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Invited

Past, Present and Future of Si LSI - Reminiscences about a Single MOSFET and Prospects for Multifunctional Si-Subsystems in the 21st Century

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Abstract

The concept of integrated circuits was initiated to overcome reliability problems by simplifying the fabrication process. Until now VLSI progress has been driven by DRAMs, approaching the integration level of 10^9 MOSFETs with a quarter-micron design rule. The economic situation has been lucky and the start of mass production for each DRAM generation has always been harmonized with new market. But since we are approaching the fundamental limitations both in devices and systems, we must reconsider the essential features of integrated circuit technology when we explore the Si VLSI of the next century.

1. The early development of Si Integrated Circuits -- with my reminiscences concerning a single MOSFET

The idea of integration of electronic components in a large system was first suggested by G.W.A. Dummer at the Electronic Components Conference held in Washington, D.C. in 1952. At that time the aim was to deal with the complexity and reliability problems of large electronic systems such as radar [1]. As a matter of fact, one of the motivations in developing monolithic semiconductor integration, invented by J. Kilby in 1958, is to simplify the fabrication process of electronic circuits both in technology and materials [1][2]. The wiring structure on the surface of semiconductors proposed by R. Noyce in 1959 also served as a key structure for VLSI's by simplifying the fabrication process, improving system reliability, and reducing assembly cost [1][3].

In the early 1960's I was working on transistor dc amplifiers for use in dc analog computers. Stable operation of three-stage high-gain transistor dc amplifiers at that time was very difficult to achieve because of the poor characteristics of the germanium transistors then available. Figure 1 shows "the new device" that I proposed and developed from a grown-type pnp transistor in order to balance out drift signals and thus increase the stability of the amplifier [4]. This was my starting point in keeping company with integrated circuits for over a quarter century.

The most important device, currently used in Si LSI's, is the Si MOSFET. In 1993, the worldwide sales of integrated circuits is estimated to be US$ 61 billion with over 78% MOSFET-based sales. The MOSFET was first proposed and fabricated by D. Kahng and M. M. Atalla in 1960. This device, shown in Figure 2, had a channel length of 25μm and a gate oxide thickness of over 1000Å.[5]

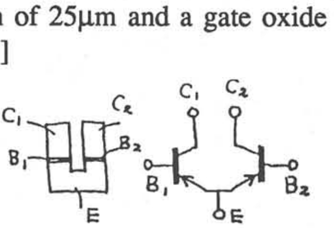


Fig. 1 "New device" for balancing out the drift signal in transistor dc amplifiers [4]

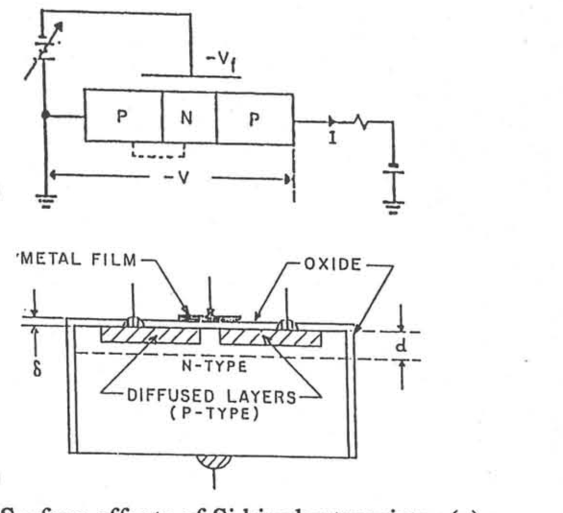
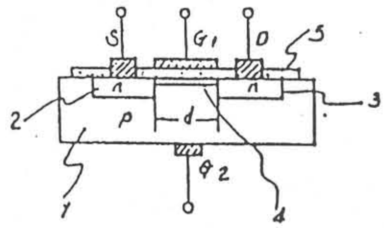
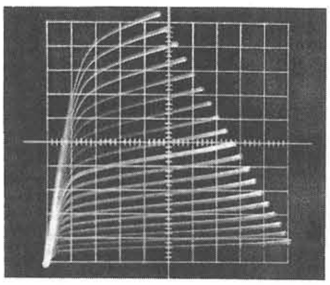


Fig. 2 Surface effects of Si bipolar transistor (a), and the first MOSFET (b)

The invention of Si MOSFET seems to have been brought about by the failure analysis of rejected Si npn transistors. In the early days, Si transistors were made by a grown/melt-back process with poor passivation on their surfaces. They frequently suffered from current gain instability due to parasitic surface channels. As a circuit engineer working on high-gain dc amplifiers, I was very much surprised to find that some of the npn transistors showed extremely high ac current gain of over 10,000 at a base current of the order of $5X10^{-11}$ amperes. This observation initiated the fabrication of the first MOSFET in Japan by M. Ono in 1963 [6]. It's structure and characteristics are shown in Figure 3. As far as I know, M. Ono invented the MOSFET independently from D. Kahng and M.M. Atalla; the basic idea of using silicon and thermally grown oxide was the same in both cases, and this method is still used in the most modern VLSIs. These are my reminiscences about the single MOSFET thirty years ago.

