# ANALOG- DIGITAL LSI ON THE $e^{+t}$ CURVE

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## INTRODUCTION

The title of this paper was selected to indicate that large scale integration (LSI) of analog (linear), digital and combined monolithic analog and digital (A & D) circuits for telecommunication systems is progressing at an exponential rate. As is the case with exponential functions, near term (i.e., when t is small) increases are rather modest, but, once started, the function grows rapidly. This is the case of A & D LSI: it is just starting to take hold, and impressive gains are expected in the future. The purpose of this paper is to explore, from the system point of view, some of the recent technology developments that have taken place and that are expected to impact the design of future telemetry, communication and sensor equipment.

## SECTION I: THE ROAD TO LSI

Digital LSI has been well established and improvements are announced almost monthly. Analog LSI, on the other hand, has not achieved the same degree of development, but is receiving considerable industry and government attention. Digital LSI has achieved densities of about 30,000 transistors, on a 200 by 200 mil silicon die. Analog LSI has not even been defined. For this presentation it is assumed it is a complex function on a die of about 9,000 square mils or larger.

The development of digital LSI started some 15 years ago, with commercial and military applications taking place mostly during the last five years. Many of the activities, decisions and conditions that took place during the development of digital LSI will no doubt influence the development of A & D LSI; some of these are described in this section.

The greatest impetus for the development of digital LSI was the existing well-established capability for producing medium scale integrated (MSI) circuits, and the expectation of a large volume market. A less appreciated condition also existed: the technical and functional requirements were well understood and as a result fewer people were involved in information gathering, coordination and decision making. The ultimate measure of success for circuit manufacturers was the delivery of a product that satisfied existing needs. LSI memories, microprocessors, and interface circuits benefited from the convergence of an established production capability, a large market place and well defined functional needs. As a result, their development has been impressive and rapid. To some degree, similar conditions exist for the development of A & D LSI.

During the past few years, a respectable number of analog LSI and MSI devices have been produced (1). These include phase lock loops, modulators, operational amplifiers, phase shifters, phase detectors, analog to digital converters, voltage controlled oscillators, comparators, multipliers, voltage regulators, correlators and function generators. The development of such general purpose devices was facilitated because the functions were well defined and had a large application base. In many systems, these basic building blocks have been combined in hybrid packages to effectively form major subsystem functions. They, in effect, provide guidance in partitioning for LSI implementation. In some special purpose space systems, the hybrids have been the basic building blocks out of which special purpose LSI circuits evolved.

General purpose monolithic A & D LSI technology has been inhibited by power-speed constraints, lack of functional definition, limited market base, and the need to combine linear/digital and bipolar/unipolar technologies. The impact of each of these constraints is being minimized. Processing changes and combined bipolar and MOS (BIFET) technology is reducing power. Existing hybridized systems and well defined subsystems for the large radio, TV, and telephone markets are providing functional definition requirements and the incentive to pursue development. The commercial and military space markets, where speed, power, reliability, and weight are of major importance, exert major forces in the development of A & D LSI. Enough linear and digital circuits, such as analog to digital converters and microprocessors with linear circuits, are already on the market to indicate that the problems of combined analog-digital processing are being solved.

The development of digital LSI required trade-offs and evaluations in terms of power, pin-count, producibility, speed, and reliability. For specialized applications, these activities continue to be of importance.

Figure 1 shows a block diagram of a typical communication system (2). The overall system consists of both analog and digital circuits over a frequency range of GHz down to Hz. The emphasis up to now has been to develop the circuits required to implement individual functions. The approach to LSI development has been to examine the functions that need to be improved, and then to define the specific circuits to be fabricated. The complexity specified is, of course, influenced by industry’s capability to produce the devices with an acceptable yield. Major requirements in the development of LSI, especially for space applications, have been higher speed, lower power and weight, and increased reliability.

Silicon bipolar and CMOS technologies have been the mainstay of A & D LSL For higher speed application (MHz and GHz frequency range), GaAs is achieving considerable application, Bubble memories, surface acoustic waves and charge transfer devices are other technologies finding increased application.

**SECTION II: RECENT DEVELOPMENTS**

This section discusses some recently developed circuits that fall under the category of A & D MSI/LSI circuits. The purpose is to point out some of the more significant LSI available to designers, and also to indicate industry's capability to produce complex and unique circuitry.

Intel recently announced an 8 bit NMOS microcomputer (the 8022) incorporating an 8 bit A/D converter (Figure 2). In addition to a digital interface that can digitize up to two analog signals, this device operates on an internal clock and has basic instruction execution time of 10 microseconds. Eight and 16 bit microprocessors are also available. The Intel 8086, 16 bit n-Acroprocessor is shown in Figure 3.

