Carbon Nanotubes for Solar Cells

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Carbon nanotubes (CNTs), graphene, and fullerene (C_{60} and derivatives) are very efficiently used in organic-thin film and organic-inorganic Perovskite solar cells.[1,2] Highly transparent and conductive films of single-walled CNT (SWCNT) and graphene can be the practical replacement[3] of ITO for the flexible and/or foldable[4] transparent electrode of inverted perovskite solar cells. Doping of SWCNT is essential for high performance solar cells through increased in-plane film conductivity and energy level adjustment. Since *p*-doping is easier than *n*-doping in general, it is more practical to use SWCNT electrode in the hole-transport side. Hence, we have developed the normal type perovskite solar cells composed of ITO/ETL/$MAPbI_3$/HTL+SWCNT. The use of SWCNT as the top electrode instead of metal enhances the stability of PSCs by removing the metal-ion migration, and considerably reduces the fabrication cost, and is suitable for the development of tandem system. Recently, we have improved the performance with higher concentration of hole-transporting material[5]. For $MAPbI_3$ system, we have obtained the highest PCE of 18.8 % compared with the control device with gold electrode with PCE of 18.1%. Because of transparency of SWCNT film is higher than that of ITO in the NIR region, SWCNT electrode based Perovskite–silicon tandem solar cells can have better performance than ITO-based one[6]. In addition to our demonstration of 24.4 % total PCE in our previous work[6], we are now demonstrating the higher preliminary PCE of about 27 %.

Double-walled carbon nanotubes (DWCNTs) often show advantages against SWCNTs in solution processes[7,8], because of the mechanical toughness. On the other hand, dry deposited film of DWCNTs could lead to the cost-efficient replacement of SWCNTs[9]. Finally, the ultimately inorganic stable doping of SWCNT could be possible by using the one-dimensional van der Waals hetero-nanotubes[10]. We have synthesized the coaxial few-layer hexagonal boron nitride nanotube (BNNT) around a SWCNT; SWCNT@BNNT[11]. Then, the further coating of coaxial MoS_2 nanotubes results SWCNT@BNNT@MoS_2NT. The inner SWCNT and outer MoS_2NT are electrically coupled through a few layer BNNT. The preliminary PSC device using the heteronanotube film shows the advantage[12]. We have observed a strong coupling of excitons of SWCNT and MoS_2NT through the thin BNNT layer as inter-tube exciton[13,14]. Hence, such hetero-nanotubes could be an interesting active layer materials of solar cells.

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