhone model partitioning the value added as follows:

- 3% ($14) assembly (China)
- 32% ($178) components (global)
- <u>66% ($368) Apple's slice (US)</u>
- 100% ($560) selling price

Conclusion: most of these jobs are likely to be in developed nations. This will overshadow potential of most other considered approaches by Governments. It also will likely involve Governments of different countries competing for retaining companies creating these high level jobs.

To estimate the magnitude of job creation I used Nasdaq. The average revenue per employee for Nasdaq 100 companies in 2011 was about $500,000.

Assuming that MEMS based component and system businesses are on a path to create a trillion dollar revenue growth and using Nasdaq average sales per employee, results in about 2 million new direct jobs and twice as many indirect jobs, for a total of about 6 million new jobs.

As a reference, the US created only 1.3M new jobs in the last 10 years, primarily in Government and medical sectors.

Creation of New Industries

In the book Outliners, Malcom Gladwell derived common denominators for the most financially successful people: they must be born at the right time and right place, enabling them to acquire right knowledge ahead of peers and be in position to take the risk to ride a Tsunami wave created by the emerging technology fueling large industrial revolution.

We already see the emergence of new businesses on the leading edge of the MEMS tsunami: sensor data processing software (multiple startups), sensor data processing centers and Internet of Things.

It is also feasible to expect the first MEMS billionaires, as it happened in each major industrial revolution…

Acceleration of MEMS Market Development

As Ullal (Maxim) pointed out, slow MEMS R&D cycles (3 to 12 months per iteration) delay product development and lack of standard processes slows down the commercialization cycle.

MEMS R&D Cycles

Based on the authors experience from his seven MEMS startups in Silicon Valley, this acceleration will require development of new software tools enabling modeling of MEMS fabrication on an atomic level.

For example:

- To enable a single pass development of DRIE (deep reactive ion etching) process for a specific trench profile(s), software should enable design engineers to enter a 3D trench profile and deliver all settings on the DRIE tool to etch the wafer with a high first pass yield. The current state of the art requires large number of process iterations, taking weeks or months. Development of such modeling software (and stable tools) will require a close cooperation between the tool makers and software developers.
- In MEMS processing, the sequence of processing steps and tools capability matters a lot, as surface conditions are usually affected by most processing steps. This, e.g., stretches wafer bonding process development to months or years. No existing software tools enables the atomic level modeling of surface condition for a given unit process/tool.
- Many of the development problems are caused by contamination. E.g., after DRIE etching, effectiveness of cleaning the etch polymer (dramatically affecting wafer bonding due to leftover atomic contamination) depends not only on the selected unit process, but also on device's 3D geometry. Experimental development of the cleaning process takes months.

Simplified analogy to the available IC software tools is the transistor design: in a given process, the design engineer can form a low power (small) transistor and a high current (large) transistor in the software domain and derive its performance (e.g., gain, bandwidth, noise) with a high degree of accuracy over process corners.

Development of equivalent models for MEMS structures will require a significant effort.

MEMS Fabrication

Currently, typical MEMS product development is outlined in Figure 2, representing paradigm one product – one process – one package - one ASIC – one test system. Multiple closed loops (in red) are required before the product could reach production phase. Material data base often needs to be updated based experimental results for a specific application. The cycle is unpredictable and often takes several years to production start.

