doi:10.1038/nature21004

The rise of plastic bioelectronics

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Plastic bioelectronics is a research field that takes advantage of the inherent properties of polymers and soft organic electronics for applications at the interface of biology and electronics. The resulting electronic materials and devices are soft, stretchable and mechanically conformable, which are important qualities for interacting with biological systems in both wearable and implantable devices. Work is currently aimed at improving these devices with a view to making the electronic–biological interface as seamless as possible.

Almost all commercially available bioelectronic devices[1–6] rely on silicon microelectronics, which is the workhorse for modern information infrastructure and technologies, including healthcare and medical devices. Indeed, many current medical implants and devices such as pacemakers, electrocardiogram sensors and smart endoscopes rely on silicon microchips[5,6]. Advances in the miniaturization of silicon microelectronics with nanometre-scale accuracy have reduced the size of these electronic modules, allowing them to be used for single-point health monitoring. This change has been made possible by the rigidity and mechanical stability of the inorganic materials used.

Creating the next generation of implantable or wearable electronics will require the introduction of new features, however, including mechanical flexibility (Box 1), large-area and facile processing of thin films, controlled biological properties, and mixed electronic and ionic conductivity. Mechanical flexibility is particularly important for device components that are in direct contact with certain areas of the skin or soft tissue to minimize the discomfort of worn or attached electronics. Regardless of whether the active devices are made of inorganic, organic or hybrid materials, the use of plastic films as substrates affords significant weight and thickness reductions while maintaining mechanical robustness and flexibility[7]. In contrast to silicon semiconductors, using inherently soft electronic materials that have a low Young's modulus to directly contact biological tissues can minimize adverse reactions, owing to the improved mechanical compliance between the tissue and the implanted device[8,9].

As well as providing favourable mechanical properties for interfacing with biological tissue, plastic electronics offer the potential for large-area, multimodal, multipoint sensing or stimulation on curvilinear surfaces[7,10] (Fig. 1). Indeed, the use of organic semiconducting polymers has rapidly expanded from flexible displays[11,12], which have already been commercialized, to more advanced (and bidirectional) devices such as flexible, stretchable sensors — so-called artificial skins[13,14]. The challenge in moving from flexible displays to sensing functions is to find a way of monitoring the complex, dynamic structures of biological organs over a large area with high spatial and temporal resolution. Flexible large-area organic circuits with an active-matrix design can already be used to reduce both power consumption and the amount of wiring involved relative to 'traditional' electronic devices[13,14].

Furthermore, the diversity and synthetic tunability of plastic materials are expected to allow features such as biodegradability[15] and printability[16], while maintaining the benefits associated with their softness and flexibility. The stimulus responsiveness of plastics also affords natural conformability to three-dimensional (3D) surfaces and changes in shape, and allows on-demand self-repair[17]. The printability of polymers is another favourable attribute for cost-competitiveness and ease of customization[7]. Cost is always a major consideration when it comes to commercialization, but disposability is the most effective way of avoiding infections in hospitals, and that can be costly. Customization is particularly important in clinical applications, as it enables devices to be made to suit the needs of individual patients. Finally, mixed electronic and ionic transport in conducting polymers also allows coupling with ions in biological media, enabling low-impedance contacts for efficient electrical recording and stimulation[18,19]. Ionic transport in polymers can also enable drug delivery through processes such as passive leaching or even electrophoretic transport[20].

This Review will discuss the latest progress in the use of soft electronic materials and their related devices in biological interfaces, and highlight future research directions and challenges that remain to be overcome. We emphasize recent work that harnesses properties that are unique to polymeric electronic materials, and consider the corresponding benefits to bioelectronics. We also briefly discuss synergies with high-performance inorganic electronic materials, which are complementary and can be used cooperatively for hybrid bioelectronics.

