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Recent Advances in Ultra-Thin Electronics

Fabrizio Antonio Viola and Virgilio Mattoli**

Soft electronics is an exciting research field that aims to seamlessly integrate electronic components and devices onto non-rigid, non-planar, complex 3D surfaces and objects. In the last decade, the research on soft electronics has been mainly driven by the increasing demand and request for a new category of portable and ubiquitous electronic systems capable to bridge the gap between biology and electronics, and to be integrated with the human body, with non-conventional features such as conformability. Targeted applications include wearable electronics, human-machine interfacing, epidermal electrodes for biopotential signals acquisition, as well as personal health-care monitoring systems.

The conformability of a material is strictly related to its bending stiffness *EI* (which determines how conformal to the underlying substrate a material is). It depends, with a good approximation, on its Young Modulus and has a cubic dependence on the material thickness. This relationship is quantified by the Equation 1:[1]

$$EI = E_M\, w_M t_M \left(\frac{1}{3}t_M^2 + t_M n + n^2\right) \tag{1}$$

where E_M represents the Young modulus of the material – laminated onto a generic substrate – while w_M, t_M, and n represent its width, thickness, and distance to the natural axis, as reported in **Figure 1**a.

Therefore, two main strategies can be followed to improve the conformability of materials and, therefore, electronics systems.[2] From one side it is possible to push on materials innovation, developing low Young Modulus, intrinsically soft and stretchable electronic materials (e.g., organic semiconductors, conductive polymers, soft substrates, etc.). On the other side, smart structural designs and architectures can enable the use of more traditional materials and components to develop conformable integrated devices. Obviously, both approaches can be pursued in parallel.

Among others, the use of ultra-thin substrates and devices is one of the most powerful approaches to achieving full conformability onto target surfaces. This is because the strain (and thus the stress) locally induced on the surface of a sheet, by bending it at a certain radius of curvature, is directly proportional to the thickness of the same sheet.[3] Moreover, according to Equation 1, the bending stiffness (the most important physical quantity toward conformability) drops dramatically down by reducing the thickness, since this is proportional to the third power of the thickness.[4] Interestingly, under a certain threshold thickness (that can vary, depending on the materials involved and substrates), the thin sheet can adhere and conform spontaneously to surfaces due to physical interactions (i.e., dispersive forces, Van Der Waals interactions),[5,6] enabling the intimate contact between such films and virtually any surface, including skin.[7–9]

In this Special Issue, we collected several recent advances and focused reviews in which low thickness is the key approach to obtaining conformable and soft electronic components and devices. We thank all the invited contributors that make it possible with their wonderful contributions, to succeed in building up this. Below we identify papers via the name of the person invited. Last, we thank Dr. Gaia Tomasello for allowing us to be Guest Editors of this exciting Special Issue. It has been a real pleasure working with her.

As introduced, one of the main drivers of conformal electronics development is the quest for unobtrusive monitoring of bio-electric signals. Four papers assess this topic, describing the use of thin and conformable electronics for various physiological signals monitoring, from the electrodes to complete systems. In article number 2200883, George Malliaras and co-workers reported a novel thin, flexible, high-density, and tissue-compatible multishank probe for high-resolution recordings. It is combined with an additively manufactured insertion shuttle that allows the probe to be implanted into the brain as a new tool for in vivo electrophysiology. Yohufan Hu and co-workers proposed in article number 2200916 a flexible wireless surface electromyography (sEMG) monitoring system. It consists of a stretchable epidermal patch and a flexible printed circuit board to provide high fidelity real-time evaluation of muscle strength and fatigue, thanks to the very low skin-electrode contact impedance and minimized background noise. In article number 2201279 Tsuyoshi Sekitani and co-workers presented an innovative printing process for the fabrication of low-noise electrodes for an organic pseudo-complementary metal-oxide-semiconductor amplifier that can perform precision brain wave monitoring. Nanshu Lu and co-workers reported in article number 2201284 a thin, stretchable, lightweight electronic tattoo device (e-tattoo) able to record a dual-mode electromechanical sensing, i.e., bio-electric cardiac signals via electrocardiography (ECG) and mechanical cardiac rhythm via seismocardiography (SCG).

