Overview of Integrated Circuits

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Abstract

In electronics, integrated circuits (ICs) are known to be electrical semiconducting devices that house many electrical components in a small area. Integrated circuits consist mainly of bipolar or field effect transistors besides other devices like diodes, resistors and capacitors. ICs can be used as chips or microprocessors which are ,at the present time, being the heart of every device we use like PCs and phones. Also, ICs can function as signal amplifiers and in digital electronics it can used as a logic gate. This paper will explore different aspects of this device.

1 Introduction

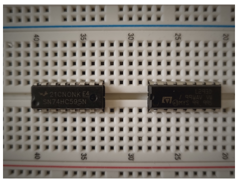

Figure 1: Two ICs. The left one from PHILIPS and the right one from Texas Instruments.

Integrated Circuits (ICs) arose from the need of a device that can include electrical components in small space. the fact that when someone wants to create a circuit means he must wire all components and solder them which can get tricky as the number of components increase. Computers would fill a whole room with wires because of the large number of vaccuum diodes that were used. Printed circuit boards took care of the hanging wires by printing them on a board and were called traces. The problem still lies in the size that each component take when designing a discrete circuit where components are manufactured and then put together. We examine in the next sections how this problem was solved using integrated circuits. We also want to see the history that ICs went through and where did they reach. In addition, we view their manufacturing process, their types and some applications.

2 History

Lots of figures were involved in the making of the first integrated circuits. We will only focus on two. The first is **Jack Kilby** who was working in Texas Instruments on a problem called at the time *the tyranny of numbers*. The problem states that as the number of electrical components in a circuit increases the possibility to increase the performance of that circuit decreases due to the time it takes to troubleshoot or fix hence the name of the problem. This is a natural consequence of wiring and soldering process which may not create reliable interconnections in the circuit.

Since most components can be made from semiconductors, this problem drove Kilby to think that manufacturing all components on the same piece of semiconductor will solve the problem by enabling them to be produced in masses and thus the need to troubleshoot the circuit when it does not work is not needed since you can replace it by a new cheap one. On the 12th of September 1958, Kilby constructed the first IC which was made out of germanium. Kilby documented a patent for his integrated circuit on the 6th of February 1959. He won the Nobel prize in physics for his invention in 2000. Kilby stated in his Nobel prize lecture that:[4]

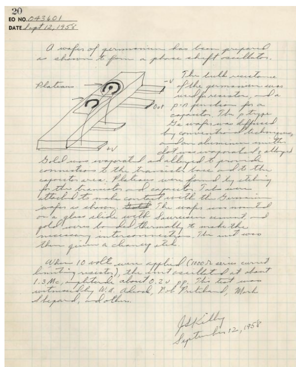

Figure 2: A page of Kilby's lab notebook where he first conceived the integrated circuit.

"In July 24, 1958 I described in my lab notebook what would come to be known as the monolithic idea. It stated that circuit elements such as resistors, capacitors, distributed capacitors and transistors if all made of the same material could be included in the single chip"

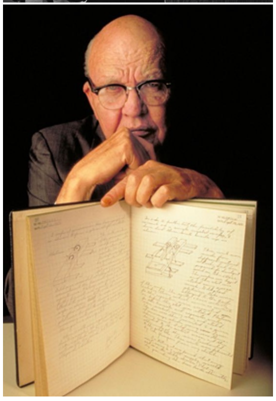

Figure 3: Above: the physicist Robert Noyce who made ICs commercially available. Below: the electrical engineer Jack S. Kilby holding his lab notebook.

Another man called **Robert Noyce** independently thought of the same idea about integrated circuits. Noyce was working along with other scientists in Bell labs under the supervision of William Shockley, the co-inventor of the transistor. Because Shockley had a bad management skills and was controlling his team in a some sense, Robert and other seven graduates like Gordon Moore and Jean Hoerni decided to leave the lab and form a group called the **traitorous eight**.

This group created their own company which became today to be the famous *Fairchild semiconductor* in 1957. Not so long after Kilby's invention of the germanium IC, Noyce made the first monolithic silicon integrated circuit in 1959 by improving Kilby's design and removing the so called flying wires which impeded Kilby's IC to be mass produced[2].Unfortunately, since Noyce was deceased before 2000 and since the Nobel prize is only given to living individuals, Kilby did not share the prize with Noyce although both contributed to the IC invention.

