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Modulation of micro-cavity effect on the spectral response of perovskite photodiodes via charge transport layer thickness engineering

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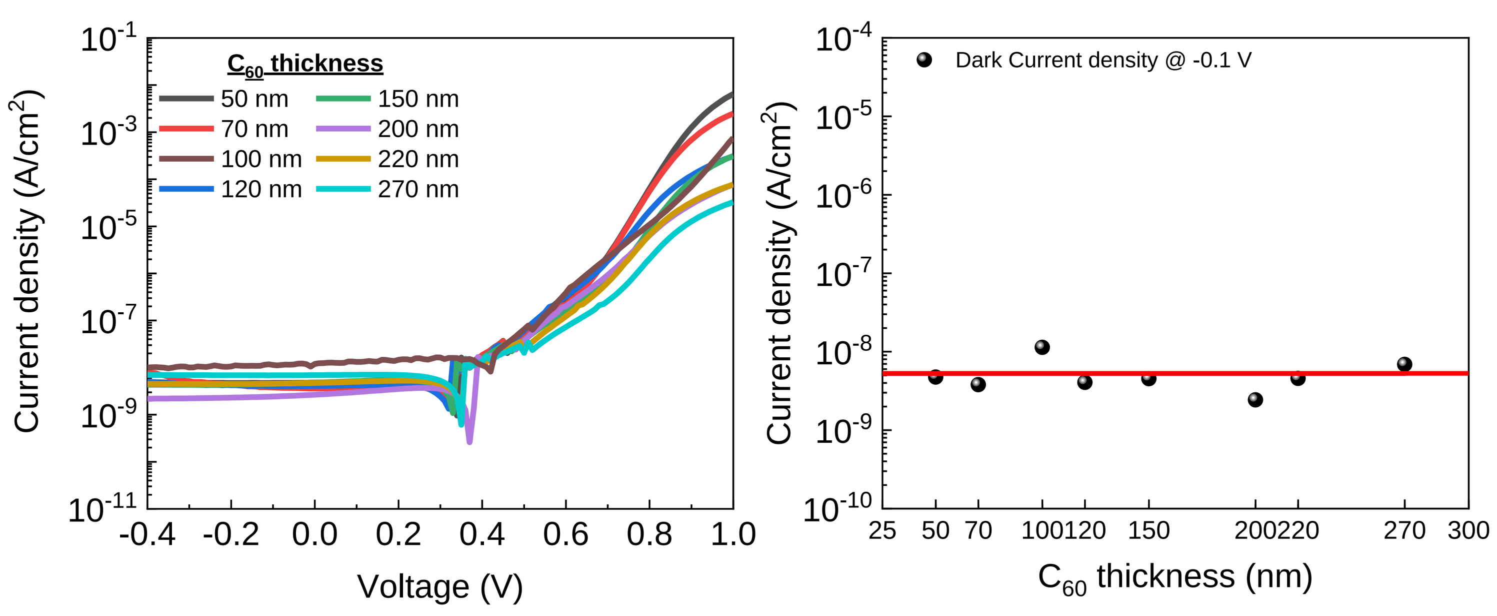
Introduction

Photodetectors are key components in a variety of industrial and scientific applications, including imaging, optical communications, environmental monitoring, and biological sensing. In order to achieve enhanced device performance, various types of semiconductors have been studied as photoactive materials. Due to the outstanding intrinsic optoelectronic and electronic properties, organic-inorganic hybrid perovskites (OIHPs) have seen a tremendous attention in the research communities of optoelectronic device. In addition, recent advancements have verified that these materials have a great potential in the field of light-signal detection.

The absorption behavior of photons incident on the active layer is affected by the Beer-Lambert law or(and) micro-cavity effect, which can be modulated by controlling the thickness of the active layer. Based on these characteristics, in many studies, the thickness of active layer has been used as a key parameter to achieve various spectral response of the perovskite photodiodes (PePDs). However, because the active layer thickness is strongly correlated with the defect density, the variation of active layer thickness occasionally affects other device performance indices, such as dark current. To solve this problem, we varied the thickness of the charge transport layer (CTL) instead of the active layer to achieve various spectral response. By controlling the CTL thickness, we could successfully modulate the micro-cavity effect and suggested an alternative approach to achieve a targeted spectral response of the PePDs.

