# The History, Current Applications and Future of Integrated Circuit

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**Abstract.** Integrated circuit is a fundamental part of modern electronics, so it can be discovered in almost every electronic product. Therefore, a summary of the development of integrated circuit is very important for the professionals. The history, current applications, and challenges of integrated circuit will be discussed. In order to include all the important events of integrated circuit, in the history section, the discovery of characteristics of semiconductors, the invention of the first transistor, the first bipolar junction transistor (BJT), the first field effect transistor (FET), the first integrated circuit, and the first microprocessor will be demonstrated. Next section is about current applications by functions, including analog, digital and mixed signal IC. Finally, challenges that IC is facing right now, and prospects will be discussed. Understanding the history and current applications will help people to predict the future and find solutions of challenges.

**Keywords:** Integrated Circuit, Digital system, current application, semiconductor, transistor.

## 1. Introduction

Integrated circuit, also better known as chip, is one of the most replicate products in the history of mankind. It is the fundamental product of any digital products and many electronics. Although it was invented in the middle of the last century, it has changed the whole world significantly in various areas. Modern computing, communication, manufacturing, transportation, internet, and many other industries all depend on IC tightly. Some scientists consider that the digital revolution, or the Third Industrial Revolution that comes with the development of IC, is the most important event in human history. The continuous improvement and development of integrated circuit will boost technology to keep leaping forward, and therefore people may feel that technology has been changed so quickly in the past few decades. IC is still currently one of the most essential components that is used in electronics, so know that past, present, and future of it is necessary.

This article will summarize the history, current applications, and the future of integrated circuit briefly. In section 2, there will be the history before transistor was invented, the history of transistors, and the history of IC. Basic theories of semiconductors, transistors and IC will be explained too. In section 3, present applications of IC will be explained and extended, including analog IC, digital IC and mix-signal IC. Problems that IC is facing right now and the potential solutions that human can implement are discussed in section 4.

By learning about the history, current applications and the future of integrated circuit, readers may have a brief view of this technology. History is the fundamental knowledge; therefore, people need to learn it at first. Current applications can be seen as what IC industries are producing now, and the future is what engineers and scientists are researching for. Readers will get a brief review of history and summary of current status of IC, and finally use that information to think about the future of this digital technology.

## 2. The Theories and Historical Development of Integrated Circuit

### 2.1. History of Basic Theories about IC

Before the first IC was invented, there was theoretical basis discovered by scientists, which made a solid foundation for the invention of IC.

Different integrated circuits are made from different combination and arrangements of transistors, and transistor technology is based on the use of semiconductor. In 1833, Michael Faraday discovered that electrical conduction increases as temperature rises in silver sulfide crystals, which means that this material has the opposite electrical resistance characteristic with metals like copper and iron [1]. This was the first characteristic of semiconductor that was discovered.

Later in 1839, a French physicist called Edmond Becquerel found the photovoltaic effect of semiconductor. Light will be absorbed by semiconductors, and there will be voltage difference between the semiconductor part and metal part, hence current will be generated [2]. In 1873, Willoughby Smith observed the effect that the resistance of selenium varies dramatically due to the amount of light it absorbed. It is the photoconductivity of semiconductors [3].

The fourth characteristic of semiconductor was discovered by a German physicist, Karl Ferdinand Braun. This effect is one of the most important characteristics for transistors. He found that a point-contact metal-semiconductor junction can rectify alternating current [4]. Its direction of conducting current is fixed, so there will be no current if the voltage is reversed.

## 2.2. History of The Development of IC

With all the theories of semiconductors, at Bell Labs, John Bardeen, Walter Brattain and William Shockley invented the first transistor successfully on December 23, 1947 [5]. This transistor is point-contact transistor, which based on the theories of electric field effects in solid state materials [6]. The design goal of this transistor was to be a substitute of vacuum tubes, and it did achieve the goal. Although the first transistor was ugly, it could work properly in a circuit, with smaller size and less power than vacuum tubes. It became the inflection point of computer, because transistors are smaller than vacuum tube or relay, which were the main components of computer before. The First Transistor Invented at Bell Labs was shown in Figure 1.

