Resonant Silicon Nanoparticles for Enhanced Light Harvesting in Halide Perovskite Solar Cells

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Abstract. Improving performance and stability of lead halide perovskites solar cells (PSC) is one of the most important direction in modern photovoltaics. For this purpose, we added low-loss and chemically inert resonant silicon nanoparticles (NPs) between electron transport layer and perovskite layer that allows to increase the efficiency enhancement via improved light harvesting, photocurrent, open-circuit voltage and fill-factor. This results in a boost of the device efficiency up to 18.8%, being a record among the previously reported results on nanoparticles incorporation into CHNH₃PbI₃ (MAPbI₃) perovskite-based solar cells. Moreover, PSC with the silicon NPs shows efficiency improvement in time with respect to the cells without NPs. The proposed method is simple and can be implemented for PSCs with various compositions and architectures.

1. Introduction

Nowadays lead halide perovskites have a huge number of possible optoelectronic applications including diodes [1], laser technologies [2], photodetectors [3] but the main attention is focused on photovoltaics [4-6]. PSCs achieved remarkable power conversion efficiency (PCE) values exceeding 22% [7] through a careful materials design and fabrication process optimizations. A lot of attempts were given to increase PCE by plasmonic NPs implementation into perovskite SC devices, which can play a role as either the absorber or increase charge transport, that makes them a promising method to engineer both optical and electronic device characteristics by making better use of incident light and engineering the carrier dynamics.

On the other hand, there is no any data about time stability of PSC contained chemical active plasmonic NPs. As shown in previous works [8], a metal part of PSC can interact with organic and perovskite layers under temperature higher that 30 °C. It is necessary to cover by additional inert shell plasmonic NPs, which not only includes complementary resources of device preparation, but also can reduces the NPs charge influence.

At the same time, Mie resonance silicon NPs recently has emerged as the powerful tool for various optical applications[9,10]. Due to their low cost, preparation simplicity, chemical inert properties and temperature resistance these NPs represent a viable and better alternative to noble metals for
photovoltaics application. In this work we incorporate Si NPs between mesoporous electron transport layer and MAPbI to increase efficiency up to 18.8%.

2. Discussion
Figure 1 shows the device structure and thickness of each layer. Meso-superstructured PSC has a n-i-p architecture. A 50-nm TiO₂ compact layer is deposited on top of an electron collecting fluorine-doped tin oxide (FTO) electrode. A mesoporous TiO₂ (m-TiO₂) ETL has a 200-nm thickness, capped by photoactive MAPbI perovskite (150/350 nm). The 400-nm hole transport layer (HTL), SPIRO-OMeTAD, doped with Bis(trifluoromethane)sulfonimide lithium salt, coats perovskite, and 80-nm gold layer, was deposited as top contact. The Si NPs, located between m-TiO₂ and perovskite, have size between 50 and 180 nm. This configuration allows to keep device morphology from thickness change or additional layers roughness.

![Figure 1](image1.jpg)

**Figure 1.** Cross-sectional bright-field STEM image and layer scheme of a complete solar cell. Bottom-up: FTO electrode, c-TiO₂ ETL m-TiO₂ ETL MAPbI perovskite, SPIRO-OMeTAD HTL.

The best reference device showed an efficiency of 17.7%, when the best performance for device with Si NPs is 18.8%. The Figure 2 demonstrates the J-V scans for the best cells with the different design (with and without Si NPs). It is clearly seen that device with Si NPs has a well shape of J-V curve due to fill factor of 78.9% (for reference it is 77%), improving $V_{oc}$ from 1.05 to 1.06 V and $J_{sc}$ from 22.0 to 22.4 mA/cm².

![Figure 2](image2.jpg)

**Figure 2.** J-V curves for best cells with (orange) and without (black) incorporation of Si NPs.
According to the statistical data, measured for 34 cells and presented in figure 3, the average efficiency for standard devices is 17.2%, whereas for Si NPs contained this performance is 17.6%. It should be pointed, that we have observed that the Si NPs presence improves the statistic device performance after 4 days up to 17.9%, at the same time, reference cells lightly decrease it to 17.1%.

![Figure 3](image)

**Figure 3.** Statistics data for PSC efficiency with (orange) and without (black) Si NPs for just prepared cells (left) and after several days (right).

3. **Conclusion**

Si NPs present a novel approach to improve lead halide perovskite solar cells, being located at an interface of MAPbI₃ and m-TiO₂. The improved PSCs have demonstrated the efficiency of 18.8%, which are higher than those for the reference devices. Moreover, Si NPs show a unique property to improve devices after few days.

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