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Perspective

Design, fabrication and assembly considerations for electronic systems made of fibre devices

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Abstract

Fibre electronic devices with one-dimensional configurations have attracted increasing interest because they are highly flexible and can be deformed. In particular, they can be woven into breathable and comfortable textiles for wearable applications. Fibre devices with various functionalities, such as energy harvesting and storage, sensing, and display, have thus been extensively explored. However, most fibre devices work individually rather than as systems. This Perspective aims to highlight promising design concepts, assembly strategies and performance improvements for fibre electronic systems. Their real-life applications are then analysed from a multidisciplinary point of view involving materials science, electrical engineering, textile engineering and health monitoring. The remaining challenges are finally summarized to guide future research for both academia and industry.

Sections

Introduction

Design of fibre electronic devices

Consistent fabrication of fibre electronic devices

Assembly of fibre electronic devices into systems

Practical considerations

Applications of fibre electronic systems

Outlook

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Introduction

A noticeable trend in the development of modern electronic devices is the push towards conformable, more convenient and readily available devices that work closely with our bodies[1]. As a result, demand for wearable devices is increasing[2–7]. Conventional planar electronic devices are too bulky and rigid to meet such demands easily, and this has spurred the evolution of electronic devices[8–11]. A general and effective solution is to reduce the thickness of the devices to make flexible films that may be attached to the skin. Further reduction of the thickness in the other dimension results in highly flexible fibre devices that can bear complex deformations, such as twisting and knotting. They may be easily woven into breathable and comfortable electronic textiles for large-scale production, presenting a promising direction for wearable applications[12–14]. Triggered by rapidly increasing interest, fibre electronic devices with almost all desired functionalities, such as energy harvesting[15–17], energy storage[18], sensing[19] and display[20,21], have been realized with remarkably improved performance over the past decade[6]. Importantly, some devices, such as fibre light-emitting devices[20] and lithium-ion batteries[22], can be inexpensively produced at large scale while maintaining high quality.

In addition, the integration of single-functional fibre devices into multifunctional systems[20,23,24] has emerged as a promising direction. Systems made of various fibre-shaped components have intrinsic advantages such as high flexibility and breathability[25]. However, the transition from individually working fibre devices in the laboratory to industrially produced multifunctional fibre electronic systems is not a small task, and great challenges must be addressed.

Fibre electronic systems are generally fabricated by electrically interconnecting fibre devices with different functions (Fig. 1). However, fibres are highly curved, which results in electric fields that differ from their planar counterparts. Other challenges include the coexistence of charge transport in both the transverse and axial directions and the achievement of stable interfaces[26]. From an industrialization perspective, fibre devices need to be produced with lengths of metres to kilometres, several orders of magnitude longer than the centimetres at the laboratory level. Although continuous fabrication[22,27,28] has emerged as a promising approach for the scalable production of fibre devices, the required thinness of the fibres makes the consistent production of devices at large scale challenging, which is exacerbated by the increasing electrical resistance scaling with fibre length. Integrated devices can be fabricated by connecting multiple fibre-based components or embedding them into textiles[29–31]. However, the development of advanced fibre electronic systems, which involve an important increase in fibre device complexity, can lead to intricate connection and electrical compatibility challenges. To address these issues, better processing accuracy and effective layout design are needed. Finally, to meet commercialization demands, practical considerations such as mechanical and electronic stabilities, wearing comfort, safety and application scenarios all affect the commercial success of fibre electronic systems.

Another strategy to design fibre electronics involves building electronic functions inside the fibre[32,33]. This strategy is, in principle, more flexible as more functions can be integrated that way, but limited material choices and the difficulties associated with precise control of the location and connection of the fibres have hindered progress. In this Perspective, we focus exclusively on the all-fibre approach. We start with fibre devices and then focus on analysing advances and understanding the difficulties encountered in designing high-performance fibre electronic systems for commercialization.

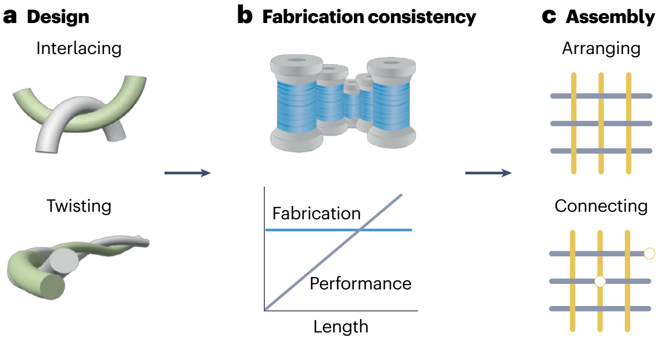

Fig. 1 | Design of fibre electronic systems. a, Design. Twisting and interlacing are two main design strategies to obtain fibre electronic devices with functionalities such as energy harvesting and storage, sensing, display and data-processing. **b**, Consistency. Fibre devices produced at large scale need to maintain fabrication and performance consistency. The vertical axis indicates performance and fabrication parameters such as capacity and diameter. **c**, Assembly. The arrangement and connection of fibre electronic devices into circuits represent two key procedures for system assembly.

