

# Technology Roadmap for Microelectromechanical Systems (MEMS)

## 1. Introduction

Micro Electro-Mechanical Systems, more commonly known by their abbreviation 'MEMS,' are micron-sized devices typically fabricated by silicon foundry-like process. However, MEMS are known by different names: MEMS in the United States; Microsystems Technologies (MST) in Europe, and Micromachines in Japan. Nevertheless, MEMS is not a single technology but a generic name for a diverse family of 'enabling' microtechnologies. Importantly, MEMS is right on track as a disruptive technology.

By and large, MEMS have moving parts that enable them to sense or manipulate the physical environment. These chip-level devices are created using micromachining processing steps derived from basic silicon manufacturing techniques developed by the microelectronics industry. In reality, MEMS have been around for many years now. Just like many other processes, most micromachining employed in MEMS fabrication is a direct offshoot from the IC industry.

MEMS is the integration of mechanical elements, sensors, actuators and electronics on a common silicon substrate through micro fabrication technology. These systems can sense, control and activate mechanical processes on the micro scale, and function individually or in arrays to generate effects on the macro scale. The micro fabrication technology enables fabrication of large arrays of devices which individually perform simple tasks but in combination can accomplish complicated functions. MEMS are not about any one application or device nor are they defined by a single fabrication process or limited to a few materials. They are a fabrication approach that conveys the advantages of miniaturization, multiple components and microelectronics to the design and construction of integrated electromechanical systems. This technology has expanded the conventional two-dimensional design of chips; it is now possible to build three-dimensional structures into numerous substrates such as silicon wafer. Thus, enabling the entire system to be embedded onto a single chip.

## 2. Applications of MEMS

Initially MEMS are most popular in the automotive industry. However, MEMS technology capabilities are not confined to the automotive industry solely but many other applications namely in industrial, military, biotechnology, and consumer markets. Today, high volume MEMS can be found in a diverse applications across multiple markets. Table 1 is a summary of applications of MEMS according to its specific market.

MARKET	APPLICATIONS
Automotive	<ul style="list-style-type: none"><li>▪ Airbag Systems</li><li>▪ Vehicle Security Systems</li><li>▪ Inertial Brake Lights</li><li>▪ Headlight Leveling</li><li>▪ Rollover Detection</li><li>▪ Automatic Door Locks</li><li>▪ Active Suspension</li></ul>
Biotechnology	<ul style="list-style-type: none"><li>▪ Diagnostics</li><li>▪ Drug Delivery</li><li>▪ Drug Discovery</li><li>▪ Implantable Devices</li></ul>
Consumer	<ul style="list-style-type: none"><li>▪ Appliances</li><li>▪ Sports Training Devices</li><li>▪ Computer Peripherals</li><li>▪ Car and Personal Navigation Devices</li></ul>
Industrial	<ul style="list-style-type: none"><li>▪ Earthquake Detection and Gas Shutoff</li><li>▪ Machine Health</li><li>▪ Shock and Tilt Sensing</li></ul>
Military	<ul style="list-style-type: none"><li>▪ Weaponry</li><li>▪ Equipment for Soldiers</li><li>▪ Embedded Sensors</li></ul>
Communication	<ul style="list-style-type: none"><li>▪ Fibre-optic network components</li><li>▪ RF Relays, Swiches and Filters</li><li>▪ Tuneable Lasers</li></ul>

Table 1: Applications of MEMS (Source: NEXUS)

As an emerging technology, MEMS products are centered around technology-product paradigms rather than product-market paradigms. Consequently, a MEMS device may find numerous applications across a diversity of industries. The commercialization of selected MEMS devices is illustrated in Table 2

Product	Discovery	Evolution	Cost Reduction / Application Expansion	Full Commercialization
Pressure Sensors	1954-1960	1960-1975	1975-1990	1990-present
Accelerometers	1974-1985	1985-1990	1990-1998	1998
Gas Sensors	1986-1994	1994-1998	1998-2005	2005
Valves	1980-1988	1988-1996	1996-2002	2002
Nozzles	1972-1984	1984-1990	1990-1998	1998
Photonics/ Displays	1980-1986	1986-1998	1998-2004	2004
Bio/Chemical Sensors	1980-1994	1994-1999	1999-2004	2004
RF Switches	1994-1998	1998-2001	2001-2005	2005

Table 2: Commercialization of Selected MEMS Devices

### 3. Adapting MEMS Into Local Microelectronics Industry

From an economy dominated by agriculture, trade and shipping Malaysia started its electronic manufacturing industries in 1970 with eight multinational companies in Penang. Due to the cheap labor and favorable tax infrastructure, most of the multinational companies took Malaysia as a place to outsource costly and low-end manual tasks. To remain competitive and keep the industries survive Malaysia need to concentrate on upstream activities such as creating IC design clusters and upgrading fabrication facilities. Now, one of Malaysia's goals is to change its position by start being a destination for activities higher up the chain, such as design and other services. To achieve this, the country is trying to replicate the success of places such as Silicon Valley and Taiwan, which created synergies by supporting growth toward an integrated cluster of companies, each contributing along the value chain.