(a)





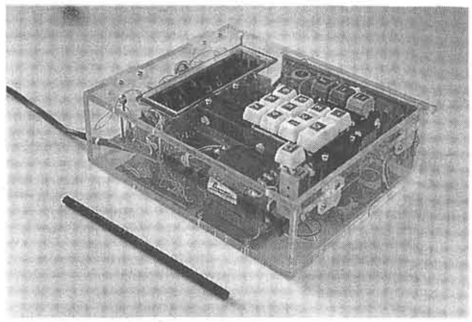
(b) 5F-100-2, #34 VD ; 2V/div, ID; 2mA/div
VG ; + 0.2 V/ step

Fig. 3 The first MOSFET in Japan developed by Mr. M. Ono (a) and its characteristics

The MOSFET would not have become a main stream VLSI device if the hand-held calculator had not been developed by Sharp Corporation. Figure 4 shows a prototype calculator with ten MOS-LSIs of 200-gate integration level, made by the author's group in 1968 [7]. The MOS-LSIs had gate length of 12.5 μm, threshold voltage of 4.0 volts and gate oxide thickness of 1200Å. The HD3200 series MOS-LSIs from Hitachi were the first commercially successful MOS-LSIs in the world, as far as I know.

To summarize Si integrated circuits were initiated and developed to overcome reliability problem by simplifying the fabrication process and their main device was invented almost by accident during a reliability study of failed bipolar transistors.

(a)



(b)

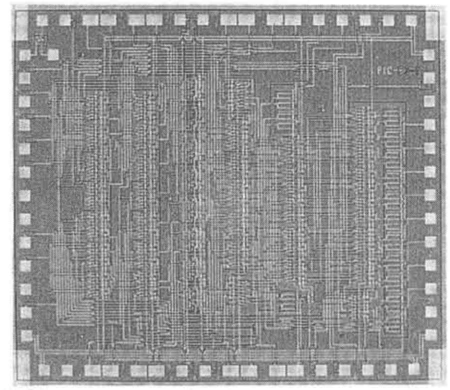


Fig. 4 Proto-type calculator (a), and 200 gate MOS-LSI used in the calculator (b)

2. Present Status of Si-VLSI's -- where we are now?

The "VLSI revolution," ushering in a new epoch in the electronic industry, has allowed progress to such an extent that more than 10^8MOSFETs are now fabricated on a single chip. For example, experimental 256-Mbit DRAMs using 0.25-μm design rule were reported at ISSCC this year [8][9][10]. A high performance processor chip operating above 300 MHz clock frequency having 468k bipolar transistors with f_T=13 GHz was also reported even earlier [11]. It is also expected that gigabit DRAMs and sophisticated VLSI processors with 2000 MIPS using deep submicron MOSFET technology could possibly appear by the end of this century [12].

On the other hand, Si bipolar technology is now challenging compound semiconductor technology up to frequencies above 10 GHz, not only for economic reasons but also because of its performance. For example, a complete Si bipolar multiplexer, demultiplexer and prescaler chip set for 10 Gb/s SONET systems, was reported at ISSCC this year [13].

Even in the area of high performance descrete devices, Si devices are performed well against compound semiconductor devices. It is true that optoelectronic devices, such as lasers and light-emitting diodes, and high-frequency low-noise devices such as HEMT devices are still dominated by compound semiconductors. But some applications such as high-frequency power amplifiers, which are now becoming very popular in mobile and personal communications, are now being challenged by Si MOSFETs using modern ULSI technology [14].

Table1 shows some of the present status of Si VLSIs and Si high performance devices in each area described above.