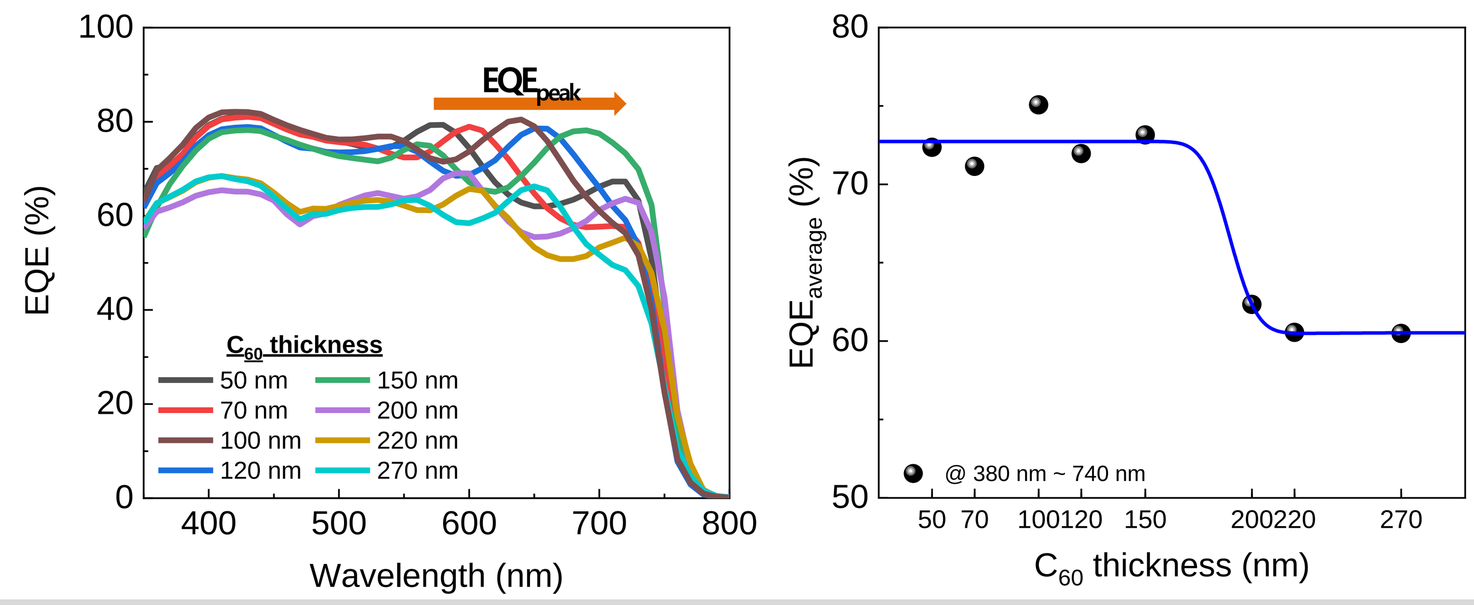
Result & Discussion

- Dark current density of the PePDs with various CTL thickness



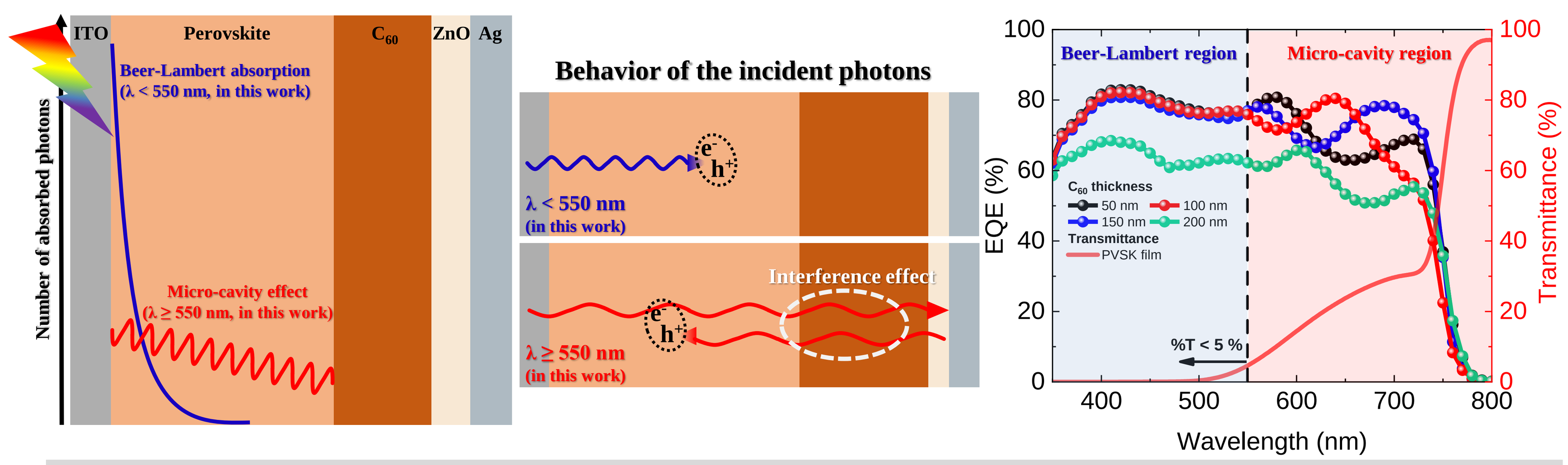
- The device structure of the PePD is ITO/OIHP/C_{60}/ZnO/Ag.
- We postulated the CTL thickness is strongly correlated with the micro-cavity effect and the device performance can be optimized by varying the CTL thickness from 50 nm to 270 nm.
- Devices show the low dark current density irrelevant to CTL thickness change. In particular, the devices have the almost same level of the dark current density, and the average dark current density at -0.1 V was measured to be 5 nA/cm^2.

