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Engineering

A 2D route to 3D computer chips

Tania Roy

Ultrathin materials have long been touted as a solution to the problems faced by the ever-growing semiconductor industry. Evidence that 3D chips can be built from 2D semiconductors suggests that the hype was justified. **See p.276**

Silicon is the electronics equivalent of the steam engine. This amazing material is the reason for the decades-long boom in semiconductor technologies, which now grants many people the technology required to work from home. But as devices become ever more powerful, the number of transistors that can be packed onto a tiny 2D computer chip is nearing its limit. The only way is up, it seems: silicon-based chips are already being reduced in size by taking advantage of the third dimension. However, silicon might not be the best candidate for the job. On page 276, Jayachandran *et al.*[1] present a 3D device built from 2D materials – ultrathin layers of non-silicon semiconductors that solve many of the problems posed by silicon.

The number of transistors on a computer chip doubles about every 18 months. This observation, known as Moore's law, is a nightmare for semiconductor engineers, who are tasked with building chips that are ever smaller and more powerful. But the electronics industry faces another challenge, which has been summed up as 'more than Moore'[2]: small devices, such as smartphones, can have multiple functions that require standard computer chips to have non-digital components (for example, sensors and actuators). Building tiered 3D chips is one way to address this challenge, but it is difficult, because the processing conditions that are needed vary between layers. For example, the temperature of the top layers must not exceed around 450 °C, which is relatively low for semiconductor processing. The quality of these layers is also compromised by rough surfaces that are created by the underlying layers.

Jayachandran *et al.* overcame these issues to fabricate a wafer (the substrate used to create chips) that consists of two integrated tiers of nanometre-scale transistors. Each layer contains more than 10,000 transistors made from sheets of molybdenum disulfide (MoS_2) of single-atom thickness. The authors grew the MoS_2 films separately before transferring them to the wafer, a process that does not require high temperatures.

Jayachandran and colleagues' achievement is sufficient in itself to incite the interest of the semiconductor industry in 2D materials. However, the authors then went further to prove the versatility of their process. They built a three-tier structure that combined MoS_2 transistors with those made from tungsten diselenide (WSe_2), and showed that all of the transistors could maintain a reasonably high performance in each level. They then scaled down the transistors in a two-tier configuration so that their channels (the structures through which charge carriers flow) were just 45 nanometres long – around one- sixth of the length of the smallest channels in the other two systems. The authors' technique could, in principle, be used to fabricate a fully functional 3D circuit (Fig. 1).

Each year, new ideas are formulated about which materials could form the basis of next-generation transistor channels. The excitement about the possibilities of 2D materials started with graphene, which is a single layer of carbon atoms that are arranged in a hexagonal lattice. After much research, graphene was relegated mainly to the realm of electrodes, because inducing it to have semiconducting properties is difficult. But other 2D materials, such as MoS_2, don't have this problem. And these materials also improve on semiconductors that aren't ultrathin, because they allow shorter channel lengths[3]. For these reasons, 2D materials have huge potential for electronics – as shown by the interest in MoS_2 and WSe_2 by semiconductor firms such as the Taiwan Semiconductor Manufacturing Company and Intel[4,5].

The process of building an integrated computer circuit is divided into two parts.

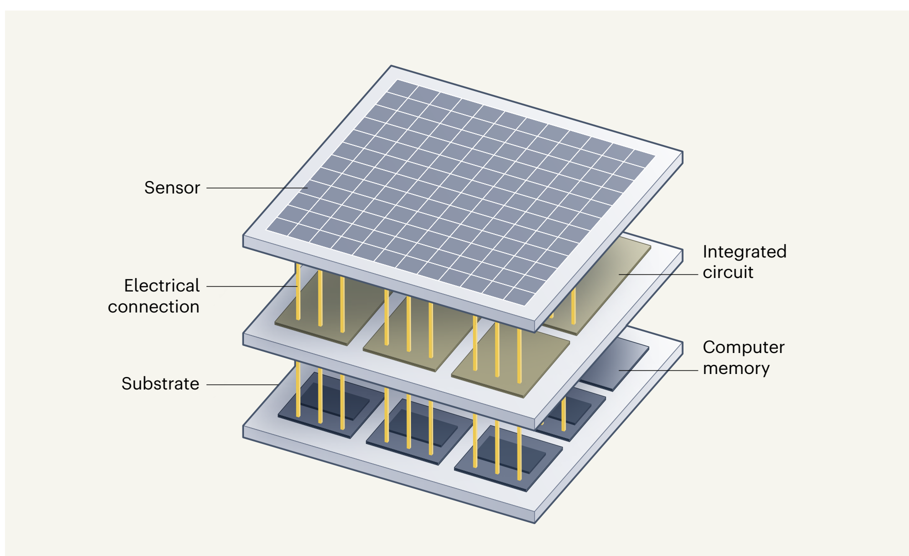

Figure 1 | A 3D circuit made from 2D materials. Jayachandran *et al.*[1] fabricated a tiered structure, in which each tier is made from ultrathin sheets of semiconductor materials, layered on a substrate, and is electrically connected to the next. The authors showed that the device could incorporate components with different functionalities, such as sensing and memory. The advance could give rise to fully functional 3D computer chips that include such components, as well as integrated circuits for computing. (Adapted from Fig. 1a in ref. 1.)