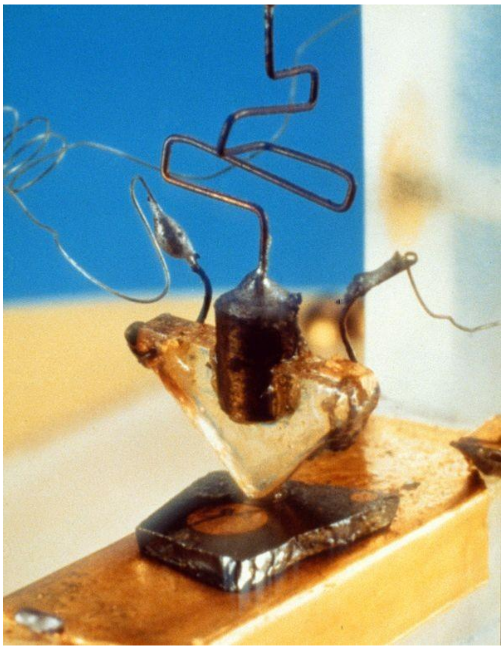

**Figure 1.** The First Transistor Invented at Bell Labs

After few months in 1948, in the same Bell Labs, William Shockley, who just invented the first transistor with his partners, invented bipolar junction transistor (BJT) [7]. As Figure 2, BJT contains three differently doped semiconductor regions: emitter, base, and collector. It can be either NPN or PNP. N represents N-type semiconductor, which has a majority of free electrons as charge carriers and holes in minority. P is P-type semiconductor, and it is the opposite from N-type semiconductor. BJT is still one of the two widely used transistors of producing integrated circuits.

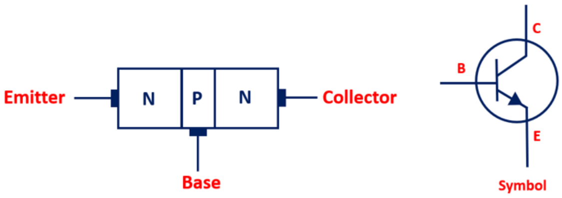


**Figure 2.** The Structure and Symbol of BJT

The next important invention of transistor was JFET, which stands for junction-gate field-effect transistor. In 1953, George C. Dacey and Ian M. Ross invented the first working practical JFET [8]. Before this great invention, the idea of FET had appeared already. Julius Lilienfeld came up with a succession of FET-like device and patented it in the 1920s. However, the material science and fabrication technology did not support the manufacture of this electronic component [9]. Then during 1940s, John Bardeen, Walter Brattain and William Shockley tried to build a FET, but they failed the attempts, and they eventually invented point-contact transistor later. Finally, JFET was invented in 1953. It was the first FET, which is the major component of modern IC. JFET is different from BJT, since it has a depletion region between N-type and P-type like Figure 3 shows.

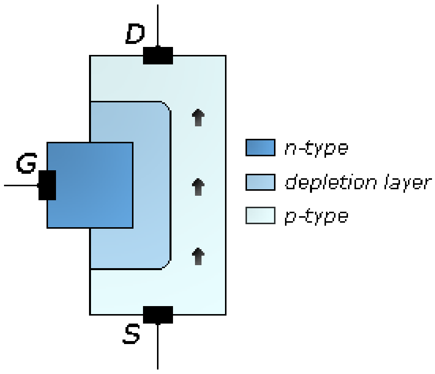


**Figure 3.** The Structure of JFET

In the year of 1958, Texas Instruments made the first integrated circuit in the world. It was first created by a new employer, Jack Kilby, and he got Nobel Prize in 2000 [10]. He was able to put two transistors on the same silicon germanium bar and connected terminals internally to integrate these connections. The IC was 7/16 inch wide. Two devices are a sufficient proof of concept of integrated electronics. All of this exploded from this year, and semiconductor industry was created and is still growing for billions of dollars. It is now a $350 billion industry today.

Intel 4004 Microprocessor was the first commercial microprocessor produced by Intel Corporation. It was originally a product for Busicom Corp., aimed to be part of an electronic calculator. It is a 3mm x 4mm, with 16 pins and 2,300 transistors. The max CPU clock rate is 740-750 kHz. Figure 4 shows this component that has similar performance as ENIAC, which is a computing machine that occupied a whole room.

