Above-IC Integration of BAW Resonators and Filters for Communication Applications

Marc-Alexandre Dubois (a), Christophe Billard (b), Guy Parat (b), Mohammed Aissi (c), Hocine Ziad (d),
Jean-François Carpentier(e), Kim B. Östman(f)

(a) Swiss Center for Electronics and Microtechnology (CSEM), Neuchâtel, Switzerland
(b) CEA-LETI, Grenoble, France
(c) LAAS-CNRS, Toulouse, France
(d) AMI Semiconductor Belgium BVBA, Oudenaarde, Belgium
(e) ST Microlectronics, Crolles, France
(f) University of Technology, Tampere, Finland.

Abstract— **This paper demonstrates the feasibility of an above-IC bulk acoustic wave technology for wireless applications in the 2 to 6 GHz frequency range. Examples of low phase noise FBAR based oscillators are used to show the potential of this technology.**

Key words—**Bulk acoustic wave devices, integrated circuit fabrication, micromachining, piezoelectric resonator filters, oscillators, radio receivers.**

I. INTRODUCTION

BULK acoustic wave (BAW) piezoelectric resonators have been developed over the last few years to be used in wireless communication systems, mainly in mobile phones. They consist in a piezoelectric thin film sandwiched between two electrodes, and isolated acoustically from the substrate over which they are built [1]. Due to their high Q factors, large power handling capability, and reasonable coupling coefficient, they can indeed be used advantageously in passive ladder filters and hence in duplexers with the low loss and steep skirts required by the latest communication standards. The duplexer is a key component in a mobile phone since it is responsible for cleaning the spectrum around the received or transmitted signal, just next to the antenna. It has then a very strong impact on the transceiver architecture and the RF design specifications. The need for efficient duplexers with small form factors has been the main driving force for the development of the thin film BAW technology, which is now mature and industrial [2][3].

Besides their use in passive high performance filters, miniature resonators can also be associated with active circuitry to provide specific electronic functions, where a high Q can be leveraged, such as low noise amplifiers or oscillators. In the latter case, the high Q factor of the resonator translates directly into a reduced phase noise, which is often the key specification for an oscillator.

Although BAW resonators and filters are processed, usually, on silicon wafers, the applied technologies are those used in the micro-electromechanical systems (MEMS) world, rather than in the IC fabrication facilities. Among the differences are the need for different materials—high resistivity silicon substrates, a piezoelectric layer and specific electrodes—fabrication tolerances either relaxed or much more stringent depending on the parameter, and possibly the wafers' size.

This paper describes results obtained in an exploratory work aiming at bringing together the BAW and IC technologies by co-integrating active and passive components on the same substrate. More specifically, piezoelectric thin film resonators and filters have been fabricated at the wafer level above BiCMOS integrated circuits in a post-processing approach.

Ultimately, such a co-integration could reduce the size of high performance RF systems and boost their perfomances through the reduction of interconnection parasitics. However, this would probably come at the expense of the fabrication yield and hence of the production cost, limiting this technological approach to high end markets where the cost is not the primary concern, unlike in the mobile phone business.

II. ABOVE IC BAW TECHNOLOGY

The two available types of BAW resonators—differentiated by the way the acoustic isolation between the vibrating film and the substrate is carried out [1]—have been shown recently to be compatible with such a co-integration scheme [4][5]. In this work, the *film bulk acoustic resonator* (FBAR) fabricated by surface micro-machining has been chosen in order to keep

Contact author: marc-alexandre.dubois@csem.ch

the technology for connecting the resonators to the topmost metal of the IC as simple as possible. Indeed, as only a very thin isolating air gap is created underneath each resonator, the latter are placed very close to the circuit and low loss interconnections can be realized without manufacturing metal-filled vias through a thick acoustic reflector.