Four papers report on thin pressure and touch sensors based on different transduction mechanisms. In article number 2200069, Massimo De Vittorio and co-workers proposed a compliant, wearable, transparent, and biodegradable ultrasound microtransducer based on a thin film of an environmental-friendly piezoelectric biopolymer. In article number 2201086, YongAn Huang and co-workers reported high-quality graphene-in-polyimide (GiP) strain sensors that can be produced by

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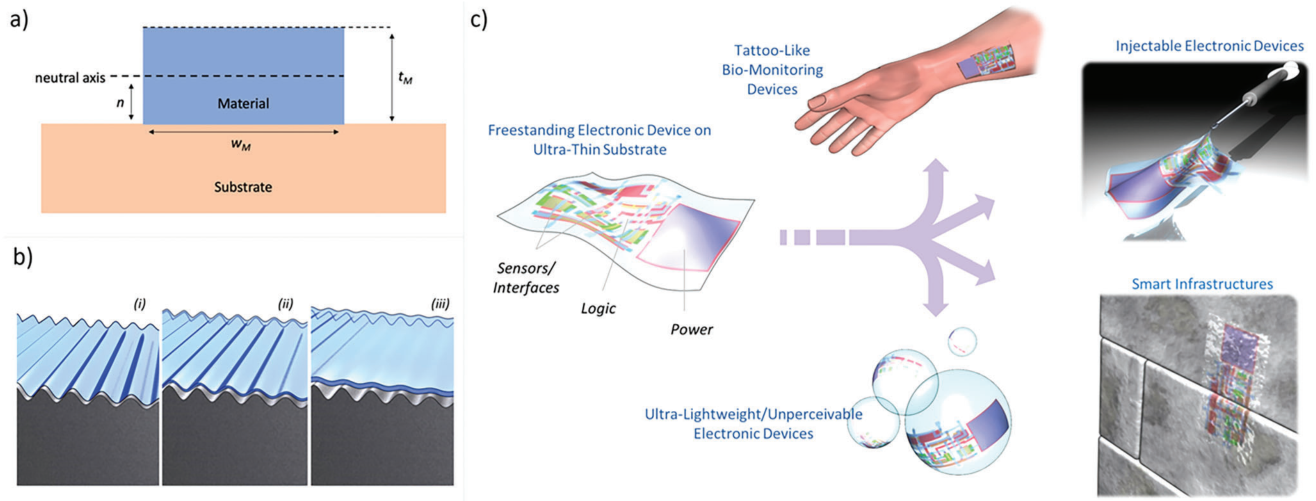

Figure 1. a) Thin-film material laminated onto a substrate. The thin-film bending stiffness depends on its Young Modulus (E_M) total thickness (t_M), width (w_M), and the distance of its neutral axis to the substrate (n); b) Graphical representation of behaviour of conformability versus thickness of the film; c) Pictorial representation of ultra-thin film electronics and possible applications.

interface ablation with a nanosecond excimer laser (308 nm). With this novel method, the authors showed that is possible to reduce the typical graphene thickness achievable by the traditional surface ablation and therefore improve the conformability, strain sensitivity as well as force sensitivity. In article number 2201333, Barbara Stadlober and co-workers presented a matrix of organic ferroelectric transducers coupled with ultralow noise level organic transistors. This system can be used for the real-time monitoring of the pulse wave with simultaneous measurements of heart rate and blood pressure and of various tactile modes. The thickness of the matrix can be downscaled to almost 2.8 micrometers, thus making it virtually imperceptible on human skin. In article number 2201304 Tomoyuki Yokota, Takao Someya and co-workers reported on a solution-processed, flexible, capacitive pressure sensor with a linear response over a wide pressure range with high sensitivity. The sensor showed a fast response time, very high stability, as well as good sensitivity and linearity and does not need a complex system calibration.