Developments in materials

The biological interface of organic electronics is a relatively recent development, but organic electronics have been intensively studied and developed over the past half-century. They have been used in commercial applications such as photoconductors in photocopying and laser printing, electrochromic films, anticorrosion and antistatic coatings based on conducting polymers, organic light-emitting diode (OLED) displays and lighting, organic photovoltaic cells (OPVs) and organic thin-film transistors (OTFTs)[10]. Some conducting polymers have been shown to achieve metallic transport behaviour[21–24], and charge-carrier mobilities of more than 10 $\mathrm{cm^2\,V^{-1}\,s^{-1}}$, which rival that of poly-Si, have been reported for organic semiconductors[25–27]. The progress made towards soft implantable and wearable devices relies not only on these advances in conducting and semiconducting polymers, but also on additional biomimetic properties, such as stretchability, self-healing and biodegradability (Fig. 2).

Stretchability is essential for comfort while wearing, for intimate attachment to curved surfaces and moving parts, and for the

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BOX 1

Developing materials for soft interfaces

It is difficult to develop materials for soft interfaces because electronics and semiconductor devices are typically made of silicon and inorganic semiconductors, which are rigid (they have a high Young's modulus of about 100 GPa), whereas biological tissues have a much lower Young's modulus (from 10 GPa for bone to 1 kPa or less for brain tissue)[102,103]. In an attempt to introduce mechanical flexibility into health-monitoring systems, components that use very thin silicon membranes and/or chips embedded in thin polymer films have been proposed and demonstrated[98, 104,105]. One example is electronic tattoos, in which a silicon microchip a few micrometres thick, which is both flexible and stretchable, is laminated directly on the skin[104]. Similar flexible and stretchable devices that have inorganic membranes can be used in devices to be implanted in the brain, heart and other organs[106,107]. It has been recognized that mechanical flexibility can be achieved by using thin membranes of silicon or other inorganic semiconductors. However, reducing the size of silicon vertically or laterally does not change the Young's modulus, and there will still be a large mismatch in the mechanical properties of inorganic materials and biological tissues.

Material	Young's modulus	Strain-to-break
Silicon	130 GPa	1%
Bone	~20 GPa	1%
Plastics	1 GPa	5%
Elastomer	0.01–10 MPa	50–4,000%
Gel	1–1,000 kPa	10–2,000%
Brain	<1 kPa	20%

maintenance of mechanical robustness. Indeed, strain tolerance of more than 80% is required for devices that are mounted on the knuckle, and more than 50% for those worn on the knee joint. A combination of organic devices on ultrathin plastic substrates and prestrained elastic substrates yields stable electrical properties under repeated strain in excess of 100% (refs 28–30). Plastic nanocomposite electronic materials are showing promising performance as stretchable conductors. For example, metal nanowires, metal nanoparticles and nanoflakes, carbon nanotubes, graphene and combinations of these have been incorporated in stretchable plastic materials to achieve both conductivity above 100 $\mathrm{S\,cm^{-1}}$ and high stretchability of up to 100% strain[31–36]. Some have also been found to have a 'programmable' response, in which the nanomaterials exhibit nanoscale buckling after the first strain release. Subsequent stretching to the same initial strain level maintained about the same conductance, even after thousands of stretch–release cycles[31]. However, if rigid 'island' structures are connected with stretchable wires, even larger strain tolerance on the wires will be required than if inherently stretchable wiring or conductors were used. Some recently reported materials can maintain a conductivity above 100 $\mathrm{S\,cm^{-1}}$, even at above 100% strain[32]. Conductivity values greater than 100 $\mathrm{S\,cm^{-1}}$ are sufficient for most practical sensors, but much higher conductivity is needed for neural stimulators. Plasticizers have been found to significantly reduce the elastic modulus of poly(3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT:PSS) and significantly increase the stretchability[37,38], but the addition of a plasticizer reduces the conductivity of the resulting polymer. It will be important to find a way of maintaining the same conductance under different strain levels for polymer conductors.

