Impact of RFIC Integration of System and Subsystem blocks on MCM Solutions

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Abstract – Wireless systems of all types, from mobile phones to satellites have developed based on a combination of integrated circuits (IC) and multi chip modules (MCM). Digital sections of these systems have benefited from increasing levels of integration at the IC level thanks to a seemingly endless ability of Si CMOS to scale itself. However, RF sections have, for a variety of reasons, evolved much more toward MCM solutions. The primary reason for this trend is that RF sections require a wide variety of subsystems that differ substantially from each other whereas virtually all digital subsystems can be constructed from Si CMOS. In addition, RF sections have substantial passive requirements for filtering, matching and tuning. However, MCM solutions are large and expensive when compared to a possible IC solution. In this paper we present a hybrid option: use of UltraCMOS® technology in subsystem-level RFIC integration to reduce size and cost of MCM system solutions. Examples from both commercial and satellite applications will be presented and discussed.

Introduction

Wireless systems of all types have evolved in recent years to increase system complexity and reduce total cost of ownership. Original equipment manufacturers ()EM) and satellite hardware manufacturers have modified their fundamental approaches in similar ways. While these systems appear to differ dramatically, they have recognized the core values inherent in integration. Relying on advanced CMOS process technologies, system architectures are now based on digital schemes that can often be provided in a single baseband chip for a complex and often multi-standard solution. RF sections have not yet found a single semiconductor technology that can serve a similar role, so MCM solutions have been the preferred approach.

The desire for integration of RF systems or subsystems is apparent from the widespread publication of efforts aimed at using Si CMOS for a single chip solution. However, this widespread publication activity also demonstrates just how difficult it is to replace the myriad technologies currently in a radio section by a single Si CMOS chip. Hence, the solutions currently in practice are almost all based on MCM solutions.

MCM solutions have several advantages including ability to combine multiple technologies, flexibility, development time and cost reduction (as compared to a traditional discrete solution). Of these traits, the first three are fairly obvious; however cost reduction is less so. MCM solutions do not dramatically reduce part count, labor cost or test time compared to a board level discrete solution; and certainly not compared to what a true IC solution would achieve. However, MCM's are widespread in virtually all wireless systems, including the world's largest and most cost competitive, mobile phones.

The cost savings for mobile phones achieved by using MCM's come from a somewhat more subtle factor: business focus. By having a function such as antenna switching delivered in an MCM, a module manufacturer can use massive economies of scale to optimise cost and performance. Each OEM reduces its R&D costs as well as assembly costs and the entire industry benefits.

In the case of satellite systems, MCM's produce similar effects. Subsystem manufacturers can deliver a module level subsystem to multiple satellite prime contractors and thereby amortize R&D and assembly costs over an entire industry. This benefits both the subsystem supplier and the prime contractor. Of course the end system operator gets a better satellite solution at a lower cost, just as in mobile phones.

This trend toward MCM solutions has been ongoing for many years, driven by ever-smaller components (especially passives) and improved ability of multi-layer substrates (especially LTCC0 to reduce costs. However, most of the benefits have been achieved, so for the trend to continue, MCM manufacturers must find new ways to reduce part count, size and cost.

In this paper we discuss examples wherein RFIC integration in a single UltraCMOS chip has been used to dramatically reduce part count, size and cost of MCM systems. We show a satellite and a mobile phone application to demonstrate that this trend is useful for both very high volume and very high performance systems. We also show that RFIC integration can enhance MCM solutions as opposed to compete with them.

UltraCMOS Technology description

UltraCMOS technology is a fully depleted CMOS technology made in a 100 nm thick Si film on sapphire. Advantages of forming UTSi CMOS transistors on a pure sapphire substrate are manifold including the following:

- Inherent radiation hardness
- Low capacitance, hence high speed at low power
- Fully depleted operation, improving linearity, speed, and low voltage performance
- Excellent RF performance:
  - f_{max} typically 3X f_t (60 GHz at L = 0.5 µm; and 100 GHz at 0.25 µm)
  - very high linearity (+38 dBm IP3 mixers)
  - high Q integrated passives (Q_L > 40 at 2 GHz for 5 nH inductor)
  - high isolation (>50 dB between adjacent devices)
- Integrated EEPROM available without additional masks or process steps
- Multiple threshold options without additional cost
- An extremely low-loss substrate at RF frequencies
- Excellent ESD protection with low parasitics
- New design options over GaAs due to availability of good PMOS transistors
- Optically transparent substrate for use in optical applications
- Processed in standard CMOS facilities on large wafers

