Microwave applications of advanced semiconductor technologies

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***Abstract* – New semiconductor technologies, used in passive microwave applications, allow the integration of passives with high quality factors and the fabrication of novel RF-MEMS components for switches and tunable capacitors and resonators. The use of these technologies results in a strong reduction of the size and the power consumption of wearable microwave systems. The scaling of silicon transistors, following Moore's law, results in RF-CMOS devices approaching the performance of III-V and SiGe devices but at a considerably lower cost and much higher integration capability. The introduction of GaN based technologies offering new possibilities in the field of power microwave devices is discussed.**

I. Introduction

Future wireless communication systems as mobile phones, wireless local area networks (WLAN) and automotive radar will require very low weight, volume and power consumption in addition to higher data rates and increased functionality. Smaller size and reduction of component count has been realized by on-chip integration. Continuing integration and chip scaling will at this point only marginally contribute to the size reduction [1,2]. Today, the situation has been reached where the presence of rather bulky expensive off-chip (or discrete) passive RF components, like high-Q inductors, capacitors, varactor diodes and ceramic filters, plays a limiting role in further reducing size. Therefore, miniaturization and integration of passive components is a necessary condition to further reduce the size of the next generation of mobile RF-terminals. Moreover, the introduction of emerging technologies such as MEMS will allow to integrate variable passives and high Q resonators and filters.

Until a few years ago, GaAs and related materials dominated the active device microwave landscape but recently two important developments are the massive introduction of RF-CMOS and the potential use of GaN based devices for power microwave applications. In Section II the recent evolution of integrated standard passives as resistors, capacitors, inductors, transmission lines and their combinations is described. Section III addresses the use of emerging technologies such as RF-MEMS to meet the requirements imposed by novel miniaturized high Q resonators and filters.

In Section IV the effect of scaling on the high frequency capabilities of CMOS will be briefly discussed resulting in a viable CMOS technology as an alternative for III-V (GaAs) mm-wave applications. Finally, in Section V, the progress made with GaN technology towards the development of more efficient power microwave devices is addressed.

II. Integration of Standard Passive Components

In recent years there is an increasing trend towards integration of passive components in a SIP (System-In-a-Package) or "Above-IC" approach. In the SIP approach the passives are integrated onto a separate passive substrate as a part of a three-dimensional stack. In the above CMOS approach the passives are made in a post-processing sequence after CMOS fabrication on top of the CMOS wafers. Thin film technology can be used for

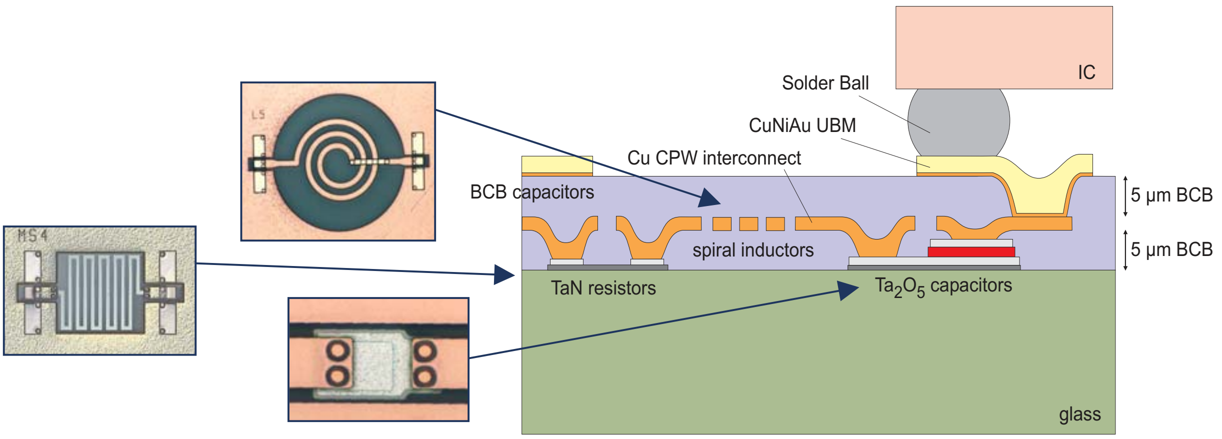


Fig.1. IMEC's microwave thin film technology.

