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DOI: 10.1109/MAHC.2009.54 · Source: IEEE Xplore

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Abstract:

Founded in 1957 by eight dissidents from Shockley Semiconductor Laboratory, Fairchild Semiconductor Corporation, later the Semiconductor Division of Fairchild Camera and Instrument Corporation, developed some of the most important innovations in 20th Century technology and sowed the seeds of the microelectronic-driven computer industry of today. This article surveys some of the key personalities who worked at the company and describes their technological and management contributions and the resulting cultural and business revolution that led to the rise of Silicon Valley.

Key words:

Fairchild
Hoerni
Integrated circuit
Microelectronics
Moore
Noyce
Planar
Semiconductor
Silicon Valley

Article Text:

“A Company of Legend”: The Legacy of Fairchild Semiconductor

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“Fairchild Semiconductor was a company of legend - perhaps the most extraordinary collection of business talent ever assembled in a start-up company. If Fairchild had a corporate culture it could only be described as volatility incarnate brilliant young engineers and marketers working long days, and partying long nights And somehow in the middle of it all, they also managed to invent the integrated circuit, the defining product of the late twentieth century, and in the process helped to create the modern world.” (1)

Michael Malone – 2007

Nineteen fifty seven may be remembered by the general public as the year that Hank Aaron was named National League MVP player; “West Side Story” opened on Broadway; the literary antitheses *The Cat in the Hat* and *On the Road* were published; the Everly Brothers recorded *Wake Up Little Susie*; Humphrey Bogart died, or when the US Congress passed the Civil Rights Act. More technically inclined observers may recall the launch of Sputnik by the Soviet Union, the resulting Space Race and the renewed impetus it gave to the importance of science and technology in this country. Few are aware that 1957 also marked the founding of Fairchild Semiconductor, an upstart start-up that through an unprecedented series of technology, business, and cultural innovations, intended and otherwise, spawned Silicon Valley and changed the world.

This article was inspired by stories told, memories rekindled, and artifacts collected at “Fairchild@50,” a celebration of the fiftieth anniversary of the company’s founding sponsored by Fairchild alumni and held at Stanford University and the Computer History Museum, Mountain View, California, in October 2007. It describes the background behind the founding of the company and summarizes those areas of the semiconductor business where Fairchild established a significant market position or where technology pioneered by its engineers made an important contribution to the industry and the later success of spin-out and other competitors, including Advanced Micro Devices (AMD), Intel, and National Semiconductor.

Overview

Founded in September 1957 in Palo Alto, California by eight young engineers and scientists from Shockley Semiconductor Laboratories, Fairchild Semiconductor Corporation pioneered new products and technologies together with an entrepreneurial style and manufacturing and marketing techniques that reshaped the semiconductor industry. The planar process conceived just 3 months later and developed in early 1959, revolutionized the production of semiconductor devices and continues to enable the manufacture of billion-transistor microprocessor and memory chips today.

Funded by and later acquired as a division of Fairchild Camera and Instrument Corporation of Syosset, New York, Fairchild was the first manufacturer to introduce silicon transistors matching the speed of germanium devices and practical monolithic Integrated Circuits (ICs) to the market. At the peak of its influence in the mid-1960s, the division was one of the world’s largest producers of silicon transistors and controlled over 30 percent of the market for ICs. Director of Research and Development (R&D), Gordon Moore observed in 1965 that device complexity was increasing at a consistent rate and predicted that this would continue into the future. “Moore’s Law,” as it has since become known, created a yardstick against which companies continue to measure their technology progress today.

Starved by the parent company for funds for investment in new production facilities, for equity to retain key employees, and torn by internal organizational issues, by the late 1960s the semiconductor division encountered serious problems with introducing new products and satisfying fast growing customer demand. As Gordon Moore explained:

“Fairchild grew to be about a \$150 million business and some 30,000 employees by the late sixties. It was a fairly significant corporation by the time we were done. But things began to deteriorate - partly, I think, because it was controlled by an East Coast company. ... We had also made a tremendous number of mistakes, and we had squandered opportunities along the way. It was excellent on-the-job training, but there probably is a more efficient way of training entrepreneurs than by letting them make all the mistakes. Fortunately, good products make up for a lot of problems in an organization, and I think that was what happened in our case.” (2)

In October 1967, a sharp industry downturn and loss of digital IC market share to Texas Instruments Transistor Transistor Logic (TTL) family resulted in the division losing money for the first time since the start-up phase. In

1968, after all but one of the founders and many senior employees had left the company, a new team composed of former Motorola executives led by C. Lester Hogan was appointed to head Fairchild Camera and Instrument Corporation. Hogan moved the corporate headquarters to Mountain View and the company continued to innovate in new technologies and products, including the industry's first volume production of high-performance semiconductor memory devices and Charge-Coupled Device (CCD) imagers that today form the sensors for digital cameras. Ventures into consumer products, including digital watches and video games, were less successful. Although revenues grew substantially under the new regime, the company was never able to regain its former profitability and prominence.

Having been overtaken in sales and significance by companies started or managed by former Fairchild employees ("Fairchildren") and buffeted by other aggressive US and international competitors, the company was purchased as a diversification move by French oilfield services conglomerate Schlumberger in 1979. Unable to restore its fortunes, Schlumberger sold the assets to National Semiconductor in 1987. In 1997 National divested a number of mature product lines in a leveraged buy-out to a group of executives based at Fairchild's former South Portland, Maine facility. Through internal development and strategic acquisition of compatible products for power, analog, logic, and mixed signal applications, the reborn Fairchild Semiconductor is once again a public company (NYSE: FCS) with annual revenue of more than one billion dollars.

Journalist Don C. Hoefler, who in 1971 was to popularize the name "Silicon Valley," published an article in 1968 that traced the lineage of fifteen local semiconductor companies directly to Fairchild. (3) Updated and printed by Semiconductor Equipment and Materials International (SEMI) as a wall chart in 1977, the number had increased to 66. A 1985 revision showed 125 spin-outs. Including systems and software businesses, the total number of companies in the Bay Area and beyond with Fairchild roots now lies in the thousands.

