Jack St. Clair Kilby

Chip and Dare Saga

Navakanta Bhat

The electronics Integrated Circuit (IC) chips have enabled us to create intelligence on silicon (Si). Hence the impact of electronics manufacturing cuts across the entire industrial ecosystem. The IC chip is arguably one of the most profound inventions of the last century. Since the invention of the semiconductor transistor towards the end of the year 1947, the entire electronic industry was struggling to deal with the tyranny of numbers – the difficult problem of manually assembling a large of number of transistors on a board to realize complex circuits. This is when Jack S. Kilby entered the stage in the year 1958. He was a hands-on engineer with a lot of imagination and intuition, but grounded to reality with a lot of practical experience. He proposed a revolutionary concept of creating all components of an electronic circuit, in-situ, on a single semiconductor piece. He successfully implemented this idea on September 12, 1958, by realizing a phase shift oscillator on a small piece of germanium (Ge), the first ever electronics IC chip. The importance of this milestone in the modern history of science and technology is highlighted by the fact that Jack Kilby received the Nobel prize in Physics, in the year 2000. The story of Jack Kilby and his remarkable achievements are very inspiring for all ages.

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Growing up in the Heartland of America

Jack Kilby was born on November 8, 1923 in Jefferson City, Missouri, a traditional mid-western state in the United States of America. His father was Hubert Kilby and his mother Vina Freitag Kilby. Jack had a sister Jane Kilby, three years younger to him. Hubert Kilby was an electrical engineer, a graduate of University of Illinois at Urbana-Champaign. He worked for an electrical power company called Kansas Power Company. In

1934, Hubert became the president of the company and had to move to its headquarters at Great Bend in Kansas state, along with the family. Then Jack was in his sixth grade, and the next six years in Great Bend were probably a turning point in his life. The city of Great Bend gets its name due to its location, where the south-east flowing Arkansas river makes a big bend towards the north. Jack grew up in this heartland of USA, quite far from the two high technology centres at that time – the Silicon Valley in the west coast and the AT&T Bell Laboratory in the east coast. When they moved to Great Bend, they rented a house popularly known as 'Komarek house' which was full of books [1]. The parents were very supportive and encouraged the children to read diverse literature and be imaginative. Jack also played in his school musical band. He was fascinated by photography and he experimented with the camera.

Ham Radio Hooks Jack Kilby to the World of Electronics

In 1938, a blizzard struck western Kansas state and crippled the telephone communication and electrical power network. The road condition was so bad, that it was difficult to travel to the locations of power stations and related installations. It was also not possible to communicate over telephone with the power company managers in different locations, to plan the strategy for restoration. Jack's father, being the president of the company, had to find a way out to restore the power across the state. Hubert approached the local genius of Great Bend, Roy Evans, who had a small radio shack behind his house. During this period, Evans helped Hubert Kilby to set up ham radio[1] communication link to the blizzard-hit areas, through other amateur ham radio operators in those locations. Hubert Kilby was able to discuss with the power company managers and help restore the power situation. Jack Kilby, the curious boy, accompanied his father Hubert in all such rendezvous, on ham radio communication. This was his first exposure to ham radio, and the fascinating world of electronics. Jack could appreciate, first hand, how an electronic device, such as ham radio, can help communities in distress. He immediately made up his mind that he would study electrical engineering in

[1] Ham Radio is an Amateur Radio broadcasting system used for non commercial applications. Anybody can become a Ham Radio operator and get the license, if they pass the examination for Amateur Station Operator Certificate.

college and take up a professional career in electronics. He fondly remembered this incident as one of the turning points in his life. In a letter written to Donald L Walters, physicist grandson of Roy Evans, he elaborates how Roy Evans helped his father during the blizzard, through the wonderful electronics gadget – the ham radio. Subsequently, Jack Kilby went on to become an amateur ham radio operator, with his call letters W9GTY.