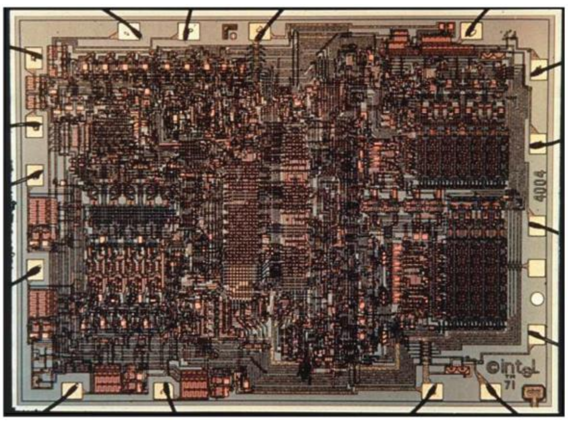


**Figure 4.** The Structure of Intel 4004

# 3. Current Application of Integrated Circuit

## 3.1. Analog Integrated Circuit

The first application of integrated circuit is analog. It is usually a combination of transistors, resistors, capacitors, and other electronic components. Analog integrated circuit can be used to proceed analog signals, such as alternating current, sound, light, temperature, etc.

Analog integrated circuit mainly includes power management IC and signal-processing IC. Power management IC is responsible for transformation, distribution and detection. It can do transformation between AC and DC, voltage transformation between two direct currents for large voltage difference, and voltage adjustment for small voltage difference, and stabilizing current [11]. It can work with other components to get an appropriate power for the power source of the device that the power source is providing energy for. Currently, power management is improving to higher speed, larger gain and better reliability, since it is one of the most significant methods to enhance the performance of the system.

Signal-processing IC is the IC that will proceed the signal from input to output, includes the functions like signal acquisition, amplification, and transmission. It will act like op-amps, linear regulators, phase locked loops, oscillators, and active filters.

Since electronic systems need power supplies, power management IC occupies a majority of the analog IC market, which is about 53%. Signal-processing IC has 47% of market.

## 3.2. Digital Integrated Circuit

Digital integrated circuit has more market share than analog integrated circuit, and it is the most important part for modern electronic products. CPUs, microprocessors, microcontrollers, digital signal processing modules (DSP) and memory units are some common products made by digital IC. It is the unit that can do the computation and clocking. There are lots of digital integrated circuits in modern personal computers, mobile phones, tablets, and so on. It is indispensable for daily life of most people.

Digital IC is a small chip that contains a maximum of billions of logic gates, flip-flops, multiplexers, and other circuits in just a few millimeters. There will be specific number of inputs of 0 and 1, and after the processing in the digital IC, designed output will be implemented. In this process, truth table or equation will be designated, optimized and designed [12].

Digital ICs are usually designed in CMOS technology and assembled from logic gates in order to get to the expected digital signal. It takes three parts to design the logic part the digital IC: electronic system-level design, RTL design and physical circuit design. In electronic system-level design, user functional specifical will be created. Various languages will be used to describe the system, including VHDL, C, C++, SystemC, System Verilog Transaction Level Models, MATLAB and Simulink. In RTL design part, user specification will be converted to register transfer level (RTL) description. It will place the behavior the digital circuits on the chip, and the connections between inputs and outputs. Physical circuit design requires a combination of RTL and standard cell library of logic gates. IC layout editor will be used for layout and floor planning. Logic gates will be confirmed, places for them will be set, and wiring them all together.

After design the logic of digital IC, there are more steps, such as physical design, verification, mask data preparation, wafer fabrication, packaging, die test and chip deployment. When a digital IC is completed, it will be installed in a PCB and work with other parts like power source.

Since the size of digital IC is so small, it has high speed, low power dissipation, and cheaper in manufacturing cost. What is more, manufacturers can combine more transistors and build up larger digital ICs that have more functions. For different numbers of transistors, the systems have different names. When transistor count is from 1 to 10, it is small-scale integration (SSI); transistor count of 10 to 500 is medium-scale integration (MSI); a count of 500 to 20,000 is large-scale integration; a count of 20,000 to 1,000,000 is very large-scale integration (VLSI); and ultra-large-scale integration has 1,000,000 and more transistors. These transistors are placed on a single chip and can run complex functions.

