Summary Review on the Early History of the Semiconductor

Ali Akbar HUSSAINI
Selcuk University

Murat YILDIRIM
Selcuk University

Since the middle of 20th century, semiconductors have been at the heart of technological progress. Early electronic devices made to solve simple equations. However, they were expensive and unreliable. Semiconductors changed all that doing the work of a basement full of vacuum tubes with one chip. In 1965, Gordon Moore predicted the number of transistors that could fit in one square inch of integrated circuits would double every two years. For half of century through competition and collaboration the semiconductor's history formed. Semiconductors powered the personal computing revolution, putting incredible capability in our homes and on our desks. They also make electronic devices of every kind smaller, more affordable and long-lasting. Moreover, Semiconductors engendered the emerging technologies literally that were almost science-fiction. Undoutedly, inventions of the transistor and the integrated circuit led to the emergence of the modern computers, telecommunications, and satellite technologies.

Through history of semiconductors, there are indisputable and essential works performed by scientists which led to advent of today's technology. In 1833, M. Faraday observed the properties of silver sulphide, and discovered a negative temperature coefficient in it. Later on, M.A. Rosenschold observed asymmetric conduction in solids in 1835. Afterwards, E. Becquerel realized the effect of the voltage on junction between a semiconductor and an electrolyte under illumination in 1839. M. Faraday also published a paper demonstrating on a temperature sensitive non-linear resistor in 1850. Soon after, Willoughby-Smith expressed the photoconductive effect in 1873, and distinguished the decreasing resistance of crystalline selenium under illumination which led to fabrication of photoconductive cells. Adams and Day discovered the photovoltaic effect existing at a contact between selenium and a metal in 1877. 17 years later, J.C. Bose applied non-linear rectifying properties of semiconductors for electromagnetic waves detection. Therafter, H. Dunwoody and G.W. Pierce discovered that rectification effects were electrical rather than being thermal in 1907-1909. In 1935, O. Heil patented a proposed field effect transistor device. However, transistor was successfully invented on December 23, 1947 by William Shockley, John Bardeen and Walter Brattain at Bell Laboratories. Later on, it was introduced to public by New York Times on July 1, 1948 (Morris, 1990).

Working on semiconductors have been intensified by the late thirties and researches continued until inevntion of integrated circuits at the end of the fifties. In 1947, Bell Lab is recorded for invention of point-contact germanium transistor and growth of single crystals of germanium and silicon which led to fabrication of the "grown- junction" transistor by Morgan Sparks by introducing dopants directly into the melted germanium during crystal growing. Despite the all fundamental works done by Bell Lab, Texas Instruments fabricated the first grown- junction silicon transistor in May 1954, for military applications due to its various advantages. Photolithography is another transistor fabrication method originated at the Diamond Ordnance Fuze Laboratory (DOFL) and at Bell Labs (Li, 2011).