College Days

Jack Kilby had a difficult time with mathematics in high school. He wanted to go to Massachusetts Institute of Technology (MIT) to study electrical engineering, but he failed the mathematics section of the entrance examination. He then entered the University of Illinois, at Urbana Champaign, in 1940. His specialization in engineering was electrical power engineering. But due to his interest in electronics he decided to take additional courses in engineering physics and vacuum tube electronics. Interestingly his engineering education got interrupted when the second world war intensified after Japan attacked Pearl Harbor. Jack Kilby enlisted in the US army and he was posted in north-eastern India to fight against the Japanese [2]. He was assigned the responsibility to manage the radio network of the army, which was the lifeline of communication. Due to his expertise as an amateur ham radio operator, he could ably support the allied forces in their conquest. After serving the army, he returned to college in 1946 and graduated with a BS degree in 1947. It is interesting to note that the field of electronics was at a turning point when Jack was about to start his professional career. The invention of the semiconductor transistor was just around the corner, with Bell Labs announcing the first transistor[2] towards the end of the year 1947. Vacuum tubes, Jack's favourite during his studies, were about to be displaced by transistors completely.

[2] The first semiconductor transistor was invented at AT & T Bell Labs by Shockley, Bardeen and Brattain. This was a point contact bipolar junction transistor built on Germanium semiconductor. The transistors liberated the electronics from the clutches of vacuum tubes, and paved the way for the unprecedented miniaturization to follow.

Early Professional Career

In the year 1947, after his graduation, Jack Kilby joined Centralab in Milwaukee, Wisconsin. Cantralab, a subsidiary of Globe-

Union Inc., was an electronics manufacturer involved in products such as radio, television and hearing aid. Jack was assigned to work on product engineering for hearing aid amplifiers and resistance-capacitance networks for television. The product engineering work gave him a very good perspective to appreciate different aspects involved in developing a product.

During the initial few years at Centralab, he worked on thick film hybrid circuits using vacuum tubes and other components. The ceramic board served as a substrate, on which silver paste was deposited to form conducting tracks, followed by carbon paste resistors, ceramic capacitors and vacuum tube electronic devices to build the complete circuit. This was the best possible miniaturization during that period. The complexity of assembling a large number of different components on a substrate, to build a complex circuit, was probably recognized by Jack Kilby during this period. Jack obtained patents on making titanate based capacitors and sand blasting for resistor trimming. These were among the 12 patents that he secured at Centralab.

During this period, the semiconductor transistor was getting wider acceptance and vacuum tubes were slowly becoming obsolete. In 1951, Bell Labs started licensing the transistor technology. Centralab obtained the license to produce transistors, and sent Jack Kilby to Murray Hill, to attend the first transistor symposium to gain expertise in the new emerging field. Jack was fully convinced about the importance of transistors in future electronics products, and this was the opportune moment for him. Due to his expertise and capabilities, he was assigned to lead a three-member team to productize transistors. He set up the basic infrastructure such as furnaces, crystal puller, etc., in Centralab and started producing Ge transistors. Centralab was able to sell a few products based on transistor circuits, by the year 1957.

Jack was convinced by then, that to make more complex circuits, higher scale of investment[3] would be required, and Centralab was too small a place to afford such investments. He had also recognized first hand, the 'tyranny of numbers' – the inability to

[3] Transistor and chip fabrication requires expensive infrastructure to process the semiconductor wafers in an extremely controlled ambient called cleanroom. In modern Silicon foundries (cleanrooms) the number of particles of size 0.5 micron and higher, in 1 cubic foot air volume is less than 1. In contrast, we will typically see more than 1 million particles in an air conditioned office.

assemble a large number of miniaturized transistors and other circuit components, fabricated ex-situ, onto a ceramic substrate. This was an extremely laborious job, to say the least, since handling transistors was more difficult than handling vacuum tubes. He was also convinced that the future of electronics would be in semiconductors and the field of electronics was headed for a major transformation. So he started looking for a new job and interviewed with a few semiconductor companies including IBM, Motorola and Texas Instruments. He finally decided to move to Dallas in 1958, to work for Texas Instruments. While at Centralab, he also completed his MS degree, while working, from the University of Wisconsin at Milwaukee.

Career at Texas Instruments and the Birth of the Chip

Jack decided to join Texas Instruments[4] (TI) in Dallas, Texas, since the job required him to work full time on the miniaturization of circuits. In retrospect it appears that Jack Kilby had dared to be the man on the mission to solve the tyranny of numbers. He accomplished this mission with lightning speed. He joined Texas Instruments in May 1958, and demonstrated the first chip on September 12, 1958! While most people would still be learning the ropes, during the first few months after joining a new place, Jack Kilby through his remarkable engineering prowess, heralded one of the most revolutionary inventions of human history in just 4 months.