Design of fibre electronic devices

The electric field is the foundation of electronic devices, by which charge transport is driven from one electrode to the other. In conventional bulky electronic devices, the electric field is uniformly distributed throughout the whole planar interface. In fibre systems, however, the electric field is normally uneven between the two fibre electrodes, owing to their highly curved surfaces[26] (Fig. 2b), which results in the concentration of charges and in non-uniform charge transport and ion deposition. Rebuilding the electric field is a straightforward strategy. For instance, a conductive weft can be designed to be elastic to fit a curved and more rigid luminescent warp by deformation, generating a uniform electric field at the weft–warp contact point, leading to uniform electroluminescence in display textiles[20]. Making the electrodes porous may be another solution so that the active materials can be evenly distributed to produce a uniform electric field[1]. Although difficult, thoroughly understanding the unique electric field distribution is necessary[34–36], because rational strategies can be developed to further enhance the properties of fibre devices. For instance, a simulation of the electric field distribution revealed that the Li^+ flux uniformity was improved by constructing a conductive scaffold in lithium–oxygen batteries[37]. Thus far, such studies are limited.

Efficient charge transport is essential for all-fibre electronic devices. There are two main charge transport processes in fibre devices: between the curved surfaces (Fig. 2c) of the electrodes and along the electrodes (Fig. 2d). For the former, strategies for increasing the mobilities of charge carriers[38], shortening the transport path[39] and reducing charge recombination[40–42] have been successfully applied to promote charge transport from one electrode to the opposite electrode. Considering the unique features of fibre devices, ways to reduce the interfacial charge transport resistance between two curved fibre electrodes should attract more attention. The composition and morphology of the active layers are two of the key factors. Constructing porous conductive architectures is an effective strategy to promote the infiltration of electrolytes, thus providing improved surface areas and pathways for charge transport across the electrode/electrolyte interface. In addition, strategies to enhance the penetration of charge carriers through

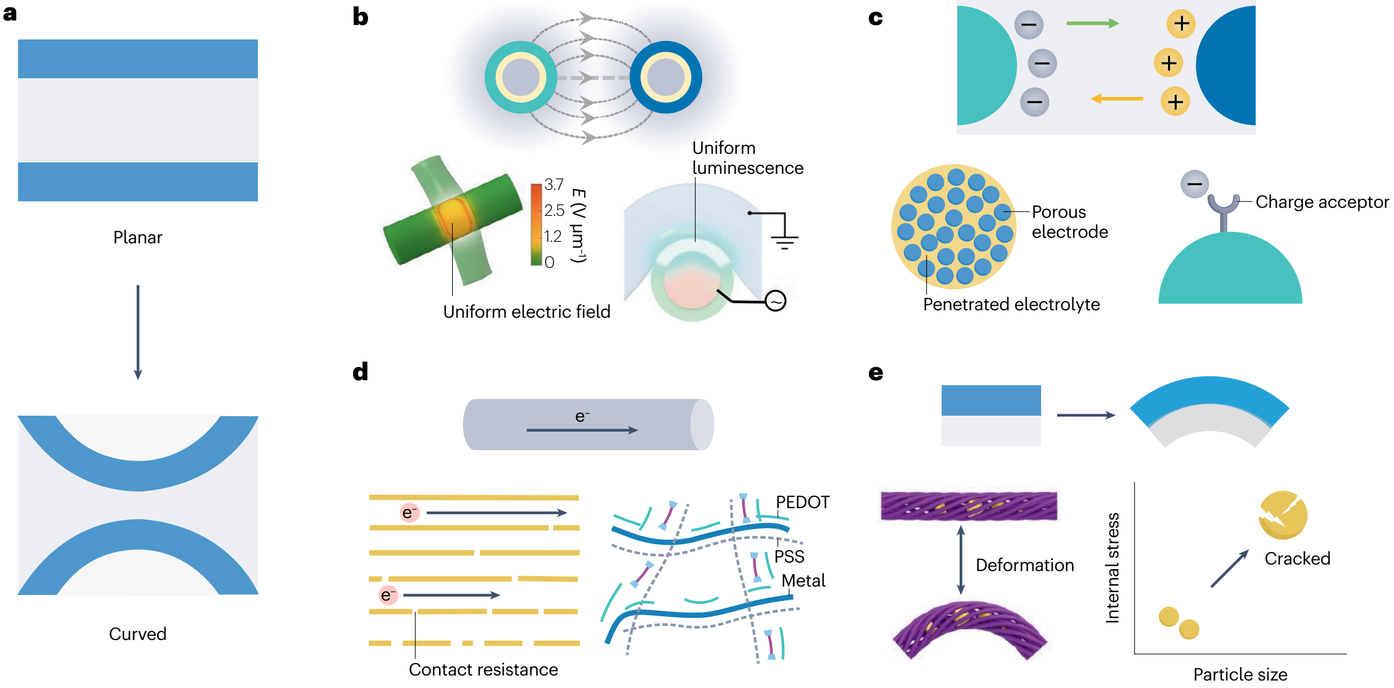

Fig. 2 | Design of fibre electronic devices. a, The highly curved surfaces of fibre electronic devices differ from their planar counterparts. **b**, Unevenly distributed electric field between fibre electrodes. The electric field at the contact area in an electroluminescence unit of a display textile could be rebuilt into a uniform field by deforming the designed elastic electrode, which results in uniform luminescence of the unit. **c**, Charge transfer on the curved surfaces of fibre electrodes. A porous structure or surface modification with charge affiliation or adsorption functions aids charge transport. **d**, Charge transport along the fibre electrode. The charge transport is more efficient through a fibre electrode with lower contact resistance. **e**, Deformation of fibre devices. The multistage twisted structure of the fibre electrode provides good support for the active materials. Reducing the particle sizes can reduce the internal stresses of active layers to prevent them from cracking or detaching. PEDOT, poly(3,4-ethylenedioxythiophene); PSS, polystyrene sulfonate. Panel **b** adapted from ref. 20, Springer Nature Limited. Panel **d** adapted with permission from ref. 11, AAAS. Panel **e** adapted with permission from ref. 54, Science China Press.

the surfaces of electrodes could aid charge transfer. For example, coating anodes with an I_3^- or Co^{2+} affiliation layer promotes electron transfer, leading to higher power conversion efficiencies for fibre solar cells[43,44], and tailoring interfaces of bioelectrodes with adsorption groups through molecular engineering enhances the sensing properties of fibre sensors[45,46].