Malaysia has been an IC packaging stronghold since the 1970s, when Silicon Valley-based chipmakers, such as AMD, Intel and National Semiconductor, set up backend

factories in Penang to take advantage of Southeast Asia's lower labor costs. This time the idea is to turn Malaysia into a chip-manufacturing base. Now it wants to take its place alongside such Asian chip powerhouses as Taiwan and Singapore. Taiwan, where, in 2002, the IC industry alone produced \$18.9 billion in revenue and had approximately 73% of the worldwide market, not to mention the hundreds of design houses and other companies that feed into the foundries. Taiwan Semiconductor Manufacturing Co. Ltd. (TSMC) and United Microelectronics Corp. (UMC), both of Taiwan together account for almost 70% of the global foundry market. The Malaysian government would like to replicate this synergy, which also includes masking firms, fabrication and packaging plants, testing firms and distribution facilities.

One emerging technology that is being considered is MEMS. Malaysia, at present, does not have a presence in the MEMS value chain. However, it does possess some of the related and supporting industries as well as the necessary semiconductor experience to take advantage of the emerging MEMS technology over a period of time.

### **Local Industrial Players & Activities**

The development of MEMS research and development in Malaysia started in 1998 with an initiative by Institute of Microengineering and Nanoelectronics (IMEN) to develop a silicon accelerometer. Then, IMEN was the only research organization equipped with facilities to embark into MEMS research and development. Subsequently, the research and development interests in micromachining, micro-sensors and later MEMS begun to grow in the country. Today, MEMS research in Malaysia are being conducted mainly by all Higher Learning Institutions and Government Research Institutes with application topics ranging from automotive, telecommunications, optical and biomedical. Table 6 lists the major Malaysian companies and Institutes of Higher Learning as well as the research institutes along with their core competencies in MEMS. Currently, AKN Berhad and Polar Twin Technology Sdn. Berhad are the only Malaysian companies investing in MEMS locally.

#### 4. Major Issues and Challenges by Domain

##### Automotive

Despite the considerable opportunity that the automotive sector offers for many different uses of MEMS technology, In-Stat/MDR reports that only a few devices have, to date, been integrated in high volume in a small number of applications. The slow rate of integration of the technology into cars to begin with, and the amount of time it takes for the trickle down effect to take place, has meant that the potential for MEMS in this sector has barely been tapped. However, the high-tech market research firm reports that a number of current niche-level applications are now reaching a higher volume threshold and, as a result, the number of MEMS per car will nearly double to an estimated 9.1 per vehicle in 2007, up from an average of 5.0 per vehicle in 2002.