[4] Texas Instruments is one of the major semiconductor company, with its head quarters at Dallas, Texas, USA. It is very well known for its Digital Signal Processing (DSP) chips and more recently for the Digital Light Processing (DLP) chips, based on Deformable Micromirror Device (DMD) technology.

When Jack Kilby joined TI, his boss Willis Adcock assigned him to work on the Micro-Module program sponsored by US Army. This was another school of thought prevalent at that time, to address the miniaturization of circuits. The idea was to build all components to look alike, with the same footprint so that the assembly of the components becomes easier. The assembly still used thick film hybrid circuit technology, that Jack had practiced at Centralab. By then Jack had enough experience to realize that this approach would never solve the basic problem of assembling several components on a single substrate. There was a second school of thought on miniaturization called thin film hybrid

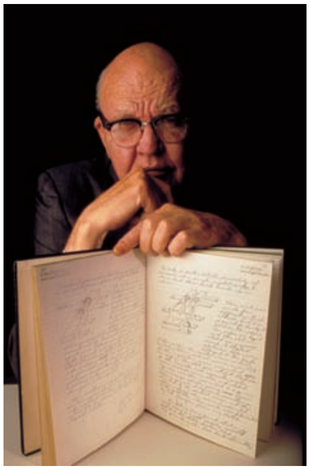

Figure 1. Jack Kilby with his lab notebook, illustrating the concept of integrated circuit chip.
http://www.ti.com/corp/docs/kilbyctr/downloadphotos.shtml
Courtesy: Texas Instruments

circuit technology. This was just an advanced version of its predecessor, but it did not attempt to solve the basic problem. Jack belonged to a third school of thought during that period. He thought a revolutionary circuit construct would be required to solve the problem. In July, most of the employees at TI went on two weeks summer vacation, but Jack was not eligible for this vacation, since he was a new employee. This was a blessing in disguise for him. He could spend a lot of time, undisturbed, thinking about the problem of tyranny of numbers [3].

On July 24, 1958, he was struck with an idea that all the circuit components could be made with the same semiconductor material. If this can be achieved, then a monolithic semiconductor chip – a piece of semiconductor – can become a very compact integrated circuit. He wrote down the blueprint of such a circuit in his lab notebook (*Figure* 1) [4]. When his boss Adcock came back from vacation, Jack showed his idea. Adcock was excited about this concept, although skeptical, and he encouraged Jack to go ahead and build a proof of concept prototype. Jack decided to first build the prototype by assembling discrete components, all made of semiconductor. He decided to make capacitors with reverse biased p–n junctions, and the resistors using the bulk resistivity property of semiconductor substrate. He took the packaged devices and built a working circuit on August 28, 1958, which demonstrated that all the components could be built on semiconductor. Then he went on to create a monolithic integrated circuit, by assembling all components in-situ during processing of chip. He chose the phase shift oscillator[5] circuit with one transistor, capacitor and distributed bulk resistors for demonstrating the concept. He used black wax to selectively mask the regions on Ge substrate to create different components. On September 12, 1958, he created 3 such chips, each with a dimension of 7/16 inch length and 1/16 inch width (*Figure* 2). The birth of the chip was

[5] Oscillator is a very important analog building block in electronics. Oscillator circuits generate a continuous alternating current (AC) waveform from a direct current (DC) supply, making use of active elements such as transistor amplifiers in conjunction with passive elements such as resistors, capacitors and inductors. An RC phase shift oscillator consists of transistors, resistors and capacitors, and its oscillating frequency can be designed for specific value by an appropriate choice of the component values.

