Advances in RFMEMS Capabilty

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***Abstract*— The requirements for successful RFMEMS are first described and then examples of highly integrated packaged devices are reported for the first time. By taking a logical approach we have been able to advance RFMEMS capability to include wafer-scale packaged millimetre-wave Phase Shifters and other switch arrays incorporating up to 40 RFMEMS devices.**

I. INTRODUCTION

In contrast to the maturity and highly successful market for MEMS motion sensors (accelerometers and gyros), the RFMEMS market has seen a difficult birth with barely a handful of companies in production despite an initial surge of interest by both academic institutions and industry alike.

This is not the result of a simple linear lengthy gestation. Initially a number of developments came to fruition relatively quickly. However the road to success has been impeded by both technical issues and commercial hurdles and failures.

This paper first recounts some of the key factors behind this and then provides an unprecedented update on the progress and innovation that BAE Systems has been applying to RFMEMS, cogniscent of this challenging background.

II. CHALLENGES FACING RFMEMS

Almost all forms of MEMS present a major technical processing challenge. However it is now clear that some MEMS such as DLP chips and motion sensors have met this hurdle, carving out their own unique market positions and proving highly successful and reliable.

Unlike the silicon motion sensors etc, RFMEMS devices compete against highly capable and advancing rf/microwave developments in CMOS, SiGe and GaAs from DC–60GHz and beyond. Furthermore these semiconductor technologies which offer high integration levels, active functions etc., are already economically satisfying large market volumes demanded by mobile communications, wireless sensors, RFID, phase arrays, automotive radar, Wireless-HD etc

Developments of individual SPST or SPDT RFMEMS switches, whilst an undoubted processing achievement thus face almost insurmountable market challenges in a head-to-head situation with very capable rival technologies. This has already given rise to major disappointments when some quite promising RFMEMS devices and indeed whole companies (such as Magfusion and Teravicta) are not able to compete and disappear from the market before viable applications could complete their development - resulting in a ‘trough of disillusionment’. Consequently it is suggested that further attempts to taken on such competitive markets are inherently risky and that a key challenge for RFMEMS is to target strong innovative niches.

Finally we should remember that a series of technical challenges must also be met. RFMEMS are inherently vulnerable to contamination, moisture etc., and so will never succeed and come out of a cleanroom if they are not packaged. Integration and functionality levels also need to be far higher and this brings into question not just building and packaging multiple switches, but the ability to drive them without undue overheads from DC path/blocks, as well as the associated testing/diagnostics.

Given that the low frequency microwave bands are generally well provided for by the semiconductor market, this inevitably means that RFMEMS processes should be capable of reaching higher value millimetre-wave markets.

III. EARLY DEVELOPMENTS

BAE Systems ATC has a successful track record in micro- and nano-engineering, notably in Silicon MEMS gyros. Based on this, in-house RFMEMS developments started in 2001. At the time the focus logically enough was on key process issues and basic single or twin X-Band devices, [1] which ultimately would have competed against GaAs T/R modules. Other MEMS developments undertaken included low-loss high-Q filters. Like many others, lessons were learnt along the way in respect of basic process and materials issues including stresses, sacrificial layer release, stiction etc. Some devices from these first generation developments are shown in Fig. 1.

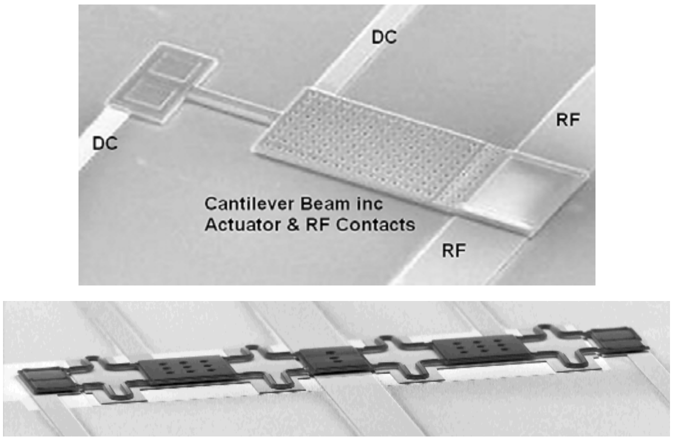

Figure 1. First Generation Cantilever and Bridge Switches

The support of MBDA-UK and UK Ministry of Defence is acknowledged

Shunt coplanar switch designs rely on their rf contact areas as their capacitive actuator. This becomes vanishing small at millimetre wave frequencies and incurs serious rf and dc isolation issues. As our roadmap was to always reach higher integration levels, capacitive microstrip cantilever designs were favoured in contrast to the popular coplanar shunt format. This had the benefits of excellent rf and dc isolation and ease of layout in compact SPDT switches and phase shifters. However their asymmetric geometry is more challenging to process and slowed the pace of improvements to rf insertion loss performance. Nonetheless persistent efforts resulted in a second generation of unpackaged switches and phase bits along with processes for low perturbation airbridges and rear-side substrate thinning/patterning for millimetre wave operation. Some of these are shown in Fig. 2. The phase bits have four devices per cell to either switch the through or delayed path.