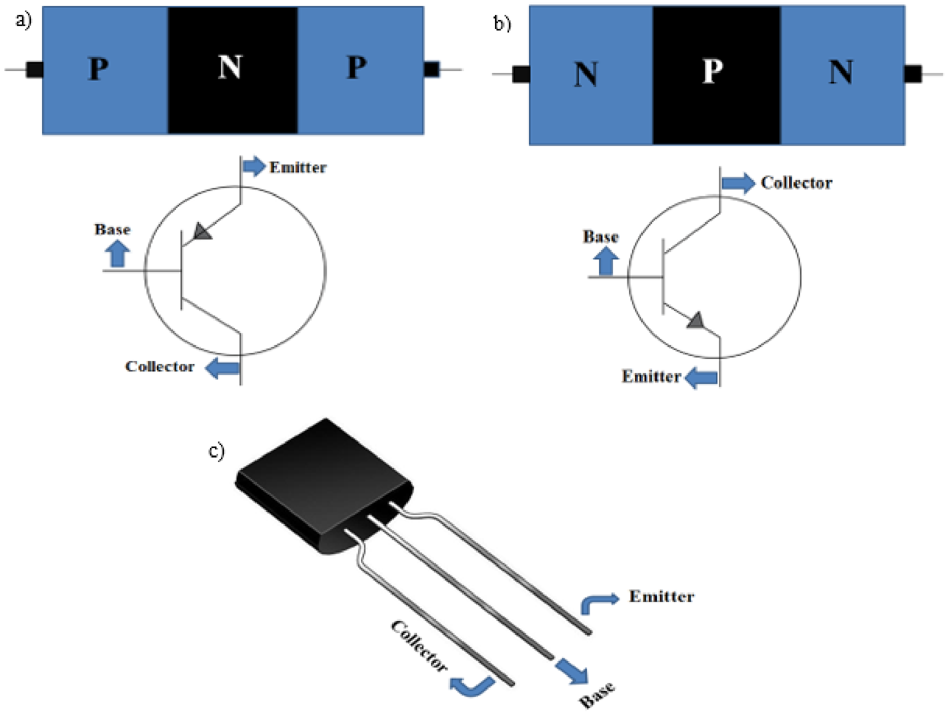

Figure 1. Images of a) PNP, b) NPN, and c) Typical Transistors.

Undoubtedly, Bell Laboratories can be considered as nucleus and origin of today's electronic and technology, which is established in New York city with huge numbers of scientists, researchers, and engineers. Among them, developing a solid-state switching device originated from Mervin Joseph Kelly, who has been director of research, president, and chairman between 1925-1959. During his career as research director, William Shockley was put in charge of the Solid State project. William Bradford Shockley Jr. was awarded the 1956 Nobel Prize in Physics for "his researches on semiconductors and discovery of the transistor effect". At the beginning, Shockley intended to investigate earlier works done by the Pohl group in Germany, and Davydov and Joffe in Russia. Moreover, they investigated the purification of semiconductor materials for microwave detector used in radar. Russell Shoemaker Ohl's researches on properties of crystal detectors for radar applications led him to discovery of the first p-n junction device. Ohl cut a section of sample across an boundary between p and n regions of a silicon ingot solidifying from a doped melt (Lojek, 2007).

Shockley stated a hypothesis that modulated the “field effect” using existing theories for Germanium and Silicon. He proposed that by inducing a surface charge using strong electric field, thin layers of semiconductors can gain conductivity. He also stated that contact potential between n and p type samples can be increased by doping. In November 1947, R. B. Gibney suggested that voltage be applied between the metal plate and semiconductor. Due to current flowed through the sample resistivity can be determined. When the potential of the electrolyte was modulated the current in the external circuit was accordingly modulated. Brattain and Gibney had fabricated amplifiers using the field effect with electrolyte to get the desired high electric field. John Bardeen held U.S. Patent 2,524,033 by modifying the suggested device by Brattain and Gibney, replacing liquid electrolyte with metal forming a rectifying contact with semiconductor. Gibney also held U.S. Patent 2, 560,792, by modifying the device which leads to transistor. Brattain also came up with a device known as “high back voltage” N-type germanium on December 8, 1947. The obtained device exhibited high resistivity. Then Brattain proposed to apply gold on a wedge and then separate the gold at the point of the wedge with a razor blade to make two closely spaced contacts (Lojek, 2007).

Shockley also invented the junction transistor highlighting on 3 significant concepts which are:

1. exponentially-increasing minority carrier injection across the base-emitter junction
2. reverse bias on the collector-base junction
3. appropriate device geometrical dimension and doping profil (Lojek, 2007).

Shockley put his signature on almost ninety U.S. patents due to his undeniable works on theory of vacuum tubes, solid state physics, semiconductor amplifier, electron microscope, nature of metallic state, band theory of solids, order in alloys, space charges and many others (Lojek, 2007).