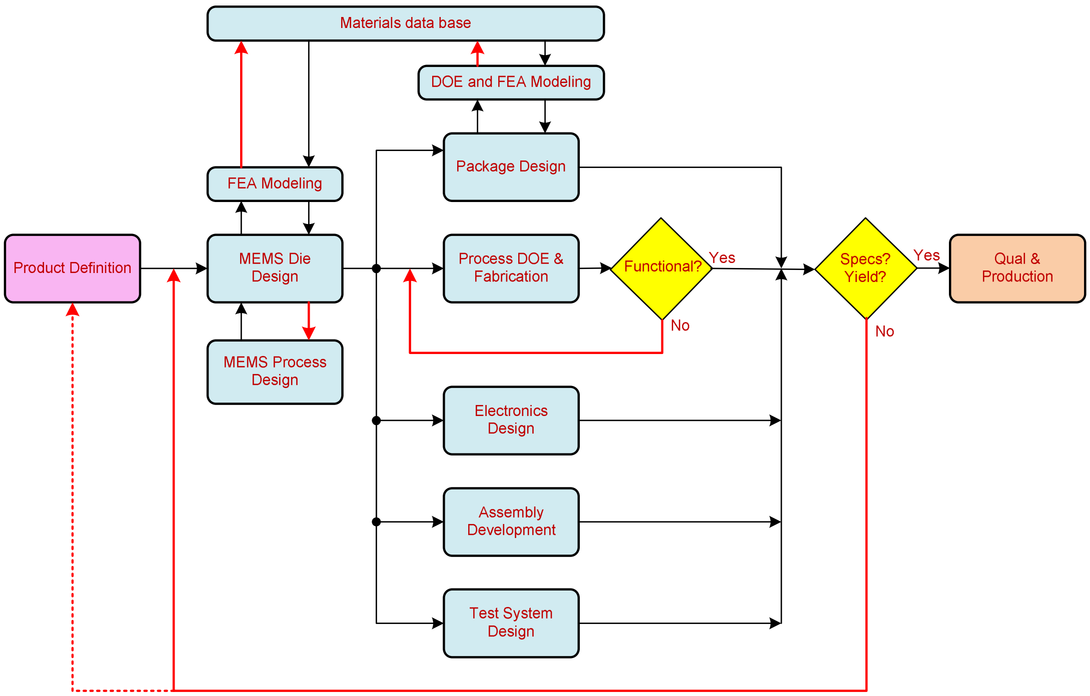

Figure 2. Typical MEMS product development.

Standardization of MEMS process would dramatically simplify development process and its predictability, as shown in Figure 3.

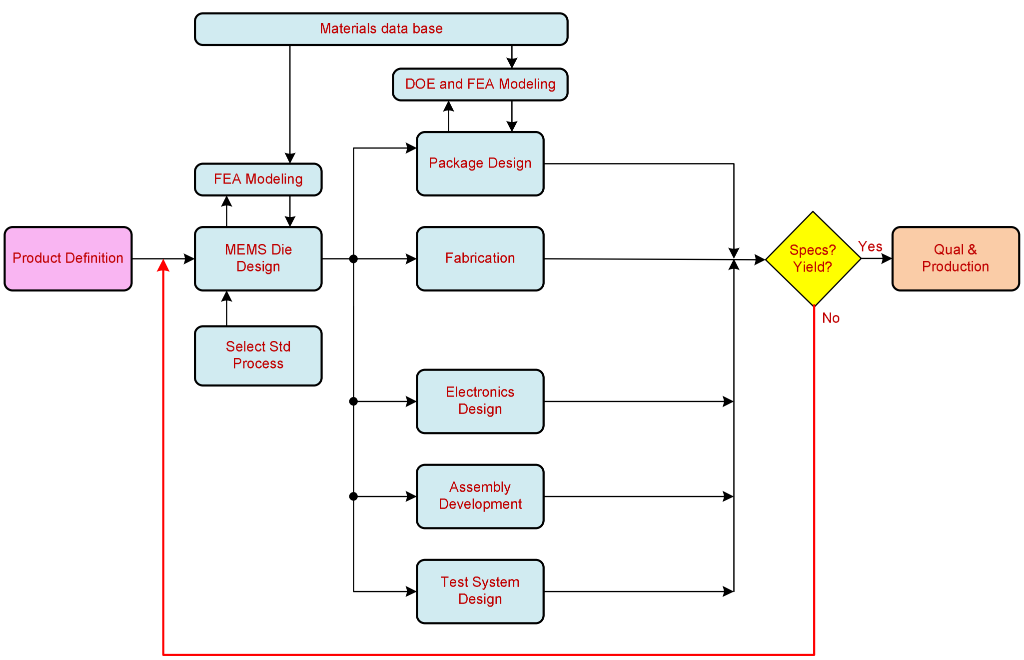

Figure 3. Simplification of MEMS based product development, if standard MEMS fabrication process would be available.

Several standard MEMS processes were developed and successfully validated on a large number of designs (e.g., Sandia's Summit V, MCMC's MUMPS), however, they were developed in disconnect with later emerging market Tornados, thus incapable of supporting large volume commercial applications. Several companies successfully developed their internal MEMS process standards, e.g., ST's Thelma used for acceleration sensors, gyros, pressure sensors, microphones and fluidic devices.

This provides a proof that customizable standard processes are practical for the narrow class of devices, wherein certain device parameters (such as membrane thickness or DRIE etch depth) could be varied for different devices, while keeping the sequence of unit processes fixed.

Several MEMS foundries started development of standardized (first step towards standard) processes targeting currently the largest segment, inertial sensors.

In parallel, the IC industry started to use selected MEMS unit processes for chip scale packaging and wafer stacking, promising wafer volumes significantly larger than the entire MEMS industry. As a result, improved processing tools from IC tool vendors started to enter the market, offering improved volume, up time and process control, promising to accelerate the commercialization path for selected MEMS unit processes.