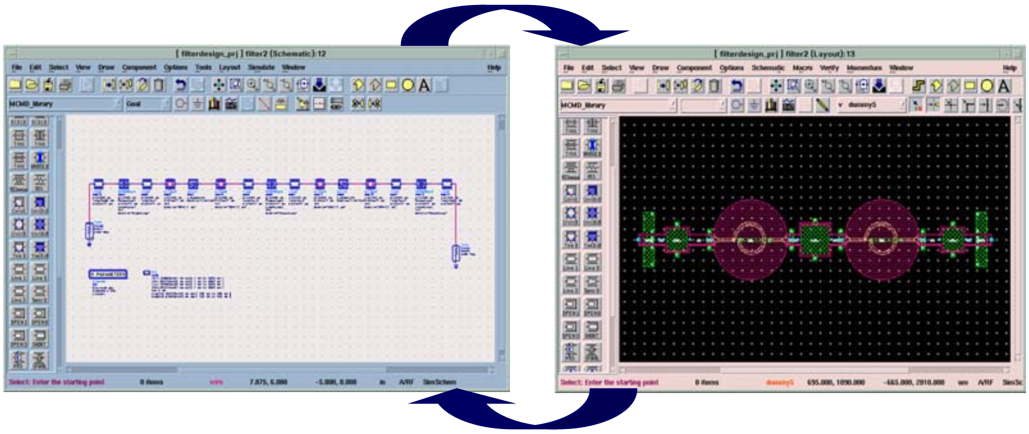


Fig. 2. Illustration of IMEC's design library for integrated

both the SIP approach or above CMOS approach. IMEC's mulilayer thin film technology for fabricated integrated passives [2,3] is shown in Fig. 1. In this example a glass substrate is used but also other substrates (ceramic, high resistivity Si) can be used.

The global features of this technology are:

- The use of high quality materials (Cu, BCB, glass, HR-Si)
- Coplanar wave guide (CPW) interconnects, offering a better performance,more flexibility without the need for through holes as compared to microstrip lines
- Flip-chip mounting of active die
- Extensive design library.

The integrated passive components have the following characteristics:
- TaN resistors (25Ω/sq)
- BCB (6.2 pF/mm2) and Ta2O5 (0.75 nF/mm2) capacitors
- Inductors (0.5 to 80 nH) with high Q-factor (30 to 150).

The design library allows, as illustrated by Fig.2, a two ways interactive design. The library will automatically generate the layout using the input data from the model; if the designer changes the layout the model parameters will be automatically adjusted.

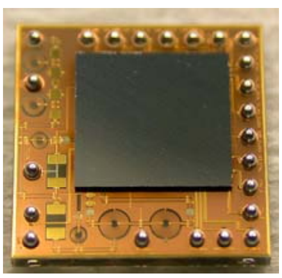


Fig. 3. RF-part of the Bluetooth System: the passives are integrated on the glass substrate and the RF BICMOS chip is flip-chip bonded onto the substrate.

Using this integrated passives technology and the design library, IMEC has recently developed a 7mm x 7mm Bluetooth module. Fig. 3 shows the RF part of the system. The active RF BiCMOS chip is flip-chip mounted on a glass substrate with passives integrated. Antenna's can also be integrated in the package, together with the feeding and matching network. Fig. 4 shows the integrated antenna for a WLAN system operating at 5.2 GHz [4].

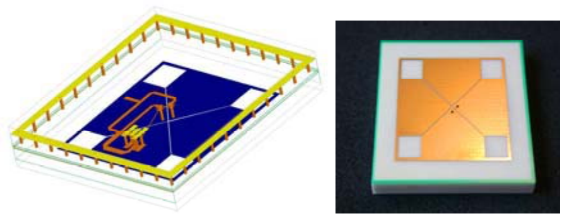


Fig. 4. Integrated antenna with feeding and matching network

In the "above IC approach" the same thin film technology is used to fabricate integrated passives on top of processed CMOS wafers. Fig. 5 shows the cross section of an inductor processed on CMOS using the thin film technology explained above [5].

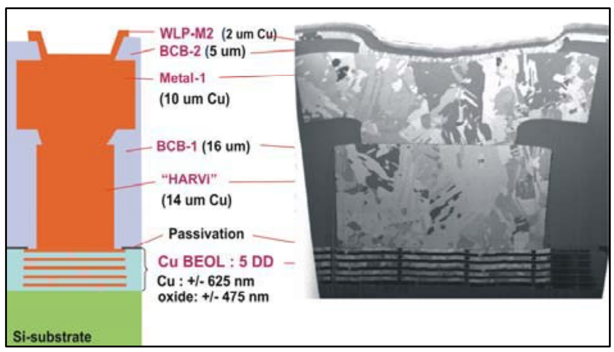


Fig. 5. Cross section of an inductor rocessed on top of CMOS using thin film post processing [3].