For the semiconducting components of devices, regio-regular poly(3-hexylthiophene) (P3HT) and its block copolymer with polyethylene can be plastically deformed to strains of more than 300% (ref. 39), although their charge-carrier mobilities are low, around $10^{-2}\,\mathrm{cm^2\,V^{-1}\,s^{-1}}$ at only 0% strain; further significant irreversible decrease has been observed under strain. Some polymers have been found to exhibit higher mobilities and less reduction under strains of about 100%. However, the reversibility and strain–release cycling stability of organic semiconducting materials still need to be improved[17,40,41]. Semiconducting carbon nanotubes and semiconducting polymer nanofibres have been shown to maintain charge-carrier mobilities and endure high strains of up to 100%, and semiconducting carbon nanotubes can also maintain high mobility[34,42,43].

Biodegradability and self-healing are also required if plastic bioelectronics are to have more-biomimetic properties. So far, the development of biodegradable plastic electronics has focused mainly on making devices on biodegradable substrates, regardless of the active materials. This is because the substrate constitutes more than 99% by weight (wt%) of the entire device, including sensors and electronic circuits. Biodegradable substrates that have commonly been used include aliphatic polyester-based biodegradable polymers, silk and cellulose[44–47]. Several metal electrode materials have also been found to be biodegradable and biocompatible under certain conditions[48]. These have been combined with biodegradable substrates and used in implantable medical devices[48,49]. Additionally, thin silicon membranes have been found to give high-performance bio-resorbable electronics, providing new opportunities for bioelectronics[50–52]. By contrast, only a limited number of biodegradable and biocompatible conducting and semiconducting organic materials have been reported so far. Attempts are being made to design and develop synthetic biodegradable conducting polymers. However, the conductivity values (currently at $10^{-4}\,\mathrm{S\,cm^{-1}}$) still need to be improved significantly[53].

Self-healing is essential for biological systems, and incorporating some form of autonomous and repeatable self-healing into electronic devices would enhance their robustness and durability, allowing them to be used in long-term implants and devices. But only a few studies have investigated self-healing in electronic devices, so there is an opportunity to make great improvements. Self-healing can be readily achieved by incorporating dynamic bonds in insulating polymer gels, such as hydrogen bonds, electrostatic interactions, and metal–ligand bonds[54]. One study has reported a self-healing conducting polymer with conjugated cores crosslinked by reversible bonds between *N*-heterocyclic carbenes and transition metals[55], although the conductivity of the polymer is only around $10^{-3}\,\mathrm{S\,cm^{-1}}$. Composites of metal particles and self-healing polymer are the most likely candidates to achieve both high conductivity and autonomous repeated healing. There have been reports of the potential applications of such materials, such as electronic skin, transparent electrodes, and binders for battery electrodes[48,49,54–58].

Current applications

Two main areas for plastic bioelectronics are currently being pursued: wearable (non-invasive) devices and implantable devices.

Wearables and beyond

The super-conformability and stretchability of ultrathin-film plastic devices make them ideal for use in the next generation of wearables, which will be attached directly to the living, moving surface of human skin[28]. Electrically, these materials have been demonstrated in electronic artificial skin (e-skin) with the use of organic transistors, for possible applications in robotics[13]. In this development, scalable circuits, which are designed for use in stretchable large-area sensors, use organic active matrices to measure pressure and temperature distributions[13].

Regardless of where wearable electronics are attached, there are two features of plastic and organic electronic devices that make them particularly well suited for use in wearable devices: their excellent mechanical durability, and their potentially large area. Various plastic and organic electronic devices, such as OTFTs[28], OLEDs[29] and OPVs[59], have been fabricated on 1-μm-thick film substrates, which are just a

