International Journal of Engineering Sciences Paradigms and Researches (IJESPR)
(Vol. 36, Issue 01) and (Publishing Month: November 2016)
(An Indexed, Referred and Impact Factor Journal)
ISSN: 2319-6564
www.ijesonline.com

Application of Soft Materials for Sustainable Electronics

Jyotirmaya Samal[1] and Ranjan Kumar Samantaray[2]

[1]Aryan Institute of Engineering & Technology, Bhubaneswar, Odisha

[2]Raajdhani Engineering College, Bhubaneswar, Odisha

ABSTRACT

In the ebb and flow shift from ordinary petroleum derivative based materials to environmentally friendly power, ecofriendly mate-rials have drawn in broad exploration interest because of their supportability and biodegradable properties. The mix of supportable materials in gadgets gives mechanical advantages from squandered bio-beginning assets and jelly the climate. This survey covers the utilization of supportable materials as compo-nents in natural gadgets, like substrates, separators, semiconductors, and conductors. We trust this survey will animate interest in the potential and viable utilizations of economical materials for green and practical industry.

Introduction

A recent trend in electronic devices is to develop specially designed organic materials that exhibit high flexibility, sometimes including mechanical stretchability, which have been considered for practical or potential applications ranging from wearable electronics to applications in mobile health, sports, and more [1]. Much of the interest in the use of organic material is associated with the desire to design electronic components that are ecofriendly and biocompatible, or even metabolizable [2–5]. The adoption of material derived from nature is a primary concern for both society and industry. This aim conflicts with the ever-increasing volume of electronic waste, which was estimated to be 5.0×10^7 Mt in 2018 [6]. In particular, plastic expenditure and waste have been presenting enormous problems in recent times. For example, polyethylene is presently at the peak of universal consumption, at about 275 Mt in 2015, and is widely used in everyday substances including plastic bags, toys, and packing materials [7]. Due to the greater demands of emerging industries and the current coronavirus disease 2019 (COVID-19) in 2020, more plastics are being consumed, and their full degradation will take over 500 years [8,9].

Therefore, inspiration from nature has led to explorations in biocompatible electronics, prompting the development of organic

bodies in the near future—just as we are currently familiar with tablet computers and smartphones.

1. Passive and active components

Substrates and dielectric layers

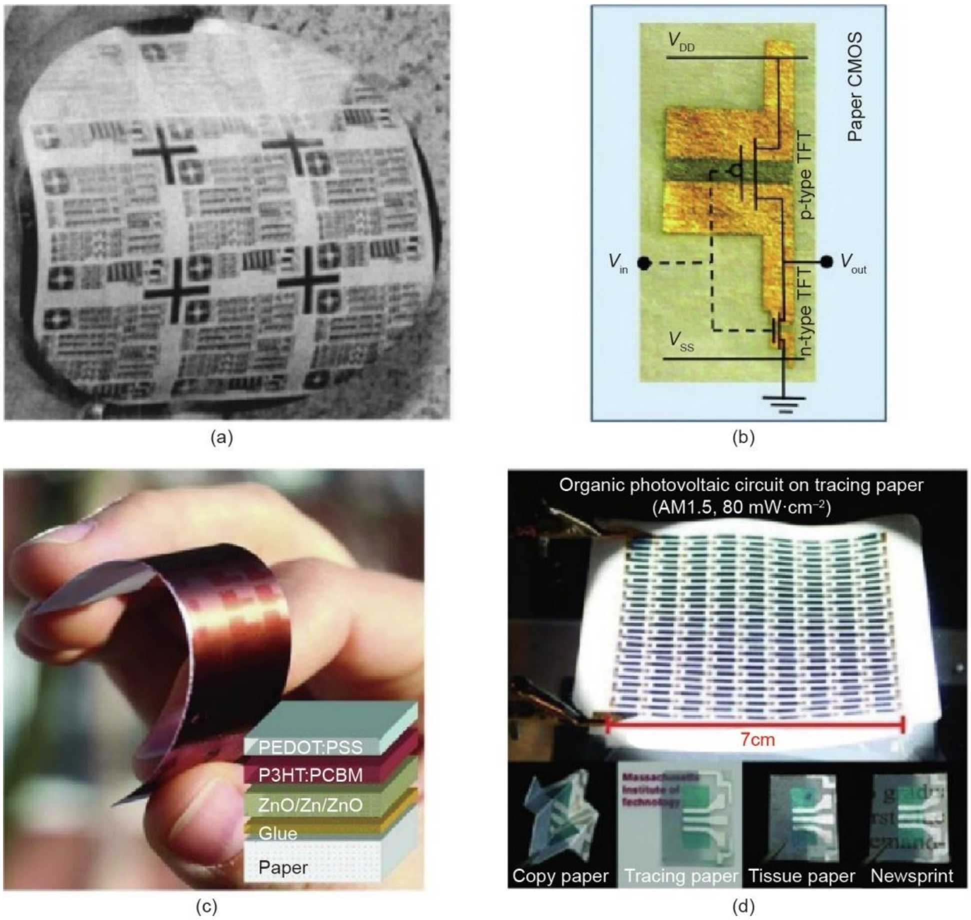
electronics that naturally break down when their use is over [10]. A broad area of sustainable organic materials originating from animals, plants, and bacteria, such as chitin, cellulose, starch, and various kinds of proteins, have been studied [11–24], and are generally adopted in various applications such as coating materials, biomedical applications, and so on. With increasing demands for sustainable devices, the question of how to integrate non-petroleum and plastics-related exotic materials with the present standards of living is coming under scrutiny. Sustainable materials with superior biodegradability have attracted a great deal of attention in terms of being integrated with devices in order to benefit from bio-origin materials while preserving the environment. However, integrating sustainable materials in electronic devices with a high-efficiency output is a continued obstacle. Nevertheless, persistent environmental concerns have rationalized the use of organic electronics in substrates, the dielectric layer, and semiconducting materials [25].