Early electronic industry on the San Francisco Peninsula (1908 - 1957)

Commercial and amateur radio electronics activity began to emerge on the San Francisco Peninsula over one-hundred years ago. Surrounded on three sides by maritime waters, the area was an early developer of ship-to-shore radio technology. Stanford graduate Cyril Elwell made one of the first "mobile" wireless phone calls from downtown Palo Alto in 1908 (4). While working for Elwell's Federal Telegraph Corporation, a couple of years later Lee de Forest built the first vacuum tube amplifier and oscillator circuits using his three electrode "Audion" device. (5) Another Stanford alumnus, Charles Herrold began the nation's first regularly scheduled music and entertainment broadcasting from San Jose's radio station FN in 1909. (6)

Several important component manufacturers emerged in the 1930s. Entrepreneur Charles Litton established Litton Engineering Laboratories to produce vacuum tube-making equipment. William Eitel and Jack McCullough founded high-power tube maker Eitel-McCullough (Eimac). At Stanford the Varian Brothers, Russell and Sigurd together with William Hansen, and Edward Ginzton developed the first microwave tube light enough for airborne use, the klystron, and the foundation of Varian Associates. (7) After World War II, these pioneers were joined by many other companies in producing high-frequency electronic components and systems for military and communications markets. They also established a supporting infrastructure of specialized suppliers as well as cadres of skilled operators and technicians. By 1955 regional employment in electronic-component related activities reached about 3,000 workers. (8)

In September 1955 William Shockley, co-inventor of the transistor at Bell Laboratories, and industrialist Arnold Beckman agreed to found the Shockley Semiconductor Laboratory as a division of Beckman Instruments "to engage promptly and vigorously in activities related to semiconductors." Shockley rented a building at 391 South San Antonio Road in Mountain View and began recruiting "the most creative team in the world for developing and producing transistors." He attracted a group of extremely capable young engineers and scientists who developed the basic equipment and processes for fabricating diffused silicon semiconductor devices. In De-

ember 1956 Shockley shared the Nobel Prize in Physics for inventing the transistor but by early 1957 his staff had become disenchanted with his abrasive management style. They also felt that the company should pursue near-term market opportunities for silicon transistors rather than the distant promise of a technically challenging four-layer (PNPN) diode for telephone switching applications that Shockley championed. (9)

After unsuccessfully petitioning Beckman to appoint a new manager, eight of Shockley's most talented employees - Julius Blank, Victor Grinich, Jean Hoerni, Eugene Kleiner, Jay Last, Gordon Moore, Robert Noyce, and Sheldon Roberts - resigned in September 1957 and founded the Fairchild Semiconductor Corporation in nearby Palo Alto. Shockley continued pursuing his four-layer diode but his company never realized a profit. Beckman sold the operation to Clevite Corporation in 1960 and Shockley became a professor of electrical engineering and applied science at Stanford University.

The founding of Fairchild stimulated an era of dramatic growth of the electronics industry on the San Francisco Peninsula. Ten years later, at the peak of the company's influence, local electronic component industry employment reached nearly 20,000 people. By 2003 it exceeded 125,000 not including the hundreds of thousands of employees in the computer hardware and software and supporting industries that sprang from the silicon. (10)

Deal triggers venture banking industry on the West Coast.

Financing for the new company was arranged by Arthur Rock, a young security analyst at New York investment bank Hayden Stone. . Rock and his boss Arthur Coyle, who specialized in developing financial services for emerging technology companies, approached more than thirty potential corporate investors before interesting Fairchild Camera and Instrument's founder and chairman Sherman Fairchild. The bankers negotiated one of the West Coast's first venture capital deals whereby Fairchild loaned the founders \$1.38 million in exchange for the right to purchase the company if it prospered. It did prosper and the founders enjoyed a handsome return on their personal investments of \$500 each. (11) Rock's success encouraged his move to California in 1961 to form a partnership with local investor Tommy Davis. Together they invested \$3 million in companies such as pioneering scientific computing company Scientific Data Systems and Teledyne, the latter firm grew into one of the most successful technology conglomerates in the history of American business. Davis and Rock's fund returned \$100 million to its investors. After establishing his own firm, Arthur Rock & Co in San Francisco, Rock worked with Fairchild co-founders Gordon Moore and Robert Noyce to launch Intel Corporation in 1968.

Figure 1

The Fairchild founders pose under the Fairchild Semiconductor Corporation "Flying F" logo in the lobby of the Whisman Road, Mountain View headquarters building in 1960. [From left to right: Gordon Moore, C. Sheldon Roberts, Eugene Kleiner, Robert Noyce, Victor Grinich, Julius Blank, Jean Hoerni, and Jay Last.] (Wayne Miller/Magnum Photos)

The financial rewards enjoyed by the Fairchild founders did not go unnoticed by later employees who had received only modest stock grants, if any. As the potential returns available in high technology investments became more widely apparent, symbiotic relationships between entrepreneurs and bankers blossomed into the now legendary capital of venture-capital lining Sand Hill Road in Menlo Park. This local availability of capital that understood technology combined with an aggressive, risk-taking culture established the San Francisco Bay Area, and Silicon Valley in particular, as one of the world's most vibrant centers of new company formation and high-wage job creation.

First commercial double-diffused silicon transistors

With the national urgency to recoup the loss of leadership in space to the Soviet Union as a result of the Sputnik success, military contractors adopted the use of digital electronic techniques in avionics equipment. Recogn-

nizing that germanium transistors would not satisfy the extended operating temperature requirements of such systems, the Fairchild founders identified an opportunity for high-speed silicon devices. Texas Instruments was in production with silicon transistors using a diffusion process for the base region and an alloy technique for the emitter. However they did not meet the IBM Federal Systems Division exacting specifications for a transistor to drive magnetic core memory in the B-70 military aircraft computer system.

Double-diffused (emitter and base) devices that offered higher speed had been produced at Bell Labs but they were not available outside the company. The Fairchild group felt they could satisfy the IBM application and create a viable commercial product by developing their own double-diffused process. However, according to Gordon Moore “we were far from developing a commercial device.” (7) At the Fairchild@50 event in October 2007, Jay Last noted that “Bell Labs believed that photolithography was impractical but both Bob Noyce and I agreed that unless we could make it work, we did not have a company.” In just five months, they set up a crystal-growing operation (Sheldon Roberts), developed photolithographic masking techniques using three matched 16 mm movie-camera lenses (Jay Last, Robert Noyce), developed new diffusion methods and established techniques for making electrical contacts with aluminum (Moore), and built their own manufacturing and test equipment (Julius Blank, Victor Grinich, Eugene Kleiner). After successful delivery to IBM, the first commercial double-diffused transistor, the 2N696/697 NPN device, was introduced to great acclaim at the Wescon electronics component trade show in August 1958.