On December 23, 1947 H. R. Moore had fabricated an oscillator by connecting the input and output of the transistor to a 1 kHz signal and an oscilloscope. In addition to this, Bell Laboratories held five patents in February 26, 1948 covering the basic principle of the transistor. Due to Gibney’s contribution his name appears only on two patent applications (Lojek, 2007).

The term of minority carriers were known from the work of Boris Davydov a Soviet scientist. Davydov expanded previous work of Walter Schottky in Siemens & Halske Laboratories in Berlin. On the other hand, Shockley accomplished his theory of junction transistors in early 1948, and used the Davydov junction theory and expanded it for transistors. Transistor, oscillator, pulse and TV amplifier were announced to public on June 30, 1948. Furthermore, W. G. Pfann and R. Ohl fabricated a “plug-point” contact transistor by modifying the structure of the 1N26 shielded microwave point contact rectifier (Lojek, 2007).

Helmar Frank and Jan Tauc have designed and fabricated successfully the first point-contact transistors outside Bell Laboratories in Prague due to high quality germanium crystals they possessed. In January 1950, Morgan Sparks succeeded in growing crystal rods with a thin-base layer. On April 12, 1950, Morgan Sparks entered into his laboratory notebook, data for a chemically-etched sample made by this grown-junction technique which was working as a large-area transistor (Lojek, 2007).

The two significant transistors developed in BTL were M-1752 and M-1852 transistor. The 1752 was encapsulated in plastic and violet-green-red. The M-1852 shown in Figure 2, was enclosed in a hermetically sealed can and the semiconductor body was covered by red-lead polyethylene-polyisubutylene to reduce some of the detrimental surface effects (Lojek, 2007).

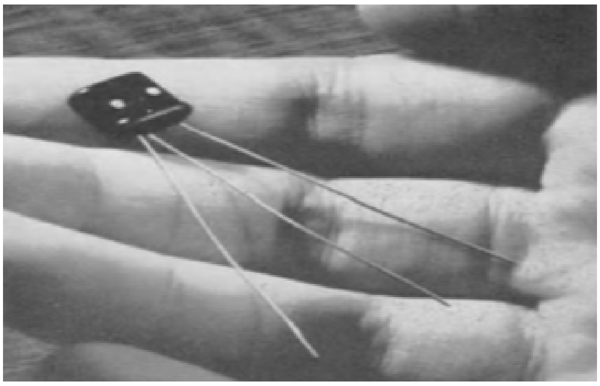

Figure 2. M-1852 Grown-Junction Transistor

John Moll and Ian Ross have developed a theory on diffused transistor impressing two factors that are the magnitude of the built-in fields and the distance over which the built-in field extends. M. Tannenbaum, D. E. Thomas, C. S. Fuller, J. A. Ditzenberger fabricated the double-diffused transistor which exhibited high speed, low saturation current, and satisfactory operation at high temperatures. Scientists from GE Research Laboratories developed the P-N junction produced by an “alloying process” in 1950 (Lojek, 2007).

Lew Miller designed the silicon NPN transistor with mesa “ring-dot” structure which was manufactured by Western Electric as the 2N560 for military logic applications (Lojek, 2007).

In 1955, Shockley decided to establish his own company (Shockley Semiconductor) and left Bell Telephone Laboratories. Bishop, Beckman and Shockley focused on four-layer diode and Junction Field Effect Transistor. A revolutionary device, the four-layer diode was supported by military contracts in 1957. Unlike common rumor, Shockley Semiconductor Laboratory never developed a mesa transistor similar Bell Laboratories's device. There were two major innovations in Shockley Semiconductor Laboratory. Firstly, they have used photoresist for patterning of semiconductor structures. Secondly, they used silicon oxide to protect the semiconductor surface during diffusion. While, the obstacles on device development were associated to the diffusion and contacting the diffusion regions. It was well-known that poor junctions and worse contacts caused a large reverse leakage current (Lojek, 2007).

