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Backgrounder

From Rock 'n' Roll to Hafnium – The Transistor turns 60

Background Summary

When it comes to helping jumpstart innovation and technology, no invention is more important than the transistor created sixty years ago at Bell Labs. Nearly all the electronics we know today would not exist were it not for the transistor.

Transistors are the main components of microprocessors, which are essential to many of the products we use every day such as televisions, cars, radios, medical devices, home appliances, computers and even the Space Shuttle.

While the first transistor radio had four transistors, the fist computer chip from Intel, which is the "brain" of the PC, contained only 2,300 transistors and the newest Intel chip based on the 45-nanometer (nm) production process released in November 2007 contains 820 million transistors.

The transistor – the "tiny engine that could" – is like a miniature "on and off switch" that enables the processing of information in a computer, bringing us all into the digital age.

What's the secret to its success? It continues to get smaller, faster and more energy-efficient with each new generation. Intel engineers have recently introduced materials to its silicon formula and manufacturing process to introduce

Facts about the Transistor

While the first transistor radio had four transistors, the fist computer chip from Intel contained only 2,300 transistors and the newest Intel chips released in November 2007 and based on the 45-nanometer (nm) production process contain 820 million transistors.

- 2,000 45nm transistors fit into the width of one human hair
- More than 30 million 45nm transistors fit onto the head of a pin
- A 45nm transistor can switch itself on and off 300 billions times per second; a beam of light travels less than a tenth of an inch during the time it takes a 45nm transistor to switch on and off
- The original transistor built by Bell Labs in 1947 could be held in your hand, while hundreds of Intel's new 45nm transistors can fit on the surface of a single red blood cell.
- If a house shrunk at the same pace transistors have, you would not be able to see a house without a microscope. To see the 45nm transistor, you need a very advanced microscope.
- The price of a transistor in Intel's latest processor is about one millionth the average price of a transistor in 1968. If car prices had fallen at the same rate, a new car today would cost about 1 cent.
- About 10,000,000,000,000,000,000 transistors are estimated to ship each year, or about 100 times the number of ants estimated to be on Earth.
- You could fit more than 2,000 45nm transistors across the width of a human hair.

innovative new chips based on the Intel® Core™ microarchitecture that use Intel's revolutionary 45 nm circuits (so small 300 of these transistors could fit in one human blood cell) and high-k metal gate transistor formula to deliver groundbreaking speed and energy efficiency.

What's next? Intel continues to push the envelope in technology innovation to introduce products that will change the way we live, work, play and communicate in ways we now can only imagine.

On or off

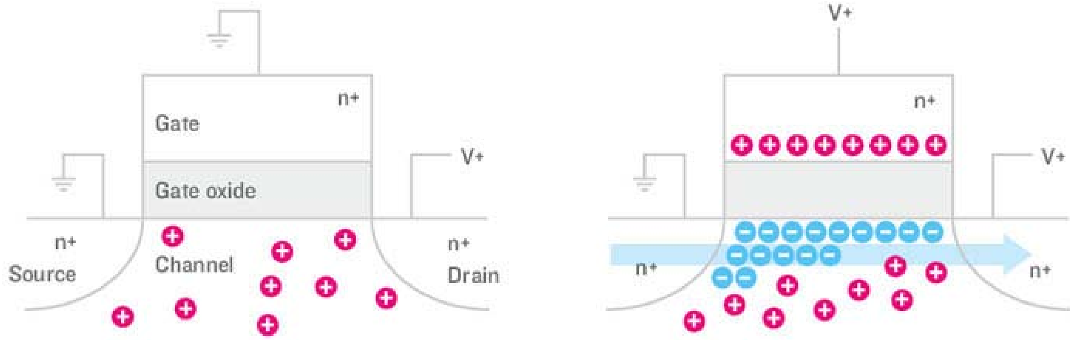
The invention of the transistor in the last two months of 1947 may very well be the most important one of the twentieth century. Certainly its influence on day-to-day life in the 20th and 21st centuries cannot be overestimated. The 'bug', as electronic geeks affectionately called it, was first used for the amplification of audio signals. Because of this, the first portable wireless sets in the fifties became better known as transistor radios. But in the long run, the transistor's most important application was as a switch in an integrated circuit (IC), better known as a chip.

Thanks to its role as a mini-switch, hundreds of millions of transistors are now found in chips that form the heart of electronics people use every day, such as PCs, laptops and servers, mobile telephones, microwaves, cars - the list is endless. Whereas the first transistor radio boasted four transistors, the new chip that Intel is released on November 12, 2007 contains 820 million. No chip can operate without a transistor, and no computer can operate without a chip, making the transistor an integral role in technological advances over the past sixty years.