- EQE spectra of the PePDs with various CTL thickness



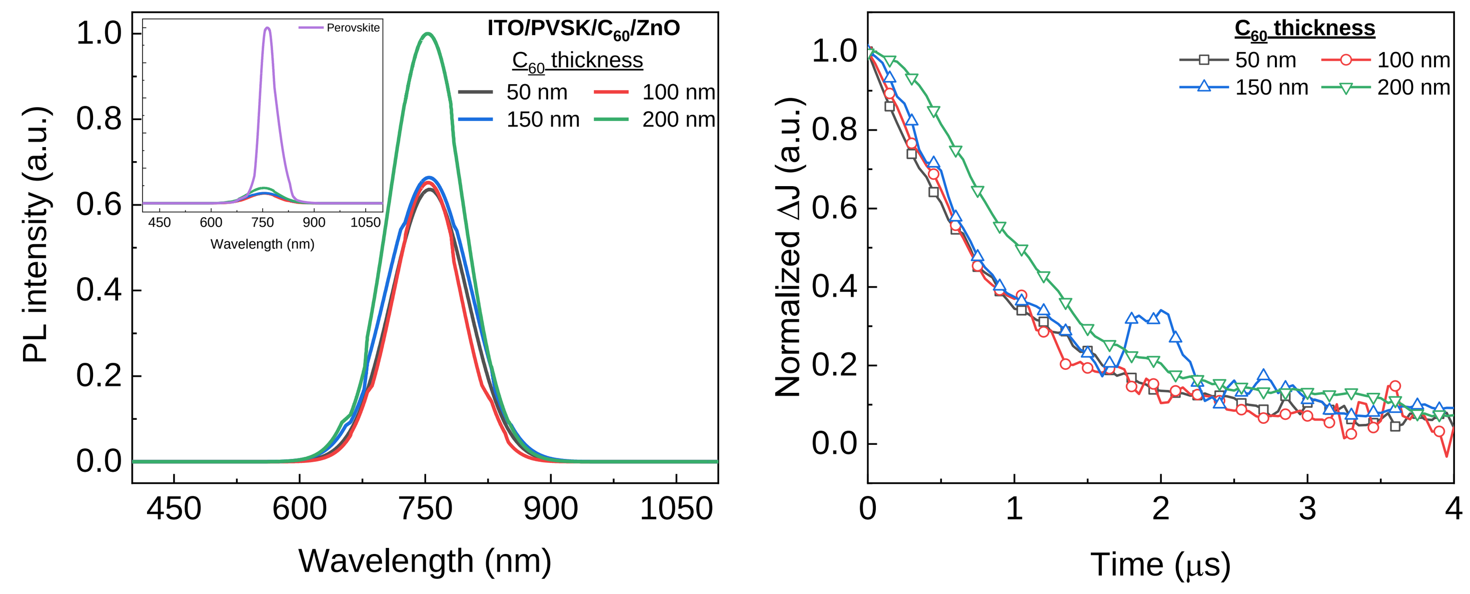
- The EQE of devices was changed at a long wavelength region(over 550 nm) by modulation of micro-cavity effect as we varied the CTL thicknesses. As a result of modulated micro-cavity effect, the wavelength where the EQE reached the peak value at a long wavelength region was red shifted when increasing the CTL thickness.
- The average EQE of the device with a relatively thin CTL(less than 200 nm) was 73 % and the average EQE of the device with a thick CTL(more than 200 nm) was 63 %. These results mean the degradation of device performance due to the increased CTL thickness.

