

# A Solid-State TiO<sub>2</sub>/InHCF Solar Cell with an Output Voltage above 1.0 Volt

Lin-Chi Chen, Ying-Chan Hsu, and  
Kuo-Chuan Ho\*

Department of Chemical Engineering  
National Taiwan University  
Taipei 10617, Taiwan

## Introduction

TiO<sub>2</sub> has been intensively investigated for photovoltaic applications since O'Regan and Grätzel [1] revealed the pioneered work in the early 1990s. It was reported that a solar cell based on the dye-coated TiO<sub>2</sub> film shows a high overall energy-conversion efficiency of 7.1-7.9% because the dye sensitizer adsorbed by nano TiO<sub>2</sub> particles greatly improves the light harvesting efficiency. Recently, by assembling a solid-state cell, Bach *et al.* [2] reported a solid-state dye-sensitized mesoporous TiO<sub>2</sub> solar cell, which not only exhibits advantages of replacing the liquid electrolyte but also converts photons to electric current with a high yield of 33% for a monochromatic incident light of 540 nm. Although the use of dye sensitizers and the solid-state configuration have promoted the practicability of a TiO<sub>2</sub> solar cell, the open-circuit voltage under illumination ( $V_{oc}^*$ ) and the voltage corresponding to the maximum power ( $V_{max}$ ) are still low when compared to that of a commercial battery.

Typically speaking, a TiO<sub>2</sub> solar cell containing the liquid electrolyte in the presence of the I<sup>3</sup>/I redox couple shows a  $V_{oc}^*$  value of about 0.70 V [1]. The solid-state TiO<sub>2</sub> cell mentioned above showed an even lower  $V_{oc}$  value of less than 0.35 V [2]. It implies that these high-efficiency TiO<sub>2</sub> solar cells have little applicability if they are not arranged in series. However, ohmic drop becomes obvious if cells are arranged in series, causing miniaturization impossible. In addition, most of the incident energy is wasted due to the low output voltage. Taking ref. [1] as an example, the dye adsorbed a photonic energy of 2eV or higher and converted to electrons with a potential of 0.7eV. Our aim, therefore, is to develop a solid-state TiO<sub>2</sub> solar cell with a high voltage. Indium hexacyanoferrate (InHCF, In[Fe(CN)<sub>6</sub>] [3]), a Prussian blue analog, known as an insertion compound and a counter-electrode material, is to be incorporated into the solar cell to achieve the aim. This paper reports the preliminary results of using the InHCF thin film as the redox couple in a TiO<sub>2</sub> solar cell.

## Experimental

The optically transparent electrode (OTE) used in the present work is the undoped SnO<sub>2</sub>-coated glass (20 Ω/sq.,  $T_{365nm} = 60\%$ ). TiO<sub>2</sub> film was deposited onto the OTE according to a general sol-gel procedure reported elsewhere [4], whereas the InHCF film was plated onto the OTE by cyclic voltammetry [5]. Since the K<sup>+</sup> is one of the favoured counter ions for the redox process of InHCF [3], we intended to assemble a solid-state cell with a KCl-saturated poly-2-acrylamido-2-methylpropane sulfonic acid (AMPS) electrolyte, denoted as "K-PAMPS" hereafter. Before cell assembly, the InHCF film (yellow state) was shortly immersed in a KCl-saturated AMPS solution and then was exposed to an UV light at 365 nm for 5 minutes to cure the polymer. After impregnating the K-PAMPS

electrolyte in the InHCF film on the OTE, the electrode was pressed together with the TiO<sub>2</sub> electrode. This resultant solid-state configuration of OTE / TiO<sub>2</sub> / K-PAMPS + InHCF / OTE, hereafter referred to as TiO<sub>2</sub>/[KP-InHCF], is based on a dye-free TiO<sub>2</sub> solar cell.

## Results and Discussions

A typical cyclic voltammogram of InHCF in K-PAMPS is given in Fig. 1. By taking the average of cathodic and anodic peak potentials, the formal potential of the redox couple, In[Fe(CN)<sub>6</sub>] and KInFe[(CN)<sub>6</sub>], in K-PAMPS electrolyte is estimated to be *ca* 0.87 V *vs.* Ag/AgCl in saturated KCl, equivalent to 1.07 V *vs.* NHE. This implies that the TiO<sub>2</sub>/[KP-InHCF] solar cell has a  $V_{oc}^*$  of 1.07 V because the Fermi level of TiO<sub>2</sub> under illumination is nearly equal to 0 V *vs.* NHE. Interestingly, the light on/off testing, as shown in Fig. 2, demonstrates the expectation of a 1.07-volt  $V_{oc}^*$ . Practically, we observed that this TiO<sub>2</sub>/[KP-InHCF] solar cell could drive some low-power electronic devices, such as electronic timers and 8-digit calculators, without further connecting cells in series. Although the solar cell made with InHCF as the redox couple indeed enhances the output voltage of a TiO<sub>2</sub> solar cell,  $V_{oc}$  in the darkened state increases with cycling and shows a memory effect (see Fig. 2). This implies that the cell acts both like a solar cell and a secondary battery, and prefers to stay at higher voltages; presumably, this memory effect was caused by a poor contact between TiO<sub>2</sub> and InHCF owing to the use of a K-PAMPS electrolyte. Attempt is underway to eliminate this memory effect by improving the contact. The photocurrent-voltage (I-V) characteristic is shown in Fig. 3. It shows a moderate fill factor of 52.4% and a poor energy-conversion efficiency of 0.37%. In another experimental run, a fill factor as high as 70% was obtained, but still a poor efficiency of 0.30% was achieved. The poor solar-to-electric energy conversion is mainly due to the lack of dye sensitizers. Dye sensitizers will be incorporated in our future experiments.