Interestingly enough, the transistor essentially does not do much more than a common light switch: switch 'on' or 'off'. The *on* position of the transistor is indicated with '1', the *off* position with '0'. Large numbers of transistors generate the ones and zeroes that computers use to calculate, process text, play DVDs and display images.

The invention of the transistor is attributed to three colleagues at the Bell Lab: John Bardeen, Walter Brattain and William Shockley, who were awarded the Nobel Prize for Chemistry for their invention in 1956. The name transistor was thought up by John R. Pierce, a researcher with the famous Bell Telephone Laboratories. In May 1948, he won the lab's vote for the catchiest name for an invention that was only six or seven months old at the time. The word is a combination of 'transconductance' (transfer of a charge) and 'variable resistor' or 'varistor'.

Rock 'n' roll



Bardeen and Brattain successfully built the first point-contact transistor in December 1947, in which the current in the transistor was transmitted along the surface of the semi-conductor. The transistor then amplified the electrical signal that was passed through it. During the early period of transistor use, the main application was to amplify an electrical signal in a more efficient manner than using the larger and more cumbersome vacuum tubes that were in use at the time.

In order to accelerate the development of the transistor as much as possible, Bell Labs decided to offer the transistor technology under license. Twenty-six companies, including IBM and General Electric, purchased a license, each paying $25,000. But if transistor technology was to become a sales success, it would need to draw the attention of a mass audience. Thanks to the transistor radio, this became the case. The first model of the transistor radio was introduced in October 1954 and contained four transistors. The now portable radio meant that music and information became available everywhere – even out of earshot of discerning adults. Thanks to the portability of the radio, a new musical revolution was born – rock 'n' roll.

The integrated circuit

By the late fifties, the transistor had found its way into radios, telephones and computers, and although they were a lot smaller than vacuum tubes, they were still not small enough for a new generation of electronic appliances. Therefore, a second invention was required to handle the enormous binary calculating power of individual transistors while making them suitable for mass production at ever-decreasing cost.

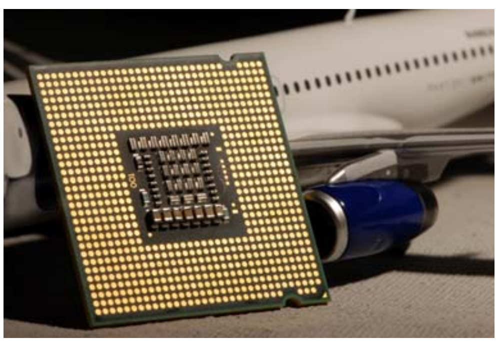
In 1958, Jack Kilby (Texas Instruments) and Robert Noyce (Fairchild Semiconductor, who subsequently went on to co-found Intel) discovered how a large number of transistors could be incorporated into one integrated circuit (IC or chip). This was an enormous step forward compared to the situation where the individual components had to be assembled by hand.

Chips had two advantages: lower cost and higher performance. Both are the result of the exponential miniaturization, which also created an enormous dynamic in the production process. Gordon Moore, who in 1968 co-founded chip giant Intel with Noyce, formulated a prediction in a magazine article published in 1965 that became known as ‘Moore’s law’. This law predicted that the number of transistors on a chip would double every two years, which in turn would bring an increase in processing power. Numerous small components, all squeezed onto a small surface, proved the decisive factor for the breakthrough of the chip.

Chip manufacturers have been able to maintain this exponential growth for more than forty years. The first computer chip from Intel, the 4004 which was produced in 1971, contained 2,300 transistors. By 1989, the i486 had 1,200,000 and in 2000, the Pentium reached 42 million. Intel’s new 45nm chip has a total of 820 million transistors.

Flirting with atoms

The demise of Moore’s law has been predicted on numerous occasions. By definition, no exponential is forever – even though chip manufacturers always seem to find a way of postponing “forever.” Last September, Gordon Moore predicted that his law will remain in affect for at least another ten to fifteen years – which is when new fundamental barriers may arise that could bring his law to a standstill. But for quite some time it looked as if the most famous law in the computer world would have difficulty making it into the 21st century.



To maintain the exponential growth dictated by Moore’s Law, transistors need to shrink by half approximately every 24 months. This miniaturization battle had pushed one critical part of the transistor to its limits: the piece of silicon dioxide (SiO_2) that acts as an insulation layer between the gate and the channel where current flows when the transistor is switched on. With each new generation of chips, this insulation layer had become increasingly thinner – until two generations ago, it was only 1.2 nm[1] or 5 atoms in thickness. Intel engineers simply were unable to skim off even just one more atom.

