

# Smart cellulose could mean flying magic paper

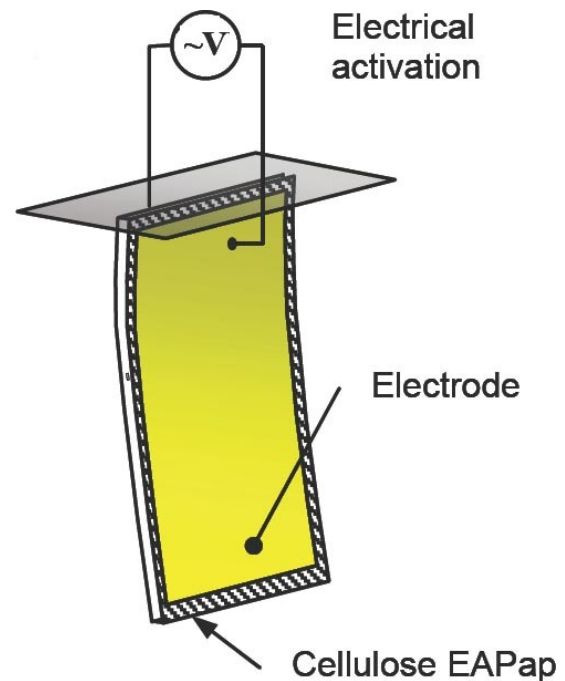
Jaehwan Kim

*Ultralightweight mechanisms constructed of a common polymer may help meet the low-power requirements of various microelectromechanical systems.*

Old-fashioned paper airplanes are generally regarded as child's play. But the next generation of paper flying objects could transform their wings, like flying magic carpets, and pack microcameras and sensors for battlefield surveillance or security monitoring. With the discovery that cellulose can serve as a 'smart' material, such applications no longer seem farfetched. Over the last 10 years, the field of electroactive polymers (EAPs) has drawn much attention owing to the development of new EAP materials that exhibit large displacement, or shift.<sup>1</sup> This characteristic has value because it means the materials can act like biological muscles. Accordingly, it has enabled potential applications such as actuators, devices that drive movement for microinsect robots and tiny flying objects. But the EAP materials used in actuators for these and other applications must meet requirements of ultralight weight and low power consumption. Moreover, the power should be remotely supplied since batteries cannot be carried onboard. A wireless power supply has the added advantage of agility and long operational distance.

Cellulose is a biopolymer that, like muscles, responds to an electrical stimulus. Such materials flap, bend, and move in other ways when given a tiny jolt of electricity. Most biopolymers, including DNA, hair, bones, and wood, exhibit shear piezoelectricity (mechanically induced electricity) due to the rotation of polar atomic groups associated with asymmetric carbon atoms. A piezoelectric response in wood was noted as long ago as 1950, and attributed to oriented cellulose crystallites (grainlike domains). Cellulose is the world's most abundant natural polymer. But until recently, no one exploited its piezoelectric potential in sensors and actuators.

We investigated cellulose to see whether it would respond in a predictable manner to electrical impulses. We coined the term 'electroactive paper' (EAPap) to refer to smart cellulose.<sup>2</sup> Figure 1 illustrates the concept of EAPap. The material is pre-

