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Emergence of a $Trillion MEMS Sensor Market

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SensorCon 2012

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Introduction to MEMS

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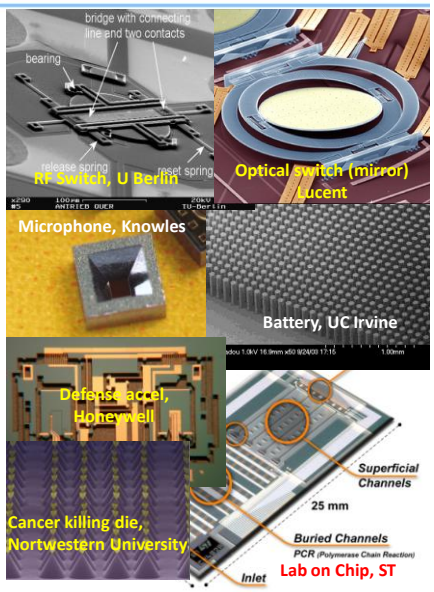
Introduction to MEMS

- MEMS: Micro Electro Mechanical Systems, or…
  - Diversified family of non- electronic ICs (mechanical, optical, fluidic, etc.)
- Silicon is used for most MEMS devices, as it is almost a perfect mechanical material:
  - No mechanical hysteresis
  - Comparable strength to steel
  - 3X lower density
  - Batch fabricatable
- Key challenges:
  - Lack of standardization
    - One device – one process – one package – one test system.
  - Difficult process integration.



MEMS Market Evolution

- Transistor and MEMS technologies originated from the pioneering Bell Labs work in the late 1940s and early 1950s.
  - Resulting semiconductor market grew to approximately $300B by 2011.
  - MEMS component market experienced much slower growth to an estimated $10 billion in 2011.
- Recent years witnessed an explosion of the consumer MEMS market.
  - Resulted from Steve Jobs' conversion of a cell phone into a powerful computer.
    - Computing power enabled 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 and pressure sensors grew to a multibillion unit market in 2011.
- This Tornado combined with low cost data processing, high quality displays, cloud storage and wireless communication promises growth of sensing nodes to trillions in this decade.

MEMS based Product Breadth

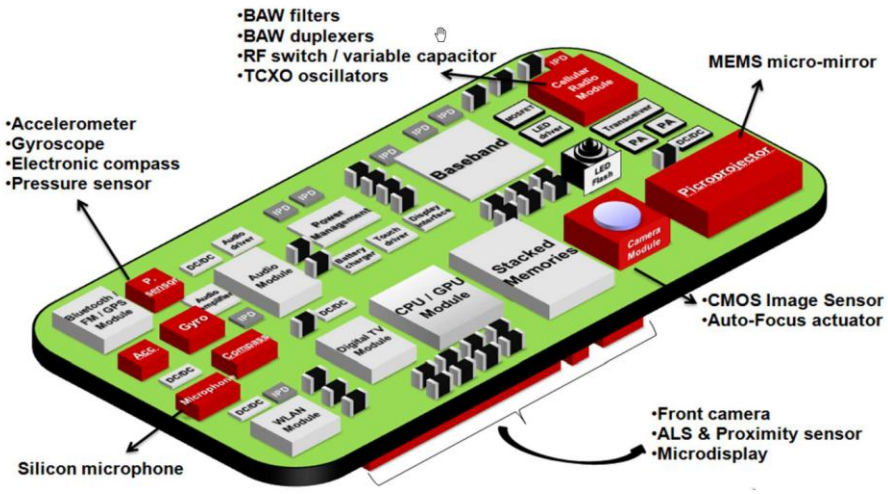
- Thousands of MEMS based products were demonstrated.
  - About 10 products are in very high volume production.
    - ~3 billion units shipping this year.
  - 10 to 30 additional MEMS based products could enter Tornado this decade.
  - 30 to 100 new devices could enter Tornado during next decade.
- Recently emerged markets for MEMS :
  - Semiconductor market:
    - Wafer level packaging.
    - Vertical IC stacking.
  - Nanotechnology:
    - Packaging of nano devices.

