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The mission of the National Academy of Engineering is to advance the well-being of the nation by promoting a vibrant engineering profession and by marshalling the expertise and insights of eminent engineers to provide independent advice to the federal government on matters involving engineering and technology.

Mechanics, materials, and microfabrication techniques have advanced the design and manufacture of flexible and stretchable electronics, which will likely revolutionize health care and human-machine interaction.

Mechanics, Materials, and Functionalities of Biointegrated Electronics

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Robust bioelectronic interfaces present unlimited potentials in wearable health monitors, implantable devices, and human-machine interfaces. But conventional high-performance electronics, which are based on planar and rigid silicon wafers, are intrinsically incompatible with curvilinear and deformable natural organisms. This challenge is being approached with a mechanics-based strategy involving the use of neutral planes and filamentary serpentine networks. The resulting structural-electrical design has enabled flexible and stretchable electronics to conform to—and deform with—biological tissues for physiological sensing, programmable stimulation, and on-demand therapeutics. This article summarizes the mechanics, materials, and functionalities of such biointegrated electronics and concludes with a discussion of future directions.

Background

Research on flexible electronics started nearly two decades ago (Bao et al. 1997; Garnier et al. 1994) with the demand for macroelectronics (i.e., large-area electronics), such as paperlike flexible displays (Rogers et al. 2001). Early research focused on organic semiconductors and conducting polymers because their intrinsic deformability, light weight, and low manufacturing cost are appealing for large-area flexible electronics, especially when merged with roll-to-roll processes (Forrest 2004). Methods to synthesize, pattern,

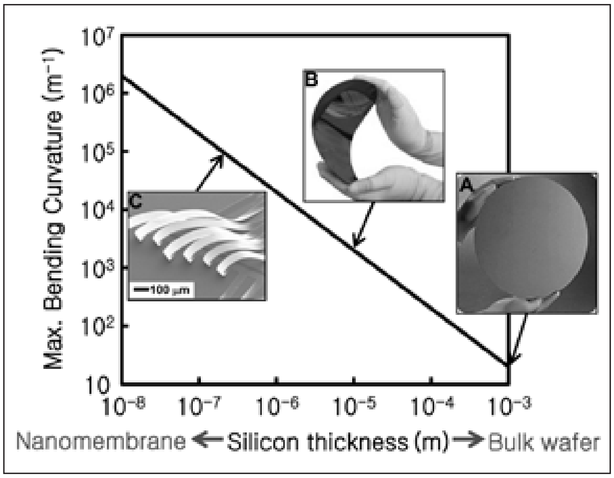

FIGURE 1 Maximum allowable bending curvature is plotted as a function of silicon plate/membrane thickness, with insets showing the bendability of (A) a bulk silicon wafer, (B) a silicon thin film, and (C) silicon nanoribbons. Reprinted from Kim et al. (2012a) with permission from Nature Publishing Group.

and passivate organic electronic materials (Forrest and Thompson 2007; Menard et al. 2007) were then developed and applied to the manufacture of devices such as organic solar cells (Kaltenbrunner et al. 2012; Lipomi et al. 2011) and artificial electronic skins for robotics (Mannsfeld et al. 2010; Someya et al. 2004; Takei et al. 2010), and flexible displays based on organic light-emitting diodes are nearing commercial reality.[1]

But the chemical instability of organic semiconductors and difficulties associated with low electronic performance have somewhat limited their application in high-speed, low-power, or long-lasting electronics. In contrast, inorganic semiconductors exhibit high carrier mobility and on-off ratio as well as excellent chemical stability in ambient environments (Service 2006). Furthermore, the material and electronic properties of inorganic semiconductors and metals have been well defined and the manufacturing processes well established after more than 100 years of research and applications. Thus flexible electronics based on rigid but high-quality monocrystalline inorganic semiconductors started to emerge in the mid-2000s (Khang et al. 2006).

To overcome the rigidity of inorganic electronic materials, thin film mechanics has been applied to enhance the deformability of polymer-bonded metallic and ceramic membranes.

