Doping in 2D

Ion implantation can be used to dope silicon devices, but can be problematic when applied to the atomically thin crystal structure of two-dimensional materials — an increasing range of alternative methods is though available.

Doping — the controlled introduction of impurities into a material in order to manipulate its properties — is an essential tool in building electronic devices. With silicon, ion implantation can be used. Here, ionized dopants are fired into a region of a semiconductor wafer, leading to an excess of electrons or holes, and thus a region of n-type or p-type material. Such techniques have played an important role in establishing silicon complementary metal–oxide–semiconductor (CMOS) technology as the dominant approach in the electronics industry. Thus, in the search for alternative materials to silicon — a focus for many researchers (and many of the pages of *Nature Electronics*) — effective doping methods are a requirement for any contender.

For two-dimensional materials, and the layered two-dimensional materials known as van der Waals heterostructures, doping is a challenge because ion implantation can lead to damage to the atomically thin crystal structure. A range of alternative approaches are though available — and new ones continue to emerge. In last month's issue of *Nature Electronics*, for example, Donghun Lee, Chul-Ho Lee and colleagues reported that remote modulation doping was possible in van der Waals heterostructure transistors¹. The approach uses a tungsten diselenide/hexagonal boron nitride/molybdenum disulfide heterostructure in which the molybdenum disulfide channel can be remotely doped via controlled charge transfer from molecular dopants on the surface of the tungsten diselenide.

The researchers — who are based at Korea University, Kyung Hee University, Ulsan National Institute of Science and Technology, and the Korea Institute of Science and Technology — show that the resulting modulation-doped field-effect transistors exhibit a room-temperature mobility of $60 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$. In comparison, molybdenum disulfide field-effect transistors that have been directly doped with the same molecular dopant (triphenylphosphine, an n-type dopant) exhibit a mobility of only $35 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$.

Alternatively, back in our January issue, Moon-Ho Jo and colleagues reported that few-layer molybdenum ditelluride and tungsten diselenide field-effect transistors can be reversibly doped with

Optical microscopy image of two silicon nitride microring resonators, with the top resonator incorporating a transparent electrode made from graphene doped with a monolayer of tungsten oxyselenide. Credit: Ipshtita Datta, Columbia University.

light². With this approach, the polarity of the molybdenum ditelluride and tungsten diselenide channels can be reconfigured from n-type to p-type using laser light of different frequencies. The behaviour is the result of particular light–lattice interactions (such as the formation of self-interstitial defects or the incorporation of substitutional oxygen into vacancies) that occur at different photon energies. The researchers — who are based at the Institute for Basic Science in Korea, Pohang University of Science and Technology, and Seoul National University — used the approach to create a CMOS device that could be reconfigured from an inverter to a switch.

These advances in two-dimensional doping continue in this issue of *Nature Electronics*, where James Hone, James Teherani and colleagues report that graphene can be doped using a monolayer of tungsten oxyselenide. The monolayer is created by oxidizing a layer of tungsten diselenide, and when the graphene is in direct contact with the tungsten oxyselenide it exhibits a mobility of $2,000 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$. By inserting tungsten diselenide layers between the tungsten oxyselenide and the graphene, the carrier density can be tuned and the mobility

increased, leading to a mobility of around $24,000 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ with four interlayers. The researchers — who are based at Columbia University, Sungkyunkwan University, the City University of New York, and the National Institute for Materials Science in Tsukuba — also show that the doped graphene is highly transparent in the infrared and illustrate its potential by using it as a transparent conductor in a silicon nitride photonic waveguide and ring resonator.

These examples highlight the range of alternative doping methods that are now available for two-dimensional materials and van der Waals heterostructures, techniques that are helping to create an ever expanding range of sophisticated devices and simple circuits. But in the continuing development of two-dimensional electronics, what demands increasing attention is the fabrication of integrated circuits. This is a topic we will return to next month. Stay tuned. □

Published online: 22 October 2021
<https://doi.org/10.1038/s41928-021-00668-9>

References

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