Figure 1 shows a cross-sectional comparison between conventional CMOS and UTSi CMOS.. The RF performance of this technology was presented at this conference.[XX]

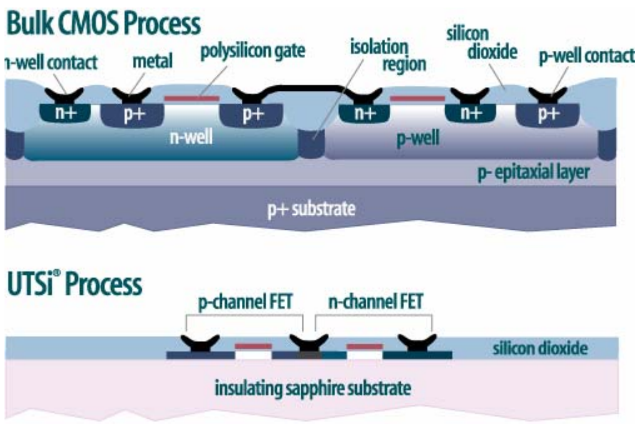

Figure 1. Cross-sectional view of bulk Si CMOS (top) and UTSi CMOS (bottom) showing reduced complexity and parasitics thanks to UTSi CMOS' sapphire substrate.

Application to MCMs

RF integration in this single technology has been discussed in several publications.[XX] Two examples of how such integration improves MCM solutions will be discussed: an antenna switch module (ASM) for GSM mobile phones and an IF downconverter for advanced digital payload of digital communications satellites. In both cases, LTCC substrates are the basis of the MCM.

ASM for GSM Mobiles

Antenna switch modules connect a single antenna to to TX and RX sections of GSM phones. This TDMA system alternates TX and RX pulses, and both cellular (two bands in ~800-950 MHz) and PCS (two bands in ~1.7-1.9 GHz) bands must be covered. Specifications are very rigorous, especially on insertion loss, harmonic distortion and isolation. Of these, distortion is the most critical due to interference constraints. If SAW filters are included, the module is called a front end module, or FEM; the portion of an FEM other than the SAW filters is an ASM.

Figure 2 shows a typical ASM for a tri-band GSM phone (2 cellular and one PCS bands, typically). The top chip is a GaAs PHEMT SP5T chip, with a Si CMOS decoder chip below it. Each throw of the SP5T requires a separate bond wire (and pad on the Si chip, which sets its size and cost) since integration of digital logic on standard PHEMT GaAs is difficult and expensive.

The blocking capacitors are used to create a negative voltage from the RF signal to ensure the switches stay off during negative swings of the TX RF power output. Not shown are complex L-C circuits needed to protect the GaAs from ESD damage (GSM has an 8 kV requirement on the antenna port).

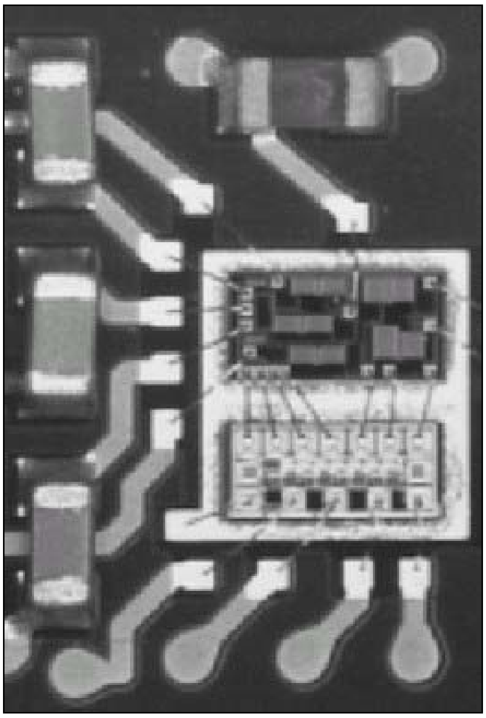

Figure 2. Top view of ASM for tri-band. GSM mbvile phone, including a GaAs PHEMT switch die (top one); a CMOS decoder die; and four decoupling capacitors for a total area of about 15 mm^2.

Figure 3 shows a functional block diagram of a quad band ASM function (both cellular bands and both PCS bands) when a single chip replaces all the components visible in Fig. 2. Key to size and area savings are elimination of all blocking capacitors and the separate decoder chip. Figure 4 shows a single UltraCMOS chip solution that incorporates all devices shown in Fig. 2. (as depicted in the block diagram of Fig. 3.

