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Novel Gel Actuator Containing TiO_2 Particles Operated under Static Electric Field

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Introduction. Certain polymer gels represent one class of actuators that have the unique ability to change elastic and swelling properties in a reversible manner.[1] These soft materials offer lifelike capabilities for the future direction of technological development.

Volume phase transition in response to infinitesimal change of external stimuli like pH, temperature, solvent composition, electric field, and light has been observed in various gels.[2−6] Their application in devices such as actuators, controlled delivery systems, sensors, separators, and artificial muscles has been suggested and are in progress.[1,7−9]

Since electric fields are convenient stimuli from the point of signal control, therefore it is of great importance to develop and study electric field responsive polymer gels. Gels consisting of ionic polymers deform when an electric field is applied through the solution immersing the gel. The control of deformation of polyelectrolyte gels by an electric field has been intensively studied during the past decades, for both the fundamental interest and the numerous possible applications.[6,10−15] In each mentioned case the deformation or displacement is due to volume change. Attempts to develop such electric field responsive gels are often complicated by the fact that structural changes are kinetically restricted by diffusion of liquid molecules into or from the polymer matrix. Formation of a collapsed polymer skin layer on the surface of gel may also block the outflow of the entrapped liquid. The swelling or deswelling rate is fairly small and strongly depends on the geometry and the size of the gel probe. This disadvantage often hinders the efforts to design an optimal gel for different purposes. In this paper we present a totally different mechanism that allows a quick and large displacement response of weakly cross-linked neutral polymer gels in a nonconducting medium. Since these gels are mainly being developed for actuator purposes, therefore the study of motion and deformation induced by electric fields has been our primary interest.

Neutral Polymer Gels in an Electric Field. All materials experience forces or torques when subjected to an electric field. These interactions are strong in the case of certain solid materials but rather weak in fluid systems. To enhance the influence of the external fields on the solution and/or the gel properties, it is necessary to combine solidlike and fluidlike behaviors. Since polymer gels contain a substantial amount of liquid as swelling agent, it is possible to fabricate field sensitive gels by using a polymer network swollen by a complex fluid. A complex fluid contains dispersed small particles in the size range of nanometers to micrometers.[16] The particles in the fluid respond to an applied field and couple the shape and physical properties of the gel to the external field. There exist different electrostatic forces acting on the fluid or fluid particles. In the presence of charges Coulomb forces are dominant. In a nonuniform electric field, the gradient force (dielectrophoretic force) acts on the polarized particles.[16]

Colloidal semiconductor particles have been used as photocatalysts in a number of reactions.[17] When these particles are embedded in a nonconducting or weak conducting polymer gel in a strong direct current (dc) field, electrons are emitted from the surface and the particles become positively charged. As a result, the gel interacts with the applied electric field. If the particles are considerably separated within the gel and carry relatively small charges, the electrostatic force between the particles can be neglected, and the only electrostatic force to be considered is the one caused by the external electric field. Therefore, we expect that those nonconducting polymer gels containing filler particles, which are able to provide charges, may be used as electromechanical actuators. These field sensitive gels can be

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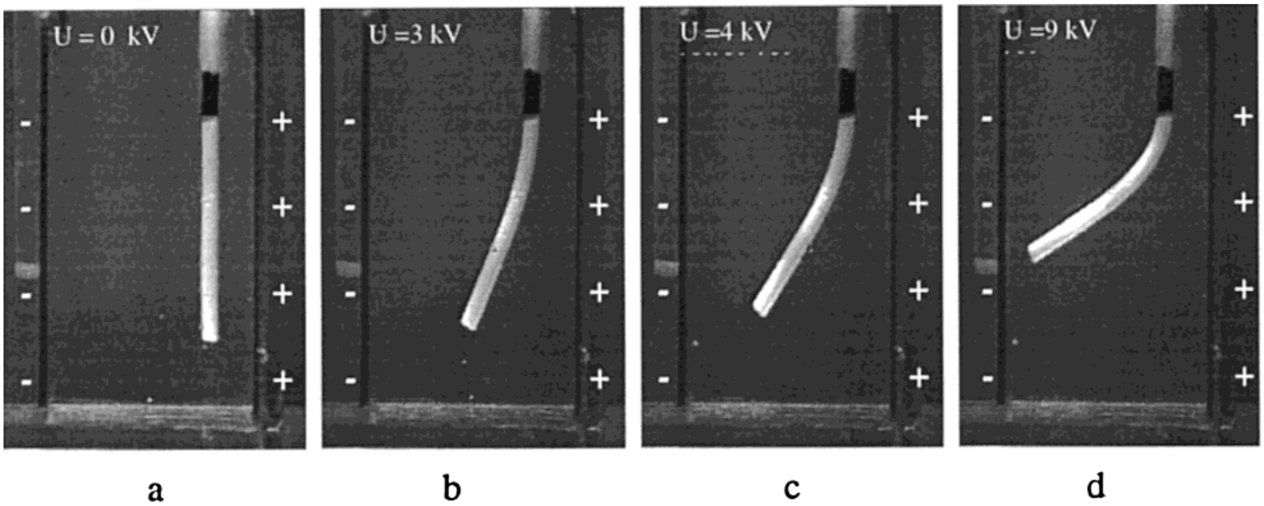

Figure 1. Deflection as a function of the electric field strength. The applied voltage is indicated on the figure. The gap distance is 3 cm.

exploited to construct new types of soft actuators, sensors, micromachines, and biomimetic energy transducing devices.