Hence, this review aims to provide a brief overview of sustainable materials for use in degradable circuit boards and organic electronics, covering the latest developments in this field. In this review, organic soft materials are classified based on function, such as ① substrates and insulators, ② semiconductors, and ③conductors. We predict that life will be as comfortable and safe with highly deformable and biodegradable electronics integrated everywhere—in clothes and with our

Paper and silk

Various materials originating from nature have been considered to be appropriate substrates for organic electronics due to their numerous advantages, including economic benefits, biocompatibility, and nontoxicity. One of the most familiar and classical organic substrates is paper, which is made from plants or wood-derived cellulose. The outstanding physical characteristics of cellulose make it possible to cover large areas and enable the mass production of paper. Paper is superior to other deformable passive materials due to its economical price, at approximately 0.2 USD m^{-2}, excellent flexibility, and roll-to-roll (R2R) fabrication capability at a fast process speed of about 25 $m\,s^{-1}$ [26]. In addition to its use in typical packaging and storage applications, paper has been developed for use as a substrate for various unconventional forms. Organic thin-film transistor (OTFT)-based circuits have been fabricated on paper and have demonstrated flexibility and specific results comparable to those of conventional polymer substrates (Fig. 1(a)) [27–29]. Low-voltage-driven OTFTs have been achieved on banknotes for applications in anti-counterfeiting. OTFTs could be fabricated on paper operating under less than 2 V with mobilities of about 0.3 $cm^2\,V^{-1}\,s^{-1}$, regardless of banknote paper's surface roughness. Yun et al. [30], Shao et al. [31], Ha et al. [32], Casula et al. [33], and Martins et al. [34] utilized low power-driven complementary metal–oxide semiconductor (CMOS) inverters based on a paper substrate. Fig. 1(b) [29] shows a photograph of a CMOS inverter operating in accordance with input-voltage (V_{in}). In addition, paper substrates have been applied to other opto-electrical devices, including organic photovoltaics (OPVs) and thermochromic displays [35–37]. In particular, the advanced performance of OPVs has been demonstrated via full R2R printing by means of a solution process using flexographic and gravure methods. The device has an inverted configuration, such as a printed ZnO/Zn bottom and a conducting polymer top electrode based on economical materials with a low-temperature solution process (Fig. 1(c) [37]). Another example is the use of low-temperature chemical vapor deposition (CVD) onto paper for photovoltaics; the device consists of conducting polymer electrodes, an active organic layer, and reflective back electrodes, as shown in Fig. 1(d) [38]. This work demonstrated arrays of OPV devices that could be folded without degradation of the electrical characteristics, demonstrated through repeated folding tests.

