On the 50th Anniversary of the Transistor

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Abstract

This paper celebrates the 50th anniversary of the invention of the bipolar transistor in late 1947. Combined with the inventions of integration and planar technology, the invention of the transistor marks the beginning of a period of unprecedented growth, the industrialization of electronics. In this paper, a short story will be told with focus on a few of the technological milestones.

Just over 100 years have passed since the first radio transmission by Marconi in 1895. Today, electronics - loosely defined as the design and application of electron devices - have impacted our lives in many ways.

We daily encounter electronics in the form of telephones, radio, and television. Electronics can be found in many household appliances as well. The corporate world relies heavily on data processing, and manufacturing relies on electronic systems for process control. In fact, it is hard to imagine a computer industry evolving without the use of electronics.

At the turn of the twentieth century, however, there were no commercial electron devices. In 1902, the diode vacuum tube was invented, and in 1907, the triode tube followed. The electron tube era enabled rapid circuit innovation, and radio transmission and reception were improved significantly (see Figure 5).

The invention of the transistor at Bell Telephone Laboratories in 1947 marked the beginning of a new era in electronics. With the inventions of *integration* in 1958, and the *planar technology* in 1959, the basic ingredients were in place for the industrialization of electronics. The inventions were crowned by the commercial introduction of the integrated circuit (IC) in 1961. During this very innovative period, a high number of discoveries and inventions were made, and it is beyond the scope of this paper to mention all of them. However, the 3 above inventions are the key to the industrialization of electronics.

The second age of electronics began with the introduction of the microprocessor in November, 1971. Together with the introduction of the semiconductor memory in 1970, these events were the start of a truly astounding evolution towards higher integration densities and performance.

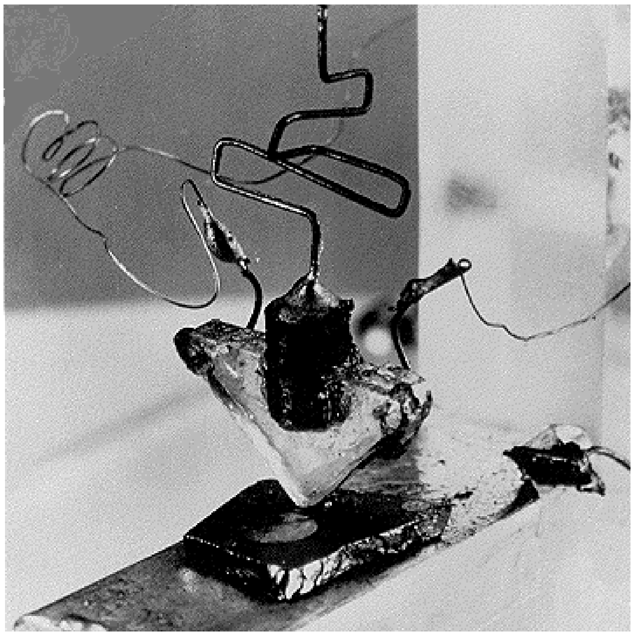

Figure 1. The original point-contact transistor structure comprising the plate of n-type germanium and two line-contacts of gold supported on a plastic wedge

Since 1961, the electronics industry has experienced four decades of uninterrupted, exponential growth. In an amazingly visionary prediction in the early 1960s, Gordon Moore, then Fairchild Corporation and later cofounder of Intel, predicted, that the number of transistors that can be integrated on a single die would grow exponentially with time[1]. Similarly, transistor count as well as clock frequency have displayed exponential growth.

In a period of less than 50 years, electronics has pervaded almost any aspect of our lives. And electronics has become an important factor in the economy of the world. One measure of the impact can be found in the gross domestic product (GDP) of the world. In 1992, the GDP of the world was approximately US$ 10 trillion, and of this total, US$ 1013 billion or 10%, was directly traceable to electronics.

*This paper was presented on 1. October at the 'Electroconference 1997' organized by E-gruppen under the Society of Danish Engineers.
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[1] This is also known as *Moore's law*: The integration density is quadroupled every 2 years. In industrial processes, the continued, exponential reduction in production costs, sometimes called *learning*, is not unfamiliar. However, the growth rate, a 50% learning curve over four decades, is!

1. The Invention of the Transistor

On December 23, 1947, in a private demonstration for AT&T executives, the Bell Laboratories research team, the 1956 Nobel Prize winners John Bardeen, Walter H. Brattain, and William Shockley, demonstrated the point-contact transistor[2] as a working amplifier. In the demonstration, speech was amplified using the transistor. The transistor was born!

The development was launched from a base of contributions made by Bell Laboratories scientists and engineers, whose pioneering work on semiconductors made a new class of semiconductors available to physicists. The invention of the point-contact transistor was the interim result in a research effort, which had begun during the Spring of 1945. The objective of this effort was the junction field-effect transistor.

