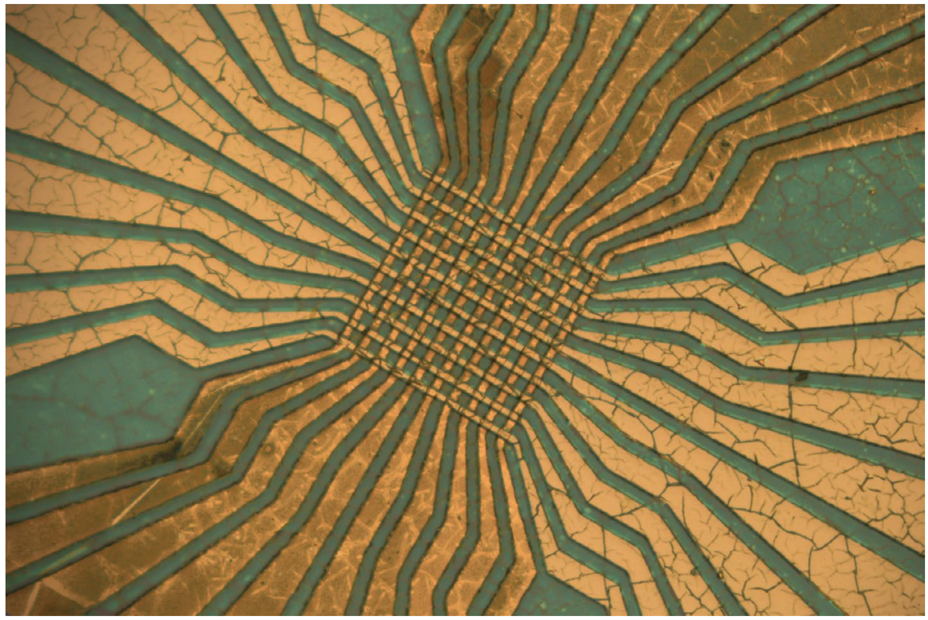
A two-dimensional outlook

Transistors made from two-dimensional materials have been around for a decade, but do the devices have a realistic future in integrated circuits?

The first commercial microprocessor — the Intel 4004 — was introduced to the general market in November 1971 (ref. [1]). Fifty years later — and after countless innovations in materials and fabrication methods, in devices and circuits — one thing remains the same: silicon. The semiconductor is still central to the electronics industry, and the scaling of silicon-based devices has underpinned decades of advances in integrated circuits and electronics technology. But silicon will eventually reach its limits and alternative materials for the channels of devices are being contemplated, including germanium and III–V semiconductors, as well as a range of other technological solutions.

One contender at the more exotic end of potential options is two-dimensional (2D) materials. These materials, which include graphene, molybdenum disulfide and hexagonal boron nitride, can offer a range of electronic properties, from conducting to semiconducting to insulating. And as such, they could be of use in device scaling and beyond. In a Focus in this issue of *Nature Electronics*, we explore the potential role of 2D materials in the future of electronic circuits.



Optical microscopy image of a 10 × 10 memristor crossbar array that uses multilayers of 2D hexagonal boron nitride as the resistive switching material[5]. Credit: Mario Lanza, Soochow University.

Following the isolation of graphene in 2004, and the measurement of its remarkably high charge carrier mobility, researchers began to consider how this zero-bandgap material could be turned into a semiconductor, and thus be used as a channel material in transistors. But modifying graphene for use in transistors proved a difficult task. For Andras Kis of École Polytechnique Fédérale de Lausanne an alternative approach seemed more promising: start with a 2D material that actually has a bandgap. Inspired by his days as a PhD student working with colleagues who were investigating inorganic alternatives to carbon nanotubes, he and his research team began exploring the potential of 2D molybdenum disulfide. And as Kis recounts in our Reverse Engineering column, it was an exploration that would lead to the fabrication of the first 2D transistor (a device made from a monolayer of molybdenum disulfide that exhibited drain current on/off ratios of 1×10^8), which was first reported in the journal *Nature Nanotechnology* in January 2011 (ref. [2]).

Today, an array of 2D materials have been tested as channel materials in transistors and other components. But their application in devices that are of use beyond the lab remains limited. In a Review Article in this issue, Saptarshi Das and colleagues at institutes from across academia and industry discuss the potential benefits and challenges of using 2D transistors in very large-scale integration (VLSI) circuit technologies. They outline, in particular, key performance indicators that should be used when assessing 2D transistors for VLSI. And discuss key challenges — including doping (as we highlighted last month[3]), contact resistance, mobility engineering, scaling and variability — within the context of the requirements set out in the International Roadmap for Devices and Systems (IRDS)[4].

While challenges still exist at the device level, there have already been several notable demonstrations of integrated circuits in which 2D materials are used as transistor channel materials, dielectrics, interconnects and electrodes. In a Perspective in this issue, Mario Lanza and colleagues at KAUST, Universitat de Barcelona and Soochow University highlight some of the most advanced circuits fabricated to date, and look ahead to what we can expect to see in the future. Much of the work so far has been exploratory, but the expanse of applications developed is impressive, ranging from basic logic to microprocessors, and from radiofrequency circuits to optoelectronics circuits.

Two-dimensional materials have the potential to drive future innovation in the electronics industry. Critical to this will be the development of industry-compatible synthesis and fabrication methods. And some of the world's largest semiconductor companies, including the Taiwan Semiconductor Manufacturing Company (TSMC), are dedicating substantial research resources to the potential use of 2D materials. So while silicon will undoubtedly remain a constant for some time to come, commercial electronics based on 2D materials may not be that distant a prospect. ❒

Published online: 25 November 2021
https://doi.org/10.1038/s41928-021-00682-x

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