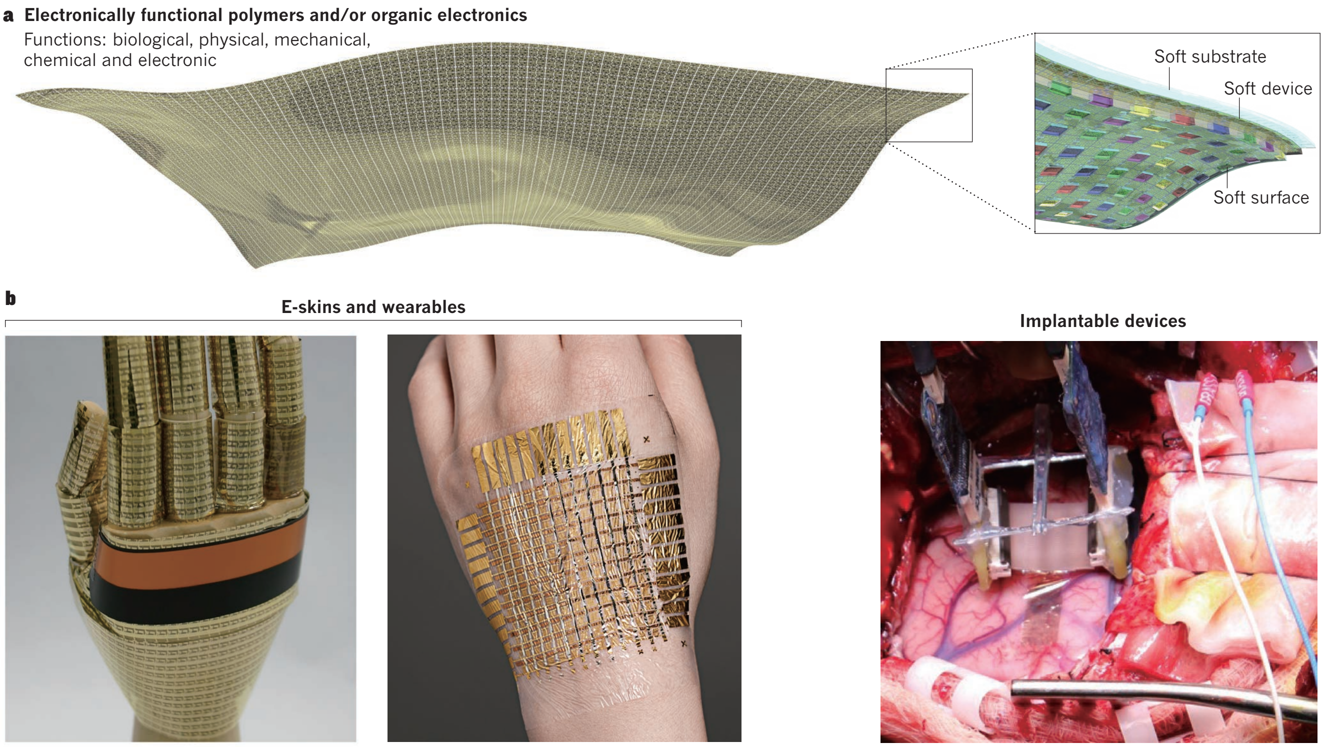

Figure 1 | The diversity of plastic bioelectronics. Electrically functional polymers and organic electronics provide a multifunctional, soft bio-interface. **a**, Polymers may have physical functions (thermal, acoustic and photonic), chemical functions (from surface modification and chemical interactions), mechanical functions (adhesiveness and softness), electronic functions (electric sensing and stimulation) and biological functions (biocompatibility). **b**, Plastic bioelectronic devices have a range of applications. Left, a flexible sensor array that detects pressure can be laminated on a robot's hands as artificial skin (e-skin)[13,14]. Reducing the thickness of sensor arrays to 1 μm allows devices to be ultraflexible, ultralightweight and stretchable, so they can be applied to the human body[28,100]. Right, plastic bioelectronics can be implanted for neural recording, drug delivery and cell control, for example[83].

tenth of the thickness of kitchen wrap. Reducing the thickness of the substrate reduces the weight of the device and improves its bendability and conformability, because the strain induced by bending the film decreases proportionally as the thickness is decreased. These organic integrated circuits have been found to exhibit extraordinary robustness despite being super-thin — indeed, their electrical properties and mechanical performance were practically unchanged, and no degradation was observed, when they were squeezed to a bending radius of 5 μm, dipped in physiological saline, and stretched to up to double their original size.

