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PERSPECTIVE

Pathway to Developing Permeable Electronics

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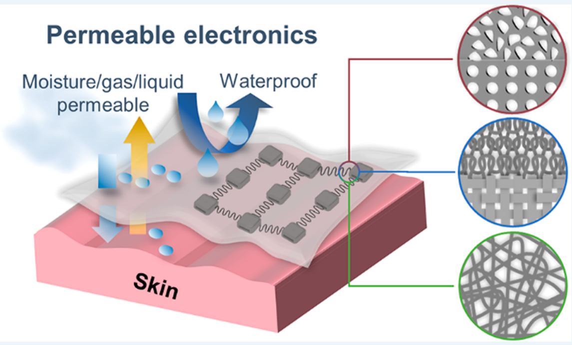
ABSTRACT: **Permeable electronics possess the capability of permeating gas and/or liquid while performing the device functionality when attached to human bodies. The permeability of wearable electronics can not only minimize the thermophysiological disturbance to the human body but also ensure a biocompatible human-device interface for long-term, continuous, and real-time health monitoring. To date, how to simultaneously acquire high permeability and multifunctionality is the major challenge of wearable electronics. Here, a critical discussion on the future development of wearable electronics toward permeability is presented. In this perspective, the critical metrics of permeable electronics are discussed, and the historical evolution of wearable technologies is reviewed with highlights of representative examples. The materials and structural strategies for developing high-performance permeable electronics are then analyzed.**



KEYWORDS: *permeability, wearable technologies, flexible and stretchable electronics, textile, thin-film technologies*

The booming development of flexible and stretchable electronics has facilitated the advances in wearable technologies that could be intimately associated with human bodies. These wearable, skin-attachable, and even implantable devices have demonstrated their application possibilities in the physiological study of human bodies for wellness and medical applications, in the human-machine interactions for communications and entertainment, and in the fundamental research of human health and diseases.[1,2] The adoption of wearable technologies in practical scenarios not only needs to overcome the mechanical mismatch between rigid electronics and soft skins/tissues but also should take critical considerations into the physiological conditions of human bodies. Such requirements have particularly led to the emergence of permeable electronics in recent years. Permeable electronics, or breathable electronics, refer to wearable technologies that can steadily perform electronic functionalities while possessing minimum thermophysiological disturbance to the biosystems of human bodies. Notably, the capability of permeating the air, water vapor, and liquid of permeable electronics can ensure a biocompatible device-human interface that benefits a long-term, continuous, and real-time monitoring of human health in a noninvasive and imperceptible way.[3] In this perspective, we provide a focus discussion on the critical metrics of permeable electronics, the historical evolution of wearable technologies, and the pathway to developing high-performance permeable electronics. In particular, we outline the advances in material structures, electrodes, and devices for permeable electronics, discuss the critical challenges, and then offer an overview of future directions for the research field of wearable technologies.

RATIONALE FOR DEVELOPING PERMEABLE ELECTRONICS

Permeable electronics possess the capability of permeating gas, water vapor, and/or liquid, while performing the device functionality when attached to human bodies, skin, or other organs. The increasing numbers of publications per year recorded on the Web of Science have witnessed the rapidly rising awareness from researchers toward this metric for wearable and on-body applications (Figure 1a). While researchers have made vast advancements toward permeable electronic devices, it is essential to investigate the rationale for proposing device permeability from the perspectives of human physiology and device functionalities.

Wearable electronic devices are designed to be either integrated into clothing and garments or directly attached to human skins. The wearing comfort of these electronics is primarily determined by the satisfaction of the human's physiological comfort (e.g., thermophysiological, sensorial/