[1] As evidenced in a promotional Samsung video, www.youtube.com/watch?v=N3E7fUynrZU, presented at the International Consumer Electronics Show (CES), January 8–11, 2013.

Mechanics: Bendability and Stretchability of Inorganic Electronic Materials

Inorganic materials such as silicon and metals are stiff and readily rupture or yield when their intrinsic strain exceeds even very small values, such as 1 percent. But the mechanical limit of a structure can be offset by the geometry of the construction even for intrinsically fragile materials.

Basic beam theory predicts that the bending-induced maximum strain of a membrane is proportional to the product of film thickness and bending curvature. If the maximum strain is limited to a critical strain to rupture of the material (e.g., 1 percent), the maximum allowable bending curvature will be inversely proportional to the thickness of the silicon plate/membrane, as shown in the log-log plot of Figure 1. As the membrane thickness decreases from millimeters to tens of nanometers, the attainable bending curvature can be enhanced by five orders of magnitude. As a result, although bulk silicon wafers are rigid plates, silicon nanomembranes (with a thickness of ~100 nm) can be readily arched to the radius of a folded paper (~0.1 mm) without rupture, as shown in Figure 1C.

Building on this unprecedented bendability, silicon nanomembranes can be made stretchable by applying two prevailing design strategies. One strategy calls for bonding flat nanoribbons to a prestretched elastomeric substrate to produce wrinkled nanoribbons (represented in Figure 2A) (Khang et al. 2006; Kim et al. 2008a; Sun et al. 2006). When the prestretch is released, the elastomeric substrate fully retracts, inducing out-of-plane sinusoidal buckling in the nanoribbons in a mechanism similar to the Euler buckling of an elastic rod under axial compression. Nanomembranes bonded to biaxially prestretched elastomeric substrates form two-dimensional wrinkled patterns as shown in Figure 2B (Choi et al. 2007). Buckling instabilities involving large displacement but small strains are the desired outcome in stretchable electronics.

With the other strategy, isolated rigid islands linked by buckled linear metallic ribbons (Figure 2C) can be stretched up to 40 percent without mechanical failure (Kim et al. 2008b; Ko et al. 2008; Lee et al. 2011). When serpentine ribbons (Figure 2D) are used instead of linear ribbons, stretchability of the system can vary from 10 percent to 300 percent depending on the serpentine tortuosity (Kim et al. 2011a,b; Xu et al. 2013).

Both wrinkling and serpentine strategies have proven effective in keeping strains in inorganic semiconducting

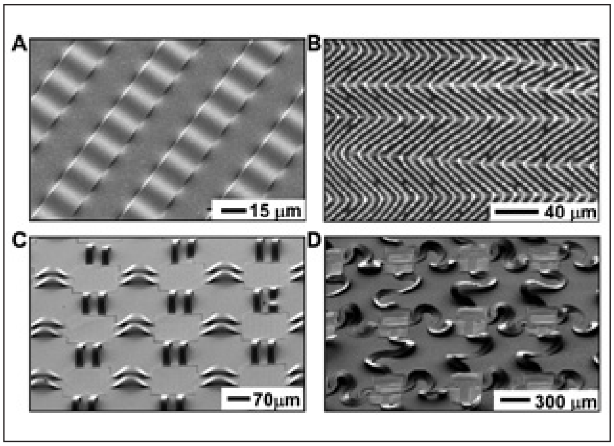

FIGURE 2 Design strategies of stretchable electronics enabled by the mechanics of film-substrate interaction. (A) Silicon nanoribbons buckled on uniaxially prestretched soft elastomer. Reprinted from Khang et al. (2006) with permission from the American Association for the Advancement of Science. (B) Silicon nanomembrane buckled on biaxially prestretched soft elastomer. Reprinted from Choi et al. (2007) with permission from the American Chemical Society. (C) Isolated device islands interconnected by popped-up linear metallic ribbons. Reprinted from Kim et al. (2012b) with permission from the Materials Research Society. (D) Isolated device islands interconnected by serpentine-shaped metallic ribbons. Reprinted from Kim et al. (2008b) with permission from the National Academy of Sciences.

or metallic materials below 1 percent when the polymer substrate is subjected to significant deformation (e.g., of orders of magnitude).

