Biohybrid energy convertors made of living plants and soft materials

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***Abstract*— We recently discovered that the cuticle-cellular tissue bilayer in plant leaves functions as an integrated energy converter that is capable of converting mechanical stimuli into electricity similar to a triboelectric generator. We created soft, flexible and transparent electrodes that, when used to stimulate the plant leaves, enhance the power output over several magnitudes. In this manner, stimulating a single leaf can power more than 100 LEDs and sensors. Moreover, living plants have been used to autonomously transduce wind energy into electricity. Such biohybrid approaches in which plants are a key component and living systems are used to harness electrical energy, have potential to reduce artificial material consumption, and to create autonomous, green and power sources.**

Keywords—Biohybrid energy harvesting, artificial leaves, plants, sensors, green energy

I. Introduction

Being "green", resource-saving, emission-free, and energy-autonomous is an essential requirement for almost all future technologies. This can be achieved by reducing artificial components which need energy-intense production on the one hand, as well as by establishing ways to harness energy from the environments. Biohybrid devices based on natural components and living organisms combined with tailored artificial components try to use both approaches. Plant-hybrid technologies for example try to take advantage of specific material/tissue properties and functionalities of living plants with applications ranging from energy harvesting to sensing.[1-4] This is supported by an advancement of the understanding of nanoscale processes and material features in plants and how to interface them with artificial technology. In addition, several ways enable producing electricity with living plants (excluding their combustion). Plant microbial fuel cells and glucose biofuel cells for example use organic matter from living plants and convert it into electricity.[2] Energy conversion, however, is done by the artificial fuel cell and not by the plant.

We recently reported, that plants can moreover directly convert mechanical energy such as from wind into electricity.[3, 4] Plant leaves are covered with a dielectric material, a thin polymer layer named cuticle (Figure 1a).[3] This surface accumulates charges upon contact with another material through contact electrification. The effect is dependent on the material the plant is touched with and investigations showed that in particular soft elastomers like silicone rubber leads to strong charging of the cuticle.[3] The charges created on the cuticle are electrostatically induced into the adjacent ion-conductive cellular tissue leading to a current that can be harvested by an electrode inserted in the plant tissue. Figure 1b shows typical signals obtained and Figure 1c illustrates the mechanism of charge generation and induction into the tissue. Living plants hence constitute a triboelectric generator (TENG) with a power output comparable to similarly operated artificial TENGs.[3] TENGs are not only considered a possible energy source for the internet of things and sensor networks but are also being discussed for application in larger scale energy harvesting farms with reported power densities of up to several hundred watts per square meter of active surface area. Using living plants as opposed to generators based on only artificial materials has several added benefits. Most materials and the structure required is provided by the plant, moreover plant's dynamic self-repair and CO_2 compensation through ongoing growth adds functionality that is extremely difficult to realize in artificial generators. This offers a great opportunity to convert plants into power sources. Yet, it still needs to be understood how to best construct and optimize plant biohybrid systems in order to exploit environmental mechanical energy such as wind.[4]

Here, we give an overview on our work on plant-hybrid

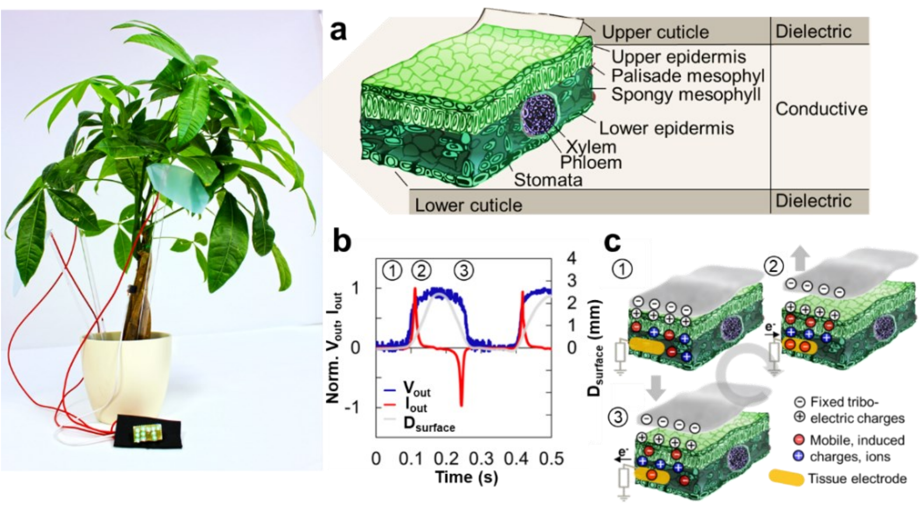

Fig. 1. Energy conversion in plants by contact electrification. a) Illustration of leaf cross-section and the bilayer formed by the dielectric cuticle and the ion-conductive tissue used for energy conversion. b) Typical voltage (blue) and current signals (red) occurring when a leaf surface is touched by silicone rubber as function of its distance from the surface (grey). c) Illustration of mechanism of cuticle charging and induction into the tissue. Initial contact between leaf and material (1) creates charges by contact electrification. After separation of the two surfaces after contact (2), the charges created are electrostatically induced into the inner plant tissue. The signals reverse when the two charged surfaces approach again (3).

generators, how they are realized and how they perform. The results show a clear potential to develop autonomous energy sources using plants for powering lights and battery-free sensors for example for environmental monitoring.

