nature reviews electrical engineering

https://doi.org/10.1038/s44287-024-00063-4

Perspective

Check for updates

Towards integrated textile display systems

Zhen Wang[1,2], Yue Liu[1,2], Zihao Zhou[1], Peining Chen[1] ✉ & Huisheng Peng[1] ✉

Abstract

We receive approximately 80% of our external environmental information through vision, making display technology an essential component of modern life. The evolution of device structures has led to the iterative development of display technology from rigid bulk to flexible films. Recently, next-generation displays have woven electroluminescent units directly into polymer composite fibres to form textile displays. Such displays are flexible and breathable, like clothing, suggesting applications such as wearables and smart textiles. In particular, they would allow users to interact with electronic devices by touching the clothing. This Perspective provides a summary of the evolution of textile displays. We then discuss recent achievements in the field, including applications of textile displays, advances in active materials, designs of interfaces between the active layer and fibre electrodes, developments in display modules, and integration of textile displays with multiple electronic functions. Finally, we highlight the potential challenges of textile displays for practical applications and suggesting future research directions in this exciting field.

Sections

[1]State Key Laboratory of Molecular Engineering of Polymers, Department of Macromolecular Science, Institute of Fiber Materials and Devices, and Laboratory of Advanced Materials, Fudan University, Shanghai, China. [2]These authors contributed equally: Zhen Wang, Yue Liu. ✉e-mail: peiningc@fudan.edu.cn; penghs@fudan.edu.cn

Key points

- Textile displays offer unprecedented flexibility that is similar to normal textiles, conforming to irregular shapes and enabling wearing comfort. Users can enjoy display functionalities seamlessly integrated into their garments or accessories.

- Luminescent materials as the basic foundation for textile displays need to be designed with high optoelectronic performance and operation durability to make textile displays suitable for practical wearable applications.

- An effective interface among fibre electrodes is essential to realize the efficient electrical connection and uniform electric-field distribution needed to enable reliable operation of textile displays.

- Challenges in resolution performance, driving modules and application explorations should be addressed for practical applications of textile displays.

Introduction

In modern society, displays emerged as an indispensable platform, enabling information to be conveyed among individuals and machines[1,2]. Owing to the escalating need for displaying devices that seamlessly integrate into daily life, the configuration of display technologies is undergoing progressive transformation for wearable devices[3]. Over time, advances in device structures and materials have facilitated the iterative development of display technologies, transitioning from rigid bulky to flexible thin-film formats.

Existing electronic devices are typically composed of bulk or planar display devices. It is difficult to make wearable devices that fit human skin dynamically while being comfortable. Textile displays with flexibility and breathability similar to regular clothes could effectively address such issues and serve as human–computer interfaces, allowing users to interact with electronic devices. Display use is extremely popular in various aspects of human life, and the continuous pursuit of flexibility and portability has promoted the emergence of textile displays, which may become an alternative technology for smart wearable electronic systems featuring displays[4,5]. The integration of displays with textiles typically involves fabricating planar light-emitting diodes (LEDs) onto textile substrates, weaving light-emitting fibres into textiles and directly building electroluminescent units at the interwoven points of textiles. In particular, textile displays based on the interwoven method exhibit almost the flexibility and breathability of normal clothes, and have the same pixel display mode as modern displays, thus enabling emerging applications such as wearable devices and smart textiles[6–10].

Through the integration of multifunctional electronic components, textile displays have emerged as a promising technology in a wide range of application areas[4,11–13] where traditional bulky displays might struggle to meet requirements, such as electronic textiles, human–machine interfaces, smart healthcare, the internet of things and athletic performance. The development of textile displays has sparked an intriguing research direction that involves interdisciplinary collaborations between fields such as electrical engineering, materials science, chemistry, physics and biomedical science. For example, higher-performance luminescent materials and emerging luminescent methods can substantially simplify device fabrication procedures like encapsulation, thus improving the designability of textile displays[14]. Alternating-current and direct-current luminescent systems requires completely different designs of device structures and driving circuits[15]. Moreover, wearable application scenarios featuring complex deformations require highly stable textile electrodes and active materials[16]. The interdisciplinary nature of this field facilitates the exploration of emerging materials, manufacturing techniques and design approaches, with the ultimate goal of enhancing the user experience and expanding the possible applications of textile displays.

In this Perspective, we discuss the requirements of textile displays, and then highlight their promising applications and advances in active materials, electrode interfaces, display modules and functional integrations. We summarize the remaining obstacles to achieving real-world applications, and foresee future research directions advancing this exciting field.

Applications of textile displays

The evolution of device structure has long driven innovative applications in the display industry, constantly pushing technological limits[17,18]. With the development of multi-type fibre devices and effective textile circuits, an integrated closed-loop system in textiles is expected to be realizable for a variety of interdisciplinary applications[4,5] (Fig. 1a,b). In this section, we discuss recent applications of textile displays.

Textile displays show immense potential in driving the evolutionary development of information technology (Fig. 1c). Existing wearables often suffer from the small size and limited capabilities of their planar displays. However, by replacing these displays with large-area textile displays that are seamlessly integrated into textiles, these limitations can be effectively overcome. For instance, unlike existing cellphones and smart watches, large-area textile displays can integrate more visualization functions into portable clothes, such as video playback, navigation, language communication, health visualization and touch control[4,5]. This integration has the potential to revolutionize wearable devices, mobile phones and computers. For example, these breakthroughs could lead to a paradigm shift wherein rigid panels are replaced with soft, flexible textiles that can display information in a comfortable and versatile manner.

Furthermore, textile display technology could transform the landscape of smart healthcare. By using textile display systems, it becomes possible to visualize emotions, physiological parameters and external stimuli in real time[4,19]. For instance, electroencephalogram signals could be collected by placing the electroencephalogram patch on the scalp. The electroencephalogram signals exhibit the frequency of brain waves, which can be used to distinguish emotional and mental states[20]. The collected signals are then processed on a computer. As a result, words related to the mental state are sent to the microcontroller of the textile display through a Bluetooth module[4]. This real-time visualization enables precise diagnosis and efficient communication in healthcare settings. We can imagine a situation in which doctors are able to monitor patients' vital signs and emotions instantly, leading to exceedingly accurate diagnoses and timely interventions. In particular, individuals with disabilities could effectively communicate their intentions in real time using smart textiles. Textile displays in smart healthcare could thus revolutionize the way medical professionals interact with their patients, improving the quality of healthcare.

In the context of the internet of things, the integration of textile display systems with wireless transmission technology brings forth an era of human–machine interaction. This integration creates a

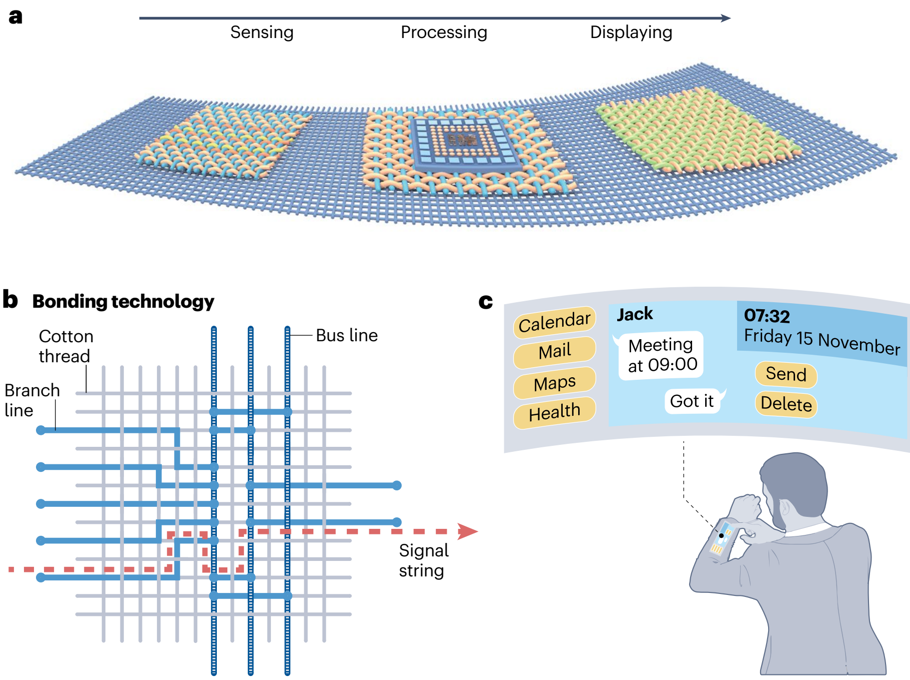

Fig. 1 | Integration and applications. a, Multifunctional integration of sensing, processing and displaying, with the goal of a closed-loop system in practical textile applications. **b**, Microscale-to-nanoscale processing for effective and stable electrical inter-device circuits. Interconnection technology is the cornerstone of integrated textiles. **c**, Schematic of textile displays promoting the evolutionary development of information technology in wearables. A user could interact with electronic systems by touching clothing.

platform where textiles can display information and seamlessly interact with internet-of-things devices, enabling intelligent homes and offices[21,22]. In this case, clothing or household textiles can display real-time information about the environment, control smart devices and provide personalized notifications. This integration would not only improve convenience but also create opportunities for efficiency and automation in our daily lives.

From revolutionizing information technology to transforming healthcare and enabling intelligent homes and offices, textile displays have the potential to reshape the way we live, work and interact with electronic technology. At present, several companies are actively engaged in the research and development of such products. For example, LITME, made by Tayho Advanced Materials, an intelligent apparel company from China[23], is diligently undertaking the incorporation of displaying textiles into products ranging from garments and wearables to automobiles. As we keep exploring, textile displays hold the promise of enhancing our daily life experience and unlocking additional levels of functionality and interactivity (Fig. 1b).

