Materials science

Vertical architecture improves transistor family

Camille Cunin & Aristide Gumyusenge

Organic electrochemical transistors could be better than conventional inorganic devices for certain uses, but have been held back by performance issues. The solution could be to build up these organic transistors like a sandwich. See p.496

Modern electronic gadgets depend on transistors – semiconductor devices that control electrical currents to amplify signals or switch between 'on' and 'off' states. Most transistors are made of inorganic semiconductors, but organic electrochemical transistors (OECTs) show great promise for certain applications, such as body–machine interfaces and wearable electronics[1]. However, the development of OECTs has been hindered by problems such as slow switching speeds and low stability during operation[2]. On page 496, Huang *et al.*[3] start to address these issues by turning conventional OECT architecture on its side.

OECTs consist of three electrodes: a 'source' and a 'drain' electrode that are connected by a thin film (known as the channel) of an organic semiconductor; and a 'gate' electrode that connects to the channel material through an electrolyte, a medium that contains mobile ions (Fig. 1). Operation of these devices typically involves applying a voltage to the gate, which causes ions in the electrolyte to be injected into the channel. This changes the electronic charge density in the channel and thereby alters the current passing between the source and drain electrodes.

Most OECTs have planar, horizontal architectures (Fig. 1a) analogous to those of conventional transistors that incorporate inorganic semiconductors, with structures determined by the location of the gate with respect to the channel (the devices can be top-, bottom- or side-gated)[2]. A few research groups have investigated vertical transistor architectures[4,5], but devices that operate reliably and can be readily integrated into large-area circuits have been elusive.

Huang *et al.* have addressed these issues using an ingenious trick: they took the architecture of a conventional horizontal OECT and rotated it by 90°. To do this, the researchers simply sandwiched the channel material between two gold electrodes to create a vertical arrangement (Fig. 1b). The ion-permeable channels were made using a semiconducting polymer blended with another polymer that provides structural robustness and operational stability for the resulting devices. The semiconducting polymer could be either an n-type semiconductor, which has more negatively charged carriers (electrons) than positively charged ones (holes), or a p-type semiconductor, which has more holes.

OECT performance is usually characterized in terms of transconductance (a property that relates the channel current to the gate voltage) and switching speed, both of which depend heavily on the channel dimensions. Common strategies for achieving high transconductance are to increase the width or thickness of the channel, or to decrease the channel length (the distance between the source and drain electrodes)[6]. However, these strategies often result in lower device speeds. In horizontal architectures, a channel length of about 10 micrometres can typically produce both high transconductance and a fast switching speed, but preparing such channels requires complex and expensive fabrication techniques, the spatial resolutions of which are often limited to the micrometre scale.

By designing a vertical OECT, Huang *et al.* were able to circumvent this limitation: the process of sandwiching the channel material between the gold source and drain electrodes involves standard, relatively simple microfabrication techniques; and the resulting channel length is several orders of magnitude smaller than has been achieved previously (the authors report channel lengths of less than 100 nanometres), because it is just the thickness of the channel material. More impressively, the resulting OECTs exhibit both high transconductance and fast switching speeds (turn-on times of less than 1 millisecond), as well as extremely high stability during more than 50,000 switching cycles. The key to such unprecedented performance was the authors' design of the channel material.

In OECTs, the channel is permeable to ions injected from the electrolyte. It is therefore important to optimize the transport of both ions and electrons at every position in the semiconducting channel to achieve high performance – that is, when a small voltage is applied at the gate electrode, injection of ions should modulate the channel's bulk conductivity, substantially changing the source–drain current[7]. The channel material can be either a p-type or an n-type semiconductor; p-type OECTs are more common, but n-type counterparts are crucial for use in sensing devices and logic circuits. Unfortunately, high-performance n-type OECTs are rare, and even the best of these lag far behind p-type devices in terms of performance, which limits applications requiring fast device responses and complementary