Furthermore, when substrate materials are too stiff to stretch but thin enough to bend (e.g., plastic sheets, paper, leather, fabric), electronics fabricated on the surface of such substrates have to survive tensile strains induced by bending curvatures. A thin compliant layer laminated between the substrate and the active device islands has been found to greatly reduce tensile strain in the islands through large shear deformation (Sun et al. 2009). Such a strain isolation mechanism has enabled bendable and even foldable electronics on lots of unconventional substrates, such as printing papers, fabrics, and aluminum foils (Kim et al. 2009).

Exciting discoveries such as these offer ways to overcome the intrinsic brittleness and stiffness of inorganic semiconductors and open the door for their applications in flexible and stretchable electronics.

Materials Processing: Microtransfer Printing

Microtransfer printing technology developed for single crystal inorganic semiconductors (Kim et al. 2010c; Meitl et al. 2006; Yoon et al. 2010) has enabled the integration of high-performance electronics on deformable substrates such as flexible displays (Park et al. 2009), high-efficiency flexible solar cells (Yoon et al. 2008, 2010), bioinspired electronic eye cameras (Ko et al. 2008; Song et al. 2013), and biointegrated electronics (Kim et al. 2012a,c,d).

Figure 3 illustrates the generalized two-step microtransfer printing method. The fabrication begins with the high-temperature process of doping silicon nanomembranes on silicon-on-insulator (SOI) wafers. Preprocessed monocrystalline silicon nanomembranes are then released from the SOI wafer and printed onto the polyimide (PI)-coated rigid handle wafer using elastomeric stamps; the precoated PI layer serves as a support and encapsulation layer for the functional metal and semiconducting nanomembranes. Conventional microfabrication processes (e.g., low-temperature sputter or electron beam deposition, photolithography, and wet or dry etching) can then be readily performed on the PI-coated wafer. The circuit is eventually patterned into

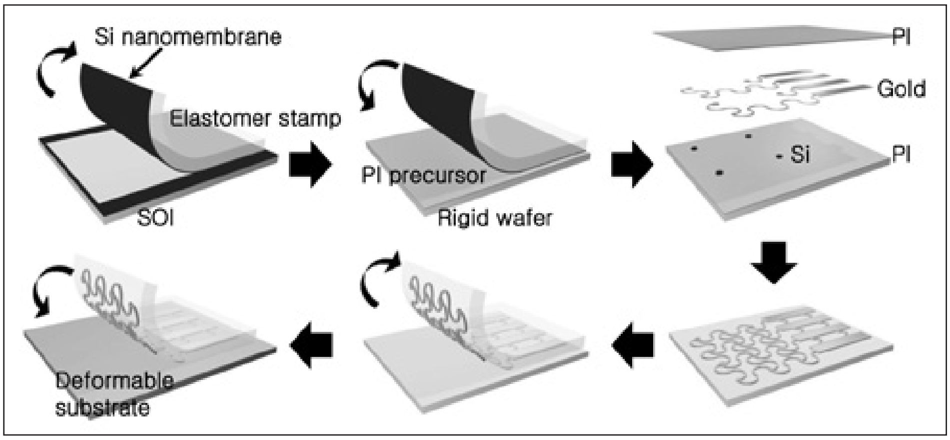

FIGURE 3 Schematics of the fabrication procedures of stretchable electronics: transfer doped silicon (Si) nanomembranes from silicon-on-insulator (SOI) wafers onto polyimide (PI)-coated rigid handle wafer with an elastomer stamp. Silicon patterning and metallization are followed by PI encapsulation. Dry etching of PI defines the serpentine open mesh structure. Finally the well-fabricated stretchable circuit is transferred from rigid wafer to a deformable substrate.