Over the years, aluminium nitride (AlN) deposited by reactive sputtering has emerged as the technology of choice for BAW resonators because it is an excellent compromise between performance and manufacturability. Its coupling coefficient is not as high as that of ZnO or PZT, but it is chemically very stable, has an excellent thermal conductivity, and a low temperature coefficient. These properties enable the fabrication of resonators featuring coupling factors of 6-7%, good resistance to corrosion, excellent power handling capability, and limited drift with temperature. Another advantage of AlN is the low process temperature and the fact that it does not contain any contaminating elements harmful for semiconductor devices, unlike most other piezoelectric materials.

Furthermore, owing to these excellent material properties and because of the very stringent specifications on thickness accuracy and uniformity set by the BAW resonator's architecture—resonance frequency is inversely proportional to thickness—equipment manufacturers developed and optimized sputtering systems specifically for AlN, rendering the process industrial and widely available [6].

The sputtering process used in this work takes advantage of the properties of a platinum (Pt) electrode, which promotes efficiently the growth of AlN films with excellent piezoelectric properties. This is due to the hexagonal symmetry of the (111)-plane of Pt that matches the (002)-plane of AlN, and to an extremely smooth surface [7][8]. The drawback of Pt is its lower electrical conduction compared to aluminium or molybdenum, which is one of the limiting factors for the series Q factor of the BAW resonator. The crystalline properties of AlN films deposited with this process have been assessed by X-ray diffraction measurements, yielding a very narrow rocking curve FWHM of 1.07° for the (002) peak. This high crystalline quality has been confirmed by a direct measurement of the piezoelectric $d_{33,f}$ extensional coefficient with a double beam Mach-Zehnder interferometer. A value of 5.3±0.22 pm/V has been obtained, representing a potential coupling coefficient k_{eff}^2 in BAW resonators larger than 6.5%.

The fabrication sequence of the BAW resonators (and filters) above IC is the following: First, silicon oxide is deposited over the passivated IC-carrying wafers and planarized by CMP, in order to get a smooth and flat surface for the FBAR fabrication. A photoresist sacrificial layer is deposited, patterned, and cured at high temperature for defining each resonator's position, and then protected by silicon nitride. Next, the active part of the devices is built up, with the subsequent deposition and patterning of the Pt bottom electrode, the piezoelectric AlN layer, and the top electrode. Via holes are then etched through the different dielectric layers until the last metal level of the integrated circuit (M5), and a thick metal interconnect is deposited and patterned to link the BAW resonator to the IC. A thin silicon oxide loading layer is then deposited and patterned to shift down the frequency of some resonators in the case of filters. Finally, the sacrificial layer is etched and the membranes are released. Fig. 1. shows a schematic cross-section of a FBAR connected to the last metal level of an IC wafer.

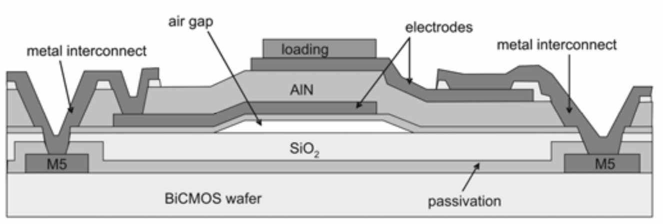

Fig. 1. Cross-section of FBAR integrated above IC

It has to be mentionned that the technology has been kept as simple as possible for these proof-of-concept integrations. Consequently, additional processing steps that would be required for large-scale production, such as the passivation of the devices for example, have been omitted.

Two different sources of IC wafers have been used: either BiCMOS 0.25µm SiGe:C technology from ST Microelectronics, or BiCMOS 0.35 µm SiGe technology from AMI Semiconductor. Likewise, two different FBAR frequencies have been explored, 2.14 GHz and 5.5 GHz.

III. CROSS-INFLUENCE OF TECHNOLOGIES

When post-processing MEMS of any kind above IC, it is crucial to control that the semiconductor devices do not suffer from the additional processing steps, and most particularly from the many thermal cycles applied to the wafer.