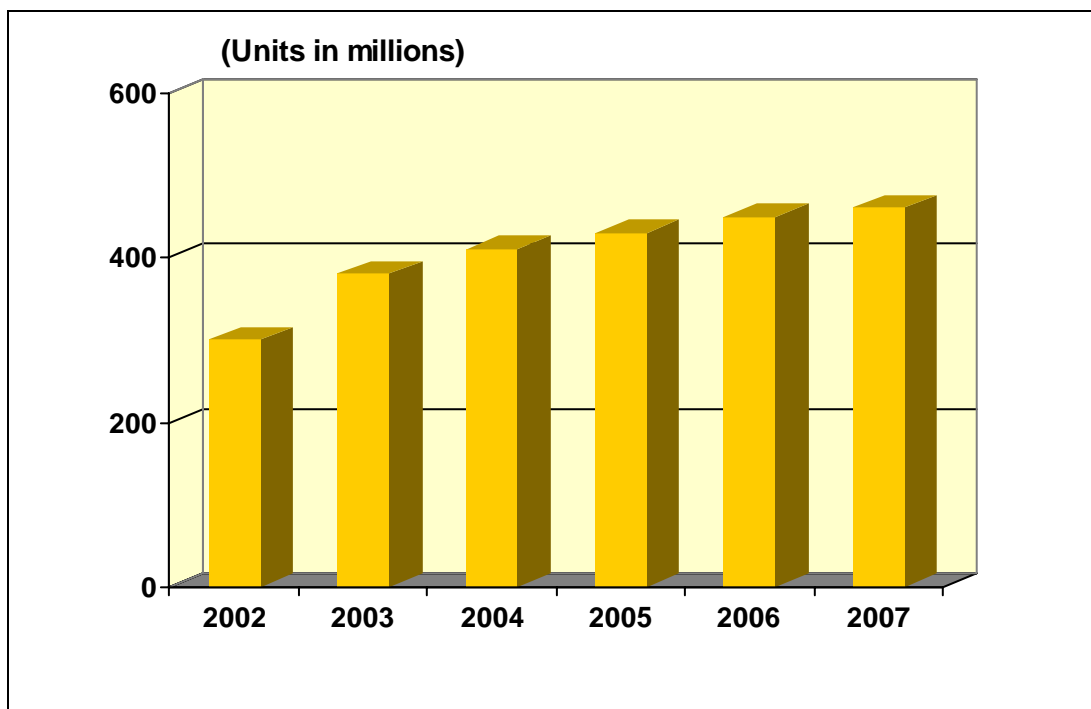


Figure 3: MEMS Unit Shipment in the Automotive Industry (Source: In-Stat/MDR 1/03)

“The next wave of MEMS devices that will have a major impact on this sector are now making their way into cars. Even better is that it appears the impetus behind the integration of MEMS technology into cars is evolving as well – from technology push to market pull,” says Marlene Bourne, a Senior Analyst with In-Stat/MDR. “As a result, it appears that new applications may reach high volumes at a faster rate than their

predecessors, and are helping to drive worldwide revenues for MEMS in the automotive sector from just under \$1 billion in 2002 to nearly \$1.5 billion in 2007.”

The areas in which MEMS will play a key role over the next five years include: electronic stability control and rollover systems, occupant detection, and tire pressure monitoring systems (TPMS). The demand for TPMS is certainly being helped by current US legislative mandates. Regulatory efforts under consideration may also have a similar effect for electronic stability and occupant detection systems.

Two applications of note that are looming on the market’s horizon are biometric sensors for comfort programs and keyless entry, and optical MEMS for heads-up and entertainment displays. Beyond that, it won’t be long before RF MEMS find their way into cars, as the convergence of GPS, satellite radio, and other telematics programs will be a strong driver.

## **Biotechnology**

### **i. Infrastructure**

Unlike what one finds in the IT industry especially during the dot com boom, most biotechnology related innovations are not made in a two man and a garage set-up. The cost of developing even a simple biotech product can run into the millions of dollars. The reason for the high cost of biotechnology innovation is due to the need for using specialised equipment, need for high quality laboratories, use of tools such as nuclear magnetic resonance (NMR), x-ray crystallography and other tools for biochemical characterization.

One way to reduce the capital expenditure required for start-ups in biotechnology is via clustering of biotechnology companies in a geographical location (if they are within walking distance of one another all the better) and the installation of shared facilities for some of the more expensive work such as structural elucidation, scale-up facilities (for producing certain biochemical compounds in bulk) and other analytical services.

Many countries all over the developed world have focused on developing biotechnology clusters to support start-ups and small and medium scale enterprises (SME). Table 5 shows the location of selected biotechnology clusters worldwide. These clusters have been successful due to a combination of factors such as the presence of universities to provide a strong scientific base, the existence of an entrepreneurially minded community, and the availability of funding (angel funding, venture capital and government grants).

## **ii. Human Resource**

In order for Biotechnology start-up companies to be successful they require an eclectic mixture of personnel to run the company. A strong scientific team is absolutely crucial as is the presence of an experienced business team to lead the company. In many cases the scientific team may not have the necessary experience and breath of view and this shortcoming can be ameliorated through the setting-up of a scientific advisory board (SAB).

Due to the interdisciplinary nature of biotechnology, scientific personal from a wide variety of backgrounds are required and they should not be limited to only biologists, biochemists and microbiologist. Many scientific teams have physicists, chemists, engineers and material scientists working hand-in-hand.

## **iii. Financing**

The availability of funding is crucial in creating an environment that is supportive of the establishment of biotechnology start-ups and SME. As noted in the previous section biotechnology clusters are built around areas in which funding is easily available to support technologically and economically viable projects. The types of funding available can be categorized according to their source

Funding for biotechnology start-ups typically involves a number of funding rounds, which can be anywhere between 3-5. The initial funding, known as seed funding is provided by universities, certain institutions, government grants and business angels.