Much lower resistivities than in the case of conventional Cu BEOL (Back-end-of-line) layers are obtained resulting in much higher Q factors of the on chip inductors. Moreover, by increasing the thickness of the dielectric layer (BCB) thickness, the substrate losses strongly reduce.

It can be shown that increasing the Cu thickness increases the Q factor in the low GHz range and increasing the thickness of the dielectric layer increases the Q factor in the higher GHz range.

This “above IC” process has been used to realize a 15 GHz VCO with a power consumption of 2.5 mW and a phase noise of –105 dBc/Hz at 1 MHz offset [3].

III. RF-MEMS

To meet the required specifications of future mobile RF systems the existing library of fixed passives must be expanded with variable passives as switches, varicaps and tunable filters. In addition there is a need to integrate miniaturized high-Q resonators and filters. Perhaps the only technology at present with the potential to enable the integration of all these passives is micromachining or MEMS (Micro-Electro-Mechanical Systems on Structure) technology. MEMS for high frequency (0.1-100GHz) applications is commonly referred to as RF-MEMS.

RF-MEMS switching devices have just like semiconductor RF switches, two stable states. Switching between the two states is achieved through the mechanical displacement of a freely movable structural part. This displacement is induced via a micro-actuator for which electrostatic actuation is mainly used. RF-MEMS switches offer great potential benefits over semiconductor switches in terms of a high isolation, a low loss over a wide frequency range, extremely low stand by power consumption and excellent linearity. An example of a typical electrostatically actuated capacitive shunt switch implemented on a CPW transmission line is shown in Fig. 6 [6].

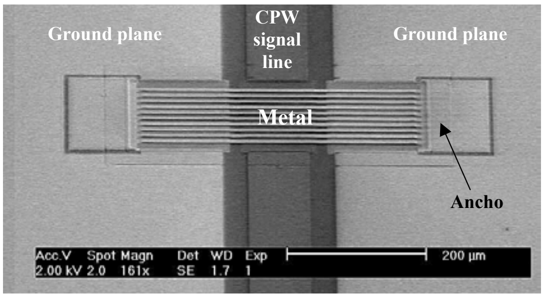


Fig. 6. SEM picture of a capacitive RF-MEMS switch [6].

Packaging of RF-MEMS components turns out to be critical. RF-MEMS switches, like many other MEMS devices, contain movable fragile parts that must be packaged in a clean and stable environment. A specific low-cost packaging approach is required offering protection during fabrication as well as during operation. The so-called 0-level packaging is carried out on the wafer during wafer processing, prior to die singulation. One approach for the 0-level package is to bond a recessed capping chip onto the MEMS devices wafer. The bonding must be performed at sufficiently low temperatures (typically below 400°C) such that the metallization and other materials of the RF-MEMS switching device are not adversely affected. In packaging an RF-MEMS switch (or any other RF-MEMS device), the package itself should have minimal effect on the device performance. In an ideal package the RF characteristics before and after capping should be the same. This requires low-loss RF transitions, and, minimal induced loss and detuning of the transmission lines due to proximity coupling to the cap.

At the moment RF-MEMS switches do not yet perform sufficiently reliably due to a number of failure mechanisms. Serious studies to solve these reliability issues have only recently been started.

RF-MEMS tunable capacitors are very promising components, but the development is still in infancy stage [7,8]. A lot of work still remains to be done and solutions must be found, in particular where it concerns the reliability, the packaging and, the mechanical and temperature stability.

Resonators find widespread use in transceiver architectures, e.g., as the frequency-controlling element in reference oscillators, as the tunable resonator tank for VCO’s, and as building elements for filters and diplexers. To meet the specifications for these applications in terms of oscillator stability and phase noise, filter insertion loss, selectivity and out-of-band rejection, and low power consumption, the resonators must have a (very) high quality factor. Depending on the application a Q-factor of around 30-50 can be acceptable, e.g., for the tank resonator in the local oscillator of superheterodyne receivers. For many functions however, e.g., for the channel selection in the IF stage of superheterodyne receiver, a Q-factor of a few thousand (even exceeding ten thousand) is required.