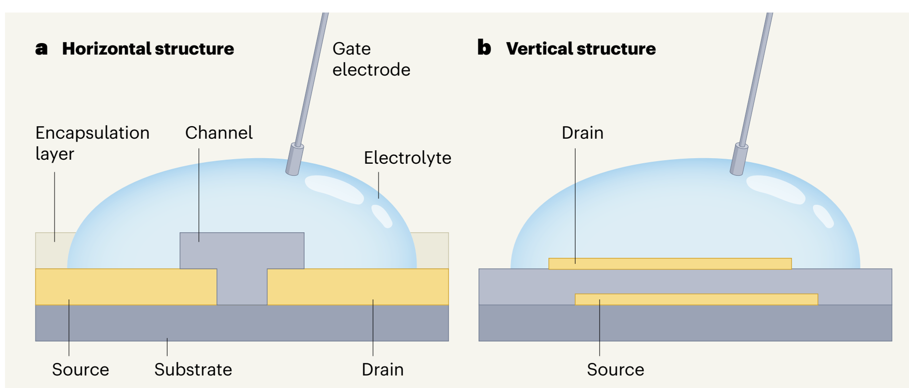

Figure 1 | Horizontal and vertical architectures for organic electrochemical transistors (OECTs). OECTs are being developed as alternatives to conventional inorganic transistors in various applications. **a**, In a typical horizontal OECT architecture, two gold electrodes (the source and drain) on a substrate are separated by an organic semiconductor material (the channel). An electrolyte medium covers the channel. A non-conducting encapsulation layer holds the electrolyte and defines the area of the channel exposed to the electrolyte. When a voltage is applied to a third electrode (the gate), ions in the electrolyte enter the channel, altering the current that passes between the source and drain. **b**, Huang *et al.*[3] report a vertical architecture in which the channel is sandwiched between the source and drain, reducing the distance between the gold electrodes to just the thickness of the channel. This arrangement, combined with the use of a new semiconducting polymer as the channel material, greatly improves the performance and stability of the OECT.

circuits (which use both p- and n-type OECTs)[8].

Huang and colleagues' combination of a vertical OECT architecture with new electro-active and ion-permeable semiconducting polymers results in the highest reported transconductance per unit area of the channel material in an OECT device, and the highest current in the 'on' state. More importantly, the authors' vertical n-type OECTs outperform any previously reported n- and p-type OECTs, when used in complementary logic circuits.

OECTs have great promise for biosensing applications, in which biomolecules are commonly anchored to either the gate or the channel[2]. However, the gate and channel are buried in the vertical architecture, so new circuit designs will be needed to use such OECTs in biosensors. Moreover, further investigations are needed to show that this architecture works for a wide range of semiconductors; to fully understand how the molecular structure of semiconductors affects device performance; to further simplify the fabrication protocols; and to incorporate this architecture into large-area circuits. Nevertheless, Huang and colleagues' devices highlight the potential of vertical OECTs to overcome the present spatial and temporal limitations of organic electronics — thereby enabling logic circuits to be reduced in size, as is needed for future wearable and bio-inspired electronic devices.

Camille Cunin and **Aristide Gumyusenge** are in the Department of Materials Science and Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA.
e-mail: aristide@mit.edu

1. Someya, T., Bao, Z. & Malliaras, G. G. *Nature* **540**, 379–385 (2016).
2. Torricelli, F. *et al. Nature Rev. Methods Primers* **1**, 66 (2021).
3. Huang, W. *et al. Nature* **613**, 496–502 (2023).
4. Ben-Sasson, A. J. *et al. Appl. Phys. Lett.* **95**, 213301 (2009).
5. Koutsouras, D. A., Torricelli, F. & Blom, P. W. M. *Adv. Electron. Mater.* **2022**, 2200868 (2022).
6. Rivnay, J. *et al. Sci. Adv.* **1**, e1400251 (2015).
7. Roh, H., Cunin, C., Samal, S. & Gumyusenge, A. *MRS Commun.* **12**, 565–577 (2022).
8. Li, P., Shi, J., Lei, Y., Huang, Z. & Lei, T. *Nature Commun.* **13**, 5970 (2022).