Evolution toward textile displays

Displays have undergone substantial transformations over the years to meet the changing demands towards higher flexibility and light weight[13]. In particular, efforts have been made in transitioning the structure design of displays from three-dimensional bulks to two-dimensional films to meet the increasing flexibility requirements for electronics, which has been a booming field from the 2010s to the 2020s.

Since the 1930s, cathode ray tube displays have dominated the display field[24,25]. With the rise of emerging information technologies such as 5G and the internet of things, wearable devices are regarded as next-generation electronics after computers and smartphones[13,26]. However, it is difficult for planar displays with multilayered structures to meet the flexible, lightweight and comfort requirements of wearable electronics. Therefore, emerging displays require transformational conformations that can seamlessly fit irregular and soft human bodies to ensure stable performance and wearing comfort. Recent advances in display technology encompass the integration of display functionality into flexible and permeable textiles, transforming the structural configuration of displays through the deliberate incorporation of emissive units as an intrinsic constituent of textiles (Fig. 2d). Textile displays utilize flexible materials, conductive fibres and weaving strategies to merge display capabilities into the textile itself[4,5]. Compared to the strict layer-by-layer deposition process of organic light-emitting diodes (OLEDs), it is simpler and more efficient to fabricate textile displays for large-scale displays. With integrations of multifunctional fibre/textile devices capable of energy supply, sensing and information processing, flexible electronic textile systems could be constructed to serve as human–machine interfaces.

Compared with textile displays, past display devices show difficulties in meeting the needs of special wearable applications. Cathode ray tube displays require a three-dimensional picture tube with vacuum space to allow the deflection of electrons (Fig. 2a). Such a bulk structure poses challenges in terms of not only poor image quality but also heavy weight and large size, thus largely limiting portability. Liquid-crystal displays revolutionize display technology by introducing a planar laminated structure (Fig. 2b), which is composed of a liquid-crystal layer sandwiched between transparent electrodes and polarizers[27,28]. By adjusting voltages on the liquid crystals, the brightness of each subpixel can be controlled to form images. This mechanism shift led to substantial improvements in weight reduction and overall size, making displays more portable and versatile. However, the use of backlight illumination makes liquid-crystal displays inflexible. OLEDs take display technology a big step further by replacing the liquid-crystal layer and polarizers of liquid-crystal displays with organic light-emitting materials, eliminating the need for complex colour filters and backlight equipment[29,30] (Fig. 2c). Despite the intricacies and demanding

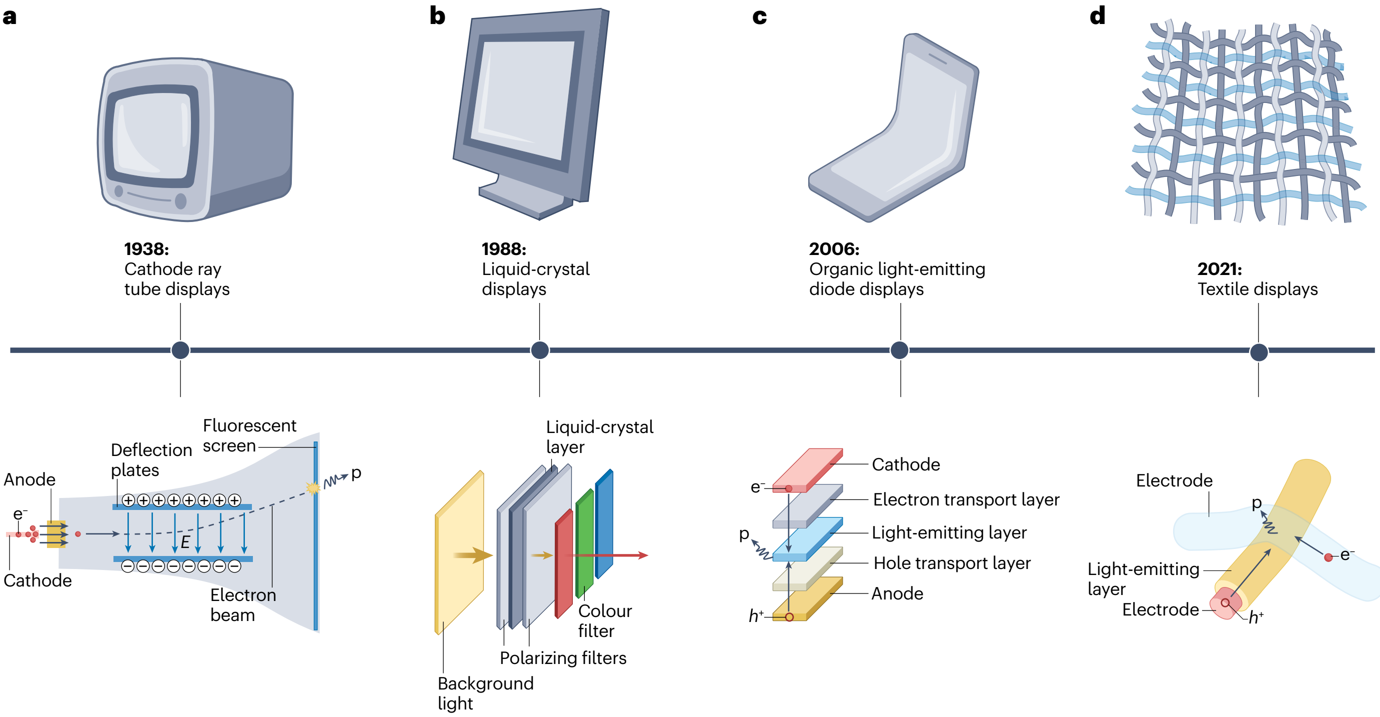

Fig. 2 | Evolution toward textile displays. The structure design of displays changes from three-dimensional bulks to two-dimensional films to meet the increasing requirements for flexibility. **a**, The structure and mechanism of cathode ray tube displays. **b**, The structure and mechanism of liquid-crystal displays. **c**, The structure and mechanism of organic light-emitting diodes. **d**, The structure and mechanism of textile displays. e^-, electron; p, proton.

interface requirements involved in the fabrication process of OLEDs, their continuous advances in image quality and energy efficiency have further augmented the capabilities of display technologies.

Such advances in display technology achieve several notable performance improvements. (1) Liquid-crystal displays and OLEDs have continuously improved image quality, colour reproduction, contrast ratio and energy efficiency compared to cathode ray tube displays. (2) With the integration of touch- and gesture-sensing functionalities, the inclusion of OLEDs and textile displays yields augmented interactivity, thereby fostering extraordinary user experiences and broader applicability. (3) The evolution from cathode ray tube displays to textile displays has substantially reduced the weight and size of displays, thus improving portability and wearability. Users can enjoy the benefits of display technology without the burden of bulky devices. (4) Textile displays offer unprecedented flexibility, similar to that of normal textiles, conforming to irregular shapes and enabling wearing comfort. Users can enjoy display functionalities seamlessly integrated into their garments or accessories. In particular, a user can directly engage with the display interface situated on their garments or other textile substrates for textile displays, providing opportunities for imaginative and captivating interactions.

Development of luminescent materials

Luminescent materials, which form the foundation for fabricating displays, have undergone substantial advances to meet diverse application requirements. It is challenging to integrate luminescent materials into textiles to realize wearable applications[31,32]. In addition to fundamental optoelectronic properties, luminescent materials must have favourable processability to facilitate high-throughput and even industrial-scale production of textile displays. Moreover, the fabricated luminescent material layer in light-emitting devices needs to be durable and reliable enough to withstand chafing and stretching during the weaving process. For practical wearable applications, the luminescent materials must also have chemical stability and mechanical flexibility. Extensive efforts have thus been spent to develop various textile displays by utilizing either organic or inorganic luminescent materials[33,34] (Table 1).

Organic luminescent materials with inherent flexibility have served to construct flexible displays, such as OLEDs and light-emitting electrochemical cells (LECs)[35]. OLED-based textile displays are typically fabricated by sequentially depositing multiple functional layers onto textile or fibre substrates, including metal electrodes, injection layers, transport layers and a luminescent layer[36]. When an external voltage is applied, charge carriers obtained at the two electrodes of OLEDs will be injected into the luminescent layer and recombine to emit light. Their electroluminescence performances are dictated by luminescent materials, such as fluorescent materials, phosphorescent heavy-metal complexes and thermally activated delayed fluorescence materials[37]. The fabricated textile displays realize notable advantages that are similar to those of OLEDs, including low operating voltage (<8 V), high luminous intensity (59,335 cd m^{-2}), high current efficiency (70.89 cd A^{-1}), long lifetime (720 h) and good flexibility (bending for 1,000 cycles)[38,39]. However, the physical vapour deposition process for OLED-based textile displays usually needs expensive and complex equipment to provide high-vacuum and high-temperature environments[40]. Moreover, the rough surfaces and deformations of textile substrates easily cause short circuits in displays because the functional layers between electrodes generally have thicknesses at the nanometre scale. To ensure optimal performance and longevity, encapsulation is essential for protecting OLEDs from the detrimental effects of oxygen and water vapours[39]. With the use of bilayer encapsulation consisted of inorganic and organic films, the optoelectronic characteristics of OLED-based textiles remain stable after immersion in water for 1,440 minutes[41]. However, the multi-layered encapsulation of luminescent materials may reduce the air permeability of textile displays, thus affecting the wearing comfort.