The subsequent round of funding is usually obtained from venture capital. Further rounds of funding can be from any of the funding sources given in the preceding list. The funding rounds finally culminate in an IPO. A successful IPO provides a convenient exit strategy for many of the financial backers, particular the venture capitalists.

## **Telecommunication**

### **i. Competing Technologies**

Technically, RF MEMS have promised to be advantageous over rival technologies due to its zero static power consumption, zero non-linear intermodulation at higher signal levels, low insertion loss, high isolation, commendable switching speed, small dimension and possibility to integrate with IC. For example MEMS switches are known to outperform Field Effect Transistor (FET) and Positive-Intrinsic-Negative (PIN) Diodes in several departments such as insertion loss, isolation and driving power while maintaining significantly smaller dimension. Electrostatic MEMS switches are preferred for low power consumption. This characteristic together with high linearity and potential integration form the main advantages of MEMS. However the actual feature that attracts companies is integration. MEMS devices are more expensive than its rivals based on part-to-part comparison. However a single MEMS component can replace up to 6 components of rival technologies and coupled with its small size allows creation of small RF devices for greater functionalities and integration. The lower component count also means higher overall system reliability while reducing cross talks. Not to be underestimated is MEMS manufacturing compatibility with IC processes, making leveraging a definite advantage for countries such as Malaysia.

Despite having special features which are hard to beat MEMS are facing stiff competition from existing technologies like PIN Diodes and Gallium Arsenide (GaAs) FET and newcomer Silicon Germanium (SiGe) mainly on price per device. The table below gives a comparison in terms of price-performance for all the technologies.

## ii. Commercialization

Few things are important for MEMS devices to address the consumer markets:

Standard package (especially CSP/WLP)

Package size : 1.2mmx5mmx5mm max (to be included in mobile phone)

Small silicon die (less than 2mmx2mm) in a 6 wafer (ie between 3500 to 5700 dies per wafer 6)

Price between \$1.5 to \$2 max (less than\$ 0.4 for Si microphone)

Digital output

Fortunately, compared to the automotive industry, the MEMS manufacturers have the ability to decrease the specifications of the devices (in term of reliability, life time and specifications) in order to reach the price target.

The price target for MEMS devices for mobile phone is clearly an issue:

For microphone, the price of the ECM microphone is \$0.3

For 3D acceleration sensor, the price target is less than \$2

For RF MEMS, the challenge is to be included in SiP/SOC approach, with adapted price

Another issue which is a big bottleneck to MEMS commercialization is packaging. Cost for MEMS packaging is between 50% to 80% of total MEMS product which contributes to delayed introduction of new products and added cost for start ups. MEMS devices require protected and clean environment. Existing hermetic ceramic packaging is typically used for RF MEMS but the cost is greater than plastic molding used to house PIN diodes and GaAs FETs by up to five times. Better approaches exist for RF MEMS such as die level sealing or overmolding and chip scale packaging (CSP). Overmolding can reduce cost by using readily available plastic packages.

Packaging also poses a real technical hurdle to MOEMS devices like Vertical Cavity Surface Emitting Laser (VCSEL) and switch, decreasing yield and reliability and increases cost. Hence, packaging for MOEMS is typically outsourced to third-parties.

## 5. Methodology

This roadmap is developed through a technology road mapping process. It is a market driven process that brings together key stakeholders (researchers, government, end-users and industry) to identify critical technologies for MEMS. It aims towards identifying existing challenges and strengths, prioritising and selecting key technology areas and formulating linkages within the MEMS multi-stakeholders. This section explains the methodology or process to develop this MEMS technology roadmap.

### i. Roadmap Planning and Implementation Process

The roadmapping deliverables are the key technology areas and its prioritisation for the purpose of the protection of the critical infrastructures. This activity of an overall roadmap development process is shown in the following Figure 1.

