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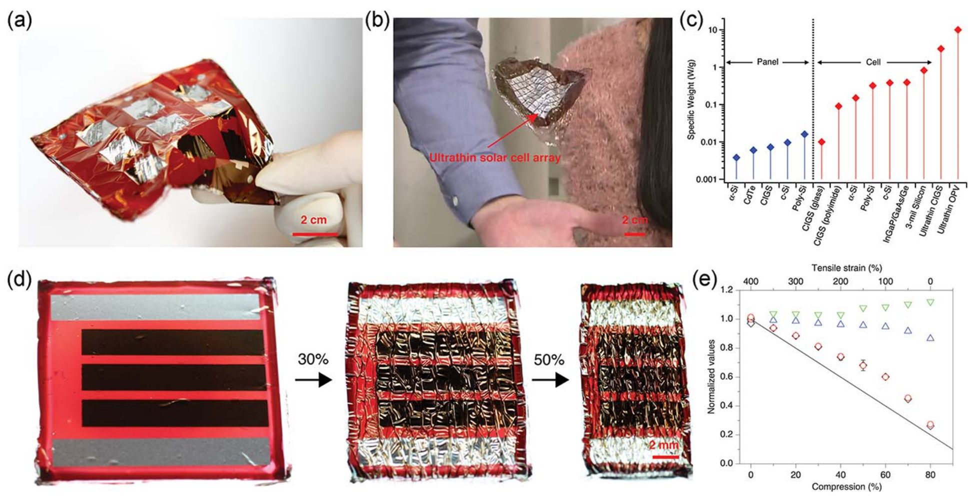

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Breakthroughs in Photonics 2012: Large-Area Ultrathin Photonics

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(Invited Paper)

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Abstract: Recent work is reviewed on organic solar cells thinner than a thread of spider silk, so flexible that they can be wrapped firmly around a human hair, lighter than autumn leaves and with an unprecedented specific weight of 10 W/g. Solar cell fabrication is based on planar process technologies only, commonly employed in semiconductor industry. The same weight per area and exceptional flexibility should easily be achievable also in organic light-emitting diodes, transistors, and integrated circuits, to realize unbreakable ultrathin electronics. When adhered on conforming surfaces, the solar cells become stretch compatible withstanding tensile strains of roughly 400%. Applications of the technology may arise wherever mass is a critical concern and span from small scale robots to health care and biomedical systems.

Index Terms: Organic solar cells, flexible electronics, stretchable electronics, wrinkles, photonic structures.

1. Introduction

Designing electronics ultrathin and ultralightweight bears distinct advantages as it reduces the energy consumption for transportation, minimizes electronic waste, and is a prerequisite for mobile appliances. Ultrathin electronic foils exhibit extraordinary mechanical flexibility; they even become stretch compatible when integrated with elastomeric materials. There are many applications of electronics and photonics where specific weight is prioritized, weather balloons, unmanned aircraft, small-scale robotic insects, and pack-weight for remote wilderness use [1]. Even more stringent requirements arise when an intimate integration of electronics into daily life systems is anticipated, e.g., in textiles [2] and on or in the human body [3]–[9]. For such applications, stretchability is an utmost prerequisite. Flexible and stretchable electronics are emerging research areas that may develop into mainstream technologies. Ultrathin electronic and photonic systems may be ideal for achieving extremely flexible and stretchable devices, so recent research was devoted to answer