The first is called the 'front end of the line' and it involves components, such as transistors, being patterned into the semiconductor chip. The next phase, known as the 'back end of the line' (BEOL), originally referred to the wiring together of these components, which required metallic materials. With the advent of 'more than Moore', however, BEOL takes on another role, because it is the fabrication step in which functionalities (for example, sensing capabilities) could be added. This would necessitate the use of components made from semiconducting materials that are BEOL-compatible, and 2D materials are possibly best suited to the task. Scientists are therefore seeking a high-performance 2D material that can be integrated with silicon in a 3D device.

Towards that goal, a few studies have investigated the prospect of using 2D materials for BEOL-compatible processes. These reports have demonstrated the growth of 2D MoS_2 at low temperatures on 200-millimetre-diameter wafers[6], as well as the development of MoS_2-based transistors that also incorporate materials known as ferroelectrics[7]. However, high material quality does not necessarily lead to high-performing transistors. Researchers often characterize only around 100 devices in such studies, which does not provide sufficient evidence of a high success rate to excite the semiconductor industry into new product development.

In this regard, Jayachandran and colleagues' work is a crucial step forward for technologies based on 2D materials. The team produced and characterized around 20,000 functional devices, which will establish 2D materials as more than just an academic curiosity. The semiconductor industry now has sufficient evidence that 2D materials are an excellent candidate for next-generation transistor channels, given their short channel lengths. The authors have also shown that memory devices and photodetectors can be realized on a large scale with 2D materials, which indicates that these materials will be able to deliver 'more than Moore'.

However, not all of the challenges facing 2D materials have been met. Jayachandran and co-workers' transistors are all 'back-gated'; that is, the entire channel is controlled by a kind of switch called a gate, which sits under the channel. A structure known as a gate dielectric also needs to be incorporated on top of the channel, to improve the performance of the transistors, but these are not currently available on a scale that would suit the authors' 3D design. The roadmap for short-channel transistors is to develop devices that are entirely enveloped by a gate, to ensure strong electrostatic control of the channel. However, this will require improvements in the gate technology for 2D channels.

Although Jayachandran *et al.* report tens of thousands of functional transistors, it is not yet clear whether their devices are affected by factors that compromise the performance of other short-channel transistors, such as drain-induced barrier lowering, in which a component called the drain competes with the gate for control of the channel. Until this issue is clarified, it will remain unclear whether the devices are fit to realize the roadmap beyond silicon. Nevertheless, the authors have proved that 2D materials are worthy of interest — and investment — from the semiconductor industry.

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Microbiology

Viruses wrap up bacterial defence systems

Tim R. Blower & Stineke van Houte

Bacteria use diverse defences against viral predators called bacteriophages. A method to identify antibacterial counter-defences in viral genomes has revealed striking modes of defence inhibition. **See p.352 & 360**

A broad set of defence systems protects bacteria from infection by viruses called bacteriophages (also known as phages)[1]. In turn, bacteriophages have evolved specialized counter-defence systems that ensure successful viral replication[2]. On pages 352 and 360, respectively, Yirmiya *et al.*[3] and Antine *et al.*[4] shed light on the battle between bacteria and bacteriophages.

Yirmiya and colleagues identify and characterize evolutionarily conserved counter-defence gene families that target three distinct types of bacterial defence. Antine and colleagues demonstrate how one type of defence system is inhibited by being effectively 'wrapped up'. These studies highlight an effective method for identifying counter-defences and provide key insights into the inhibition mechanisms. Together, they expand and deepen our understanding of the genomic organization and the evolutionary diversity of bacteriophage counter-defences.

> "Molecular sponging of immune signalling molecules might have evolved numerous times."

Yirmiya *et al.* gathered genetically similar bacteriophages and tested their ability to grow in association with bacterial hosts that expressed a range of previously identified defence systems[1]. Quantitative assessment of viral replication enabled the authors to categorize each bacteriophage as either sensitive or resistant to the target defence system. They thereby identified resistant bacteriophages with potential counter-defence activity against five bacterial defence systems — called Thoeris, Hachiman, Gabija, Septu and Lamassu[1]. Analysis using comparative genomics enabled the authors to identify candidate counter-defence genes against three defences (Thoeris, Hachiman and Gabija), which were present in the genomes of resistant bacteriophages but not in those of sensitive bacteriophages.

To verify whether these genes indeed counter bacterial defences, Yirmiya *et al.* generated genetically modified bacteriophages in which the counter-defence gene was either deleted from the genomes of resistant phages, or inserted into the genomes of sensitive phages. Testing these modified bacteriophages against bacteria expressing the target defence system confirmed counter-defence activity. Subsequent analysis of DNA sequences mapped the distribution of counter-defence genes in