An alternative to OLEDs, LECs have been developed by adding mobile ions such as solid polymer electrolytes, ionic liquids and ionic transporters into the organic electroluminescent materials typically used in OLEDs[42]. With no need for multiple semiconductor layers, LECs have simplified configurations, of an active layer and two electrodes. This simplification allows LEC-based textile displays to be easily fabricated by low-cost and facile solution deposition processes over large areas[43]. Benefiting from the polymer matrix of the active layer and the air-stable thin metal electrodes, LEC-based textiles exhibit promising advantages over OLEDs, including flexibility, mechanical durability and chemical stability[44,45]. Without any encapsulating layer, LEC-based textiles showed stable luminescent performance after bending with a curvature radius of 5 mm for 100 cycles, and they could withstand ten cycles of washing with detergent and stirring[46]. Under an applied electric field, the mobile ions in LECs redistribute and form electrical double layers at the interfaces between the active layer and the electrodes. The electrical double layers thus formed lead to a remarkable drop in electric potential at the interfaces, reducing the injection barrier of charge carriers[47]. This phenomenon facilitates the injection of charge carriers from the electrodes, which subsequently recombine in the active layer to emit light[31]. Nevertheless, the slow ionic mobility in the displays inevitably gives rise to certain limitations, such as a long response time (21 minutes), low luminous intensity (609 cd m^{-2}), low current efficiency (0.83 cd A^{-1}) and relatively short operating lifetime (4 hours)[45,48].

Compared with organic materials, inorganic luminescent materials exhibit increased stability and processability, making them intrinsically suitable for textile displays. In particular, inorganic LEDs prevail over OLEDs in terms of luminous intensity (>10,000 cd m^{-2}) and lifetime (about 10 days)[49,50]. The core component in an LED is a high-quality semiconductor layer based on materials such as gallium nitride, indium gallium nitride and gallium arsenide phosphide, which are generally formed through epitaxial growth techniques. Subsequently, the semiconductor layer is doped to create a p–n junction within the crystal structure, where electrons and holes recombine to emit light under an electric field. Finally, LED-based textile displays are fabricated by transferring and embedding small-sized and rigid LEDs into fibres[49,51], exhibiting durability after 100,000 cycles of bending at a curvature radius of 2.5 mm, stretching at a strain of 10% and around 40 minutes of ordinary washing. However, such LED textiles suffer from limitations in realizing high-resolution, large-area textile displays, owing to the need for complex etching and assembly processes and the heavy weight and insufficient flexibility of LED fibres[52]. For large-scale production, a type of LED-based fibre was fabricated at a speed of 1.6 m per minute by thermal drawing[53].

Unlike the abovementioned current-driven devices, alternating-current electroluminescence devices (ACELs) are driven by an electric field thanks to their unique luminescent layer. The luminescent layer is created by dispersing phosphor materials into an insulating polymer matrix, simply sandwiched between two electrodes. Zinc sulphide has emerged as the most frequently used phosphor material in ACELs, which can emit various colours upon doping with elements such as aluminium, copper, manganese, silver and chlorine[54]. When a high voltage is applied, the electrons and holes tunnel through the ends of the doping units and become trapped by active sites within the phosphor matrix. Upon reversal of the electric field, these trapped electrons and holes undergo recombination, leading to light emission facilitated by bipolar field emission[55]. Therefore, the light emission in ACELs relies on spatial electric-field distribution at the working area rather than on the carrier injection and transport process. This intrinsic characteristic enables ACELs with enhanced durability to be produced, making them an attractive option for fabricating textile displays[56,57]. ACEL-based fibres can be readily manufactured at large scale by continuously dip-coating luminescent slurry onto fibre substrates at a production speed of 10 m per minute. ACEL-based textile displays have exhibited stable luminous performances after 1,000 cycles of bending, stretching and pressing, 10,000 cycles of folding and 100 cycles of accelerated industrial washing. Although ACELs fulfil the production requirements of stability and scalability, their high operating voltages (>100 V) and low brightness (about 100 cd m^{-2}) restrict their wearable applications in outdoor scenarios (>1,000 cd m^{-2})[4,58].

Thus each luminescent material employed in textile displays shows distinctive strengths and weaknesses. Further research is needed to overcome material-related limitations and to fulfil the aesthetic and functional demands of practical applications. On the one hand, advances in luminescent materials should focus on improving display performance, such as enhancing power efficiency to reduce energy consumption, reducing operating voltage to ensure safety and developing effective encapsulation techniques to prolong the lifespan of

Table 1 | Performances of textile displays based on different luminescent materials

Textile display	OLED-based textile display[38,39,41]	LEC-based textile display[45,46,48]	LED-based textile display[49,50,53]	ACEL-based textile display[4,58]
Deposition techniques	Vacuum deposition, dip coating	Dip coating, extrusion	Thermal drawing, microfabrication	Dip coating, extrusion
Brightness	High (>1,000 cd m^{-2})	Medium (500–1,000 cd m^{-2})	High (>10,000 cd m^{-2})	Low (<300 cd m^{-2})
Working voltage	Medium (5–10 V)	Medium (5–20 V)	Low (<5 V)	High (>100 V)
Bendability	Medium (1,000 cycles with a radius of 3.5 mm)	Low (100 cycles with a radius of 5 mm)	High (100,000 cycles with a radius of 2.5 mm)	Medium (1,000 cycles with a radius of 4 mm)
Washability	Low (1,440 min of immersing)	Medium (10 cycles with detergent and stirring)	Medium (40 min of ordinary washing)	High (100 cycles of accelerated washing)

ACEL, alternating-current electroluminescence device; LEC, light-emitting electrochemical cell; LED, organic light-emitting diode; OLED, organic light-emitting diode.

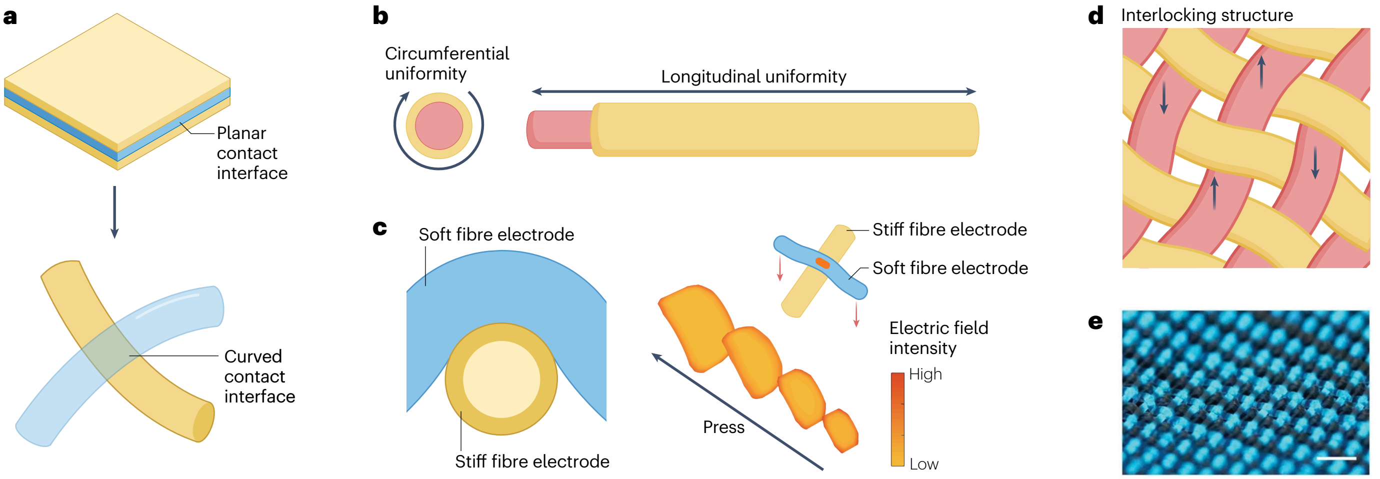

Fig. 3 | Design of effective interfaces. a, Diagram of distinguished contact interfaces from planar to textile displays. **b**, Uniform luminescent layer, substantially enhancing interfacial contact and stability between fibre electrodes. **c**, Mechanical and electrical matching between fibre electrodes, improving the stability of interfacial contact and carrier transport efficiency. **d**, Plain-weave fibre electrodes with interlocking structure offering uniform contact interfaces among multiple electroluminescent units. **e**, Photograph of electroluminescent units with uniform luminance in a plain-weave textile display. Scale bar, 2 mm. Panels **c** and **e** are reproduced from ref. 4, Springer Nature Limited.

displays[59]. The encapsulation process is also essential to ensure the stability of textile displays in complex environment like daily washing with detergents and mechanical frictions[41]. On the other hand, alternative luminescent materials should be synthesized to meet the high-resolution and full-colour requirements of textile displays[60]. Concurrently, efforts should be devoted towards optimizing fabrication techniques suitable for different-shaped fibres in the textile displays[61,62]. For flat fibres, the deposition and electrical connection methods are similar to that of planar displays[14], and the resultant textile displays generally exhibit comparable light-emission efficiency with planar displays. Textile displays woven from round fibres have good wearability, but the light-emission efficiency is relatively low. Alternative fabrication methods, including micro-pinhole dip coating[4], electric-field-assisted assembly[63] and vapour deposition by axial-rotated equipment[40], will be needed to achieve high-quality luminescent films. Patterning technologies based on rotating lithography[64] and three-dimensional masking[65] will help to improve efficiency by optimizing light-emission direction and the area at the contact point between round fibres.