Manufacturing

Integrated circuits (ICs) are fabricated on semiconductor substrates such as silicon or gallium arsenide[7]. For consistent performance, semiconductors must be exceedingly pure and single crystals. The fundamental process for producing huge single crystals was discovered in 1916 by **Polish scientist Jan Czochralski** and is now referred to as the Czochralski method. The Czochralski process involves heating electronic-grade silicon (refined to less than one part contaminant in 100 billion) to approximately 1,500 °C (2,700 °F) in a fused quartz crucible. A few parts per billion of an electron-donating element such as phosphorus or arsenic (for p-type semiconductors) or an electron-accepting element such as boron (for n-type semiconductors) are mixed in. A small "seed" crystal is suspended from the end of a rod and lowered until it just pierces the silicon's molten surface.

It has a diameter of roughly 0.5 cm (0.2 inch) and a length of roughly 10 cm (4 inches). The rod is then carefully extracted at a few millimeters per second while being rotated in opposing directions with the crucible. These processes lead to the gradual development of a single crystal when they are properly synced. After several days, a single crystal will be 300 mm (11.8 inches) in diameter and longer than 1 meter (3.3 feet) in length. Several integrated circuits (ICs) are simultaneously fabricated on thin wafers that are created by slicing the big ingot like a loaf of bread. After fabrication, the integrated circuits are sliced and separated.Each die that passes testing is placed in a hard plastic package. These plastic packages, known as chips

P- and n-type semiconductors can be used to create a wide variety of devices, including diodes, transistors, capacitors, and resistors. The fact that all of these various electronic components can be fabricated using the same few fundamental manufacturing steps. A completed chip may contain 30 or more layers and is constructed on a semiconductor substrate using layers that range in thickness from around 0.000005 to 0.1 mm. Identifying the precise locations of n- and p-type areas on each layer is necessary to produce the various electrical components on a chip. Lines and geometric shapes are used to etch each layer precisely where the material is to be deposited. There are three main approaches to modifying a wafer: deposition (adding a layer), etching or removing a layer, or implantation (changing the composition of a layer).

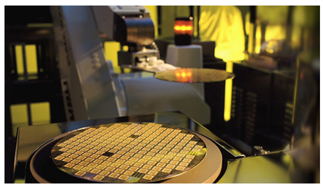

Figure 4: Above: Integrated Circuit Design and Manufacturing

Photolithography

Initially, a photoresist layer is applied to wafers in order to alter specific locations. Photoresist, or simply resist, typically dissolves in a high-pH solution after being subjected to light (including ultraviolet radiation or X-rays), and this procedure, known as development, is controlled by the use of a mask. A mask is created by applying a thick deposit of chrome to a glass plate in a specific pattern. The chrome casts a shadow across the majority of the wafer, allowing "light" to shine through only in specific areas. This allows for the creation of extremely small areas that are unprotected by the hard resist (depending on the wavelength of the light used). Following the removal of the produced resist, the unprotected portions can be altered without harming the rest of the wafer using the deposition, etching, or implantation operations. The leftover resist is then dissolved by a specialized solvent after these alterations are complete. To make changes to the wafer, this procedure is repeated with different masks at about 30 layers total.

Following the completion of all wafer changes, the thousands of specific IC units are separated into slices. This is known as dicing the wafer. Each IC unit is now referred to as a die. All die that passes testing is placed in a hard plastic package. These plastic packages, known as chips

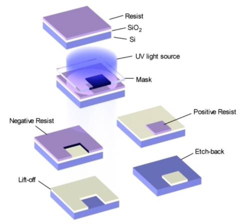

Figure 5: Above: Photolithography's procedures.

Applications

The use of integrated circuits is now widely adopted due to the distinct advantages that they provide over traditional electrical circuits. From smartphones and electronic music players to video game consoles, personal computers, and other digital devices with microprocessors, they are everywhere. This is because, by modern 21st-century standards, an integrated circuit (ICs) or chip is a highly sophisticated device that combines millions of electronic components such as transistors, resistors, and capacitors into a few square centimeters on a silicon wafer as discussed in the previous sections.