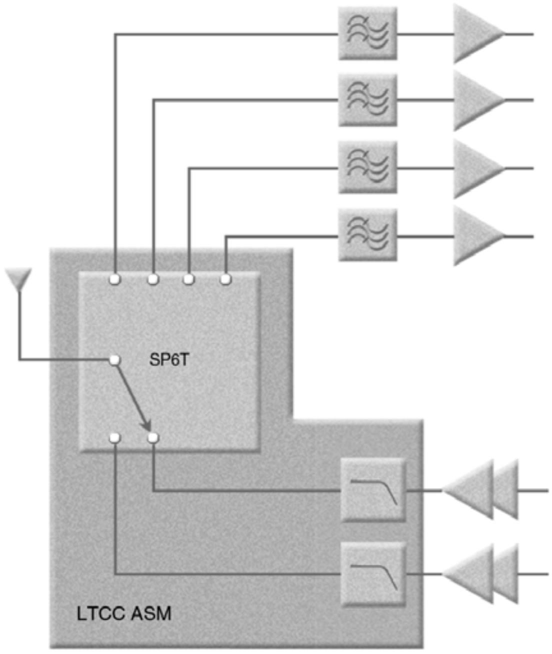

Figure 3. Functional block of ASM. All circled elements of Fig. 2 are contained in a single UltraCMOS IC with total area of 1.5 mm^2, a 90% reduction.

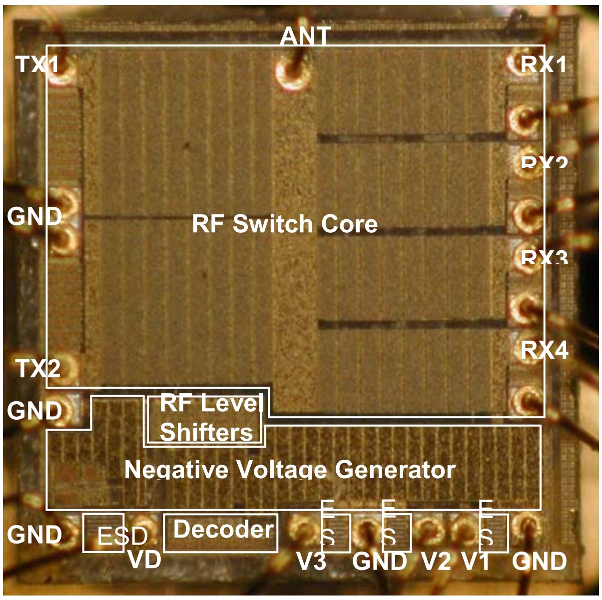

Figure 4. Single chip solution that replaces all the components in Fig. 2, plus adds 4 kV ESD antenna port protection.

In Figure 4 we show the impact of UltraCMOS integration. As can be seen, the ASM reduced in size by over 75%. Since LTCC substrate area and part count were reduced by the similar amounts, overall cost was dramatically reduced. Customer benefits include size and cost reduction along with substantially improved ESD protection. In addition, all active circuits are manufactured in a CMOS technology, the world's most reliable and reproducible semiconductor process.

Satellite IF down converter

The ASM example shown above has semiconductor content for switching and CMOS control logic, but no gain blocks. In Figure 5, we show the block diagram of an IF down converter that has also been reduced to a single UltraCMOS chip.

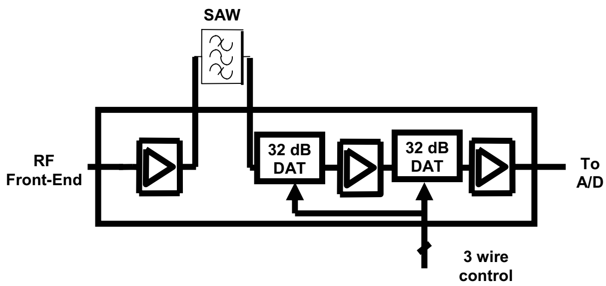

Figure 5. Block diagram of IF down converter on a single UltraCMOS IC, including 64 dB or digital step attenuation (at 0.5 dB/step), 3-wire serial interface, and an overall gain of 80 dB.

Figure 6 shows the complete IF down converter chain in a single chip. Key to its usefulness is integration of two 32 dB (6 bit) digital step attenuators (DAT) both of which are controlled through a single serial interface. Use of digital DAT's has two key advantages:

1. The entire gain control loop remains digital, simplifying design and test, and
2. Gain blocks can be designed as fixed gain rather than variable gain, improving stability and power consumption.

