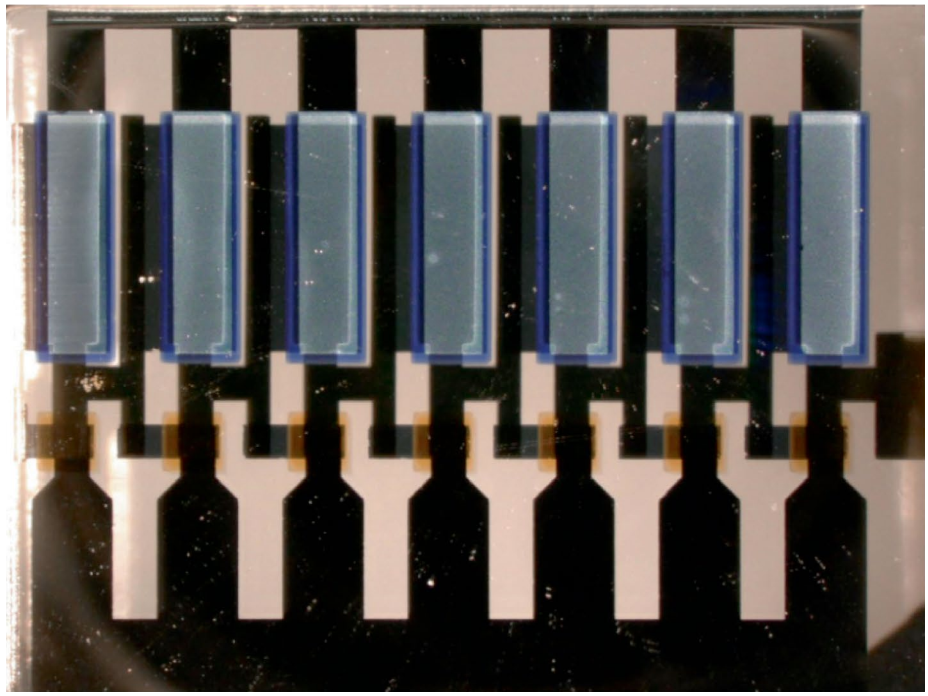
35 years of organic transistors

Flexible devices based on organic semiconductors could be of use in the development of wearable electronics and the Internet of Things, but face competition from other established and emerging technologies.

Transistors made from organic semiconductors were first reported 35 years ago. In November 1986, and writing in *Applied Physics Letters*, researchers at the Mitsubishi Electric Corporation described building a field-effect transistor in which the semiconducting channel was a film of the polymer polythiophene[1]. The p-type device had a carrier mobility of around 10^{-5} cm^2 V^{-1} s^{-1}, and used a silicon wafer with an oxide layer as the substrate.

Today, organic field-effect transistors can offer mobilities over 10 cm^2 V^{-1} s^{-1} (though the field has also been plagued by concerns about the overestimation of such values)[2], and the devices can be fabricated on almost any substrate, including flexible ones such as plastic and metal foil. The materials can be deposited with simple methods, such as printing, and don't require the high-temperature processing that is typical of inorganic devices. As a result, the transistors are of particular interest in the development of wearable technologies and the Internet of Things. (Beyond transistors, organic semiconductors are of use in other — commercially more advanced — devices: namely, solar cells and light-emitting diodes; see the Review Article in this issue of *Nature Electronics* for an analysis of the potential of organic light-emitting diodes in next-generation data communications.)

Organic transistors typically have a lateral-channel architecture (where the source and drain electrodes are in the same plane). But various vertical-channel architectures have also been explored and have recently offered encouraging capabilities, particularly in relation to high-frequency performance and stability. Building any digital circuit requires logic gates, and with vertical organic transistors, different logic circuits (including inverters and NAND/AND gates) have already been built[3]. These circuits were though based on unipolar technology. It may be preferable to follow the approach currently at the heart of the electronics industry — silicon complementary metal–oxide–semiconductor (CMOS) technology — and use a complementary technology composed of pairs of n-type and p-type transistors. Such an approach offers reduced power consumption because one transistor of the pair is always off.



Photograph of a seven-stage ring oscillator based on vertical-channel organic transistors. Reproduced with permission from the Article by E. Guo et al., Springer Nature Ltd.

In an Article in this issue, Erjuan Guo, Zhongbin Wu, Hans Kleemann and colleagues report organic complementary circuits made from vertical-channel transistors. The circuits are created with triode-like vertical devices called permeable base transistors. These devices have electrodes (known as base electrodes) sandwiched between a charge-carrier-injecting electrode (the emitter) and a charge-carrier-extracting electrode (the collector); the base electrode controls the current flow from the emitter to the collector, and has nanoscale holes that make it permeable to charge carriers. The researchers — who are based at Technische Universität Dresden, Helmholtz-Zentrum Dresden-Rossendorf and Northwestern Polytechnical University in Xi'an — show that the approach can be used to create low-voltage complementary inverters and that seven of these complementary inverters can be integrated to create a ring oscillator (pictured).

In a race to develop flexible integrated circuits for wearable technologies and the Internet of Things, organic transistors face stiff competition from both established (such as metal-oxide thin-film transistors) and emerging (such as two-dimensional transistors) competitors. At the forefront of this race — in terms of complexity, at least — is recent work[4] from researchers at Arm and PragmatIC Semiconductor, companies based in Cambridge, UK. (See also a News & Views on the work in this issue.) Using metal-oxide thin-film technology based on indium–gallium–zinc oxide (IGZO), the team have fabricated a 32-bit microprocessor on a plastic substrate. The flexible microprocessor, which is termed PlasticARM, contains more than 18,000 NAND gates. ❐

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