Autonetics selected the new Fairchild transistor for a guidance-and-control system on the Minuteman ballistic missile, the largest defense program of the era. In late 1958 a potential reliability problem put the new firm’s survival at stake. Tiny particles flaking off the inside of the metal package threatened to short across exposed junctions on the surface of the silicon. Swiss-born physicist cofounder Jean Hoerni, who had developed the diffusion profiles for the company’s mesa-structure silicon transistors, proposed a solution that revolutionized the industry.

Invention of the “Planar” Manufacturing Process

Hoerni had recorded the essential ideas of a new process in his notebook on December 1, 1957. (12) This entailed leaving the oxide masking layer in place on top of the silicon wafer to protect the sensitive junctions between the underlying p and n-type semiconductor regions. Due to concerns about possible contamination by the oxide, conventional wisdom required removing this layer after completion of masking operations, thus exposing the junctions. Recalling his idea, Hoerni viewed the oxide instead as a possible solution to the exposed junction problem. His “planar” approach, named after the flat topography of the finished device, would protect these junctions. After writing a patent disclosure in January 1959, he demonstrated a working planar transistor that March. As Hoerni had predicted the oxide layer was found to protect the junctions and was eventually qualified as the preferred Minuteman transistor process.

Planar devices also proved to have better electrical characteristics - particularly far lower leakage currents, which is critical in computer logic design. Fairchild introduced the 2N1613 planar NPN transistor commercially in April 1960. With a guaranteed useful current gain (beta) parameter over a wide operating current range of 100 μ A to 0.5A, the device was received enthusiastically by the market. When matched with a PNP transistor counterpart, Fairchild products enjoyed a several-year monopoly in high reliability applications that resulted in fast growing sales and high margins. According to the annual report for that year, “By the end of 1961, Fairchild Semiconductor was the largest producer of high performance silicon transistors in the United States.”

Figure 2

The Fairchild Semiconductor diffusion area in 1960

(The Computer History Museum Collection. Courtesy: National Semiconductor Corporation, successor to Fairchild Camera & Instrument Corporation)

Translating the planar concept into a high-volume production took extraordinary efforts in process control engineering and fabrication equipment design ingenuity but production volumes quickly surpassed all previous techniques used for manufacturing semiconductors for both high-speed and low-power applications. Fairchild's licensing of the planar process to other semiconductor companies encouraged standardization of manufacturing processes across the industry. This in turn opened up opportunities for independent producers of equipment and spawned an important new semiconductor equipment industry. As it permitted fabrication of all the components of a semiconductor device from one side of a wafer, modern billion-transistor microprocessors and memories continue to rely on Hoerni's breakthrough idea. Historian Christophe Lécuyer describes it as "the most important innovation in the history of the semiconductor industry." (7)

Silicon transistors surpass germanium in speed

In the early 1950s Bell Labs' scientists Howard Christensen and Gordon Teal developed a process, called epitaxial deposition, to grow a thin layer of material on a germanium wafer that continued the underlying crystal-line structure. This offers the ability to form layers having different doping characteristics than the substrate. The first description of a silicon transistor that took advantage of this process to improve speed and increase the breakdown voltage was published by Henry Theurer of Bell Labs in 1960. Fairchild engineers were pursuing epitaxial technology in this same timeframe but lacked the equipment necessary to bring a device to market until March 1961. (13) The resulting 2N914 became one of the company's most successful transistors. When later applied to the manufacture of integrated circuits, epitaxy offered up to a fifty-times improvement in production yields.

Seymour Cray of Control Data Corporation (CDC) awarded Fairchild a development contract for a silicon transistor that switched in under 3 nanoseconds. Existing silicon transistors offered operation superior to germanium at the elevated ambient temperatures prevalent in large computers but were too slow for Cray's planned new model 6600 supercomputer. Jean Hoerni met CDC's demanding specification by combining "gold-doping" - the addition of gold impurities (a technique he had developed for use on the company's original product line in 1959) - together with the new epitaxial deposition process. The 2N709 NPN device was introduced in July 1961 as the first silicon transistor to exceed germanium speed. (14) In 1964 CDC placed "one of the largest single orders in the history of the semiconductor industry" with Fairchild for over ten million of the devices.

The Monolithic Integrated Circuit Concept

As electronic systems grew more complex, engineers sought simpler ways to interconnect the thousands of transistors used to implement them. Government agencies funded micro-module and multi-chip hybrid circuit projects in search of a solution to this "tyranny of numbers." In 1952, Geoffrey W.A. Dummer of the Royal Radar Establishment, England proposed, "With the advent of the transistor ... it seems now possible to envisage electronic equipment in a solid block." (15) In 1953 Harwick Johnson filed a patent for a single-chip phase shift oscillator. He also worked with Torkel Wallmark on an "integrated semiconductor device" concept announced by the Radio Corporation of America (RCA) in 1958. (16) Yasuro Taru of Japan's Ministry of International Trade and Industry (MITI) filed a patent in 1957 that disclosed both junction and field-effect transistors (FET) on one chip. (17) Work at Bell Labs to make a device configured as a telephone stepper and Shockley's ill-fated four-layer diode were attempts to integrate the function of multiple separate components onto a single-chip. While achieving various degrees of integration, none of these ideas yielded a general-purpose solution.

On September 12, 1958, Jack Kilby of Texas Instruments (TI) built a circuit using germanium mesa PNP transistor slices he had etched to form transistor, capacitor, and resistor regions. Using fine gold "flying-wires" he stitched them together to create an oscillator function. One week later he demonstrated an amplifier. TI announced Kilby's concept in March 1959 and introduced the first commercial "solid circuit," the Type 502 Bina-

ry Flip-Flop, at \$450 each in 1960. While the 502 and other members of TI's Solid Circuit family demonstrated the concept of fabricating both active and passive components of an electronic circuit from semiconductor material, it did not address the critical manual interconnection challenges behind the "tyranny of numbers" problem.

Challenged by patent attorney John Ralls to identify other uses for Hoerni's planar process, Fairchild co-founder Robert Noyce conceived the idea for a monolithic integrated circuit. (18) One in which the diodes, transistors, resistors, and capacitors diffused into the silicon wafer could be interconnected by depositing aluminum metal lines directly on top of the protective oxide coating rather than using Kilby's hand-stitched gold wires. Noyce filed his "Semiconductor device-and-lead structure" patent in July 1959.