Consumer Sensor Explosion

Consumer MEMS

- Four market needs started a massive adoption of sensors in consumer market:
  - Wave solderable microphones for cell phones.
  - Portrait/landscape image rotation in iPhone (accel).
  - Gaming motion detection in WII (accel + gyro).
  - Camera image stabilization (gyro).
- Once sensors found their way into cell phones, many new sensor based apps were and are being developed.

MEMS in Mobile Devices

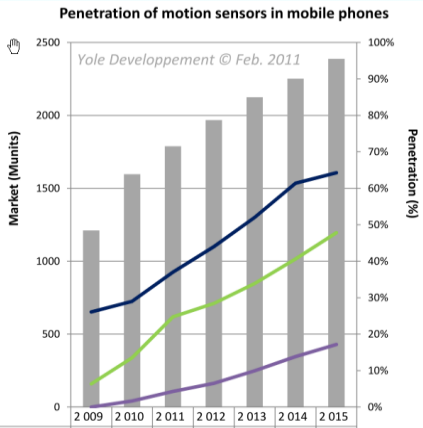


Yole 2011

Proliferation of MEMS/Sensors in Cell Phones

2000	2005	2010	2015
Temperature	Temperature	Temperature	Temperature
Simple RF filters	Simple RF filters	Simple RF filters	Advanced RF MEMS
	Camera	Rear facing camera	Rear facing camera
	Microphone	Front facing camera	Front facing camera
		Microphone	Microphone array (2-5)
		Ambient light sensor	Ambient light sensor
		Proximity sensor	Proximity sensor
		Acceleration (iPhone)	Acceleration
		Gyro (iPhone4)	Gyro
		Compass (iPhone4)	Compass
		Touch screen	Touch screen
		GPS	GPS
			Altimeter
			Humidity
			CO
			Projector
			Health sensors and actuators

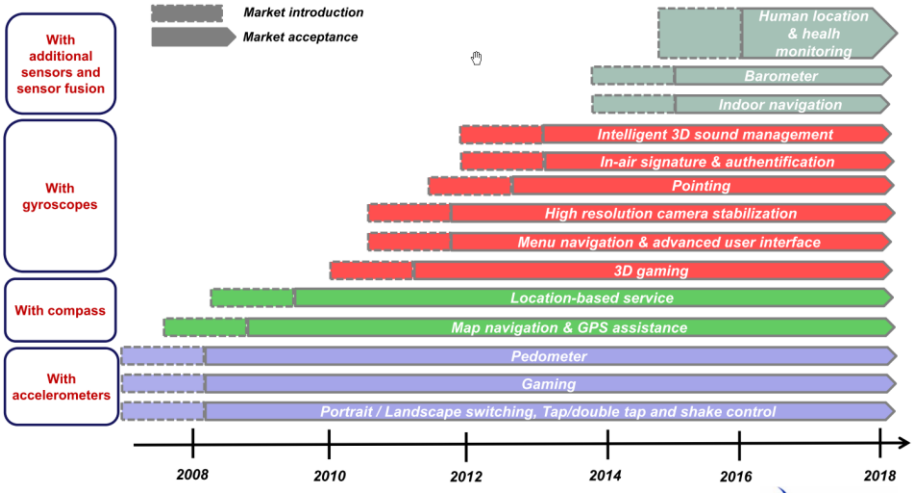
Cell Phones Driving the Growth



	2 009	2 010	2 011	2 012	2 013	2 014	2 015
Total cellphone market TAM (Munits)	1211	1597	1788	1967	2125	2252	2387
Compass penetration on mobile phones (%)	6%	13%	25%	28%	34%	41%	48%
Accelerometer penetration on mobile phones (%)	26%	29%	37%	44%	52%	61%	64%
Gyroscope penetration on mobile phones (%)	0%	2%	4%	7%	10%	14%	17%