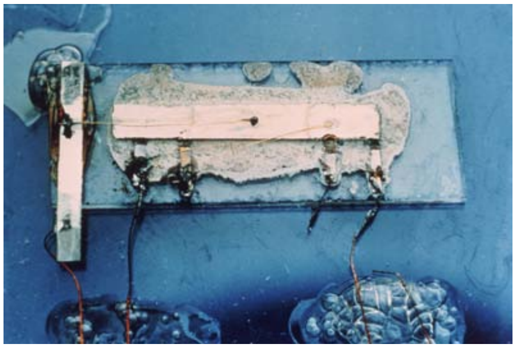

Figure 2. The first integrated circuit chip, a phase shift oscillator, built by Jack Kilby.
http://www.ti.com/corp/docs/kilbyctr/downloadphotos.shtml
Courtesy: Texas Instruments

confirmed, when the circuit started oscillating to give a sine wave output of 1.3 MHz, as soon as power was supplied to the circuit. On September 19, 1958, he also demonstrated the realization of digital circuits by creating a flip-flop[6]. TI filed the patent for miniaturized electronics circuits on February 6, 1959 and made the formal public announcement of solid-state circuits in March 1959.

[6] Flip-flop is a very important digital building block in electronics. There are different flip-flop configurations such as RS flip-flop, JK flip-flop. It is essentially a memory element which can store one bit of information in digital form (logic "0" or logic "1"). Its output can be switched between 0 and 1 by providing appropriate values to the inputs (R/S or J/K).

Although the advantages of the monolithic integration were obvious, it took some time for the electronics industry to accept it in the mainstream. The skeptics doubted the reliability of such circuits. Ironically, the mainstream commercial acceptance and the deployment got a major boost, when the two strategic programs – Apollo moon mission and Minuteman missile program – embraced the chips. Jack Kilby was the team leader in building the integrated circuit chip based on-board computer for the Minuteman II missile. Jack Kilby also helped the commercial acceptance of the chip, by co-inventing handheld electronic calculator and thermal printer, which turned out to be very popular products. He was very prolific in his inventions during his tenure at TI, with more than 60 patents to his credit. He was proud to be recognized as an engineer, rather than a scientist. He was of the view that scientists explore knowledge, and engineers enable the practical exploitation of the knowledge. He was convinced that good engineering was as much a creative process as anything else. He was really motivated by solving practical problems in electronics, which would make a difference to mankind [5].

Jack Kilby took leave of absence from Texas Instruments from 1970 to 1978 to work as an independent inventor. This was indeed a very bold experiment. He was of the firm opinion that big corporations do not provide sufficient freedom for unconstrained explorations. So he decided to work as an independent investigator with unfettered freedom. During this period, one of his important contributions was on silicon solar photovoltaics technology for electrical power generation. In 1978, he joined Texas A&M University as a Distinguished Professor of Electrical Engineering. He really enjoyed this tenure working with students on a variety of research topics. He continued in this capacity until 1984. He retired from TI in 1983, but continued his association with the company until his death on June 20, 2005. Texas Instruments created The Kilby Centre, a research centre for silicon manufacturing technologies, to honour the exemplary contributions made by Jack Kilby.

Jack Kilby and Robert Noyce

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Any discussion on Jack Kilby is incomplete without a brief reference to Robert Noyce, who was also trying to solve the tyranny of numbers at Fairchild Semiconductors in the Silicon Valley. Robert Noyce was a physicist, who got his PhD from MIT and migrated to California, USA to work under the Nobel Laureate William Shockley, the inventor of the fist semiconductor transistor. However, he could not get along with Shockley and hence decided to quit Shockley Semiconductors.

In 1957, he founded a new company – Fairchild Semiconductors – along with seven other colleagues. He soon started working on his own independent idea of making an integrated circuit chip on Si using planar technology. But by the time he could realize his idea, Jack had already proved the concept and had filed for a patent. In order to avoid any infringement on Jack Kilby's patent, he made a very detailed patent application on his idea, in July 1959. The most important departure in his idea was the notion of planar technology – creation of all the metal contacts on only one side of the chip, using a layer of silicon oxide insulator for

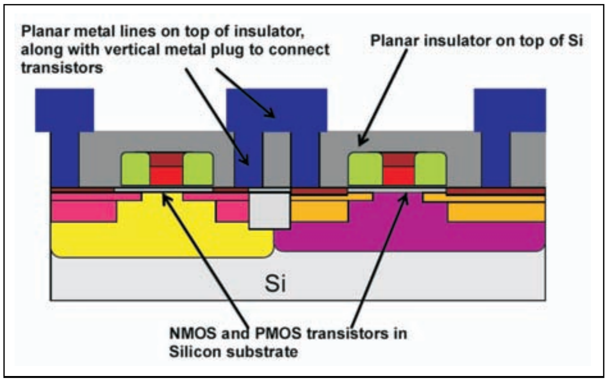

Figure 3. Illustration of modern planar CMOS technology[7]. The state of the art chip has more than 10 layers of metal interconnects on top of Si. In this figure, only 1 layer of metal interconnect is shown for simplicity. All connections come out only on top side of the silicon wafer, and nothing on the back side.