Fairchild and TI engaged in litigation over IC patents for many years. The Supreme Court eventually ruled in Fairchild's favor but by then the companies had already settled on a cross-license agreement that included a net payment to Fairchild. Kilby and Noyce both received the National Medal of Science and today are celebrated as co-inventors of the integrated circuit. As Noyce died in 1990 he did not enjoy the Nobel Prize awarded to Kilby in 2000, but many believe they would have shared the prize had he lived.

First Planar Integrated Circuit is Fabricated

In August of 1959, Bob Noyce asked co-founder Jay Last to construct a concept microcircuit to "show the flag" at the Wescon component trade show. Last fabricated "a little device with four individual transistors in it and resistors from pencil lead" that they dubbed the "Ticonderoga" process – after the pencil company. In September Last assembled a team including Sam Fok, Isy Haas, Lionel Kattner, and James Nall to develop a monolithic integrated circuit based on the Hoerni and Noyce patents. Robert Norman, head of the applications department under Vic Grinich, designed a modified Direct Coupled Transistor Logic (DCTL) circuit, later called Resistor Transistor Logic (RTL), as most compatible with the first generation of planar processing. (19)

Integrating multiple interconnected active and passive devices on one chip posed many new implementation challenges. The Hoerni and Noyce patents described concepts; they did not define step-by-step how to build a product. Over the next 12 months Last's group developed many innovative approaches to accomplish the task. Their first working monolithic device with four-transistors and five resistors in a flip-flop configuration was tested on May 26, 1960. Components were electrically isolated from each other by etching physical isolation channels into the silicon from the rear of the wafer and back-filling with epoxy. A more robust diffused p-n junction-isolation solution, requiring a difficult 20-hour boron diffusion devised by Isy Haas and Lionel Kattner with advice from diffusion expert David Allison, yielded working circuits on September 27, 1960. Under the trade name μ Logic (Micrologic), the type "F" flip-flop function was introduced to the public in March 1961 via a press conference at the IRE Show in New York and a photograph in LIFE magazine. Six additional logic building blocks, including the type "G" (3-input NOR) gate function, a half adder (type H) and a half shift register (type S) were added to the family before the end of the year. In December 1961, an internal sales memo stated "We are at a point now where we can discuss micrologic as a true product. Our shipments by the end of December will be in the \$500,000 region and the current backlog is about 5K units."

Figure 3

A mid-1960 implementation of the first Micrologic flip-flop using a physical isolation technique. (The Computer History Museum Collection. Gift of Lionel Kattner)

Using six different Micrologic part types, the AC Spark Plug Division of General Motors MAGIC I system, "the first complete airborne computer to be mechanized exclusively with integrated circuits," was operational in late 1962. Against the advice of conservative advisers who warned that ICs may not be reliable, system design contractor Massachusetts Institute of Technology (MIT) Instrumentation Laboratory selected the Fairchild type

“G” gate function as the basic logic building block for NASA’s Apollo Guidance Computer (AGC). The design was upgraded to a dual-gate device in 1963. Built by Raytheon, each system used about 4,000 ICs. Consuming 200,000 units at \$20-30 each, the AGC was the world’s largest user of ICs through 1965. (20)

Early MOS technology

In 1959 M. M. (John) Atalla and Dawon Kahng at Bell Labs had achieved the first successful insulated-gate field-effect transistor (IGFET), which had been anticipated as early as 1926 (13) by overcoming the long troublesome “surface states,” electrons at the silicon surface that blocked electric fields from penetrating into the semiconductor material. Today the device is known as an MOS transistor after its Metal-Oxide-Semiconductor sandwich structure. Although the MOS structure was much smaller than bipolar devices and it consumed less power, due to its lower speed the device addressed no pressing needs in the telephone system and it was not pursued further at Bell Labs. In a memorandum written in 1961, however, Kahng pointed out its potential “ease of fabrication and the possibility of application in integrated circuits.”

But researchers at Fairchild Semiconductor and RCA did recognize these advantages in 1960 when Jean Horni fabricated an MOS diode (Fairchild) and Karl Zaininger and Charles Meuller fabricated an MOS transistor (RCA). In early 1961 Fairchild’s C.T. Sah demonstrated an MOS tetrode device. Both companies introduced commercial products in 1964.

In a 1963 paper co-authored with C. T. Sah, Frank Wanlass of the Fairchild R & D Laboratory in Palo Alto showed that when in standby mode logic circuits combining a p-channel and an n-channel MOS transistor in a complementary-symmetry circuit configuration drew close to zero current. (21) Wanlass patented the idea, now known as Complementary MOS (CMOS), but manufacturing and reliability challenges prevented Fairchild and the industry from exploiting the low-power advantage of the technology in the near term. It took collaboration between researchers from industry and academia around the globe to resolve the fundamental issues that allowed CMOS to emerge as the dominant IC technology of today. Important contributions were made by the pioneering teams at Fairchild and RCA. Between 1963 and 1966, Bruce Deal, Andrew Grove, and Ed Snow at Fairchild identified the significant issue of sodium contamination and published numerous papers that explained the electrical nature of oxides. Technologist Federico Faggin believes that “Fairchild developed the most cogent understanding of the silicon-silicon dioxide interface of the late 1960s.” Much of this work informed Grove’s classic textbook *Physics and Technology of Semiconductor Devices* that was published in 1967.

Figure 4

Andy Grove, Bruce Deal and Ed Snow discuss MOS technology in at Fairchild R&D in 1966 (The Computer History Museum Collection. (The Computer History Museum Collection. Courtesy: National Semiconductor Corporation, successor to Fairchild Camera & Instrument Corporation)

Fairchild was also an important contributor to the next major improvement in speed and density of MOS devices - the extension of silicon-gate technology to ICs. Bell Labs had showed that the speed, reliability, and packing density of discrete MOS transistors could be improved by replacing the conventional aluminum metal gate electrode with a polycrystalline layer of silicon. At Fairchild R&D, Federico Faggin worked with Tom Klein to adapt the process to ICs. He redesigned an existing metal-gate, 8-channel analog multiplexer to take advantage of the self-aligning gate feature and in 1968 Fairchild introduced the first commercial silicon-gate IC, the 3708. Other innovations developed by Faggin at Fairchild, the buried contact and the bootstrap load, played a critical role in implementing Intel’s first microprocessor, the 4004, after he joined the latter company in 1970. (22)

Standard Logic Families

With its early to market advantage, Fairchild Micrologic was the most popular first generation standard digital