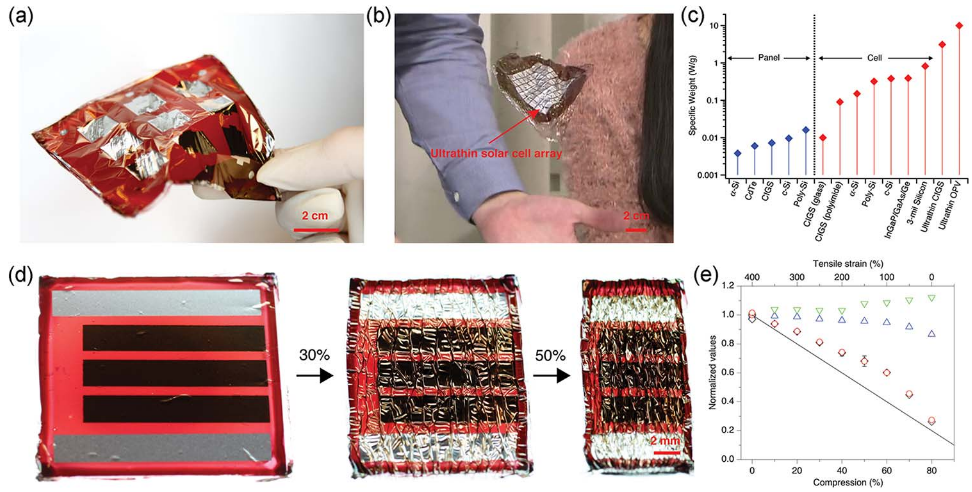

Fig. 1. (a) Photo of a sub-2-μm-thick organic solar cell. (b) The ultralightweight solar cell with only 4-g/m^2 mass per area floats through the air, much like autumn leaves. In such a free fall experiment, the ultrathin film instantly reaches an end velocity of 0.2 m/s, rendering the cells virtually indestructible even when dropped from large heights. (c) Comparison of the specific power of various photovoltaic technologies from complete modules to individual cells. The specific weight of 10 W/g is the largest value reported for any photovoltaic technology to date. (d) Ultrathin solar cells become highly stretchable when attached to a pre-stretched elastomer. They are shown in various states of linear compression from flat to 30% and 50%, forming wrinkles and deep folds. When placed on a biaxially pre-stretched elastomer, the cells conform to arbitrary 3D free forms. (e) Fill factor (green downward triangles), open circuit voltage (blue upward triangles), short-circuit current (red circles) and power (black diamonds) versus stretch from 0% to 80% compression. All parameters are normalized to their pre-compression values. The area-related performance metrics as maximum power and short-circuit current of the solar cell decreases less than expected from a linear decrease in area, wrinkles and deep folds act as light-harvesting photonic structures. Adapted from [1] and reprinted with permission from Macmillan Publishers Ltd.

questions as "how light," "how flexible," and "how stretchable" these systems can be [1]. There are several approaches for ultrathin electronic and photonic systems, based on inorganic and organic materials [10], [11]. Technology for fabrication ranges from transfer printing [12] to planar large-area processing [1]. Here, we review and compare these existing approaches, with potential applications in consumer and mobile appliances, athlete monitoring in sports, healthcare, and biosystems.

2. Ultrathin Electronics and Photonics

Electronic circuits and photonic elements of today comprise thin layer stacks of different inorganic and/or organic materials. They can be inherently thin with a total thickness of roughly a few hundred nm. A comprehensive review on the state of the art in flexible and stretchable electronics is found in [13]. Breakthroughs in 2012 include bio-absorbable silicon electronics [8] and large-area ultrathin inorganic circuits on flexible substrates [14] and ultrathin chip package systems [15]. In April 2012, we reported a technology platform for the development of ultrathin film electronic and photonic devices in a contribution to Nature Communications [1]. We proposed to free electronic and photonic devices from their rigid thick substrates by fabricating them on ultrathin polymer film substrates. Such polymer films, usually polyethyleneterephtalate (PET) or polyethylenenaphtalate (PEN) are mass produced on large areas for capacitor applications, with a thickness down to 0.5 μm and excellent dielectric and insulating properties [16]. Film capacitors are fabricated in large quantity using high-throughput reel-to-reel processes. The compatibility with well-established industrial manufacturing techniques and the potential for large-area fabrication makes ultrathin capacitor foils an ideal platform for ultraflexible lightweight electronics. Demonstrating the viability of this technology platform, we fabricated organic photovoltaic (OPV) solar cells on 1.4-μm-thick PET foils. OPV cells comprise two electrodes, a light harvesting active layer, and blocking or transport layers. The total thickness of a functional OPV cell is only a few hundred nanometers, and the total device thickness is less than 2 μm, including the substrate. Fig. 1(a) shows a photograph of a sub-2-micron organic solar foil with nine individual solar cells on a 8 cm by 8 cm film. For laboratory scale fabrication, we loosely adhere the ultrathin foil to a PDMS-coated supporting substrate (glass or 125-μm PET foils) and fabricate them with exclusively planar and easy-to-scale techniques. The finished devices can be easily peeled off and operated free standing or transferred to arbitrary foreign bodies by simple peel and place. Owing their extreme mechanical resilience, such electronic foils conform to virtually any 3D free form and malleable surface, providing electrical functionality in yet unexplored ways through simple and cost-effective fabrication. In our paper, we employ an ITO-free OPV architecture with high conductivity PEDOT:PSS as transparent electrode, P3HT:PCBM as photoactive layer, and Ca/Ag as metal cathode. Reaching 4.2% efficiency under 1 sun illumination, our ultrathin cells are as efficient as their glass-based counterparts. With a total mass per area of 4 g/m^2, ultrathin solar cells are extremely lightweight. The still image in Fig. 1(b) shows a free-fall experiment, where the solar cell floats in air much like an autumn leaf. Being dropped, the thin solar foil almost instantly reaches an end velocity of 0.2 m/s, slowly gliding down. This renders the cells virtually indestructible even when dropped from large heights. For situations that require portable power, where payload is a premium such as aircraft, spacecraft, or personal pack load, the power output per weight (specific weight) of a solar cell may become the dominant metric. In Fig. 1(c), we compare the specific weight of various solar technologies (panels and cells) for terrestrial and space applications. Our OPV devices constructed on 1.4-μm PET have a per-area mass of 4 g/m^2 and 4% efficiency, giving 10 W/g. This is the largest value reported for any solar cell technology (organic and inorganic) to date and amongst the highest in a broader picture of weight specific power [17]. The particular materials used in our paper are not comparable with the most efficient or air-stable organic semiconductors, interlayers, or electrodes used in state-of-the-art OPV devices, so there is large potential for optimization by enhancing both efficiency and lifetime of such ultrathin OPV devices while maintaining low weight and high flexibility. The technology platform introduced here is not limited to organic solar cells but should be readily expandable to large-area lightning, sensor and actuator systems.