isolation (*Figure* 3). Jack Kilby's chip had metal connections from both the front and back sides of the Ge wafer, which would not be scalable for chips with a large number of transistors. All the semiconductor chip manufacturers including TI, have been using planar technology till date. Hence both Jack Kilby and Robert Noyce are considered as co-inventors of the monolithic integrated circuit chip. Interestingly, Robert Noyce was granted the patent earlier in 1961 for "Semiconductor Device-and-Lead structure Integrated Circuit" (US patent #2,981,877). Jack Kilby was awarded patent on "Miniaturized Electronic Circuit" in 1964 (US patent number #3,138,743). There was a long legal battle between the two companies to claim the ownership of the IC chip. But eventually the two companies arrived at a wise decision to cross license each others' patents, recognizing and respecting the importance of both the inventions.

[7]Today, more than 90% of the electronics market is captured bythe Silicon Complementary Metal Oxide Semiconductor (CMOS) technology. The chips built on CMOS consist of two kinds of Field Effect Transistors (FETs) – n-channel transistors (NMOS), where current is carried by negatively charged electrons and p-channel transistors (PMOS), where current is carried by positively charged holes.

In 1968, Robert Noyce quit Fairchild and co-founded another semiconductor giant – INTEL. He is sometimes referred to as the 'Mayor of Silicon Valley' for his very important contributions to the industry, both in terms of his invention of planar technology and establishment of two major semiconductor companies. Noyce passed away in the year 1990, when he was 62 years old. In his brief biography, provided to the Nobel Committee, Jack Kilby comes out as a very humble gentleman when he states, that he was fortunate to be the first person with right idea, right resources and at the right time. He also adds [6], "I would like to mention another right person at the right time, namely Robert Noyce, a contemporary of mine who worked at Fairchild Semiconductor. While Robert and I followed our own paths, we worked hard together to achieve commercial acceptance for integrated circuits. If he were still living, I have no doubt we would have shared this prize."

Jack Kilby the Humanitarian

Jack was very humble, soft spoken and down to earth, without any air of superiority. When somebody asked him whether he was responsible for the information technology revolution, he recounted the story of the beaver and the rabbit. When the rabbit asks the beaver whether he built the Hoover dam, the beaver stares at the dam and replies, "No I didn't build it myself. But it is based on an idea of mine!" [4]. When his friends and well-wishers appreciated the great impact created by his invention, and told him that he deserved a Nobel Prize for his invention[8], he would humbly state, "Nobel prizes are for scientists, who are motivated by pure knowledge. But, I am an engineer motivated by desire to solve problems, to make something work. For guys like me the prize is seeing a successful solution" [7]. When he was asked,

[8] Nobel prize in Physics is very rarely awarded on topics related to Applied Physics. In fact, Jack Kilby's invention of IC chip is more of an engineering feat rather than applied physics. The fact that he was awarded the Nobel prize for this invention, speaks volumes about the importance of Kilby's work. The Nobel committee comments that "the 2000 Nobel prize in Physics is awarded for the basic work done on information and communication technology".

Table 1. Important awards and honors presented to Jack Kilby [8].

1966	Fellow, IEEE
1966	IEEE David Sarnoff award
1967	Elected Member of National Academy of Engineering
1970	National Medal of Science
1978	IEEE Credo Brunetti Award
1982	Holley Medal from American Society for Mechanical Engineers
1982	Inducted into National Inventors of Hall of Fame
1984	IEEE Centennial Medal
1989	Charles Stark Draper Prize, NAE
1990	National Medal of Technology
1993	Kyoto Prize
2000	Nobel Prize in Physics

Honorary Doctorate from Southern Methodist University, the University of Miami, University of Illinois, University of Wisconsin-Madison, Texas A&M University, Yale and Rochester Institute of Technology whether his name would become prominent in the world history of science and technology, he said it would probably grab a small footnote!

