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Device physics

The advent of crystalline organic electronics

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A transistor fabricated from the crystalline phase of an organic semiconductor material could provide a path to improved switching speeds — rivalling those of devices built from inorganic materials such as silicon. **See p.700**

Transistors are the building blocks of digital circuits — they can be used to amplify a signal, or to switch between 'on' and 'off' states, through control of a current of charge carriers, which are either electrons or their positive counterpart (holes), or both. The bipolar junction transistor is a specific type of transistor that uses both types of carrier, and is particularly appropriate for high-power and high-frequency applications. Such devices are typically made from inorganic materials, but switching to organic semiconductors would grant access to a wide library of materials, opening the door to flexible and transparent electronics. On page 700, Wang *et al.*[1] report the fabrication of an organic bipolar junction transistor that could help the semiconductor industry to make that switch.

Bipolar junction transistors consist of three terminals — known as the emitter, the base and the collector — that are separated by junctions made from semiconducting materials. The semiconductors are either p-type (for positive, because their hole concentration is higher than their electron concentration) or n-type (for negative), and are arranged alternately, in either a 'pnp' configuration or an 'npn' configuration. Organic bipolar junction transistors have not been attempted before because the mobility of charge carriers is low in organic compared with inorganic semiconductors.

Achieving high mobilities is straightforward for inorganic materials, such as silicon, but more difficult for organic materials. Nonetheless, since the first fabrication of an organic transistor[2], an organic solar cell[3] and an organic light-emitting diode[4] (OLED) in the 1980s, tremendous progress has been made in the field of organic electronics, in particular in the OLED display industry. The advantages and bottlenecks of organic semiconductors now determine the design of devices that are studied and commercialized.

Aside from their low charge-carrier mobility, organic semiconductors have another drawback that is particularly relevant for bipolar junction transistors — and that's an imbalance between carrier mobilities. Specifically, the mobility of minority carriers (those that are less abundant in a device than their oppositely charged counterparts) is usually much smaller than that of majority carriers.

This mobility imbalance can be accommodated in the organic field-effect transistor, a type of unipolar transistor that uses just one type of charge carrier and is operated in accumulation mode — in which the current comprises majority carriers only. This solves the problem, but it also compromises performance relative to inorganic field-effect transistors; these can easily operate in 'inversion' mode, in which the current is made of minority carriers.

The development of molecules and polymers with improved material properties has led to organic materials routinely overtaking amorphous silicon in terms of mobility, but the performance of organic field-effect transistors remains unsatisfactory for high-frequency applications. One way of mitigating this shortcoming involves reducing the distance that charge carriers need to travel. This is challenging in conventional organic field-effect transistors, which are horizontal in design, so vertical designs are being investigated as an alternative[5]. A bipolar junction transistor (Fig. 1a) preserves the benefits of a vertical structure, and opens new avenues for amplification and switching in organic electronics.

The challenge, then, is to fabricate a functional bipolar junction transistor by engineering an organic material with high mobilities for both majority and minority carriers. The low-mobility characteristic of organic materials arises in part from a lack of crystalline order.