Design of effective interfaces

The reliable operation of displays depends on efficient electrical connection and uniform electric-field distribution at the interfaces, so it is critical to design effective interfaces among the functional layers during preparations and applications (Fig. 3). For textile displays fabricated by attaching thin-film display units onto a textile, the design of effective interfaces among different layers follows similar principles to that of planar devices[41]. For textile displays fabricated by interweaving optoelectronic fibres, it is challenging to realize a stable interface between the interwoven area and the curved surface[44]. In textile displays having distinct curved configurations it is more challenging to achieve effective interfaces than in conventional displays having planar multilayered structures[66] (Fig. 3a). Methods that are widely used in planar devices, such as physical vapour deposition, chemical vapour deposition and spin coating, can rarely be adapted to incorporate one-dimensional fibres with highly curved surfaces to obtain high-quality interfaces, because active materials tend to partially aggregate or are sparse on uneven surfaces of fibre substrates, easily resulting in rough films and inefficient contacts[67]. Additionally, the contact interfaces among functional films in textile displays should be robust enough to withstand mechanical deformations during production and use. Therefore, textile displays crafted by weaving luminescent fibres together with transparent conductive fibres need effective interfaces at each interwoven working point.

For luminescent fibres, it is important to design robust and reasonable interfaces to enhance the performance of textile displays. To avoid interface breakages under deformation, it is essential to consider mechanical compatibility between electrode fibres and luminescent layers, including factors such as flexibility, modulus and thermal expansion coefficient[68]. Simultaneously, the bonding strengths at the interfaces can also be improved by surface treatments[69], by post-processing and by introducing transition layers[70]. Furthermore, materials with optimal electronic properties should be selected to facilitate charge transport through the comparison of conductivity, work function, Fermi level and dielectric constant[71]. Uniform luminescent layers could enhance interfacial contact and stability between fibre electrodes (Fig. 3b). Aside from identifying appropriate materials, it is also important to construct luminescent composite fibres with high-quality interfaces by using tailored techniques such as micropinhole coating[4], melt extrusion coating[72] and electric-field-assisted assembly[63]. These techniques can also be employed for the continuous and precise deposition of multilayer structures on hundred-metre-long fibres, simply by adjusting the precursor composition, deposition speed and environmental conditions in the manufacturing processes.

For transparent conductive fibres, it is imperative to simultaneously satisfy the requirements of light transmission and electrical conductivity (Fig. 3c). On the one hand, the materials selected for transparent conductive fibre electrodes should possess optimal electrical properties similar to those of luminescent fibre electrodes to achieve electrical compatibility. On the other hand, because a conductive fibre electrode needs to be placed upon the luminescent fibre electrode in textile displays, its transparency can affect the luminescent brightness and colours of each display unit[2]. Therefore, obtaining electrodes with excellent transparency without compromising conductivity is of increasing importance to satisfy the requirements of electroluminescent applications. Typically, the transparent conductive fibres should have low electrical sheet resistance (<10–20 Ω per square) and high optical transparency (>90%)[73]. The materials widely utilized for constructing transparent conductive fibre electrodes include transparent conducting oxides[74], conducting polymers[75], carbon-based materials[76], metal nanowires and nanoparticle materials[77]. Furthermore, the design of fibres with different cross-sectional shapes (such as round, oval and rectangular) can further mitigate light-propagation losses during reflection, refraction and scattering processes[78].

Considering textile displays, transparent conductive fibres are designed to be elastic and deformable to conform to the highly curved surfaces of luminescent fibres, enabling effective interfaces at each interlaced point (Fig. 3d). Thus, the contact point in interlaced fibres forms a uniform electric field and enables efficient carrier transport similar to that in planar devices, as has been verified by both experiments and theoretical studies[79] (Fig. 3e). For practical applications of textile displays, it is essential to establish stable and reliable electrical contacts at each weft–warp contact point, even under deformations such as bending, stretching and twisting. Therefore, textile displays with high-density and interlocking structures could be created by the plain-weave method, ensuring the functionality and reliability of each luminescent unit in the whole display[80]. Using this method, the production of a large-area textile display containing approximately 5×10^5 luminescent units was achieved with relative deviations in emission intensity of less than 8%[4]. This remarkable consistency has been attributed to the uniform distribution of loading and strain at each interwoven point.

More efforts should focus on the integration of emerging textile displays with traditional textile industries to enhance interface functionality and effectiveness in the future[17]. Exploring fibres with various structures—such as polygonal fibres, flat fibres, patterned fibres and hierarchical assemblies of multiple fibres—offers great potential in customizing the interface morphologies at contact points[81]. The interlacing patterns can be adjusted by optimizing contact interfaces by plain weave (crossing the warp fibre over and under the weft fibres), twill weave (interweaving the warp fibre over and under multiple weft fibres in a regular progression), jacquard weave (lifting the warp or weft fibres according to typical patterns) and satin weave (floating the warp fibre over multiple weft fibres before interlacing)[82,83]. These weaving methods endow textile displays with different performance levels. For instance, textile displays based on plain weave offer enhanced durability thanks to their compact and interlocking structure, whereas those based on satin weave exhibit good stretchability and breathability[84,85]. When subjected to harsh working conditions, maintaining effective and reliable interfaces in textile displays remains a great challenge, and the encapsulation of individual luminescent units might provide a viable solution to this challenge[86].

Advances in textile display modules

A necessity in daily life, textiles offer natural advantages in the field of human–computer interaction[4,87]. A textile mainly comprises flexible fibres that interlock to form a network[88], simultaneously giving the textile high air permeability, comfort and durability while conforming well to the human body[89]. Existing display devices are typically composed of bulk or planar display devices, which tend not to meet the requirements of wearable devices that could comfortably and dynamically fit over human skin. The seamless integration of displays with textiles could effectively address the above issues.

The simplest method of producing flexible textile displays is to directly fabricate planar LEDs (Fig. 4a) onto textile substrates[90,91] (Fig. 4b). Both organic and inorganic thin-film LEDs have been widely explored. OLEDs require the substrate to be very flat. To this end, it is valuable to apply a polymer buffer layer onto rough textile surfaces through techniques such as hot pressing or ultraviolet photopolymerization. This approach creates a flat surface with nanoscale roughness, enabling the fabrication of high-performance textile displays that exhibit comparable properties to thin-film OLEDs. Alternating-current inorganic LEDs require less stringent flatness for the substrate[53,92]. Elastic conductive textile substrates can be directly gold-plated, and a uniform zinc sulphide luminescent layer can be subsequently prepared through techniques such as painting or printing. Transparent electrodes, such as silver nanowires, poly(3,4-ethylenedioxythiophene)/poly(styrene sulfonate) (PEDOT:PSS) conductive polymers or ionic liquid conductive gels, are incorporated into the top layer to fabricate alternating textile displays with favourable stretching properties. Although their overall luminous performances are comparable to those of their planar thin-film counterparts, they suffer from limited gas permeability and the challenges associated with continuous mass production. Importantly, the modulus mismatch between thin-film displays and textile substrates can lead to membrane layer ruptures, easily resulting in performance degradation and even device failure (Fig. 4c).

Textiles predominantly consist of fibres that are interwoven with each other[88] (Fig. 4d). The abovementioned textile module largely relies on the preparation method of planar displays, which fails to adequately prioritize the structural characteristics of textiles. Therefore, another potential way to achieve textile displays is to directly weave light-emitting fibres into textiles as displays[19,38,44,56,93,94] (Fig. 4e). Both organic LEDs[38,44,93,94] and inorganic alternating-current LEDs[19,56] have been made for light-emitting fibres. Consequently, the integration of light-emitting fibres into textiles can be accomplished through sewing and embroidery, which allows for the creation of diverse display patterns (Fig. 4f). These light-emitting fibres can be consistently manufactured and possess favourable attributes such as resistance to abrasion, bending and washing after being woven into textiles[19,56]. However, such textile displays based on light-emitting fibres can present only predesigned patterns, making it difficult to use them as human–computer interaction platforms. Although dynamic image playback can be partially realized in these systems through the implementation of advanced circuits or the direct utilization of LED strips, the rigid packaging and loose distribution of LEDs result in not only poor performance, such as low image resolution and inability to play videos, but also poor flexibility and heavy weight.

A planar display entails a dynamic display functionality by providing rows and columns of electrical signals to control the programmed illumination of individual microlight-emitting units, referred to as display pixels. Textiles made by weaving methods inherently have thousands of warp–weft interwoven points[88] (Fig. 4h). Textiles can withstand complex deformations and offer breathability by appropriate control of weaving process, fibre thickness and distance between fibres[89]. A dynamic pixel display can be realized in a flexible and breathable textile form, where microluminescent units are built at these warp–weft interwoven points (Fig. 4i). For instance, such displays highly integrated with textiles have been created by interweaving warp yarns loaded with alternating-current electroluminescent slurry with

