THE POSSIBILITIES ARE INFINITE

FUJITSU

Motivation for RF Integration

WHITE PAPER

Introduction

While CMOS technology has made great strides in its ability to fabricate radio frequency (RF) circuitry, many RF chip designers have yet to take advantage of this capability. After long relying on more expensive technologies such as silicon germanium (SiGe) and gallium arsenide (GaAs), RF designers who transition to the latest RF CMOS processes gain the enormous advantages of full system-on-a-chip (SoC) integration.

Proliferation of a wide range of wireless applications, from cellular phones to wireless audio/video products, has created enormous opportunities for the semiconductor industry. Although major components in traditional wireless systems have long been fabricated in a variety of CMOS and compound semiconductor process technologies, recent advances in RF CMOS have made it the technology of choice for these applications. RF CMOS is contributing greatly to the successes of wireless products in the marketplace.

The Wireless Landscape

By increasing performance while decreasing cost, wireless semiconductor devices have been key drivers for improving productivity and quality of life for the last two decades. Making phone calls from virtually any location and exchanging text messages and emails has become a way of life.

Instant wireless access to the Internet and location-based services has become affordable and will become ubiquitous in many parts of the world over the next few years. The digital home is being realized with access to high-quality audio and high-definition video anywhere in and around the home—all connected wirelessly. Very-high-speed local and metropolitan wireless networks promise to make the knowledge-based workforce more productive than ever before.

The technologies that make these capabilities available will continue to drive costs down. RF CMOS process technologies are helping to make these products affordable.

The RF System

A typical RF system includes the following basic components:

- Antenna
- RF filter
- Low-noise amplifier
- Mixer
- Oscillator
- Phase-locked loop
- Frequency synthesizer
- Analog-to-digital and digital-to-analog converters
- Power amplifier

Figure 1 is an illustration of an RF system. The baseband processor or the controller, depending on the application, is a system-on-a-chip device that typically contains one or more CPUs, memories, complex logic and analog circuits to make the device function as a cellular telephone, wireless LAN, etc.

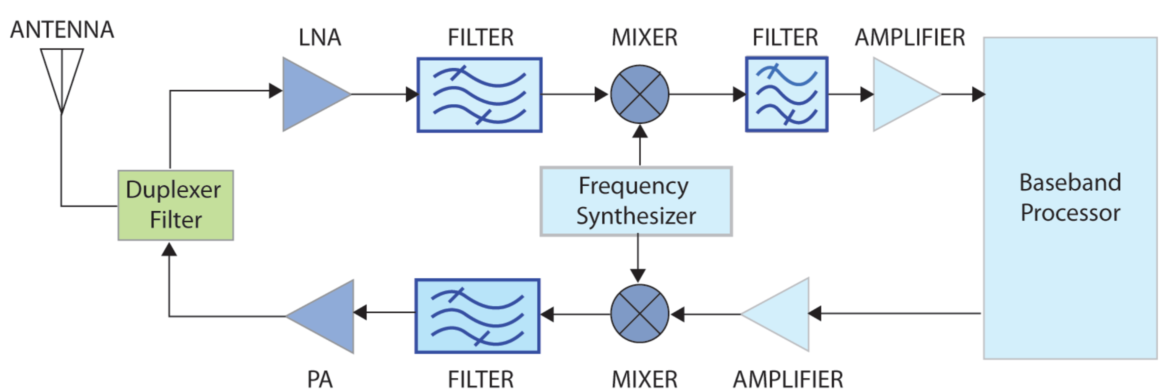

Figure 1 – Simplified RF Transceiver

System-in-Package vs. RF Integration

Most RF systems incorporate several integrated circuits (plus other components) that are fabricated using different process technologies. These processes are optimized for their specific functions. In order to lower the overall bill of materials (BOM) and reduce the form factor of the end product, engineers always want to integrate these functions into the fewest number of chips possible.

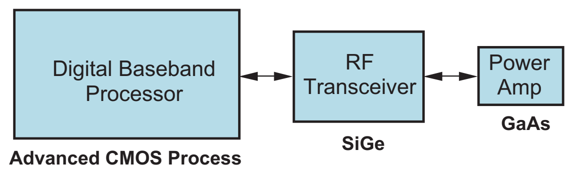

Figure 2 – Block Diagram of an RF System

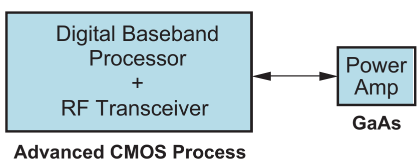

Figure 3 – Integrated RF System

The digital baseband processor or controller is normally implemented in advanced CMOS process technologies – perhaps in the 90 or 65nm nodes.

