editorial

60 years of integrated circuits

The past, present and future of interconnected devices on a chip.

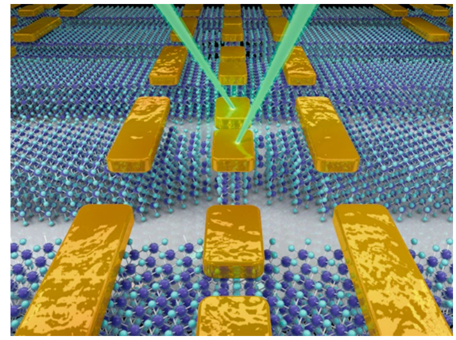
On 12 September 1958, Jack Kilby of Texas Instruments demonstrated a working integrated circuit[1]. The circuit was a phase-shift oscillator that used transistor, resistor and capacitor elements built from a single piece of germanium; the elements were connected into a circuit with the help of thin gold wires. A few months later, Robert Noyce, working at Fairchild Semiconductor, proposed a monolithic integrated circuit[2]. This planar design was based on silicon and used lines of aluminium, deposited on the insulating silicon dioxide layer that can form on the surface of silicon wafers, to connect the different circuit elements in the single chip. By 1960, a team of engineers at Fairchild Semiconductor had turned this design into a reality. Electronic components, which had previously been discrete units connected with individual wires, could now be integrated into the same piece of semiconducting material.

In the 60 years since Kilby's initial demonstration, progress in integrated circuits has been astounding. Noyce would go on to co-found Intel, and just how far the company — and the design of integrated circuits — has come in that time is highlighted in this issue of *Nature Electronics*. In a News & Views article, Suman Datta of the University of Notre Dame reports on Intel's 10-nanometre logic technology. With this latest design iteration[3], the company has introduced a number of unconventional approaches to improve transistor density and performance, including a technique to reduce the spacing between cells and a method to add gate contacts directly over the active area. As a result, they can deliver around 100 million transistors per square millimetre — a transistor density that is 2.7 times higher than that of their previous 14-nm technology, which was introduced in 2014.

At this level of complexity, developments are far from straightforward. Earlier this year, it emerged that Intel have encountered problems in the manufacturing of the 10-nm chips, leading to delays in mass production[4]; the chips are now expected to ship in volume in 2019. And in the past few weeks, GlobalFoundries announced[5] that they would stop development of their 7-nm chips (thought to be comparable to Intel's 10-nm technology). The continued scaling of silicon complementary metal–oxide–semiconductor (CMOS) technology beyond these levels is also likely to prove increasingly difficult. But, at the same time, the applications of computers are evolving, and demand the processing of ever larger amounts of data. As a result, the search for strategies and materials beyond silicon, which could help create the next generation of devices and integrated circuits, remains vital.

Carbon nanotubes are among the contenders fighting for a place in the future of electronics, and in our Reverse Engineering column in this issue, Cees Dekker recounts how the first carbon nanotube transistor was built back in 1998. A related contender in this fight is two-dimensional materials, as well as the vertical stacks of different two-dimensional materials known as van der Waals heterostructures. These materials have been used to build a range of promising devices and some basic circuits — even a microprocessor[6]. The unique challenges involved in trying to build practical integrated circuits from two-dimensional materials are just starting to be addressed, but innovative ideas are emerging. For example, in an Article in this issue, Moon-Ho Jo and colleagues illustrate how a scanning light probe can be used to write monolithic integrated circuits on two-dimensional molybdenum ditelluride ($MoTe_2$).

The researchers — who are based at the Institute for Basic Science in Pohang, Pohang University of Science and Technology, the Korea Institute of Materials Science, and Yonsei University — first pattern gold electrodes onto the $MoTe_2$. Then, by shining the light probe (a visible laser) onto the electrodes, the semiconducting $MoTe_2$ beneath can be converted from an n-type semiconductor to a p-type semiconductor. (With silicon CMOS technology, such doping is typically achieved using ion implantation.) The approach allows the two-dimensional material to be doped precisely and quickly, and Jo and colleagues use it to create arrays of bipolar junction transistors and circular diodes.



Writing integrated circuits on two-dimensional molybdenum ditelluride using an optical laser. Credit: Moon-Ho Jo, CALDES, IBS

Integrated circuits are the basis of so much of modern technology and here at *Nature Electronics* we aim to also consider the wider social, ethical and legal issues that surround the implementation of such technology. To this end, this issue sees the start of our Books & Arts section. Here, Arlindo Oliveira of the Instituto Superior Técnico in Portugal reviews *Hello World*, a book by Hannah Fry on the roles — both good and bad — that algorithms play in everyday life. Then Christiana Varnava from our editorial team reviews *The Future Starts Here*, an exhibition at the Victoria and Albert Museum in London that brings together a collection of emerging technologies in order to explore the ways they could shape society in the years to come. ❐

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