Jean Amédée Hoerni, who was a silicon transistor pioneer, developed the planar process. Later on, Shockley hired Hoerni to work with him at the Shockley Semiconductor Laboratory division of Beckman Instruments. Hoerni focused mainly on the diffusion and samples evaluation; Harry Sello developed the wax masking; Sheldon Roberts and Noyce worked on the ohmic contacts (Anonymous a, 2021).

Hoerni made the second big invention after the invention of the junction transistor by silicon planar device fabrication on Wednesday, March 4, 1959. He also developed a sophisticated oxidation method which was affecting the pinholes in oxide film. The significant advantage of the planar process is oxide passivation of the semiconductor substrate, which improved the electrical parameters such as reverse leakage current, breakdown voltage, noise figure, and low current hFE. Hopefully, the planar process eliminated the main disadvantage of the mesa transistor which was collector-base junction being vulnerable to contamination during contacting and assembling. Fairchild Semiconductor demonstrated the diffused planar transistor in March 1960 and the planar version of the 2N696 begun for sampling in August 1960. Regarding to 1000 hour test, the planar transistor challenged all mesa transistor by exhibiting less than one nA of leakage at VC = 60 V compared to other mesa transistor (10 nA at VC = 30 V). The novel device made Fairchild sales increasing to 80% and booking to 90% (Lojek, 2007). Side views of mesa and a planar transistor are shown in Figure 3.

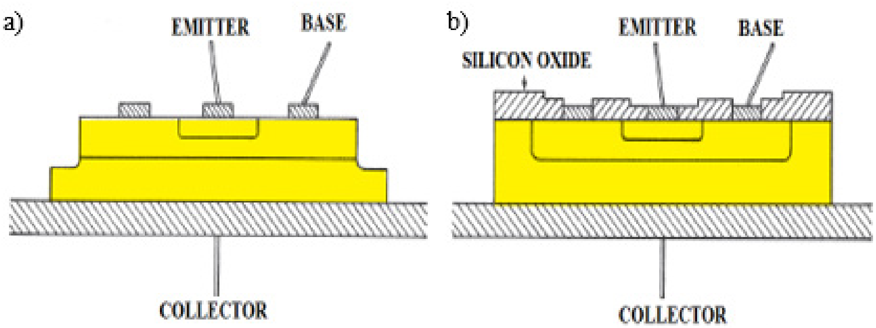

Figure 3. a) Side Views of a Mesa and b) a Planar Transistor, from a Report Hoerni Prepared in 1960 (Riordan, 2007).

Jay T. Last a silicon pioneer was born on October 18, 1929 and worked at the Shockley Semiconductor Laboratory from April 1956 to September 1957. Jay Last figured out the significance of linear integrated circuits and made Amelco the first major supplier of linear integrated circuits. Amelco's contributions were high-end weapons systems, submarines, space launchers, satellites, space stations, and many other applications (Anonymous b, 2021).

Fairchild Semiconductor International, Inc. was established in 1957 located in San Jose, California. The Fairchild's establishers were Gordon Moore, Jean Hoerni, Robert Noyce, C. Sheldon Roberts, Jay Last, Victor Grinich, Eugene Kleiner, and Julius Blank (Li, 2011). It became a pioneer in the manufacturing of transistors and of integrated circuits. By the end of 1957, Fairchild decided to continue the same approach as Shockley Laboratories with wax masking and patterning structure on mesa transistor fabrication. Moreover, they used photoresist developed by Eastman Kodak for patterning of printed circuits. Fairchild Semiconductor fabricated the first silicon transistors (2N696 and 2N697) in Silicon Valley, in 1958 (Lojek, 2007). Fairchild Semiconductor's paramount innovations were technology for diffused silicon devices, the planar process, and the planar integrated circuit (Li, 2011). Whereas, Fairchild Semiconductor applied combining diffusion, oxide masking, and photolithography methods.