Table 1. Impact of post-process on BiCMOS technology

	unit	before	after	delta
NMOS 10x0.35 V_{bd}@10nA	V	9,4682	9,5689	-1.06%
PMOS 10x0.35 V_{bd}@10nA	V	-8,6168	-8,6625	-0.53%
NMOS 10x0.35 V_{t0}	V	0,60358	0,59291	1.77%
PMOS 10x0.35 V_{t0}	V	-0,63017	-0,6334	-0.51%
M3/M2 via chain	Ω/via	0,84329	0,85834	-1.78%
M2 resistance	mΩ/sq	48,498	48,805	-0.63%
HIPO resistor W100L10	Ω/sq	1090,4	1073,52	1.55%

As an example, in the case of post-processing above BiCMOS 0.35 µm SiGe wafers, about 50 different test devices characterizing globally the performance of the semiconductor technology have been measured, before and after the fabrication of BAW resonators and filters. Table 1 shows an excerpt of this measurement campaign with only a few relevant parameters. The stable breakdown voltage V_{bd} of the transistors show that there is no significant alteration of the gate oxide integrity. The MOS threshold voltage V_{t0} is likewise not affected. The resistance measurements indicate that the thermal cycles experienced by the circuits do not lead to any intermetallic formation in the interconnections since the resistive paths are nearly unchanged. In general, no major deviation due to the post-process have been observed in any measured parameter. All differences are below 2% except for 2 leakage measurements, which seem actually to have been improved by the BAW processing. This show that the impact of the BAW fabrication upon the BiCMOS circuits is very limited.

The opposite has also been observed, namely that the BiCMOS wafers do not impact the performances of the resonators. Indeed, individual resonators exhibit the same performances above-IC as on plain silicon wafers, meaning that the presence of active circuits underneath the FBARs does not modify their performances. Typical coupling and quality factors measured on test resonators are 6.5% and 900 in the 2 GHz range, and 6.6% and 750 in the 5GHz range. If the coupling coefficients confirm the high quality of the AlN layer, the Q factors could be further improved with a better thickness and acoustic impedance ratio between the electrodes and the piezoelectric film and the suppression of the lateral modes propagating in the membrane. The latter can be seen as wavelets on the fundamental resonance circle of a test rectangular FBAR in Fig. 2.

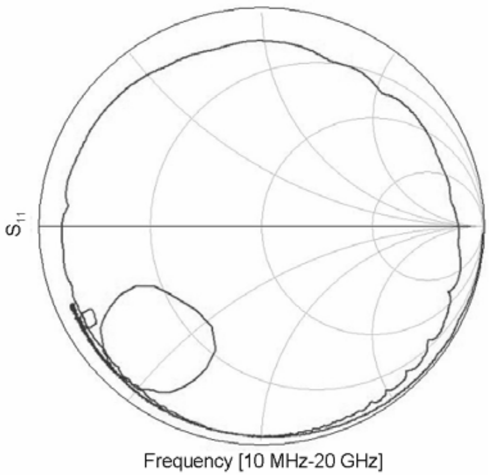

Fig. 2. Smith chart of a test FBAR at 5.5 GHz. The large circle is the fundamental resonance, whereas the 2 smaller ones are harmonics at 12.5 and 17.8 GHz respectively.

IV. WCDMA RF FRONT-END

The potential of this above-IC technology has been demonstrated through the design and fabrication of the receiver part of a simplified RF front-end set at 2.14 GHz. The latter is described thoroughly in [5]. This front-end chip contains a low noise amplifier, a single-to-differential converter, a high rejection double lattice FBAR filter, a matching network and a mixer. For the characterization of the circuit, the differential mixer was fed by an external signal generator.

Fig. 3. shows pictures of a newer version of the same RF front-end, which includes this time an FBAR-based VCO (seen at the right of the micrograph).

