

## D5.2: Public executive summary

ARRRO, proposal/contract N° 027752, 15/06/07



### Applied Research Roadmap for RF micro/nano systems Opportunities

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| Deliverable ID       | D5.2                     |
| Deliverable Title:   | Public executive summary |
| Responsible partner: | WTC                      |
| Authors:             | Jérémie Bouchaud (WTC)   |

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| Partner organisation                                     | Contact                                                | Web                                                                             |
|----------------------------------------------------------|--------------------------------------------------------|---------------------------------------------------------------------------------|
| WTC – Wicht<br>Technologie Consulting                    | Jérémie Bouchaud<br>(coordinator)<br>Bernardo Knoblich | <a href="http://www.wtc-consult.de">http://www.wtc-consult.de</a>               |
| Centre National de la<br>Recherche Scientifique          | Fabio Coccetti                                         | <a href="http://www.laas.fr/laas/">http://www.laas.fr/laas/</a>                 |
| Interuniversity<br>MicroElectronics Center               | Harrie Tilmans                                         | <a href="http://www.imec.be">http://www.imec.be</a>                             |
| BAE Systems, Systems<br>Engineering Innovation<br>Centre | Ayman El-Fatatry                                       | <a href="http://www.seic-loughborough.com">http://www.seic-loughborough.com</a> |

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# 1. Introduction

## 1.1. Context

RF MEMS based developments offer promising advancements and wealth creation opportunities for several areas where Europe has established industrial and technology leadership from mobile telephony, automotive, through to aeronautics and aerospace.

The European research organisations are well placed in global competition in the field of RF MEMS and AMICOM, the Network of Excellence (NoE), was created in 2004 to help coordinate such research efforts. However, European R&D could benefit from clear guidelines in order to address the research and technology development needs especially with regards to RF micro and nano systems for European companies over the next 10 to 15 years. The EU has been supporting research in RF MEMS since 1998. As yet, it is perceived difficult for funding bodies to evaluate the return on investment in this field. Also at the industrial level, some industries are beginning to harvest the first fruits of their investment. However, these same industries are still lacking a roadmap for their future products, such as the one developed by ITRS (International Technology Roadmap for Semiconductors), in order to help them define clear strategies in terms of development and time to market

## 1.2. Objectives of ARRRO

The objectives of ARRRO are twofold:

- To Assess the **current status** and develop a vision of the **future requirements for RF MEMS and RF NEMS** technology, products and applications. To enhance the integration of the European IST research in RF MEMS, through an assessment of the European RF MEMS and nanosystems research areas, in the context of global competition. The study culminated in producing recommendations for strengthening the position of Europe in RF MEMS research by developing the long term vision for research and exploitation of RF MEMS.

Following these objectives for the project, the three main deliverables of ARRRO were:

- An RF MEMS roadmap (D3.1)
- An analysis of the position of Europe in RF MEMS (D3).
- A set of recommendations to the European Commission to help direct funding and investment in RF MEMS research in future calls

This study was undertaken as a complementary activity to those underway as part of the AMICOM Network of Excellence programme. In addition, ARRRO progressed the major RF MEMS industry analysis carried out, to date, within the NEXUS User Supplier Club for Telecommunications as well as by the ARRRO leading partner, WTC.

The list of the collaborating contractors in ARRRO is provided in the following table:

| Partner organisation                         | Participant short name | Country        |
|----------------------------------------------|------------------------|----------------|
| WTC – Wicht Technologie Consulting           | WTC                    | Germany        |
| Centre National de la Recherche Scientifique | LAAS                   | France         |
| Interuniversity MicroElectronics Center      | IMEC                   | Belgium        |
| BAE Systems Advanced Technology Centre       | SEIC                   | United Kingdom |

### 1.3. Methodology

The information derived by the ARRRO consortium has been collated using both desk/office-based research and direct contact (interviews). The interviews have contributed to the most important source of information used to produce the roadmaps and the analysis of the position of Europe.