Another A & D MSI device is the Motorola MC 3418 Continuously Variable Slope Delta Modulator/Demodulator. This device receives analog voice signals and generates a pulse width modulated digital train for transmission. It receives a similar digital serial pulse train and generates the analog equivalent.

The telephone industry has identified a need for converting voice analog signals for digital transmission. Non-linear analog to digital to analog converters, such as the Signetics ST-100, referred to as "Codecs" (for coders/decoders) have been developed. These devices receive a voltage in the ± 3 volt range and generate 8 bit digital words according to standards established by the telephone industry. They also receive 8 bit digital words and provide the corresponding analog voltage.

Sprague recently announced an "integrated motion detector" the ULN-2232A. This device detects light, and when the light level changes ± 5% it generates four second alarm signals to drive flashing lights or generate musical sounds. It contains linear and $I^2L$ digital circuits in the form of voltage regulator, amplifiers, photodiode, counter, timer, oscillator, D to A converter, and output drivers. The die size is 116 by 75 mils, and it was developed primarily for the toy market! What technology breakthroughs were needed to produce this device ? The answer is that only refinements of existing processing capability were used, and the business decision was made that a large market existed for the circuit.

Sprague has also developed monolithic linear circuits (ULN 2204A and ULN 2242A) that provide complete AM/FM receiver functions. These circuits are significant because many different analog functions are incorporated in a single chip; these include an analog multiplier for the mixer function, IF amplifiers, AM detector, FM detector, and power amplifier.

Multiplication of two signals is one of the basic signal processing functions. When two sinusoidal signals are multiplied, the result consists of sum and difference frequency signals. One means of combining (modulating) or separating (detecting) complex signals is to provide the appropriate multiplication and filtering. Analog multipliers have been on the market for several years. A typical multiplier is the XR-2208, a four quadrant multiplier with an output buffer amplifier and an operational amplifier.

Analog multipliers depend on transconductance parameters which are subject to temperature variation and the use of matched transistors. Further, high power is required since the active devices must operate in the active region. Digital multipliers eliminate most of these problems. Eight and 16 bit multipliers are available that operate at about $10^7$ multiplications per second.

Other basic telecommunication signal processing functions include signal delay and filtering. Charge coupled devices (CCDs), such as the Reticon 512 stage "quad chirped transversal filter/R5601" (4) and surface acoustic wave (SAW) devices have been developed that provide improved functional performance with appreciable reduction in power and weight over discrete implementations. SAW's devices are delay lines, used for IF filtering. They consist of a piezoelectric quartz or lithium niobate crystal substrate over which interdigitated electrodes are deposited to generate a surface acoustic wave and to sense the piezoelectrically induced voltage (5).

Power supply systems have been a major component of telemetry and other electronic equipment. Within the last two years complex integrated circuits have been produced that simplify considerably the design of switching power supplies and have resulted in reduced power, volume, complexity, cost and design/test time and have improved reliability. Typical of these devices is the Silicon General SG 1524. This is a 16 pin device that on a single chip generates a chopping pulse, pulse width modulates the chopped pulse by sensing the level of the output regulated voltage and provides current limiting and shutdown control capability.

Correlation of analog and digital signals is another common operation in signal processing. TRW produces a 64 bit digital correlator (TDC 1004J) with a 15 MHz correlator speed. This device correlates two 64 bit signals and generates a current that is proportional to the correlation function.

Analog to digital and digital to analog conversion are other functions widely used in the communication industry. This has resulted in several devices, typical of which is the National 8 bit CMOS A/D converter. This converter has an internal 16 channel multiplier which selects one out of 16 analog signals for conversion into an 8 bit digital output. The converter utilizes a successive approximation algorithm. Fast converters (up to 100 x $10^6$ samples per second) using voltage comparators have also been available. To minimize circuitry, these converters are usually resolution limited to 6 bits or less.

Other LSI circuits that are well-known are the 4K to 64K bit (Figure 4) MOS RAM memories, the $10^5$ to $10^6$ bit bubble memories, and the interface circuits in the form of universal synchronous and asynchronous receivers/transmitters (USARTs) and the MIL-Standard 1553 and IEEE interface controllers.

## CONCLUSION

Analog and digital LSI have made appreciable inroads in the design and implementation of communication systems. LSI/MSI circuits that have found considerable application have been microprocessors, memories, A/D converters, delay lines, filters, interface circuits, multipliers, op-amps, phase shifters-detectors, and correlators. The use of these devices has resulted in considerable reduction in power, weight and volume, increased reliability and provided improved functional performance.

