Some Recent Developments in RF and Microwave Circuit Integration

To meet the demand for more features, smaller size and lower cost, the design of all electronic equipment keeps moving to higher levels of integration. The size and functionality advantages are obvious, but there are many different aspects of the cost equation. Highly integrated devices cut the total component cost of finished products, which reduces assembly cost. In high volumes, automated manufacturing keeps the unit cost low.

The up-front engineering costs of a semiconductor IC or other type of integrated device is usually higher than discrete designs. This is due to the additional design effort to translate the electronic design into a physical design for the chosen fabrication process. Thus, this discussion applies to products with a large potential customer base, or which have uncompromised requirements for the space savings that comes with an integrated device.

Although "integrated circuit" has traditionally meant a monolithic device on a semiconductor substrate, this term now has a wider meaning. Now, any technology that offers a substantial reduction in size, usually accompanied with automated fabrication, may be referred to as an IC. This report will highlight some of these "IC" technologies that apply to high frequency (RF, microwave and optical) systems.

RFICs and MMICs

First are the "classic" semiconductor integrated circuits, where all the technologies have undergone significant changes in recent years. The low-cost workhorse, CMOS, is now being fabricated with dimensions in 0.1 micron range. In addition to the high-profile 2+ GHz computer MPUs, RF and microwave devices in this same frequency range are in production. WLAN, Bluetooth, and similar cost-sensitive technologies have benefitted from the low processing costs—and low power consumption—of CMOS.

CMOS has the disadvantage of higher noise than other RF/microwave IC technologies, so its applications have been primarily in systems with communication range and modulation formats that do not require maximum signal-to-noise performance. Still, there are plenty of applications where CMOS is the best choice.

For higher performance, another "old" technology continues to be improved. BiCMOS, which can accommodate designs with both CMOS and bipolar devices, continues to have a solid niche. It is also a low cost process, but is not low power. In general, BiCMOS is used when the application has a combination of digital and analog circuits on the same chip, in a circuit that required a combination of RF and low microwave frequency response, medium power levels and low noise. Process improvements are largely incremental, since this is a mature technology.

It has been barely ten years since IBM began its major promotion of silicon-germanium (SiGe) technology. In a relatively short time, the process successfully found the answers to problems that arose during early production efforts. Today, SiGe is replacing BiCMOS as the process of choice for most mainstream RFIC applications. Its promise of lower noise and higher frequencies has been met, as well as its promise to deliver that performance with only a tiny cost premium.

Gallium arsenide (GaAs) has had a more dramatic history. Even with a lot of government money behind its development, and early success in providing a huge step forward in microwave IC development, it took a long time and much turmoil to reach today's status of GaAs as a commonly-used MMIC process. Among the companies involved in the MIMIC program that created the GaAs industry, very few remain in the GaAs business.

However, the technology remains strong. It is the process most commonly used for wireless phone power amplifiers, thanks primarily to the development of the heterojunction bipolar transistor (HBT) and indium-gallium-phosphide (InGaP) process enhancements. With its ability to handle higher power than other processes, GaAs is also the typical choice for RF switches. Its original advantage of higher frequency operation is still significant, making GaAs (and its enhancements) the only choice for many microwave and mm-wave ICs.

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There are other processes and materials that have an impact on high frequency ICs. Some of these are derivatives or enhancements of those noted above; others are not yet in significant production. The most significant new processes are aimed at mm-wave and higher frequencies, and we are watching their progress with great interest.

Multi-Chip Modules

Sometimes, the applications demands an optimum combination of performance and cost features—for example, complex digital circuits (CMOS), RF/IF circuitry (SiGe) and power amplifier/switching circuits (GaAs). In addition, filters and couplers may be required to support the active devices, which may be SAW devices or microstrip circuits on high quality substrates.

In the past, these devices were collected in an assembly on a printed circuit board or ceramic substrate. Perhaps they were even individual modules in an enclosure. The evolution to smaller size has made the multi-chip module (MCM) a growing part of the "integrated circuit" family. MCMs can be assembled with automated wirebonding equipment, improving device-to-device consistency, and the smaller dimensions accommodate the higher frequency of many new applications.

At this time, MCMs contribution to lower costs is not in materials cost—they remain a "premium" solution. They do, however, greatly simplify the assembly of the finished product. In many cases, an MCM is purchased as a drop-in solution for the radio portion of a non-radio product in the computer, entertainment, security, or other market segment. When used this way, the savings in engineering time are substantial.

Multilayer Technologies

Another means of integrating more functions into a single package is by embedding them into extensions of conventional printed circuit or ceramic substrate technology. Low-temperature co-fired ceramic (LTCC) and multi-layer laminate assemblies dominate this type of circuit integration. Both have advantages over traditional semiconductor fabrication for key high frequency performance issues.

The first advantage is three-dimensional construction. In these circuits, inductors can be helical, which have much higher Q than a planar spiral, as required for a 2-dimensional surface. Cross-coupled stripline topologies such as Lange couplers are easily implemented. Shielding layers are easily fabricated to isolate portions of the circuit.

The second advantage is better dielectric properties. With the exception of silicon-on-insulator (SOI) processes, semiconductor substrates do not have an optimum dielectric constant, and may be lossy at microwave frequencies. On the other hand, ceramics and established laminate materials are designed specifically for microwave applications. Although the low-temperature ceramics used in LTCC circuits are not as good as traditional alumina, but they are a lot better than silicon.

Packaging Challenges

When more functions are included in small space, it can be difficult making the necessary connections to external circuitry. Signals, power and control voltages need to be routed to the necessary parts of the integrated circuit. There are several issues that require attention by the designer, beyond the basic functionality of the device itself.

First, there must be enough connections to gain access to the various points on the IC. If many connections are required, a ball grid array (BGA) package is the typical solution. When a more modest number of connections is required, an SOIC-type package or embedded edge connections (as in a TQFP) are used.

The next issue is isolation between connections. Small size means closer spacing and potentially greater coupling. Routing of signals on- and off-chip requires extra attenuation. Finally, the reactance of the connection itself can be a significant factor. IC designers now include the package as part of the circuit, and their simulation tools include packages as available circuit element models.

Fundamental Engineering Changes

Higher levels of integration require corresponding changes in engineering skills. Just as engineers had to adapt when changing from vacuum tubes to transistors, or from waveguide to microstrip, they need to move from modular designs to integrated circuits. Instead of designing on PTFE laminates or ceramic substrates, they now are designing on GaAs, SiGe or other material.

Integrated design is somewhat harder to divide into the different disciplines—DC power, RF/microwave, analog and digital control, etc. Several designers may be working on the same piece of silicon, which requires greater interaction than working on different modules inside a big box. In just the past two to three years, EDA tool providers have made huge strides toward accommodating all the designers involved in a single project, and company management has implemented new teamwork procedures.

There will be new challenges in the future for higher integration and the use of new materials and technologies. The next frontier appears to be reaching low costs for mm-wave circuits. After that, distributed systems, reconfigurable circuits ... who knows what else?