During the project, the ARRRO partners interviewed over 80 organisations in total:

- 50 phone-based interviews,
- 38 face-to-face interviews (14 company visits and 24 interviews at conferences)

The interviews have accessed representatives from across the world in order to provide an relative position for European activities within a global context:

- 26 organisations based in Asia
- 15 organisation based in North America
- over 40 organisations based in Europe

The interviews were evenly distributed between:

- Potential users of RF MEMS in mobile handsets, base station, automotive radar, satellite and aeronautics industry
- Industrial developers of RF MEMS components
- Industrial suppliers of alternative technologies
- Research organisations involved in RF MEMS developments

Several return visits and iterations were necessary to present and discuss intermediate results with some of the key European stakeholders from industry, research and public bodies, including:

- three teleconferences enabled by the UK MNT network (April, May and July 2006)
- an industrial workshop in parallel to the European Microwave Week 2006 (September 2006)
- a presentation at the AMICOM review meeting (March 2007)

## 2. The RF MEMS roadmap

This report provides an outline of the roadmap for RF MEMS and RF nanosystems covering the time period of 2005-2020. The roadmap addresses three specific domains:

- **The RF MEMS components roadmap** addressing RF MEMS switches, tunable capacitors, Bulk Acoustic Wave devices (BAW), Micro-mechanical resonators, and also emerging RF MEMS component technologies such as cavity resonators, tunable inductors and Carbon nanotubes (CNT) based RF nano-systems.
- **The application roadmap** addressing wireless telecommunications, automotive and road transportation, satellites and aeronautics<sup>1</sup>.
- **The implementation roadmap:** “how to make it happen?” addressing transversal technologies relating to the successful implementation of RF MEMS such as design and modelling, materials and processes, packaging and assembly, testing, characterisation and reliability.

This study was funded by the European Commission and aimed to support the EU in defining the future technology focus and funding priorities for RF MEMS and NEMS R&D. As a result, this study also provides recommendations to help strengthen the European Research Area in this field.

A generic product and application roadmap is shown in Fig. 2.1.

### 2.1. Component roadmap

There are three RF MEMS components which have benefited from a strong industrial R&D effort since 2000 and are expected to be implemented by 2010, namely:

- BAW duplexers and filters which are the most mature RF MEMS components and have been implemented in cell phones since 2002 by Avago Technologies and Infineon.
- RF MEMS switches which are being sampled by US start-ups since 2003 and are currently shipped in small quantities (1000 to 10,000 units per month). The first commercial application for such components was Automated Test Equipment championed since end 2005 by Advantest. Other applications will include base stations by around 2008/2009 and possibly cell phones by 2010.
- Micro-mechanical resonators currently being sampled by US start-ups where mass production is promised for August of 2007 when the 1<sup>st</sup> million unit milestone is to be achieved by SiTime. The first of the applications for such devices is likely to be in portable consumer products.

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<sup>1</sup> The scope of applications covered by this the roadmap corresponds to the objectives of the 6<sup>th</sup> framework programme of the European Commission. For this reason, test (RF test and Automated Test Equipment for semiconductors) and defence applications are not addressed in this study.

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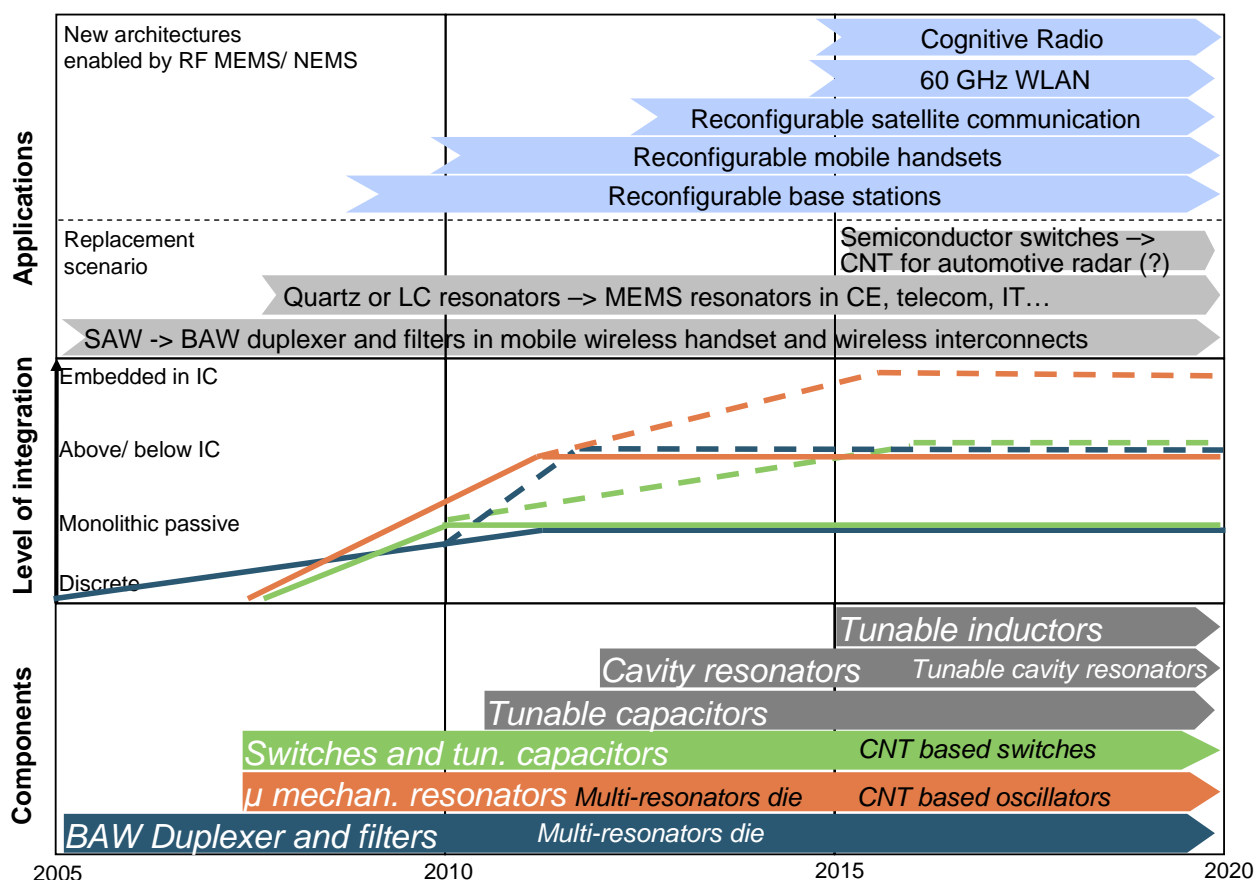