Low-loss transport ensures the expected high performance of fibre devices with increasing length[33,47]. Carbon-nanomaterial-based fibre electrodes, including carbon nanotube and graphene fibre electrodes, have been widely used to construct high-performance fibre devices, owing to their good flexibility, light weight and high active material loading capacity[48–51]. However, the relatively high contact resistance among carbon nanotubes or graphene sheets in long fibres leads to large transport loss[3]. To reduce contact resistance, the synthesis of longer or larger building blocks may be a good solution. For instance, carbon nanotubes with lengths of 550 mm have been reported[52], but they still cannot be produced with a high fabrication stability at a large scale[53]. Metal wires are well known for their high electrical conductivities, but they are heavy and rigid, and may easily break under frequent deformation. To overcome these difficulties, efforts have been made to incorporate a second phase to produce composite materials: for example, mixing metal powders with flexible polymers, preparing metal coatings on fibre surfaces, and winding or twisting metal wires with chemical fibres. In particular, liquid metals with melting points below room temperature are promising candidates for achieving good flexibility and high electrical conductivity.

Another challenge for fibre devices lies in the realization of high interface stability (Fig. 2e). Because the fibre electrode surface is highly curved, establishing robust adhesion for active materials is difficult. The hierarchical assembly of multiple fibre electrodes may be an effective strategy to reduce the effect of interfacial attenuation on device performance. A representative example is multistage twisted carbon-nanotube-based electrodes, in which abundant nanoscale gaps among the aligned carbon nanotubes provide good confinement for active materials and thus stabilize their adhesion on electrodes[54]. However, fibre devices have to undergo various deformations in actual working conditions, such as bending, stretching and twisting, which greatly increases the possibilities of cracks and detachment of active layers[55]. These cracks and detachment are mainly induced by stresses under deformations or volume changes (for example charge and discharge processes in fibre batteries)[56]. Particles with diameters below a critical value of ~150 nm are resistant to stress-induced cracking during lithiation because of the insufficient particle-size-dependent crack extension driving force[57], suggesting a route towards stable fibre devices.

Overall, a thorough understanding of the unique properties of fibre devices remains the key for good performance. In addition, the synthesis of new active materials, the design of aligned microstructures that allow for rapid charge transport and the optimization of curved interfaces are necessary.

Consistent fabrication of fibre electronic devices

For their assembly into systems, fibre devices should be orders of magnitude longer than the laboratory level of centimetres. This imposes great challenges on their consistency in both fabrication and performance (Fig. 3). Fabrication consistency is an essential prerequisite for fibre devices to be integrated into systems[58,59]. Continuous fabrication methods such as solution extrusion, thermal drawing and continuous coating stand out for the large-scale fabrication of fibre devices.

Solution extrusion

Solution extrusion is based on the extrusion of functional inks through the channels of a spinneret and the rapid curing of the extrudate in a coagulation bath. A high extrudate viscosity is desired to maintain a uniform composition, microstructure and shape for the fibre in both the axial and transverse directions[60–62]. However, this requirement makes the continuous flow of the extrudate through the spinneret difficult because of the small diameter of the fibres ($<10^{-3}$ m). Introducing shear flow forces to taper extrudates along the extrusion direction (Fig. 3a) can effectively address this issue. Using this strategy, fibre batteries with both structure and performance consistencies exceeding 90% have been achieved.

Thermal drawing

Thermal drawing is another important method for continuous fabrication, in which the pre-assembled components are heated to melt and scaled down into fibres. To achieve good fabrication consistency, the mainstream strategy is to tune melts with similar viscosities so that they can be stably drawn without mixing[47,63] (Fig. 3b). Despite the great success of this strategy, high requirements on the viscosity matching of melts reduce flexibility for the choice of materials and their ratios, and the performance of fibre devices sometimes has to be sacrificed[64,65]. Therefore, enriching the libraries of extrudable or drawable components or modifying viscosities to make materials of various viscosities compatible are desired. For example, like for tissues that can be cryopreserved in situ with the help of cryoprotectants[66], developing viscosity-modifying agents that preserve the geometry of the extrudate while in a low-viscosity state may be a feasible direction.

Continuous coating

Continuous coating that relies on the substrate passing through a slurry at a given velocity has been widely used in industry. Achieving fabrication consistency in the production of fibre devices is challenging, however, because of the highly curved fibre surfaces, which can lead to uneven coatings, especially for slurries with a high surface tension. Introducing additional components, such as polyvinylidene fluoride and sodium carboxymethyl cellulose, as binders is an effective strategy to enhance the interfacial adhesion of the slurry to produce 100-metre-long fibre electrodes with uniform and robust coating layers[22].