- Theoretical and experimental demonstration of micro-cavity effect modulation



- The absorption of short-wavelength light which has high absorption coefficient in the active layer would be predominantly determined by Beer-Lambert law, whereas the absorption of long-wavelength light which has low absorption coefficient would be determined by micro-cavity effect.
- The long-wavelength light which can partially penetrates through the active layer is reflected by the metal electrode, the optical interference effect occurs between the reflected light and the incident light. Thus, the variation of the CTL thickness could affect the optical interference effect and modulate micro-cavity effect.
- Due to Beer-Lambert absorption, all devices have almost the same spectral shape of EQE from 350 nm to 550 nm. In this region, the perovskite photo-active layer shows relatively low transmittance represented by 5 % or less.
- The EQE at a long-wavelength region where the perovskite photo-active layer has enough transmittance(5 % ~ 50 %) to induce optical interference was changed as a function of CTL thickness. These results experimentally demonstrate that CTL thickness engineering could affect the micro-cavity effect.

- Origin of the performance degradation of the device with thick CTL



- We confirmed the charge transport characteristics as a function of CTL thickness through PL spectra and transient photocurrent analysis.
- Because the perovskite has direct band-gap, the perovskites with high intensity in PL spectra have large recombination rate for the photogenerated charge carriers. In PL spectra, the PL intensity was slightly increased when the thickness of CTL was increased from 50 nm to 150 nm, whereas the PL intensity of the sample which has 200 nm thick CTL was strongly increased. This result shows the sample with 200 nm thick CTL has large recombination rate and poor charge transport properties.
- The samples with 50 nm, 100 nm, and 150 nm thick CTL show almost the same level of the transient photocurrent (TPC) decay time. The TPC decay time of these devices was 3 μs, while the device with 200 nm thick CTL exhibited the longest TPC decay time of 4.2 μs.
- These results verify that the charge transport characteristics of the device with 200 nm CTL are poor, and that an increase in the CTL thickness over the critical thickness can cause the degradation of device performance.

Conclusion

- The PePDs with a structure of ITO/OIHP/C_{60}/ZnO/Ag were fabricated.
- By varying the CTL thickness of the PePDs, the spectral response at a long wavelength region has been modulated without apparent variation of the dark current density of the PePDs. Because the spectral response at a long wavelength region is related with micro-cavity effect, this result proves that modulation of the micro-cavity effect is available by changing the thickness of CTL rather than the photoactive layer.
- Although the change of the spectral response at a long wavelength region was observed in the device which has CTL thickness of more than 200 nm, a sharp decrease of the average EQE was measured when the CTL thickness exceeded 200 nm, which could be ascribed to the poor charge transport properties of the device with thick CTL.
- These results will provide an alternative approach to achieve a targeted spectral response of the PePDs.

Acknowledgement

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