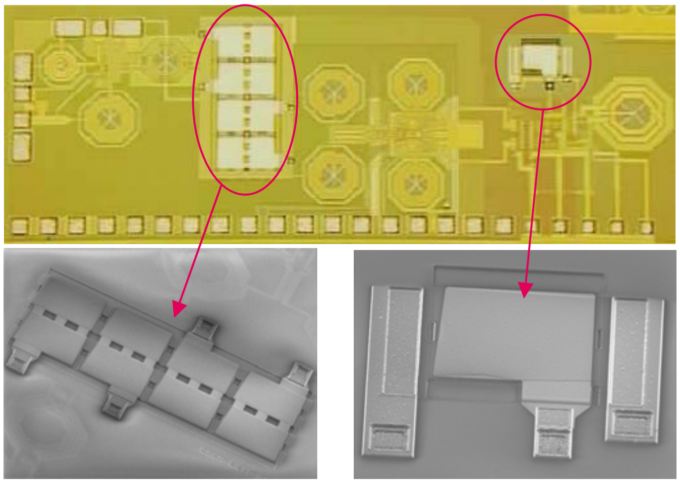

Fig. 3. Chip micrograph (top) of an integrated WCDMA receiver and SEM inserts of the BAW filter (bottom left) and resonator (bottom right).

The architecture and the performances of this differential VCO are described in details in [9]. Fig. 4. shows the measured phase noise of the FBAR VCO compared to the noise of a reference LC VCO, as well as a micrograph of the Si chip including the BAW resonator. The phase noise of the FBAR VCO is significantly lower than the one of the LC tank VCO, with a value as low as -143.7 dBc/Hz at the optimum operating voltage. The tuning range of the VCO is 15 MHz. It is not yet sufficient to cover the whole frequency band as required by the WCDMA standard, but it is much more than what has been obtained until now with FBAR oscillators [10][11].

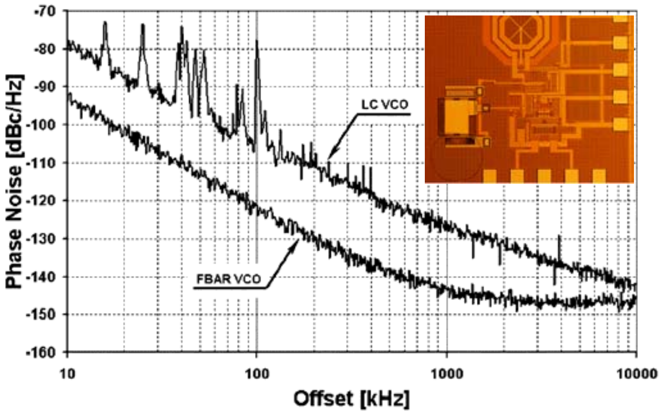

Fig. 4. Phase noise measurement of the FBAR differential VCO compared to a reference LCVCO.

Despite this limited tuning range, the receiver of Fig. 3. is functional, as it is shown by Fig. 5. It represents the spectrum measured at the output of the mixer with a -40dBm signal at 2.1138GHz fed at the LNA input. The supply voltage and VCO control voltage have both been set at 2.4V.

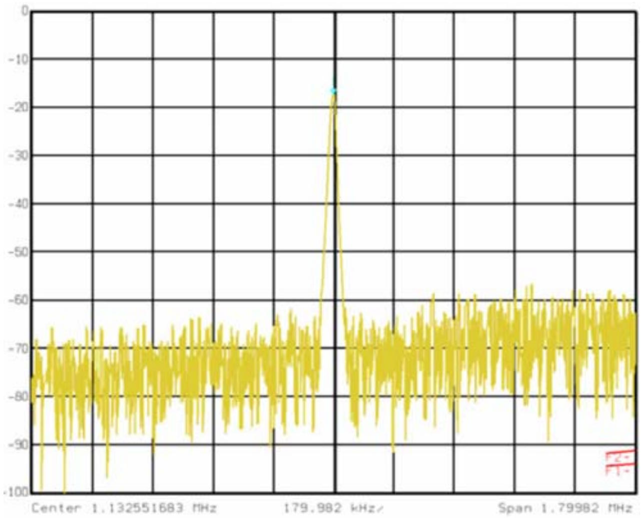

Fig. 5. Output spectrum of the monolithic WCDMA receiver, with the demodulated output at 1.13 MHz.