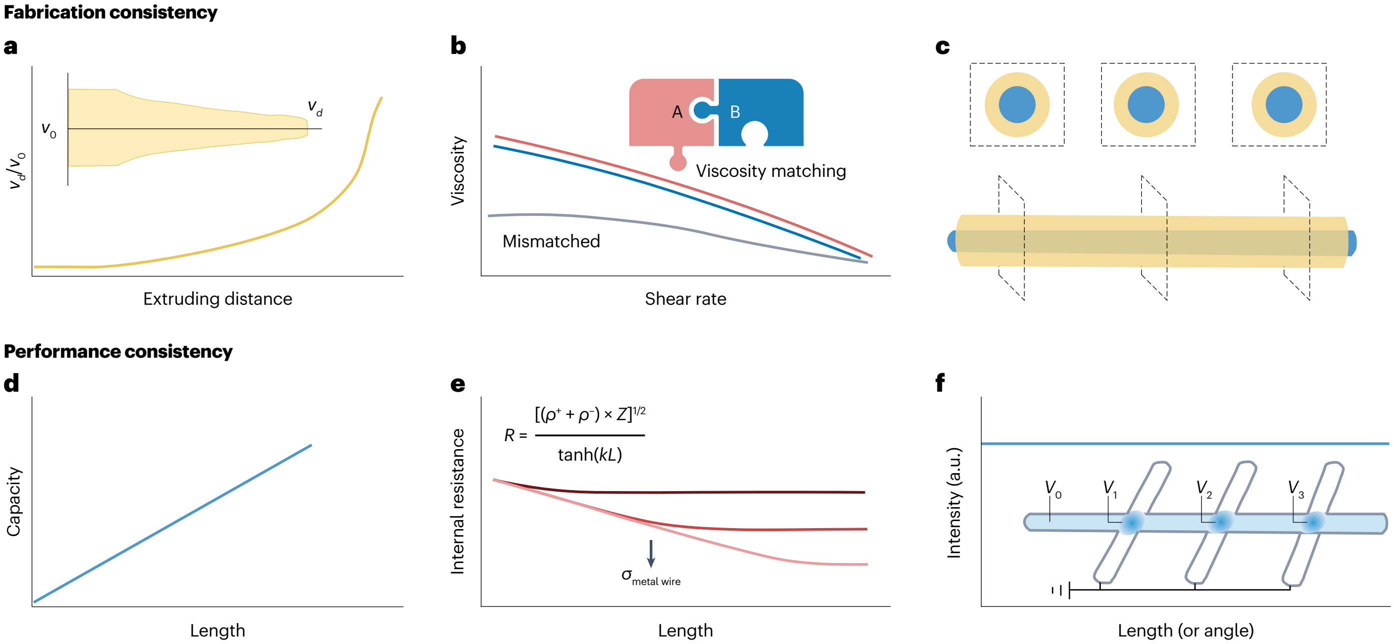

Fig. 3 | Consistency of fibre electronic devices. a, Shearing ensures stable extrusion and induces alignment to enhance the performance. **b**, Solution extrusion and thermal drawing require the viscosity matching of the components. υ_0 and υ_d represent the flow velocities at the centre of the entrance and the exit of the tapered channel. **c**, The coating layer must be consistent along the length. **d**, Performance parameters, such as the capacity, should linearly increase with the length of fibre batteries. **e**, The internal resistance of the current collector decreases, then remains stable. The insert shows the hyperbolic cotangent functional relationship between the internal resistance and length of fibre batteries. ρ^+ and ρ^- represent the resistances of positive and negative fibre current collectors, respectively. Z, the polarization resistance of the fibre battery; L, the length of the fibre battery; $k = ((\rho^+\rho^-)/Z)^{1/2}$; σ, electrical conductivity that increases in the direction of the arrow. **f**, In devices such as light-emitting fibres, performance parameters should remain consistent with the length or observation angle. The inserted diagram shows that light-emitting fibres will experience a voltage drop along the length direction. V_0–V_3, voltages at different points of the light-emitting fibre, and $V_0 > V_1 > V_2 > V_3$.

Therefore, tuning the composition of the slurry to suppress such surface tension is a promising development direction. On the other hand, according to the Landau–Levich law, which describes the thickness of a deposited film when a liquid flows over a solid[67,68], the consistency of the coating layer is also affected by the coating speed, rheology and viscosity of the slurry. In coating methods currently used, a low speed is adopted to avoid the Plateau–Rayleigh instability (that is, when a liquid column breaks up into droplets) for consistent coating, but this leads to low fabrication efficiency[69]. In addition, coating a thick slurry while maintaining a uniform circular cross-section is difficult[70]. Hence, we envisage that accurately controlling the coating process is a more important development direction. For example, the control of the thermal, lighting and electrical conditions (respectively during drying, photocuring and electrostatic processes) as well as the control of other experimental conditions during coating can be used to precisely coat layers. In addition, self-assembly to achieve large-scale coating layers with nano-level fluctuations is promising. Such precise coating and self-assembly methods are also efficient in forming multilayer fibre structures. Layer-by-layer self-assembly can accurately control the sequence and amounts of components during coating[71,72] (Fig. 3c).