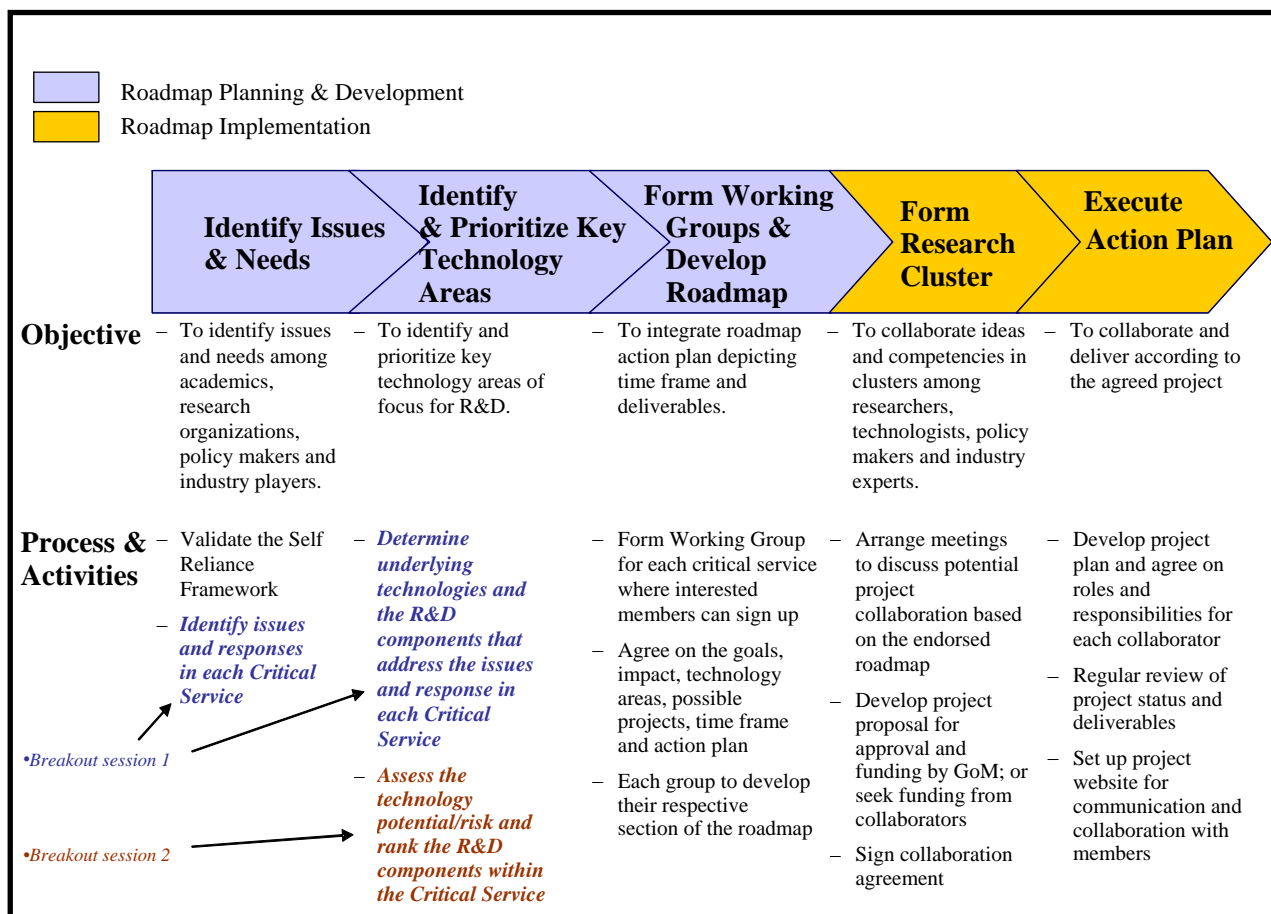


Figure 1 : Overall Roadmap Development Process

The process is divided into 5 stages.

Two workshops have been conducted to formulate and develop the main roadmap deliverables.

i. Issues and Needs Identification

The first stage is the identification of the Issues and Needs related to the MEMS technology. The framework was discussed amongst the consortium members and clarifications were made and subsequently the framework was adopted.

ii. Identify and Prioritize Key Technology Areas

The second stage of the process identified the key technology and R&D areas and rank them based on criticality and need. The key activity in this stage is to identify the technology and R&D areas apart from the itemization of issues and responses to each critical service. Then assessment is made on the technology potential and R&D risk if a particular technology or R&D area is not developed locally. It is also required to develop a realistic timeline and cost range for the technology and R&D areas. Workgroups are formed to develop the roadmap in the following stage.

iii. Form Working Groups and Develop Roadmap

The third stage uses the output from the second stage to develop the roadmap for the technology and R&D areas. The main objective is to integrate the action plan depicting the timeframe and deliverables. This is to be done through the formation of workgroups, one for each critical service, from the consortium members as well as including other interested parties who can contribute to the effort.

The workgroups will bring the development of the roadmap to the final level of detail to include clear goals, impact of the technology, identified projects and the timeframe for development and the action or execution plan i.e. how the technologies will be realized in a manner that will lead to a logical set of products or deliverables that will incrementally be used by the critical infrastructure providers as well as to build the self-reliance goals for such technologies. Preliminary project funding disbursement may also be identified to harmonize and coordinate the research spending.