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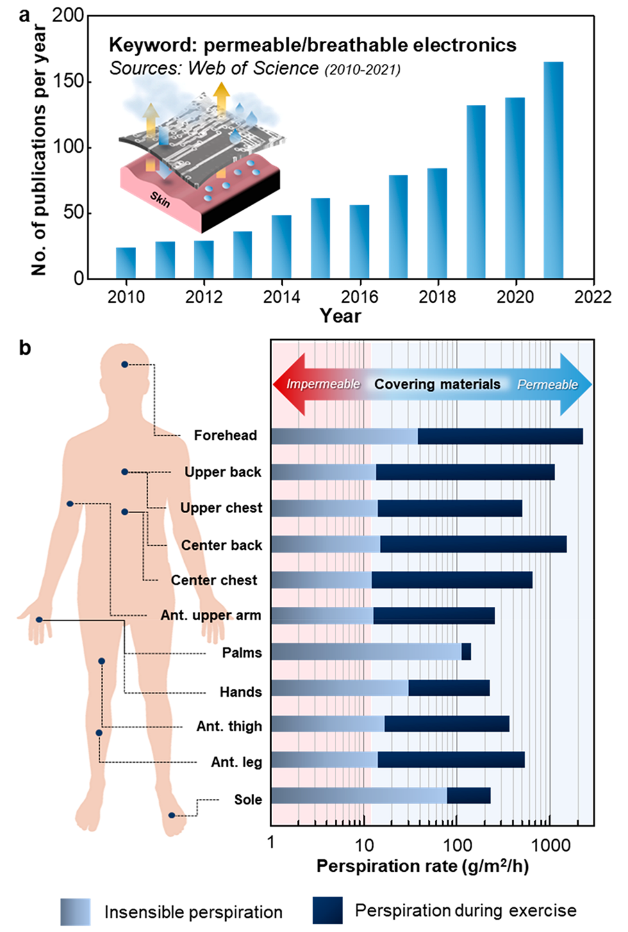

Figure 1. Benchmark for developing permeable electronics. (a) Summary of the publication records relating to "permeable electronics" or breathable electronics" recorded in Web of Science. (b) Body mapping of insensible perspiration and sensible perspiration during intensive exercise.

tactile, and body movement comfort). While improving the mechanical compliance of electronic materials could satisfy the wearing comfort associated with body movement and touch sensation,[4] the thermophysiological comfort requires a suitable thermal microenvironment between the skin and the covering devices. In a normal circumstance, such a thermal microenvironment is controlled by balancing the water and heat loss from the skin surface by means of sensible or insensible perspiration.[5] For example, under the rest condition, the human body will insensibly lose water in the form of moisture vapor from the skin at an average evaporation rate of 23−28 $g/m^2/h$ for thermoregulation.[5] During the intensive training, 1.5−2.5 L of sweat per hour is discharged to maintain a suitable body core temperature.[6] If perspiration cannot quickly and sufficiently escape from the skin, moisture will accumulate on the skin surface and within the covering, leading to uncomfortable thermophysiological sensations (e.g., dampness, clamminess).[7]

Importantly, it has been widely recognized that perspiration varies in different regions of the body under different conditions of outside environments (Figure. 1b). The mapping study of regional sweat distribution shows that the forehead, palms, hands, and soles exhibit relatively higher insensible perspiration rates (>30 $g/m^2/h$) than other positions when the bodies are at rest, while the sensible perspiration rate of foreheads and back bodies during exercises could exceed 1000 $g/m^2/h$.[5,8] Given the demand for physiological comfort and biocompatibility, the development of wearable technologies thus needs to be body position-oriented and application-oriented. Materials of devices designed to cover the wearers' bodies should not hinder the evaporation and transmission of the perspiration (either in the form of moisture vapor or liquid water) from the targeting skin surface to the outside. To some extent, the permeability of materials, devices, and electronic systems for wearable and on-skin applications should at least exceed the insensible perspiration rate of human bodies.

From the perspective of device functionality, electronics with permeability to gas and liquid could enable the possibility of monolithic electronics integrated with multilayered high-density integrated devices. Analytes, either in gas or liquid forms, such as body fluids and volatile substances of odor, could penetrate through the permeable layers to reach the targeting position of the device. In this way, different types of chemical or electrochemical reactions could be simultaneously induced for physiological signal detection and analysis. Such permeable, highly integrated, and multifunctional device systems are foreseen to provide a comprehensive analysis of multiple biosignals in a real-time, continuous, and non-interfering manner, significantly benefiting personalized healthcare management and the biomimic control of soft robotics.[9]

HISTORICAL DEVELOPMENT OF WEARABLE TECHNOLOGIES TOWARD PERMEABLE ELECTRONICS

It has been widely recognized that the concept of wearable technologies could be dated back to the 1500s when the wristwatch was developed.[10] Over the past centuries, the evolution of wearable technologies can be reflected by the development of different types of materials, the revolution of device form factors, and the incorporation of various functionalities ranging from flexibility, stretchability, and permeability. Figure 2 graphically depicts the typical milestones of the development of wearable technologies.