Jack Kilby always urged the young students to be imaginative. He was of the clear opinion that imagination to think big was essential requirement for great inventions and discoveries.

T R Reid, a journalist, recollects a humane incident that happened during Kilby's visit to Japan to receive the Kyoto Prize. During this period, Reid was stationed in Japan with his family, on an official assignment. Reid's family, including their 8-year-old daughter Katie, visited Kilby's hotel in Tokyo. Katie had an assignment from her school, to write an essay on Jack Kilby. So Jack started helping her to write her essay. Then he was alerted by his hosts, that it was time to go for an interview session with the media since the crew from TV networks and newspapers were waiting for him. He was very firm in his response: "We can do the TV Asahi interview," he said, "after I finish talking to Katie." [7]. Jack Kilby was always very enthusiastic in interacting with children, since he was convinced that the children of today are our future, and time well spent in advising children will have a long lasting impact. He volunteered a lot of his time to interact with school children. Jack Kilby always urged the young students to be imaginative. He was of the clear opinion that imagination to think big was essential requirement for great inventions and discoveries. It is said that a mother once asked him to advise her on how to teach her child to be a great inventor. He advised her to read the children fairy tales and encourage them to be imaginative.

He was also very proud of his family. He had two daughters and five granddaughters. He had said in a lighter vein that Kilby family had specialized in girls. He loved to take his family along with him to various places he had to travel. After the early demise of his wife, he depended a lot on his sister Jane, who took good care of him. In fact his health deteriorated drastically, after his sister passed away in 2004. After a brief fight against cancer, he passed away on June 20, 2005.

Epilogue

The world of electronics will always be indebted to Jack Kilby

Year of production	2012	2015	2018	2021	2024	2026
Technology node (nm)	32	23	15.9	11.3	8	6.3
Transistor gate length in Microprocessors (nm)	22	17	12.8	9.7	7.4	5.9
Wafer diameter (inch)	12	18	18	18	18	18
Lower limit on number of transistors in DRAM (billion)	64	128	256	512	550	1024
Number of interconnect layers in the Microprocessor	12	13	14	15	15	16
Number of pins for packaged chip (Microprocessor)	5346	6191	7167	8297	9605	TBD
Operating voltage (V)	0.87	0.8	0.73	0.66	0.61	0.57

Table 2. International Technology Roadmap for Semiconductors (ITRS) projections.

and his imaginative leap in the invention of the monolithic integrated circuit chip. The chips have continued to become faster, cheaper and more powerful with the 32nm Complementary Metal Oxide Semiconductor (CMOS) technology in volume production. The field of electronics has moved on from Microelectronics to Nanoelectronics [8]. From the very humble beginning of one transistor per chip invented by Kilby, we have metamorphed the chip to have more than 1 billion transistors integrated on a small silicon piece. The worldwide electronics industry has crossed the trillion dollar revenue mark. In addition to building a variety of electrical components in-situ, as envisioned by Kilby, we have also started creating sensors and actuators on the chip. The International Technology Roadmap for Semiconductors (ITRS)[9] predicts that the miniaturization of transistors will continue through the next decade, with the possibility of achieving trillion transistors on a chip [9]. But we owe it all to Kilby's revolutionary idea of integrating all the constituent parts of an electronic circuit/system on to a single piece of substrate. The opportunities in the field of electronics have

[9] International technology Roadmap for Semiconductors (ITRS) is an authoritative document which provides research directions for miniaturization of semiconductor technology. It is the effort of an unique consortium consisting representatives from all the major semiconductor companies, academic institutes and research labs from across the world. This document is revised every year to ensure its relevance, and it projects the technology requirements for about 10 years into the future.

exploded, and for the youngsters looking up for career options, it is one of the most fertile field to get into. To paraphrase Kilby's words, "get involved in this exciting field and get started early".

Suggested Reading

[1] http://www.jackkilby.com/index.html

[2] http://www.anb.org/articles/13/13-02677.html

[3] Jack S Kilby, Invention of the Integrated Circuit, *IEEE Transactions on Electron Devices*, Vol. 23, No.7, July 1976.

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