Mechanics and Materials of Bio-Integrated Electronics

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Planar and rigid wafer-based electronics are intrinsically incompatible with curvilinear and deformable organisms. Recent development of flexible and stretchable electronics enabled conformable and intimate bio-integration for physiological sensing and therapeutic treatment. This article summarizes the mechanics, materials, and functionalities of bio-integrated electronics based on inorganic electronic materials. Remaining challenges and outlook of future directions are provided at the end.

BACKGROUND

Research on flexible electronics started almost 20 years ago (Bao ZN et al. 1997, Garnier F et al. 1994) with the demand of macroelectronics (Reuss RH et al. 2005), such as paperlike flexible displays (Rogers JA et al. 2001). Organic semiconductors and conducting polymers were appealing materials for large-area electronics attributing to their intrinsic flexibility, light weight, and low cost, especially when merged with the roll-to-roll processes (Forrest SR 2004). Methods to synthesize novel organic materials and their printing, patterning and passivation techniques (Forrest SR and Thompson ME 2007, Menard E et al. 2007) were later applied to manufacture artificial electronic skins for robotics (Sekitani T et al. 2008, Someya T et al. 2004) and organic solar cells (Kaltenbrunner M et al. 2012, Lipomi DJ et al. 2011). As of today, flexible displays based on organic light emitting diodes (OLED) are nearing commercial reality.

The other branch of flexible and stretchable electronics based on high-quality monocrystalline inorganic semiconductors started to emerge in the mid-2000s (Khang DY et al. 2006). Inorganic semiconductors exhibit high carrier mobility and excellent chemical stability in ambient environments (Service RF 2006). Well-defined properties and well-established manufacturing processes make them even more appealing. Their intrinsic stiffness and brittleness, however, greatly hindered their application in flexible/stretchable electronics until the discovery of unconventional mechanical behaviors of inorganic materials (micro-/nano- wires, ribbons, and membranes) when bonded to polymer substrates (Gray DS et al. 2004, Hsu PI et al. 2002, Huang ZY et al. 2005, Lacour SP et al. 2003, Li T et al. 2005, Lu NS et al. 2007).

BENDABILITY AND STRETCHABILITY OF INORGANIC ELECTRONIC MATERIALS

Although inorganic materials such as silicon and metal are stiff and easy to rupture or yield when their intrinsic strain exceeds very small values, e.g. ~ 1%, the mechanical response of a structure depends on not only the intrinsic material properties, but also the geometry of the structure. For example, according to basic beam theory, the bending stiffness of a plate or film scales with thickness cubed and the bending-induced maximum strain is proportional to thickness at a given bending curvature. Figure 1 elucidates the bending stiffness of silicon plates/membranes can be reduced by eighteen orders of magnitude as the thickness decreases from millimeter to nanometer. The insets of Fig. 1 illustrate that although bulk silicon wafer is not bendable, silicon nanoribbons can survive large bending curvatures without fracture. The bendability can be transferred to stretchability with the help of deformable polymer substrates. Two prevailing design strategies, i.e. wrinkled nanoribbons (Fig. 2A) and nanomembranes (Fig. 2B) (Khang DY et al. 2006, Kim DH et al. 2008a, Sun YG et al. 2006) and isolated device islands interconnected by noncoplanar (Fig. 2C) (Kim DH et al. 2008b, Ko HC et al. 2008, Lee J et al. 2011) or serpentine-shaped metal wires (Fig. 2D) (Kim DH et al. 2011a, Kim DH et al. 2011b, Xu S et al. 2013), were proven to be effective of minimizing strains in inorganic electronic materials. Systems designed by these strategies can be stretched up to tens of percents without inducing any intrinsic strains in silicon or metal beyond 1%. When substrate materials are stiff in-plane but thin and flexible out-of-plane (e.g. polyimide, paper, leather, fabric etc), a thin compliant interlayer laminated in between the substrate and the active device islands can greatly decouple strains from the substrate to the device through large shear deformation (Kim DH et al. 2009, Sun JY et al. 2009).

MICRO-TRANSFER PRINTING

Micro-transfer printing technology developed for single crystal inorganic semiconductors (Kim S et al. 2010, Meitl MA et al. 2006, Yoon J et al. 2010) has enabled the integration of fully functional flexible and stretchable electronics including flexible displays (Park SI et al. 2009), high efficiency flexible solar cells (Yoon J et al. 2008, Yoon J et al. 2010), bio-inspired electronic eye cameras (Ko HC et al. 2008, Song YM et al. 2013), and bio-integrated electronics (Kim DH et al. 2012a, Kim DH et al. 2012c, Kim DH et al. 2012d). Figure 3 provides the schematics of the generalized two-step micro-transfer printing to fabricate high performance inorganic electronics on polymer substrates. The fabrication begins with high temperature processes such as doping and annealing on silicon on insulator (SOI) wafers. Pre-processed monocrystalline silicon nanomembranes are then released from the SOI wafer and printed onto the polyimide coated rigid handle wafers using elastomeric stamps. Conventional low temperature micro-fabrication processes including sputter or E-beam deposition, photolithography, and wet or dry etching can be readily performed on the rigid handle wafer.