Yole 2011

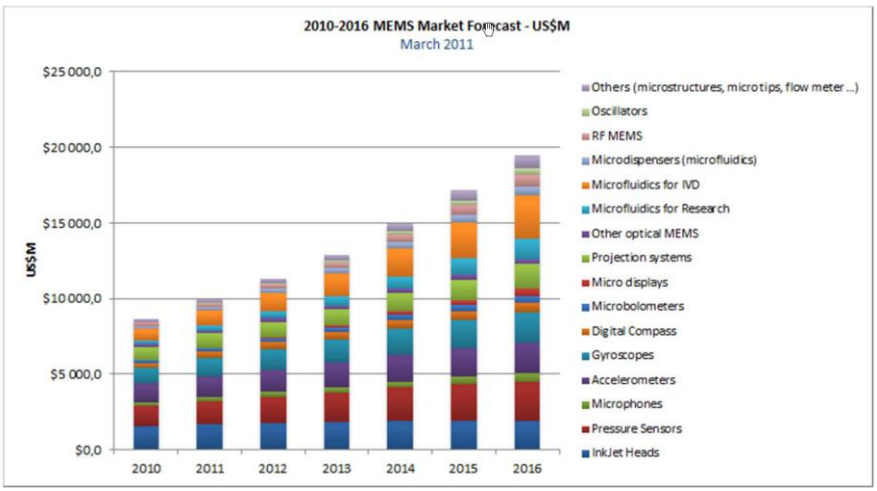
Sensor Based Apps



Yole 2011

MEMS Market ($)

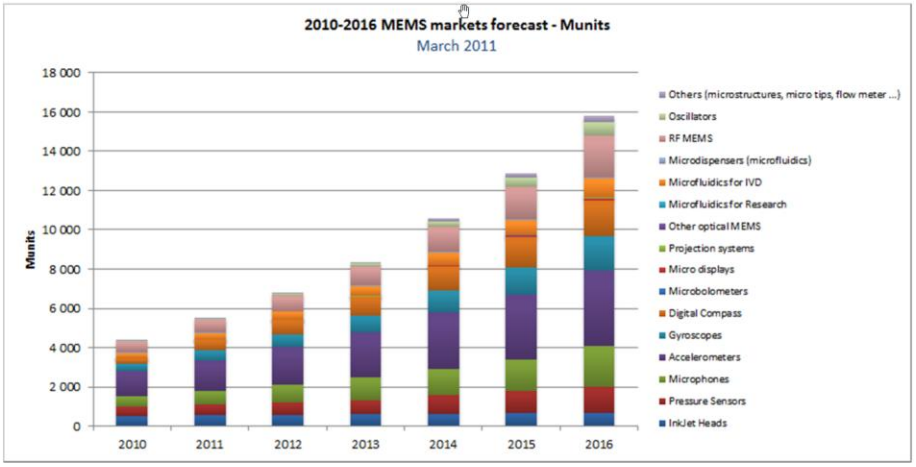
MEMS will be a $19.5B market in 2016 ($8,6B in 2010) **with a 14% CAGR over 2010-2016**



Yole 2011

MEMS Market (Units)

- **15.8 Bunits of MEMS devices in 2016 with a 24% CAGR over 2010-2016**



Yole 2011

Sample 2012 Sensor Based Products

Basis Band. A watch combining a heart monitor with temperature sensors and an accelerometer, sending information to a computer.

Metria Sensor Patch. A seven-day wearable patch tracks up to 5,000 data points per minute, such as calories, sleep patterns and steps taken, sending them to a cell phone.

Valencell's V-LINK uses the ear to capture heart and respiration rate, energy expenditure, metabolic rate, recovery time and VO2 Max (a measure of cardiovascular fitness).

http://gigaom.com/mobile/ces-trend-digital-health-gadgets-galore/

Babolat "Play & Connect" racquet with integrated sensors register the flow of player data and enable to analyze them afterwards on a computer.

http://www2.babolat.com/#/tennis/us/whatshot/684

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Pointers to Accelerated MEMS Growth to a $Trillion

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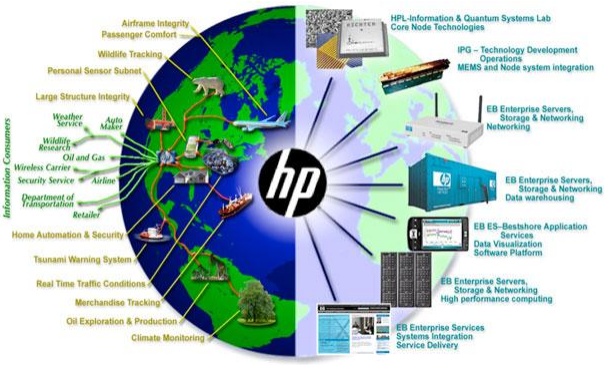
Can MEMS Market Growth Accelerate

- While MEMS market finally reached a respectable $10B, there are visible signs that market could grow faster.
- All the pointers imply that the acceleration should happen primarily due to a massive adoption of sensors, especially enabling the wireless and Internet connectivity.