In recent years the strongest interest in the resonator field is in film bulk acoustic resonators (FBARs). FBARs can be considered as the micromachined or MEMS version of conventional bulk acoustic wave resonator, e.g., a quartz crystal. Bulk acoustic wave resonators in essence consist of a parallel plate capacitor with a piezoelectric layer used as the dielectric. By applying an ac electrical signal to the electrodes, a longitudinal acoustic wave is excited in the bulk of the piezoelectric film. This wave is trapped by the reflecting electrode surfaces thus forming an acoustic resonator. In order to attain a high-Q, the acoustic losses into the supporting substrate must be made as small as possible. One way is to isolate the structure from the substrate by (locally) removing the substrate underneath as illustrated in Fig. 7 showing a membrane supported FBAR. In FBARs. In FBARs, thin films of aluminum nitride (AlN) or zinc oxide (ZnO) are commonly employed for the piezoelectric layer. For these materials, resonances in the

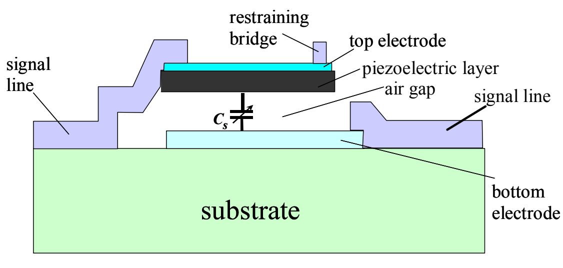


Fig. 7. Tunable FBAR resonator [9].

low GHz regime result for a piezoelectric layer thickness on the order of 1µm and are thus well within reach for thin film technologies. The resonators are made as small as a few ten's to a few 100's of µm's on a side, typical for a MEMS design. Membrane supported FBARs using AlN films have been demonstrated to operate at resonant frequencies in the low-GHz range with loaded Q's typically of a few hundred but Q's over 1,000 have also been measured.

Tuning of the FBAR resonator is possible by changing the DC voltage over the series capacitor C_S (Fig. 7). The frequency tuning characteristic of the tunable FBAR in Fig. 7 is shown in Fig. 8 [9].

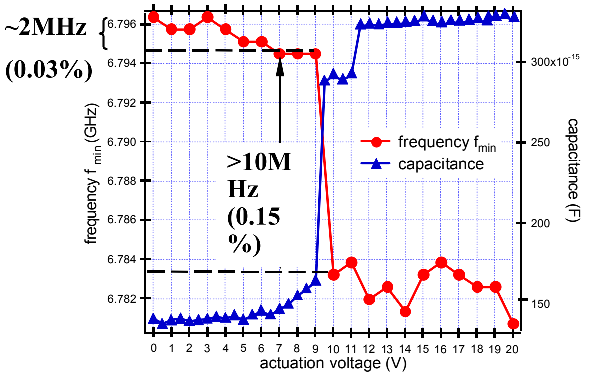


Fig. 8. Frequency tuning characteristic of an FBAR resonator [9].

IV. RF-CMOS

During the last years the high frequency capabilities of CMOS have considerably improved through scaling such that the question is not if, but when will CMOS become a viable alternative for mm-wave applications [10].

0.25µm CMOS technology allows for low-cost radio solutions up to nearly 6 GHz, using relatively conventional circuit design. It has been demonstrated [10] that through careful optimization and modeling, a standard 0.13 µm CMOS process is capable of 60 GHz operation and that subsequent generations will simply provide higher performance at lower power levels. The performance of the technology strongly depends on the quality of the transmission lines that can be made on Si and an "above CMOS' approach can be very useful at this point. Other important issues are the noise modeling and the breakdown voltage. RF-CMOS is particularly useful for antenna-array systems where also complex logic is needed. Point-to-point connections where directional antennas are necessary seem most interesting. The power amplifier is a smaller issue since in antenna array systems several power amplifiers will operate in parallel. In the coming years it will become clear how much market share RF-CMOS will gain at the expense of GaAs, InP and SiGe technologies.

V. GALLIUM NITRIDE TECHNOLOGY FOR POWER MICROWAVE DEVICES

Regarding the expansion of wireless communications, RF and microwave systems must handle larger and larger data flow, while moving towards higher frequency: from S band for base stations to K-Ka band (VSAT) and tomorrow even higher for direct home-satellite communication. High power needs, coupled to stringent linearity requirements, are increasing nowadays the complexity of system design and associated costs, at the expense of lower overall efficiency. A real breakthrough for microwave systems in terms of power and efficiency can only stem from a change of the semiconductor material itself, in which devices are processed. As shown in Figure 9, physical limits of Si devices, which are now being reached, can largely be overcome by the use of wide bandgap technologies.