Due to the ubiquitous interaction between humans and clothing as well as the excellent intrinsic permeability and wearing comfort of textile materials, the incorporation of electronics into wearables appeared in apparel and accessories in the early development stage. In fact, before the creation of electronic textiles (E-textiles), the use of metallic threads in fabric fabrication could be found in textile antiquities as far as the second century.[11] The evolution of E-textiles has undergone three generations. The first generation of E-textiles is represented by simply adding commercial off-the-shelf electronic components onto a garment. Such applications could be dated back to 1883 when a ballet dress embedded with an electric light headband and a battery was debuted at a masquerade ball in New York.[10] The embedment of microprocessors into such a type of lighting garments could further enable the customized control of display patterns, providing smart functionality to E-textiles.[10] While the first generation has exhibited the proof-of-concept wearable format for electronics, the second generation of E-textile majorly developed functional fabrics to replace some of the rigid electric components (e.g., sensing electrodes, switches, conductive tracks) in the circuit design.[12] At this second development phase, conductive threads were embedded into textiles via conventional textile technologies such as embroidery, weaving, and knitting to form conductive tracks and fabric electrodes.[13−15] Solution-processable functional materials could be directly printed onto the fabric substrates to fabricate textile-based electronic devices.[12]

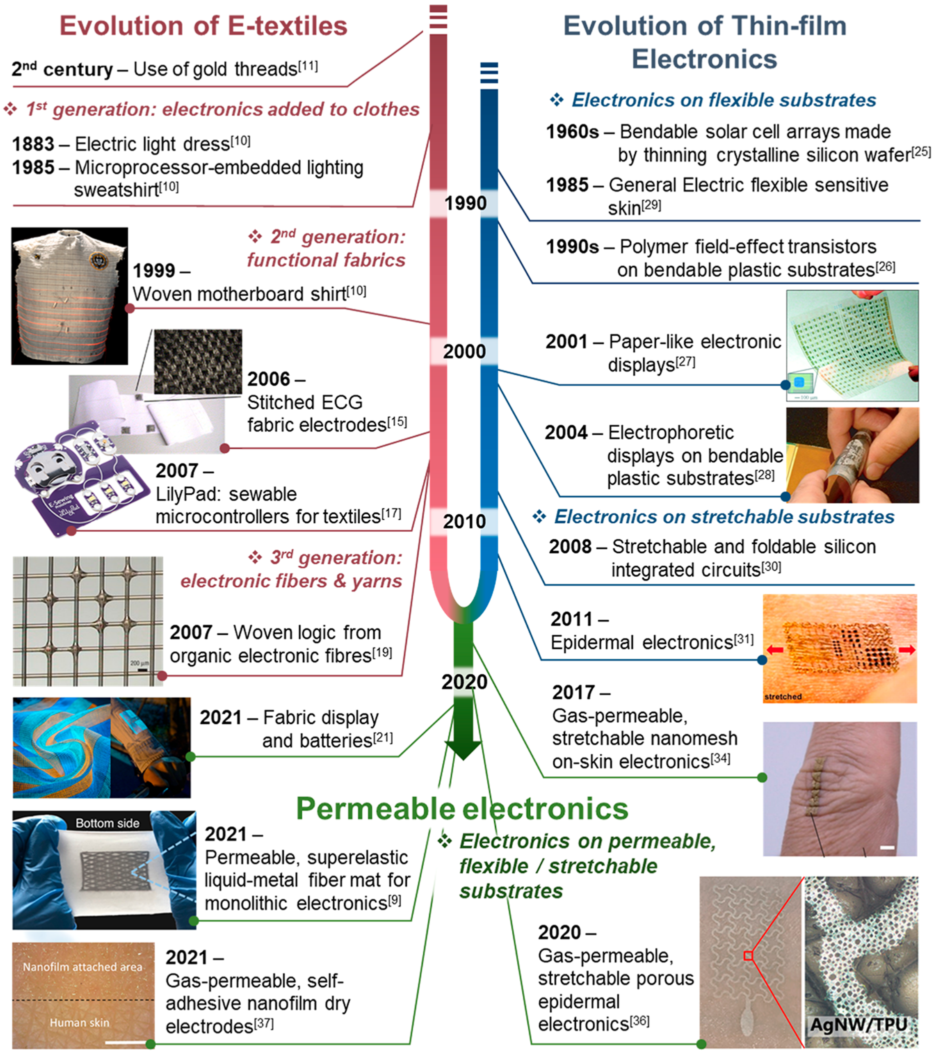

Figure 2. Historical development of wearable technologies toward permeable electronics. Image for "woven motherboard shirt" was reproduced with permission from ref 10. Copyright 2016, Springer Nature. Image for "stitched ECG fabric electrodes" was reproduced with permission from ref 15. Copyright 2006, Elsevier. Image for "lilyPad: sewable microcontrollers for textiles" was reprinted with permission under a Creative Commons Attribution 2.0 Generic (CC BY 2.0) License from ref 17. Copyright 2022, SparkFun Electronics. Image for "woven logic from organic electronics fibers" was reproduced with permission from ref 19. Copyright 2007, Springer Nature. Image for "fabric display and batteries" was reproduced with permission from ref 21. Copyright 2021, Springer Nature. Image for "paper-like electronic displays" was reproduced with permission from ref 27. Copyright 2001, National Academy of Sciences, U.S.A. Image for "electrophoretic displays on bendable plastic substrates" was reproduced with permission from ref 28. Copyright 2004, Springer Nature. Image for "epiderma electronics" was reproduced with permission from ref 31. Copyright 2011, The American Association for the Advancement of Science. Image for "gas-permeable, stretchable nanomesh on-skin electronics" was reproduced with permission from ref 34. Copyright 2017, Springer Nature. Image for "permeable, superelastic liquid-metal fiber mat for monolithic electronics" was reproduced with permission from ref 9. Copyright 2021, Springer Nature. Image for "gas-permeable, stretchable porous epidermal electronics" was reproduced with permission from ref 36. Copyright 2020, American Chemical Society. Image for "gas-permeable, self-adhesive nanofilm dry electrodes" was reproduced with permission from ref 37. Copyright 2021, National Academy of Sciences, U.S.A.