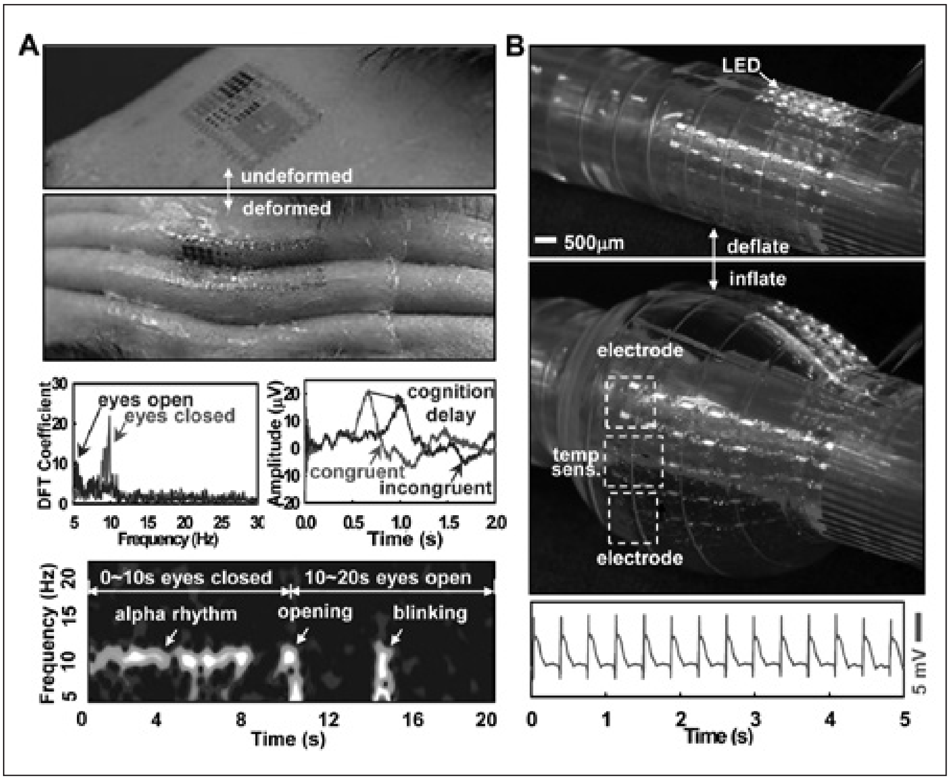

FIGURE 4 Biointegrated sensors based on stretchable electronics. (A) Ultrathin, ultrasoft epidermal electronic system laminated on a human forehead to read human electroencephalograph (EEG) (upper frames). Discrete Fourier transform coefficients of EEG alpha rhythms (middle left), demonstration of Stroop effects in EEG (middle right), and spectrogram of alpha rhythm (bottom). Reprinted from Kim et al. (2011b) with permission from the American Association for the Advancement of Science. (B) Multifunctional "instrumented" balloon catheter incorporating stretchable electrophysiological and radio frequency ablation electrodes, temperature sensors, pressure sensors, flow sensors, and arrays of microscale inorganic light-emitting diodes (μ-ILEDs) performing electrocardiogram recording of a rabbit heart. Reprinted from Kim et al. (2011a) with permission from Nature Publishing Group.

stretchable open mesh networks and transfer printed from the wafer onto a wide variety of deformable substrates, again using elastomeric stamps to render a fully functional flexible/stretchable system.

Because high-quality monocrystalline silicon is used as the semiconductor and low-resistance gold wires are used as the conductor in these devices, their electronic performance and long-term chemical reliability are on par with wafer-based electronics while high flexibility and/or stretchability is incorporated through the structural design. Similar fabrication strategies are applicable to the fabrication of stretchable AlInGaP[2] optoelectronics (Kim et al. 2010b) and gallium arsenide (GaAs) photovoltaics (Lee et al. 2011).

[2] Aluminum gallium indium phosphide.

Functionalities

Epidermal and in Vivo Sensing

With the maturity of the enabling technology for microtransfer printing, flexible and stretchable electronics found their exemplary applications in the late 2000s with the emergence of biointegrated electronics, a field that has greatly facilitated epidermal and in vivo sensing (Rogers et al. 2010).