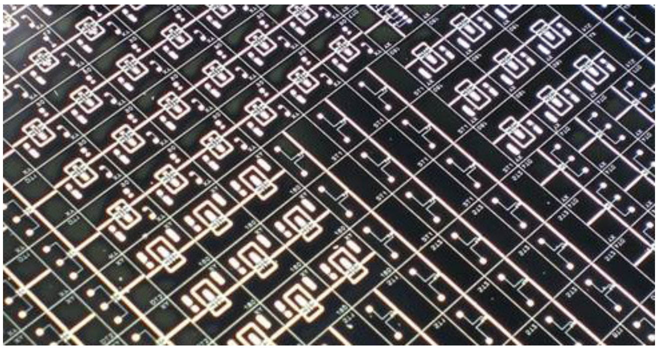

Figure 2. Second Generation Switches and Phase Bits

Whilst some RFMEMS developers and end users have been concerned with high drive voltages (up to 90-100v), our own results have been at times been below 30v. Indeed our view now is that in order to optimise rf switch speeds and powers it is more important to preserve or even increase stiffness to maintain rapid off-switching rather than be too concerned with low switch-on voltages (for which drive circuitry is readily available in any case).

IV. Advancing Capability

In recent times all developments have been aimed at – higher integration levels, packaging and key millimetre applications and performance – i.e. the key elements for RFMEMS to achieve market success. In our case a particularly stretching requirement for 35GHz packaged phase shifters has been a key driver, followed more recently by the need to broaden our capability. The salient points from these latest developments are summarised and illustrated with the aim of providing an overview, rather than detailed technical descriptions of every variant and process.

V. Phase Shifters and Higher Integration Levels

The phase shifter requirement is for a low cost four-bit true time-delay device. The design incorporates a total of sixteen switches (four per bit). The layout topology also requires that the drive signals be fed to the actuators in the middle of the phase bits with minimal perturbation of the rf path (and likewise to minimise rf coupling back to the drivers). This is implemented with sixteen airbridges (formed with the same process as the switches) which minimise their capacitive coupling by narrowing their geometry above the microstrip lines.. Thus each phase shifter has a total of 32 three-dimensional MEMS constructs – relatively high by comparison to most other developments. The device layout was strongly influenced by its packaging and modelled in Agilent-ADS and Ansoft-HFSS. The design and a photograph of an actual device are shown in Fig. 3, below.

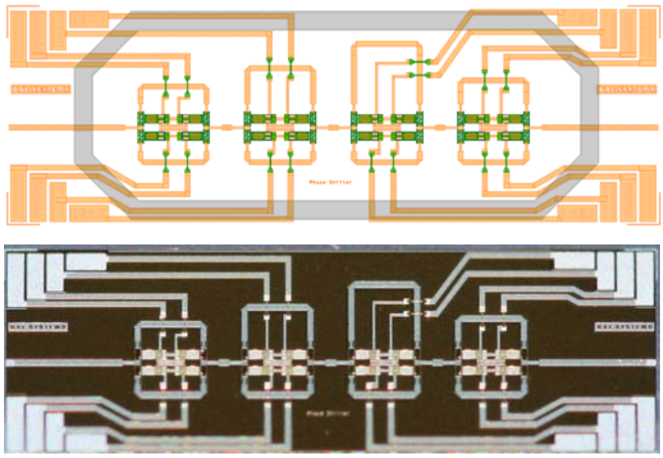

Figure 3. Four Bit 35 GHz Integrated Phase Shifter incorporating 16 switches and 16 airbridges (Grey = packaging outline)

Recognising that capacitive cantilever switch contact profiles could undermine the low insertion loss levels needed, we have also revisited bridge switch concepts. The current design generation includes a variety of new series-bridge switch topologies intended to maintain the advantage of rf isolation, but incorporate stronger and more symmetric forces to optimise rf contact insertion loss and off-speeds.

In practice a whole series of new test vehicles have been incorporated into the latest generation development. Some test chips have arrays of up to forty switches within each package to enable switching and reliability tests in a conventional laboratory environment. As RF losses improve and become more difficult to de-embed, four and eight-gang serial switches that feature higher total circuit losses provide clearer indications of underlying rf performance. The wafer that incorporates the phase shifters and these other high integration developments is shown in Fig. 4, prior to packaging.