Fig. 2.1: Overall RF MEMS roadmap

Other RF MEMS and NEMS components are less in the focus of industrial R&D or are at an earlier stage of development. As a result, their implementation is expected to be after 2010 or even 2015.

- Although tunable capacitors are technically close to MEMS capacitive switches, little industrial R&D effort is currently spent on these components so that commercial products are not expected to be available before 2010 or 2012. It is foreseen that base stations will be the first application.
- Cavity resonators are technologically not as challenging as switches or micromechanical resonators. No commercial product is, however, expected before 2012 as no industrial company is, to our knowledge, working on this type of component and there is little academic R&D currently being undertaken with the exception of the EC project 3Dptune. Applications will be in 60 GHz WLAN, satellites and automotive radar.
- Tunable inductors are still at a very early stage of academic R&D. Commercial products are expected at the earliest from 2015, although the serial manufacture of these devices has still to be demonstrated. Tunable inductors are promising for base stations and even potential mobile wireless handsets.
- Carbon Nanotubes based RF NEMS such as switches and oscillators are currently at the basic R&D stage of development in projects such as the EU's Nano RF project. Commercial products are not expected before 2015. Potential applications are numerous such as mobile handsets and automotive radar.
- It should also be noted that the combination of RF MEMS components with novel meta-materials will potentially allow for wider tuning ranges. LC MEMS/NEMS (micro-machined L

and C) type filters based on meta-materials could be an enabler for breakthrough RF architectures such as cognitive radio.

## 2.2. Application roadmap

From this type of roadmap, it is possible to distinguish between two main implementation scenarios:

1. A replacement scenario
2. New architectures enabled by RF MEMS

The replacement scenario is possible when:

- The advantages provided by the RF MEMS are such that a price premium is acceptable. In this context, there is a unique case with BAW duplexers from 2 GHz which is 30% more expensive than SAW.
- RF MEMS are expected to cost significantly less than conventional components such as the case for reference oscillators with smallest form factors
- RF MEMS switches based on Carbon Nanotubes could replace semiconductor switches for automotive radar applications due to their higher level of integration combined with superior electrical performances. One note of caution however, CNT based RF MEMS are still at an early stage of academic R&D, where the requirement for nano-second switching times is only achievable in theory and still needs to be demonstrated.

**More exciting, however, is the possibility of creating completely new reconfigurable architectures** leveraging superior performances from RF MEMS such as of the linearity of the switches and tunable capacitors and/or the superior integration potential of RF MEMS enabling, for example, the monolithic integration of resonators.

