Toward a real system integration; A direction of IC technology

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Abstract

A direction of IC technology is discussed with relation to mixed signal and interconnects technology for realizing real system integration. IC technology has progressed from an integration of simple digital circuits to an integration of increasingly complicated circuits and devices. Mixed signal technology is currently widely used for SoCs to compensate damage of externally received signals. In CMOS RF circuit technology coping with the size of on-chip inductor technology is vital for many SoCs for wireless systems. Millimeter wave communication will realize Giga-bit wireless data transfer and requires interesting new IC technologies such as a transmission line and an on-chip antenna technology. Transmission of electric power to chips will be an important future IC technology for fine-grained power management systems and ubiquitous systems.

1. Introduction

IC technology has progressed from an integration of large scale digital circuits toward real system integration. A real system needs not only digital circuit but also analog, RF, and power management circuits. This paper discusses a direction of IC technology and required interconnection technologies.

2. Mixed signal technology

A role of System-On-Chip technology (SoC) is to realize system level integration with reasonable cost. Since a SoC can increase the system performance and reduce the needed number of LSIs and total cost, it has enabled the emergence of a new market of new digital consumer electronics, such as digital cameras, DVD systems, and digital TVs.

Almost all electrical systems, even if it is called a digital system, need analog circuits. This is because the main signal processing is done with digital method; however external signals often needs to be treated like an analog signal even if it is called digital. The wave shape of external digital signal is deteriorated by imperfect frequency response of the transmission channel, signal reflections, and cross talk. One example is a DVD recorder. Figure 1 shows signal processing circuits for the DVD recorder [1]. The DVD system uses digital recording; however a pick up signal from the DVD disc is unclear and will result in unacceptability large error rate since it contains large noise, signal damage, and large timing jitter. For the reduction of error rates, digital filter, error collection, and clock recovery circuits are required. Digital processing methods can solve these system issues however analog circuits are still required.

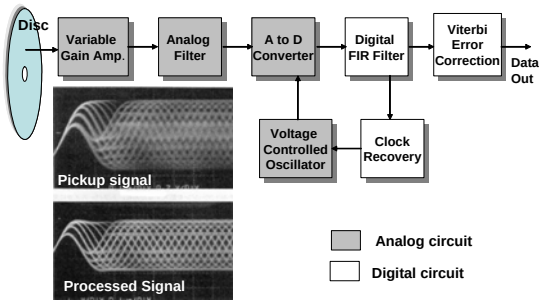

Fig. 1. Mixed signal processing for a DVD system [1].

An ADC is needed to convert the wave shape of a pick up signal to digital values for digital signal processing. An analog filter and a variable gain amplifier are needed for preprocessing before the ADC. Processed signal is very clear and will realize stable low bit error rate systems.

This is just one example and currently almost all digital recording system such as HDD and digital network systems such as Ethernet use this mixed signal processing technology.

CMOS process has been modified slightly to address this technology. MIM capacitors are added to provide small mismatch capacitance needed for high precision A/D converters and triple-well technology used to isolate substrate noise between digital circuits and analog circuits have been introduced.

3. CMOS RF technology

Digital wireless communication technology emerged during 1990's and the market of cellular phones has become almost the same as or larger than that of the personal computer. Communication between people and between chips is becoming more important than processing the data itself. Wireless communication is often more desirable than wire-line communication**.** CMOS technology had not been regarded as a more suitable device for RF applications than bipolar technology in 1990's, however technology scaling has

increased the cutoff frequency up high enough for GHz frequency signal processing, in addition circuit design technique aimed for CMOS technology has enabled the use of CMOS technology for RF applications. After the year 2000; beginning with wireless networking chips, followed by cellular phone chips have used CMOS technology. CMOS process had to be addressed to realize high Q inductors and varactors.

The quality factor Q of inductors affect the fundamental performance of RF circuits.

Phase noise S and current consumption I of LC oscillators which is one of the most important performance factors in wireless systems, have the following relations with Q of inductor.

$$I_{osc} \propto \frac{1}{Q} \qquad S_{\phi} \propto \frac{1}{Q^2}$$

Thus increase of Q is the first priority of oscillator design.