Various modes of product realization will be explored. In some cases a proof of concept is required before further work can be carried out. In some other areas a pilot implementation is necessary. Technologies that can serve as a base and crosses several critical services e.g. the artificial intelligence engines will be identified and blended into the overall technology roadmap as intermediate deliveries.

The above are just some of the foreseen considerations in the development of the roadmap but the final shape and form and detail of the roadmap that will meet the needs of the critical services will be guided and moderated by MIMOS after the workshop.

iv. Form Research Cluster

Research Clusters will be formed in the fourth stage of the process. This will involve organizations and institutions in both the private and public sectors who have the potential to contribute or whose potential to contribute can be developed with the

appropriate support and funding from the government or other sources. Collaboration of ideas and competencies are expected to take place to optimize research cluster focus.

The clusters will be formed through a variety of mechanisms. Where possible collaboration with other established outfits in particular technology areas whether locally and especially overseas will help jumpstart some of the technology initiatives while meeting self-reliance objectives.

The detailed funding strategy and details on disbursement schedule will be developed. Project proposals will be developed and approval sought for funding and moving to the next stage of product realization. Funding can come from the Government or from collaborators of technology and other interested parties that will fit into the national self-reliance agenda.

v. Execute Action Plan

The plan developed from the previous stage will be executed in this final stage with the research clusters obtaining the appropriate funding and work towards product realisation.

A detailed project plan with clear indication of roles and responsibilities of the various parties will be finalised. Project control and progress monitoring mechanisms will be instituted. The project plan will work towards actual product realisation for the use of the critical infrastructures.

**ii. The High Level Roadmap**

The roadmap provides a long-term strategy for attaining a self-reliant state for the country. It maps out a logical prioritised sequence of cyber security R&D programmes to deliver what the short-term to future needs for the protection of critical infrastructure. It provides a consolidated view as depicted in Figure 2,3 and 4 of all the R&D programmes that possess high value for potential/risk for each of the critical service. Absence of any of these programmes will compromise Malaysia's e-sovereignty. The roadmap serves as a foundation for formulating the national R&D initiatives in collaboration with Government, RI's and industry