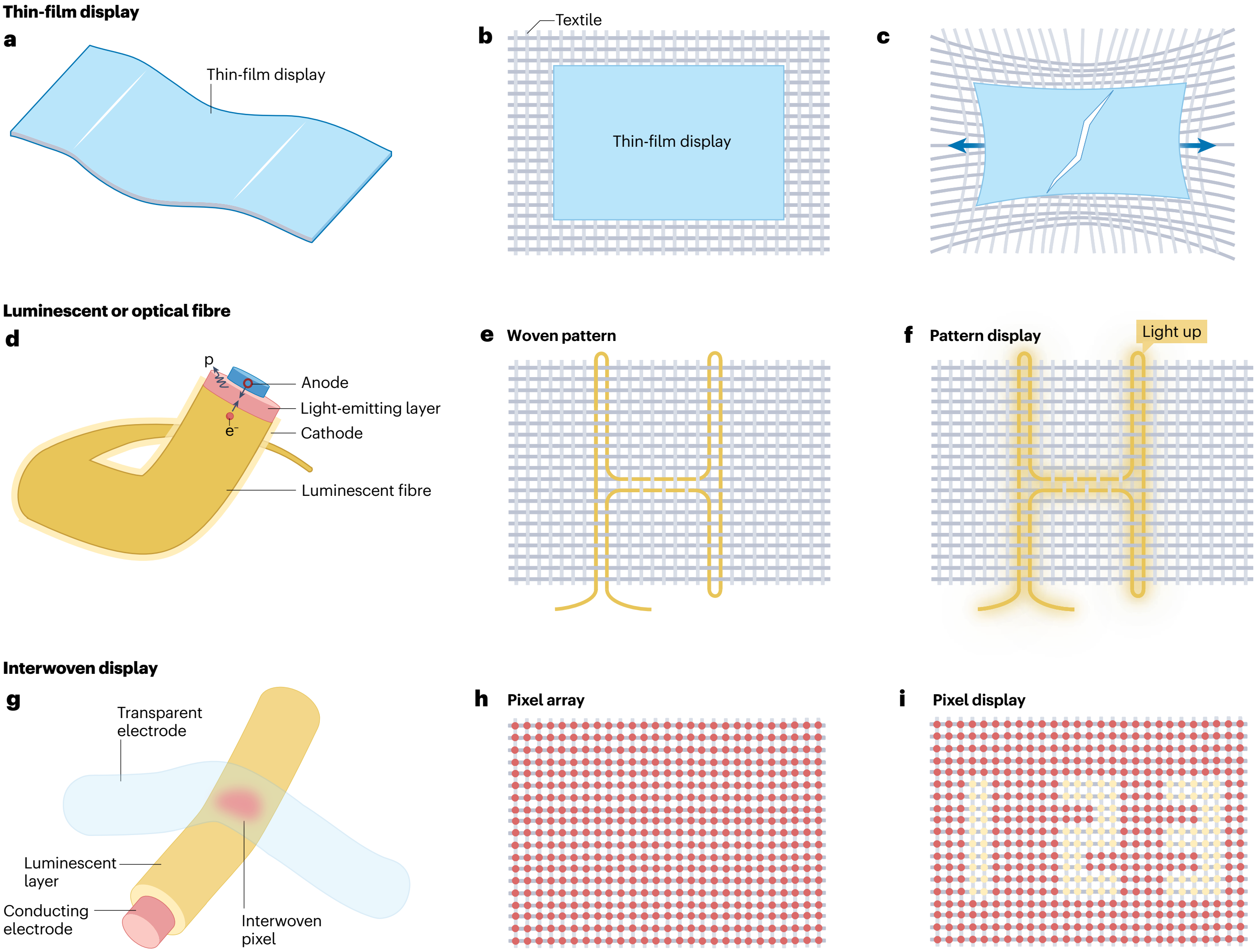

Fig. 4 | Advances in display modules. a, Thin-film displays. **b**, Textile display realized by attaching a thin-film display to a textile. **c**, Performance failure of attached thin-film display on textile after deformation. **d**, Luminescent or optical fibres. **e**, Textile display realized by weaving luminescent or optical fibres into a textile. **f**, Pattern display realized by a pre-woven pattern of luminescent fibres. **g**, Interwoven display pixels. **h**, Textile display realized by interwoven display pixels. **i**, Pixel display capable of showing arbitrary input patterns.

transparent conductive fibres as the weft yarns[4,5]. By incorporation of ionic liquids into transparent elastic polymers and subsequent use of melt spinning, low-modulus elastic transparent conductive fibres were obtained. In these interwoven interfaces, warp and weft fibre electrodes produced tight contacts, thereby generating a uniform electric field between them. Consequently, stable light-emitting pixel units are formed at the warp and weft intertwined points (Fig. 4g). This method relies on a continuous fibre preparation process and a continuous weaving process, enabling the light-emitting units to emit light uniformly and making them programmable for dynamic displays through microelectronic circuit designs. Moreover, fabricating these displays into textiles can enable integration with an energy supply, sensing module, wireless communication system and other functional devices, facilitating the development of smart textile systems as wearable human–computer interaction platforms.

Although such display textiles made by weaving methods already integrate well with textiles, substantial changes in the contact area and interwoven position between two fibre electrodes still exist in daily use. The success of stable textile displays through the physical contact of two fibre electrodes is enabled by the relatively low interfacial requirements for alternating-current light-emitting systems. However, an alternating-current light-emitting system necessitates both high driving voltage and frequency, causing difficulties in the design and integration of driver modules in textiles. A passive matrix drive is typically used, because alternating-current luminous materials require a high driving voltage (several hundred volts). Active drive technology is urgently desired to improve the refresh rates of textile displays for high-quality image or video playing. The washability of textile displays is another important issue that should be addressed. The textile display based on interweaving method could withstand 100 cycles of accelerated washing, but the washability of the ones in other display modules has not been carefully evaluated as yet. Consequently, there remains a need for further optimization of display modules before textile displays can meet commercial demands. For direct-current luminescent systems, it is necessary to focus on addressing these interface issues in display modules. For alternating-current luminescent systems, the design and improvement of driving circuits have become increasingly important topics. A display module that integrates well with the textile and ensures more efficient and stable display performance will substantially advance textile display technology, particularly for daily use.

Integration into textile systems

Integrating textile displays into electronic textile systems could revolutionize the paradigms of human–machine interaction. However, designing effective assembly strategies in textile systems remains challenging[17].

A seamless integration of display devices and driving modules is paramount in constructing textile display systems, whether driven by passive-matrix or active-matrix technologies[95]. Passive-matrix driving modules possess intrinsic cross-bar configurations that are compatible with woven structures in textiles, making them highly suitable for applications in textile display systems. An initial endeavour was undertaken by interconnecting all conductive wefts and luminescent warps within the textile display to the display driver and then transmitting the electrical signals row by row onto the display array to generate the image[4]. Although passive-matrix driving modules have the benefits of simple circuit structures and low energy consumption, they can only meet the demands for binary, greyscale and low-resolution displays. Toward realizing high-resolution and full-colour displays, active-matrix driving modules have been introduced into textile display systems by integrating information-processing devices such as fibre field-effect transistors, wire electrochemical transistors and fibre memristors[96–98]. These information-processing devices can be seamlessly incorporated into textile displays to enhance the functionality of displays through advanced fabrication techniques such as cylindrical projection lithography, coaxial fibre drawing and fibre blending processes[64,99]. For example, the luminance of fibre LEDs has been modulated by adjusting the gate voltage of fibre transistors connected with them at the system level because their anodes were connected with the source electrodes of fibre transistors[100]. Furthermore, an alternative circuit configuration was employed by equipping every eight fibre LEDs with a dedicated controller to achieve up to 700 pixels of display by connecting two power lines and one data line[52]. In conclusion, the implementation of controllable and dynamic textile displays necessitates the integration of an individual processing device or microcontroller for each luminescent unit, unavoidably contributing to circuit complexity. Simultaneously, the efficient encapsulation of these devices is critical to ensure the overall working reliability of active-matrix driving systems.

Like any electronic equipment, electronic textile display systems should also be accomplished by incorporating diverse electronic components (Fig. 1a). Recently, increasing attention has been given to the field of multifunctional fibre devices, such as energy harvesting, energy storage, sensing and data processing[98,101]. Specifically, energy-harvesting fibre devices can be woven to collect energy from the environment and human body to realize self-powered wearables, such as photovoltaic, piezoelectric, triboelectric, thermoelectric and water-to-electricity generators[7,102]. Energy-storage fibre devices can be integrated to serve as stable and continuous energy supplies, including capacitors and batteries[87]. Sensing fibre devices are expected to provide real-time environment detection and personalized health management by monitoring various physical and chemical signals[103]. Data-processing fibre devices have been harnessed to form lose-loop functional systems, facilitating practical applications in different scenarios such as artificial intelligence, personal healthcare and human–machine interaction[96].

The design of conductive circuits is also necessary to electrically connect these distinctive single-functional fibre/textile devices (Fig. 1b). Similar to traditional planar technologies, conductive lines can be precisely patterned onto textile substrates by three-dimensional printing, screen printing and inkjet printing[104]. Inspired by techniques used in the mature textile industry, conductive yarns with appropriate diameters have also been selected as conductive lines to be co-woven into textile circuits by double lock stitches, suitable for large-scale assembly[105]. Nonetheless, the integration of numerous electronic devices in textile systems usually causes high-density and complex circuit connections, which compromises the flexibility, comfort and reliability of the systems. To overcome this challenge, electronic fibre platforms, near-sensor and in-sensor microchips and wireless technologies are being studied. Specifically, electronic fibre platforms could be fabricated by integrating multifunctional electronic components and complex circuits into fibres for high-density and scalable electronic textile systems. Moreover, near-sensor and in-sensor microchips can be strategically positioned close to or inside each sensing network terminal to preprocess redundant data[106]. The extracted information can then be efficiently transmitted to the central processing unit via a single bus line to enhance the overall system efficiency[52]. To further simplify the complexity of textile circuits, wireless technologies such as passive radiofrequency identification, active radiofrequency identification, Bluetooth and WiFi in wireless local area networks can also be employed to directly transmit signals to local processors or cloud-based systems[50,107].

Challenges and opportunities

The emergence of textile displays represents a substantial advance in the field of display technologies and might lead to new era of visual communication. However, the practical application of textile displays is currently impeded by several unresolved challenges, including difficulties in achieving full-colour displays, high display resolution, small refresh delay and high integration level. We critically analyse these bottlenecks and propose potential solutions (Fig. 5).