Organization	64M X 4b
Technology	0.25 μm CMOS, 3-level metal
Chip / Cell size	14.4 X 33.2 mm^2 / 0.6 X 1.2 μm^2
Access Time	70 ns
Active current	34 mA (t_{RC} = 130 ns)
Standby current	26 μA
Refresh cycle	16384
Function	128b parallel test

Table 1 (a) 256 Mb DRAM for File Applications [8]

Device Parameter	0.3 μm U-groove, double poly-silicon, SOI substrate Bipolar transistor fr 32 GHz, fmax 53 GHz, C_{TC} 4.9 fF, C_{TE} 7.2 fF
Multiplexer IC	Function 4 : 1 multiplex Speed 10.5 GHz Power 1.9 W
Demultiplexer IC	Function 1 : 4 demultiplex Speed 12.0 GHz Power 2.1 W
Prescaler IC	Function 1 / 64 prescale Speed 16.0 GHz Power 1.4 W

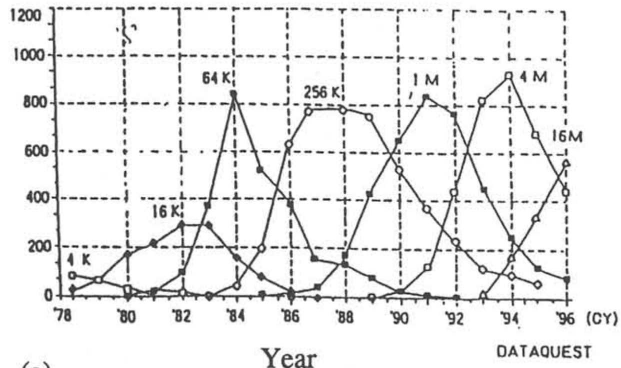
Table 1 (b) Multiplexer, Demultiplexer and Prescaler ICs for 10 Gb/s SONET Systems [13]

Device Parameter	Lg Wg	0.8 μm 30.0 mm
DC Characteristics	BVds Id max gm Ciss	20 V 6A 1.3 s 43 pF
AC Characteristics (f = 1.5 GHz Vdd = 6V)	f_T η_d max G power P out	5 GHz 65 % 8 dB 2 W

Table 1 (c) 1.5 GHz Si Power MOSFET for Digital Cellular Telephones [14]

Until recently, Si VLSI technology has been improving by a factor of four, every three years, and the industry has enjoyed an expanding market with an average annual growth rate of approximately 14% for the decade of the 1980's. This situation is illustrated in Figure 5 which shows the production and price of packaged devices for each DRAM generation. This figure shows a very happy situation for integrated circuit engineers who pursue the technology itself. We have all been accustomed to that for a long time. But is it natural?

Million units / month



(a)

Market Price of DRAM's (dollars)

	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992
642K	3.84	1.92	1.28	0.90	1.09	1.47	1.59	1.25	1.33	1.45
256K	51.20	21.76	3.58	2.25	2.41	3.84	3.58	2.69	1.80	1.70
1M	—	—	100.00	35.00	25.00	17.00	12.00	5.54	4.50	3.00
4M	—	—					124.00	36.43	18.35	12.11
16M	—	—							275.00	205.00

(b) ICE

Fig. 5 D-RAM production: market size (a), and cost reduction (b)

If we look back at the history of VLSI progress, which has been brought up using DRAMs as the technology driver, most of the effort has been put into increasing integration level; four-times improvement in device integration has been achieved with each generation by making devices smaller and smaller, just following a scaling-rule. This is a straightforward and easy approach for management. Needless to say, the chip price is determined by supply and demand and improvement of total sales is achieved by increasing quantity and better chip price/value. It should be noted that Si people have been lucky because the start of mass production for each new generation of DRAMs has always been in parallel with the creation of a new system and/or new market that demanded new devices with higher integration by a factor of four.

It may be said that the present status of Si VLSIs is the limit of the happy age where simple and easy way to develop technology by chip manufactures, although not necessarily easy to accomplish, by making dimension smaller and sticking to same device structure – MOSFETs, has been matched to the demand of system manufactures, creating new innovative market for majority of customers, thus enjoyed sharing of the profit between both side.

3. Future Prospects for VLSI Technology

-- what we should do in the 21 Century

The situation seems to be changing both in technology and in economics. Technology is becoming more and more challenging because we are approaching the inherent or fundamental limitations in materials, devices, circuits and systems [15]. Also the investment method for R&D and production equipment is increasing rapidly [16].

