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Onion artificial muscles

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Artificial muscles are soft actuators with the capability of either bending or contraction/elongation subjected to external stimulation. However, there are currently no artificial muscles that can accomplish these actions simultaneously. We found that the single layered, latticed microstructure of onion epidermal cells after acid treatment became elastic and could simultaneously stretch and bend when an electric field was applied. By modulating the magnitude of the voltage, the artificial muscle made of onion epidermal cells would deflect in opposing directions while either contracting or elongating. At voltages of 0–50 V, the artificial muscle elongated and had a maximum deflection of $-30\,\mu$m; at voltages of 50–1000 V, the artificial muscle contracted and deflected 1.0 mm. The maximum force response is 20 μN at 1000 V. *© 2015 AIP Publishing LLC*.
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Recently, much actuator development has been conducted on a variety of soft materials such as dielectric elastomers;[1] electrostrictive polymers;[2] thermal,[3] optical,[4] and conducting polymers;[5] ionic polymer-metal composites;[6] ionic polymer gels;[7] carbon nanotubes;[8] and nanoporous composites.[9–12] The mentioned actuators are capable of either bending or contracting/elongating and thereby often referred to as artificial muscles.[13] In our previous research, Lin *et al*. has shown a compartmentalized dielectric elastomer actuator capable of bending.[14] However, that actuator is difficult to produce and unable to simultaneously contract/elongate and bend. We found that the corrugated upper and lower cell walls in latticed arrangement of onion epidermal cells can be utilized to make an artificial muscle that can be autonomously driven at contraction or elongation mode by simply modulating the constant driving voltage. Meanwhile, large bending deformation is obtained. Onion epidermal cells occur naturally, which removes much of the efforts on making an actuator with the desired shape.

Onion epidermal cells are relatively easy to separate from the rest of the body, despite being one cell thick (20–30 μm).[15] Fig. 1(a) shows the process of removing and preparing the onion epidermal cells. A single layer of epidermal cells was taken from the core-facing side of a fresh, peeled onion and then washed clean with water. The fact that the cell interior is filled with water is unfavorable to the actuator's reliability as the long-term cell dehydration due to spontaneous water evaporation would cause unpredictable corrugations, rupture, and pin holes on cell walls. The corrugations disorder the actuator's deformation while the rupture and pin holes short the circuit of the driving electrodes. Therefore, a freeze-drying treatment for 24 h was employed to remove the water without collapsing the cell walls (Fig. 1(b)).[16] Obtained SEM images post freeze-drying show that these cells are irregularly sized, packed tightly together, and rectangular in shape (Figs. 1(c) and 1(d)). The cell walls are tough and sturdy, providing support and protection for the cells, and remain so following the removal of water.[17,18]

The freeze-drying process not only keeps the microstructure of the onion epidermal cells intact but also makes them stiff and brittle. Naturally, the cell walls are composed of 21% cellulose, 36.6% hemicellulose, and 42.4% pectin,[19] wherein the cellulose and hemicellulose were separated by water. The entanglement between cellulose and hemicellulose fibrils as the cells dry out hinders the cells to be driven in elastic deformation. The hemicellulose is thought to play a role in regulating elongation of the cell wall. To make the dried cells elastic, an acid pretreatment process was utilized to remove the hemicellulose from the cell wall.[20,21]

After the acid pretreatment, only a small amount of hemicellulose is left in the cell wall of the onion epidermal cells. Fig. 2(a) depicts a comparison of the amount of hemicellulose prior to and after the acid pretreatment process. In order to determine whether or not the hemicellulose had been hydrolyzed and removed from the cell wall interior, we used the phenol-sulfuric acid method to detect the presence of any sugar in our solution.[22] So as to accurately represent the amount of sugars in the solution, a standard curve was first prepared[23] (supplementary Fig. S1). The treated cell walls were analyzed with x-ray diffraction (XRD). By removing the hemicellulose with acid pretreatment, only the crystalline of cellulose remained, which a strong diffraction peak at 23° of cellulose crystalline was enhanced[23,24] (supplementary Fig. S2). The hemicellulose can be hydrolyzed