Preparation of Electric Field Sensitive Poly(dimethylsiloxane) Networks. Poly(dimethylsiloxane) gels (abbreviated as PDMS gels) containing randomly distributed TiO_2 particles have been prepared. A commercial product of a two-component reagent (Elastosil 604 A and Elastosil 604 B) provided by Wacker Co. was used. The component A contains the polymeric material and the cross-linking agent; the component B provides the catalyst with Pt content. The TiO_2 filler particles in form of anatase (Kronos 1171, obtained from Biesterfeld Gräen GmbH & Co. KG.) have an average diameter of 0.3 μm. These chemicals were used without further purification.

The TiO_2 particle was stabilized in the Elastosil 604 A mixture by adding a 1 wt % solution of Tween 65 (Merck) surfactant. After mixing up it with the Elastosil 604 B component, the solution was transferred into glass and plastic tubes. The cross-linking reaction was carried out at ambient temperature for 24 h to obtain gels. The concentration of the filler particles in the gel was varied from 10 to 30 wt %.

After the gelation was completed, the gel cylinders were removed from the tubes and were placed into silicone oil (DC 200 Fluka) in order to wash out the unreacted chemicals and to attain the swelling equilibrium.

Measurements. To study the elastic response of the gels to an electric field, the cylindrical gel was vertically suspended into silicon oil between a pair of parallel copper electrode plates (50 mm long, 50 mm wide, and 1.2 mm thick). A rigid plastic thread fixed either the position of the top surface of the gel (as shown in Figure 1) or the middle point of the gel (as shown in Figure 2). A high dc voltage was applied in a noncontact mode through the electrodes, which were 30 mm apart. The electric response of the gel was recorded by a video camera, and the deflection was analyzed by a digital image analyzer. Both the voltage and the current were monitored as well. All the measurements were carried out at ambient temperature.

Results and Discussion. The filler-loaded gel cylinder, suspended in silicon oil, showed significant and rapid bending toward the cathode, when an external electric field was applied. This behavior was reversible, when positive and negative electrodes were alternated. Figure 1 shows the bending of a TiO_2-loaded PDMS gel measured at different uniform electric field strengths. The TiO_2 content of this gel was 10 wt %. By applying a dc field, the gel cylinder gradually bent toward the cathode. The displacement of the free bottom end of the gel depends on the strength of the electric field. These experimental results have evidenced that in an external electric field the gel accumulates positive charges. Large deflection has been observed due to the interaction of the applied external electric field with the charged gel.

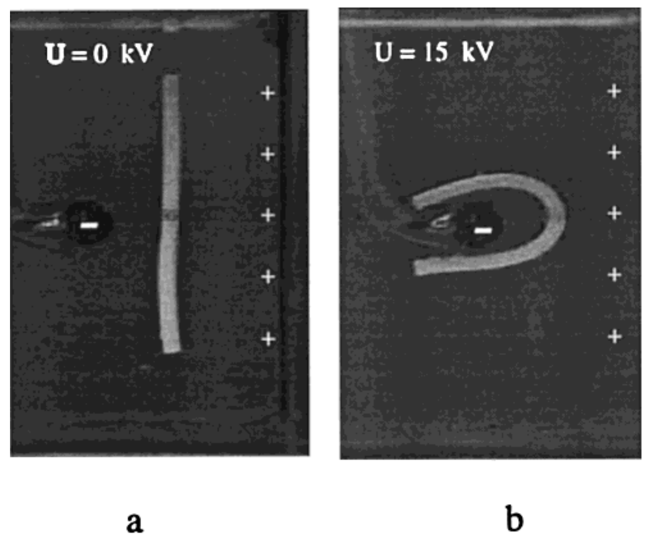

Figure 2. Bending of an electric field responsive PDMS gel in a nonuniform field. The polarity of the electrodes is indicated on the figure.

To study the effect of the spatial distribution of the electric field on the electromechanical response, the geometry of the electrodes was modified to create a nonuniform field. This electrode arrangement is shown in Figure 2. One of the electrodes was replaced by a metal ball with a diameter of 5.5 mm. The other electrode was a copper plate. Figure 2 demonstrates the effect of a nonuniform electric field on the deformation of the gel. The TiO_2 content of this gel was 15 wt %. It is obvious from the pictures that the nonuniform field can also induce bending of the same gel.

It can be concluded, from these experimental observations, that the electric field distribution does not play a significant role; thus, the effect of possible gradient force can be neglected. On the basis of our observations, we can conclude that under high dc electric field the TiO_2 particles emit electrons. These electrons are probably captured by the inpurities present in silicon oil, providing a small current necessary for the electrons to escape. It is worth mentioning that the measured current was less than 0.8 μA in each case. This means that despite the high voltage, the input energy is rather small, offering a great promise in application as actuator devices.

As the electrons can leave the gel, the particles embedded in the polymer matrix obtain a positive charge. Coulomb interactions of these charged particles with the external electric field are responsible for the gel deformation. It has to be mentioned that the bending was rapid and the final equilibrium shape was reached within 5 s. The rate of the electromechanical response was found to be proportional to the dc field strength.

For any technical application, besides the fast response, it is important to have large forces and large displacement. The force derives from the interaction of charges with the external electric field. The maximum charge before breakdown depends on both the voltage and electric field.[18] The magnitude of the electric field, in practical applications, is usually confined in the range 0.1−50 kV/mm. The lower limit is usually considered too weak to move macroscopic objects, while the upper one is set by the occurrence of the electrical breakdown. A higher value of electric fields, far beyond the value, which causes the breakdown in macroscopic cases, is typical of very small devices. It is the main reason why electrostatics tend to become more important on small size scales, where the fields, and hence the forces, can be relatively high. Thus, scaling down the size of the electric field sensitive gels gives hope to develop a new type of soft microelectromechanical actuator.

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