Silk is another natural material with a long history that has been applied in the dielectric layer and as an electronic device



(a) (b) (c) (d)

Fig. 1. Paper-substrate-based electronic devices. (a) OTFT arrays fabricated on a paper substrate; (b) a CMOS inverter circuit on a paper substrate; (c) a flexible, solution-processed OPV on paper with the device configuration (bottom right corner); (d) image of CVD-based solar cells on semitransparent paper. TFT: thin-film-transistor; V_{in}: input-voltage; V_{out}: output-voltage; V_{DD}: voltage drain to drain; V_{SS}: voltage source to source; PEDOT:PSS: poly(3,4-ethylenedioxythiophene) system doped with polyanionic poly(styrene sulfonate); P3HT:PCBM: poly(3-hexylthiophene):(6,6)-phenyl-C_{61}-butyric acid methyl ester. (a) Reproduced from Ref. [27] with permission of AIP Publishing, ©2004; (b) reproduced from Ref. [29] with permission of Wiley-VCH, ©2011; (c) reproduced from Ref. [37] with permission of Wiley-VCH, ©2011; (d) reproduced from Ref. [38] with permission of Wiley-VCH, ©2011.

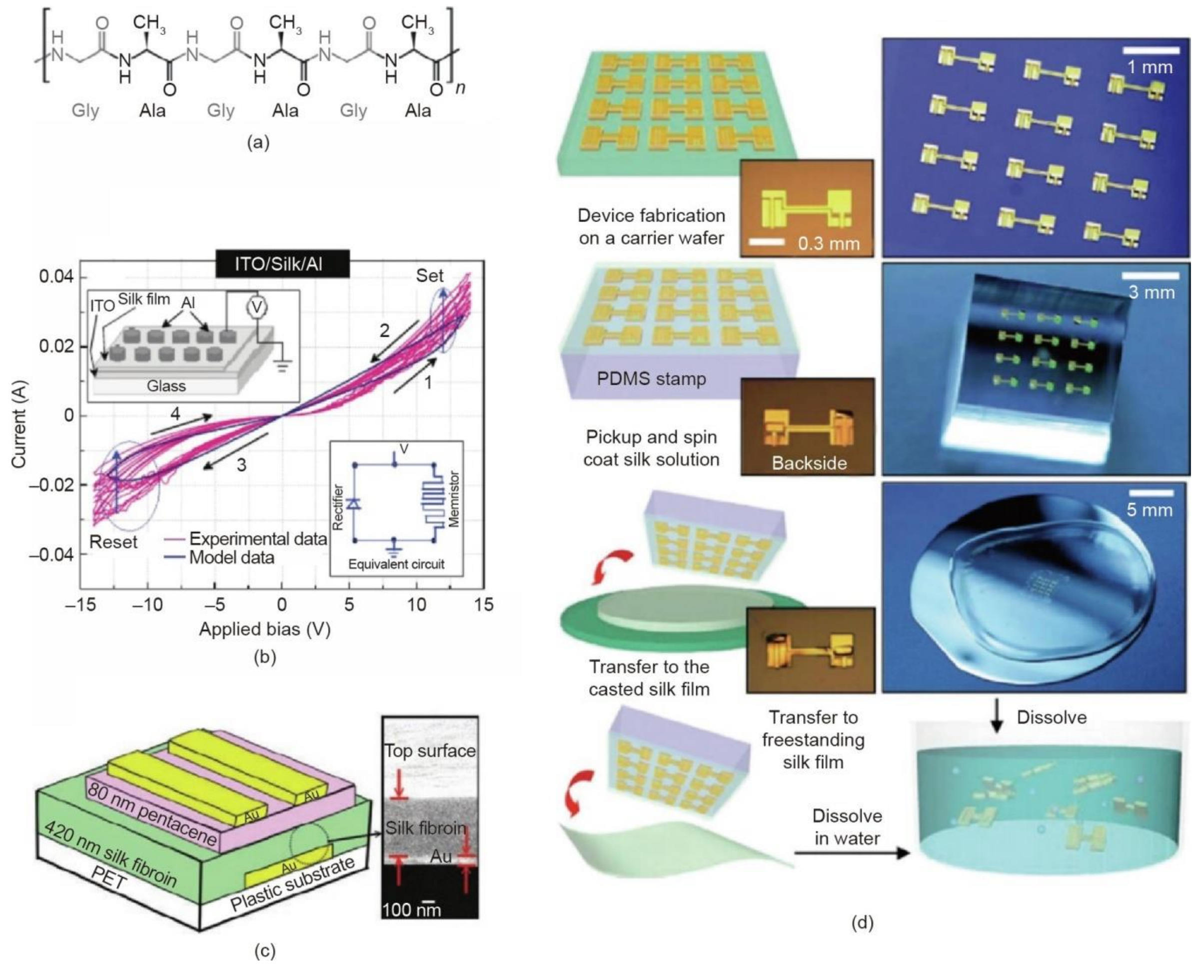


Fig. 2. Dielectric layer and substrates based on silk. (a) Chemical structure of silk fibroin; (b) bio-memory resistor based on silk fibroin protein showing reversible and nonvolatile properties; (c) solution-processed silk fibroin films as the dielectric layer in flexible OTFTs; (d) bioresorbable silk substrates for the transfer of a sensor array onto brain tissue. ITO: indium-tin-oxide; PDMS: poly(dimethylsiloxane); PET: polyethylene terephthalate. (b) Reproduced from Ref. [40] with permission of Wiley-VCH, ©2012; (c) reproduced from Ref. [41] with permission of Wiley-VCH, ©2011; (d) reproduced from Ref. [44] with permission of Springer Nature, ©2010.