Central Nervous System for the Earth

- Starting in 2010, in multiple presentations, Hewlett-Packard outlined a vision for CeNSE, a Central Nervous System for the Earth.
- CeNSE is expected to deploy a trillion nano sensors and actuators.
- 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…



http://www.hpl.hp.com/news/2009/oct-dec/cense.html

CeNSE

- HP pointed to several markets for CeNSE:
  - 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 sensor information would require increasing the size of Internet 1000 times, creating along the way by 2013:
  - $70B global market for sensing systems,
  - $290B market for value added sensing services.
- First deployments:
  - 1M wireless sensors over 10 km^2 for Shell's oil exploration project.
  - 1000s of wireless sensors on large bridges.

Sensory Swarms

- Bosch presented a vision for 7 trillion devices consisting of Sensory Swarms connected to the Internet to serve 7 billion people by 2017.
  - In 2010 there were already 5 billion mobile phone subscribers.
- All devices would be a part of mobile internet servicing:
  - “Internet of People” (social people networking).
  - “Internet of Things” (“social” machine networking).
- This vision translates to 1000 sensors per average person.
  - Current applications supported by large number of sensors:
    - Advanced cars have close to 100 sensors.
    - Smart homes use 10s and 100s of sensors.
    - Smart phones use 6 sensors.
    - Medical diagnostics uses 10s of different sensors, which will be migrating to personal use.
  - It is thus not too big of a stretch to foresee the growth outlined by Bosch.
- With a 7 trillion nodes, the market will be large, even at $1 sensor node …

Sampler

- ARM Flycatcher, "world's most energy-efficient microprocessor".
  - Targets the "***internet of things***: using microcontrollers to provide machine-to-machine communication, management and maintenance across a range of wirelessly connected devices is a concept known as the.
  - Core is measures 1mm by 1mm, ASP $0.20.

- Nike FuelBand:
  - High-end pedometer using an accelerometer to count steps and color to provide instant feedback and software to track progress on a smartphone.

- X2Impact
  - Building MEMS accelerometer and gyroscope sensors into sports mouthguards.
  - Use in football and in non-helmeted sports to detect sports brain injuries, such as concussions.

http://www.bbc.co.uk/news/technology-17345934

Smart Business

- Harbor Research introduced a concept of Smart Systems in the era of Pervasive Internet.
  - 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
  - Industrial systems
- Smart business will enable collective awareness, creativity and better decision making capabilities, driving the

  largest growth opportunity in the history of business.

http://www.harborresearch.com/Home.htm

Third Industrial Revolution

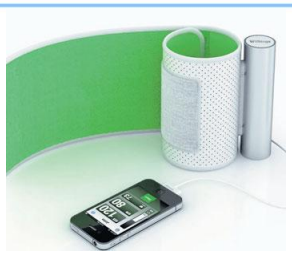
- Looking back, all major technologies coming to market were changing world's productivity and balance of power.
- In 2011, VP of Maxim referenced three major technology revolutions:
  - 1st revolution increased productivity by bringing steam, electricity, internal combustion, radio and aeronautics.
  - 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, will free humans for creative work and enable MEMS market to catch-up with semiconductor market.
- 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 *cooptition* (cooperating competitors).

Mobile Health

- 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 to reduce health care cost.
- Wearable (wireless) devices market (ABI Research) is forecasted to grow from 12M devices in 2010, to 420 million wearable health monitors in 2014.
  - 59 million to be used at home.
- By 2015, 30 percent of the world's smart phone users is expected to use mobile health product.
- By 2020 most smart phones are likely to be connected to a variety of health device.
  - Activity sensors, bio-sensors, chemical sensors, spectrometers, microfluidic diagnostics and drug delivery devices, ultrasound scanners, proteomic analysis, gene analyzers, etc.
- Trillion dollar market for 7 billion mobile users would require:
  - $143 of medical devices per average user.
    - Easy target?
      - Mosante ultrasound scanner was introduced in 2011 at $7495.