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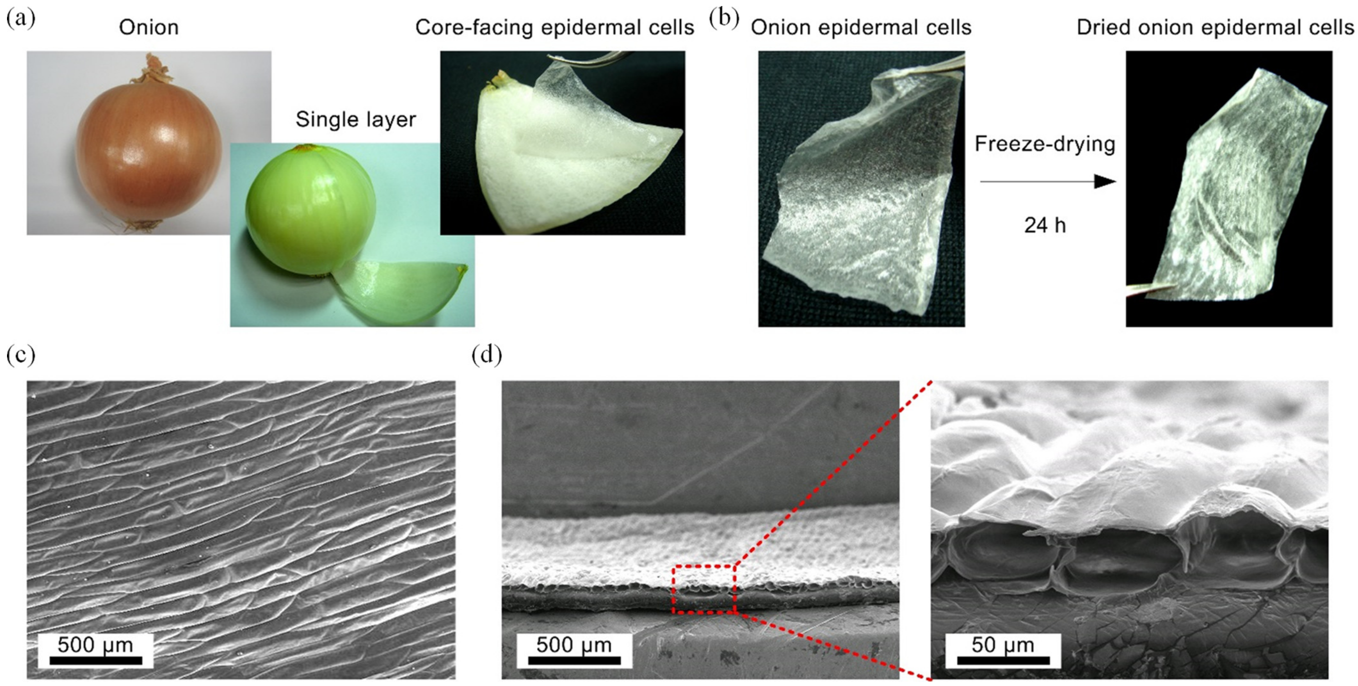

FIG. 1. Schematic of the onion epidermal cells. (a) Obtaining the onion epidermal cell layer. (b) Photographs of the cell layer before and after freeze-drying. The cells were freeze-dried for 24 h. (c) Top-down SEM image of the cells post freeze-drying. Scale bar, 500 μm. (d) Side view SEM image of the cells post freeze-drying (left-hand side: scale bar, 500 μm; right-hand side: scale bar, 50 μm).

and removed from the cell wall for sulfuric acid concentrations of 1 wt. % at least.