Importantly, standard silicon-based components have evolved into a form factor that is stitchable and mountable onto textile fabrics. The introduction of LilyPad Arduino, the sewable microcontroller released in 2007 and provided a pioneer computing platform for the design of interactive fashion and textiles.[16,17] Such an evolution resulted in a discrete series of rigid but small computing components that were distributed on the garment surface and interconnected with soft conductive tracks and electrodes at the fabric level, significantly enhancing the conformability of the electronics to textiles with better wearing comfort.[18]

Nevertheless, the use of bulky and rigid electronic components (e.g., controllers, batteries, signal processing units), and the coverage of packaging materials over a large area will affect the permeability of garments, which is unfavorable to long-term wearing. Rather than using fabrics as building blocks to assemble electronic devices and circuits, the third generation of E-textiles shifts to fabricating electronic fibers and yarns. In the past decade, a large variety of fiber/yarn-shaped electronic devices, such as transistor fibers, sensor yarns, illuminative filaments, and battery fibers, have been developed.[19−22] Braiding, stitching, weaving, or knitting these functional fibers/yarns provides a bottom-up approach to integrate various types of electronic functions ranging from sensing, display, and actuation to energy harvesting and storage in one fabric, while retaining the softness and permeability of textiles.

On the other hand, the effort to advance wearable technologies is also motivated by the rapid development of thin-film electronic technologies in recent years. In principle, anything thin enough is flexible, because of its bending strain that decreases linearly with the thickness of the material.[23] Silicon wafers are known to be rather rigid and inflexible, but they can be made flexible when they are thin enough (∼0.1 μm).[24] Bendable solar cell was fabricated by thinning the silicon wafer cells and then assembling them on bendable plastic sheets in the 1960s.[25] Since then, similar thinning strategies have been implemented in the fabrication of other types of flexible electronic devices, such as bendable thin-film transistors, bendable displays, and bendable physical/chemical sensors.[26−28] Advanced printing techniques such as lithographic printing, screen/stencil printing, and inkjet printing have also been extensively studied to enable the direct patterning of functional materials and devices onto flexible subtracts.[23,26] The integration of these thin-film devices on thin and flexible sheets allows the realization of artificial skins (or electronic skins, E-skins) mimicking human-like sensory capabilities; this concept was demonstrated by General Electric as early as in 1985.[29] This early generation of E-skins could be sensitively aware of the thermal changes and avert potential obstacles of their surroundings, exhibiting great application promise in artificial intelligence, prosthetic devices, and medical diagnostics.