IC family. Signetics offered the first commercial integrated Diode Transistor Logic (DTL) configuration in 1962 but the higher speed and lower cost of Fairchild's 930 Series, designed by Dick Bohn and Robert Seeds in 1964, quickly gained acceptance and dominated the market through much of the 1960s and established a competitive industry leap-frog pattern that is a characteristic of the business. (23)

Inspired by an application note on "New Forms of All Transistor Logic," written by H. Ruegg and R. Beeson of Fairchild in 1961, Thomas Longo developed the first commercially successful Transistor Transistor Logic (TTL) family, Sylvania Universal High-level Logic (SUHL) at Sylvania in 1963. (24) Texas Instruments implemented a lower cost SN7400 series TTL in 1966 and through aggressive marketing and high-volume manufacturing capability surpassed Fairchild as the leading logic supplier by the end of the decade. Through technological initiatives, such as defining the most popular TTL medium scale integration (MSI) functions, the 9300 Series, and applying Isoplanar oxide-isolation technology (see item on bipolar memory below) to deliver the highest speed family with Fairchild Advanced Schottky Technology (FAST), the company held the second place position in digital bipolar logic sales behind TI during much of the 1970s but never regained its initial market prominence. Fairchild also developed a very-high speed ECL family, designated 100K, which enabled the Cray 1 supercomputer in 1976.

Linear IC market breakthrough

Analog, also called linear, circuits amplify and condition signals from continually varying phenomena such as sound, temperature, and radio waves. Because of the nearly infinite resolution required to process these signals, analog circuits demand high precision in design and manufacturing. Fairchild as well as Amelco, RCA, TI, Westinghouse and others developed integrated versions of simple differential amplifiers as early as 1962 but they achieved limited market acceptance.

It took the unique genius of the colorful young designer Robert Widlar working with creative process engineer Dave Talbert to conceive the first widely-used linear device, the Fairchild μ A702 operational amplifier (op-amp) in 1964. Believing that a traditional sales approach would not adequately promote his product, Widlar demanded and received possibly the industry's first dedicated linear circuit marketing manager. (25) Jack Gifford moved up from the Los Angeles sales office to begin a long and successful career in the analog IC business. He retired as chairman of Maxim Integrated Products in 2007.

Figure 5

Analog circuit design guru Bob Widlar adopts a fighting pose
(The Computer History Museum Collection. Courtesy: National Semiconductor Corporation, successor to Fairchild Camera & Instrument Corporation)

Widlar and Talbert's successor device, the μ A709 op-amp solved important design quirks of the μ A702 to establish a mass market for analog ICs and a highly profitable business unit for Fairchild. In late 1965, the pair departed for Molectro (later acquired by National Semiconductor) where they built a linear dynasty that eventually surpassed Fairchild's. In another example of technological competitive leap-frog, by adding an internal compensating capacitor to one of Widlar's early designs for National, the LM101, Fairchild R&D engineer Dave Fullagar created the μ A741, the most popular op-amp of all time. (26) Long after his retirement, Fullagar's circuit remains in production today.

Digital is the most efficient form for manipulating many kinds of information. However, real world data is analog in nature and must be converted to digital form for processing. Integrated circuits incorporating analog and digital circuitry where signals are translated between these two modes are called mixed-signal devices. In 1968 Fairchild designer George Erdi developed the μ A722 10-bit Current Source, one of the first IC building blocks specifically created to integrate an important functional component of many data conversion circuits. With the

proliferation of digital consumer products, mixed-signal devices represent one of the fastest growing sectors of the industry today.

The Dual-Inline-Package (DIP) – the first system oriented IC package

Semiconductor devices are typically enclosed in a robust outer package to prevent damage to the chip and its fragile connecting wires. Despite this important consideration, packaging was one of the most neglected aspects of early IC design. Typically an existing transistor package was modified to squeeze in an IC chip. The first Micrologic devices were etched into a disk shape small enough to fit inside the pin-circle of a TO-18 can (TO stands for Transistor Outline). None of these formats were convenient for high-density, printed circuit board layout.

In 1965 Don Forbes, Rex Rice, and Bryant (“Buck”) Rogers at Fairchild devised a 14-lead ceramic Dual-in-Line Package (DIP) with two rows of pins 100 mils apart that revolutionized computer manufacturing by simplifying layout and allowing automated insertion into printed circuit boards. (10) Versions of the DIP with pin-counts increased up to 64 leads and molded with low-cost, plastic compounds dominated production volumes until surface mount technology became widely used in the 1980s.

Gordon Moore’s insight becomes a self-fulfilling prophecy

In 1965 Electronics magazine published an article “Cramming more components onto integrated circuits” by Gordon Moore, Fairchild Semiconductor’s Director of R&D. Moore’s goal was to encourage computer designers take advantage of future, higher-density ICs by predicting “the development of integrated electronics for perhaps the next ten years.” He drew a line through five data points representing the number of components per integrated circuit for minimum cost per component developed by Fairchild between 1959 and 1964. Extrapolating the trend to 1975 he projected that the practical number of components per chip would reach 65,000; a doubling every 12 months. (27)

Figure 6

Gordon Moore as head of Fairchild R&D in 1962

(The Computer History Museum Collection. Courtesy: National Semiconductor Corporation, successor to Fairchild Camera & Instrument Corporation)

At the 1975 IEEE International Electron Devices Meeting Moore, by then president and CEO of Intel, noted that advances in photolithography, wafer size, process technology, and “circuit and device cleverness,” especially in semiconductor memory arrays, had allowed his 1965 projection to be realized. Adding more recent data, that included a higher mix of microprocessor designs that were somewhat less dense than the memory chips that had sustained his initial trend line, he slowed the future rate of increase in complexity to “a doubling every two years, rather than every year.” This prediction became a self-fulfilling prophecy that emerged as one of the driving principles of the semiconductor industry. Technologists world-wide were challenged, and continue to be challenged, with delivering regular breakthroughs that ensured compliance with “Moore’s Law,” as it was later dubbed by Carver Mead. (28)

Pioneering semiconductor memory activities

According to Gordon Moore, in the early days of the Micrologic family development Bob Norman suggested that multiple semiconductor flip-flops could be used to build a memory array but “I decided it was so economically ridiculous, it didn’t make any sense to file a patent on it.” (29) However by 1963 Moore had changed his opinion and described the possibility of semiconductor memory as “especially inviting.” In 1964 John Schmidt designed a 64-bit MOS p-channel static random access memory (RAM) and in 1965 a Memory Products busi-

ness unit was established at 2525 Charleston Road, Mountain View. A thirteen-member R&D staff was chartered with developing both ferrite core and monolithic semiconductor memory assemblies. The company employee journal *Leadwire* (October – December 1965) noted that “semiconductor IC memory systems pioneered by Memory Products promise to be the wave of the future.”