For epidermal sensing, physiological electrodes are mounted on the skin (via adhesive tape, mechanical straps, or needles) with terminal connections to separate boxes that house collections of rigid circuit boards, power supplies, and communication components (Gerdle et al. 1999; Webster 2009). These systems have many important capabilities, but they are poorly suited for practical application outside of research labs or clinical settings.

The development of novel electronic systems with matching form factors and the mechanical properties of biotissues is essential for long-term, intimate bioelectronic interfaces. To that end, the application of serpentine structural designs and transfer-printing methods has enabled the development of ultrathin, ultrasoft electronics composed of high-performance inorganic materials. Such biointegrated electronics have in turn led to exciting applications such as epidermal electronics for vital sign monitoring (Huang et al. 2012; Kim et al. 2011b; Yeo et al. 2013), brain-computer interfaces (Kim et al. 2010a; Viventi et al. 2011), electrocardiogram (ECG) mapping devices (Kim et al. 2012b; Viventi et al. 2010), and smart or minimally invasive surgical tools (Kim et al. 2011a, 2012e).

Figure 4 illustrates the use of biointegrated electronics for epidermal and in vivo physiological sensing.

Electroencephalograph (EEG) measurements are shown in Figure 4A, based on epidermal electronic systems laminated on a human forehead in a manner much like a temporary transfer tattoo, mechanically invisible to the wearer (Kim et al. 2011b). Because the attachment is enabled solely by van der Waals force without any conductive gels, these systems can function for more than two weeks at the exact same position without decomposition of the adhesives. Depending on where the electronic tattoo is placed, EEG, ECG, and EMG (electromyogram) measurements are possible with very high signal-to-noise ratio, thanks to the low impedance enabled by the intimate interface.

In addition to electrophysiological sensing, studies have successfully demonstrated the monitoring of skin temperature, mechanical deformation (strain), and hydration (Huang et al. 2012; Kim et al. 2011b; Yeo et al. 2013). Wireless power and data transmission coils as well as a stretchable battery (Xu et al. 2013) and stretchable memory patches (Son et al. 2013) further contribute to the stand-alone operation of wearable physiological sensors.

Soft electronics can integrate with not just human skin but also internal organs for in vivo monitoring. As an example, Figure 4B shows a multifunctional, "instrumented" balloon catheter that maintains a small initial diameter to travel through human veins and then inflates by 200 percent in cardiovascular cavities to perform minimally invasive surgeries such as the deployment of coronary stents. Electrodes and temperature, contact, and flow sensors integrated on the balloon skin provide in vivo endovascular and endocardial information, which used to be very difficult to obtain (Kim et al. 2011a).

Studies have also shown the effectiveness of other in vivo functionalities, such as epicardial ECG and beating amplitude sensing (Kim et al. 2012b; Viventi et al. 2010) as well as the mapping of brain activities (Kim et al. 2010a; Viventi et al. 2010, 2011).

Stimulation and Treatment

The most sophisticated version of biointegrated electronics will be a fully automated, closed-loop sensing-diagnosis-feedback device; the "feedback" that the device transmits will be information (e.g., a reminder to take medicine) or therapeutics (e.g., a pacemaker adjustment). Although the development of closed-loop biointegrated electronics is not yet fully realized, several types of stimulation and treatment are available.

One type involves the administration of a modulated electrical current to human skin to excite cutaneous mechanoreceptors, which provide instantaneous electrotactile feedbacks to the wearer in an acute and time-controlled manner (Warren et al. 2008). Figure 5A features a wearable finger tube that integrates high-performance