Medical Mobile Tornado Started

- In 2011, first mobile products have received FDA clearance:
  - Blood pressure monitoring cuff.
  - CT-scan viewer.
- The cost and approval time should shrink in 2012.
  - 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 is forecasted to use mobile health product.



Blood pressure monitoring cuff
http://www.deccanherald.com/content/230784/monitoring-your-health-mobile-devices.html

Ultrasound scanner for babies
http://www.yankodesign.com/2012/01/25/ibaby/

Sampler

Alcohol breathalyzer, a $79 accessory.

http://www.latimes.com/business/la-fi-idrunk19-2008dec19,0,3073178.story

Digestible sensors send wireless signal through the body to a receiver.

Records type of drug, the dose, and the place of manufacture.

Measures an heart rate, activity, and respiratory rate.

Source: Proteus

Low cost DNA chips containing up to 64 reactions of less than 1 µl volume. Assay time is 10-30 minutes, cost < $1,000, assay cost $5-$10 per chip.

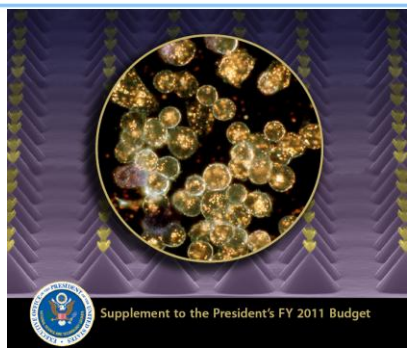
Nanodiagnostics: $50B Market by 2021

- Current size: $1.7B.
- Applications range:
  - From highly affordable point-of-care diagnostics with the potential to make mass screening and early detection of disease possible.
  - To highly targeted therapeutics with drugs being delivered and released only where needed.
- Promises to revolutionize medical diagnostics:
  - Earlier detection of disease
  - Higher sensitivity and higher accuracy
  - Higher throughput capability
  - More results per assay
  - Time saving and cost-effectiveness.
- Medical diagnostics technologies:
  - Quantum dots, gold nanoparticles, exosomes, nanoporous silica, nanowires, micro- and nanocantilever arrays, carbon nanotubes, ion channel switch nanobiosensors, and many more.
- Cientifica estimates medical imaging is the sector showing the highest growth.

http://www.cientifica.com/research/market-reports/nanotechnology-for-medical-diagnostics/

NanoCuring the Cancer

- Breast cancer cells with gold nanopyramids attached to the cell surface by antibodies on the nanopyramids (right).
  - NEMS integrated on MEMS
- As a result of targeting provided by antibodies, gold nanoparticles can be used as both, localized therapeutic agents and diagnostic probes.
- Nanoparticles can identify cancer cells and visualize location of biomarkers.
- Under IR, nanopyramids heat up and selectively destroy cancers cells.



Gold nanopyramids have 200 nm base and 1 nm tip.
Source: Odom/O'Halloran, Northwestern University.

Job Creation

- Forecasted dramatic MEMS market growth would result in massive creation of new jobs.
- These high tech jobs may follow the iPhone value added model:
  - 3% ($14) assembly (China)
  - 32% ($178) components (global)
  - 66% ($368) Apple's slice (US)
  - 100% ($560) selling price
- Most of these jobs is thus likely to be in developed nations.
  - This will overshadow potential of most other considered approaches by Governments.
  - Will force Governments of different countries to compete for these jobs.
- Assuming the average revenue per employee $500,000/year (2011 Nasdaq 100 companies).
  - $Trillion dollar new revenue would results in about :
    - 2 million new direct jobs.
    - Twice as many indirect jobs.
    - Total of about 6 million new jobs.
- As a reference, US created only 1.3M new jobs in the last 10 years, primarily in Government and medical sectors.