The circuit is eventually patterned into open mesh networks and transfer printed from the rigid handle wafer onto a wide variety of flexible/stretchable substrates again using elastomeric stamps. Because high quality monocrystalline silicon is still used as the semiconductor in these devices, their electronic performance and long-term chemical reliability are on par with wafer-based electronics while flexibility or even stretchability is incorporated.

EPIDERMAL AND *IN VIVO* SENSING

Flexible and stretchable electronics found their destined application in the late 2000s when the concept of bio-integrated electronics was proposed (Rogers JA et al. 2010). While organisms are soft, curvilinear, and deformable, wafer-based electronics are not. Novel electronic systems with matched form factors and mechanical properties with bio-tissues can help establish long-term, intimate bio-electronic interfaces. So far, bio-integrated electronics have enabled exciting applications including epidermal electronics for vital sign monitoring (Huang X et al. 2012, Kim DH et al. 2011b, Yeo W-H et al. 2013), brain-computer interfaces (Kim DH et al. 2010, Viventi J et al. 2011), electrocardiogram (ECG) mapping devices (Kim DH et al. 2012b, Viventi J et al. 2010), and smart or minimally invasive surgical tools (Kim DH et al. 2011a, Kim DH et al. 2012e). Figure 4 illustrates epidermal and *in vivo* sensing carried out by bio-integrated electronics. Figure 4A demonstrates electroencephalography (EEG) measurements with epidermal electronic systems (EES) laminated on a human forehead, in a manner that is mechanically invisible to the user, much like a temporary transfer tattoo (Kim DH et al. 2011b). Since attachment is purely enabled by van der Waals force and hence does not require conductive gels, these systems can function for a prolonged period of time. Figure 4B demonstrates a multi-functional, 'instrumented' balloon catheter that is capable of 200% inflation within cardiovascular cavities to perform minimally invasive surgery with *in vivo* ECG mapping, temperature, tactile, and flow monitoring (Kim DH et al. 2011a). More detailed materials and mechanics strategies for bio-inspired and bio-integrated electronics have been summarized in several recent review articles (Kim DH et al. 2012a, Kim DH et al. 2012c, Kim DH et al. 2012d).

STIMULATION AND TREATMENT

In addition to sensing and monitoring, the development of stimulation and treatment functionalities represents the progress toward closed-loop bio-integrated electronics. Electrotactile stimulation could be acute and timely controllable by passing a properly modulated electrical current into the skin, which can excite cutaneous mechanoreceptors (Warren JP et al. 2008). Figure 5A features a wearable finger tube which integrates high-performance, inorganic electronics for electrotactile stimulation (Ying M et al. 2012). Modulated current sent through each pair of electrodes can create a localized tingling feeling, known as the electrotactile sensation. The voltage-frequency combination to enable sensible stimulation is provided in the right frame of Fig. 5A. As an example of *in vivo* therapeutic treatment, Fig. 5B illustrates lesions on rabbit heart as a result of radio frequency (rf) ablation which was performed using stretchable electrodes on an inflatable balloon catheter (Kim DH et al. 2011a). Lesion size and depth can be inferred through *in situ* temperature monitoring during rf ablation as offered in the right frame.

CHALLENGES AND OUTLOOK

Compliant and stretchable power supply and wireless data transmission are two key components to enable the practical use of compliant bio-integrated electronics. Stretchable piezoelectric generators (Nguyen TD et al. 2013) offer a viable solution to harvest biomechanical energy but the energy density is still far lower than what is needed for powering small electronic devices (Starner T 1996). Stretchable wireless power transmission systems were proven to be effective for turning on micro-LEDs (Kim DH et al. 2011b) and recharging lithium ion batteries (Xu S et al. 2013), but were still suffering from the distance and efficiency limitations. In addition, experiments have shown that mechanical deformation can change the coil spacing and hence the resonant frequency of the LC oscillator, which is undesirable for wireless data transmission (Kim DH et al. 2011b). In summary, stretchable power supply and data transmission components will have to catch up with the stretchable sensors and stimulators to enable truly standalone bio-integrated electronics.

CONCLUSIONS

In the past decade, flexible and stretchable electronics have demonstrated increasing impact in areas of biomedical engineering including physiological sensing, stimulation, and therapeutic treatment. New materials, mechanics principles, and micro-fabrication methods are the driving forces for the fast development in this field. New opportunities in stretchable power supply and data transmission are wide open for wearable and implantable bio-integrated electronics.

