Experimental demonstration of the generalized reciprocity relation in *p-i-n* junction solar cells

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The optoelectronic reciprocity relation in Eq. (1) is a useful theorem in developing novel characterization techniques and enhancing our understanding of the mechanisms in solar cells. This relation, which was first derived for the *p-n* junction diodes with the assumption based on the original Donolato's theorem [1,2], reveals the connection between the electroluminescence (EL) and the short-circuit external quantum efficiency (EQE). However, due to the non-linearity of the carrier transport with the excess minority carriers in *i*-region, this reciprocity relation is invalid in the solar cells with *p-i-n* configuration, for instance, amorphous silicon and quantum structures. The generalized reciprocity relation (Eq. (2)) applicable for both *p-n* and *p-i-n* junctions, proposed by our group, has been derived based on the voltage-dependent photocarrier collection efficiency, the generalized version of the Donolato's theorem. [3]

$$\Phi_{\mathrm{EL}}(\varepsilon, V) = \mathrm{EQE}(\varepsilon, 0\,\mathrm{V})\Phi_{\mathrm{BB}}(\varepsilon)\left(e^{qV/kT} - 1\right) \quad (1)$$

$$\Phi_{\mathrm{EL}}(\varepsilon, V) = \mathrm{EQE}(\varepsilon, V)\Phi_{\mathrm{BB}}(\varepsilon)\left(e^{qV/kT} - 1\right) \quad (2)$$

In this study, the generalized optoelectronic reciprocity theorem has been experimentally verified through the absolute EL measurements and the voltage-dependent EQE measurements of the InGaAs/GaAsP multiple quantum well (MQW) solar cells. These *p-i-n* junction solar cells were specifically designed to possess different barrier thicknesses while other parameters were fixed as shown in Fig. 1, resulting in the same absorption spectrum but different carrier collection efficiency and non-radiative carrier lifetime. These structures allow us to investigate to which extent this reciprocity relation is applicable. The device fabrication methods are described in [4]. The EQE spectra, EL spectra and EL images of the fabricated devices were measured as a function of the applied forward bias. Figure 2 shows the absolute EL from the measurements and the estimated EL calculated from voltage-dependent EQE by using Eq. (2). The results clearly show the agreement between the theoretical values and the experimental values. It is worth mentioning that the highly strained sample (24.6-nm-thick barrier) shows the inaccuracy in estimating EL from EQE under high voltage. This observation confirms the assumption, which has been predicted in [3], that the generalized reciprocity relation is invalid when the electric field becomes weak and the carrier mobility is low. These conditions lead to a drop of the quasi-Fermi level of the majority carrier under carrier injection, which violates the assumption in deriving Eq. (2).

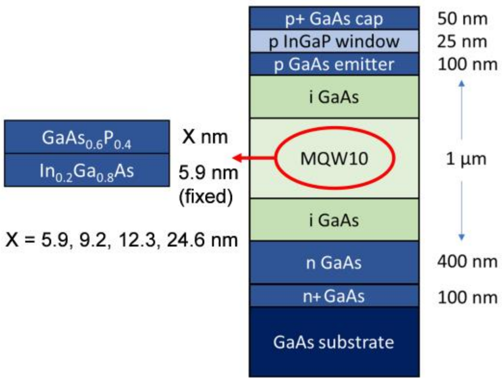

Fig. 1 The structure of InGaAs/GaAsP multiple quantum well (MQW) solar cells with barrier thickness of 5.9, 9.2, 12.3 and 24.6 nm.

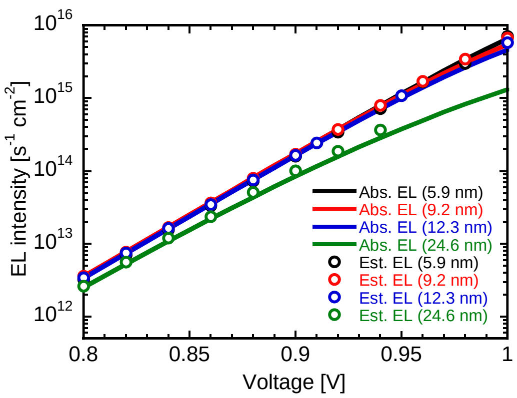

Fig. 2 Comparison between the absolute EL (lines) and the estimated EL from EQE (circles) by using the generalized reciprocity relation

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