The Q of inductor is defined as;

$$Q(\omega) = \frac{1}{2\pi} \cdot \frac{E_{magnetic} - E_{electric}}{E_{loss\,/\,cycle}}$$

Thus to increase Q, increase of inductance and substrate resistance and decrease of parasitic capacitance and series resistance are needed. Conventionally thicker metal, far from the substrate and neighboring metals, and a highly resistive substrate are effective, as shown in figure 2.

The thicker third layer metal attains a higher Q of 8 compared with thinner metal and the thicker 5th layer metal increases Q up to 11. Higher resistive substrate increases Q even further.

This condition is just the same as the condition for high quality global interconnects. Conventional Q of on chip inductor is less than 10 and an inductor of which the thickness is greater than several um and formed on a passivation film is used to obtain higher Q.

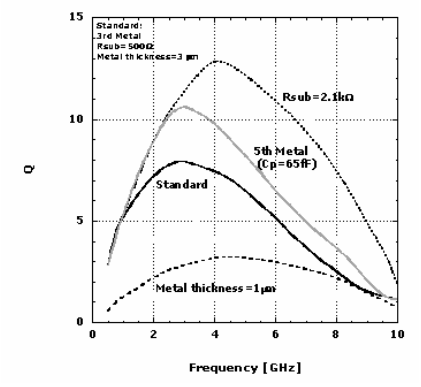

Fig. 2. Characteristic of inductor Q.

Another issue of the inductor is the large occupied area. Figure 3 compares chip area and chip cost of mixed signal SoCs for several design rules normalized by 0.35 um technology [1]. If an occupied area of analog circuits can't be scaled, the total cost will increase even if the area of digital circuits is scaled by decreasing the design rule. A use of inductor to form resonators is effective to reduce noise power, to separate wanted signal from unwanted signals, and increase signal power. Thus conventional RF circuits use many inductors. However recent RF LSIs decrease the number of inductors [2]. One reason is to reduce occupied area and the other reason is to address wide frequency range such as UWB and multi-band radio. An oscillator still needs inductor to reduce phase noise, however almost all RF circuits can be designed without inductors. The performance without inductor decreases a little however the chip cost can be decreased remarkably.

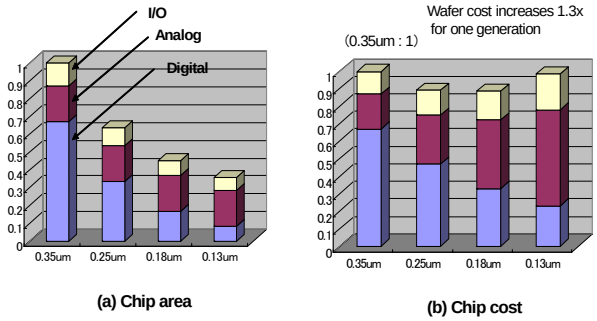

Fig. 3. Chip area and cost of mixed signal SoC [1].

4. Millimeter wave SoCs and proximity data links

The frequency range used in current wireless systems is less than 5 GHz, however 60 GHz will be used for future millimeter wave communication. Millimeter wave communication is suitable for short distance broadband communication such as in-room communication between a tuner and a display in HDTV systems. Device size can be scaled and data rate can be increased up to several Gbps. Small size of inductor and/or transmission line will be used to realize impedance matching, resonators, and filters. The size of transmission line becomes feasible on IC technology when signal frequency is 60 GHz corresponding to a wavelength of about 2.5 mm.

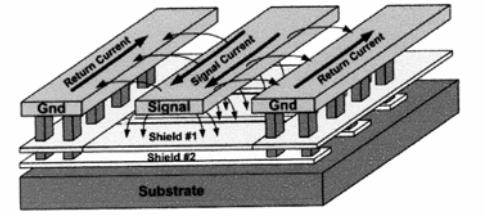

Fig. 4. A coplanar transmission line [3].

The structure of transmission line should be designed so as to minimize the energy loss at high frequency. One large loss occurs in silicon substrate. Some shielding techniques should be applied as shown in figure 4 [3].

Another interesting technology for millimeter wave application is on-chip antennas. Antennas can be integrated on a chip and this means all needed components for wireless systems can be integrated on a chip.

Figure 5 shows one example of the on-chip antenna [4]. Four antennas are integrated to form the phased-array system. The phased-array system can change the radiation

pattern and realize beam forming that is useful to increase sensitivity of wireless systems or to separate channels by controlling signal phases of each transmission signal to the antennas. On-chip antenna is a new technology and more suitable structures will be investigated in the future. Applications for millimeter wave technology will open new vistas for silicon integrated technology.