Figure 1. Bending stiffness as a function of silicon plates/membranes thickness, with insets showing the bendability of bulk silicon wafer, silicon thin film, and silicon nanoribbons.

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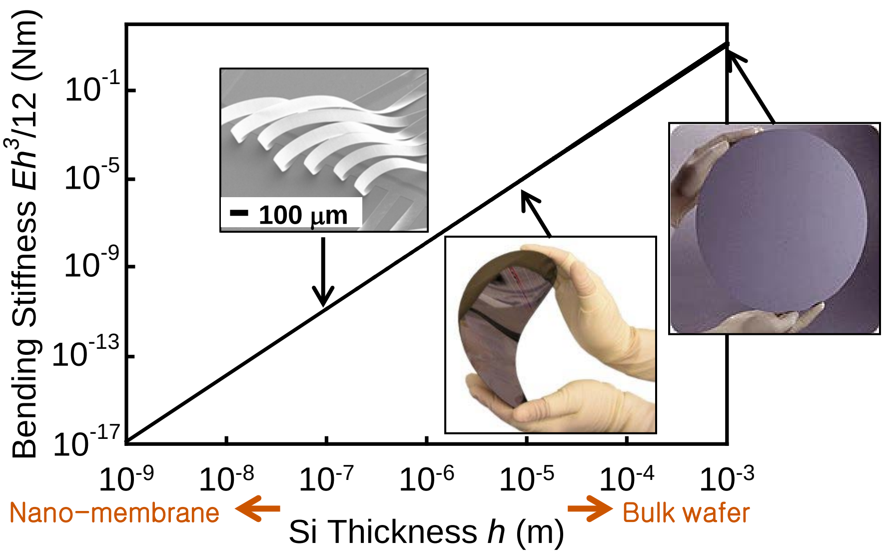

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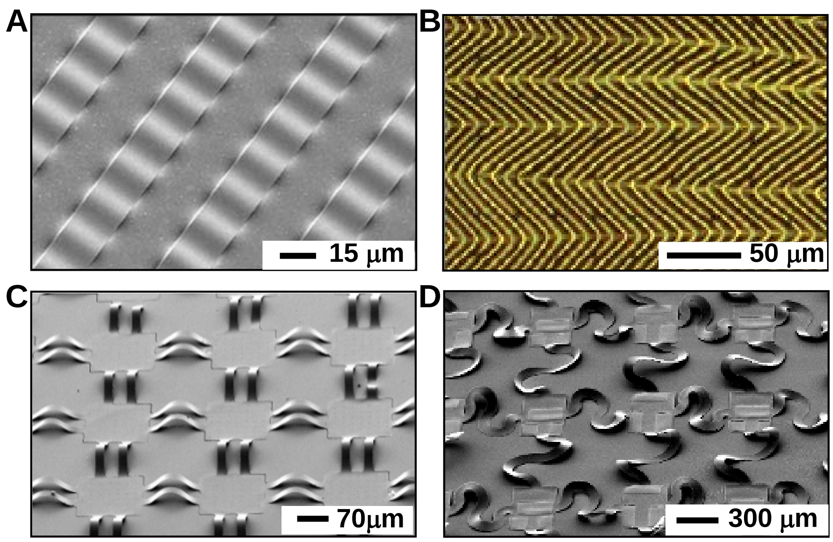

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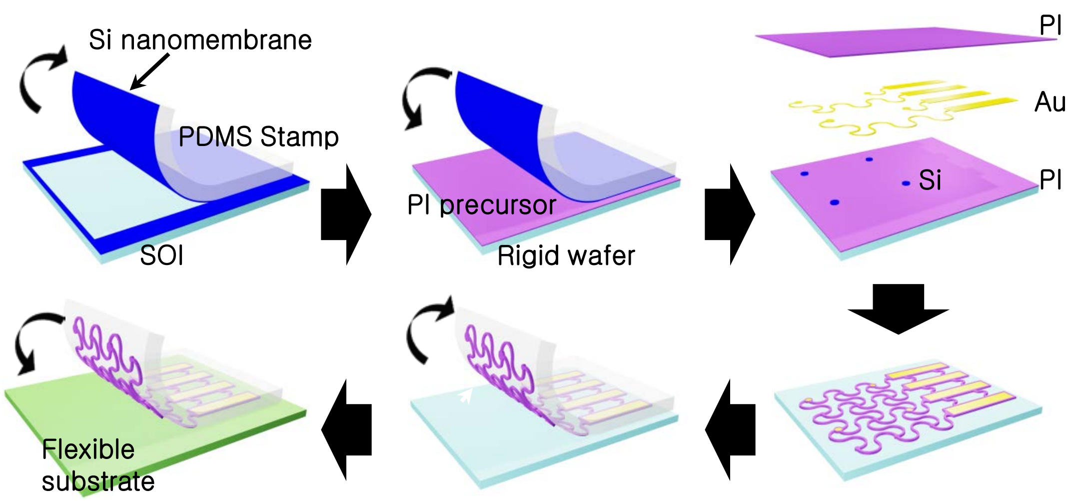