First, the development of high-performance luminescent materials and robust device structures promises to enhance the performance of textile displays. The predicament lies in the concurrent enhancement of contrast, colour gamut and resolution while concurrently guaranteeing continuous fabrication and reliable operation in diverse applications. For instance, the integration of quantum dot technology into textile substrates might enable vibrant and high-resolution colour displays[108–110]. By harnessing the unique optical properties of quantum dots, such as narrow emission spectra and excellent colour purity, textile displays can achieve a wider colour gamut and improved colour accuracy. Simultaneously, the optimization of fibre and textile structures can greatly enhance the resolution of displays. Increasing the fineness of fibres and intensifying the density of weaving structures can efficiently yield higher display resolutions. Unlike traditional active displays, passive displays endow textile displays with attractive features such as low power consumption and natural light reflection[111–113]. However, passive textile displays with satisfactory lifetime and process scalability have not yet been produced. The development of fibrous driving circuit boards could be a possible solution for improving textile lifetime, thanks to morphological unity and modulus matching. Meanwhile, the existing continuous scratch-coating lines used for fibres could be used to encapsulate the driving module. Addressing these concerns will help to unlock the potential of passive textile displays and pave the way for their interactive applications in wearables.

Second, the development of textile driving systems and microscale-to-nanoscale integration methods constitutes a pivotal strategy for overcoming the existing limitations in refresh rates and integration levels in textile displays. Techniques such as conductive yarns, printed electronics and flexible circuits have enabled the creation of smart textiles with embedded display functionalities. In future, enhanced automation of flexible circuit interconnections, advances in photolithography techniques for intricate surface topographies, and innovative approaches in microscale-to-nanoscale assembly will synergistically propel the convergence of structural and functional dimensions within textile electronic systems. For example, the fabrication of microscale or nanoscale devices on fibres such as sensors and driving systems will allow closed-loop functionality of sensing–processing displays within a flexible fibre, which might greatly enhance the functionality of wearables[114]. Additionally, the contact points in the textile tend to deform to a certain extent when the textile is pressed, twisted or stretched, thus causing uneven changes in display brightness. Elastic weaving methods like knitting could effectively address this issue.

Finally, the development of continuous production technologies is pivotal to ensuring the practical application of textile displays. Continuous manufacturing processes, such as fibre extrusion or spinning, roll-to-roll printing and inkjet printing, enable the cost-effective and efficient production of large-scale textile displays with consistent performances[53,115–118]. These production techniques enhance product homogeneity, reduce average production costs, and establish a foundation for the future integration of textile display products into daily life. The development of flexible and light-weight encapsulation materials during continuous production is also an effective way to enhance durability. Undoubtedly, further enhancing the safety of textile displays during use warrants the utmost consideration. The utilization of materials with high biocompatibility will ensure that the devices operate within the established safe voltage range for humans and will augments the stability and durability of the devices under diverse environmental conditions. All these are areas of optimization for the future integration of textile displays into daily life.

As one of the important technical indicators of displays, the current resolution of textile displays (30–50 pixels per inch) can meet

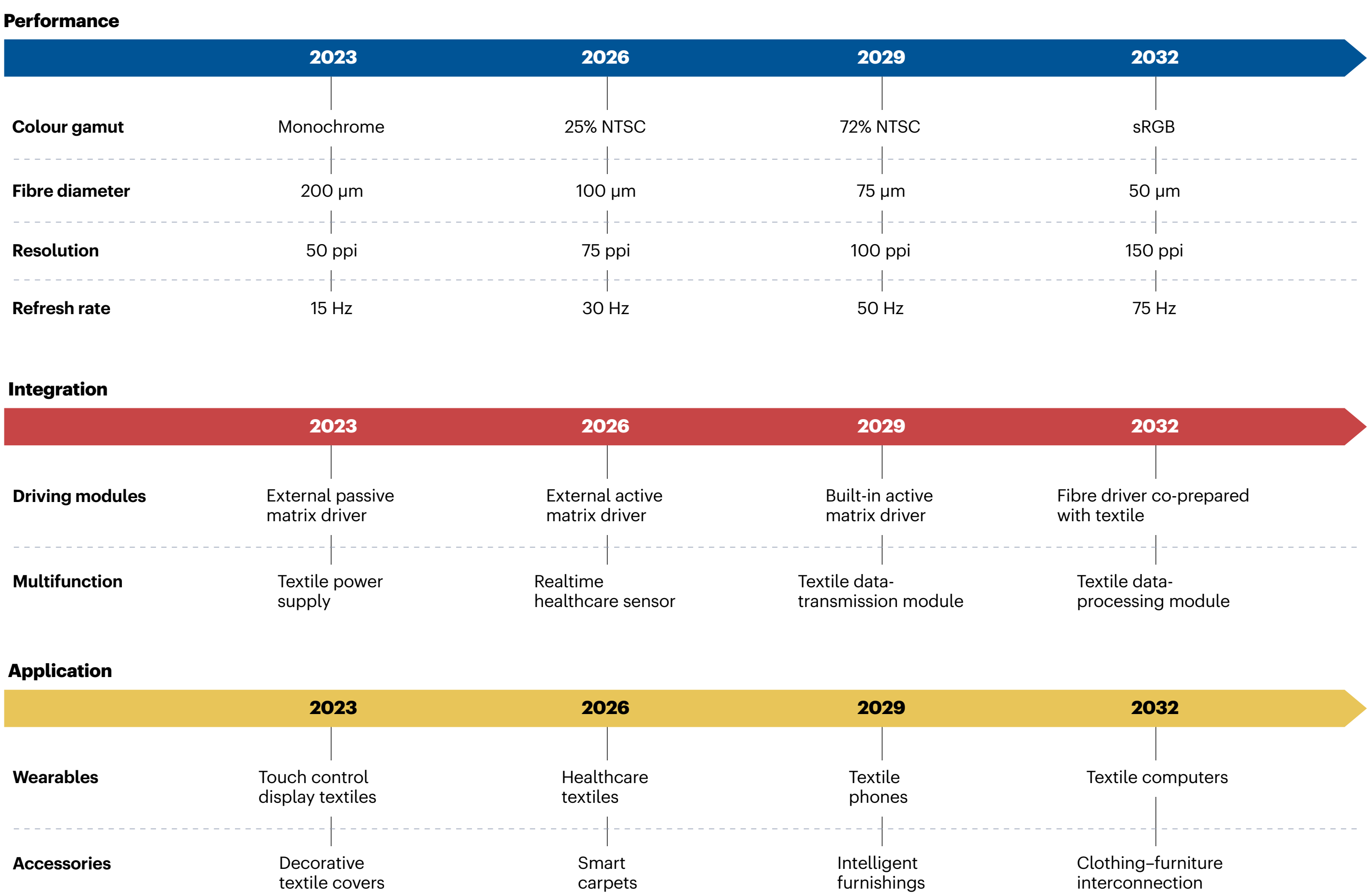

Fig. 5 | Roadmap to realizing display textiles within ten years. Research in high-performance luminescent materials, novel textile driving systems and interdisciplinary applications are all crucial steps toward the practical applications of textile displays. This emerging field requires joint efforts from these distinct domains to explore the possibilities and optimize the performance of textile displays. NTSC, National Television Standards Committee; sRGB, standard red green blue; ppi, pixels per inch.

the basic requirement for text displays. In contrast, a higher image resolution (100 pixels per inch) is required for image display applications. Because an alternating-current luminous system requires a high driving voltage (several hundred volts), a passive matrix drive is typically used. The development of active drive technology is expected to improve the refresh rate of textile displays (30 Hz) for high-quality video. Meanwhile, with the further demand for full-colour displays, the colour gamut of textile displays is expected to reach 72% NTSC—the colour gamut standard of the National Television Standards Committee—with the improvement of colour purity of monochromatic luminous materials and the optimization of multi-pixel weaving methods.

In conclusion, although textile displays have great potential, there are still several bottlenecks that need to be addressed. The use of high-performance luminescent materials, the development of novel textile driving systems and microscale-to-nanoscale integration methods, the development of continuous production processes, the assurance of wearing safety and the exploration of interdisciplinary applications are all crucial steps towards realizing practical applications of textile displays. This emerging field requires collaborations between these distinct domains to explore the possibilities and optimize the performance of textile displays. Achieving this integration will not only lead to advances in display technology but will also contribute to the evolution of smart textiles, where functionality and aesthetics converge (Fig. 5).