3.1 Some fundamental limitations for VLSIs. [15]

The signal processing capabilities of a device can be measured by its frequency response (speed of operation) and dynamic range (bit accuracy), and is limited by the following equation:

$$V_m f_T = \frac{E_m v_s}{2\pi} \quad (1)$$

where Vm is the maximum allowable applied voltage to the device, f_T is the cut-off frequency of the device, Em is the material breakdown field, and vs is the saturated drift velocity of the carriers in the device material [17]. Since f_T and Vm represent the operation speed and dynamic range of the device respectively, the product represents the total signal processing capability of the device, which is limited by the characteristics of the material as seen on the right of the equation (1). The maximum value for Si is approximately 2×10^{11} or 200 V · GHz.

Another important limitation is the maximum temperature at which a semiconductor functions properly. The power dissipated in a circuit increases its temperature because there is thermal resistance between the device and its environment. The author has previously shown that the integration level NG (gates/chip) and the speed t_{pd} (switching time) of an integrated circuit must obey the following relationship [18] :

$$\frac{N_G}{t_{pd}} \leqq \frac{\Delta T}{\theta E} \quad (2)$$

where ΔT is the maximum temperature rise between the device and its environment, θ is the thermal resistance between them, and E is the switching energy of each gate. This relationship shows that VLSI performance and cost — that is, speed and packing density — are limited by the quantities on the right side of the equation (2) which are closely related to the packaging system and the rates of heat production and dissipation. If we use typical values of ΔT=100 °C, θ=2.5 °C/W, and E= 0.1 pJ, then

$$N_G / t_{pd} \leq 4 \times 10^5 \text{ (gates / ns).}$$

In other words, the maximum number of gates on a chip, if all the gates are operating, must be less than 400 thousand if the switching speed of each gate is 1 nano-second, when the switching energy is 0.1 pico-joule and the power dissipation of the chip is 40 watts.

If circuit integration trend continue unchanged, we can predict that around the year 2000, a 4-Gbit DRAM or a microprocessor with more MIPS than today's conventional mainframe computers will be put on a single chip [12]. It has already been shown that a CMOS device with a gate length of less than one tenth of a micron is feasible [19][20][21]. So if the circuit problems in using them in VLSI can be overcome, this will become a reality. Figure 6 compares the trends in microprocessor chip area and CPU board area of mainframe computers [15]. If the trends shown in Figure 6 continue, it will be possible to put a mainframe CPU on a single silicon chip. The number of components integrated on such a chip is estimated to be $10^8 \sim 10^9$ or even $10^9 \sim 10^{10}$ in the case of DRAMs. Can we design such huge systems within a reasonable time? Can we test them with confidence? "Design limits" and "test limits" are the real challenges for system breakthroughs. We might have to

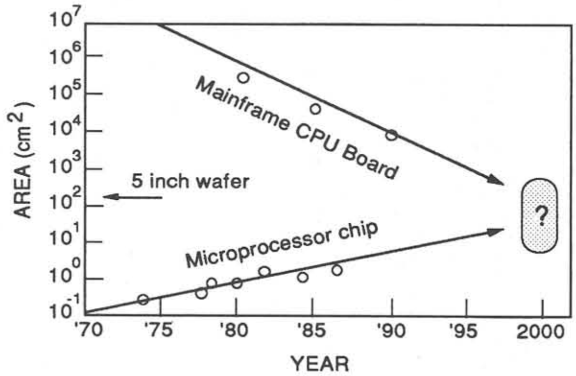


Fig. 6 Trends in microprocessor chip area and CPU board area

create completely new techniques that will allow us to use imperfect designs and imperfect testing to make super VLSI in order to fully use deep submicron VLSI advantages. Neural networks are expected to be one solution, but it is not yet clear whether they will provide new breakthroughs to future VLSIs.

3.2 What are the Essential Features of Integrated Circuits and Why do we need them?

Let me remind you of the essential features of LSI's as described at the beginning of this paper and consider why we need LSIs. In integrate circuits, all the components, both active and passive, are made by the same process on the same semiconductor chip and all the interconnections are made simultaneously. A simple assembly technique that is reliable and provides a chip that satisfies the functional requirements of the users are the essential features of integrated circuit technology. Future technology should inherit these features.

What a customer really wants is not complex state-of-the-art chips but rather chips that provide particular functions that he needs. For example, customers want to know the time, enjoy music, and type letters. They want to have watches, radios, and word processors. But they do not care whether 1 Gb DRAMs or 1000 MIPS RISC processor chips are in them. This means that the real goal of the engineer in the future will be function development, mixed analog/digital integration for example, rather than simply scale of integration. It is essential to keep this viewpoint when we explore the Si VLSI of the next century.

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