# Bending of PET-Ag Nanoparticle Strip
# in Electrolyte Solution

Xiao-Ming Chen, Guang-Tao Fei[*], Li-Min Liang,
Ping Cui and Yong Li

Key Laboratory of Materials Physics, Institute of Solid State Physics, Hefei Institutes of Physical
Science, Chinese Academy of Sciences, Hefei 230031, China

A novel bilayer strip was made by depositing Ag nanoparticles on the surface of poly(ethylene terephthalate) (PET) film via physical evaporation deposition (PVD). The result shows that the free tip of this strip can move 16 mm in 1 M NaOH electrolyte when a potential of 0.36 V is applied. The displacement exhibits asymmetry when positive and negative potentials are applied. The mechanism of the bending is discussed.

## 1.    Introduction

Recently, there has been considerable interest in electrochemically driven actuator materials capable of converting chemical or electrochemical energy to mechanical energy because they are critically important for many devices such as robots, microvalves, optical fiber switches, prosthetic devices, optical displays and sonar projectors. Some materials can be used as actuators, for example, the conductive polymer polypyrrole based on the electrochemical oxidation and reduction of polymers,[1,2] polymer gels distorted by aniso- tropic association of surfactant molecules under an electric field,[3] carbon nanotubes undergoing bond elongation or shortening caused by electrochemically inducing surface charge,[4] nanoparticle actuators based on the structure and conductivity of nanoparticles,[5] and nanoporous metals based on surface-stress-induced deformation [6]. For actuators made from nanoparticles or nanoporous materials, the reported maximum movement is about 3 mm when responding to an external potential stimulus.[5,6]

It is well known that a large response means a high accuracy and easy control. Consequently, it is necessary to explore new kinds of actuator material, which experience a greater displacement under external stimulus. Considering the inexpensiveness of silver and the flexibility and antierosion capability of PET, the combination of silver nanoparticles and PET may be intriguing to develop a new actuator material. In this paper, we prepare a new material composed of a silver nanoparticle layer and a thin PET film, here called a PET-Ag nanoparticle strip, which was made by a simple PVD method. It is found that the

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*Corresponding author, e-mail address: gtfei@issp.ac.cn.

PET-Ag nanoparticle material has a much larger displacement than that reported before, when small potentials were applied in electrolyte solutions.

## 2. Materials and methods

A PET-Ag nanoparticle strip was prepared by physically depositing Ag nanoparticles on one side of a PET thin film under vacuum ($2.5 \times 10^{-5}$ torr). Raw Ag (99.9%) was heated in an electric resistance heater, and the PET thin-film substrate about 20 μm thick, 4mm wide and 50 mm long was cooled using liquid nitrogen. The thickness of the Ag layer was about 4 μm after preparation. The structure of this strip is shown in Fig. 1(a). The surface microstructure of the Ag layer was observed by field-emission scanning electron micros-copy (FESEM, Sirion 200).

