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History of Flexible and Stretchable Devices

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Flexible devices such as transistors and transducers have been developed since 1990 by forming organic thin film or transferring inorganic thin film on plastic substrates. From the 1990s to the early 2000s, flexible transistors and light emitting diodes (LEDs) were mainly developed on a flexible substrate using organic materials because organic materials are fundamentally mechanically flexible compared to inorganic films and can be formed by using solution-based or evaporation processes on amorphous plastic substrates [1–4]. However, by utilizing inorganic thin film transfer technique from a bulk wafer to another substrate that was developed by Konagai *et al.* [5] and Yablonovitch *et al.* [6], inorganic-based flexible devices have been also developed since 2000 [7–15]. During the early stages of development of flexible electronics, the fundamental characteristics of devices such as transistors and sensors with relevance to organic and inorganic materials, their electrical characteristics, mechanical reliability, and bendability were deeply studied [7–10]. Although the fundamental properties using similar material systems as well as new material systems are still being investigated [16, 17], the approach for flexible and stretchable electronics is now to develop flexible and/or stretchable device applications [11–15, 17–34]. As device integrations on flexible substrate, Rogers *et al.* developed a paper-like electronic display using organic material-based active matrix backplane in 2001, which was most likely the first demonstration of the material integration for flexible device applications [4]. Following this development, Someya *et al*. demonstrated an artificial electronic skin (e-skin) to detect pressure distributions similar to that in human skin in 2004 [35], and in 2005, his group further developed a pressure and temperature distribution sensing device using organic-based thin film transistors (TFTs) for the active matrix backplane [36]. At the same time, thin film Si TFTs were transferred from silicon-on-insulator (SOI) wafer to a flexible substrate, which allows it to operate TFTs with high mobility and high stability in ambient air [8, 10]. During the 2000s, one of the bottlenecks for flexible electronics using organic materials as the active component was low performance and instability in ambient air. However, subsequent to the demonstration of inorganic-based TFTs, possibilities arose for inorganic material to be flexible electronics. Since

Flexible and Stretchable Medical Devices, First Edition. Edited by Kuniharu Takei.

the Si-based TFTs are a matured technique as the industrial standard for Si-based integrated circuits (ICs), the properties of flexible Si-TFTs show a great performance with a field-effect mobility of 180 cm^2/Vs on a flexible substrate [8]. In 2008, Rogers *et al.* successfully fabricated a highly integrated digital circuit of a four-bit row decoder using carbon nanotube networks as p-type transistors [13]. After several developments of inorganic material formations, device structures, and new organic materials, flexible transistors using both organic and inorganic materials have displayed high potential for flexible electronics due to improvements in their performance and stability. Using the platforms of organic transistors and organic light emitting diodes (OLEDs), active matrix OLED flexible display was demonstrated by Someya *et al.* [37]. In 2010, two e-skin device demonstrations were reported at the same time by Bao *et al.* [19] and Javey *et al.* [20]. Each e-skin has unique structures. The device reported by Javey *et al*. has an inorganic nanowire array active matrix backplane to show high flexibility and performance realized by nanowire printing technique [20], and Bao *et al*. proposed a unique structure to detect tactile pressure with high sensitivity [19]. The flexible and stretchable devices were then applied to medical and neuroscience fields for implantation or *in vivo* experiments by utilizing their flexibility [18, 38–40]. One interesting approach is to use the material such as silk dissolved in water [18, 39]. This eventually allows it to use the sensors and curing devices for the implantation, and it is not necessary to remove it after surgery and curing because it is dissolved in the body, which helps to reduce medical cost and patient load for re-surgery. Subsequent to these developments, many kinds of flexible and stretchable device applications have been developed to date, such as self-healing sensors [23], ultrathin flexible devices [41], photovoltaics devices [30]. In addition, recently, fully printed, multifunctional, low-cost, wearable flexible healthcare devices have been also reported by integrating with multiple sensors for healthcare detections and human activity [42]. However, many demonstrations were often focused on the sensor and transistor integration on flexible and stretchable substrates, and there were still challenges toward moving forward for realizing practical applications. The biggest problem of these devices is how to realize signal processing circuits, wireless systems, and battery because flexible transistors are not capable of building complicated circuits although there has been significant improvements and developments from many groups. To overcome this challenge, in 2016, Javey *et al.* demonstrated a hybrid system integrating flexible chemical sensors and inflexible conventional ICs for signal processing of the sensing results and a wireless system on a flexible printed circuit film [34]. Furthermore, Rogers *et al.* also developed the battery-free hybrid system to monitor health conditions wirelessly by integrating flexible and stretchable antenna and chip-based circuits [43].