To transform the processed onion cells into a functioning actuator, we first sputtered the onion epidermal cell layer with different thicknesses of gold on both sides (top, ~24 nm; bottom, ~50 nm). The gold layers were intentionally deposited at different thickness as to generate different bending stiffness on the upper and bottom cell walls. This was to make the bending actuation more prominent. Following this, the cell layer was cut into a rectangular strip with dimensions of 25 mm × 5 mm (Fig. 2(b)). The long sides of the cells are perpendicular to the length of the electrode[23] (supplementary Fig. S3). This is because the measured modulus of elasticity in the perpendicular direction was

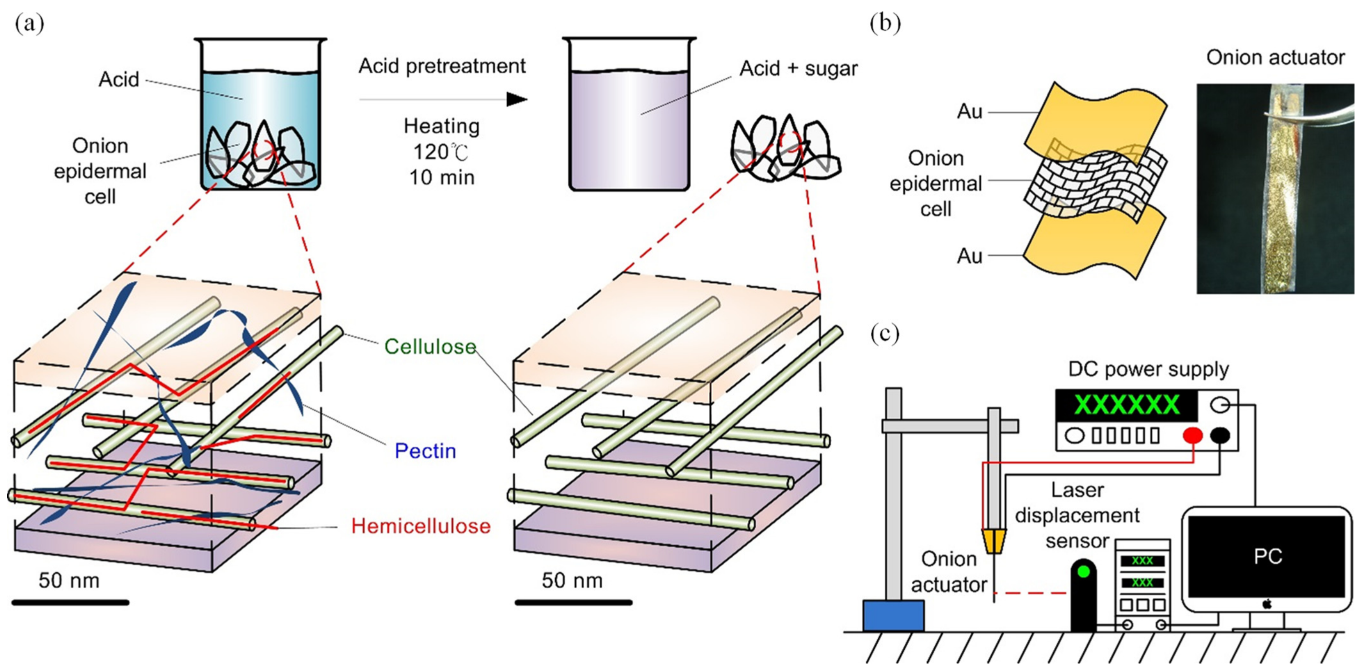

FIG. 2. The removal of hemicellulose and subsequent results. (a) Cellulose, pectin, and hemicellulose are shown in green, blue, and red, respectively. The left image shows the onion epidermal cell layer in dilute sulfuric acid, with a large amount of hemicellulose present. After heating at 120 °C for 10 min, most of the hemicellulose is dissolved, as shown in the image in the right. (b) The image in the left is a schematic diagram of the onion epidermal cells plated with gold of different thickness acting as the top and bottom electrodes. The image in the right displays the completed onion actuator. (c) Schematic of the experimental setup and measurement system.

smaller than that in the parallel direction[23] (supplementary Fig. S4). Thus, a relatively softer and more flexible actuator was obtained. Fig. 2(c) shows the schematic of the experimental setup and measurement system. The free-end deflection of the onion cell actuator was then measured with a laser displacement sensor (KeyenceLK-G3001V).