Published online: 28 June 2024

References

1. Larson, C. et al. Highly stretchable electroluminescent skin for optical signaling and tactile sensing. *Science* **351**, 1071–1074 (2016).
2. Tan, Y. J. et al. A transparent, self-healing and high-κ dielectric for low-field-emission stretchable optoelectronics. *Nat. Mater.* **19**, 182–188 (2020).
3. Koo, J. H., Kim, D. C., Shim, H. J., Kim, T. H. & Kim, D. H. Flexible and stretchable smart display: materials, fabrication, device design, and system integration. *Adv. Funct. Mater.* **28**, 1801834 (2018).
4. Shi, X. et al. Large-area display textiles integrated with functional systems. *Nature* **591**, 240–245 (2021).
5. Shi, X., Chen, P. & Peng, H. Making large-scale, functional, electronic textiles. *Nature* **591**, 240–245 (2021).
6. Tian, X. et al. Wireless body sensor networks based on metamaterial textiles. *Nat. Electron.* **2**, 243–251 (2019).
7. Chen, G. R., Li, Y. Z., Bick, M. & Chen, J. Smart textiles for electricity generation. *Chem. Rev.* **120**, 3668–3720 (2020).
8. Weng, W., Chen, P. N., He, S. S., Sun, X. M. & Peng, H. S. Smart electronic textiles. *Angew. Chem. Int. Edn* **55**, 6140–6169 (2016).
9. Carey, T. et al. Fully inkjet-printed two-dimensional material field-effect heterojunctions for wearable and textile electronics. *Nat. Commun.* **8**, 1202 (2017).
10. Neubrech, F., Duan, X. & Liu, N. Dynamic plasmonic color generation enabled by functional materials. *Sci. Adv.* **6**, eabc2709 (2020).
11. He, Q. et al. P–N junction-based ZnO wearable textile nanogenerator for biomechanical energy harvesting. *Nano Energy* **85**, 105938 (2021).
12. Chen, C. et al. Functional fiber materials to smart fiber devices. *Chem. Rev.* **123**, 613–662 (2023).
13. Zhang, W. et al. A single-pixel RGB device in a colorful alphanumeric electrofluorochromic display. *Adv. Mater.* **32**, 2003121 (2020).
14. Song, Y. J. et al. Fibertronic organic light-emitting diodes toward fully addressable, environmentally robust, wearable displays. *ACS Nano* **14**, 1133–1140 (2020).
15. Pan, Y. et al. Recent advances in alternating current-driven organic light-emitting devices. *Adv. Mater.* **29**, 1701441 (2017).
16. Levitt, A. et al. MXene-based fibers, yarns, and fabrics for wearable energy storage devices. *Adv. Funct. Mater.* **30**, 2000739 (2020).
17. Zeng, K. et al. Design, fabrication and assembly considerations for electronic systems made of fibre devices. *Nat. Rev. Mater.* **8**, 552–561 (2023).
18. Song, J., Lee, H., Jeong, E. G., Choi, K. C. & Yoo, S. Organic light-emitting diodes: pushing toward the limits and beyond. *Adv. Mater.* **32**, 1907539 (2020).
19. Zhang, Z. et al. Textile display for electronic and brain-interfaced communications. *Adv. Mater.* **30**, 1800323 (2018).
20. Müller-Putz, G. R., Riedl, R. & Wriessnegger, S. C. Electroencephalography (EEG) as a research tool in the information systems discipline: foundations, measurement, and applications. *Commun. Assoc. Inform. Syst.* **37**, 912–948 (2015).
21. Perkel, J. The internet of things comes to the lab. *Nature* **542**, 125–126 (2017).
22. Yang, Y. Multi-tier computing networks for intelligent IoT. *Nat. Electron.* **2**, 4–5 (2019).
23. LITME Smart Fiber. Applications. *Tayho* http://en.tayho.com.cn/product/Applications5.htm (2023).
24. Macedonia, M. It's the end of the tube as we know it. *Computer* **39**, 83–85 (2006).
25. Normile, D. Field emitters finding home in electronics. *Science* **281**, 632–633 (1998).
26. Son, D. et al. An integrated self-healable electronic skin system fabricated via dynamic reconstruction of a nanostructured conducting network. *Nat. Nanotech.* **13**, 1057–1065 (2018).
27. Ji, Y., Fan, F., Zhang, Z., Cheng, J. & Chang, S. Active terahertz liquid crystal device with carbon nanotube film as both alignment layer and transparent electrodes. *Carbon* **190**, 376e383 (2022).
28. Penterman, R. et al. Single-substrate liquid-crystal displays by photo-enforced stratification. *Nature* **417**, 55–58 (2002).
29. Yoshida, K. et al. Electrically driven organic laser using integrated OLED pumping. *Nature* **621**, 746–752 (2023).
30. Fusella, M. A. et al. Plasmonic enhancement of stability and brightness in organic light-emitting devices. *Nature* **585**, 379–382 (2020).
31. Kwon, S. et al. Recent progress of fiber shaped lighting devices for smart display applications — a fibertronic perspective. *Adv. Mater.* **32**, 1903488 (2020).
32. Huang, Y., Hsiang, E. L., Deng, M. Y. & Wu, S. T. Mini-LED, micro-LED and OLED displays: present status and future perspectives. *Light Sci. Appl.* **9**, 105 (2020).
33. Cinquino, M. et al. Light-emitting textiles: device architectures, working principles, and applications. *Micromachines* **12**, 652 (2021).
34. Cho, S., Chang, T., Yu, T. & Lee, C. H. Smart electronic textiles for wearable sensing and display. *Biosensors* **12**, 222 (2022).
35. Liu, Y., Feng, J., Bi, Y., Yin, D. & Sun, H. Recent developments in flexible organic light-emitting devices. *Adv. Mater. Technol.* **4**, 1800371 (2019).
36. Yin, D. et al. Highly flexible fabric-based organic light-emitting devices for conformal wearable displays. *Adv. Mater. Technol.* **5**, 1900942 (2020).
37. Hong, G. et al. A brief history of OLEDs — emitter development and industry milestones. *Adv. Mater.* **33**, 2005630 (2021).
38. Hwang, Y. H. et al. Bright-multicolor, highly efficient, and addressable phosphorescent organic light-emitting fibres: toward wearable textile information displays. *Adv. Funct. Mater.* **31**, 2009336 (2021).
39. Kong, S. U. et al. Anode-patterned monorail-structure fiber-based organic light-emitting diodes with long lifetime and high performance for truly wearable displays. *Adv. Opt. Mater.* **11**, 2203130 (2023).
40. O'Connor, B., An, K. H., Zhao, Y., Pipe, K. P. & Shtein, M. Fiber shaped organic light emitting device. *Adv. Mater.* **19**, 3897–3900 (2007).
41. Jeong, S. Y. et al. Foldable and washable textile-based OLEDs with a multi-functional near-room-temperature encapsulation layer for smart e-textiles. *npj Flex. Electron.* **5**, 15 (2021).
42. Scholz, S., Kondakov, D., Lüssem, B. & Leo, K. Degradation mechanisms and reactions in organic light-emitting devices. *Chem. Rev.* **115**, 8449–8503 (2015).
43. Pei, Q., Yu, G., Zhang, C., Yang, Y. & Heeger, A. J. Polymer light-emitting electrochemical cells. *Science* **269**, 1086–1088 (1995).
44. Zhang, Z. et al. A colour-tunable, weavable fibre-shaped polymer light-emitting electrochemical cell. *Nat. Photon.* **9**, 233–238 (2015).
45. Yang, H., Lightner, C. R. & Dong, L. Light-emitting coaxial nanofibers. *ACS Nano* **6**, 622–628 (2012).
46. Lee, S. et al. Water washable and flexible light-emitting fibers based on electrochemiluminescent Gels. *ACS Appl. Mater. Interf.* **14**, 17709–17718 (2022).
47. Costa, R. D. et al. Luminescent ionic transition-metal complexes for light-emitting electrochemical cells. *Angew. Chem. Int. Edn* **51**, 8178–8211 (2012).
48. Yang, Z. & Su, H. Recent advances in optical engineering of light-emitting electrochemical cells. *Adv. Funct. Mater.* **30**, 1906788 (2020).
49. Cherenack, K., Zysset, C., Kinkeldei, T., Münzenrieder, N. & Tröster, G. Woven electronic fibers with sensing and display functions for smart textiles. *Adv. Mater.* **22**, 5178–5182 (2010).
50. Lee, H. E. et al. Wireless powered wearable micro light-emitting diodes. *Nano Energy* **55**, 454–462 (2019).
51. Nashed, M. N., Hardy, D. A., Hughes-Riley, T. & Dias, T. A novel method for embedding semiconductor dies within textile yarn to create electronic textiles. *Fibers* **7**, 12 (2019).
52. Choi, H. W. et al. Smart textile lighting/display system with multifunctional fibre devices for large scale smart home and IoT applications. *Nat. Commun.* **13**, 814 (2022).
53. Rein, M. et al. Diode fibres for fabric-based optical communications. *Nature* **560**, 214–218 (2018).
54. Yang, Z., Wang, W., Pan, J. & Ye, C. Alternating current electroluminescent devices with inorganic phosphors for deformable displays. *Cell Rep. Phys. Sci.* **1**, 100213 (2020).
55. Li, S., Peele, B. N., Larson, C. M., Zhao, H. & Shepherd, R. F. A stretchable multicolor display and touch interface using photopatterning and transfer printing. *Adv. Mater.* **28**, 9770–9775 (2016).
56. Liang, G. et al. Coaxial-structured weavable and wearable electroluminescent fibers. *Adv. Electron. Mater.* **3**, 1700401 (2017).
57. Qu, C. et al. Multifunctional displays and sensing platforms for the future: a review on flexible alternating current electroluminescence devices. *ACS Appl. Electron. Mater.* **3**, 5188–5210 (2021).