One early result of this effort was a series of multi-chip memory modules described as Semiconductor Active Memory (SAM) planes. In 1968, Zeev Droori, who later founded Monolithic Memories (MMI), managed the development of a 1024-bit SAM module for Burroughs Corporation comprising sixteen of Schmidt’s 64-bit RAMs face-down bonded to a 1.5” by 1.5” ceramic substrate that formed the base of an 80-lead package. These 1K planes were then stacked 3” high to form complete memory systems of up to 16,000 bits. However, monolithic solutions soon overtook this multi-chip approach.

Figure 7

A SAM multi-chip 1024-bit MOS memory plane from 1968

(The Computer History Museum Collection. Courtesy: National Semiconductor Corporation, successor to Fairchild Camera & Instrument Corporation)

Fairchild applications engineer Lee Boysel promoted the use of a dynamic four-phase circuit technique to increase the speed and packing density of MOS circuits. In 1967 he defined a family of computer-oriented MOS-Large Scale Integration (LSI) building blocks. Several of these functions, including a 256-bit dynamic RAM (DRAM), were fabricated before he left to found Four Phase Systems in 1968. At Four Phase he used this work as the basis for a 1024-bit DRAM used in the company’s System IV/70 computer. The device preceded merchant market DRAMs by several years. (16)

Fairchild was never able to leverage these important pioneering efforts in MOS semiconductor memory into a significant market position, but it did become a dominant player in high-speed bipolar memory devices.

Bipolar memories serve high-performance computing systems

A 1966 Fairchild Semiconductor Integrated Circuits short-form catalog includes four bipolar memory devices of up to 16-bit density offered in CML (Current Mode Logic, aka ECL), DTL, and TTL compatible versions. They were designed for scratch-pad memories and for local and bulk storage “to allow the computer manufacturer to realize fully-integrated systems at the lowest possible cost.” At the 64-bit density level Fairchild competed with concurrent offerings from Sylvania and TI but was first to market with the next generation 256-bit TTL device. Designed by H. T. Chua before he left to craft Intel’s first memory chip and later MMI’s Programmable Array Logic (PAL) device, at 104 x 134 mils, the 4100 (aka 93400) was one of the largest production chips of its era.

Illiac IV was a high-performance computer system funded by the U.S. Department of Defense’s Advanced Research Project Agency (ARPA). The project was conceived and managed by Daniel Slotnick of the University of Illinois. The system hardware was designed and built by Burroughs. Illiac IV initial specifications called for 2,048-word, 64-bits-per-word of memory, a total of 131,072 bits for each of the machine’s 64 parallel processing elements. The memory was to operate with a cycle time of 240 ns and access time of 120 ns. When the planned thin-film memory could not deliver this performance, in 1970 Burroughs contracted with Rex Rice, manager of the Fairchild R&D Digital Systems Department, to build the systems using semiconductor devices. By May 1971 a team led by Frank Greene and Wendell Sander designed and shipped 70 processor element memory (PEM) systems to Burroughs using Chua’s 256-bit TTL device. According to Slotnick, “Illiac IV was the first machine to have all-semiconductor memories. Fairchild did a magnificent job of pulling our chestnuts out of the fire . . . the memories were superb and their reliability to this day is just incredibly good.” (30)

Figure 8

The Illiac IV Processor Element Memory (PEM) system used 256-bit TTL chips
(The Computer History Museum Collection. Gift of Frank Greene. Courtesy David A. Laws)

In 1971 Fairchild announced a 256-bit TTL RAM (93410), the first commercially available memory using an oxide-isolated bipolar process that the company called Isoplanar. (31) Developed by Douglas Peltzer, in concept the technology was conceptually similar to Jay Last's physical isolation approach used to make the first planar integrated circuits, The epoxy-filled trenches being replaced by thick oxide walls. The smaller die sizes and improved performance of Isoplanar enabled Fairchild to establish the industry's largest and most profitable memory business unit producing TTL and ECL bipolar chips for high-speed applications. Seymour Cray continued his earlier working relationship with the company when he designed the iconic 1976 Cray 1 supercomputer to use up to 65,000 Fairchild 1024-bit ECL RAM chips per system together with 250,000 dual-ECL gate elements.

The beginnings of EDA and its application to ASIC design

As ICs began to incorporate hundreds of gates and thousands of transistors, the computers they enabled were harnessed to speed the development process and eliminate design errors. IBM pioneered some of the earliest work in what was called Computer Aided Design (CAD) and later Electronic Design Automation (EDA). By 1966 James Koford and his colleagues at IBM Fishkill were capturing Solid Logic Technology (SLT) hybrid circuit module designs for the Series 360 machines on graphical displays, checking them for errors and automatically converting the information into mask patterns.

Recruited to Fairchild R&D by Gordon Moore and Bob Seeds, Koford worked with Hugh Mays, Ed Jones, Rob Walker and others to apply this process to monolithic ICs. They designed graphic displays optimized for efficient layout of mask designs, wrote logic simulators (FAIRSIM), and created test program generators to work with Fairchild Instrumentation Division-designed computer-controlled test systems. (32) Place and route software for implementing custom mask patterns laid the ground work for generations of electronic design automation tools and the beginnings of an important independent EDA industry in Silicon Valley.

Figure 9

A mask designer works at an IBM 360/67 powered CAD system graphic display terminal (The Computer History Museum Collection. Courtesy: National Semiconductor Corporation, successor to Fairchild Camera & Instrument Corporation)

Gate arrays were developed by several vendors in the mid-1960s to speed the design turn-around time for custom ICs. The custom metal layer masks were designed manually. The Micromatrix family of gate arrays employed Fairchild CAD tools to perform this operation interactively. The Micromatrix 4500 array introduced in 1967 offered 32 DTL gates interconnected with two layers of metal. One year later the 4700 array offered 150 TTL compatible gates. Micromosaic standard cell products implemented customer designs in less silicon area but required custom masks for all production layers. Fairchild's first MOS Micromosaic units shipped for revenue to General Electric Avionics unit in 1968. These ground-breaking programs were technically successful but the high cost of computer time on the IBM 360/67 mainframe-powered CAD systems rendered the business uneconomical. Fairchild exited the business in the early 1970s.