The field-effect device was by no means unknown by then. The basic principle of the field-effect transistor was proposed by Julius Edgar Lilienfeld[3] [8] as early as 1925. In 1934, Oskar Heil [6] described a structure similar to the junction field-effect transistor. However, practical implementations were impossible due to materials-related problems. The technology to produce such devices on a commercial basis did not yet exist.

The 1945 experiments, proposed by William Shockley, on a thin-film field-effect transistor failed. In early 1946, John Bardeen proposed that problems of surface-state charges shielded the gate field from the semiconductor interior, and for the next eighteen months the 'transistor research team' focussed on penetrating the shield. In an experiment on 17 November, 1947, Walter H. Brattain overcame the blocking effect of the surface states, and during the forthcoming '*magic month*'[12], a sequence of '*creative failures*' led to the invention of the point-contact transistor:

> ... Bardeen and I were simply trying to make a good 'Field Effect' device and as a result, we were put in a situation to observe, for the first time, a phenomenon (namely minority carrier injection [3]) now called the 'Transistor Effect' - and to use this to make a transistor![5]

An entry in W.H. Brattain's notebook shows that on 16 December, 1947, point-contact amplification [2] was observed. The discovery was demonstrated to AT&T executives on December 23 and recorded in Brattain's Christmas Eve notebook entry. The invention of the junction (bipolar) transistor, superior to the point-contact transistor, followed shortly after, on 23 January, 1948. And eventually, on 30 June, 1948, the bipolar transistor was announced[4].

The impact of the transistor was no less than revolutionary. Inherent to the transistor is the availability of electrons to meet the transistor operation needs without the use of power e.g. to energize a hot cathode as in the vacuum triode tube. Small size, low power consumption, low collector potentials and finally, a dramatically improved reliability, were the immediate benefits over electron tubes. With the maturing of technology, the manufacturing costs should proove much less than electron tubes.

For the U.S. Military, the urgent requirements for national security overrode the high costs of early transistors, and the military initiated several research programs to develop transistors and circuits for military use. The motivation was to promote the effort to miniaturize complex electronic systems to be installed in equipment in which size, weight, and power consumption were severely constrained[4]. In a paper in 1952 by I.R. Obenchain [11], the development of portable computers as well as advanced electronic control systems for weapons was forecasted. And for three decades to come, military initiated research should remain the primary funding for research in integrated circuits.

2. Integration and Planar Processing

The drive for a miniaturization of electronic systems had caused several attempts to miniaturize conventional components in the 1950s. These attempts were largely unsuccessful, but they illustrated the demand and potential market for some form of microelectronics.

In 1958, Jack St. Clair Kilby of Texas Instruments, introduced the monolithical integrated circuit [7]. A semiconductor device was mounted in a hermetically sealed unit together with resistors and capacitors constituting an electronic circuit. The connections between the various components were made by soldering leads to tiny wires internally. However, the significance of Kilby's original invention was soon put into the shade by the almost simultaneous, independent developments at Fairchild Semiconductor.

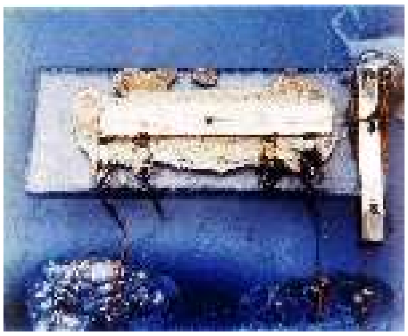

Figure 2. The first monolithic integrated circuit by Jack Kilby, Texas Instruments

The invention of the bipolar transistor incited new re-

[2]The word *transistor* was not used until several months after the invention of the device. The word is an abbreviation of *transfer resistor* and is ascribed to John R. Pierce of Bell Labs.

[3]The patent describes how to control an electrical current in a thin film using an electrostatic potential for use in an amplifier circuit

[4]The historical fact is that early efforts to miniaturize electronic components were not motivated by computer engineers. Indeed, the potential of the digital computer was not quickly appreciated for civilian economy.

search into the further exploitation of the characteristics of the semiconductor. The body resistance of the semiconductor and the *pn* junction capacitance combined with transistors could be combined in the same material to realize a complete circuit, an integrated circuit. Several technology developments[5] were required before this potential could be realized.

At Fairchild Semiconductor, a company founded in 1957, a team of research scientists focussed their research efforts on silicon planar technology[6]. In 1958, Robert N. Noyce developed the planar junction field-effect transistor [10]. The same year, Jean A. Hoerni developed the planar surface field-effect transistor. In this structure, a thin layer of silicon dioxide was used to insulate the gate from the channel of the transistor. The insulating oxide permitted the use of metal lines placed directly on top of the oxide to be used for interconnecting between components.