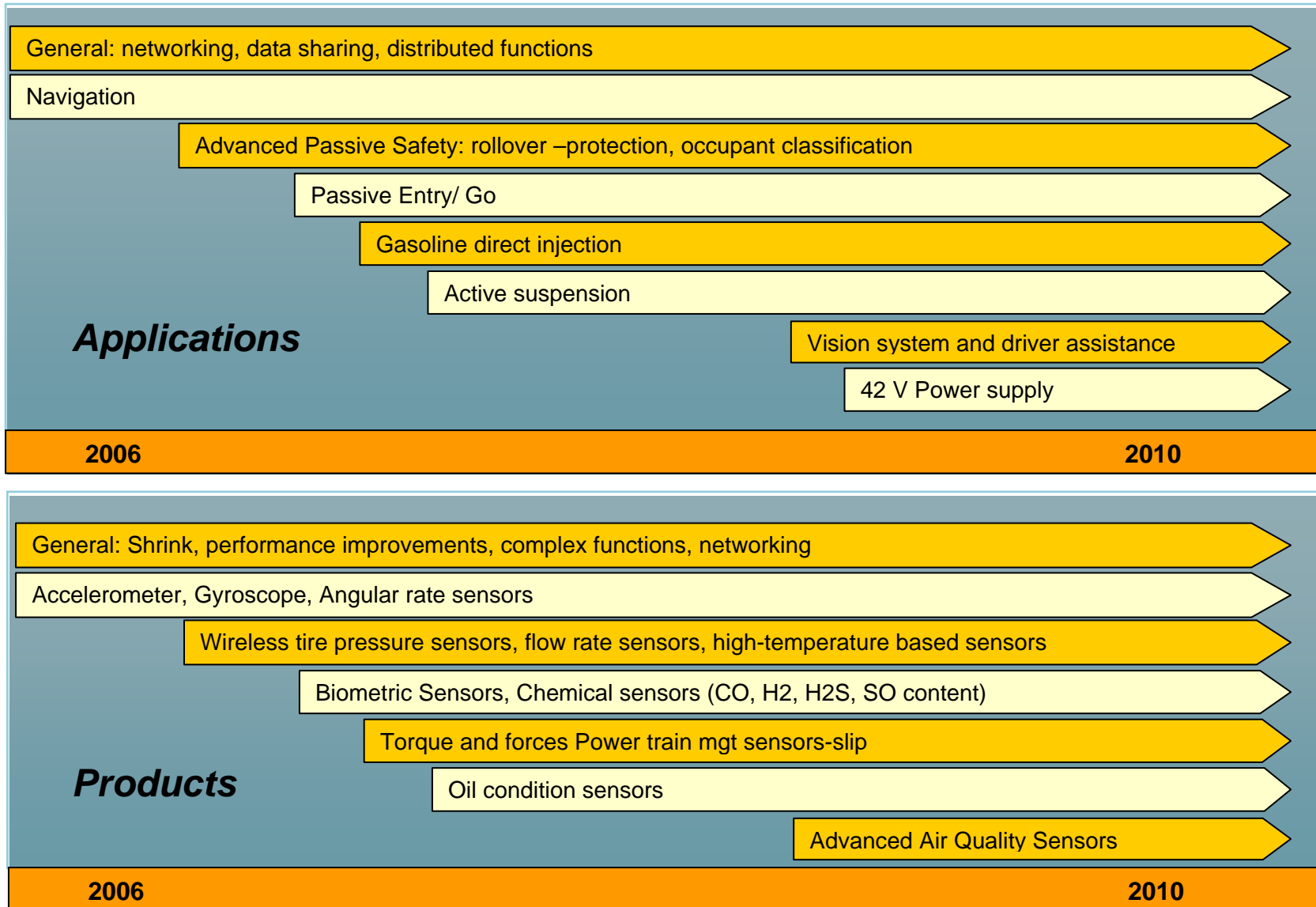


Figure 2: Roadmap for Automotive MEMS Applications

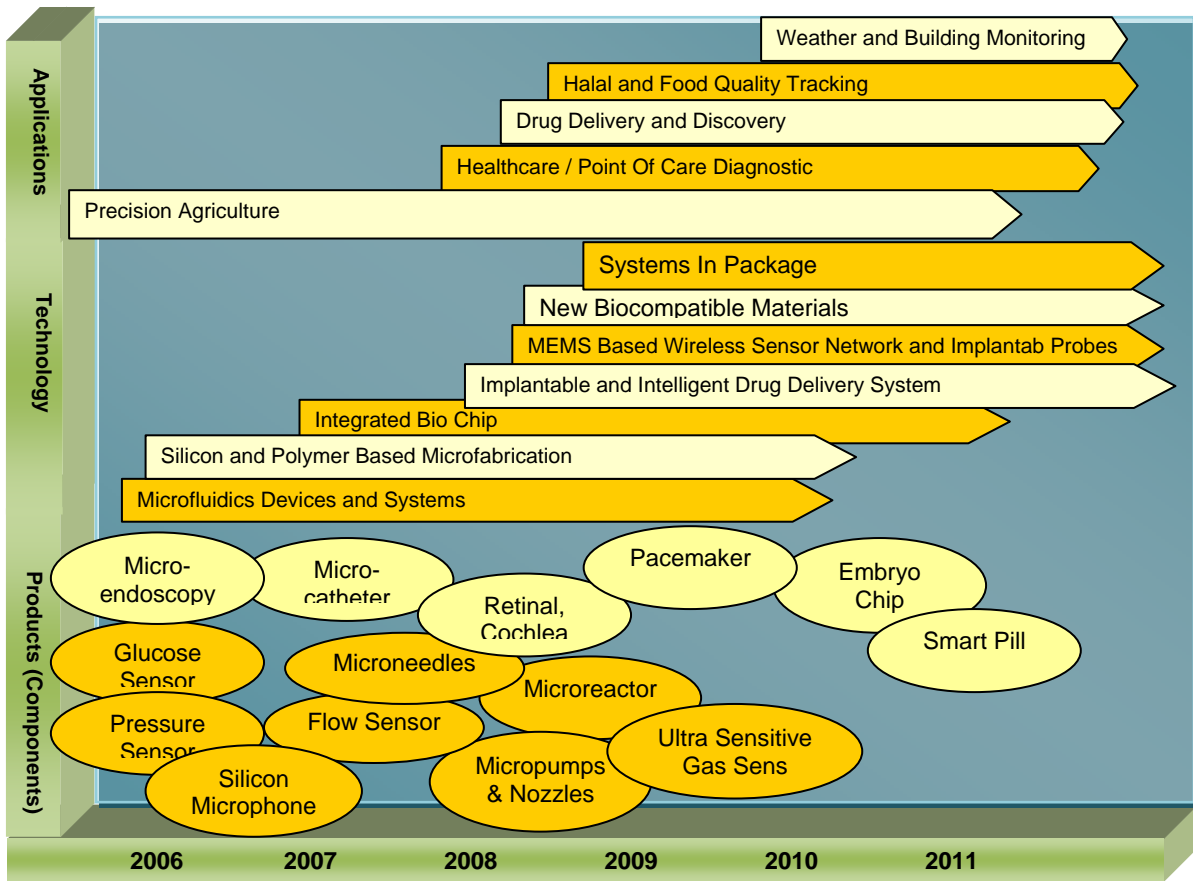