The performance of fibre devices should linearly increase or remain consistent with the length of the fibre to ensure high-performing systems. For example, capacity that linearly increases with length is required for long fibre batteries[22,27,28] (Fig. 3d). For display fabrics, the luminescent intensities at each position along the fibre length direction need to be the same to get uniform light-emitting pixels[20,36]. To this end, improving the conductivity of materials is one approach that has been widely studied. However, theoretical innovations may be even more important to achieve good consistency by providing insights into the performance variations versus length. For example, the unexpected finding of a hyperbolic cotangent functional relationship between the internal resistance and the length of fibre batteries (meaning that the internal resistance first decreases and then reaches a plateau as the length increases; Fig. 3e) enables high-performing long fibre lithium-ion batteries[22]. This direction provides a good entry point for other fibre devices. For instance, consistent light-emitting fibres may be achieved by designing differential light-emitting points along the length direction, such as by varying the thickness of the dielectric layer[73], or by introducing voltage compensation lines for the unexpected voltage drops along the length direction that correspond to luminescence intensity attenuation[74] (Fig. 3f).

To summarize, during the transition from laboratory to fabrication ('lab to fab'), fabrication and performance consistencies are two key parameters. Enriching the libraries of materials and reducing their viscosity dependences will further support their continuous fabrication. The development of completely new continuous fabrication methods is also critical to provide new entry points to solve fabrication problems. For example, vapour deposition can be used to precisely control the thickness of functional layers independent of their viscosity and of the high curvature of the fibre. Bottom-up fabrication of fibre devices using the Schulz–Flory distribution[52] and electrostatic spinning[75,76] can be used to simultaneously construct functional layers and the core along the axial direction in one step and irrespective of viscosity issues. Efforts to develop low-resistance electrode materials and to understand the relationship between the length and properties will also contribute to improving the performance consistency.

Assembly of fibre electronic devices into systems

Several achievements have made fibre electronic systems possible[77,78]. Fibre devices with different functions can be twisted into fibre systems along the axial direction for in vivo applications such as the monitoring of multiple biomarkers and the simultaneous optical, electrical and chemical interrogation of neural circuits[19,79], or they may be woven into textile systems for wearables[20,21]. However, assembling single-functional fibre devices into versatile systems remains a technical challenge.

Arranging conductive lines among fibre devices and connecting fibre electrodes into circuits are two key procedures for system assembly. Printing and transfer techniques are two mature methods for realizing planar circuits[80,81] that could be applied to electronic textiles by replacing the flexible film substrate with a textile substrate. Printing flexible conductive patterns on textiles allows the formation of textile-based circuit lines, following which conductive yarns can be integrated according to the patterns of the textile circuits (Fig. 4a). Processing precision is crucial to pattern conductive lines for connecting fibre electrodes woven in the textile. Depending on the printing method, such as extrusion or screen printing of conductive inks, the precision can reach hundreds of micrometres[82,83]. In the transfer method, the flexible circuit, fabricated on plain substrates, is released and fixed onto the textile through an adhesive layer[84,85]. Because flexible circuits can be patterned using high-precision lithography, the accuracy of the transfer method is higher than the printing method, which is advantageous for textile circuits.

Embroidery and weaving can enable the fabrication and configuration of textile systems through a bottom-up approach, by which conductive yarns can be co-woven into textiles[86,87] or fixed on textiles by a double lock stitch[88] (Fig. 4a). Using fine conductive yarns as building blocks, the processing precision can largely meet the requirements of textile circuits. In addition, weaving is suitable for large-scale assembly, and embroidery allows the arrangement of conductive lines in arbitrary custom-designed patterns regardless of the original texture of the textile substrates. Therefore, combining them would be a good choice for the construction of textile circuits. However, the arrangement of the conductive lines is strongly correlated to the intrinsic weaving structures, which increases difficulties during industrial production. For example, micronized patterns cannot be embroidered on sweaters woven from millimetre-sized loops, and printed patterns easily peel off textiles covered by velvet. Thus, a processing database for fabricating conductive lines on various commercial fabrics must be established, based on optimal strategies for the precision, flexibility, breathability and durability needed.

The interface between the conductive line and the fibre electrode is the weak point of a fibre electronic system. The contact between them can be fixed by using fibre-interlocking structures[89,90]. However, the contact interface between interlocking fibres may be easily changed during repeated deformations, and resistance fluctuations or disconnection may occur at the connection point. Interfaces between soft fibres must provide strong, flexible mechanical bonding and high electrical conductivity (Fig. 4a). Interface-connecting materials used in traditional planar systems, such as metals for welding[91,92] and conductive glue[93], have been used to connect fibre electrodes, but a general strategy that can strongly bond various materials remains an unmet need, because materials used for fibre electrodes, such as gels, carbon materials, metals and conductive polymers[6], differ widely in molecular structure and surface properties. In addition, stress concentration at the interface can easily lead to the mechanical failure of the connection. Dynamically stable interfaces with strong interfacial adhesion