- RF MEMS are considered as enablers for reconfigurable **base stations** due to a combination of their superior linearity, quality factor and tuning range. MEMS based impedance matching networks, tunable filters and multiband synthesizers will, it is foreseen, appear from 2009/2010.
- In **mobile handsets**, impedance matching networks could be enabled by MEMS-based switched capacitors as early as 2010. The high linearity of MEMS combined with their potential to be monolithically integrated with other passive components in a cost competitive module will drive the use of RF MEMS.
- Reconfigurable **satellite** communication systems as well as phased array antennas could make use of RF MEMS switches, tunable capacitors and cavity resonators. The first space test flights with systems using RF MEMS components are scheduled for 2007 and commercial implementation is expected by 2012.
- **60 GHz WLAN** systems are under development for wireless home networks. At this frequency, phased array antennas are required and RF MEMS could be an ideal technology by 2015 combining the superior RF performances with the possibility for monolithic integration with SiGe MMICs.
- **Cognitive radio** is a novel next generation radio standard targeting the optimal use of the available spectrum by implementing opportunistic sharing techniques. The front-end for such systems must be very flexible and able to handle any band in the (available) spectrum. RF MEMS could be suited for cognitive radio as they could provide continuously tunable (or small-step tunable) filters with steep (passband) characteristics. Metamaterial based MEMS and CNT based filter banks employed for this purpose could be implemented by 2015.

### 2.3. Implementation roadmap: how to make it happen

To make this roadmap come true, one must ensure that RF MEMS components will meet performances, reliability, cost and time to market requirements as demanded by each application. *To make it happen*, a significant effort is still required with regards to horizontal technologies, namely: design and modelling, materials and processes, packaging and assembly, testing, characterisation and reliability.

The ARRRO consortium would like however to highlight the **integration** issue as featured in the overall roadmap. Indeed, integration directly impacts the key pre-requisites for the successful implementation of RF MEMS in commercial products:

- **Cost:** for example “in-IC” resonators could enable the implementation of these components at little additional cost using standard IC process steps for cell phones
- **Size:** monolithic integration of switches with passives or 3D stacking are methods to significantly reduce the size of the modules
- **Performance:** monolithic integration allows for the dramatic reduction of parasitics and losses
- **Reliability:** appropriate integration and packaging will impact mechanical resistance as well as the lifetime of the RF MEMS components.

Particularly for volume applications such as mobile handsets, more so than in any other application, pressure on cost reduction is high and **RF MEMS must be cost competitive when compared to alternative technologies even if they are superior in performance.** In most cases, the only possibility for RF MEMS to attain cost competitiveness and compete on size constraints is at the system level through a higher level of integration.

The various means to increase the integration of RF MEMS include:

- Monolithic integration of passive components (switches, tunable capacitors with high Q inductors and fixed capacitors)
- Hybrid heterogeneous integration using advanced packaging techniques such as 3D stacking and RF SiP (system-in-package)).
- In some cases above-IC/below-IC or embedded within IC such as for micro mechanical resonators

### 2.4. Benchmarking analysis: RF MEMS versus alternative technologies

The ARRRO consortium has been allocating significant effort towards comparing RF MEMS components and RF MEMS based modules with alternative technologies.

- The consortium compared the state of the art of RF MEMS components with the state of the art of alternative components (established such as PIN diodes or emerging such as ferroelectric).
- The consortium also investigated the potential of improvements of RF MEMS and of alternative technologies so that it is possible to forecast which technology will meet the requirements of the various applications in future.

This approach was necessary to produce a realistic and unbiased application roadmap.

Here are some of the key findings of this benchmarking analysis:

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### **Not to under-estimate “established” technologies.**

MEMS are sometimes considered as replacement components for established and proven technologies which have been around for decades such as SAW filters, Quartz oscillators or PIN diodes, because it is perceived that these technologies have reached a “plateau” and have no potential for further improvement.

Recent developments in SAW technology, or to a lesser extent PIN diodes, prove the contrary. Indeed, new technologies such as MEMS provide an impetus which propels the established technologies forward to surpass their current limitations. As has been recently demonstrated by Murata, SAW devices have not, as yet, reached their limits in performance and have still a significant potential for improvement. SAW manufacturers particularly expect significant improvements in the insertion loss and power handling characteristics.

This is why it is recommended to continue with R&D aimed at advancing the capabilities of the RF MEMS component technology, in order to maintain the edge over alternative technologies.

### **“Established” technologies and MEMS may converge**

As manufacturers of “established” technologies are investing in MEMS, the distinction between MEMS and alternative technologies sometimes becomes unclear. These players are able in some cases to merge both technologies to incorporate the best of both.

This is the case with micro mechanical resonators and quartz oscillators. Seiko Epson is using micromachining technology to fabricate its smallest products since 2006 (Q-MEMS). This option enables designers to further push the limits in miniaturisation of quartz products (especially as the mounting of the electrode with electroplating is easier than with conventional techniques while maintaining the advantages of quartz in terms of temperature stability and quality factor).