II. Results

A. Detailed analysis of energy conversion in plants

After our initial observation of energy conversion by contact electrification of plant surfaces and induction of the charges into the tissue, we investigated the effect in detail by analyzing voltage and current signals generated during controlled mechanical stimulation (varying parameters like amplitude, force, contact area) in addition to high-resolution mapping of charge generation by Kelvin force microscopy and analyses of the plant surface structure.[3] One of the key aspects are the materials as contact or triboelectrification is strongly dependent on the material-pair interacting and their surface properties. By measuring the voltage signals generated in *Rhododendron* when touching with a selected material at a given force, we determined that silicone elastomers such as PDMS or Ecoflex result in highest signals. Figure 2a gives an overview of the amplitudes of the alternating voltage signals obtained from contact and release of a leaf and the indicated materials. Furthermore, the effect is dependent on the contact area as shown in Figure 2b

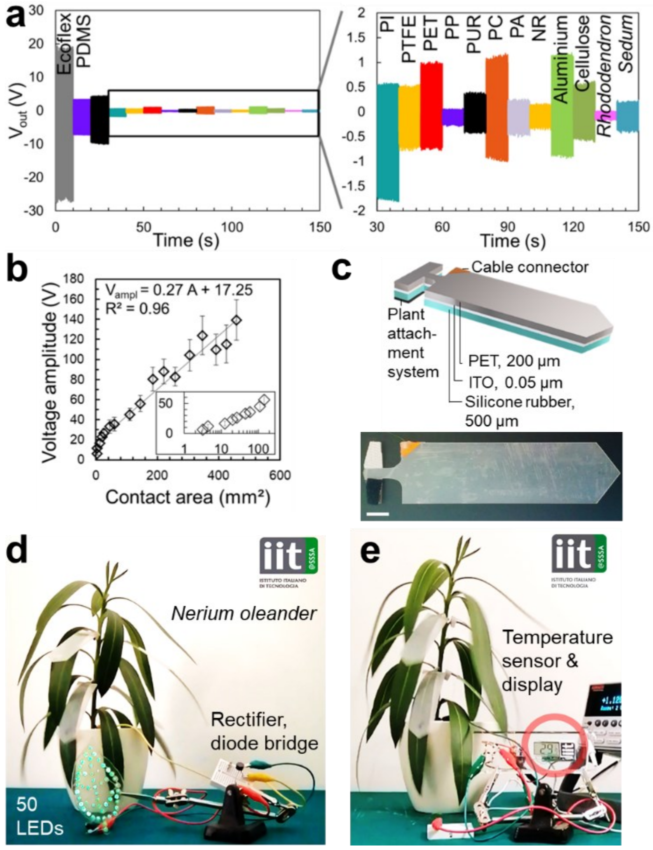

Fig. 2. Performance of plant-biohybrid energy converters. a) Alternating voltage signals generated when touching a Rhododendron leaf with a constant force of 1 N using different materials. b) Scaling of the voltage amplitude on the contact area. c) Illustration of an artificial leaf that enhances plant energy conversion. d) and e) Powering of 50 LEDs and a temperature sensor, respectively by a plant hybrid generator exposed to wind.

at a constant force. It follows that the more leaves and the more area, respectively is used, the higher the signals and the power generated. We could power more than 100 LEDs each time just a single leaf is touched on its surface using a silicone rubber sheet.[3] The soft elastic nature of the silicone rubber has the further advantage that its elastic deformation avoids damages to the leaf during mechanical solicitation and its transparency enables to let light pass at wavelengths essential for plant growth and photosynthesis so that a minimal influence on the plant can be expected.

B. Wind energy harvesting, powering LEDs and sensors

We thus constructed artificial leaves such as shown illustrated and shown in Figure 2c. The thin < 1 mm thick artificial leaves consist of a polyethylene terephthalate (PET) support, an indium tin oxide (ITO) electrode and a layer of silicone elastomer as well as plant attachment system.[4] The latter enables to attach the leaves onto the petioles of the plant in a manner that during exposure to wind, the artificial and the plant leaf come into transient contact followed by a separation of the two layers. Each time the two parts contact and separate, charges are generated and induced into the tissue and the electrode in the artificial leaf, respectively. Wind induces autonomous mechanical oscillations between the artificial and the plant leaf which can thus be transduced into electricity.[4] We investigated in detail how parameters like wind speed, wind direction and factors like humidity influence the energy conversion by the plant-hybrid wind generators. The power output scales with the wind speed and is strongest at cross-flow orientation of wind direction towards leaves.[4] The electricity generated can be stored and used to power sensors or power lights directly. Figure 2d shows a single frame of a video recording of a *Nerium oleander* equipped with four artificial leaves that power 50 LEDs when exposed to wind. Figure 2e shows the same plant connected to a temperature sensor. After about 10-15 minutes exposure to wind, the plant accumulated enough energy (stored in a 50 µF capacitor) to perform a temperature measurement and to display the reading on a liquid crystal display.[4] Further experiments show that also sensors with wireless data transmission can be powered in a similar configuration.

III. Conclusions

Our results indicate that a combination of plants and tailored soft artificial leaves can autonomously convert mechanical energy such as wind energy into electricity. The straight forward systems provide a scalable power source for driving lighting and sensors and have potential as power supply, e.g., for sensor networks in environmental and agricultural monitoring.

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