However, bendable-only devices are difficult to achieve conformal on curvilinear biosurfaces of human skin/tissues, making them poorly suited for the on-skin/implantable applications with bioelectronic integrations. The recent decade has witnessed the expansion of research scope to developing stretchable types of thin-film electronics to mitigate the mechanical mismatch between electronics and biotissues.[4,23] Circuit systems integrated with different types of electronic components, such as multifunctional sensors, transistors, diodes, and capacitors, have been engineered into stretchable thin-film format through materials engineering and structural designs, enabling the formation of bioelectronics that effectively overcome obstacles associated with the curvilinearity, softness, and deformability of biotissues.[30−32]

It should be noted that bendable and stretchable thin-film substrates are unfavorable for long-term wear because of their very limited permeability. The idea of promoting permeable electronics thus is to achieve high water and gas permeability to electronics via hybridizing the fibrous/porous structured membranes with flexible or stretchable electronic devices. Ever since 2010, significant efforts have been made on engineering the function materials and devices into thin, lightweight, and fibrous/porous layouts with similar modulus, stiffness, and strain range to those of human skins/tissues, while maintaining the electronic multifunctionality and reliability.[33,34] Permeable electrodes, devices, and even integrated systems with flexibility, stretchability, and biocompatibility have been developed based on advanced nano/microfiber mat, permeable thin films, or even in a substrate-free manner.[9,34−37] Detailed strategies toward permeable electronics are discussed in the following section.

STRATEGIES FOR DEVELOPING PERMEABLE ELECTRONICS

Most of the functional materials for electronics, such as metal, semiconductor, and ceramic materials, exhibit poor permeability. They even show relatively high sensitivity to oxygen and moisture; their electronic performance may degrade when exposed to oxygen and moisture in the ambient environment.[38] To simultaneously achieve high permeability and reliable device functionality to electronics, functional materials and electrodes can be assembled onto a permeable but waterproof format, through which electronic components could be well protected, and meanwhile, sufficiently associate with gas/liquid analysts and allow for normal skin "breath". This will lead to an electronic system with well-encapsulated electronic components rationally distributed onto a permeable building block, retaining sufficient spaces for gas/liquid transmission, as illustrated in Figure 3.

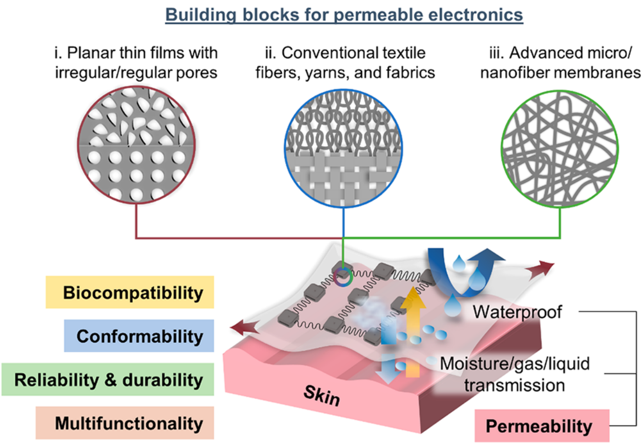

Figure 3. Schematic illustration showing the pathway to developing permeable electronics.

While waterproof encapsulation is mainly achieved by the coating of barrier layers onto electronics and has been extensively investigated in both electronic research and industry, the permeability of electronics is largely determined by the structural designs of the electronic materials, devices, and integrated systems. In this perspective, the specific focus will be placed on discussing the pathway of achieving permeability to electronics.