Haas and Kattner modified the diffusion process and Lionel Kattner produced the very first integrated circuit in May 1960. Haas tested the circuit which suprisingly seemed functional with the maximum operating clock 1 megahertz and the delay 60 nanoseconds. Haas modified the transistor geometry by replacing the Carbon resistors with diffused resistors in August 1960. Unfortunately, the device passed tests at room temperature and failed at 70 ^{o}C (Lojek, 2007).

L. Kattner modified an integrated epitaxial transistor based on the Fairchild 2N914 device in March 1961, to simplify the isolation problem. Besides, Bob Norman designed the first Micrologic Flip-Flop circuit. Bob Norman and Bob Anderson designed and introduced Flip-Flop (4 transistors, 2 resistors), Half-shift register (9 transistors, 5 resistors), Gate (3 transistors, 1 resistor), Buffer (3 transistors, 3 resistors), Half Adder (4 transistors, 3 resistors), Counter Adapter (6 transistors, 5 resistors), and Shift Register (17 transistors, 9 resistors) in summer 1961 (Lojek, 2007).

National Semiconductor preserved patent notebooks carefully and donated materials and reports of Fairchild to Stanford University, after they took management of Fairchild in 1987. On the other hand, Sylvania introduced the world's ever fastest silicon switching transistor (2N2784) in August 1963, with high beta in the microamperes range, with gradual fall off beyond 10 mA, low saturation voltage, typically 0.2 V and switching speed of 12 nsec (Lojek, 2007).

Texas Instruments convinced Regency Radio to invest in TI for radio receiver fabrications and certainly made it a pioneer in the germanium transistors marketting. Haggerty was another investor in TL and put $3 million for silicon transistor fabrications during 1952–55. Eventually, in early 1954, they had fabricated a working silicon device similar to the germanium junction transistor designed at Bell Labs. Therafter, the effect of strong electric fields on the observed spreading resistance of metal-germanium point-contact rectifiers was investigated by Lark-Horovitz and R. Bray during 1949–1950, which somehow resembled to the work carried out at BTL (Lojek, 2007).

Lehovec equipped the laboratory and intended not to duplicate BTL devices. Additionally, he worked on the photo-voltaic effect, light-emitting diodes and lithium batteries, and successfullu came up with the concept of p-n junction isolation used in every circuit element. Furthermore, he realized and highlited the exhausting labor to manipulate under a microscope two tiny wires to the correct position and the possibility of sliding of the wires during the handling the device as 2 main hurdles being in BTL transistor which the Sprague Company licensed. Lehove's contributions were mainly to CV techniques, solar cells, solid-state batteries, and LED diodes (Lojek, 2007).

The Sprague Electric R&D group successfully introduced the first design of their first integrated circuit during 1961-1962. Sprague Company was also pioneer in the lead of ion implantation technology in the early sixties (Lojek, 2007).

The Signetics hired a former employee of Fairchild Orville Baker who developed the DTL series SE100. The Signetics DTL series contained a metal-overoxide capacitor, with a propagation delay of 25 nsec with a power consumption of 6 mW per gate (Lojek, 2007).

By early 1965, Sylvania was credited for the largest selection of compatible digital circuits production. The Sylvania company produced the best speed-power and the highest level of noise immunity devices. On ther hand, Fairchild did not produce any high quality memory devices before 1968. The only memory device available was an 8 bit Micrologic element with a cost of $2 per memory bit and a 256-bit static RAM 4100 designed by H. T. Chua (Lojek, 2007).

At the end of a semiconductor industry recession during 1970 and 1971, Longo's group introduced a new product line including low power Schottky logic (the 9600 series) and later ECL logic. The group started work on a 1k static RAM, which Longo offered to his old friend Seymour Cray who was developing the Cray-1 computer. Fairchild's 1k (and later 4k) static RAM was used in the Cray-1 as a main memory. The cost per bit dropped to 17 cents and other main-frame computer manufacturers such as Univac, CDC, Burroughs, Fujitsu, and Siemens also switched from core memory to semiconductor memory (Lojek, 2007).