Disruptive Technology Life Cycles

Commercialization of disruptive technologies takes a long time to convert academic prototypes to volume production. The summary of commercialization cycle for many MEMS devices is shown below:

MEMS/MSTCOMMERCIALIZATION TIMETABLE

Product	Discovery	Product Evolution	Cost Reduction	Full Commercialization	Elapsed Time in Years
Pressure Sensors	1954-1960	1960-1975	1975-1990	1990	36
Accelerometers	1974-1985	1985-1990	1990-1998	1998	24
Gas Sensors	1986-1994	1994-1998	1998-2005	2005	29
Valves	1980-1988	1988-1996	1996-2002	2002	22
Nozzles	1972-1984	1984-1990	1990-2002	2002	24
Photonics/Displays	1980-1986	1986-1998	1998-2005	2005	25
Bio/Chemical Sensors	1980-1994	1994-2000	2000-2012	2012	30
Radio Frequency (R.F.)	1994-1998	1998-2001	2001-2008	2008	13
Rate Sensors	1982-1990	1990-1996	1996-2006	2006	22
Micro Relays	1977-1993	1993-1998	1998-2012	2012	32
Oscillators	1965-1980	1980-1995	1995-2011	2011	46
				Median	**28**

ROGER GRACE ASSOCIATES
MARKETING COUNSEL

Figure 2: Roger Grace's presentation at MEMS Technologies Summit, Oct 2010, Stanford University.

Long development cycles are not restricted to MEMS. Other disruptive technologies show long cycles as well:

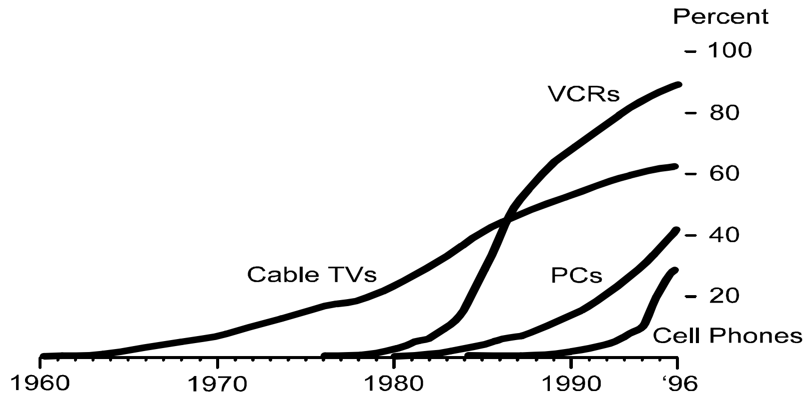

Figure 3. Percent household penetration vs. time for a variety of products. Courtesy of Nadim Maluf.

Based on these cycles, the acceleration of MEMS market growth in the next 10 years can rely only on devices already demonstrated, thus reasonably visible, simplifying market research.

Key technical components behind the accelerated MEMS market growth, after acceleration of R&D cycles and introduction of standard processes, seems to be the integration of low cost wireless VLSI technology with MEMS. The integration will likely focus on System-in-Package, as opposed to the same wafer integration.

Another element that will need to be addressed is manufacturing capacity. Assuming the emerging devices will be ranging from 1 mm^2 to 4 mm^2, with an average die size of 2 mm^2 and an average 2-wafer stack, 1 trillion devices would consume over 140 million 8" wafers.

EU to pursue smart system R&D (EE Times -- EDN, November 23, 2011)

The European Union is launching a three-year, $13 million effort to develop standards for smart systems that will be coordinated by STMicroelectronics.

The initiative comes several weeks after a similar US announcement to pursue smart systems in a national effort coordinated by the National Institute of Standards and Technology. While EU effort if focused on the emerging future systems (thus in sync with the author's proposed Roadmap), NIST effort (from author's perspective) is not yet focused on the future.

Smart systems combine digital computers, analog electronics, RF devices, MEMS, and other sensors along with actuators, power sources, and wireless communication capabilities into software-driven applications ranging from humanoid robots to smartphones.

Called the "SMArt systems Co-design" program, SMAC will create a design and integration platform that lowers costs and time-to-market for smart systems development. Applications would include energy, automotive, health care, factory automation, and consumer electronics. Program officials have singled out advanced packaging technologies like system-in-package and chip stacking (3D IC) as particularly important, but will integrate all levels of the development effort into a single platform.

Along with ST, the SMAC platform will be co-designed by Philips Medical Systems, ON Semiconductor Belgium, Agilent Technologies Belgium, Coventor Sarl, MunEDA, and EDALab, among others.

Conclusions and Call for Action

Potential of accelerating the growth of MEMS industry to a $Trillion exists. How much acceleration could be developed will depend on the industry cooperation and overall funding of the effort.

The first funding of the effort comes from Mancef (http://mancef.org/), which secured initial funds to launch a global development of the Roadmap to a $Trillion MEMS Market.

MIG represents the largest MEMS industry association. It is possible that MIG could get involved in supporting the effort.

Anybody else?