V. WLAN OSCILLATOR

As a second example of co-integrated system, an oscillator with Colpitts architecture has been designed for operating at 5.5 GHz. A micrograph of the chip and the schematic of the circuit are shown in Fig. 6. The core of the oscillator is a common collector transistor T_1, with the feedback capacitors C_1 and C_2 ensuring the negative resistance necessary to compensate the losses in the resonating FBAR. Transistor T_2 is used as a buffer to isolate the resonator from the load impedance. The active circuit has been implemented in the BiCMOS 0.35 µm SiGe technology from AMI Semiconductor.

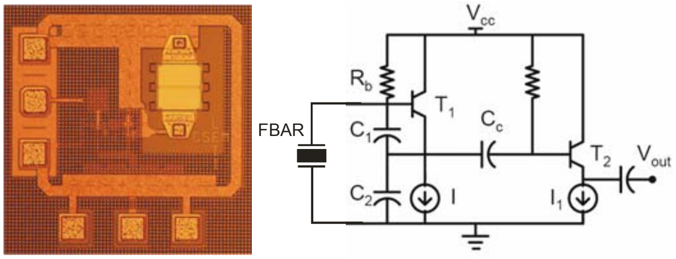

Fig. 6. Chip micrograph (640×650µm^2) and schematic of the oscillator

The active circuit and the ground line have intentionally been kept away from the resonator to prevent any possible coupling with the FBAR. However, it is certainly possible to reduce further the silicon area of the oscillator, by placing the FBAR over the active elements. In that case, a careful shielding of the sensitive part would be needed.

The output power of the oscillator is –8.4dBm for a total current consumption of 4.7mA at 2.7V, out of which 3mA are drawn by the buffer amplifier. Fig. 7. shows the output power spectrum of the circuit. A phase noise of –117.7dBc/Hz has been measured at 100kHz offset from the carrier.

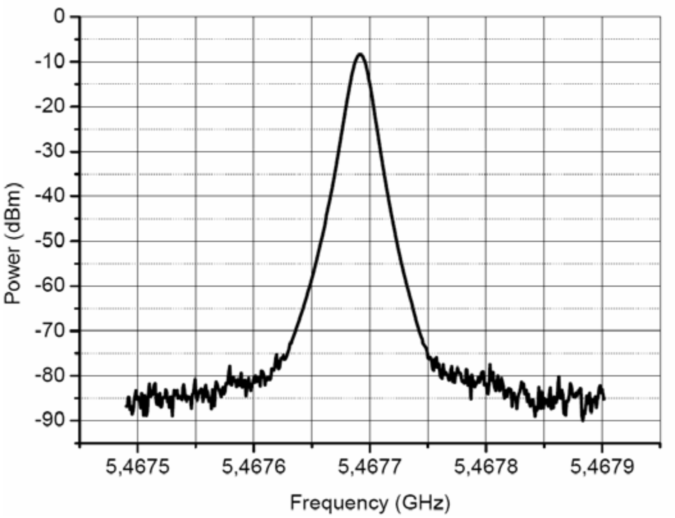

Fig. 7. Output power spectrum of Colpitts oscillator

Further information about FBAR Colpitts oscillators can be found in [12][13].

VI. CONCLUSION

FBAR processing is compatible with advanced BiCMOS technology, and hence enables the co-integration of RF high-Q passive and active devices on a single chip. Many circuit blocks such as LNAs or VCOs can take advantage from such a co-integration with high Q BAW devices. Performances can be further enhanced through the reduction of size, the limitation of interconnection parasitics, and the possibility to use the IC metal layers for shielding the BAW devices.

However, the complexity of the technology will certainly limit the fabrication yield in a production environment. Hence the validity of this above-IC approach is restricted to high-end applications, where RF performances outweight the cost issues.