The process opened the path for the development of the planar technology [9] by Gordon E. Moore and Robert N. Noyce in 1959. In this technology, all components of the IC are incorporated into the same monolithical structure[7], and the separation and interconnection of transistors and other circuit elements is done electrically rather than physically using reverse-biased *pn* junctions. The era of the IC was inaugurated.

The planar technology combines the advantages of junction formation by solid-state diffusion and the masking property of silicon dioxide for precise definition of device geometry. Device geometries are transferred to the wafer using photolithography. Actually, planar processing technology derives its success from the properties of thermally grown silicon dioxide.

Further, planar technology makes use of the important fact that the electrical characteristics of a silicon surface covered with an oxide layer are superior to those of a bare surface. Due to this feature, the sensitivity of semiconductor devices to their environments has been greatly reduced with a corresponding increase in the reproducability and stability of device characteristics.

The final step in the development is to replace bipolar transistors by MOS field-effect transistors (MOSFET)[8]. In 1960, Martin M. Atalla of Fairchild demonstrates the first MOS field-effect transistor [1]. A few years later, the first commercially available CMOS IC is available [13].

The first consumer product containing IC's was a hearing aid developed jointly by Zenith Radio Corporation and Texas Instruments introduced on 14 February, 1964. From the same period, pMOS technology ICs were used for applications such as calculators. In the late 1960's, the technology shifted to the inherently faster nMOS technology.

The complexity of the manufacturing process delayed the full exploitation of the CMOS technology for almost twenty years. Today, CMOS technology has become the dominant VLSI technology.

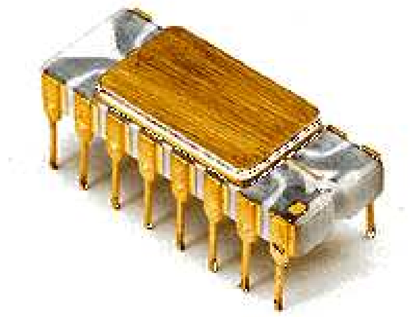

Figure 3. The Intel 4004

3. The Microprocessor

As in the inventions of the transistor at Bell Laboratories and the planar technology at Fairchild Semiconductor, the next significant development took place in a research environment in which a smaller number of scientists mutually inspired each other in the pursuit of their research goals.

In 1968, Robert N. Noyce, Gordon E. Moore and Andrew S. Grove decided to leave Fairchild Semiconductor and form a new startup company, Intel. With a 1-page business plan, they raised US$ 2.5 million venture capital. In 1970, Intel introduced the 1103, a 4 kbit DRAM, the first high-density semiconductor memory.

In mid-1969, Busicom, a now-defunct Japanese calculator manufacturer, asked Intel to design a set of microchips for a line of high-performance calculators. The specifications provided called for at least twelve chips. Marcian E. Hoff of Intel decided that this solution was to complex and expensive and came up with the concept of a general-purpose information processor.

Further refinements led to the design of the Intel 4004, a single-chip microprocessor, released on 15 November 1971. The 4-bit 4004 had 46 instructions, ran at 108 kHz and contained 2,300 transistors in a 16-pin dual in-line package (see Figure 3). Program and data memory were separate, 1K data memory and a 12-bit program counter for 4K program memory (in the form of a 4 level stack, used for CALL and RET instructions). Finally, the 4004 provided sixteen 4-bit (or eight 8-bit) general purpose registers.

The performance of the 4004 had been designed to match the performance of Eniac, the first general-purpose elec-

[5]Solid-state impurity diffusion, photolithographic processing, wafer batch processing, etc.

[6]The technology progressed during the early 1950s, using germanium as the semiconductor material. However, germanium proved unsuitable in certain applications because of its propensity to exhibit high junction leakage currents. For this reason, silicon became a practical substitute and has almost fully supplanted germanium as a material for solid-state device fabrication.

[7]The various components are interconnected using metal lines 'on top' of the circuit, i.e. the metal lines are formed as part of the process

[8]Bipolar logic 'looses' for the very same reason that haunted the vacuum tubes; the large power consumption limits the number of transistors that can be placed on a single die.

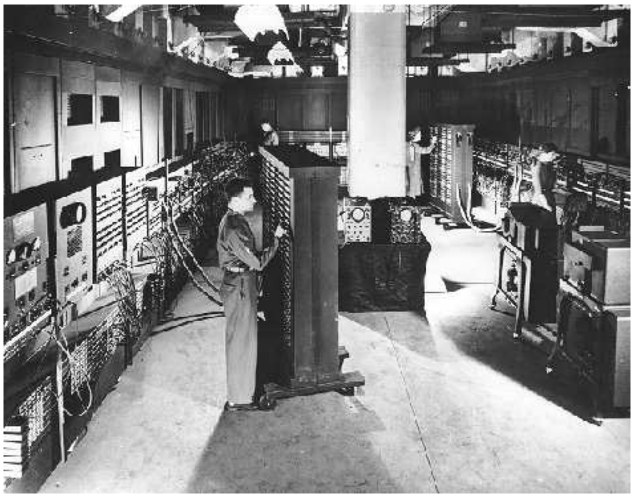

Figure 4. The Eniac 1. U.S. Army Photo

tronic computer (see Figure 4) constructed using during World War II using approximately 19,000 vacuum tubes[9].