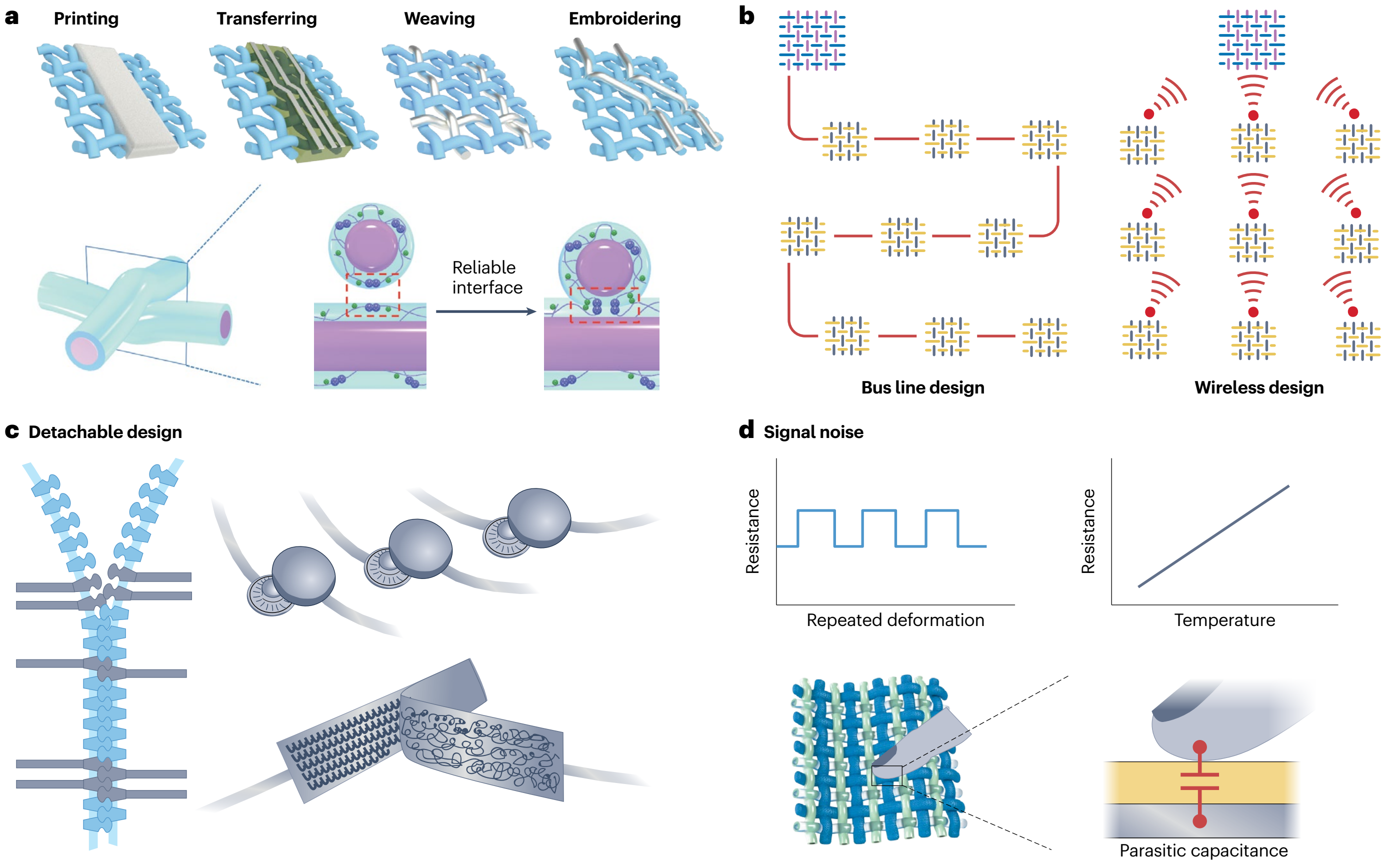

Fig. 4 | Assembly of fibre electronic systems. a, Fabrication of textile circuits by arranging conductive lines and connecting fibre electrodes. **b**, Layout design for a fibre electronic system, including bus line and wireless design. **c**, Detachable textile modules assembled by zippers, buttons or hook-and-loop tape. **d**, Signal noise caused by deformation, temperature variation and parasitic capacitance. Panel **a** adapted from ref. 94, Springer Nature Limited.

could overcome this challenge. Instead of passively interlacing fibre electrodes, introducing disulfide and amide groups into the fibre coating layer can locally sinter fibre electrodes by spontaneously forming disulfide or hydrogen bonds[94]. Reliable physical adhesion can be realized by applying thermoplastic polymers at the fibre crossover points[95], using an ultrasound treatment to aid the adhesion between the polymers and fibres, which is a universal strategy to connect fibre electrodes that have mismatched properties. Furthermore, the cylindrical geometry of the fibre electrodes results in minute contact areas at the crossover points, resulting in unstable charge transportation across such insufficient contact. Another strategy to improve the interface stability is to fabricate a soft buffer layer with a Young's modulus orders of magnitude lower than fibre electrodes, for example by using conductive gels[20,96]; the buffer layer can elastically deform and fit the curved surface of fibres, maintaining contact even under complex deformations.

If the challenges of arrangement and connection can be overcome, more fibre devices with various functions could be integrated to make systems more powerful. This means, however, that the complexity and scale of the textile circuits will be greatly increased. For example, sensing and display fibre modules usually require hundreds of lines to connect with data-processing modules[20,97]. Such densely distributed connections will decrease the flexibility and reliability of the systems. Therefore, a future solution to simplify the connections should be considered. Here, we suggest that a bus transmission design should be taken into consideration to address this challenge (Fig. 4b). By integrating fibre devices with a microchip to form a submodule, one bus line can connect a large number of submodules to the central processing unit (CPU). Typically, bus lines send decoded signals using time division multiplexing (TDM) and frequency division multiplexing (FDM) principles. In TDM, signals are divided into separate, non-overlapping time segments. In FDM, they are separated into distinct frequency bands. Each segment or band carries an individual signal. Microchips integrated in textile modules can both encode data gathered from fibre devices into multiplexed signals and decode these signals into control instructions for each fibre device, allowing simultaneous transmission and processing between the CPU and textile modules through the bus lines. Alternatively, wireless technology such as Bluetooth, near-field communication and wireless local-area networks[98] can be used for signal transmission (Fig. 4b). However, transmitting high-quality signals requires more power and results in high energy consumption. This problem may be addressed by integrating metamaterials into textiles, as they can decrease power consumption by orders of magnitude by effectively localizing electromagnetic waves close to the body[99].