The full benefits of LSI can be realized when a larger portion of the system can be reduced to LSI circuitry. This will require that systems designers generate a clear definition of the requirements. The requirements will provide the direction that industry needs to proceed to develop and produce the required circuits. Since the newer LSI circuits will be for specialized and customized applications, the combined efforts of system and circuit designers will be of greater importance. The specialized circuits will not have the advantage of a large volume market, but the semiconductor industry has demonstrated the capability of producing cost effective specialized LSI.

## REFERENCES

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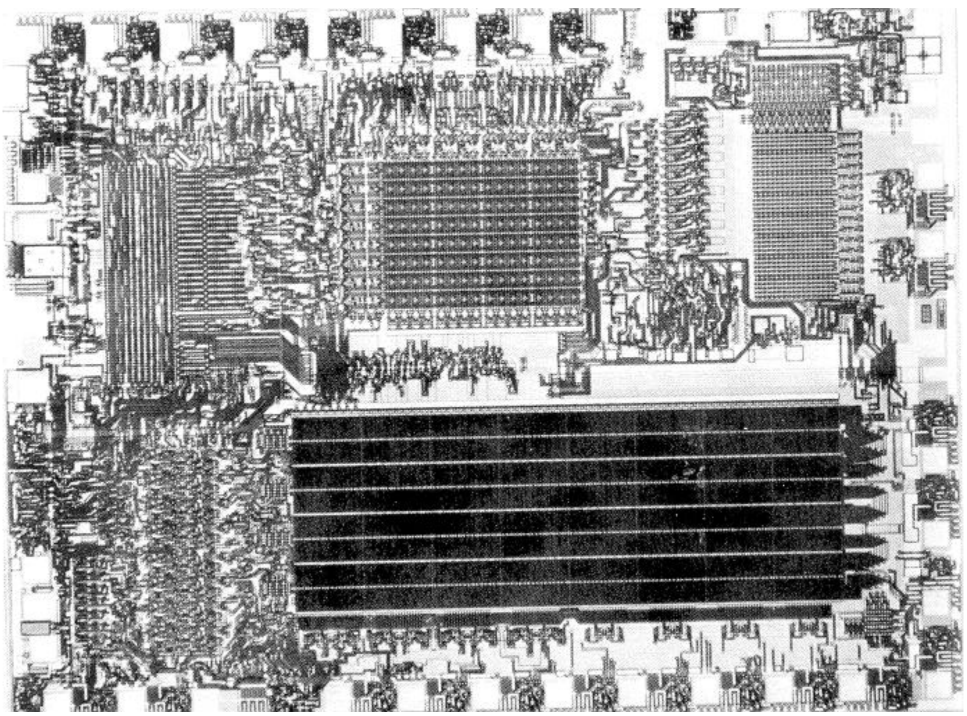

**Fig. 2: The INTEL 8022 Microcomputer consists of an A to D converter 2K bytes of ROM, 64 bytes of RAM, 8 bit CPU, clock and oscillator and 26 digital I/O lines. Die size is 200 x 225 mils. (Photo courtesy Intel Corporation)**