To collate, compute and communicate the vast amount of data acquired by wearable sensors, flexible digital circuits such as processors[60], shift registers[61] and memories[62], as well as wireless circuits[63], have been developed. Although many state-of-the-art wearable devices are connected to rigid digital circuits, such flexible elements should be chosen appropriately and integrated with rigid, high-performance, inorganic semiconductor devices, so that the mechanical and electronic requirements may be satisfied simultaneously. In addition to digital and wireless circuits, analogue circuits, such as amplifiers, may also be required, because of the low magnitude of biological signals, which typically range from tens of microvolts in electroencephalography to millivolts in electrocardiography. To position the first-stage amplifier as close as possible to where the signals are generated, flexible amplifiers with a power gain exceeding 50 dB for a bandwidth beyond 1 kHz have been reported[64].

As well as semiconductor devices, there are various types of unique polymeric sensor. For bioelectronic applications, such sensors are broadly classified into two categories: physical sensors, which measure temperature, pressure, strain and light, for example; and (bio-)chemical sensors, such as ion, DNA, metabolite and protein sensors. Physical sensors are made from polymers to provide softness, which enables the measurement of pressure sensitivities of up to a few pascals[65,66]. These sensors are most sensitive at about body temperature[67,68]. Conversely, (bio-)chemical sensors use the material diversity and synthetic flexibility of polymers to achieve greater specificity and sensitivity. Polymer transistors modified with odorant-binding proteins can provide sensitive and quantitative measurement of the weak interactions associated with neutral enantiomers[69], and allow for the sensitive and dynamic monitoring of cells for toxicology[70] without requiring reporter molecules. Chemical information such as oxygen concentration in the blood can be measured by using organic photonics comprising OLEDs and organic photodetectors (OPDs)[71,72].

Plastic integrated circuits and devices can be manufactured in large numbers by printing on large-area plastic films. Transistors with submicrometre channels have also been fabricated by surface modification and inkjet printing[73]. Furthermore, a prototype of a wearable electronic circuit was recently printed on a 1-μm-thick film by exploiting the film's thinness and large area[74]. In the age of the 'internet of things', the ability to customize wearable sensors will lead to an increase in 'on-demand' digital fabrication, and a combination of 3D and inkjet printing is likely to be crucial to meeting these needs.

Implantable devices

Implants traditionally rely on hard electronic materials, but these often elicit a 'foreign body' response, which limits their lifetime. This is a major limitation of neural implants, which have been developed for research purposes, for the diagnosis and treatment of various pathologies such as epilepsy and Parkinson's disease, and for brain–machine interfaces that seek to restore lost function. A typical example is the use of microfabricated silicon shuttles, which have metal electrodes that penetrate the brain and record neural activity. The use of soft organic coatings on the metal electrodes is being explored as a strategy for improving stability[75]. Tuning the mechanical properties of these coatings leads to a variety of forms, including hydrogels that have