substrate. Fundamentally, silk is a polypeptide polymer consisting of fibroin and sericin. Fibroin has repeated glycine, serine, and alanine units, which enhance the mechanical robustness due to interchain hydrogen bonding (Fig. 2(a)) [39]. Hota et al. [40] manipulated bio-origin silk fibroin to make a transparent bio-memory resistor and analyzed the device's endurance and retention characteristics. As shown in Fig. 2(b) [40], metal–insulator–metal capacitors based on silk fibroin exhibited memory resistor functionality with simultaneous rectifying properties. In addition, silk was applied as an efficient gate insulator layer on a polyethylene terephthalate (PET) substrate (Fig. 2(c)), exhibiting a mobility of about 23 $cm^2{\cdot}V^{-1}\,s^{-1}$ with low-voltage operation [41]. Another example of silk being applied as a dielectric layer was demonstrated by Capelli et al. [42], whose organic light-emitting transistors based on silk yielded a light emission of 100 nW. Chang et al. [43] made use of spider silk as a polyelectrolyte dielectric layer in OTFTs based on a pentacene semiconductor and investigated the hydration of the silk dielectric with respect to reproducibility under different levels of humidity. In addition, various research groups have investigated the characteristics of silk, which include deformability and outstanding mechanical properties. Kim et al. [44] demonstrated metal electrodes with the bioresorbable properties of silk (Fig. 2(d)), and showed the transfer printing process. In the fabrication sequence, metal–oxide field effect transistors (FETs) were fabricated on a poly(methyl methacrylate) temporary substrate. Next, the devices were fished on a poly(dimethylsilox- ane) substrate. As a result, the electrodes were transferred to the silk film above a silicon substrate, resulting in resorbable elements that could be safely implanted into the body, and in which the degree of crystallinity was tuned to modulate transient times. In subsequent research, Hwang et al. [45] demonstrated biomedical applications based on electronics interacting with living tissue, with controlled transient times and resolution.

Conclusions and perspectives

In this study, we reviewed the use of ecofriendly materials in opto-electronics and discussed their promising—and practical—electronic performance as a replacement for conventional inorganic or fossil-fuel-based materials. Materials originating from nature can be used as passive or active components in electronic devices, in applications such as substrates, templates, insulators, semiconductors, and conductors. However, issues remain with their direct application as active electronic components in sustainable electronics, limiting their effective integration with opto-electronic devices. First, solubility is of concern because eco-friendly materials will only dissolve in water-based solvents, which can be harmful to device fabrication. Second, thermal stability should be considered due to the numerous hydroxyl groups in natural materials, which would suffer under the high temperatures required for device fabrication, deteriorating the stability of both the device elements and device performance. The third issue to consider is tuning the degeneration rate of sustainable materials integrated with common inorganic or fossil-fuel-based materials, as some materials can be vulnerable to device preservation issues. Despite these issues, sustainable materials continue to draw global attention for the vast number of options they open up and for their ecofriendly properties. In addition, there is room for improvement in the electrical properties and stability of such materials by means of physical and chemical modifications and composite technologies. There are abundant opportunities for further investigation, ranging from the verification of sufficient balanced bio-origin materials that are applicable for device configuration and advancement through optimization, to commercialized prototypes. Ultimately, from natural materials to electronic devices, this area of investigation provides insight into the merging of a wide range of multidisciplinary sciences, such as chemical engineering, material science, biotechnology, and electronic engineering, in order to advance the next generation of sustainable devices.

Acknowledgements

This work was supported by a grant from the National Research Foundation (NRF) funded by the Korean Government (MSIT, 2017R1E1A1A01072798 and 2019K1A3A1A14065772).

Compliance with ethics guidelines

Moon Jong Han and Dong Ki Yoon declare that they have no conflict of interest or financial conflicts to disclose.