This is also the case with SAW and BAW. Epcos has unveiled in 2007 the first prototypes of a BAW-SAW hybrid duplexer for W-CDMA cell phones. It has the advantage of a single component with high power and the low insertion loss of BAW combined with high miniaturisation and simple impedance and signal conversion of SAW technology.

### **The competitive technology may not excel at the component level but may do so at the system level**

All aspects of the system need to be considered when addressing alternative technologies. In essence, it may not be at the component level but at the architecture or even at the full concept level where gains are achieved.

In the case of automotive radar for example, RF MEMS switches are very promising for the beam steering approach investigated within the European project MIPA. ARRRO’s interviews with the automotive industry show, however, that a digital beam forming approach is much more promising, as it has a very low cost potential because of the digital processing content. In this context, RF MEMS are unsuitable as short switching times of some nano-seconds is required for digital beam forming systems.

With regards to automotive roof antennas - as developed within the EU project HARMS or the ESA project NATALIA - RF MEMS are promising for the development of low profile phased array antennas. However, the ARRRO consortium does not believe in the success of automotive roof antennas. The reason for this statement is the presence of 3G+ systems that could provide the same service at lower costs. Terrestrial infrastructure (base stations) are considerably cheaper than satellites. In addition, the great majority of users possess a mobile handset whilst travelling.

### 3. The position of Europe in RF MEMS

The position of Europe in the context of RF MEMS is rich with contradictions!

On the one side, research in RF MEMS started in the late nineties in Europe, almost 10 years after the USA which has been carrying out the bulk of the pioneering work in this field. Public funding in Europe since 2000 is also four times lower than that expended by the USA and two times smaller than that invested by Asia. In addition, the funding in Europe tends to be more spread out and less focussed on applications, components or expertise. As a result, **Europe is lagging the world with regards to certain technical developments in RF MEMS such as switches and tunable capacitors, particularly in relation to demanding applications in aerospace, automotive and the defence sectors.**

On the other side, Europe boasts a high quality resource in research and infrastructure. The large telecommunication and semiconductor companies have been leading the research developments in RF MEMS, supported by EU and national programmes since 2002. As a result, **Europe enjoys a good position in global competition with regards to the commercialisation of RF MEMS for cellular phone applications.**

Currently, the main challenge for Europe is to secure future access to RF MEMS technologies – particularly switches and tunable capacitors – in order to serve key European strategic industries such as aerospace, space, defence, the telecommunication infrastructures (base stations) and the automotive sector. Indeed, the ARRRO partners could not identify a single industrial company in Europe which will be in a position to supply such components to the European user industry in the near future. This user industry has, in most cases, also a limited access to technologies from the USA due to ITAR export restrictions.

In light of this global analysis, the ARRRO consortium proposes two ways to strengthen the European position:

- **Enhanced focus of R&D for RF MEMS in Europe.** In this context, a higher focus implies succeeding by achieving the critical mass on a carefully selected number of technical themes. A special effort with dedicated R&D projects should address and solve the key challenges which have been hampering the commercialisation of RF MEMS switches and tunable capacitors to date. These challenges include aspects such as modelling, simulation, reliability and packaging. Learning from the European success with FBARs and micro-mechanical resonators, the R&D resource and funding effort should also be focused on a limited number of industrial and academic partners.
- **Secure the commercialisation supply chain for RF MEMS.** The commercialisation supply chain is incomplete within Europe particularly with respect to switches and tunable capacitors aimed at, key, strategic markets. In this context, measures should be taken to create a pool of MEMS foundries and centres of manufacturing excellence with experience and expertise in RF MEMS. The IP service “RF platform” is a first step towards realising such a capability but, on its own, it is not sufficient. The EU could prescribe the inclusion of a foundry or manufacturing partner within all of their funded R&D projects in order to nurture the supply chain and create a pool of future product suppliers.

In conclusion, Europe has many positive assets in this field that, given a well structured plan, should maintain her competitiveness in developments relating to RF MEMS for cellular phones whilst enabling the potential of bypassing the competition in other sectors such as aerospace, defence and even the test equipment sectors.

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### **Coordinators contact details:**

Jérémie Bouchaud

WTC – Wicht Technologie Consulting

Frauenplatz 5

D-80331 Munich

Tel : +49 (0)89 20 70 260-20

Jeremie.bouchaud@wtc-consult.de

Start date of project: 01.01.2006

Project coordinator name: Jérémie Bouchaud

Project coordinator organisation name: WTC

Date of issue: June 15<sup>th</sup> 2007

Duration of study: 16 months

More information on ARRRO: [www.amicom.info/arro](http://www.amicom.info/arro)