From the viewpoint of materials structure, the underlying mechanism to enable permeability is to fabricate the electrode components and their supporting substrates into forms that possess a sufficient number of pores with suitable pore sizes, thus allowing the diffusion of gas and moisture vapor/perspiration (molecular ∼0.3 nm in diameter) and/or the transportation of liquid/sweat droplets (molecular ∼100 μm in diameter) throughout the materials.[6] Given that body sweat is secreted from the glands at the skin surface, pore density of the covering materials (i.e., electrode, devices, and their supporting substrates) needs to be comparable to that of the sweat glands (varying from ∼100 glands/cm^2 on arms to over 300 glands/cm^2 on hands and feet).[39] While the diffusions of gas and moisture vapor are mainly dependent on the porosity and thickness of the material structures, the transportation of liquid/sweat is also significantly determined by the properties of the materials.[40] To date, the permeability of materials for wearable electronic applications is usually expressed by the water vapor transmission rate (WVTR) in grams per square meter and per hour ($g/m^2/h$) by following the testing standard ASTM E96 Cup Method. A higher WVTR value generally indicates a higher permeability to water vapor or perspiration. As a general guideline, the WVTR value of electronics designed for wearable/on-skin applications at least should be comparable to the average rate of insensible perspiration of human skin (i.e., > 20 g/m^2/h), so that skin could "breathe" normally without any discomfort or inflammation under the rest condition. However, considering the high perspiration rate (i.e., average ∼1000 g/m^2/h of a person) under the moderate exercise condition, coping with a high water transport rate of even more than 1000 g/m^2/h would be a reasonable target.[41] Such a sweat-permeable path with a high water transport capability could prevent the sweat-trapping-induced failure of electronic functions.[42]

Among various types of flexible and stretchable materials that serve as supporting substrates for electronics, thin films made of plastics (e.g., polyethylene terephthalate and polyimide films) or elastomers (e.g., polyurethane (PU), polydimethylsiloxane, Ecoflex) are regarded as impermeable materials with poor moisture vapor permeability and gas. Their WVTR values are typically <∼5 g/m^2/h, which are far below the rate of insensible perspiration in any position of the human.[9,33] One simple approach to achieving permeability is introducing pores to these substrates.[43] A variety of structure-modified methods have been adopted to engineer the porosity (Figure 3i), which particularly relied on sacrificial templates (e.g., easily dissolved materials such as sugar, ice, salts, and water droplets). For example, breath figure, a nature-inspired method facilitating the ordered assembly of water droplets, could introduce the porous skeleton with pore sizes of ∼40 μm to the stretchable PU film, enabling the formation of stretchable epidermal electronics with WVTR of 23 g/m^2/h.[36] Another approach to achieving permeability to thin-film materials is thinning the polymeric film to a nanoscale membrane. It has been reported that a 90 nm-thick thermoplastic elastomer nanomembrane made by the bubble blowing method could exhibit a high WVTR value of ∼24 g/m^2/h, so that the normal insensible perspiration of skin would not be impeded.[44] Although the permeability of thin films has been significantly improved, they are still less than the sweating rate of an average person under exercise. In addition, such ultrathin permeable electronics may suffer a weak signal-to-noise ratio and inferior stability due to the difficulties in device encapsulation, which may result in obstacles to practical applications.[3]

Compared to thin-film electronics, electronic devices fabricated on conventional textile materials including yarns and fabrics exhibit outstanding gas and liquid permeability due to their intrinsic three-dimensional fibrous configurations (Figure 3ii). Macro- and micro-scaled spaces in the intrayarn and interyarn regions of these textile materials provide a larger amount of permeable portion than those in planar films/membranes, so that gas and moisture vapor can diffuse more sufficiently and quickly. Conventional textiles such as knitted and woven fabrics exhibit high moisture vapor permeability with WVTR typically ranging from 20 to 250 g/m^2/h, which are highly promising substrates as building blocks for wearable electronics.[45] For example, the moisture vapor permeability of strain sensors that are made by the interlacement of conductive yarns could exceed 50 g/m^2/h.[46] Pressure sensing fabrics fabricated by the carbonization treatment on conventional hemp knitted fabrics could retain the intrinsic air and moisture vapor permeability (WVTR > 40 g/m^2/h).[47] Through the rational engineering of the fabric composition structures and the incorporation of hydrophilic/hydrophobic coating or multi-layered lamination, commercially available breathable fabrics with directional sweat transport capability can even allow a WVTR up to ∼460 g/m^2/h and the fast transport of sweat from one side to another.[48] However, electronic devices developed based on such types of fabrics with directional moisture vapor and fast sweat transport are very rare.[49] On the other hand, because of the interlacement (weaving) or interloping (knitting) of yarns within the fabric structure, the surface roughness of conventional fabrics was much higher than those of thin films. The extremely rough surfaces are difficult to realize in high-resolution device fabrication and integration. Although direct weaving or knitting of functional yarns into fabrics could form electrodes and devices with scales down to 10−100 μm (typical diameters of fibers and yarns for fabric formation is ∼10 μm and ∼100 μm, respectively) and retained permeability, the fabrication processes involve the sophisticated pattern designs of conductive connections that are less compatible with the microfabrication techniques of electronics.