References

[1] Bettinger CJ, Bao Z. Biomaterials-based organic electronic devices. Polym Int 2010;59(5):563–7.
[2] Kim DH, Lu N, Ma R, Kim YS, Kim RH, Wang S, et al. Epidermal electronics. Science 2011;333(6044):838–43.
[3] Kim YJ, Chun SE, Whitacre J, Bettinger CJ. Self-deployable current sources fabricated from edible materials. J Mater Chem B Mater Biol Med 2013;1 (31):3781–8.
[4] Norton JJS, Lee DS, Lee JW, Lee W, Kwon O, Won P, et al. Soft, curved electrode systems capable of integration on the auricle as a persistent brain–computer interface. Proc Natl Acad Sci USA 2015;112(13):3920–5.
[5] Tao H, Hwang SW, Marelli B, An B, Moreau JE, Yang M, et al. Silk-based resorbable electronic devices for remotely controlled therapy and *in vivo* infection abatement. Proc Natl Acad Sci USA 2014;111(49):17385–9.
[6] Balde K, Wang F, Huisman J, Kuehr R. The global e-waste monitor 2014: quantities, flows and resources. Bonn: United Nations University; 2015.
[7] Jambeck JR, Geyer R, Wilcox C, Siegler TR, Perryman M, Andrady A, et al. Marine pollution. Plastic waste inputs from land into the ocean. Science 2015;347(6223):768–71.
[8] Shah AA, Hasan F, Hameed A, Ahmed S. Biological degradation of plastics: a comprehensive review. Biotechnol Adv 2008;26(3):246–65.
[9] Singh B, Sharma N. Mechanistic implications of plastic degradation. Polym Degrad Stabil 2008;93(3):561–84.
[10] Kang SK, Murphy RKJ, Hwang SW, Lee SM, Harburg DV, Krueger NA, et al. Bioresorbable silicon electronic sensors for the brain. Nature 2016;530 (7588):71–6.
[11] Li J, He Y, Inoue Y. Study on thermal and mechanical properties of biodegradable blends of poly(e-caprolactone) and lignin. Polym J 2001;33 (4):336–43.
[12] Hosoda N, Tsujimoto T, Uyama H. Plant oil-based green composite using porous poly(3-hydroxybutyrate). Polym J 2014;46(5):301–6.
[13] Nigam PS, Singh A. Production of liquid biofuels from renewable resources. Prog Energy Combust Sci 2011;37(1):52–68.
[14] Eichhorn SJ, Gandini A. Materials from renewable resources. MRS Bull 2010;35(3):187–93.
[15] Nakai Y, Yoshikawa M. Cellulose as a membrane material for optical resolution. Polym J 2015;47(4):334–9.
[16] Sunilkumar M, Gafoor AA, Anas A, Haseena AP, Sujith A. Dielectric properties: a gateway to antibacterial assay—a case study of low-density polyethylene/chitosan composite films. Polym J 2014;46(7):422–9.
[17] Huang X, Zhang S, Zhang Y, Zhang H, Yang X. Sulfonated polyimide/chitosan composite membranes for a vanadium redox flow battery: influence of the sulfonation degree of the sulfonated polyimide. Polym J 2016;48(8):905–18.
[18] Rinaudo M. Chitin and chitosan: properties and applications. Prog Polym Sci 2006;31(7):603–32.
[19] Xu C, Arancon RAD, Labidi J, Luque R. Lignin depolymerisation strategies: towards valuable chemicals and fuels. Chem Soc Rev 2014;43(22):7485–500.
[20] Besson M, Gallezot P, Pinel C. Conversion of biomass into chemicals over metal catalysts. Chem Rev 2014;114(3):1827–70.
[21] Pérez S, Bertoft E. The molecular structures of starch components and their contribution to the architecture of starch granules: a comprehensive review. Starke 2010;62(8):389–420.
[22] Damager I, Engelsen SB, Blennow A, Møller BL, Motawia MS. First principles insight into the a-glucan structures of starch: their synthesis, conformation, and hydration. Chem Rev 2010;110(4):2049–80.
[23] Lligadas G, Ronda JC, Galià M, Cádiz V. Renewable polymeric materials from vegetable oils: a perspective. Mater Today 2013;16(9):337–43.
[24] Chen GQ. A microbial polyhydroxyalkanoates (PHA) based bio- and materials industry. Chem Soc Rev 2009;38(8):2434–46.
[25] Irimia-Vladu M. ‘‘Green” electronics: biodegradable and biocompatible materials and devices for sustainable future. Chem Soc Rev 2014;43 (2):588–610.
[26] Tobjörk D, Österbacka R. Paper electronics. Adv Mater 2011;23(17):1935–61.