Not only sense, but ultra-thin electronics can also do more. In particular, three papers describe the implementation of thin actuators exploiting three different but effective mechanisms. In article number 2200165, Toshinori Fujie and co-workers reported skin-contact dielectric elastomer actuators (DEAs) based on large-area, roll-to-roll gravure-coated single-walled carbon nanotubes onto a nanosheet of poly(styrene-*b*-butadiene-*b*-styrene), which can be exploited for skin-contact haptic devices. Shizuo Tokito and co-workers proposed in article number 2201040 a simple haptic system based on a soft actuator fabricated by means of a scalable, large-area compatible printing process. The actuator is fabricated by using a unique composite of (i) piezoelectric poly(vinylidenedifluoride-trifluoroethylene), (ii) single-walled carbon nanotubes, (iii) graphene oxide and (iv) poly(3,4-ethylenedioxythiophene) polystyrene sulfonate. In article number 2201327, Virgilio Mattoli and Arianna Mazzotta presented a conformable and thin electronic device for electro-thermo-pneumatic stimulation, capable of providing localized tactile sensations thanks to its slight expansion that causes pressure sensations on the human skin. Interestingly, tests on a voluntary subject demonstrate how it is possible to discriminate the tactile sensation elicited by the active device, thus opening the potential of the new approach for developing wearable tactile displays.

In order to achieve more complex and integrated devices on the ultra-thin embodiment, additional components are required, as well as new fabrication and integration approaches. In this vision, two papers assess the problem by proposing specific solutions (and materials) for energy storage and for ultra-thin, stretchable transistors, while two more works propose innovative solutions for fabrication, including smart hetero-integration of components and conformal transfers of ultra-thin electronics. Specifically, in 2201095 Sunghwan Kim and co-workers reported a thin, breathable, and skin-compatible charge-storing electronic tattoo, based on carbon nanotubes, silk protein nanofibers, and poly(vinyl alcohol) nanofibers. The tattoo showed excellent mechanical and electrical stability, as well as frequency-dependent capacitances and, therefore, the capability for memory operation. The authors also showed that the same approach can be used for the fabrication of a triboelectric nanogenerator. Qingxin Tang and co-workers presented in article number 2200438 thin organic field effect transistors based on a stretchable organic semiconductor based on a blend between poly[4-(4,4-dihexadecyl-4H-cyclopenta[1,2-b:5,4-b′]dithiophen-2-yl)-alt-[1,2,5]thiadiazolo[3,4-c]pyridine] (PCDTPT) and styrene-ethylene-butylene-styrene (SEBS). The blend can improve the crack-onset of the pristine PCDTPT (around 5%) up to 182%, still maintaining high mobility (above 2 cm^2/Vs). In article number 2201281, Nico Munzerieder and co-workers proposed an interesting method to transfer substrate-free thin electronic devices onto unconventional surfaces. The devices, namely thermistors and resistive temperature sensors, are transferred on several surfaces showing good adhesion and are capable to be bent to a radius of almost 15 micrometers, showing a low variability in performance. Ravinder Dahiya and co-workers reported in article number 2201116 a novel and reliable printed route to integrate thin chips and nanowires-based electronic layers on the same substrate. The excellent interfacial behavior between printed chip with nanowires and substrate was tested by performing cyclic bending tests at a 20 mm radius which revealed no delamination/crack on the printed chip with nanowires, thus assessing the reliability of the proposed fabrication process for electronic skin applications.