In the 1980s two companies founded by former Fairchild personnel associated with these programs established leading positions in, what was by then called, the Application Specific Integrated Circuit (ASIC) business by building on the pioneering efforts of their former employer. VLSI Technology, Inc was founded in 1979 by Jack Balletto, Dan Floyd, and Gunnar Wetlesen - all from Fairchild by way of Synertek - and Doug Fairbairn from Xerox Palo Alto Research Center (PARC) to offer standard cell devices supported by a broad suite of EDA tools. LSI Logic Corporation was founded in Santa Clara, CA in 1981 by former Fairchild CEO Wilfred Corri-

gan together with Mick Bohn, Jim Koford, Bill O'Meara, and Rob Walker to apply CAD software tools and fast turnaround prototype capability to deliver complex gate array devices.

“Peculiar physical effects”

In Fairchild's continuous search for new product opportunities, Gordon Moore recalls “calling the senior people in the laboratory together and saying ‘OK, we've done integrated circuits. What'll we do next?’ And we started looking for all the peculiar physical effects we could find to see what new devices we could invent.” (2) Some of these ideas used compound semiconductor materials such as gallium arsenide and led to the establishment of a Microwave Products group in 1965. Under the leadership of former Bell Labs' MOS pioneer John Atalla, in 1971 the was business expanded to embrace optoelectronic, radio frequency, and transducer products as the Microwave and Optoelectronics Division (MOD) on Deer Creek Drive in Palo Alto.

Member of the Technical Staff at the R&D Lab Gene Weckler worked on the development of processes and structures to improve silicon photodetectors and wrote a 1967 paper that has been cited as the original CMOS sensor paper. He came up with a design that resulted in a 128-element self-scanned linear sensor array product introduced in 1970. Together with MOS technologist Ed Snow, they founded Reticon Corporation in 1971 to commercial these ideas.

The first planar technology gallium arsenide device, an infra-red emitting diode, was produced in 1969 and followed the next year by monolithic, visible light emitting diode (LED) display digits based on gallium arsenide phosphide. Along with many other Silicon Valley companies, Fairchild rode the boom in seven-segment LED displays for calculators and watches in the early 1970s until they were displaced by low-power, liquid crystal displays.

Continuing his early Bell Labs work on charge-coupled devices, at Fairchild Gil Amelio led the design and manufacturing of CCD products for serial storage and imaging applications. The latter proved to have the most lasting value as the basis for today's scanner and digital camera sensors. The company announced the “world's first commercially available CCD device,” a 1 x 500 element linear image sensor, in 1973 (33). Sold by Schlumberger in 1982, the business continues today in Milpitas as Fairchild Imaging.

Offshore Assembly pioneer

Most early high-tech companies tended to expand within their immediate geographical region, but even as it committed to doubling its just completed new plant size in Mountain View in 1959, Fairchild began to look outside the local area for further growth. The first facility beyond the San Francisco peninsula, a dedicated diode manufacturing plant in San Rafael, California opened in 1960 and the first outside the state, a test and assembly operation in South Portland Maine, in 1962.

In 1963 Manager of Administration & Planning Jerry Levine launched a feasibility study into how to take advantage of the highly-skilled, low-cost labor pool in Asia. Following a vacation in Hong Kong, he made a recommendation to director of manufacturing Charlie Sporck to open an assembly plant there. After start-up in rented facilities, the board approved the construction of a company-owned high-rise building in 1964. Led by plant manager C.E. (Ed) Pausa, within a year Fairchild was the largest electronics employer in the colony. Two years later there were 5000 employees in Hong Kong and 3000 in California. The success of this venture attracted the attention of other US component manufacturing companies and began the high-tech industry drive to major offshore operations throughout Asia.

Figure 10

The Flying F logo on the Fairchild high-rise assembly plant dominated the Hong Kong harbor front. (The

Computer History Museum Collection. Courtesy: National Semiconductor Corporation, successor to Fairchild Camera & Instrument Corporation)

A less enduring assembly operation initiated in 1965 in cooperation with another “sovereign state,” the Navajo Nation, led to the construction of a 120,000 square foot facility employing 950 people on the Navajo Reservation at Shiprock, New Mexico. After resolving early cultural differences the operation ran successfully and received several awards for its innovative practices until internal political differences within the tribe resulted in an armed take-over of the plant and its subsequent closing in 1975.

Marketing and Sales initiatives

Fairchild marketing mavens, beginning with the first head of sales and marketing Tom Bay and including such luminaries as Don Valentine (who later moved to National Semiconductor and Sequoia Capital), W. J. Sanders III (AMD), Robert Graham (Intel, Novellus), and Floyd Kvamme (National Semiconductor, Apple Computer), initiated practices that are now taken for granted in the sales and marketing of high technology products world-wide. A systems and applications group published applications notes and designed printed circuit boards showing how the new planar devices could be used most efficiently in the design of end products. Transistor radio designs based on Fairchild circuits proliferated throughout Hong Kong and other Asian countries. These are commonly known today as reference designs. Notably, applications engineers built a prototype set showing how high-frequency transistors could be used in color television. (8) The concept was mass-produced with only minor changes by General Electric, Sylvania and Zenith using kits of parts supplied by Fairchild.

Creative approaches were developed to aid the sales force in getting the Fairchild story across to engineering decision makers. A flexible vinyl phonograph record with engineer Richard Anderson describing the characteristics and applications of the new Micrologic integrated circuit family was pressed and bound into the July 1961 issue of EDN (Electrical Design News) magazine. In an attempt to reach the broadest possible audience of potential customers on October 10, 1967, the company purchased air time on 32 TV stations that broadcast to the major centers of electronic systems design across the country. Fairchild’s Harry Sello and Stanford Electrical Engineering professor Jim Angell presented a half hour “Briefing on Integrated Circuits” in what is claimed to be one of the first television infomercials. They described the steps in the fabrication of the planar process and the economic and competitive advantages of designing with integrated circuits. Bold and extravagant use of the latest communications medium to promote high-tech products is common today. In the 1960s it was unique and controversial.

Faust/Day a new Southern Californian agency was signed to develop aggressive advertising programs. The principals implemented an unusual campaign for a technology client by developing a brand image that included contracting the company name in the logo to “FAIRCH.” One memorable ad entailed packing a low-cost line of plastic encapsulated transistors in baked-bean cans and pricing them by the pound. According to advertising manger Elliott Sopkin, “No one had tried to sell technology like soap before.” The agency merged into Chiat/Day in 1968 and went on to produce distinctive work for Apple Computer, including the Macintosh “1984” Super Bowl commercial.