ACKNOWLEDGMENT

This work was funded by the Swiss Office for Education and Science and the European Commission under Grant IST-2001-37362. Part of the processing has been realized at CMI-EPFL.

REFERENCES

[1] K. M. Lakin, "Thin Film Resonators and Filters," presented at IEEE Ultrasonics Symposium, Lake Tahoe, NV, 1999.

[2] R. Aigner, J. Kaitila, J. Ellä, L. Elbrecht, W. Nessler, M. Handtmann, T.-R. Herzog, and S. Marksteiner, "Bulk-Acoustic-Wave Filters: Performance Optimization and Volume Manufacturing," presented at IEEE IMS, Philadelphia, PA, 2003.

[3] R. C. Ruby, P. Bradley, J. Larson, Y. Oshmyansky, and D. Figueredo, "Ultra-Miniature High-Q Filters and Duplexers Using FBAR Technology," presented at IEEE International Solid-State Circuits Conference, San Francisco, CA, 2001.

[4] L. Elbrecht, R. Aigner, C.-I. Lin, and H.-J. Timme, "Integration of Bulk Acoustic Wave Filters: Concepts and Trends," presented at IEEE MTT-S, Fort Worth, TX, 2004.

[5] M.-A. Dubois, J.-F. Carpentier, P. Vincent, Ch. Billard, G. Parat, C. Muller, P. Ancey, P. Conti, “Monolithic above-IC resonator technology for integrated architectures in mobile and wireless communication”, *IEEE Journal of Solid State Circuits*, vol. 41, pp. 7-16, 2006.

[6] R. Lanz, C. Lambert. E. Kuegler, L. Gabathuler, L. Senn and K. Onuki, "Properties of Sputter deposited AlN, Mo, W and SiO_2 Thin-Films for Bulk-Acoustic-Wave Applications on 200mm Si Substrates", Proc. of 8th Int. Symposium on Sputtering and Plasma Processes (ISSP 2005), June 2005, Kanazawa, Japan.

[7] M.-A. Dubois and P. Muralt, "Stress and piezoelectric properties of aluminium nitride thin films deposited on metal electrodes by pulsed direct current reactive sputtering," *J. of Appl. Phys.*, vol. 89, pp. 6389-6395, 2001.

[8] H. P. Loebl, M. Klee, C. Metzmacher, W. Brand, R. Milsom, and P. Lok, "Piezoelectric thin AlN films for bulk acoustic wave (BAW) resonators," *Materials Chemistry and Physics*, vol. 79, pp. 143-146, 2003.

[9] K. B. Östman, S. T. Sipilä, I. S. Uzunov, and N. T. Tchamov, “Novel VCO Architecture Using Series Above-IC FBAR and Parallel LC Resonance”, *IEEE Journal of Solid State Circuits*, vol. 41, pp. 2248-2256, 2006.

[10] Y. H. Chee, A. M. Niknejad, and J. Rabaey, “A sub-100 _W 1.9-GHz CMOS oscillator using FBAR resonator,” in *IEEE RFIC Symp. Dig. Papers*, 2005, pp. 123–126.

[11] A. P. S. Khanna, E. Gane, and T. Chong, “A 2 GHz voltage tunable FBAR oscillator,” IEEE MTT-S Dig., pp. 717–720, 2003.

[12] M. Aissi, E. Tournier, M.-A. Dubois, G. Parat, and R. Plana, “A 5.4GHz 0.35µm BiCMOS FBAR resonator oscillator in above-IC technology,” presented at IEEE International Solid-State Circuits Conference, San Francisco, CA, 2006.

[13] M. Aissi, E. Tournier, M.-A. Dubois, Ch. Billard, H. Ziad, and R. Plana, “A 5 GHz above-IC FBAR Low Phase Noise Balanced Oscillator”, presented at IEEE RFIC Symposium, San Francisco, CA, 2006.