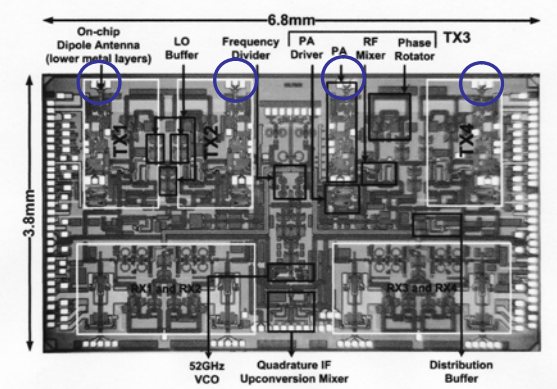

Fig. 5. On-chip antennas on a millimeter chip [4].

Another use of the inductor is for inductive coupling for high speed data link to realize proximity data transmission between chips as shown in figure 6 [5]. 3D integration needs high density, high speed, and low power data transmission techniques. The inductive coupling link can realize high speed data transfer to stacked chips. Furthermore the ESD protection circuit is not required in contrast to the conventional metal to metal contact. An ultra high speed data rate of Tbps with ultra low energy has been reported.

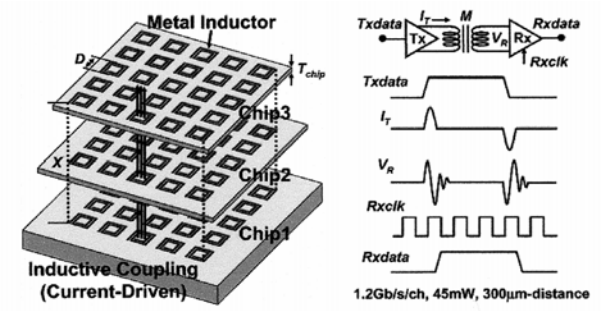

Fig. 6. Inductive coupling high speed data link [5].

5. Micro power systems

High speed data transfer has been realized; however electrical power transfer and control will become important for real system integration. An adaptive V_{dd} control is needed for current SoCs to reduce power dissipation. A relatively higher V_{dd} is needed for high speed operation and lower V_{dd} is adequate for low speed operation. External DC-DC converter are used for current SoCs, however on-chip distributed DC-DC converters are more effective to fine-grained adaptive controllers for each circuit block.

High Q and compact inductors and high density capacitors are required. Conventional inductance used for DC-DC converter is too large to be embedded on a chip. However higher operating frequency with introduction of high permeability materials can reduce the occupied area of inductors. Figure 7 shows a cross section of the inductor surrounded by insulation and CoZrTa magnetic core material [6].

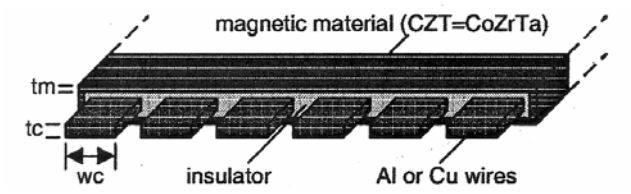

Fig. 7. A inductor surrounded by magnetic core [6].

A coupling factor of 0.98 and L/R ratio of 50 ns have been obtained at wire width of 8 um and wire thickness of 1.25 um. The DC-DC converter has attained 85 % efficiency with this on-chip inductor.

Wireless power transfer to the chip is another important technology to realize real system integration. In-vivo chips need micro power supply systems and some applications need wireless power transfer systems. Figure 8 shows artificial retinal prosthesis system [7]. An external transmitter transfers electric power as well as image data to the chip located in an eye ball by the inductor coupling.

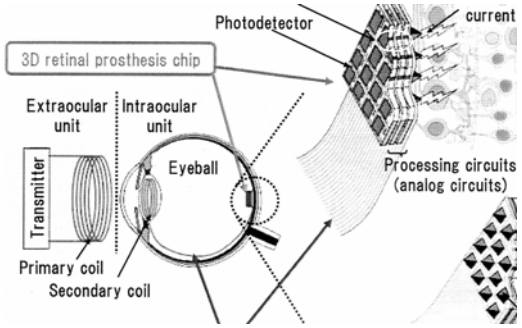

Fig. 8. Artificial retinal prosthesis system [7].

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