New Billionaires

- Emerging MEMS tornados will likely create multiple new industries, some not yet existent.
- In the book "Outliners", Malcom Gladwell derived common denominators for the most financially successful people:
  - Born at the right time and right place, enabling them to acquire right knowledge ahead of peers.
  - Be in a position to take the risk to ride a Tsunami wave created by the emerging technology fueling large industrial revolution.
- Next technology revolution fueled by micro/nano sensors and actuators has just started.
  - Should we expect the emergence of first MEMS $Billion companies and billionaires by 2022?

Acceleration of MEMS Market Development

Key Factors

- Two elements slow down MEMS commercialization:
  - Slow R&D cycles.
    - 3 to 12 months per iteration.
  - Lack of standard manufacturing processes.

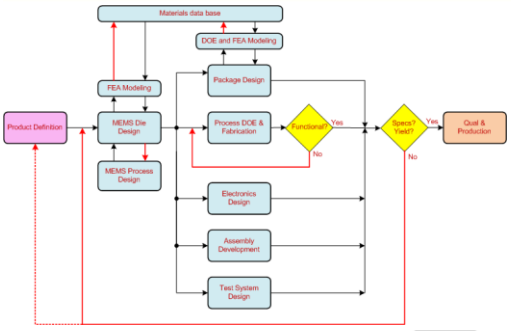
MEMS R&D Cycles

- MEMS device modeling tools enable most MEMS designs to be optimized with high accuracy in software domain.
- No tool reliably models the outcome of MEMS processing, forcing long DOEs.
- Examples of what is needed:
  - DRIE: enter the required profile of DRIE trenches across the die and let software spitout the tool settings.
  - Processing sequence: enter a process sequence and list of tools, and let software calculate the atomic level surface damages affecting, e.g., fusion bonding.
  - Stiction: enter process sequence and mask set, and let software to define stiction problems.
  - Vacuum: enter process sequence and used materials and let software to detect the vacuum in sealed cavity, including outgassing of materials and micro leaks.
  - Design rules: extract resign rules based on device geometry and sequence of unit processes.
  - Yield: predict yield based on device geometry and sequence of unit processes.
- Development of equivalent models for MEMS structures will require a significant effort.
  - Stable and predictable tools.
  - Cooperation between tool makers and software developers.

MEMS Fabrication

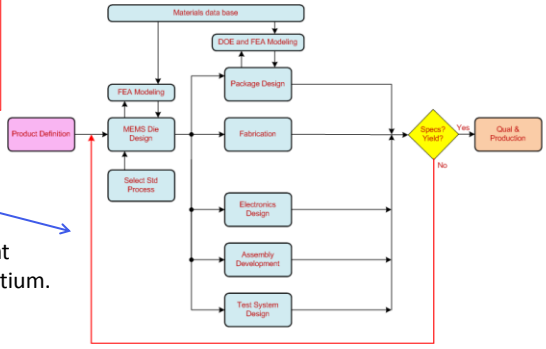
- Contrary to IC industry, MEMS still faces a “one product – one process – one package – one test system” reality.
- Several standard MEMS processes were developed and successfully validated on a large number of designs (e.g., Sandia’s Summit V, MCMC’s MUMPS).
  - Developed in disconnect with later emerging market Tornados.
- Several companies developed their internal MEMS process standards.
  - E.g., ST’s Thelma.
- Standard MEMS processes are thus feasible, if properly defined.
  - Possible only for one class of devices (e.g., group of mechanical sensors).
  - Need to enable customization, such as device thickness, trench width, etc.
    - Analogy: transistor design in a given process can deliver either low-noise low-power or high current.
  - Several MEMS foundries started development of standardized processes targeting currently the largest segment, inertial sensors.
- In parallel, the IC industry started to use MEMS unit processes for chip scale packaging and wafer stacking.
  - Promising wafer volumes significantly larger than the entire MEMS industry.
  - Drive pull for improved processing tools from IC tool vendors

MEMS Product Development



Current reality

If standard MEMS process is developed



Transitioning will require a significant funding, perhaps an industry consortium.