The development of micro/nanofiber membranes as substrates is an effective approach to addressing the trade-off between permeability and the ease of high-resolution fabrication. To date, micro/nanofiber membranes are mainly fabricated by electrospinning techniques. Unlike the fibers in those conventional fibrous materials discussed in the previous session, the diameters of fibers in electrospun micro/nanofiber membranes are typically less than several μm or even smaller than several tens of nm. Such micro/nanofiber assemblies are expected to possess nano/micro-scaled texture with a very high surface-to-volume ratio, enabling the transport properties of membranes toward gas and moisture vapor (Figure 3iii). To date, various types of epidermal electronics and E-skin with functions of healthcare monitoring, energy harvesting, and storage have been developed based on these electrospun fibrous membranes.[50] All-nanofiber-based electric circuits integrated with sensors, transistors, and capacitors have also been fabricated by utilizing the conventional vacuum deposition method for biomedical applications.[51] Multilayered monolithic electronics with the integration of device multifunctionality have also been demonstrated by taking advantage of the high permeability of electrospun fiber membranes.[9] In general, the WVTRs of these fibrous-membrane-based devices range from 8 to 50 g/m^2/h at the ambient temperature, depending on the porosity and thickness of the membranes as well as the loading of electrode materials.[9,52,53] Moreover, through the special engineering of the hydrophilicity of the electrospinning materials and the configuration of the electrospun membrane, highly breathable, all-fiber-based membranes with outstanding directional sweat permeability could be obtained. In such a Janus composite structure, the hydrophilic outer layer can ensure the strong capillary force to drive the sweat away from the skin surface and then evaporate it rapidly under the condition of a large wetting area, while the hydrophobic inner layer can effectively block the reverse penetration of sweat to the skin to keep the human skin dry and comfortable. Epidermal electronics with a high WVTR of ∼73 g/m^2/h have been achieved recently by utilizing such a Janus hydrophilic−hydrophobic asymmetric membrane structure.[54]

The above discussion mainly focuses on the pathway to developing building blocks with permeable structures for the assembly of permeable electronics. Alternatively, one can implement the use of a substrate-free strategy for the development of permeable electronics, in which the device component (particularly metal electrodes) shall be engineered into an ultrathin, lightweight, and conformable configuration without any supporting substrate and shall be able to directly adhere to either skins or clothing. One typical example is to construct the metallic electrode into a serpentine or mesh structure and then directly transfer them onto the skin surface, allowing moisture and liquid to transport from the skin to the outside environment through the voided spaces of the electrode.[55] Substrate-free nanomesh electrode fabricated by evaporating a gold layer on a dissolvable electrospun poly(vinyl alcohol) (PVA) nanofiber membrane was reported. Dissolving the PVA nanofiber membrane could lead to the formation of a nanomesh-structured gold conductor bonding to the human skin, enabling long-term on-skin health monitoring without skin inflammation.[34,37] Though such a "tattoo-like" epidermal electronics could maximize the skin breathability in terms of sweat evaporation and heat dissipation, there are still concerns associated with the biocompatibility of electrode materials that are directly contacting human skins as well as the system integration with other electronic components.