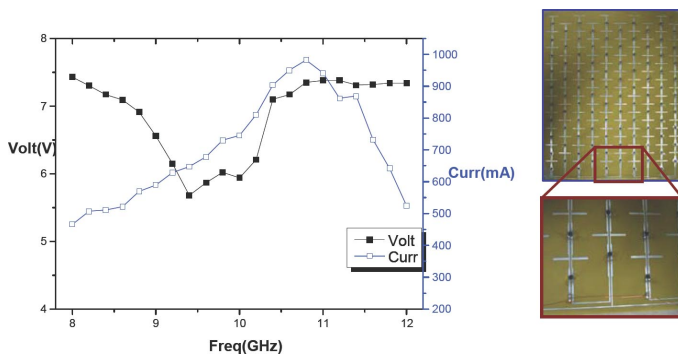


**Figure 1.** Schematic of an electroactive polymer paper (EAPap) bending actuator.

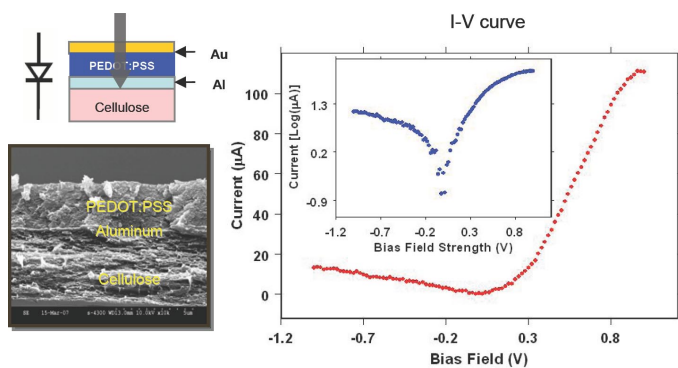
pared using a film of cellulose, with extremely thin electrodes deposited on both sides. When electrical voltage is applied to the electrodes, the EAPap bends (see video<sup>3</sup>). Cellulose EAPap has many advantages in terms of biodegradability, biocompatibility, large deformation, low actuation voltage, low electrical power consumption, and reasonable cost. The actuation mechanism of EAPap is based on a combination of piezoelectric effects associated with the crystal structure and migration of ions in cellulose.

No wires or batteries are needed for sensors developed from EAPap. Instead, a special microstrip antenna called a rectenna (rectifying antenna) and other lightweight electronic components can be integrated into the material. Radio waves beamed to the antenna would be converted into electricity that moves

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**Figure 2.** Rectifying antenna array: (left) power transmission performance and (right) photo.



**Figure 3.** Schottky diode fabricated from PEDOT:PSS-pentacene polymer and its current-voltage characteristics. PEDOT:PSS: Poly(3,4-ethylenedioxythiophene) poly(styrenesulfonate).

the EAPap. These actuators can thus be remotely driven using microwaves, making them attractive candidates for ultralightweight multifunctional applications such as microinsect robots, moving wings for flying objects, smart wallpaper, and microelectromechanical systems (MEMS).

We have created rectenna arrays that consist of dipole microstrip antennae and Schottky diodes. For example, a 15×15cm rectenna array of 100 elements was fabricated on flexible polymer membrane, and electrical power (~7W) was successfully transmitted (see Figure 2). Integrating the rectenna with EAPap to make flying magic paper will require building the Schottky diode directly on cellulose EAPap. We have produced such a structure using poly(3,4-ethylenedioxythiophene) poly(styrenesulfonate) (PEDOT:PSS)-pentacene polymer material (see Figure 3). This process requires an unconventional soft-lithography technique known as microtransfer printing. Tests of the device performance are ongoing.

EAPap will enable inexpensive and lightweight biomimetic actuators and MEMS devices. Cellulose EAPap material is also

promising as a biosensor since it is biodegradable, biocompatible, sustainable, capable of broad chemical modification, and has high mechanical stiffness and strength. A sheet of smart paper could be coated with chemicals for detecting pollutants or atmospheric particles and equipped with a tiny rectenna to convert microwaves to a slight electrical charge. With microwaves beamed at it, the paper could be powered continuously, flapping its way across the sky. There is clearly much still to discover and admire in cellulose.

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### Author Information

**Jaehwan Kim**  
 Center for Electro-Active Paper (EAPap) Actuator  
 Inha University  
 Incheon, Republic of Korea  
<http://www.eapap.net>

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### References

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2. J. Kim, S. Yun, and Z. Ounaies, *Discovery of cellulose as a smart material*, **Macromolecules** **39**, pp. 4202–4206, 2006.
3. [http://spie.org/documents/newsroom/videos/1066/EAPap\\_DF.mov](http://spie.org/documents/newsroom/videos/1066/EAPap_DF.mov) Applying electricity to a sheet of cellulose causes it to bend. **Credit: Jaehwan Kim, Inha University.**
4. K. S. Kang, H. K. Lim, K. Y. Cho, K. J. Han, and J. Kim, *Durability of PEDOT:PSS-pentacene Schottky diode*, **J. Phys. D: Appl. Phys.** **41**, p. 012003, 2007.