In a 1M NaOH electrolyte solution, a DC potential was applied to the PET-Ag nanoparticle strip and a carbon counter plate electrode (Fig. 1(b)), and the potential values were measured and quoted versus a commercial Ag/AgCl reference electrode.
The potential-dependent flexing movement was quantified in terms of the horizontal displacement d of the free end of the PET-Ag nanoparticle strip (Fig. 1(c)). A ruler was placed near the bottom of the container to measure the displacement of the actuator.
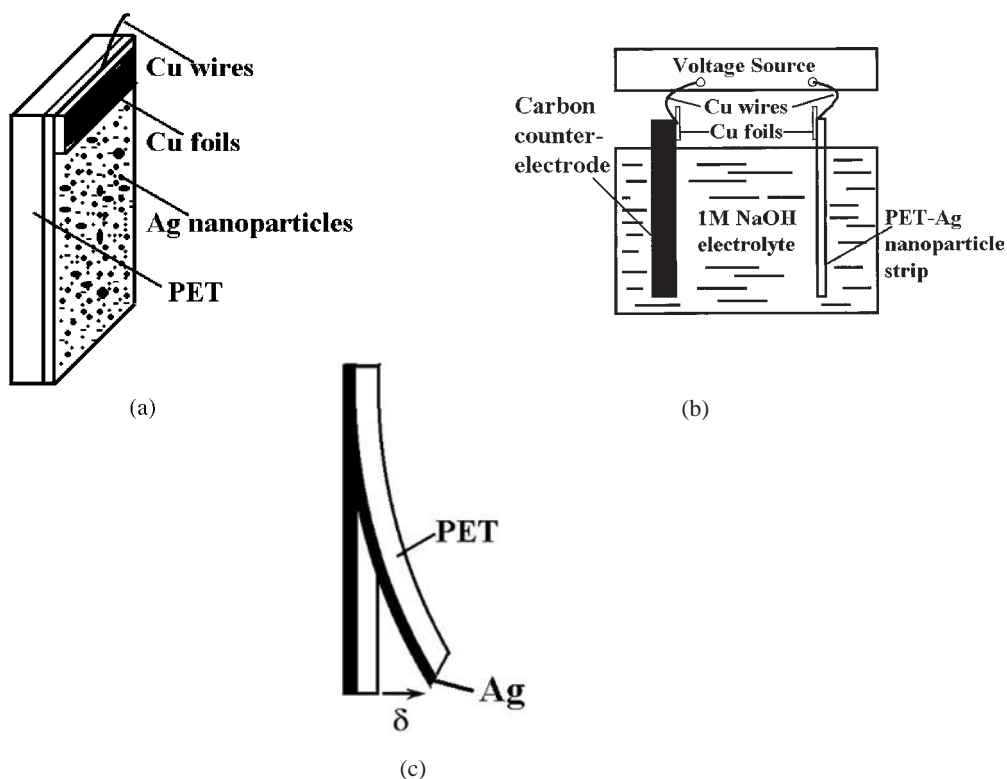


(a)

(b)

(c)

Fig. 1. (a) Schematic drawing of PET-Ag nanoparticle strip construction, (b) setup for bending experiment, and (c) bending of strip.

## 3.    Results

Figure 2 shows a top-view FESEM image of the Ag layer.   The size of Ag particles is between 30 and 80 nm, and some interspaces exist among the nanosized Ag particles.
As the positive potential E is applied to the PET-Ag nanoparticle strip, the free tip of the strip flexes toward the side of the PET substrate.  The flexing movement increases with increasing positive potential.  A maximum displacement of 16 mm was obtained at an applied potential of +0.36 V (vs Ag/AgCl reference electrode).  The $\delta$ decreases with decreasing $E$.  However, when $E$ decreases to zero, the strip cannot come back to the zero point and shows a small delay.  When the potential continues decreasing to –0.24 V, the $\delta$ decreases and finally arrives near zero (Figs. 3 and 4). To avoid the oxidation of the Ag layer, the applied potentials cannot go out of the range of –0.24 V ~ +0.36 V.
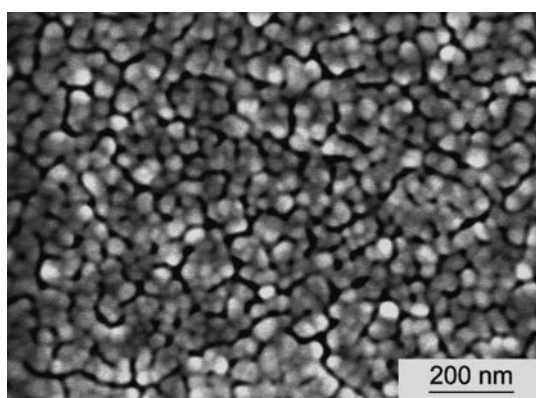


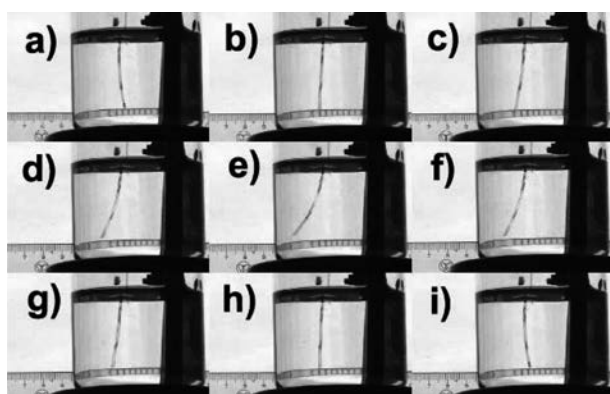Fig. 2.   FESEM top-view image of Ag layer.