As introduced at the beginning, materials matter. Especially in this specific field. Five papers are thus dedicated to investigating more fundamental aspects, such as stretchability, charge-transport, and stability, of materials that can be used in soft, conformable, and thin electronics. In particular, in article number 2201055 Zhenan Bao and co-workers reported a systematic investigation on the tunability of the fractural strain of the blend based on poly[((2,6-bis(thiophen-2-yl)−3,7-bis(9-octylnonadecyl)thieno[3,2-b]thieno [2′,3′:4,5]thieno[2,3-d]thiophene)−5,5′-diyl)(2,5-bis(8-octyloctadecyl)−3,6-di(thiophen-2-yl)pyrrolo[3,4-c]pyrrole-1,4-dione)−5,5′-diyl]] (P2TDPP2TFT4) and polystyrene-block-poly(ethylene-ran-butylene)-block-polystyrene (SEBS), by changing the molecular weight of both P2TDPP2TFT4 and SEBS. In article number 2201107 Wen-Yong Lai and co-workers presented a facile solution crystallization method that can bring superior order and enhanced carrier transport without external treatments in small molecules when blended with conjugated polymers. In article number 2201346, Beatrice Fraboni and co-workers performed X-ray nanoanalysis in order to study the role of [6,6]-phenyl-C_{61}-butyric acid methyl ester fullerene (PCBM) molecules when interacting with methylammonium-lead-iodide (MAPbI3) polycrystalline thin films acting as photo-conductors in X-ray detectors, showing that the addition of the PCBM increases the photocurrent generation and the charge collection becomes uniform over the full crystallite volume. The results establish the X-ray nanoanalysis techniques as a powerful tool to investigate charge transport and collection in perovskite films for X-ray detection. Karl Leo and co-workers presented in article number 2201350 an organic donor-acceptor blend with a low energy and broad charge transfer (CT) feature, with a significant absorption over 1000 nm. When used as active material in an organic photodetector, authors showed that thanks to its spectrally narrow response of only 18 nm, it can be used for highly resolved measurements. Esma Ismailova and co-workers proposed in article number 2201282 a study on the mechanisms that influence the electrical, electrochemical, and mechanical stability of bioelectronic transducers based on thin electrodes coated with poly(3,4-ethylene dioxythiophene) polystyrene sulfonate conductive polymer, deposited by means of electropolymerization.

Finally, three reviews will complete the Special Issue, addressing the field from different perspectives. In article number 2200512, Naoji Matsuhisa and co-workers deeply discussed the "comfort-of-wear", (i.e., the adherence of wearers to wearable devices), giving a strict definition and reporting the main approaches to improve the comfort-of-wear of devices reported in the literature so far. Dae-Hyeong Kim and co-workers in article number 2201271 analyzed the recent advances and studies on the integration of perovskite materials onto thin flexible substrates with a proper encapsulation layer, including a brief discussion on future prospects. In article number 2201294, Woon-Hong Yeo and co-workers summarize the recent advances in materials, manufacturing, and integration technologies to develop thin soft sensors for monitoring various human physiological signals, sharing the details of soft sensors, integration processes, manufacturing methods, and their applications to target physical, electrical, and chemical signals.

As Guest Editors, we strongly believe that the impressive quality of the technical content, as well as the variety of the papers here published, make this Special Issue a milestone and guideline for the next decade of research into ultra-thin electronics.

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Conflict of Interest

The authors declare no conflict of interest.

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Fabrizio Antonio Viola received his MS degree in electronic engineering (cum laude) from the University of Cagliari in 2014, and earned his PhD in Bioengineering and Robotics, working on multimodal tactile sensors based on organic field-effect transistors – under the supervision of Prof. Annalisa Bonfiglio – from the University of Genova in 2018. From 2018 to 2022 he worked as Postdoc Researcher at Center for Nano Science and Technology@PoliMi (CNST) of the Istituto Italiano di Tecnologia in the Printed and Molecular Electronics group, led by Dr. Mario Caironi. He is currently Research Assistant at University of Cagliari, working on printed electronics, ultra-thin/imperceptible electronics and biomedical/physical sensors for the health care. He is also a 2022 Young Researcher SoE grantee.

Virgilio Mattoli received received his PhD in 2005 in bio-engineering (cum laude) from Scuola Superiore Sant'Anna. From June 2008 to October 2009 he obtained a temporary position of Assistant Professor of bioengineering at the Scuola Superiore Sant'Anna (SSSA). From 2009 he has worked at the Center for Materials Interfaces of the Istituto Italiano di Tecnologia. His research interests include: smart nano- and bio-inspired materials, soft electronics, sensors, micro/nano-fabrication technologies, and biorobotics. He is currently involved in several research projects on these topics, including the EU FET Project 5D NanoPrinting and the EU EIC challenge project IV-Lab, of which he is the coordinator. He is (co)author of about 180 journal papers and 45 invited talks.