Although many RF CMOS SoCs have been made, the RF transceiver is still typically manufactured using a silicon germanium BiCMOS process. Gallium arsenide or BCDMOS are among the processes of choice for the power amplifier, which requires high current drive and very linear characteristics.

One way to reduce component count on circuit boards is to put two of the chips into a single package. This system-in-package (SIP) approach reduces the component count, board footprint and power consumption, but not the system cost. The more complex assembly procedure and higher package cost may actually increase the bill of materials.

A better approach is to integrate the RF transceiver and the digital baseband processor into a single SoC. The power amplifier is likely to remain a separate IC in most cases due to its unique functional requirements. Integrating the RF functions with the predominately digital baseband/controller chip has the benefits of lowering the BOM as well as reducing power consumption and the system form factor.

Table 1 summarizes the advantages and disadvantages of the process technologies.

Function	Process Technology	Advantages	Disadvantages
Baseband/Controller	CMOS	High integration level, good analog devices, relatively inexpensive, proven evolutionary technologies, multiple foundry sources	Not suitable for high-power applications
RF Transceiver	Silicon Germanium BiCMOS	Very high frequency capability, high-drive bipolar devices	Costly, two to three process nodes behind logic CMOS
Power Amplifier	Gallium Arsenide	Extremely high performance, very high-drive capability	Very expensive

Table 1: Advantages and Disadvantages of Process Technologies

Why RF CMOS?

The RF system's digital baseband processor is usually the system's largest chip that includes an embedded CPU, millions of logic gates and large blocks of memories. The RF transceiver requires a smaller die and contains up to thousands of transistors and many of the passive components. The power amplifier consists of a handful of large transistors that provide high-current drive to send RF signals through the antenna.

Silicon germanium (SiGe) has been the process of choice for the transceiver for its excellent high-frequency capability and high-current drive. SiGe achieves switching frequencies that are about as high as CMOS that is two generations ahead. However, SiGe is an expensive process technology. It also lags behind the process geometries of CMOS by two to three lithographic generations.

Figure 4 shows that advanced RF CMOS processes have switching speeds (represented by transistor cutoff frequency f_T) that are fast enough for most of the wireless technologies in use today or in development. Future generations of CMOS processes will be even faster, making extremely-high-frequency (EHF) systems that operate between 30GHz to 300GHz affordable.

In addition to switching speeds, transistor architects have also been able to improve MOSFET parasitics and oxide quality to achieve good *1/f* noise performance that is essential for low-noise, high-gain amplifiers and low-distortion oscillators. Production engineers are able to tightly control manufacturing to minimize device mismatch for high-quality circuits. These transistor enhancements allow engineers to design high-gain, low-noise RF circuits with excellent dynamic range.

Passive Components

While characteristics of active devices are critical for amplifiers and oscillators, equally important is the quality of passive components such as resistors, inductors, capacitors and varactors, which are used for filters, mixers, dividers, etc. The passive components fabricated in advanced RF CMOS technologies are as good as or better than those found in traditional RF processes.

RF CMOS technologies have special process modules for passive devices to optimize the characteristics for RF designs. Polysilicon resistors are available with values ranging from several ohms per square (silicided) to one thousand ohms per square (unsilicided). Thick copper wires, up to 3 microns, are available for inductors to achieve high inductance per unit area yet with Q factors in excess of 10 for most common carrier frequencies.

In addition to standard MOS capacitors, RF CMOS commonly offers metal-in-metal (MiM) capacitors with