In this book, the fundamental physics of electrical components such as flexible and stretchable transistors, memories, and sensors are first introduced to understand the present status of the flexible and stretchable electronics including techniques to fabricate the devices as emerging technologies. After understanding the fundamental characteristics and techniques, medical and healthcare applications using the flexible and stretchable device components are introduced. Especially, skin-mounted healthcare devices, implantable medical devices, and neuroscience

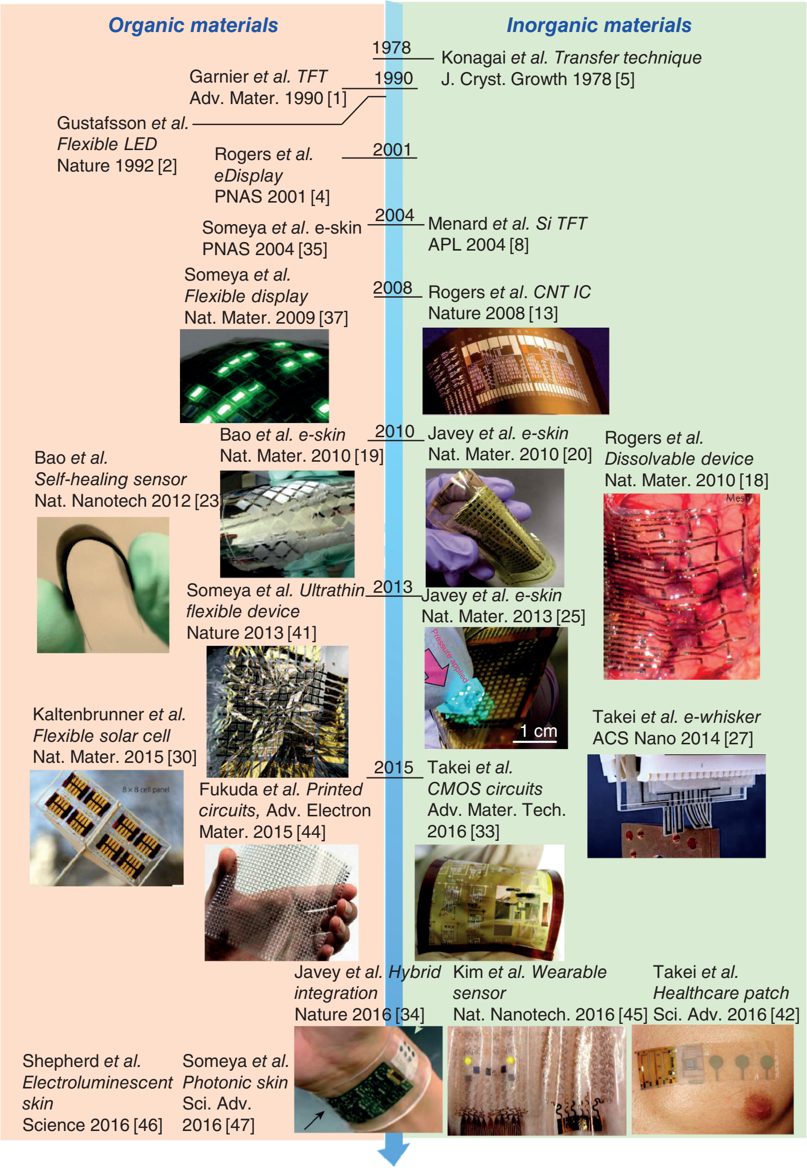

Figure 1.1 History of flexible electronics using organic and inorganic materials. Qing 2008 [13]. Reproduced with permission of Nature Publishing Group; Kim *et al*. 2010 [18]. Reproduced with permission of Nature Publishing Group; Mannsfeld *et al*. 2010 [19]. Reproduced with permission of Nature Publishing Group; Takei *et al*. 2010 [20]. Reproduced with permission of Nature Publishing Group; Tee *et al*. 2012 [23]. Reproduced with permission of Nature Publishing Group; Wang *et al*. 2013 [25]. Reproduced with permission of Nature Publishing Group; Kaltenbrunner *et al*. 2013 [41]. Reproduced with permission of Nature Publishing Group; Harada *et al*. 2014 [27]. Reproduced with permission of American Chemical Society; Kaltenbrunner *et al*. 2015 [30]. Reproduced with permission of Nature Publishing Group; Honda *et al*. 2016 [33]. Reproduced with permission of John Wiley & Sons; Gao *et al*. 2016 [34]. Reproduced with permission of Nature Publishing Group; Lee *et al*. 2016 [45]. Reproduced with permission of Nature Publishing Group; Sekitani *et al*. 2009 [37]. Reproduced with permission of Nature Publishing Group; Fukuda *et al*. 2015 [44]. Reproduced with permission of John Wiley & Sons.

devices are discussed to show the insights into these flexible and stretchable electronics. In addition to the device applications, nanosheet materials for the practical medical and wearable sheets are also discussed (see Figure 1.1).

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