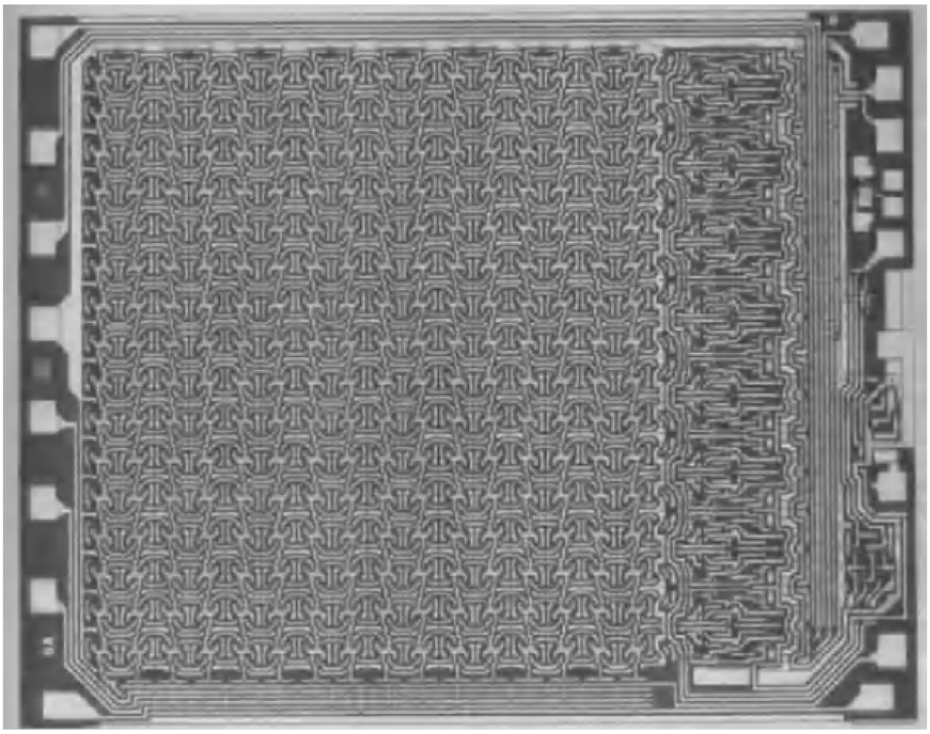

Figure 4. Fairchild's 256-bit Static RAM 93410 (2650×3400μm) (Lojek, 2007).

After Tom Longo left Fairchild in 1984, he established Performance Semiconductor Corporation to manufacture fast CMOS and static memory. Later on, the world's fastest 16 bit 40 MHz microprocessor 1750 was developed for airborn computers and weapons systems. The 1750 was mainly produced in radiation resistant forms for military applications. Tom Longo argued that BiCMOS will almost double the mask count and the bipolar part will not be scalable. Performance Semiconductor expanded business up to a $200 million annually. Unfortunately, after the fall of the Soviet Union military projects stopped (Lojek, 2007).

An eminent engineer of General Electric company, Dr. Robert N. Hall invented power rectifier device made of germanium and figured it out the recombination of the electrons and holes that it can produce. Somehow, rectifiers developed by silicon are widely used in power delivery, locomotives, power distribution system and dc transmission. He also invented the first semiconductor laser, intrinsic detectors and hyper pure germanium detectors. As a one of the pioneers in semiconductor history he held 43 U.S. patents (Anonymous c, 2021).

Hoerni established Intersil with $300,000 of his own budget, then investments on Intersil increased to $4.5 million. The first N-MOS memory technology was developed by Intersil, which had low voltage metal-gate CMOS technology for the quartz clock and EPROM (Lojek, 2007).