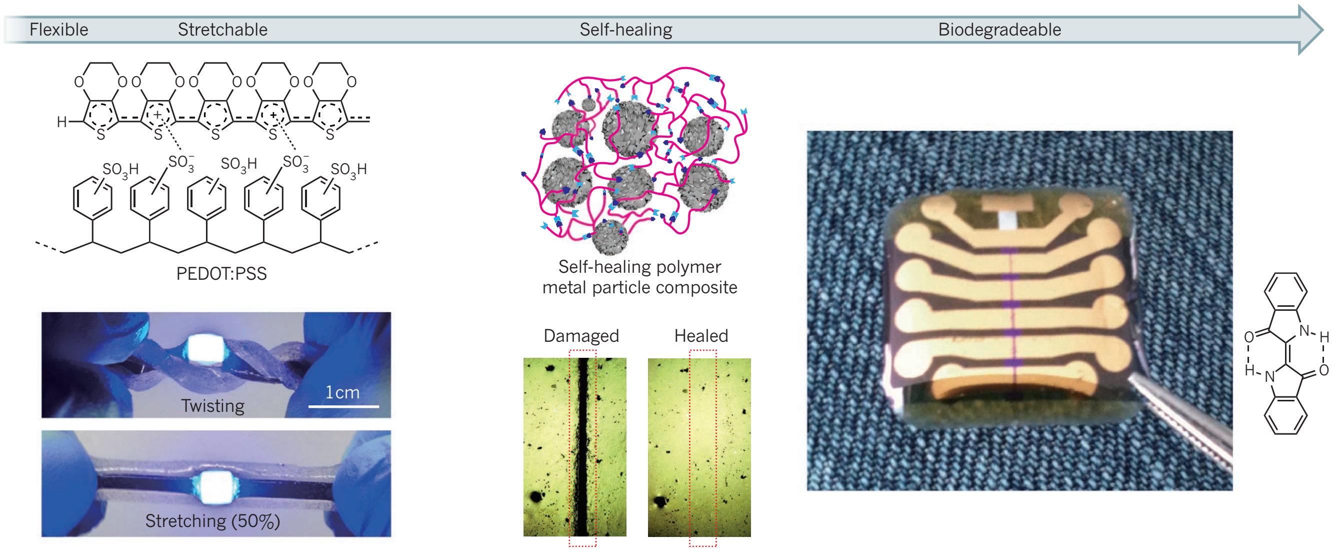

Figure 2 | Soft electronic polymers for plastic bioelectronics can be stretchable, biodegradable and have self-healing properties. Left, chemical structure of the conducting polymer PEDOT:PSS, which can be made stretchable by adding a surfactant[38]. Reproduced with permission of Wiley-VCH Verlag from ref. 38. Middle, a self-healing conductive material made from a self-healing polymer and nickel particles with nanospikes[58]. Right, a sheet of organic field-effect transistors made with natural and biodegradable materials: shellac substrate, aluminium oxide and tetratetracontane dielectric, and indigo semiconductor. Electrodes were made of aluminium and gold. Reproduced with permission of Wiley-VCH Verlag from ref. 101.

mechanical properties similar to those of brain tissue[76]. In some situations it is possible to harness the soft nature of polymer substrates to replace the hard shuttle altogether. Such implants can be inserted in the brain by using a temporary shuttle that is removed after insertion[77], or they can be placed on the brain or on a nerve where they can access neurons close to the surface. Using only polymer substrates can reduce the mismatch of mechanical properties at the biotic–abiotic interface, resulting in longer-lasting implants. This has been demonstrated by silicone-based spinal-cord implants with stretchable metal electrodes, which show excellent bio-integration with the central nervous system[78].

Using polymer coatings can improve the mechanical properties of devices, but it can also significantly lower the impedance of metal microelectrodes and enable high-quality recording and efficient electrical stimulation of neurons in laboratory animals[79–81]. The uptake of ions from the biological environment into electronic polymers is exploited in organic electrochemical transistors for signal amplification. This improves the signal-to-noise ratio of brain recordings, as shown in animal-based models of epilepsy[82]. Most of the research has concentrated on using such coatings on hard, penetrating shuttles that help to access different areas in the brain, and combining them with soft, conformable polymeric substrates has been particularly effective for interfaces with the cortex. The use of PEDOT:PSS microelectrodes on thin poly(p-xylylene) film has provided single-neuron recordings from the surface of a rat's brain[83]. Because these devices do not penetrate the brain, they are already being used on human patients diagnosed with epilepsy for high-resolution intraoperative recordings. More recently, PEDOT:PSS electrodes have been combined with flexible electronics and sensors on silicone elastomers that were cast and cured on 3D models of the epicardium. These hybrid devices showed improved electrical recording characteristics in animal models[84]. Finally, transparent graphene electrodes integrated with poly(p-xylylene) substrates have been shown to enable the simultaneous use of various optical techniques including optogenetics, fluorescence microscopy, and 3D optical coherence tomography[85].

The flexible fabrication offered by organic materials has led to new ways of interacting with living systems. For example, *in situ* polymerization of conducting polymers in the brain is seen as a potential way of rebuilding the charge transport pathways across the glial scars caused by an implant. PEDOT that is grown in the hippocampus of rats does not seem to disable their memory, as observed by the way they navigate a maze[86]. Conducting polymers grown inside hydrogels and seeded with live cells are also being developed with the objective of creating 'living electrodes' that can establish new neural connections between an implanted device and the brain[87].