Various organizational structures were tried and tested to improve the effectiveness of the marketing and sales activities in winning designs and booking orders. The most lasting may be a matrix of technically-trained generalist sales personnel focused on major markets, such as computer, consumer, industrial, and military customers, supported by factory marketing functions aligned by in-depth product expertise. Not all of these experiments were successful but many of them resulted in methods and procedures that continue to inform the current generation of Silicon Valley Internet-focused marketeers.

Fairchildren and Silicon Valley culture

While journalist Michael Malone's characterization of the corporate culture as "volatility incarnate" quoted at the start of this article may represent hyperbole incarnate, the management style and culture that emerged from Fairchild certainly differed from the straight-laced, bureaucratic, almost feudal ethos of its East Coast parent. Youth, inexperience, testosterone, passion, a diverse mix of immigrants from across Europe and Asia, a tolerance for risk taking, and a strong engineering discipline evolved into a formula that was replicated across the valley as ex-employees spun-out to successor companies such as AMD, Intel, and National Semiconductor and on to Apple, Atari, Netscape and Sun and thence to Cisco, Google, and Yahoo.

A recent magazine article proclaimed enthusiastically, "Fairchild's 50th anniversary commemorated not just the founding of a company but an epochal turning point in human evolution." (34) As numerous books, academic treatise, and popular journals have expounded on this topic and the impact of the company on the creativity and rise of Silicon Valley at great length it will not be explored further here.

Fairchild cannot be assigned full credit or blame for the phenomenon of Silicon Valley. However there is little disagreement that the events that began with the spin-off of Fairchild from Shockley Semiconductor Labs in 1957 set the juggernaut in motion. Urban cultural historian Peter Hall notes in comparing the rise of Silicon Valley to that of other great centers of creativity, including Florence during the Renaissance and Manchester, England during the Industrial Revolution, "Creative cities... are places of great social and intellectual turbulence, not comfortable places at all." (35) Many of the Fairchildren who attended the anniversary event in October 2007 described their tenure at the company as the most rewarding professional experience of their lives. Few chose the adjective "comfortable."

Acknowledgement

I would like to thank Michael Riordan co-author of *Crystal Fire: The Birth of the Information Age* and Adjunct Professor of Physics at the University of California, Santa Cruz, CA for his contributions to the research and writing of the Computer History Museum website "The Silicon Engine: A Timeline of Semiconductors in Computers" (36) that provided many resources and references used in the preparation of this article.

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SIDEBAR TEXT [Photos of these machines can be supplied on request]

"The Legacy of Fairchild" in the Computer History Museum's Visible Storage Gallery

The Visible Storage gallery of the Computer History Museum displays approximately 500 artifacts from the museum's collection. Every machine in the gallery produced after the early 1960s depends to some degree on the Fairchild planar process. Six of the most significant artifacts that are related directly to processes, products, and/or people associated with Fairchild Semiconductor are described below. All six machines are included in

the online exhibit at:

<http://www.computerhistory.org/virtualvisiblestorage/>

1. Philco Model 212 Computer (1962)

Robert Noyce contributed to Philco's surface-barrier transistor technology

On graduating from MIT in 1953, Robert Noyce joined the transistor research group at Philco in Philadelphia where he developed etching techniques for high-speed germanium transistors. These transistors are used in the Philco Model 212 computer.

2. Autonetics Minuteman I Missile Guidance Computer (1962)

Potential reliability problem stimulates Jean Hoerni's invention of the planar process

Fairchild's first transistor, the 2N697, was selected for the Minuteman I missile guidance computer. Late in 1958 Autonetics reported a potential reliability problem. Jean Hoerni's solution was the planar process in which a protective oxide layer covers the sensitive p-n junction region. Planar devices replaced the mesa technology in Minuteman and went on to revolutionize the semiconductor industry.

3. Raytheon/MIT Apollo Guidance Computer (1965)

The first production computer to commit to use monolithic integrated circuits

Developed by the MIT Instrumentation Laboratory and manufactured by Raytheon, the Apollo Guidance Computer (AGC) guided the Apollo Spacecraft Command Module from Earth orbit to the Moon and back. In 1962 the AGC was the first major computer project to commit to use monolithic ICs. Each system used 4,000 Fairchild Micrologic "Type-G" (3-input NOR) gates.

4. Control Data Corporation 6600 Supercomputer (1964)

The first high-performance computer to use silicon transistors

Seymour Cray, chief architect of scientific computer manufacturer CDC awarded Fairchild a contract to develop a new high-speed silicon transistor for its model 6600 supercomputer. In 1961 Jean Hoerni combined his "gold-doping" process with the new epitaxial deposition technology to create the 2N709 NPN device as the first silicon transistor to exceed germanium in speed. In 1964 CDC placed with Fairchild one of the largest single orders in the history of the semiconductor industry for over 10 million devices.

5. Cray Research Inc. Cray-1A Supercomputer (1976)

This iconic machine was powered by Fairchild ECL logic and memory devices

ECL bipolar logic and memory devices provided world beating performance of 160 MFLOPS in Seymour Cray's first supercomputer design for his own company. Fairchild Isoplanar oxide-isolated technology delivered about 50% faster performance in half the die size of the previous generation of junction-isolated chips to implement the 250,000 dual ECL gates and 65,000 1024-bit ECL RAMs consumed by each machine.

6. Burroughs Illiac IV Supercomputer (1975)

The first machine to employ all-semiconductor main memory

Illiac IV was designed and developed at the University of Illinois by Professor Daniel Slotnick and built by Burroughs Corporation, Paoli, PA. The exhibit at the Museum includes the central control unit, a processing element (PE) cabinet, and a disk drive. In 1970 Fairchild R&D engineers used a 256-bit bipolar TTL chip designed by H.T. Chua to build 2048 word by 64 bit (131,072 bits) memory systems for each of the computer's 64 paral-

1el PEs. According to Slotnick, Illiac IV was the first machine to employ all-semiconductor main memory.

Biography

David A. Laws is Staff Director of the Semiconductor Special Interest Group at the Computer History Museum. Laws was born and earned a B.Sc. (Physics) in the United Kingdom. He moved to California, Mountain View in 1968 where he worked for Fairchild Semiconductor, Advanced Micro Devices, Altera and other semiconductor companies in roles from product marketing engineer to CEO.

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[Rev 6: dl 5.31.08 – removed images, added abstract, etc from rev 5]