Furthermore, hardware replacement is important for prolonging the lifetime of the system and promoting its upgrade if accidental device damage occurs or device additions are required. Replacing fibre devices that interlace with other fibres in textiles without damaging the textile structure is difficult. Assembling detachable textile modules into a system should be considered[100] (Fig. 4c). A series of textile modules with different functions, performances and appearances could be developed by weaving fibre devices and connecting fibre electrodes to commonly used connectors in clothing such as buttons and zippers that not only mechanically anchor textile modules but also act as universal electrical interfaces. Assembling the system without weaving or embroidery will also make it convenient for electronic engineers and garment designers to independently develop fibre electronic systems with specific functions.

A versatile fibre electronic system can be assembled over a large area by printing, transfer, embroidery and weaving. A bus line design or wireless transmitting architecture and detachable textile modules would enable long-term practical applications.

Practical considerations

For fibre electronic systems to better meet specifications for real-world applications, practical issues before, during and after use should be addressed.

Before fibre electronic systems reach the consumer, they will go through the processes of design, cutting, packaging, transportation and storage. Consumers usually have a demand for aesthetics. The combination of fibre electronics with traditional fabrics, such as fibres that are coated with polyurethane after being woven with cotton yarn[101], can be compatible with mature dyeing processes, providing more customized colours and appearance for aesthetic design. Furthermore, a suitable tailoring method needs to be considered to ensure the functional integrity of fibre devices during design[32]. However, many fibre devices cannot be tailored because their structural and component integrities are threatened[102]. Introducing 3D printing to prepare fibre electronics with the desired shape and length in situ may be a future development direction[27,103,104].

After the system has been processed as designed, it needs to be packaged and transported to reach consumers. These processes involve complex physical environments such as compressive environments, low or high temperatures and vibration. In addition, because fibre electronic devices can have toxic, harmful and flammable components, leak detection, such as colour indicators[105,106], and separate transportation and storage should be considered. The maintenance of the stability of the structure and of the functions of fibre electronic systems in the above processes should also be considered, as well as matching with existing supply chains.

During use, safety, comfort and washability have attracted great interest from both academia and industry, with washability being the most concerning[6,23,29,107]. Encapsulation perhaps presents the best solution, especially for fibre devices with functional coating layers such as lithium fibre batteries[108]. For fibre devices where encapsulation is not available, such as fibre electrocardiograph electrodes, embedding functional components into fibre substrates, using co-blending or chemical deposition[109,110], is a viable option.

Because fibre electronic systems are used in complicated and changing environments, a reduced signal-to-noise ratio for electric signals in dynamic situations is another major challenge (Fig. 4d). As broadly investigated in sensing applications, fibre conductors show resistance or capacitance variations under deformation[111], temperature changes[112] and human touch[113]. However, such responses are undesired noise when conductive fibres are used to transmit electrical signals. To be specific, the dependence of a conductor's resistance on its geometry can be expressed by $R = \rho L/S$, in which R, ρ, L and S represent resistance, resistivity, length and cross-sectional area of the conductor, respectively. When the fibre conductors are deformed by stretching, bending or compressing, the cross-sectional area and length of the conductors vary at the deformation sites, which leads to resistance fluctuation. To obtain strain-insensitive conductors, spiral twisted structures[114,115], wrinkles[116,117], hierarchical nanoparticles[118] and unwoven fibre-based devices[119] effectively buffer the strain of conducting materials. Owing to heat generation in electronics and widespread human activities, the resistance variation caused by fluctuation of the local temperatures in the textile will inevitably induce electrical interference in the circuits. In addition, when the conductive human body contacts the insulated fibre conductors, a parasitic capacitance forms at the contacting area and induces extra current if alternating signals are transported along the conductors. This also generates non-negligible noise in long-distance and high-speed transmission. Filtering, smoothing and machine learning are mature technologies used in communication engineering to reduce various types of noise in signals, and they could be introduced into fibre electronic systems. Additionally, smart materials can have important roles in enhancing the reliability of fibre systems against the changing environment[120]. For example, shape memory materials[121] and self-healing[122] materials can repair mechanical damage, and thermally responsive electrolytes[123] can adjust the performance of energy storage fibres in different temperatures.

Over 50 million tonnes of electronic and electrical waste are produced in the world, and 10 million tonnes of textiles are sent to landfills in North America each year[124]. At a time when throwaway or fast fashion remains dominant[125], textiles based on fibre electronic systems will inevitably be treated the same, which means that great waste will need to be processed in the future. Hence, sustainability after use should be considered. We envisage that the following strategies might be effective in reducing electronic waste. First, each module of the fibre electronic system should be detachable after use, and different processing procedures should be applied for different modules. For example, fibre batteries could be handed over to battery recycling factories and ordinary fabrics to fabric recycling factories. In addition, sustainable materials such as recycled polyester could be used to fabricate fibre devices[126,127]. Finally, fibre electronic systems based on biodegradable materials could be developed[128,129].

Designability, safety and eco-friendliness are critical issues in the lifecycle of fibre electronic systems. Drawing inspiration from traditional fabrics and electronic systems is expected to be an effective entry point.