The authors declare no competing interests.

Scientific community

Self-publishing is common among academic editors

Molly M. King

An analysis of the publication records of academic editors shows that one-quarter of them publish 10% of their own papers in the journals they edit and reveals that fewer than 10% of editors-in-chief are women.

Journal editors determine which manuscripts go out for review, which reviewers are chosen and how reviews are adjudicated and processed. Consequently, they exercise considerable influence over scholars' careers. Although high-profile scientific journals tend to have full-time editors, most journals are edited by academics. Writing in *Nature Human Behaviour*, Liu *et al.*[1] present a comprehensive analysis of the publication records of academic editors. Their results suggest that the prevalence of self-publication could exacerbate inequalities in academia.

The authors gathered data on names and affiliations for 103,000 editors of 1,167 journals published by Elsevier, across 15 disciplines and several decades. Although these data came from the editorial-board web pages of Elsevier, similar trends would be expected for other publishers. The researchers matched this information to publication records in the Microsoft Academic Graph (MAG; a database of scholarly publications) for 21,600 of their editors. This enabled them to determine the editors' affiliations, publication history and academic age (the number of years since first publication).

The resulting data set is of unprecedented size for an investigation of editorial self-publishing, and forms the basis of the first cross-disciplinary study of this type that has international reach. One concern is that editors that Liu and colleagues were able to match to publications are disproportionately productive (these individuals would be more likely to appear in MAG), but an analysis by the authors found that this did not substantively affect the results. However, the authors did not test whether this sampling approach affected their results related to gender.

Liu and colleagues asked what makes editors distinct from other academics. When they compared editors' publication records with those of other academics during the year before the editors took up their positions, they found that the productivity gap had increased fourfold since 1980. As of 2017, people who were about to become editors had collaborated with more than six times as many people as had an average academic in the same discipline and with the same academic age. In addition to being collaborative and productive, the authors found that publishing work that is highly impactful and well-cited seemed to matter more in 2017, compared with 1980, in terms of becoming an academic editor.

The researchers also looked at whether practices differ by gender, using a gender classifier to assign first names. Such classifiers are imperfect[2], and this is one limitation of the study — use of the classifier led to the exclusion of more than 20,000 editors from much of the analysis, because their gender could not be identified from their first name. Moreover, classifiers enforce an artificial binary categorization of gender. Nonetheless, they are a powerful tool with which to understand gender inequalities on a large scale. The authors found that editors are disproportionately likely to be men; only 14% of editors and 8% of editors-in-chief are women, compared with 26% of authors in the publication records in MAG.

Women and men have comparable levels of productivity and impact during the years in which they are active in research[3], so this cannot account for the difference. By comparing editors and academics of the same discipline and academic age, and with the same impact and level of productivity, Liu *et al.* showed that the gender disparity between editors (although not the greater disparity between editors-in-chief) can be explained by differences in career length. Indeed, previous work has shown that because women are more likely than men to leave the academic workforce when they become parents[4], they are less likely to accumulate sufficient publications and citations in their careers to become editors. Because women also have, on average, more university-service commitments (such as serving on committees or being involved in faculty governance) and care-work commitments than do men[5], they might be reluctant to accept the extra responsibilities of editorial work.

The authors next demonstrated that self-publishing is common — nearly one in four editors publishes at least 10% of their own papers in the journal they edit (Fig. 1). The group noted that the self-publication rates of journal editors were higher than the publication rates of other academics and members of the editorial board of the same journal. Neither the previous level of productivity of these individuals nor the culture of the journal explained the high self-publication rates. Liu and colleagues compared the publication rates of the editors before and during their editorships, and also compared the rates with those of academics who were similar in terms