The delivery of drugs such as neurotrophins and anti-inflammatory molecules *in vivo* is being used to reduce the inflammatory response to a foreign-body implant, and more generally for controlled drug delivery past the blood–brain barrier. Polypyrrole-coated electrodes loaded with neurotrophin-3, for example, can be used for the simultaneous electrical and biochemical stimulation of cochlear neurons. Using a guinea-pig model, the release of neurotrophin-3 was shown to have beneficial effects on the auditory brainstem response threshold and on the density of the spiral ganglion neurons that survive implantation[88]. In addition, a device called an organic electronic ion pump (OEIP) uses plastic electronics to achieve the dry electrophoretic delivery of ions from a reservoir to a target tissue. And OEIPs that deliver neurotransmitters have been used to tune the sense of hearing[20], reduce pain[89] in animal models, and stop epilepsy-like activity[90] in a brain-slice model.

Nerve regeneration and repair is another emerging application of plastic bioelectronics. This work is motivated by the *in vitro* demonstration that electrical stimulation through a conducting polymer can enhance the outgrowth of neurites[91]. *In vivo* electrical stimulation of sciatic-nerve defects in a rat model by using conducting polymer scaffolds has also been shown to promote axonal regeneration and remyelination[92].

Many other devices have been tested *in vitro* and are being developed for use as implantable devices in the clinic. These include a variety of physical and biological sensors that can be used for multimodal sensing. For example, a conformable thermal sensor has been developed[67] that uses organic circuitry on a plastic substrate to resolve spatial temperature gradients on the surface of a lung. When combined with electrophysiology, such devices can provide valuable information about the functioning of the human body. Other examples include devices that use conducting polymers to electrically control cell adhesion[93] and signalling[94]. Devices of this sort are potentially applicable to the diagnosis and treatment of diseases such as cancer, and the engineering of tissues for organ regeneration and replacement. Other examples include photoconducting, conjugated polymer-based layers, which show promise for the restoration of vision in explants of blind rat retinas[95]. All these devices bring unique capabilities to the interface with biology that go far beyond simple electrical recording and stimulation of neurons. Coupling them with soft polymeric substrates may deliver advanced 'multi-implants' that could one day potentially be inserted under the skin or be implanted deeper in the body through minimal openings, or even be injected by a syringe[96].

Challenges and prospects

The first tangible goal of plastic bioelectronics is the development of next-generation user interfaces for machines, and the second goal is advanced health care. With regard to the first goal, comfortable controls for prosthetic limbs and skeleton robot suits are needed to develop a system that can estimate the exact amount of force required to perform a task. And the accurate monitoring of sensations and emotions will have an important role in the creation of intelligent robots that can perceive human feelings and respond accordingly. In these applications, plastic electronics can be used to monitor and stimulate the skin, using a vast number of sensors. Direct control by a brain–machine interface could be possible if a large-area, high-density implantable plastic multiplexing system is used to connect electronics with neurons in the brain. Devices for medical applications will largely use the same platform as non-medical plastic devices, although the goals of the two types of device will differ. For healthcare devices, minimum invasiveness is required, but it is essential to maintain function and high performance.

Efforts aimed at implementing biologically inspired principles of operation will require systems with different architectures from conventional von Neumann systems, in which the physical separation between processing and memory limits throughput. Such systems would be adaptive, fault tolerant and would require little power, making them suitable for handling signals from a variety of biosensors. Indeed, electronic touch sensors have recently been used to transform the intensity of pressure signals to frequency-modulated spiky signals, which are characteristic of animal skin and nerve cells in general (including brain cells), and even to directly stimulate the brains of mice[97].