When a voltage from 0–1000 V was applied, electrostatic forces deformed the onion cells, causing them to simultaneously bend and, either contract or elongate. Due to the special structure of onion cells, changing the magnitude of the applied voltage will cause the onion cell actuator to bend in different directions. When no voltage is applied, no deformation occurs. When a low voltage (0–50 V) is applied, the actuator elongates and bends downwards (Fig. 3(a), top image). This elongation occurs because the original curved structure of the onion cells flattens out. Due to the differences in gold thickness between the top and bottom sides of the cell layer, the top is more flexible than the bottom. This flexibility allows for the top of the cells to elongate more than the bottom, forcing it to bend downwards. When the voltage is increased to 50–1000 V, the flattened top and bottom faces of the actuator cave in, causing the cells to contract and bend upwards (Fig. 3(a), bottom image).

Figs. 3(b) and 3(c) graph the deflection of the actuators produced from onion epidermal cells pretreated with dilute sulfuric acid ranging from 0 to 5 wt. % concentration against applied voltages ranging from 0–250 V and 250–1000 V, respectively. The deflection measurements for the actuators pretreated with 1 to 5 wt. % dilute acid, when compared with the untreated actuator (0 wt. %), are much greater. That the deflection measurements for the concentrations from 1% to 5% range from 0.8 to 1 mm. The maximum downward deflection achieved for any of the pretreated actuators is around 30 μm at 50 V. Above 50 V, the actuator begins to bend in the opposite direction. The maximum upward deflection achieved for any of the pretreated actuators is about 1 mm at 1000 V. The actuator made from the onion epidermal cells that have not undergone the acid pretreatment process show a maximum upward deflection of less than 50 μm at 1000 V. The analysis method of Maxwell stress effect on the reduced link model,[23] as indicated by the solid lines in Fig. 3(c) (supplementary Figs. S5 and S6). Thus, it is clear that the hydrolyzation and diffusion of hemicellulose resulted in a softer, more flexible cell wall. This softer cell wall allows for greater deformation. Detailed characterization also indicates that the artificial muscle after the acid pretreatment has the strain rate ranging from 10^{-5} s^{-1} to 10^{-3} s^{-1}, and the sweep rates are even much greater than 1 V/s (supplementary Figs. S7 and S8).[23] In a reliability test, the artificial muscle was statically driven at 1000 V for continuous 6 h, and the displacement shift was negligible[23] (supplementary Fig. S9).

Finally, using a SEM, pictures were taken while varying voltages were applied. The results are shown in Fig. 4. Figs. 4(b)–4(e) show the side view of the actuator inside of the SEM. The red dotted line represents the starting point of the actuator at 0 V. In these images, when applied low voltages (50 V), the actuator is below the red line, which is representative of a downward deformation. As the applied voltage increases, the actuator begins to be above the red line, which represents a deformation in the upward direction. Figs. 4(g)–4(j) show the top-down view of the actuator in the SEM. As before, the red line shows the starting position of the actuator. At low voltages (50 V), the actuator is elongated to be above the starting position, which represents a downward deflection. When the voltage is increased to 200 and 250 V, the actuator contracts to be below the red line, which represents an upward deflection. When a low voltage is applied, the actuator elongates. At higher voltages, the actuator begins to contract. For demonstrating potential applications, two onion artificial muscles were combined to act as tweezers, which gripped a small cotton ball of around 0.1 mg in weight, as shown in Fig. 5 (Multimedia view).