As the insulation layer became thinner, leakage arose. It was like a dripping tap: the insulation layer began leaking current into the transistor. This caused the transistor to behave differently, dissipating increasing amounts of energy. The result: chips used more and more current, generating extra heat in the process.

The fundamental limit

The leaking transistor was the greatest challenge for the semiconductor industry: without a major breakthrough, they would find themselves pushed against the long-expected

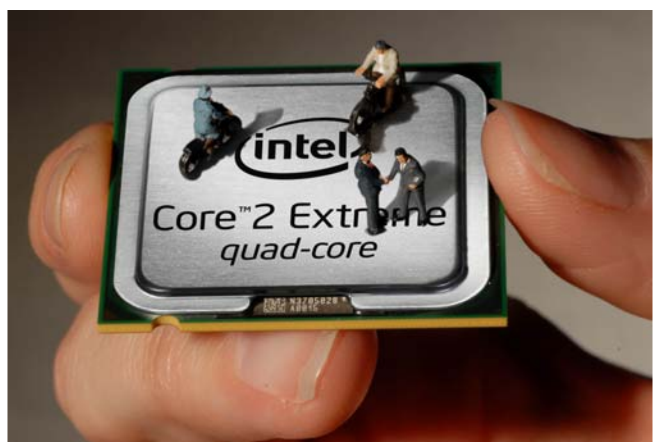
[1] A nm is one billionth of a metre

fundamental limit. This would not only mean the end of Moore's Law – it also threatened to bring the digital revolution of the past decades to an abrupt halt. Computer chips that doubled their performance every 24 months would be a thing of the past.

The solution to the crisis was found by making the layer of insulation thicker. Something which only proved possible by manufacturing the layer from a different material – containing extra atoms. In January 2007, Intel announced that for the first time in forty years, the insulation layer would not be made of silicon dioxide but of hafnium, a silver-grey metal which has better electrical properties and reduces the leakage of current by a factor ten. Gordon Moore himself called this breakthrough the 'most important change in transistor technology since the late sixties'.

But this breakthrough was only half the solution. The new material turned out to be incompatible with another important part of the transistor: the gate. Worse, the first transistors using the new insulation material performed less efficiently than the old transistors. The answer was found in using a new material for the gate as well: a unique, proprietary combination of metals, which Intel is keeping a carefully-guarded secret.

On November 12, 2007, Intel introduced a new generation of chips that uses these new materials and which are based on the 45nm production process. Compared to the previous 65nm process, this smaller production process allows Intel to nearly double the number of transistors on the same surface area, enabling the company to choose between increasing the total number of transistors or making smaller chips. As the 45nm transistors are smaller than the previous generation, they require up to 30 percent less energy for switching on and off. The result: Intel's new generation of 45nm chips not only sets new records for performance, it also represents a breakthrough in energy consumption.



Over the past few decades, the transistor and the chip have provided more processing power at a lower cost. That has proved the ultimate engine for automating the world economy. But the chip and the computer still have a long road ahead. Over the years, the computer has grown into an excellent *executor* of orders issued by people. It prints letters, sends e-mails, handles calculation chores in spreadsheets and play films. In the future, the computer is set to become an *advisor* to people; it will learn from our behaviour and adapt itself accordingly. The first tentative steps in this direction can be seen on consumer-focused sites such as Amazon and iTunes. They make suggestions to the consumer for other purchases based on the consumer's own buying behaviour.

The higher processing power that is the result of Moore's law also enables mankind to address the problems of our time with greater impact: climate, (hereditary) diseases, affordable health care, unravelling the mysteries of genetics. The way in which and the speed with which such problems are currently being researched was unthinkable five years ago. These types of applications change lives and save lives. The greater the processing power in computers and chips, the more remarkable the results in these research areas that are so essential for mankind. Another decade of Moore's Law would be very welcome.

How many transistors fit on one chip?

First Intel chip:

4004	1971	2,300
First IBM PC (1981)		
8086	1978	29,000
i486	1989	1,200,000
Pentium III	1999	9,500,000
Pentium4	2000	42,000,000
Announced on November 12, 2007:		
Penryn	2007	410,000,000

The chips and the production technology:

1993	Pentium	800nm
1999	Pentium III	250nm
2002	Pentium 4	130nm
2003	Centrino	130nm
2005	Pentium D	90nm
2006	Core 2 Duo	65nm
2007	Next-Generation Core 2 Duo (formerly Penryn)	45nm

For more information, please visit http://www.intel.com/pressroom/kits/events/60th_anniversary **or go to www.facebook.com and type in "transistor" in the search field.**