But several scientific and engineering challenges need to be overcome before we can fully exploit the benefits of plastic bioelectronics in practical devices. For a start, we currently have only a limited understanding of electronic–biological interfaces, so it will be important to have a theoretical model of complex systems that include water and ions. We also need a better understanding of the interplay of molecular design rules if we are to incorporate multiple functions of soft materials, such as charge transport, stretchability, degradation control and self-healing. Because plastic bioelectronics is a new and multidisciplinary field, it is expected to dovetail with other emerging fields, such as microfluidics[98] for drug delivery, and the study of induced pluripotent stem cells for regenerative therapy, for example.

From an engineering viewpoint, one of the biggest challenges facing plastic electronics — particularly plastic bioelectronics — is data analysis, because they generate large amounts of new types of data. Recently developed methods for handling huge amounts of data, and machine-learning technology, will be required for the analysis of the enormous amounts of data flowing in from the biosensors that are being deployed in this emerging field. Potential applications for bioelectronic devices, such as high-resolution neural recording of the brain, and 24-hour monitoring of metabolite and disease-marker concentrations in the blood, will generate complex data, which must be analysed to determine their biological meaning.

The long-term environmental stability and mechanical durability of plastic devices must be improved, and devices on the skin and other organs will need to be permeable to gases and moisture. Some bioelectronic devices require direct contact with aqueous media that contain large concentrations of salts, proteins and other biological molecules, and this must not affect their ability to function. So several questions remain about the long-term chemical and physical stability of exposed electronic surfaces and the effects of the body on their electronic and mechanical properties. Finding solutions will require the use of materials that are stable when exposed to air and water for the parts that make contact with the biological environment, and encapsulation technologies are needed to protect the parts that do not. A plastic device by itself is mechanically durable, but there is a need to ensure the mechanical robustness of the entire system by establishing reliable electric interconnections between the soft elements (such as conductive gels and stretchable conductors) and the rigid elements (miniature batteries and silicon wireless chips).

The development of large-volume production facilities is also important for the creation of a new industry. In particular, handling ultrathin and rubbery substrates is a big challenge. Having disposable plastic sensors would substantially reduce the risk of infections in hospitals, especially for devices that directly touch the skin, but the production of such components must be cost-effective. Ultimately, high-throughput production lines need to be developed by combining roll-to-roll processes with digital fabrication, such as inkjet printing, to achieve self-alignment and fine resolution on plastic substrates, which are easily deformed. Once such production lines are established, printable inorganic materials such as carbon-nanotube inks and solution-processed polycrystalline silicon, as well as semiconducting polymers, can be used to further improve the electronic performance of large-area sensors[99].

Finally, non-technical issues will also have a bearing on future developments in plastic bioelectronics. The ethics of data collection, storage and analysis is a challenge facing products developed for the internet of things, especially for devices that regulate or monitor human health, regardless of whether they are based on plastic or other materials. Non-technical issues also have a major role in determining the commercial viability of any new biomedical or clinical use, especially for implantable devices. The biocompatibility of devices made from new materials requires strict evaluation, leading developers to be conservative in adopting new materials, especially in implanted devices. For this reason, the first clinical applications of plastic bioelectronics are likely to be *in vitro* diagnostics or cutaneous devices. The subsequent demonstration of significant gains in performance (for example, a lower-impedance conducting polymer coating that extends the battery life of a stimulator) and the enabling of new capabilities (such as a low-impedance coating that is capable of drug delivery) will provide strong incentives for implant manufacturers to adopt plastic bioelectronics, and accelerate support from doctors and patients.

The ultimate goal of plastic bioelectronics is the development of seamless, bidirectional interfaces between humans and machines. A huge number of challenges face materials and devices for large-area, multipoint and multimodal sensors on 3D curved, dynamically moving, living objects. But synergies between plastic or organic materials and high-performance inorganic materials for hybrid devices will accelerate and expand the development of bioelectronics. And one day it will seem normal to have a bionic interface and to interact with plastic bioelectronics as an integral part of the body. ■

Received 9 December 2015; accepted 1 September 2016.

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Acknowledgements The authors acknowledge R. Nawrocki for fruitful discussions and J. Xu for help with formatting.

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