The performance of the 4004 is estimated at 0.06 MIPS. From its inception in 1971, the microprocessor has grown exponentially in performance and complexity according to the predictions in Moore's law. By comparison, the Intel Pentium Pro (1995) is a 200 MHz chip with 5.5 million transistors and a performance of 428 MIPS.

As a general-purpose device, the microprocessor impacted electronic systems design severely. Since the early 1970's, a wide variety of electronic products have been realized using standard microprocessors. Unfortunately, the general-purposeness of microprocessors implied that not all electronic systems could reach the full potential of technology.

4. The Future Steps of Integration?

In the mid-1980s, in response to requirements for higher performance, lower cost, shorter product life time, and faster time-to-market, a market developed for application specific ICs (ASICs). ASICs are ICs taylored to meet the critical system requirements in an otherwise traditional system composed of ASICs and standard components. Typically, though not always, the volume is small. In 1988, in Denmark, an estimated number of 70-80 ASICs were designed.

In this model, the semiconductor company acts as a process provider, while the system designer takes on the design of the device. Such a division of work may not result in reaching the limit of technology.

According to the predictions of *Moore's law*, an increasing number of transistors will be available in IC's in the forthcoming years. Thus, even more complex microprocessor devices can easily be foreseen. In the ASICs case, entire systems may be realized in a single chip. The obvious question is, how we may organize design to benefit from this potential complexity.

The answer to this question is abstraction. In the near future, the system designer may need the ability to select layout entities, which may be provided by providers independent from the process providers, in order to manage system complexity. This requires the emergence of entity providers, who hold the intellectual rights to specific layout entities but are independent of the semiconductor process houses. System design will consist of selecting layout entities from one or more entity providers.

[9] As a consequence, the Mean-Time-Between-Failure was of the order of a few hours. Note the position of the oscilloscope in the center of the room. Early programmers recall designing software programs, I quote "*taking into account the MTBF*". The introduction of transistors immediately raised the value of the MTBF by decades.

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[12] W. Shockley. The path to the conception of the junction transistor. *IEEE Transactions on Electron Devices*, ED-23(7):597–620, July 1976.

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Electron-tube era		
1901	J.C. Bose	Vacuum rectifier
1902	Ambrose Fleming	Vacuum tube (diode)
1906	G.W. Pichard & L.W. Austin	Crystal detector
1907	Lee de Forest	Audion 3-electrode tube (triode)
1925	Julius Edgar Lilienfeld	Principle of the field-effect transistor
1934	Oskar Heil	Structure of the junction field-effect transistor
1938	W. Schottky	Schottky-barrier diode
Bipolar transistor era		
1947	J. Bardeen, W.H. Brattain, & W. Shockley	Germanium point contact transistor
1948	W. Shockley	Germanium junction transistor
1950	W.J. Pietenpohl & R.S. Ohl	Si bipolar transistor
1952	G.K. Teal & E. Buehler	Si single crystal
1952	Texas Instruments	Commercial production of Si bipolar transistors
1957	R.C. Sangster	Vapor phase epitaxial growth
Integration era		
1958	Jack S. Kilby	Monolithical integrated circuit
1958	Robert N. Noyce	Planar junction field-effect transistor
1958	Jean A. Hoerni	Planar surface field-effect transistor
1959	Gordon E. Moore & Robert N. Noyce	Planar technology
1960	H.C. Theuerer & J.J. Kleinach & H.H. Lour & H. Christensen	Epitaxial diffused transistor
1960	D. Kahny & M.M. Atalla	MOS field-effect transistor
1961	Fairchild Semiconductor	First commercial digital IC
1963	Frank Wanlass, Fairchild	CMOS integrated circuits
Application era		
1967	Dalbergh Hearing Aids	First hearing aid 'worn in the ear'
1968	Hodges et al.	MOS 64-bit RAM memory
1968	Fairchild Semiconductor	μA709 operational amplifier
1970	Dennard (IBM)	One-transistor dynamic memory cell
1970	Marcian E. Hoff, Intel	1103 4kbit DRAM
1971	Intel	4004 4-bit microprocessor
1972	Intel	8008 8-bit microprocessor
1974	Intel	8080 8-bit microprocessor
1981	J.W. Beyers et al (HP)	450,000 transistor microprocessor
1984		Megabit memory chip
1995		Experimental gigabit memory chip

Figure 5. Milestones in Integrated Electronics