Fig. 3.   Photograph of tip movement when applying potential E values of (a) 0.00,  (b) 0.26,  (c) 0.30,  (d) 0.33,  (e) 0.36,  (f) 0.31,  (g) 0.22,  (h) 0.66 and (i) –0.24 V vs Ag/AgCl reference electrode.
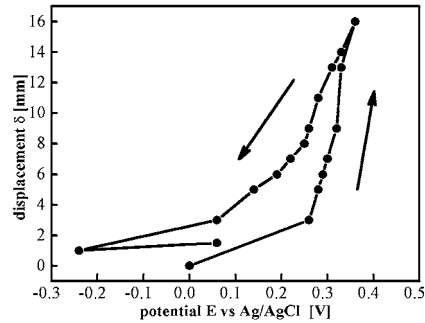
Fig. 4.   Displacement  vs potential *E* (in 1 M NaOH)

## 4.    Discussion

In the previous studies, Gleiter predicted that, by deviating from charge neutrality, the properties of materials are deeply influenced and also proposed that the properties of solid state materials with nanometer-sized microstructures may be tuned by tuning the applied potential.[7]  This principle can be used to explain these results.

When the PET-Ag nanoparticle strip is immersed in the 1 M NaOH electrolyte solution, an electric double layer forms at the interface of the Ag nanoparticle layer and the electrolyte solution.  In this experiment, the applied potential is sufficiently small so that the Ag layer cannot be oxidized.  When potentials are applied to the strip, electrons are injected into or extracted from the Ag layer.  Then the surface charge density is changed.

The relationship between the surface charge density *s* and the potential *E* can be expressed by equation 8, $\partial g/\partial E = -s - \partial s/\partial e$, where *g* and *e* are the surface stress and surface strain, respectively.  The surface stress *g* can be tuned by the external potential *E*.   This kind of surface stress causes the Ag layer to expand and contract.  The PET strip is made up of isolated material, that cannot exchange electrons with the Ag layer or the electrolyte, and therefore keeps its original dimensions.  The PET-Ag nanoparticle bilayer strip bends, just like the bend of a bilayer metal plate with different thermal expansion coefficients driven by temperature.  A similar effect has also been observed in nanoporous gold cantilevers.[6]  In ref. (6), one side of a cantilever is a condensed thin layer of Au and the other is a nanoporous Au layer, and the reported maximum displacement is about 3 mm.  Compared with the solid-state gold layer, the PET film is much supper, so the PET-Ag nanoparticle strip can move a greater distance than the nanoporous gold cantilever.

If *E* is positive, electrons are extracted from the Ag nanoparticle layer and Coulomb repulsive forces between surface atoms increase, inducing lattice parameter expansion.  On

the other hand, OH⁻ anions penetrate into the surface nanoholes of the Ag layer. Both of these events induce the expansion of the Ag layer, while the PET substrate does not expand, so the tip bends toward the PET side. While applying negative potentials, the injection of electrons causes the lattice parameter to decrease; however, the penetration of $Na^+$ cations into the surface nanoholes makes the Ag layer expand. The two opposite effects make the displacements of the tip much smaller than that when positive potentials are applied. The displacements of the tip are not symmetrical under positive and negative potential conditions.

In addition, a Ag-PET-Ag nanoparticle strip was also prepared by depositing Ag nanoparticles on both surfaces of the PET film. In the 1M NaOH electrolyte the displacements are symmetrical when positive and negative potentials are applied to this strip.

The bending of the PET-Ag nanoparticle strip may support the concept of modifying the properties of nanomaterials at the surface by controlling the net charge in space-charge layers at metal surfaces.[7]

## Acknowledgments

## References

1    Q. Pei and O. Inganäs: J. Phys. Chem. **96** (1992) 10507.
2    E. Smela, O. Inganäs and I.Lundström: Science **268** (1995) 1735.
3    Y. Osada, H. Okuzaki and H. Hori: Nature **355** (1992) 242.
4    R. H. Baughman, C. X. Cui, 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** (1999) 1340.
5    B. Raguse, K.- H. Müller and L.Wieczorek: Adv. Mater. **15** (2003) 922.
6    D. Kramer, R. N. Viswanath and J. Weissmuller: Nano Letters **4** (2004) 793.
7    H. Gleiter, J. Weissmüller, O. Wollersheim and R. Würschum: Acta Mater. **49** (2001) 737.
8    W. Haiss, R. J. Nichols, J. K. Sass and K. P. Charle: J. Electroanal. Chem. **452** (1998) 199.