DAT's require high value and high precision resistors integrated with low loss and low distortion switches. The control function and serial interface takes fewer than one thousand logic gates which is trivial for CMOS technology to integrate and consume less than 100 µA of current. The fixed gain blocks reduce power consumption because their range of required operation is reduced as compared to a variable gain amplifier. Since the part is designed in UltraCMOS it meets all radiation hardness requirements of the satellite application.

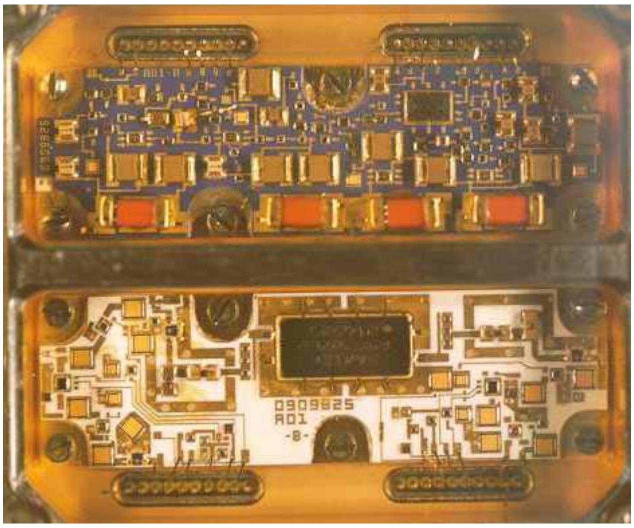

Figure 6. Photograph of existing IF down converter using chip and wire on LTCC substrate (white area in lower half of photo). The integrated solution in Fig. 6 provides about 65% reduction in part count, cost and assembly.

In Fig. 6 we show a MCM module requiring multiple variable gain amplifiers (VGA) and chip and wire assembly of multiple components. Use of digital attenuators was more complex with many components, hence the choice of VGAs with their known power consumption and design issues.

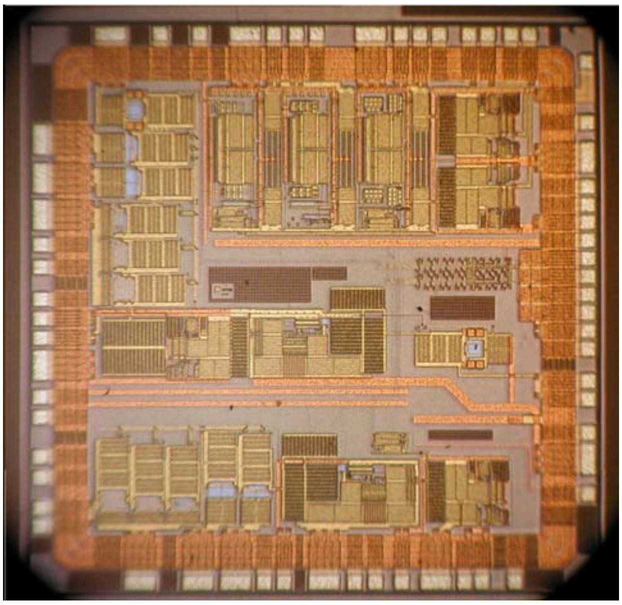

Figure 7. Photomicrograph of single chip IF down converter providing same function as shown in Figures 5 and 6. Digital attenuators and gain control are integrated in a die less than 3 mm on each side.

In Figure 7 we show a single chip solution to the entire lineup of Fig. 5. A new module based on the IC of Fig. 6 has a part count reduction of approximately 65%, which is very valuable in the space environment in which obsolete parts can cause expensive and time consuming redesign or re qualification. Area, weight and assembly cost are reduced approximately in ratio to parts count reduction. And fixed gain amplifiers could be designed to cover broader band than VGAs, so a single part can be used for multiple frequency lineups.

Conclusions

We have shown that MCM solutions can receive substantial benefit by using more highly integrated IC solutions as building blocks inside the MCMs. Area and part count savings of 65 – 90% have been demonstrated. These benefits have been shown to apply in divers applications such as mobile phones and satellite payloads. RFIC integration has been shown to be a complement, rather than competitor, to MCM approaches in RF systems.

Reference:

1. R. Reedy & M.C. Comparini, "Perspective of RF CMOS/Mixed Signal Integration in Next Generation Satellite Systems," EuMW 2003.
2. Dan Nobbe., "Integration-by-parts: An Approach to the RFIC Market", RF Design, pp. 26-30, Feb., 2004.