The Semiconductor Department of Westinghouse decided to fabricate high power semiconductor devices. Westinghouse applied the technology used at TI and introduced the industry's first silicon power transistors, 2 and 5 amp units rated at a maximum collector current of 7.5 amps with the highest available power rating of 150 W. They also developed and delivered Molecular Receiver AN/ARC-63 to Air Force in 1961 (Lojek, 2007).

Within the history of microelectronics, Bob Widlar remains as inventive genius due to his various inventions such as linear integrated circuits, the Widlar bandgap voltage reference, µA702, µA709, LM100, LM105, super-beta transistors (LM108), and the first operational amplifiers (LM101). Bob and Dave Talbert developed brilliant manufacturing methods and process control to decrease the price of the planar process. Dave also worked on development of a process which included an epitaxial layer. Moreover, John Barrett determined probable performance of a differential amplifier using the Micrologic kit block on April 1, 1962 (Anonymous d, 2021). The µA709 operational amplifier is shown in Figure 5.

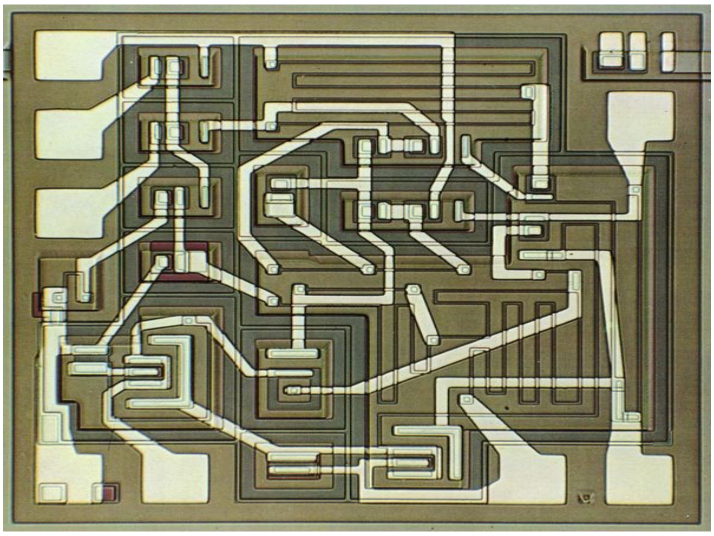

Figure 5. The µA709 Operational Amplifier Developed by Widlar (Anonymous e, 2021)

Computer components and calculator chips increased the demand for MOS technology in 1960s. In July 1970, AMI developed the 6-chip set that contained all the MOS circuitry for an arithmetic calculator. AMI was quickly followed by Texas Instruments and North American Rockwell (Lojek, 2007).

MOS technology and its advantages attracted engineers worldwide. Due to its huge demands 20 companies started developing MOS technology by 1969. MOS technology were used in calculator, electronic memories and electronic wristwatches fabrications which rose the MOS market to $80 million in 1970. However, a significant loss in global market share appeared between 1990-2000 (Lojek, 2007).

In conclusion, owing to the invention of transistor, the human race is more interwined to technology. Inspite of it's simple archietecture, it is absolutely the foundation of the modern technology and devices. Without the transistors, accessing to myriad of informations would be time-consuming and troublesome. Moreover, in order to understand it's impact, we need to ponder over the science and history behind it.

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About the Authors

Ali Akbar HUSSAINI is a PH.D. candidate at Selcuk University since 2021. He received the bachelor's degree in Food engineering from Necmettin Erbakan University in 2018, and master's degree in Biotechnology from Selcuk University in 2020. His research interests include nanomaterial, semiconductor materials, diode and solar cell fabrications.

Email: aliakbar.hussaini.1994@gmail.com, ORCID: 0000-0002-7128-9994

Murat YILDIRIM obtained a Ph.D. degree in Physics. He is now a Assoc. Prof. at Selcuk University in the Department of Biotechnology. His current field of interest includes organic semiconductor, green synthesized nanomaterials and metal oxide based sensors.

Email: muratyildirim@selcuk.edu.tr, ORCID: 0000-0002-4541-3752

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