

Polymers for Flexible Electronics

The discovery of conductive polyacetylene by Heeger, MacDiarmid, and Shirakawa *et al.* in 1977 opened a new era, which led them to win the 2000 Nobel Prize in Chemistry for “The discovery and development of conductive polymers”.^[1] In 1987, Tang and VanSlyke reported sandwiched electroluminescence device structures, representing a milestone in the field of organic electronics.^[2] In 1990, Friend, Holmes, Bradley, and their coworkers from the Cavendish Laboratory and Melville Laboratory with Cambridge University developed their polymer-based electroluminescent devices, which was widely recognized as opening the door of plastic electronics.^[3] Since then, the technologies of organic light-emitting diodes (OLED), organic photovoltaics (OPV), organic field-effect transistors (OFET), and organic solid-state lasers (OSSL), based on conductive polymers have been pushing forward quite rapidly.

With the flexibility of a large number of information electronic devices, flexible electronics has come into being. Over the past decade, flexible electronics research has experienced rapid growth, which is also driven by the demand for the portable and wearable instruments. Flexible electronics, a rampant technological invention that requires the use of soft dielectric and conductive materials, encourages the use of polymers due to their superior optoelectronic characteristics such as conductivity, optical absorbance and carrier transport as well as attractive mechanical properties including flexibility, deformability and solution-processed fabrication. Flexible electronics has been considered as a disruptive technology based on pioneering and interdisciplinary research, which can break through intrinsic limitations of the classical silicon-based electronics. This can open innovative prospects for the integration design, energy revolution, medical technological changes, providing important opportunities for leading the industry development in the future *via* self-dependent innovation.

The superiority of flexible electronics is first ascribed to the ultimate pursuit of the performance of electronic elementary devices. The flexible design of core components plays a crucial role in developing flexible electronic devices. A major issue of concern for flexible electronics is often a trade-off between the best optoelectronic characteristics and device flexibility. For the purpose of fabricating high-performance organic flexible devices, different methods have been explored, mostly concentrating on the following four aspects: a) intrinsically flexible organic components (semiconductors, electrodes, insulators, and substrates), b) device engineering, c) fundamental mechanical deformability, and d) fabrication techniques. Polymers with intrinsic flexibility are used to construct flexible

electronic devices. Firstly, with their intrinsically low elastic modulus, polymers are naturally pliable to enhance the strain in fully flexible devices, which can be extensively employed in flexible electronics. Secondly, structural engineering plays an important role in improving deformation tolerance with the introduction flexible interconnects. Thirdly, internal electrical stability *via* external mechanical stimuli is crucial for flexible electronics. For instance, recent advances in polymer-based electronics on flexible substrates offer substantial rewards in terms of being able to develop displays that are thinner, lighter, robust, and conformable, and can be rolled away when not required. Generally speaking, polymers can be divided into two classes: conjugated polymers with a delocalized π -electron system and polymers with functional units attached to a nonconjugated backbone. State-of-the-art polymers composed of alternating electron rich and electron deficient aromatic moieties allow for widely tunable absorption in the visible up to the near infrared region of the electromagnetic spectra, as well as close π - π stacking distances. This kind of polymers makes a great contribution to improving the device performance particularly in the field of OFETs and OPVs. Polymers not only act as the active layer of electronic devices but also serve as the substrates. Compared with thin glass and metallic foil substrates, polymer substrates such as poly(ethylene naphthalate) (PEN), poly(ethylene terephthalate) (PET), polynorbornene (PNB), poly(cyclic olefin) (PCO), polyimide (PI), polyethersulphone (PES), polyarylate (PAR) and polycarbonate (PC), can serve as attractive candidates for flexible electronics owing to their mechanical robustness, dimensional stability, optical clarity, surface roughness and solvent resistance. Based on such polymer substrates, among many others, some leading researchers, for example, Zhenan Bao, Wei Huang, Yonggang Huang, John Rogers, and Takao Someya, have done copious excellent studies in the field of flexible electronics. Besides, polymers can be formulated as inks for inkjet-printing, enabling large area device processing and integration of flexible electronic devices with low cost and high efficiency. In the future, the fabrication of flexible electronics will be as easy as printing a document.