We presented an actuator made from botanic epidermal cells. This soft actuator changes its actuation direction by simply changing the magnitude of the applied voltage. We

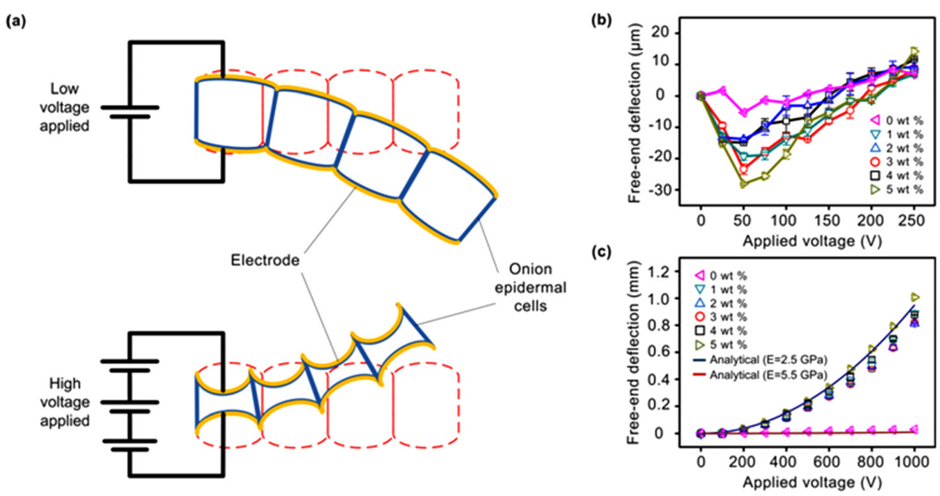

FIG. 3. The actuation principles and experimental results. (a) The top image shows the actuator simultaneously elongating and bending downwards at low voltages (0–50 V). The bottom image shows the actuator simultaneously contracting and bending upwards at higher voltages (50–1000 V). (b) Free-end deflection of the actuators pretreated with dilute acid concentrations (0 to 5 wt. %) graphed against applied voltage (0 to 250 V). The maximum downward deflection of about 30 μm in the actuator pretreated with 5 wt. % acid occurs at 50 V. (c) Free-end deflection of the actuators pretreated with dilute acid concentrations (0 to 5 wt. %) graphed against applied voltage (250 to 1000 V). The maximum upward deflection of about 1.0 mm in the actuator pretreated with 5 wt. % acid occurs at 1000 V.