Manufacturing Capacity

- Assuming the following averages for emerging devices
  - MEMS die size at 4 mm^2.
  - 2 MEMS wafer stack.
  - ASIC die size 5 mm^2.
- 1 trillion devices would consume:
  - 307 million 8” MEMS wafers.
    - 70 million 12” wafers
  - 78 million 12” ASIC wafers.
- All of them would require packaging…

Historical MEMS Development Cycles

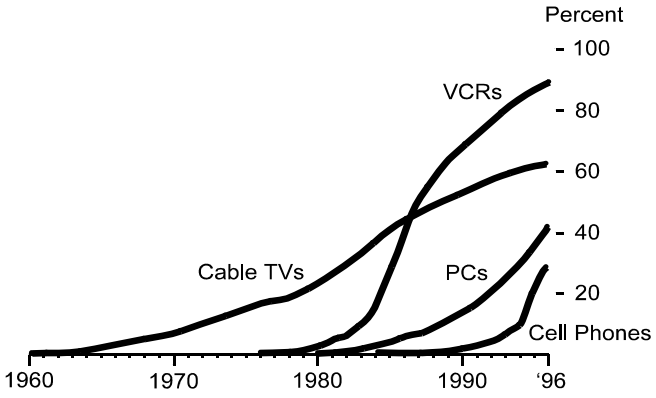
MEMS/MSTCOMMERCIALIZATION TIMETABLE

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

Roger Grace’s presentation at MEMS Technologies Summit, Oct 2010, Stanford University
http://www.rgrace.com/

Historical New Technologies Cycles



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

Path to a $Trillion?

- Acceleration of MEMS market growth in the next 10 years can rely only on devices already demonstrated over the last 10 years.
  - More or less the list of MEMS devices from Yole's market forecast.
- Enhancements of MEMS devices will like be formed by:
  - Ultra-low power wireless connectivity.
  - Ultra-low power Internet connectivity.
  - Ultra-low power embedded processing.
  - Multi-sensory systems on a chip or in a package.
  - Software.
  - Creative packaging.

Growth to a $Trillion

ACGR	14%/y	39%/y	43%/y	56%/y
2022 Market	$42B	$300B	$400B	$Trillion

- Without acceleration, in 10 years MEMS market is expected to grow to $42B.
- To match the current semiconductor size of $300B in 2022, MEMS market would have to grow 39%/y.
- To match the 2022 size of semiconductor market growing 3%/y, MEMS market would have to grow 43%/y.
- To reach 1 $Trillion in 2022, MEMS market would need to grow 56%/y.
  - It such growth feasible???

First Actions

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

(EE Times -- EDN, November 23, 2011)

$Trillion Roadmap

- The author started a first phase activity towards acceleration of MEMS market: development of a $Trillion MEMS Roadmap.
- The Roadmap is intended as a longer term (10 year) market study defining:
  - Likely product mix creating $Trillion market.
  - Likely market segments driving the growth.
  - Answering key questions: who will need/buy all these products and what problems will they solve.
  - Recommended activities (such as creating industry consortium and estimating need for Government/Industry funding).
- Mancef (http://mancef.org) so far secured a seed funding to launch Roadmap development.
- The first PR events are being planned as follows:
  - MEPTEC will present the status of the Roadmap at their May 2012 MEMS conference in San Jose.
  - Mancef will include the Roadmap presentation at COMS 2012 in June 2012 in Norway.

Benefits to Roadmap Participants

- Advanced information about growth opportunities.
- For product manufacturers: early alignment of production technologies with specific users' interest.
- For end users, applications development in parallel with enabling technology development.
  - Instead of traditional serial development.
- For foundries and infrastructure vendors: early visibility of capacity supporting the growth.
- Equipment and materials suppliers: early access to the Roadmap for development of robust equipment, materials, infrastructure and software tools.
- For policymakers, assist in focusing the resources enabling jobs creation.
- For financing organizations such as Venture Capital firms, Angels, and M&A community: a reference landscape.

Conclusions

- Low cost wireless and Internet infrastructure are expected to be fundamental technologies accelerating growth of MEMS market to a trillion.
- The byproduct of these new MEMS Tornados will be more fun for most of us, better healthcare and better quality of life.
  - How different from first MEMS applications in 1960s aiming at better way to kill, driven by cold war…
- Growth will create multiple opportunities for many of us!