Flexible electronic devices are one of the main forms of flexible electronics. Developing multifunctional flexible electronic devices based on flexible materials *via* micro/nano fabrication and integration technology is highly desirable yet challenging. Flexible functional materials with unique physical and chemical characteristics such as light, electricity and heat can find extensive utilization such as flexible displays, information encryption and wearable perception. Our group has exerted great efforts on

flexible electronics. The *p-n* band regulation strategy of organic semiconductors was proposed to achieve the design, synthesis and device application of dynamic self-adjusting organic photoelectric materials. High-performance organic semiconductor devices with blue emission was developed, among which the efficiency of non-doped blue OLEDs reached the international level. A new strategy of developing flexible sensors *via* micro/nano fabrication was proposed, yielding a series of new flexible health sensors with high sensitivity. The stabilization of black-phase formamidinium lead iodide perovskite under various environmental conditions was realized based on a vertically aligned lead iodide thin film grown from an ionic liquid, methylamine formate regardless of humidity and temperature. Solution processable heterostructures of organic-inorganic hybrid perovskites were achieved *via* a room-temperature epitaxial welding process, allowing for large scale fabrication of optoelectronic devices. The world's first pure organic long-afterglow luminescent material without metal and heavy elements was developed, which can be widely applied in data encryption and information security.

Flexible electronics continues to evolve every day, new research is driven from functional polymers to new methodologies of fabricating devices in unconventional shapes, in faster, cheaper, and more accessible manners. Rather than competing with conventional electronics in terms of performance, they offer innovative ways to interact with environments that were not possible before. The future of flexible electronics includes an infinity of new applications ranging from consumer electronics like folding phones and rollable displays to wearable and implantable bioelectronics that monitor our health and make diagnostics simpler using machine learning.

In summary, polymers can hold a great promise for flexible electronics due to their unique mechanical flexibility, excellent solution processability, and tunable optoelectronic properties. Impressive advances have been made in this booming field, encompassing flexible displays, wearable electronics, biomedical devices, among others. Although the progresses in this area are hugely exciting, several problems remain yet to be solved from both the academic and industrial perspectives. For instance, stretchability is still more challenging to achieve than simple flexibility. Structural engineering is an auxiliary approach, but usually needs complex preparation processes. Another challenge may lie in simultaneously achieving superior mechanical flexibility and high electrical properties in polymers. It is necessary to guarantee that high electrical properties should remain when polymers are under large deformation such as bending, twisting and stretching. In this case, more efforts should be devoted to exploring the structure-property relationship at a molecular level. Understanding the effects of molecular structure parameters, such as molecular weight, regioregularity, backbone and side chain modifications on the film morphology, will provide general guidelines for achieving favorable micro-

structures, *i.e.*, balanced distribution of crystalline and amorphous regions in polymer films that allow mechanical deformation without degrading electrical properties. Besides, a deeper knowledge of the mechanical properties of polymers will bring about other fascinating attributes that are indispensable for smart wearable electronics and bio-inspired devices, such as biodegradability and self-healing ability. Thus, polymers could more fully embody colloquial meanings of “organic” and “plastic”, by which they are often referred to. With the rapid advancement of new polymers, advanced fabrication methods, and rational geometric design strategies, we firmly believe that flexible electronics based on polymers is bound to cause another revolution in human lifestyles in the future.

REFERENCES

- 1 Shirakawa, H.; Louis, E.; MacDiarmid, A. G.; Chiang, C. K.; Heeger, A. J. Synthesis of electrically conducting organic polymers: halogen derivatives of polyacetylene, (CH)_x. *J. Chem. Soc., Chem. Commun.* **1977**, 28, 578–580.
- 2 Tang, C. W.; VanSlyke, S. A. Organic electroluminescent diodes. *Appl. Phys. Lett.* **1987**, 51, 913–915.
- 3 Burroughes, J. H.; Bradley, D. D. C.; Brown, A. R.; Marks, R. N.; Mackay, K.; Friend, R. H.; Burn, P. L.; Holmes, A. B. Light-emitting diodes based on conjugated polymers. *Nature* **1990**, 347, 539–941.



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