In summary, the permeability of wearable and on-skin electronics can be achieved either by applying the permeable building blocks for the assembly of electronic devices or by engineering the electronic components into a permeable format with suitable porosity. Generally speaking, electrodes and electronics with a WVTR of ~20 $g/m^2/h$ are the underlying requirements for those applications in wearable or on-skin healthcare monitoring, therapy, and human-machine interacting activities (augmented reality and virtual reality under a rest situation). Regarding the wearable applications in extreme sweating conditions such as sports, high-temperature/high-humidity workplaces, and in-body scenarios with high fluid penetration, reaching a WVTR larger than 100 $g/m^2/h$ and even coping with a fast liquid/sweat transport rate over 1000 $g/m^2/h$ are highly promising. In this case, a special design for the materials and structures to enable the directional and fast transportation of moisture and sweat in permeable electrodes and devices is highly necessary. In addition, considering the influencing attributes for physiological comfort and device functionality, the permeability of electronics should also be reflected by their capability for gas diffusion and liquid transmission. Other than taking WVTR as the sole indicator to evaluate the permeability of materials and structure in the specific humidity and temperature conditions, methods for assessing gas and water transport properties, which are largely overlooked currently, should also be implemented. Standard testing methods for the air and liquid permeability of textile materials and polymeric films, such as ASTM D737-96 for air permeability of textiles fabrics, ASTM D1434-82 for gas permeability of plastic films, AATCC test method 42-2000 for water resistance of fabrics, and AATCC test method 195 for liquid moisture management properties of fabrics, can be adopted, which could provide a more throughout evaluation on the permeation performance of materials, electrodes, devices, and their integrated system.[6]

CONCLUSIONS AND OUTLOOK

Permeable electronics leverage electronic functionalities with physiological compatibility to the biosystems of human bodies. It provides a biocompatible device-human interface that can effectively facilitate long-term, continuous, and real-time health monitoring imperceptibly. This perspective outlines the rationale for developing permeable electronics, the historical development of wearable technologies, and the key strategies for achieving permeability to high-performance electronics. Despite the great potential, the practical applications and the commercialization of permeable electronics are still constrained by several key challenges associated with how to achieve high biocompatibility, good conformability, promising performance reliability and durability, and high device multifunctionality.

In laboratory development, most breathable electronics focus on the permeability and biocompatibility of the electrodes instead of the integrated electronics. There is still a lack of study on the symmetrical evaluation of the permeability and biocompatibility of the integrated device systems comprising various types of electronic components. A rational system design and arrangement of electronic components in a safe, permeable, and biocompatible manner thus is highly demanding. For on-body continuous healthcare monitoring, achieving conformability especially in a sweat environment over a long period of wearing or skin-attaching is of vital importance, which can ensure that the device function would not deteriorate over time or generate noise in electrophysiology. Permeable materials and structures have to offer flexing/stretching and adhesion characteristics that are similar to those of the targeting tissues, so that the assembled devices could be fully wrapped around or conformed to the human body for reliable and durable performance functioning. Considering the booming development of personalized healthcare systems and the constraint of the limited areas of human bodies, high-density integrations of different electronic modules, including various sensors, data processing units, energy supply units, and their circuit designs, into a stacked-multilayered monolithic configuration is of need. The permeability of electronic materials allows the analytes to travel through the multilayered layout of devices in a preprogrammed directional transport manner, which can promise the fabrication of a multifunctional electronic system with multilayered electrode designs and a high density of electronic functions.

With the importance and opportunities of permeable electronics in fundamental and applied research, future directions of wearable technologies would be to achieve biologically safe and compatible, mechanically conformal and reliable, superior multifunctional permeable electronic systems. We expect that intrinsically permeable and soft materials and structures, flexible and stretchable device designs, and micro/nanofabrication technologies that are compatible with flexible and stretchable electronics as well as multiscale human-device interface modeling will play significant roles in the future development of permeable electronics. In seeking the migration of permeable electronics out of the laboratory and into the practical application fields, intensive collaboration with experts from both academia and industries in engineering, clinics, biology, informatics, and product designs is highly required. As such, permeable electronics could be constructively utilized in combination with existing knowledge from flexible and stretchable electronics, microelectro-mechanical systems, information technologies, textile electronics, and healthcare realms for benefiting the development of wearable technologies in the years to come.

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Notes

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