### 3.3. Mix-signal Integrated Circuit

Mix-signal integrated circuit is the IC that has both analog and digital integrated circuits on a semiconductor die. Its usage has grown significantly in the past decade because of the explosive growth of smart phone market, automobiles, and other electronics. Sensor system with on-chip digital interfaces that are in modern smart mobile phones is an example of mix-signal IC.

Mix-signal IC has many functions, and it is often used to convert between analog signals and digital signals, so that digital device can continue to proceed [13]. Another function is to use digital part of the IC to control the analog IC. Its design and manufacturing processes are more complex than simple analog and digital ICs, because the voltage requirement of the analog part and digital part is always different and making the voltage to fit those two parts is a great challenge, and other problems like necessary resistors, capacitors, and coils.

## 4. Challenge and Future Prospects

### 4.1. Physical Limitations of Integrated Circuits

In 1965, Gordon Moore wrote this in his paper, "The complexity for minimum component costs has increased at a rate of roughly a factor of two per year. Certainly, over the short term, this rate can be expected to continue, if not to increase. Over the longer term, the rate of increase is a bit more uncertain, although there is no reason to believe it will not remain nearly constant for at least 10 years. That means by 1975, the number of components per integrated circuit for minimum cost will be 65,000." This is known as Moore's Law, and it has been proved by previous devices.

Moore's Law has been successfully predicted for the development of integrated circuit for more than fifty years. Transistors per die did double for every 18 to 24 months, and the size of the integrated circuit decreased. From 1972 to 2020, the size decreased from 10μm to 5nm, and the computing speed increased dramatically.

However, Moore's Law will not last forever. What is more, according to Gordon Moore himself, he thinks that there are several obstacles that will end Moore's Law: the speed of light, the atomic nature of materials and growing costs [14].

The speed of light is constant, and it will provide a natural limitation of the number of computations that transistors can process. Information cannot be transmitted faster than the speed of light, so the bits stored as electrons will be limited. Transistors and wires are characterized by resistance and capacitance. The miniaturization will cause resistance to increase and capacitance to decrease, hence it will be more difficult to perform correct computations.

As we know, atoms have specific physical sizes, and that will be a problem of making the size of IC smaller. The atomic size of silicon is about 0.2nm, and modern transistors are about 70 silicon atoms wide. The final limit of increasing transistors number by decreasing the size of them is close.

IC is a huge business that runs by big companies, so cost is a problem that they need to think about. The cost of manufacturing a new 10 nm chip is around $170 million, $300 million for 7 nm chip, and $500 million for 5 nm chip [15].

There is also quantum limit of IC. James R. Powell consider that Moore's Law will end by 2036, due to the Heisenberg's uncertainty principle alone.

### 4.2. The Future of IC

IC is getting closer and closer to the limitations, so what can scientists do to keep improving IC, or computing speed?

The first solution of the problems is specialized architecture to particular algorithms. This area is growing rapids because of the large demand from machine learning, and there are over 50 companies manufacturing AI chips, such as Habana, Horizon Robotics and Graphcore. AI will keep learning and find out better algorithms for computing, hence the used time will be less.

Field-programmable gate array, or FPGA, is also a good way out. It is a hardware that can be programmed after manufacturing by users, which is possible for the chip to do multiple tasks without designing and manufacturing again. Algorithms will be adjusted by engineers themselves.

Another solution is quantum computer. Classic IC has physical limitations of electrons and atom size, and there is no possibility to overcome those limitations directly. However, quantum will not be limited by them. Quantum computer is based on qubits and use quantum effects like entanglement and superposition [16].

## 5. Conclusion

To conclude this article, it provides a basic and brief summary of the history, current applications and the future of integrated circuit, and it may give readers a fundamental view of this technology. Readers may learn from the history, know current applications, and finally they will come up with ideas about the future. This is also what learners of integrated circuit will follow when they are studying it in schools. Many scientists consider that current IC is getting closer to its physical limitations, so we need the idea of new technologies as mentioned in section 4.2. Although IC is still the governing technology of digital systems, people need to look further and realize the challenges it is facing right now. If digital system needs to keep improving, new technologies need to be created, or else it will be trapped by the physical limitations of IC.

The ultimate goal of this article is to guide readers to think about what improvements can mankind make in the future by reviewing history and seeing present. This may just be a starting point of one’s inspiration, but that is enough. People need the developing mindset to prepare for the upcoming challenges, not only in IC, but also other fields.

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