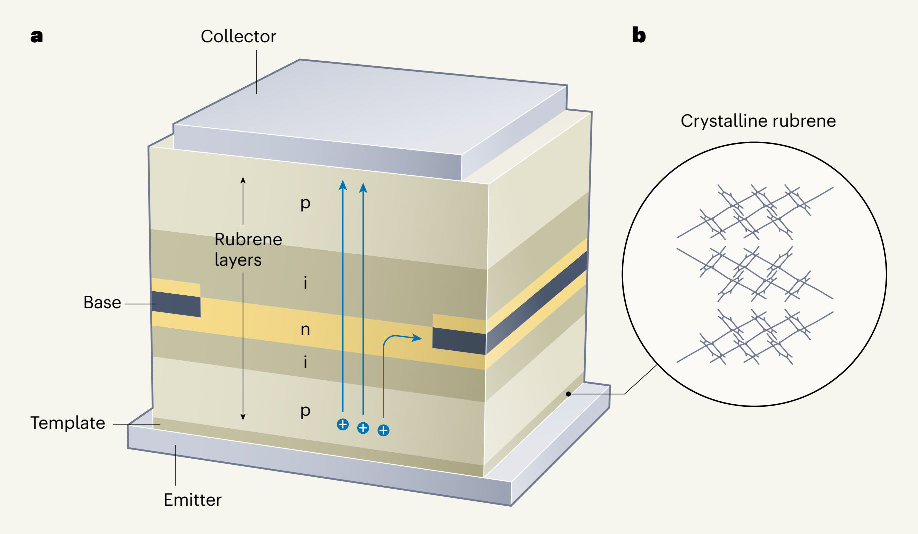

Figure 1 | A high-speed transistor structure made from an organic semiconductor material. **a**, Wang *et al.*[1] fabricated a bipolar junction transistor (a type of transistor that is suitable for high-power and high-frequency applications) from layers of an organic semiconductor material known as rubrene. The semiconductors are p-type (where positive charges dominate), n-type (negative charges dominate) or i-type (for intrinsic, where neither dominates) and are arranged in three terminals known as the emitter, base and collector. Device performance requires that the mobility of positive charges (indicated by the arrows) is high in both the p-type and n-type layers, because mobility sets the speed of the current. This is, however, challenging to achieve in organic materials. (Adapted from Fig. 1a in ref. 1.) **b**, Wang *et al.* engineered their device from a crystalline template of rubrene to achieve higher carrier mobilities. Subsequent rubrene layers in the device are expected to follow the same crystalline phase.

Indeed, crystalline silicon offers a much higher mobility than amorphous silicon. Wang *et al.* used the crystalline phases of a high-mobility organic semiconductor known as rubrene to fabricate a bipolar junction transistor (Fig. 1b).

As well as needing high carrier mobilities, a bipolar junction transistor requires both p- and n-type layers. Authors from the same group as Wang and colleagues had previously developed p- and n-type rubrene films fabricated with high crystalline order[6,7]. In the present study, these films were engineered on a very thin crystalline template, with a thickness of around 20 nanometres; this acted as a seed for subsequent p- and n-type layers. The authors now report the construction of an organic bipolar junction transistor made with these layers, as well as layers that are i-type (for intrinsic, meaning that neither positive nor negative charges dominate).

Wang *et al.* estimated the device's transition frequency — a quantity characterizing the speed of the transistor — and found that it was 1.6 gigahertz (1 GHz is 10^9 Hz). This value is well above the record transition frequencies for organic field-effect transistors, which are 40 MHz for a device in a vertical configuration[8] and 160 MHz for a device in a horizontal one[9]. However, the transition frequency was evaluated indirectly, so further work will be required to directly estimate the metrics and figures of merit for such devices, and to determine whether crystalline organic bipolar junction transistors are viable for high-frequency applications.

As well as expanding the portfolio of organic devices, Wang *et al.* showed that their transistors could be used to measure a semiconductor property known as the minority-carrier diffusion length, which had not previously been probed in organic semiconductors. This metric defines the distance that a minority carrier can travel before it recombines with a carrier of the opposite charge, and is therefore 'lost'. It is a key parameter for optimizing efficiency in bipolar junction transistors. Wang and colleagues' study suggests that the organic bipolar junction transistor might present a means of accessing this fundamental parameter, enabling a better understanding of these materials and enhancement of existing technologies.

> **"The bottlenecks of organic semiconductors determine the design of devices that are commercialized."**

With the quality of crystalline films improving, some of the limitations typically associated with organic semiconductors might be lifted. This progress broadens the horizons of organic-based technologies in the emerging era of crystalline organic electronics, as shown by Wang and colleagues' organic bipolar junction transistor. The high-speed switching achievable by such devices will allow for the exploration of technologies, such as gigahertz electronics, that have long been considered inaccessible to organic electronics.

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