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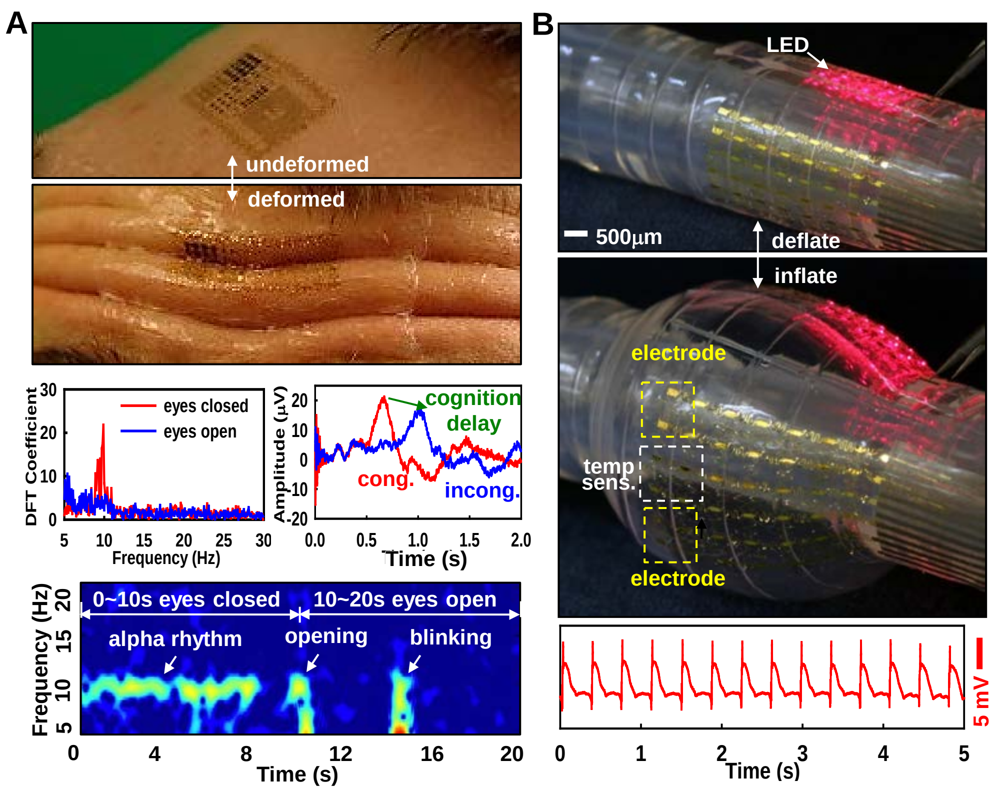

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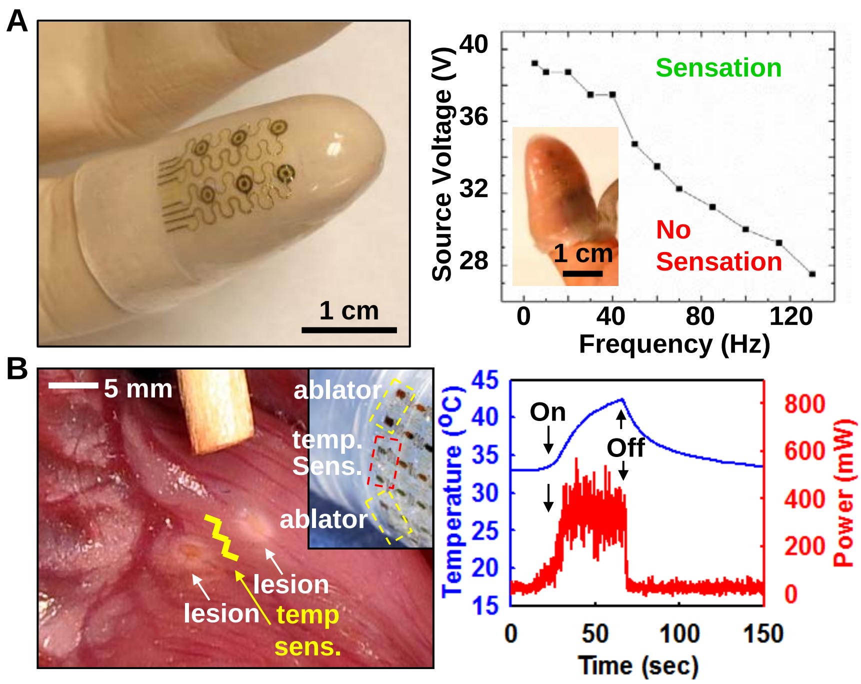

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