58. Andrén, B., Brunnström, K. & Wang, K. P-37: readability of displays in bright outdoor surroundings. *SID Symp. Dig. Technical Pap.* **45**, 1100–1103 (2014).
59. Jou, J. H., Kumar, S., Agrawal, A., Li, T. H. & Sahoo, S. Approaches for fabricating high efficiency organic light emitting diodes. *J. Mater. Chem. C* **3**, 2974–3002 (2015).
60. Jiang, K. et al. Red, green, and blue luminescence by carbon dots: full-color emission tuning and multicolor cellular imaging. *Angew. Chem. Int. Edn* **54**, 5360–5363 (2015).
61. Shi, H. H. et al. Sustainable electronic textiles towards scalable commercialization. *Nat. Mater.* **22**, 1294–1303 (2023).
62. Zhang, H. & Rogers, J. A. Recent advances in flexible inorganic light emitting diodes: from materials design to integrated optoelectronic platforms. *Adv. Opt. Mater.* **7**, 1800936 (2019).
63. Liu, Y. et al. Robust memristive fiber for woven textile memristor. *Adv. Funct. Mater.* **32**, 2201510 (2022).
64. Yang, Z., Zhang, Y., Itoh, T. & Maeda, R. Flexible implantable microtemperature sensor fabricated on polymer capillary by programmable UV lithography with multilayer alignment for biomedical applications. *J. Microelectromech. Syst.* **23**, 21–29 (2014).
65. Kim, Y., Zhang, Y. & Hayase, M. Fiber-based temperature microsensor by using three-dimensional photomask. *Jpn J. Appl. Phys.* **56**, 06GG13 (2017).
66. Sun, H., Zhang, Y., Zhang, J., Sun, X. & Peng, H. Energy harvesting and storage in 1D devices. *Nat. Rev. Mater.* **2**, 17023 (2017).
67. Parsons, G. N. & Clark, R. D. Area-selective deposition: fundamentals, applications, and future outlook. *Chem. Mater.* **32**, 4920–4953 (2020).
68. Ma, J., Liu, Y., Gao, C. & Xu, Z. Sequence spinning axially encoded metafibers. *Matter* **6**, 3940–3955 (2023).
69. Wu, H. Y. et al. Seamlessly-integrated textile electric circuit enabled by self-connecting interwoven points. *Chin. J. Polym. Sci.* **40**, 1323–1330 (2022).
70. Park, S. et al. Adaptive and multifunctional hydrogel hybrid probes for long-term sensing and modulation of neural activity. *Nat. Commun.* **12**, 3435 (2021).
71. Zuo, Y. et al. Flexible color-tunable electroluminescent devices by designing dielectric-distinguishing double-stacked emissive layers. *Adv. Funct. Mater.* **30**, 2005200 (2020).
72. Liao, M. et al. Industrial scale production of fibre batteries by a solution-extrusion method. *Nat. Nanotechnol.* **17**, 372–377 (2022).
73. Nguyen, V. H. et al. Advances in flexible metallic transparent electrodes. *Small* **18**, 2106006 (2022).
74. Spencer, J. A. et al. A review of band structure and material properties of transparent conducting and semiconducting oxides: Ga_2O_3, Al_2O_3, In_2O_3, ZnO, SnO_2, CdO, NiO, CuO, and Sc_2O_3. *Appl. Phys. Rev.* **9**, 011315 (2022).
75. Won, D. et al. Digital selective transformation and patterning of highly conductive hydrogel bioelectronics by laser-induced phase separation. *Sci. Adv.* **8**, eabo3209 (2022).
76. Liang, J. et al. Silver nanowire percolation network soldered with graphene oxide at room temperature and its application for fully stretchable polymer light-emitting diodes. *ACS Nano* **8**, 1590–1600 (2014).
77. Zhao, Y. et al. A self-healing electrically conductive organogel composite. *Nat. Electron.* **6**, 206–215 (2023).
78. Liu, A. P. & Ueda, K. Propagation losses of pump light in rectangular double-clad fibers. *Opt. Eng.* **35**, 3130–3134 (1996).
79. Dhawan, A., Seyam, A. M., Ghosh, T. K. & Muth, J. F. Woven fabric-based electrical circuits. Part I. Evaluating interconnect methods. *Text. Res. J.* **74**, 913–919 (2004).
80. Liu, P. et al. Polymer solar cell textiles with interlaced cathode and anode fibers. *J. Mater. Chem. A* **6**, 19947–19953 (2018).
81. Babaarslan, O. & Hacioğullari, S. Ö. Effect of fibre cross-sectional shape on the properties of POY continuous filaments yarns. *Fibers Polym.* **14**, 146–151 (2013).
82. Gao, Z. & Chen, L. A review of multi-scale numerical modeling of three-dimensional woven fabric. *Compos. Struct.* **263**, 113685 (2021).
83. Jordan, J. V., Kemper, M., Renkens, W. & Gloy, Y. Magnetic weft insertion for weaving machines. *Text. Res. J.* **88**, 1677–1685 (2018).
84. limeneh, D. Y., Ayele, M., Tesfaye, T., Liyew, E. Z. & Tesema, A. F. Effect of weave structure on comfort property of fabric. *J. Nat. Fibers* **19**, 4148–4155 (2022).
85. Begum, M. S. & Milašius, R. Factors of weave estimation and the effect of weave structure on fabric properties: a review. *Fibers* **10**, 74 (2022).
86. Jinno, H. et al. Stretchable and waterproof elastomer-coated organic photovoltaics for washable electronic textile applications. *Nat. Energy* **2**, 780–785 (2017).
87. He, J. et al. Scalable production of high-performing woven lithium-ion fibre batteries. *Nature* **597**, 57–63 (2021).
88. Henry, P. Textile physics. *Nature* **200**, 1138–1139 (1963).
89. Bell, J. Moisture in textiles. *Nature* **188**, 823–824 (1960).
90. Choi, S. et al. Highly flexible and efficient fabric-based organic light-emitting devices for clothing-shaped wearable displays. *Sci. Rep.* **7**, 6424 (2017).
91. Song, S. et al. Textile-fibre-embedded multiluminescent devices: a new approach to soft display systems. *Mater. Today* **32**, 46–58 (2020).
92. Liu, X. et al. High-efficiency multi-string LED driver based on constant current bus with time-multiplexing control. *Electron. Lett.* **52**, 746–748 (2016).
93. Kwon, S. et al. Weavable and highly efficient organic light-emitting fibres for wearable electronics: a scalable, low-temperature process. *Nano Lett.* **18**, 347–356 (2018).
94. Song, Y. J. et al. Fibretronic organic light-emitting diodes toward fully addressable, environmentally robust, wearable displays. *ACS Nano* **14**, 1133–1140 (2020).
95. Gao, H. et al. Advances in pixel driving technology for micro-LED displays. *Nanoscale* **15**, 17232–17248 (2023).
96. Zeng, W. et al. Fiber-based wearable electronics: a review of materials, fabrication, devices, and applications. *Adv. Mater.* **26**, 5310–5336 (2014).
97. Hamedi, M., Forchheimer, R. & Inganas, O. Towards woven logic from organic electronic fibres. *Nat. Mater.* **6**, 357–362 (2007).
98. Liu, Y. et al. Highly reliable textile-type memristor by designing aligned nanochannels. *Adv. Mater.* **35**, 2301321 (2023).
99. Zhang, Z., Wang, Y., Jia, S. & Fan, C. Body-conformable light-emitting materials and devices. *Nat. Photon.* **18**, 114–126 (2023).
100. Lee, S. et al. Truly form-factor–free industrially scalable system integration for electronic textile architectures with multifunctional fiber devices. *Sci. Adv.* **9**, eadf4049 (2023).
101. Xu, X., Xie, S., Zhang, Y. & Peng, H. The rise of fiber electronics. *Angew. Chem. Int. Edn* **58**, 13643–13653 (2019).
102. Kim, H., Pyun, K. R., Lee, M.-T., Lee, H. B. & Ko, S. H. Recent advances in sustainable wearable energy devices with nanoscale materials and macroscale structures. *Adv. Funct. Mater.* **32**, 2110535 (2022).
103. Chen, G. et al. Electronic textiles for wearable point-of-care systems. *Chem. Rev.* **122**, 3259–3291 (2022).
104. Yoon, J. et al. Robust and stretchable indium gallium zinc oxide-based electronic textiles formed by cilia-assisted transfer printing. *Nat. Commun.* **7**, 11477 (2016).
105. Lin, R. et al. Digitally-embroidered liquid metal electronic textiles for wearable wireless systems. *Nat. Commun.* **13**, 2190 (2022).
106. Zhou, F. & Chai, Y. Near-sensor and in-sensor computing. *Nat. Electron.* **3**, 664–671 (2020).
107. Niu, S. et al. A wireless body area sensor network based on stretchable passive tags. *Nat. Electron.* **2**, 361–368 (2019).
108. Kim, T. et al. Efficient and stable blue quantum dot light-emitting diode. *Nature* **586**, 385–389 (2020).
109. Won, Y. H. et al. Highly efficient and stable InP/ZnSe/ZnS quantum dot light-emitting diodes. *Nature* **575**, 634–638 (2019).
110. Dai, X. et al. Solution-processed, high-performance light-emitting diodes based on quantum dots. *Nature* **515**, 96–99 (2014).
111. Comiskey, B. et al. An electrophoretic ink for all-printed reflective electronic displays. *Nature* **394**, 253–255 (1998).
112. Chen, Y. et al. Flexible active-matrix electronic ink display. *Nature* **423**, 136 (2003).
113. Palffy-Muhoray, P. Liquid crystals new designs in cholesteric colour. *Nature* **391**, 745–746 (1998).
114. Hwang, S. et al. Integration of multiple electronic components on a microfibre towards an emerging electronic textile platform. *Nat. Commun.* **13**, 3173 (2022).
115. Happey, F. Spinning and drawing. *Nature* **219**, 771 (1968).
116. Yan, W. et al. Single fibre enables acoustic fabrics via nanometre-scale vibrations. *Nature* **603**, 616–623 (2022).
117. Yan, H. et al. A high-mobility electron-transporting polymer for printed transistors. *Nature* **457**, 679–686 (2009).
118. Chen, C. et al. Perovskite solar cells based on screen-printed thin films. *Nature* **612**, 266–271 (2022).

Acknowledgements
This work was supported by the Ministry of Science and Technology of China (grants 2022YFA1203001 and 2022YFA1203002), the Science and Technology Commission of Shanghai Municipality (grant 21511104900) and the National Natural Science Foundation of China (grants T2321003, 22335003, T2222005 and 22175042).

Author contributions
Z.W. and Y.L. contributed equally to this work. Z.W. researched data for the article. All authors substantially contributed to discussion of content. Z.W., Y.L., Z.Z. and P.C. wrote the manuscript. Z.W., P.C. and H.P. reviewed and edited the manuscript before submission.

Competing interests
The authors declare no competing interests.

Additional information
Peer review information *Nature Reviews Electrical Engineering* thanks Caroline Murawski, who co-reviewed with Giuseppe Ciccone; John S. Y. Ho; and the other, anonymous, reviewer(s) for their contribution to the peer review of this work.