Applications of fibre electronic systems

The development of applications is important for the successful commercialization of fibre electronic systems. As the building blocks of such systems, conductive fibres including stainless steel sewing threads[130], metal-plated chemical yarns[131] and carbon composite fibres[132] were the first to be commercialized. Conductive fibres are woven or sewn to connect the blocky components that are necessary for an electronic system. Such conductive-fibre/block-component hybrid textile systems have a wide range of application prospects in the fields of human–computer interaction, intelligent temperature control and physiological signal sensing. For example, the Jacquard fabric project by Google brings touch to textiles by weaving conductive threads in jackets and bags, offering a new avenue to interact with smartphones[133]. Clim8, an intelligent thermal technology company for wearables, has developed garments that can monitor the body and environment temperatures and regulate the skin temperature based on sensing modules and on the electrical heating of conductive fibres[134]. The German company Embro GmbH focuses on the technical embroidery of conductive fibres to meet different needs and specifications, such as medical applications and wireless communication[135].

However, the integration of rigid block electronic modules decreases comfort, and they cannot cover all areas of the human body (for example, the joints), limiting improvement of system functions and performance. Flexible fibre systems integrate electronic components over large areas and at high densities without losing the flexibility and breathability of the textile. Continuous production has been initially realized for fibre devices with display[20], sensing[97], energy collection[136] and storage[22] functions, which are expected to replace the blocky electronic modules used in state-of-the-art textile systems. Such a fibre-integrated system will probably open up new applications for wearable devices. For example, large-area display devices can be seamlessly integrated with textiles by weaving functional fibres[20]. A new type of visual interaction interface could be developed that not only enables wearable human–machine interaction but also provides a new platform for human-to-human communication in addition to vocal communication, by which, for example, people with language disorders could communicate by displaying the words on smart textiles[20]. Clothing that collects force information and maps the force distribution can be realized by weaving piezoresistive fibres for strain-sensing functions[97]. Compared with traditional camera imaging, such sensing textiles are expected to reconstruct the body's posture more accurately in real time based on a large amount of sensing data collected from the whole body. By integrating fibre sensors, textile systems can be developed to monitor human physiology and analyse environmental parameters in real time[9]. For example, O_2 levels and pH values are important indicators for monitoring biological information such as the blood supply to the brain and the nutrient supply to a tumour; a textile system with implantable electrochemical sensing fibres that can accurately detect O_2 content and pH values is thus expected to provide effective biological signalling for medical treatments[137]. In addition, fibre batteries can be easily woven into textiles to provide sufficient capacity to power various wearable electronics[22], and energy-harvesting fibres that collect frictional[136], electromagnetic[138] and solar[139] energy can charge fibre batteries to realize a self-powering system.

With the scale expansion and multiple possible functionalities of fibre electronic systems, we envisage an all-fibre autonomous textile system that integrates textile modules for powering, computing, interacting, healthcare monitoring and communicating. In addition to having the functions of traditional electronic systems, all-fibre autonomous systems retain the original structure of textiles and are highly flexible and comfortable, working closely and imperceptibly with our bodies. All-fibre autonomous systems could replace existing portable terminals such as computers and mobile phones. By using all-fibre autonomous systems, people could monitor biological signals, such as O_2 content and pH value, that correlate to biological information such as blood supply to the brain and nutrient supply to a tumour. Personalized medical treatment free from current costly and centralized medical facilities could be realized through the collection, analysis and feedback of physiological information. By establishing wireless communication networks, textiles will become widely available nodes for the Internet of Things, allowing people to build real-time and high-speed interactions with the digital world. In addition to hardware advancements, the integration of fibre electronic systems with artificial intelligence would further power their applications. Combined with machine learning, fibre electronic systems could recognize human languages, gestures and brain waves by processing and analysing data from wearable sensors, helping people to communicate without any barriers[140,141]. In addition, studying physiological parameters over the long term could allow the provision of personal healthcare advice about nutrition, sleep and exercise.

With the increasing number of fibre devices of different functions that are integrated into systems, the applications of fibre electronic systems are evolving from electric conductors to multifunctional wearable modules and autonomous all-fibre smart terminals. We envisage that such electronic textiles will become an independent part of human life for communication, physiological monitoring, body protection and human–machine interaction.

Outlook

Flexible and breathable fibre electronic systems are a versatile platform for future wearable electronics. Encouraging achievements have been made in function, performance, large-scale fabrication and assembly, but efforts should now focus on developing active materials that better adapt to the highly curved features of fibres. Current materials are mainly adopted directly from their planar counterparts, resulting in inferior properties. In addition, the library of functionalities achievable with fibre devices needs to be further enriched, especially with data-processing devices, although this is extremely challenging. Future fibre electronic systems for energy applications should integrate fibre batteries with fibre solar cells that can convert sunlight and indoor light into electricity. Finally, optimized engineering design is the final step for the 'lab to fab' transition of fibre electronic systems. The process flow of materials should be low-cost, safe and environmentally friendly, and material design should meet durability and safety requirements for different application scenarios, such as autoclaving, extreme temperatures, immersion in natural waters, ultraviolet exposure and their use by infants and young children. The integrated system should also resist wear and tear, and should inhibit allergic reactions. Establishing industrial standards for quality and reliability is also crucial; based on these standards, the influence of the production process on the yield of fibre systems can be investigated, allowing the establishment of a database relating the fibre production with different functions and performance. Additionally, fibre systems should be compatible with existing electronic devices, encompassing aspects such as wireless communication protocols, hardware connection interfaces and electrical specifications such as drive voltages and power consumption.

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Author contributions

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Competing interests

The authors declare no competing interests.

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