3. Stretchable Electronics and Photonics

Stretchable electronics is the frontier research of large-area electronics [18]–[22]. There are impressive demonstrations of stretchable conductors [23], circuits, solar cells, displays, and sensors [24]–[31]. It promises applications of electronics in high-strain environments, on arbitrary 3D forms, in textiles, and on and in the human body. A state-of-the-art description (through 2012) is provided in a special issue of the Materials Research Bulletin and in the first book on stretchable electronics [18], [32]. Breakthroughs in 2012 include the demonstration of high areal coverage in inorganic PVs [10] and wirelessly powered implantable light-emitting systems [12]. Wrinkles and deep folds that form on polymers when subjected to mechanical stress were shown to act as nature-inspired light-harvesting photonic structures that significantly improve the light harvesting efficiency of photovoltaic devices [33]. Device fabrication started with optical adhesive films supported on glass substrates. First, wrinkles were formed on the adhesive with tunable wrinkle wavelengths between 1.2 and 5 μm. Deep folds are then created by subjecting the wrinkled surfaces to ion implantation via corona discharge. Finally, organic solar cells were constructed on these composite surfaces. The folds were shown to induce light trapping and waveguiding within the solar cell, substantially increasing the light harvesting efficiency of the device.

As shown in Fig. 1(d) ultrathin solar cells become stretchable when attached to a prestretched highly optically transparent acrylic elastomer. Upon relaxation, an irregular structure of wrinkles and folds is formed, with wrinkle wavelengths below 100 μm and bending radii as small as 10 μm. Fig. 1(e) shows solar cell parameters normalized to their precompression values versus stretch from 0% to 80% compression. This corresponds to 400% tensile strain (taking the length when fully compressed as reference) for a fully functional electronic device. The fill factor and open circuit voltage remain nearly constant during compression, indicating that the mechanical stress does not damage the solar cells. Area-related parameters such as short-circuit current and power versus stretch decrease less than expected from the corresponding linear reduction in area, showing the light harvesting capabilities of the out-of-plane wrinkles and folds formed upon relaxation of the elastomer. No additional process steps on the adhesive are required, and such solar cells can easily be embedded between glass substrates to enhance their lifetime, thus providing a simple and cost-effective microstructuring method. Attached to biaxially prestretched elastomeric substrates, such ultrathin solar foils can deform in three dimensions and adapt to complex shapes.

A natural next step may be to extend the approach to other electronic and photonic systems, e.g., stretchable organic light-emitting displays and active matrix integrated circuit backplanes for sensor arrays.

4. Conclusion

Ultrathin photonics on capacitor grade polymer substrates is an emerging area of research. Ultrathin solar cells have been already successfully introduced as a highlight contribution to photonics research in 2012. More advanced devices await experimental demonstration, such as organic light-emitting displays, active matrix arrays, and fully integrated circuits. When combined with stretchable power sources, such devices allow for electronic and photonic elements that are practically unbreakable and hardly visible.

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