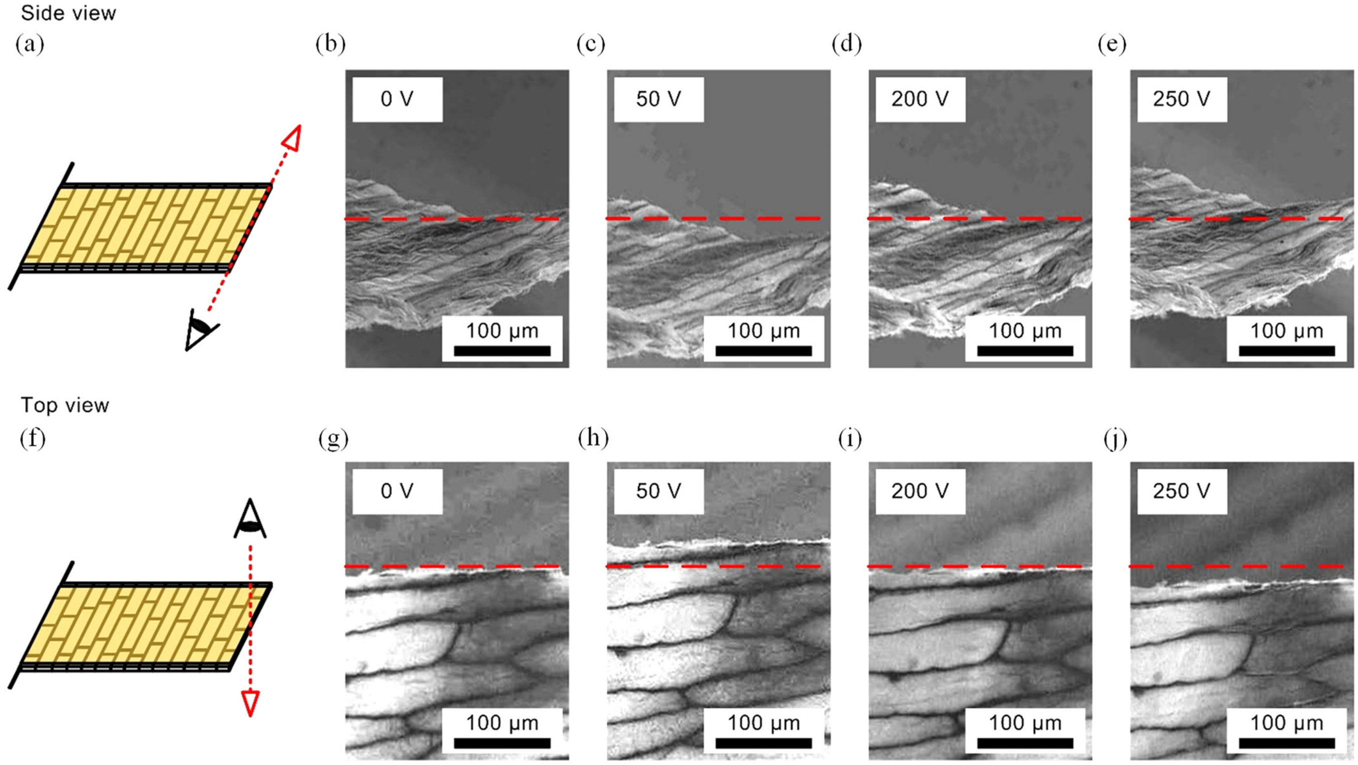

FIG. 4. The actuator operating in a SEM; side view of the actuator displayed in (b)–(e). The red lines represent the starting point. The actuator produces a displacement in different directions depending on the applied voltage. Top view of the actuator displayed in (g)–(j). The red lines represent the starting point. When low voltage is applied, the actuator elongates. At higher voltages, the actuator begins to contract.

presented the relationship of the hemicellulose content of the cell and the orientation of the onion cell, respectively, with regards to their modulus of elasticity subjected to an acid treatment process. In addition to transforming the epidermal cells for use as an actuating element, we have also demonstrated its use in fixture applications. In the demonstration, at voltages of 0–50 V, the onion artificial muscle elongated and bended downward; and at voltages of 50–1000 V, the artificial muscles contracted and bended upward. The motion of the actuators has confirmed the improved flexibility of the onion epidermal cells. The plant epidermal cells are cheap and easy to obtained, at no cost to the environment. Due to the diversity of plants and their cell structures, discovering the use of natural structures in engineering is of interest. Onion epidermal cell, for example, has a unique structure in that, when varying magnitudes of the applied voltage, it will bend in different directions due to electrostatic attraction. Currently, the maximum displacement and out force of onion-actuator are 1 mm and 20 μN at 1000 V (supplementary Fig. S10).[23] In the future, more research will be conducted to increase the maximum displacement and output force, while simultaneously minimizing the applied voltage.

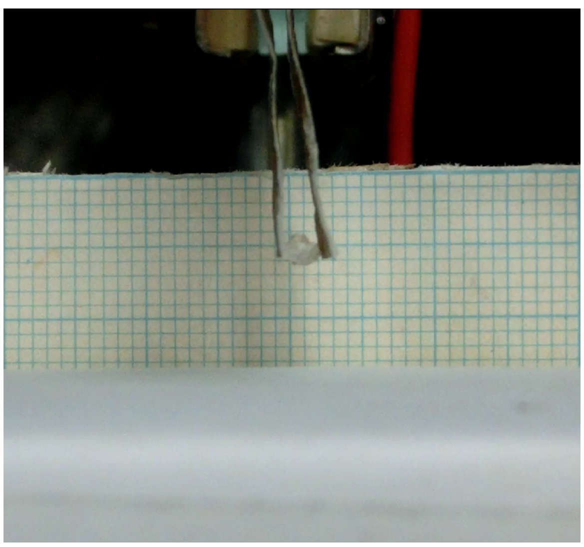

FIG. 5. Tweezers made of onion artificial muscle. (Multimedia view) [URL: http://dx.doi.org/10.1063/1.4917498.1]