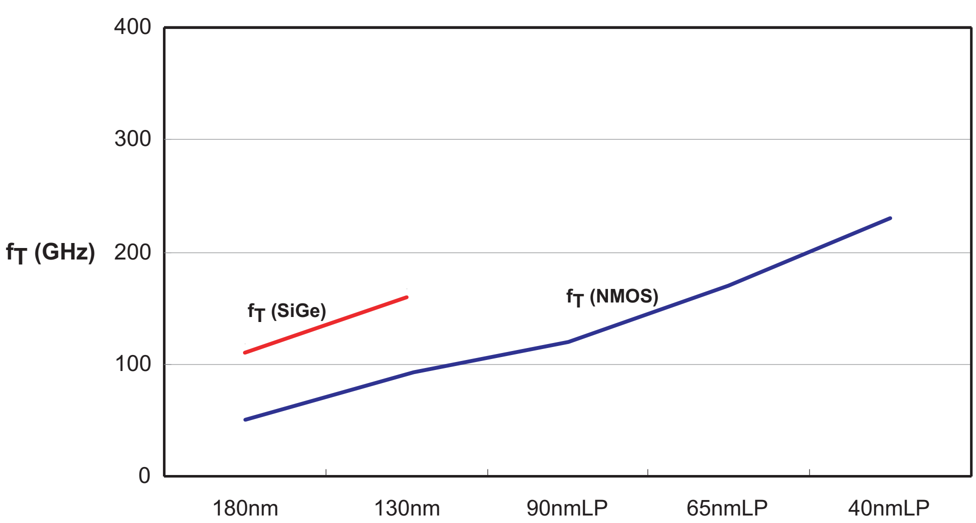

Figure 4 – Typical f_T for NMOS and BJT Transistors in CMOS and SiGe Processes, Respectively (GHz)

unit capacitance from 1.0 to 2.0 fF/μm^2. MIM capacitors can be stacked to produce twice the unit capacitance in the same die area at the expense of additional process steps. Another way to build linear capacitors is using stacked metal fingers to form metal-oxide-metal (MOM) fringe capacitors. A stack of four to five metal layers can produce unit capacitance comparable to that available in MIM capacitors.

CMOS Cost Advantage

Silicon germanium wafers typically cost three to four times more than comparable CMOS wafers of the same lithographic node. Adjusting for switching frequency (since SiGe is faster), SiGe is still about 30 to 50 percent higher than CMOS at comparable performance levels. Clearly it is more economical to integrate the RF circuits in CMOS than to integrate logic in SiGe.

Process Design Kits

Digital designs can be synthesized from RTL using readily available EDA tools. Analog and RF circuits, on the other hand, must be custom designed using components from a wafer foundry's process design kit (PDK). Contents of the PDK include schematic symbols for circuit entry for both active and passive devices, SPICE models for circuit simulation, layout technology files and parameterized cells and physical verification command files for design rule check, layout-versus-schematic verification and parasitic extraction.

Many RF and analog designers prefer to run their own test structures and develop their own design kits due to the inadequacies of foundry-provided PDKs. The benefit is that engineers are able to extract electrical parameters using the exact layout styles proven in previous RF designs. However, it takes several calendar quarters to design and layout the test structures, fabricate a test chip, extract electrical parameters and develop device models before the actual circuit design can begin. The risk of missing the market window due to the long design cycle is high.

To help customers shorten their product development time, some wafer foundries invest in comprehensive RF-optimized PDKs with rich device selections and highly accurate models. Some design kits feature scalable, surface-potential-based transistor models such as PSP for better accuracy. PSP models provide more accurate noise modeling and avoid the problem of discontinuity at high-order derivatives found in common threshold-based BSIM4 models.

Rather than furnishing only a simple collection of pre-defined elements, a high-quality PDK provides tool kits for designers to automatically generate the complete device layout and accompanying models for the exact design requirement. For example, an inductor tool kit enables designers to easily generate the complete layout and device models for a 3nH inductor. This process is far more efficient than having to construct a custom inductor to obtain the proper value or selecting one from a pre-defined collection that includes only 2 and 4nH inductors.

Another capability that improves both design quality and productivity is statistical analysis. Sophisticated PDKs thus provide statistical analysis tools that allow engineers to explore process variation spaces to optimize the design and make appropriate tradeoffs.

Depending on the experience of the design team, RF circuits may require three to four cycles to tune to perfection. However, a good PDK with accurate device models allows designers to minimize time-consuming and expensive silicon re-spin to achieve quicker time to market and lower product development cost.

Summary

Advances in process technologies and circuit design techniques, along with sophisticated RF design kits, have made CMOS technology the platform of choice for wireless designs. Using RF CMOS to fabricate highly integrated single-chip solutions enables products that are smaller, more affordable, more power efficient and have a longer range than previously possible. Proliferation of applications such as cellular communication, navigation systems, personal and local wireless networks, and wireless audio/video links will help drive revenue for the entire semiconductor industry.

For more information

For more information on Fujitsu Manufacturing Services capabilities, please visit the company web site at http://www.fujitsu.com/us/services/edevices/microelectronics/sms/ or send e-mail to iinquiry@fma.fujitsu.com.

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