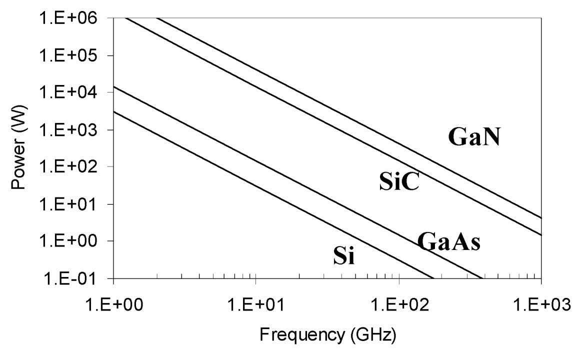
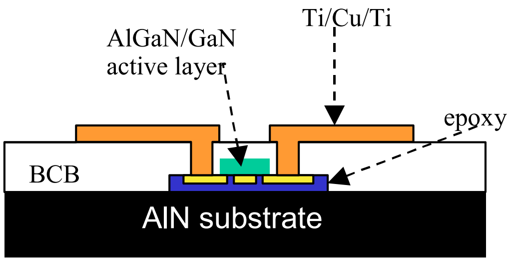


Fig. 9. Power capabilities of semiconductor materials at RF frequencies: theoretical limits.

A large bandgap results in high breakdown electrical field (typically ten times higher than Si), allowing transistors to operate at high voltages. As it moreover contributes to high channel current density, high output power can be achieved. Among wide bandgap materials, Gallium Nitride (GaN) has emerged recently as the "front runner". It indeed combines high power capabilities with excellent transport properties. Saturation velocity reaches $2\ 10^{7}$cm/sec (over a large range of electric field), allowing for very high frequency operation. Today, the best GaN device is the AlGaN/GaN High-Electron Mobility Transistor (HEMT). Electron concentration can reach $2\ 10^{13}$ cm^{-2}, whereas mobility in the channel can be as high as 2000 cm^2/Vs [11], compared respectively to $2.6\ 10^{12}$ cm^{-2} and 1400 cm^2/Vs for Si. This unique combination of outstanding physical properties has allowed for the demonstration of the highest RF output power density generated by *any* single device: 12 W/mm at 4 GHz (5W/mm without passivation [12]), 30.6 W/mm at 8 GHz (field plate gate) or 4.13 W/mm at 35 GHz have been reported.

Besides these excellent results proving GaN capabilities, many challenges remain to be solved before its widespread use in telecommunication. Three major areas can be identified: material aspects, DC to RF slump, packaging and thermal aspects. The availability of high quality material is complicated by the lack of GaN bulk substrates, requiring the use of sapphire or SiC, or more recently, but very interesting for low cost applications, Si. High-quality low-defect density hetero-epitaxial wafers have been grown at IMEC by Metal-Organic Vapor Phase Epitaxy on such substrates [11]. Concerning DC/RF slump, attributed to surface states effects, passivation of the top surface appears an effective way of reducing the influence of surface states on electrical performance. IMEC has recently demonstrated that in-situ passivation of HEMT, prior device processing, leads to spectacular improvement of transistor dc characteristics: the drain-source current more than doubles from 0.5 A/mm in the reference sample to 1.2 A/mm with in-situ passivation. Associated RF measurements, for a gate length of 0.2 µm, showed a f_t of 40 GHZ and f_{max} of 80 GHz.

Finally, the unusually high power density handled by those devices renders thermal management and packaging issues very acute. The System-in-a-Package approach presents many advantages here. On the one hand, as previously discussed, it leads to high integration levels at RF on a low cost substrate. On the other hand, it offers advanced possibilities for thermal management solutions: even integration of active cooling in the substrate, close to the active device could be realized for very high power density. Flip-chip mounting of an AlGaN/GaN HEMT on an AlN substrate, followed by substrate removal for better thermal management, is shown in Fig. 10 as a first step towards GaN System-in-a-Package integration.



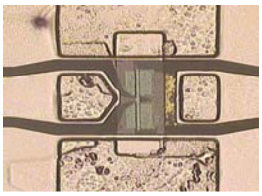


Fig. 10. System-in-a-Package approach for GaN amplifiers: integration of AlGaN/GaN HEMT on AlN substrate. Top: cross-section; Bottom: top view.

VI. Conclusions

It has been shown that new semiconductor technologies allow the integration of passive components with high quality factors but also the fabrication of novel RF-MEMS components for switches and tunable capacitors and resonators. Use of these technologies results in a strong reduction of the size and the power consumption of wearable microwave systems. The scaling of silicon transistors, following Moore's law, results in RF-CMOS devices approaching the performance of III-V and SiGe devices but at a considerably lower cost and much higher integration levels. The introduction of GaN based technologies offers new possibilities in the field of power microwave devices.

VII. Acknowledgement

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