Although the preliminary results only show an energy-conversion efficiency of 0.37% for a TiO<sub>2</sub>/[KP-InHCF] solar cell without a dye sensitizer, it has been demonstrated that the use of InHCF as the redox couple results in a TiO<sub>2</sub> solar cell having a  $V_{oc}^*$  value of 1.07V. Such a high  $V_{oc}^*$  offers a sufficient voltage required for low-power electronic devices without adding cells in series. This preliminary work also shows the interests of applying an electrochromic or insertion compound to enhance the performance of the solid-state solar cell. To be sure, the electrochemistry and photoelectrochemistry hidden behind the TiO<sub>2</sub>/[KP-InHCF] solar cell should be interesting topics for the researchers, who are working on the battery and solar-cell areas.

## Acknowledgement

This work was supported in part by the Chinese Petroleum Corporation and by the National Research Council of the Republic of China under contract number NSC 89-CPC-7-002-008.

## Key References

- [1] B. O'Regan and M. Grätzel, *Nature*, **353**, 737 (1991).

- [2] U. Bach, D. Lupo, P. Comte, J. E. Moser, F. Weissörtel, J. Salbeck, H. Spreitzer, and M. Grätzel, *Nature*, **395**, 583 (1998).
- [3] K.-C. Ho and J.-C. Chen, *J. Electrochem. Soc.*, **145**, 2334 (1998)
- [4] C. J. Barbé, F. Arendse, P. Comte, M. Jirousek, F. Lenzmann, V. Shklover, and M. Grätzel, *J. Am. Ceram. Soc.*, **80**, 3157 (1997).
- [5] S. Dong and Z. Jin, *Electrochim. Acta*, **34**, 963 (1989).

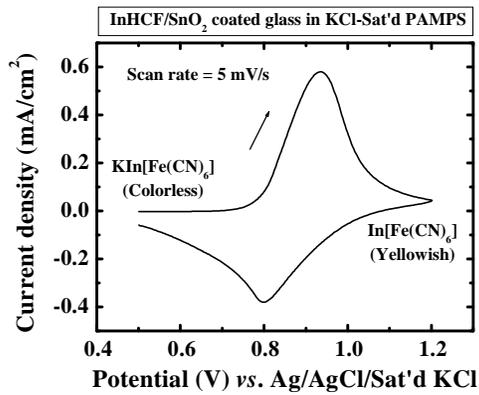


Fig. 1. Cyclic voltammogram of InHCF in a KCl saturated PAMPS electrolyte.

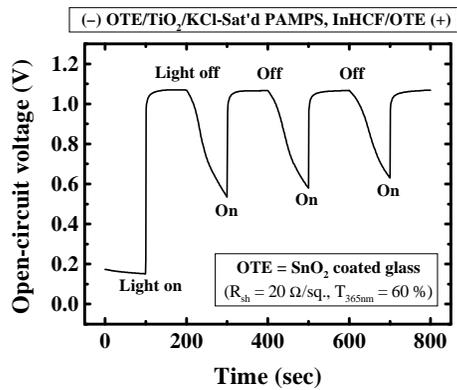


Fig. 2. Light on/off test for the TiO<sub>2</sub>/KP-InHCF solar cell.

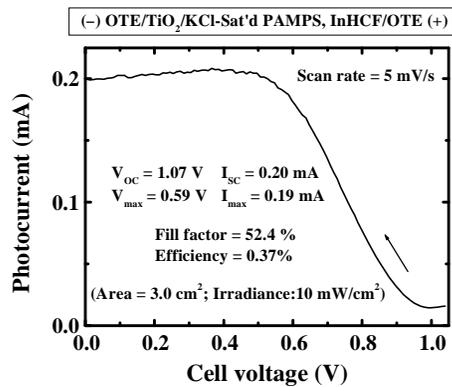


Fig. 3. Photocurrent-voltage characteristics of the cell as shown in Fig. 2.