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[1]G. Kofod, Ph.D. thesis, The Technical University of Denmark, Copenhagen, 2001.
[2]R. E. Pelrine, R. D. Kornbluh, and J. P. Joseph, Sens. Actuator, A **64**, 77 (1998).
[3]Z. Q. Pei, Y. Yang, Q. M. Chen, E. M. Terentjev, Y. Wei, and Y. Ji, Nat. Mater. **13**, 36 (2014).
[4]M. Camacho-Lopez, H. Finkelmann, P. Palffy-Muhoray, and M. Shelley, Nat. Mater. **3**, 307 (2004).
[5]S. Hara, T. Zama, W. Takashima, and K. Kaneto, Polym. J. **36**, 151 (2004).

[6]M. Shahinpoor, Y. Bar-Cohen, J. Simpson, and J. Smith, Smart Mater. Struct. **7**, R15 (1998).
[7]B. Ewen and D. Richter, *Neutron Spin Echo Spectroscopy Viscoelasticity Rheology* (Springer, New York, 1997), pp.1–129.
[8]R. H. Baughman, C. X. Cui1, A. A. Zakhidov, Z. Iqbal, J. N. Barisci, G. M. Spinks, G. G. Wallace, A. Mazzoldi, D. De Rossi, A. G. Rinzler, O. Jaschinski, S. Roth, and M. Kertesz, Science **284**, 1340 (1999).
[9]E. Detsi, M. S. Selles, P. R. Onck, and J. T. M. De Hosson, Scr. Mater. **69**, 195 (2013).
[10]E. Detsi, Z. G. Chen, W. P. Vellinga, P. R. Onck, and J. T. M. De Hosson, J. Nanosci. Nanotechnol. **12**, 4951 (2012).
[11]E. Detsi, P. R. Onck, and J. T. M. De Hosson, ACS Nano **7**, 4299 (2013).
[12]E. Detsi, P. R. Onck, and J. T. M. De Hosson, Appl. Phys. Lett. **103**, 193101 (2013).
[13]S. Ashley, Sci. Am. **289**, 52 (2003).
[14]S.-C. Lin, W.-P. Shih, and P.-Z. Chang, J. Intell. Mater. Syst. Struct. **24**, 347 (2013).
[15]A. Ng, M. L. Parker, A. J. Parr, P. K. Saunders, A. C. Smith, and K. W. Waldron, J. Agric. Food Chem. **48**, 5612 (2000).
[16]E. Asahina, Contrib. Inst. Low Temp. Sci. **10**, 83 (1956).
[17]C. E. Wyman, *Polysaccharides: Structural Diversity and Functional Versatility* (Marcel Dekker, New York, 2005), pp.1023–1062.
[18]S. Kerstens, W. F. Decraemer, and J.-P. Verbelen, Plant Physiol. **127**, 381 (2001).
[19]A. T. Mankarios, M. A. Hall, M. C. Jarvis, D. R. Threlfall, and J. Friend, Phytochemistry **19**, 1731–1733 (1980).
[20]U. Tamburini, Wood Sci. Technol. **4**, 284 (1970).
[21]M. Chen, L. Xia, and P. Xue, Int. Biodeterior. Biodegrad. **59**, 85 (2007).
[22]M. DuBois, K. A. Gilles, J. K. Hamilton, P. A. Rebers, and F. Smith, Anal. Chem. **28**, 350 (1956).
[23]See supplementary material at http://dx.doi.org/10.1063/1.4917498 for detailed experiment and analysis.
[24]H. B. Zhao, J. H. Kwak, Z. C. Zhang, H. M. Brown, B. W. Arey, and J. E. Holladay, Carbohydr. Polym. **68**, 235 (2007).