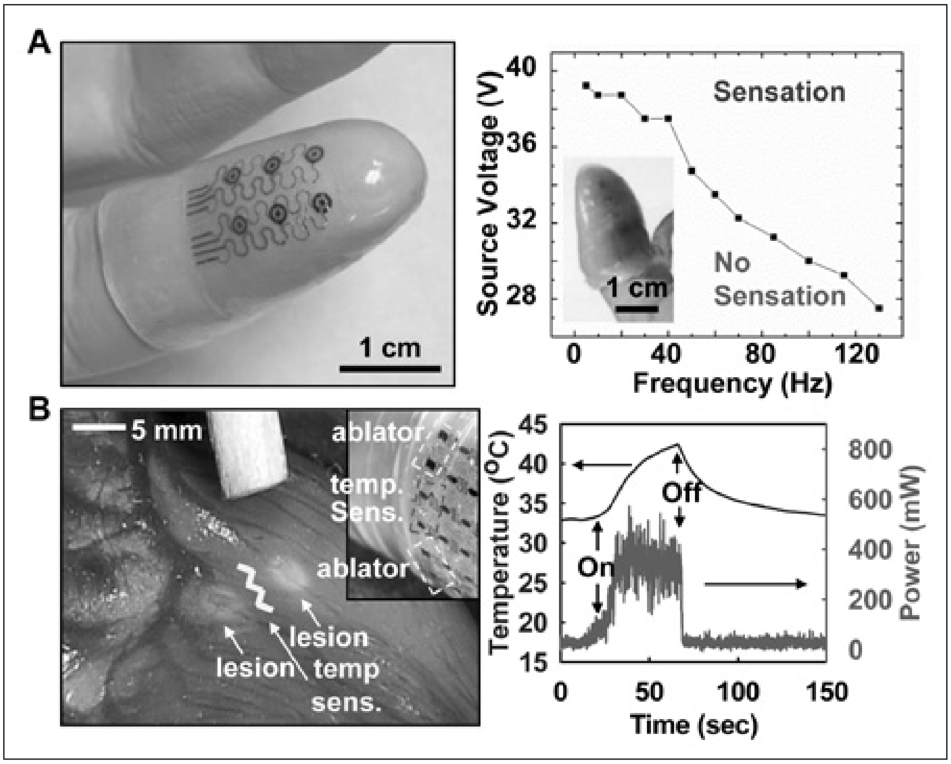

FIGURE 5 Biointegrated electrotactile stimulation and treatment tools based on stretchable electronics. (A) Wearable, conformable finger tube generates electrotactile sensation on human fingertip with suitably modulated current. Reprinted from Ying et al. (2012) with permission from IOP Publishing. (B) Lesions on a rabbit heart created by radio frequency (RF) ablators integrated on a balloon catheter (left frame). The supplied RF power and in situ tissue temperature measured by adjacent temperature sensors are shown in the right frame. Reprinted from Kim et al. (2011a) with permission from Nature Publishing Group.

inorganic electronics to sense finger-tip motion and provide electrotactile stimulation. The voltage-frequency combination to enable electrotactile sensation is shown in the right frame of Figure 5A (Ying et al. 2012).

As an in vivo example, Figure 5B shows lesions on a live rabbit heart, treated by radio frequency (RF) ablation as a therapeutic procedure to stop heart arrhythmia. The ablation was performed using stretchable electrodes on an inflatable balloon catheter (Kim et al. 2011a). Lesion size and depth can be determined with the use of in situ temperature monitoring during RF ablation (right frame). In vivo pretreatment sensing can provide critical information to guide treatment, and in situ posttreatment sensing can provide immediate data to evaluate treatment results and help guide the next treatment if any.

Outlook

In the past decade, studies on mechanics, materials, and microfabrication techniques have advanced the design and manufacture of flexible and stretchable electronics, and it is likely that biointegrated electronics will soon revolutionize personal health care and human-machine interaction.

Further progress will likely depend on advances in the following areas. Maximization of the application potentials of wearable and implantable electronic systems will require the development of mechanically compatible and electronically sufficient microcontrollers, memory, power supply, and wireless data transmission modules. Multifunctional compliant systems that incorporate optical and biochemical tools would also be desirable. Another frontier of biointegrated electronics concerns transient electronics (Hwang et al. 2012). Roll-to-roll transfer printers for the deterministic assembly of inorganic semiconductors on polymer substrates hold the key for large-volume, low-cost manufacture of biointegrated electronics (Yang et al. 2012). More detailed discussion on the mechanics, materials, and functionalities of biointegrated electronics is available in several recent review articles (Kim et al. 2012a,c,d; Lu and Kim 2013).

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