

### Improved energy conversion efficiency of dye-sensitized solar cells based on the freestanding TiO<sub>2</sub> nanotube arrays with carbon materials and scattering layer

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Dye-sensitized solar cells were fabricated with closed- or open-ended freestanding TiO<sub>2</sub> nanotube arrays as photoelectrodes that were decorated with carbon materials and large TiO<sub>2</sub> nanoparticles to enhance the energy conversion efficiency. The main role of carbon materials is to improve the electron transports by pi-pi conjugation and the main role of large TiO<sub>2</sub> nanoparticles is to improve the light harvest by scattering in the TiO<sub>2</sub> nanotube arrays. The energy conversion efficiency of DSSC based on open-ended freestanding TiO<sub>2</sub> nanotube arrays is increased from 4.47% to 5.39% compared to the DSSC based on closed-ended freestanding TiO<sub>2</sub> nanotube arrays. In DSSCs based on the open-ended freestanding TiO<sub>2</sub> nanotube arrays, the energy conversion efficiency of DSSC with carbon materials or scattering layer is increased from 5.39% to 6.19% or from 5.39% to 6.24% compared to the DSSC without carbon materials and scattering. Moreover, the energy conversion efficiency of DSSC based on the open-ended freestanding TiO<sub>2</sub> nanotube arrays with carbon materials and scattering layer is increased from 5.39% to 6.98%, an enhancement of 29.50%.