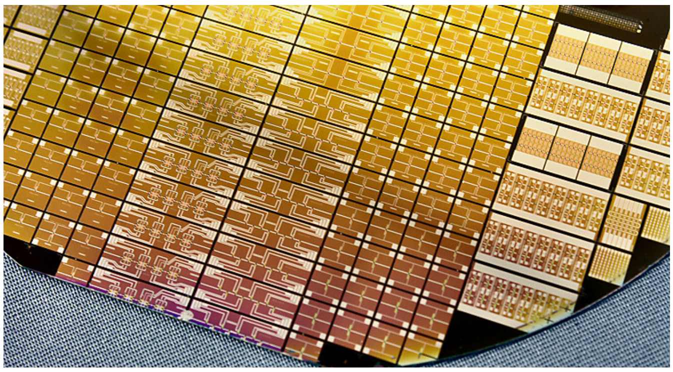

Figure 4. High Integration Packageable Wafer

VI. WAFER-SCALE RFMEMS PACKAGING

The other key element has been to bring to bear BAE Systems background expertise in packaged MEMS gyros, which use a wafer-scale glass process. The nature of highly integrated millimetre wave devices on a variable grid pattern has led us to develop the process further. Thermally matched glass is pocketed to form cavities over the devices and wirebond sites. This is attached to the released wafer, protecting it prior to substrate back-thinning and groundplane deposition stages. An example of this is shown in Fig. 5, where the devices can be seen through the transparent profiled glass packaging layer.

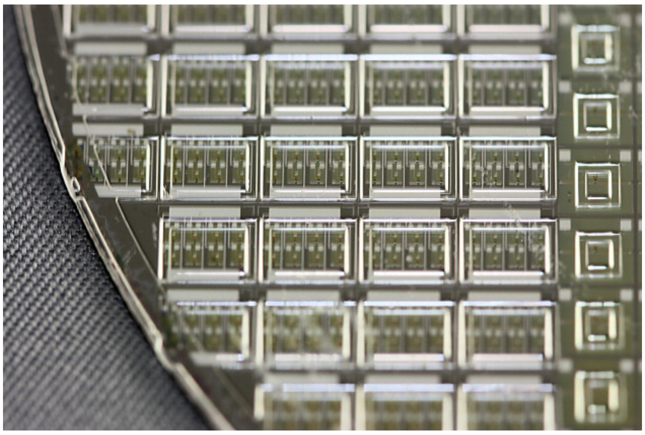

Figure 5. Packaging over RFMEMS Test Arrays

Further processing permits selective glass removal above the bondpad sites prior to wafer sawing. This permits significant flexibility for the size of chips and their interfaces, rather than being constrained to a single fixed grid on the wafer. Examples of the final devices are shown in Fig.6

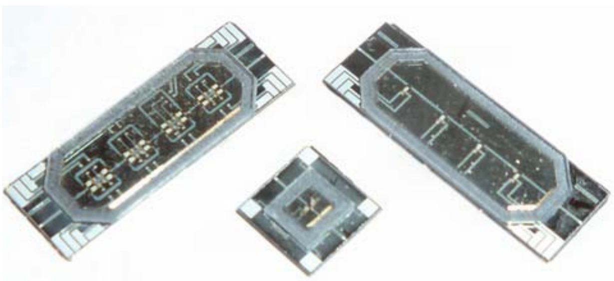

Figure 6. Packaged RFMEMS Devices

A patented roadmap for the packaging process extends to eliminating wirebonds to open a future route for surface mount assembly. The other consideration we have accommodated is that as integration levels rise, (creating challenges for testing), packaging should not impede the ability to monitor and diagnose the internal operation of the devices.

In summary, every wafer cell whether it be it an rf design, a lifetime test array or a process/alignment feature, has been laid out in such a manner as to be compatible with wafer scale packaging.

VII. CONCLUSIONS

RFMEMS still face many challenges in achieving rf performance, maturity and seeking markets. We do not claim to have solved all of these issues. However in this paper we have described how BAE Systems has taken a logical and industrial approach to the necessary process, integration levels, and crucially packaging, needed to mature the technology. We have reported innovative highly integrated packaged devices incorporating up to 30-40 MEMS as a demonstration that RFMEMS capability is advancing.

ACKNOWLEDGMENTS

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[1] “2×2 RF MEMS switch matrix”, McErlean, E.P.; Hong, J.-S.; Tan, S.G.; Wang, L.; Cui, Z.; Greed, R.B.; Voyce, D.C.; Microwaves, Antennas and Propagation, IEE Proceedings, Dec-2005 pp.449-454