- Radar
- Computers
- Logic devices
- Video processors
- Memory devices
- Audio amplifiers

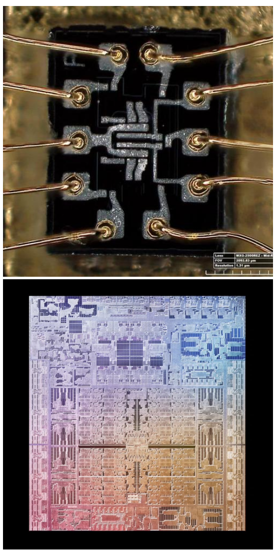

Figure 6: Above: The AGC's chip with 10 pins connected by bond wires. Below: Apple's M1 Ultra microprocessor with 114 billion transistor. Compare the two.

Types

When talking about ICs we can divide them into categories depending on the feature we are looking into, such as scale[5]. The scale or the integration level divides ICs into groups depending on the number of components they contain.[1]

the first group is called **small-scale integration** (SSI). circuits in this size contain no more than 12 components including BJT (bipolar junction) transistors ,diodes and resistors or transistor count of less than 10. These kind of circuits were first used by NASA in their Apollo program inside the *Apollo Guidance Computer* (AGC). The chips in the AGC had eight resistors and six transistors and used 2 NOR gates.

for the next group we have the **medium scale-integration** (MSI)
. This type have integrated components between 12 and 100 and uses either MOS transistors or BJTs but the latter are mainly being used. The 256-bit meomory is an example of MSI chips.

The third type is the **large-scale integration** (LSI). This type of chips have more than 100 components inside them. This term was coined by the physicist Rolf Landauer who worked at IBM, and from which all the other terms in this section are derived.The 1k-bit and 16k-bit RAM chips are considered LSI chips.

Our next type is the **very large-Scale integration** (VLSI).[1] The components in these circuits ranges from thousands to hundreds of thousands or we can also define them by having more than 3000 logic gates. They were developed in the late 1970s and them and LSI chips mainly uses MOS transistors rather than BJTs since they are easier to fabricate and have a less cost. examples of VLSI chips are the microcontroller and microprocessor.

The last category is the **ultra large-scale integration** (ULSI). In this scale, ICs have more than 1 million integrated component.

[1] The definition of integration level is rather loose. Some sources use transistor count, others use logic gates number and some use the number of integrated components.

As of 2022, many microprocessors have passed this number by huge difference and reached a transistor count of 1 billion and more. A concrete example is Apple's M1 Ultra microprocessors which contains 114 billion transistors.

As we have seen in this section, the number of transistors increase with each year. This increase follows some law called Moore's law which is the topic of next section.

Moore's law

Moore's law is an extrapolation or a predication made by **Gordon Earle Moore** (co-founder of Intel along with Robert Noyce and also co-founder of Fairchild Semiconductor) which states that the number the number of transistors inside an integrated circuit doubles every two year. The name, Moore's law, is a misnomer since it is a prediction rather than a law with certain outcomes and therefore it is not guaranteed to hold in the future. Initially Moore predicted the increase to be annually (every year) by stating:[6]

"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."

He backed his claim a decade later in 1975 and modified his law by stating that the complexity of ICs is doubling every two year. The size of the transistor is getting smaller as time progresses which threatens Moore's law. In 2021, IBM revealed an integrated circuit with size of 2nm[3] (for a MOSFET, this means the distance between the Drain and the Source) built on a wafer 300mm in size. When looking at the radius of a silicon atom we find it to be 0.2nm. This means that the distance between the source and drain is just 10 silicon atoms apart. At such lengths quantum effects like tunneling can take place since the potential barrier is too thin, making the transistor a useless switch. Moore's law does not take into account the physical limits for which we can shrink transistors and therefore may come to an end in the next few years.

Conclusion

In this section we summarize the article. Integrated circuits are semiconducting devices that are used to eliminate size problems faced when using many discrete components. also wiring problems are eliminated by ICs.

We got a glimpse into the history of this invention which was made possible by Jack Kilby and Robert Noyce independently between 1958-1959. Kilby made his circuit from germanium and had some external wiring which constituted some problems. Later Noyce improved this by using printed copper wires and made the ICs out of silicon.

Then we talked about how ICs are manufactured. ICs go through many steps starting from cutting a p-material cylinder into wafers and then forming an n-type material on it. Then we do surface passivation by forming SiO_2 on top of them. We then divide the wafer into rectangular areas to create a chip on each and make integrated components.

We saw where applications of ICs arise like microprocessors and digital electronics. We talked about the levels of integration and how the number of components per chip increased over the years. Then, we finished the article by the so called Moore's law which states that components per chip doubles every two year.

References

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