Figure 3: Roadmap for Biotechnology-based MEMS products

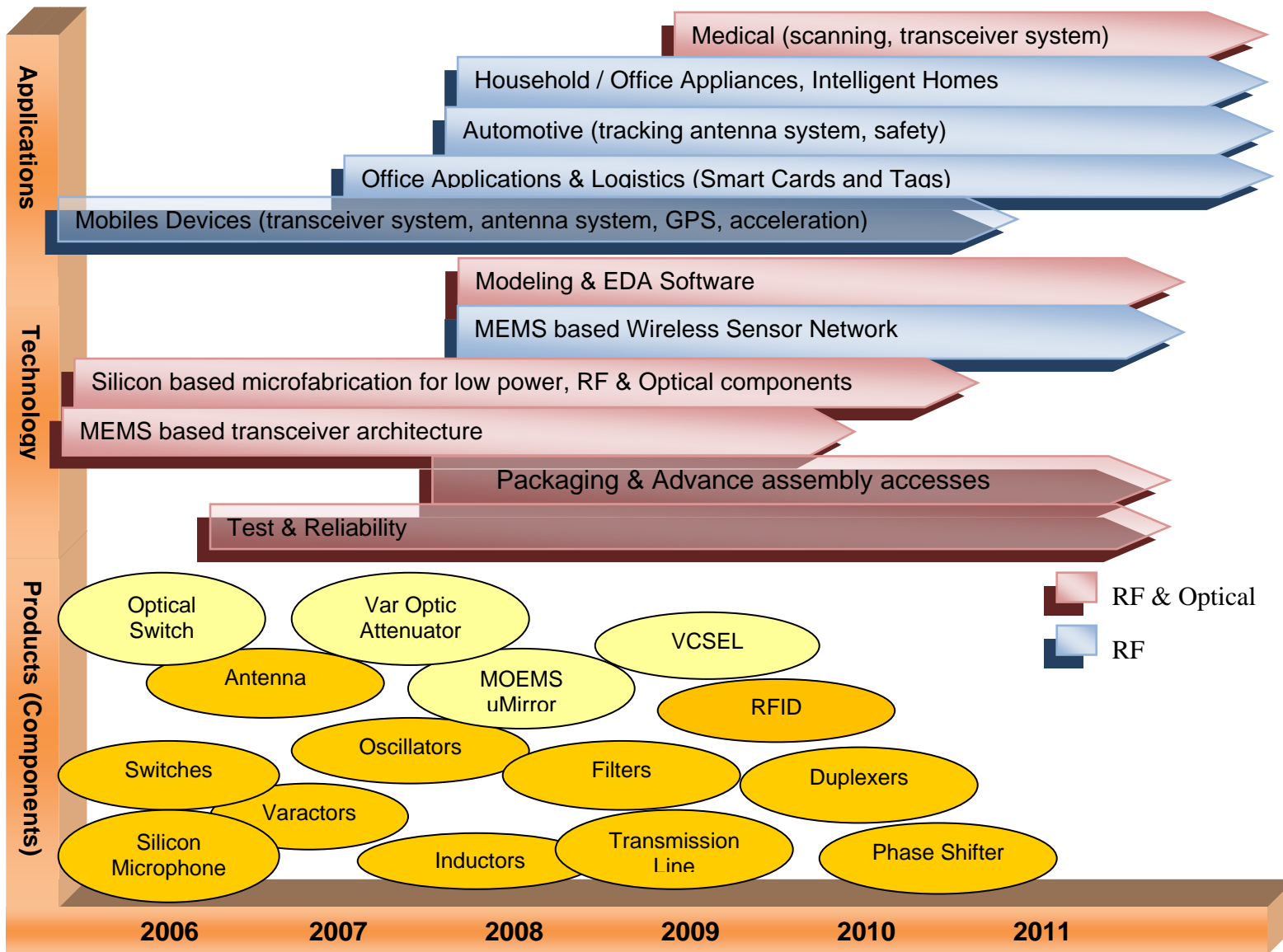


Figure 4: Roadmap for Telecommunications