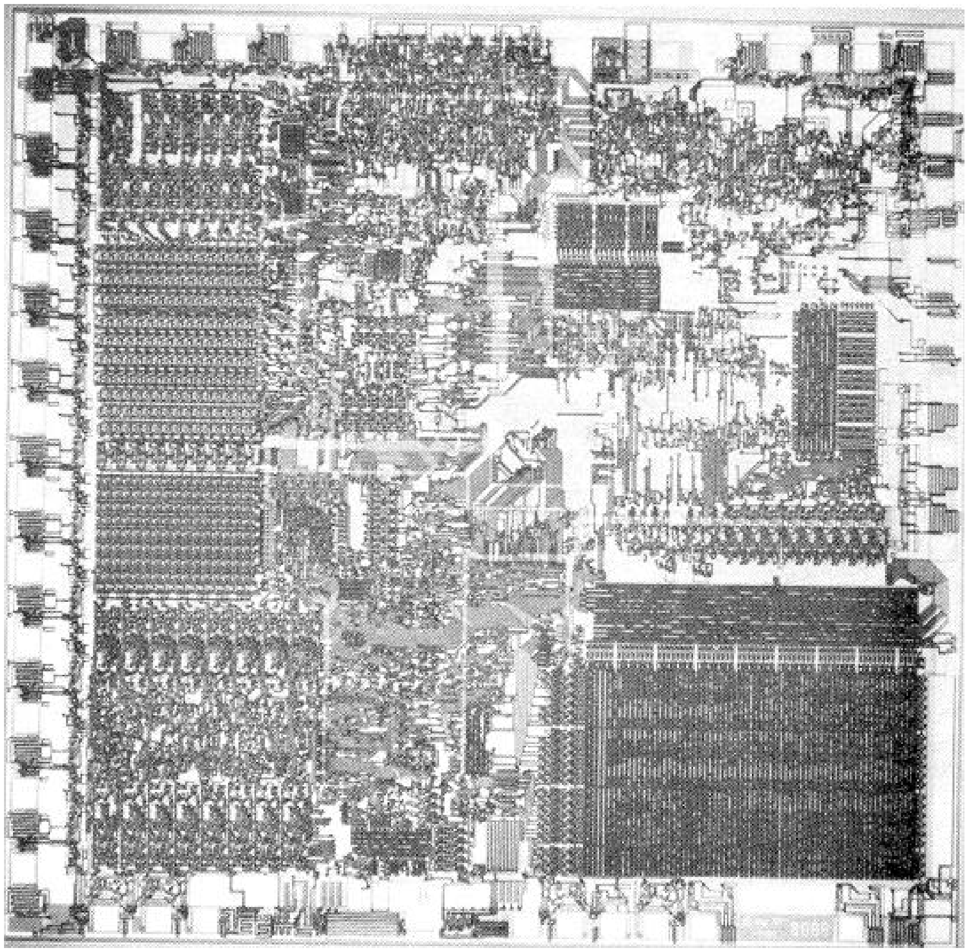

**Fig.3: The INTEL 8086, 16 bit NMOS microprocessor on a 225 x 225 mil silicon die contains 29,000 transistors. It executes over 200 instructions, including multiply and divide. (Photo courtesy Intel Corporation)**

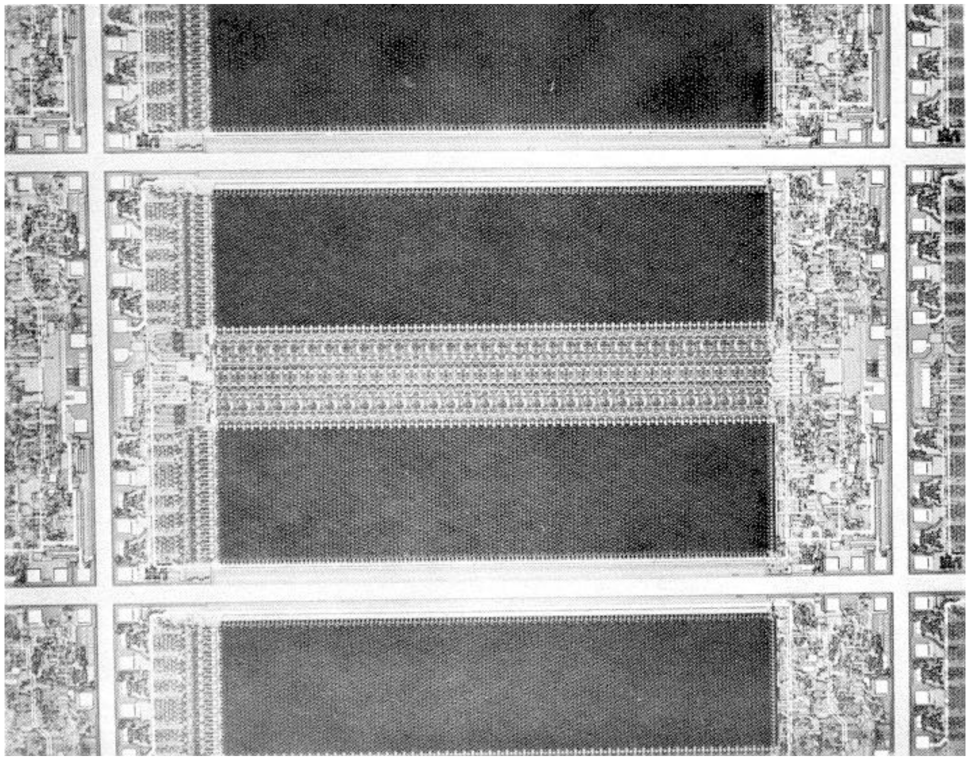

**Fig. 4: The MK4116 (P)-2 is a 16,384 x 1 bit dynamic RAM on a 105 x 205 mil die. It has a cycle time of 320 nanoseconds and consumes 462 mw. (Photo courtesy MOSTEK Corporation)**