NONEQUILIBRIUM THEORY ON THE CONVERSION EFFICIENCY LIMIT OF SOLAR CELLS INCLUDING FINITE THERMALIZATION AND EXTRACTION TIME

Kenji Kamide¹, Toshimitsu Mochizuki¹, Hidefumi Akiyama²,³, and Hidetaka Takato¹

¹AIST, Japan, ²ISSP, Univ. Tokyo, Japan, ³AIST OPERANDO-OIL, Japan

Detailed balance limit of solar cell conversion efficiency, 29.5% for a single-junction planer silicon (Si) solar cells (at 1 sun and AM0 condition), is known as the SQ limit given by Shockley and Queisser [1]. While their theory is based on several assumptions, the requirements in real devices are not fully discussed. Here we focus on their two assumptions: (1) Photo-generated carriers lose the kinetic energy via phonon emission and fully relax to the band bottom in a moment. (2) Photo-generated carriers are extracted to carrier reservoirs in a moment. As a result, the carriers in the cell are assumed to be in thermal equilibrium with the bath. By using a theoretical model (Figure 1(a)) accounting for the carrier relaxation and extraction dynamics with the time scale, \(\tau_{ph}\) and \(\tau_{out}\), respectively, we reformulate a nonequilibrium theory for solar cells which covers both the equilibrium (where the detailed balance applies) and non-equilibrium regime. Here we define the regime where the standard SQ theory can be used, and show what could happen outside the regime.

In terms of the carrier extraction time, \(\tau_{out}\), we found three different regime (Figure 1(b)), where the solar cell device character will be different: (i) \(\tau_{out} \gg \tau_{out}^{ul}\), (ii) \(\tau_{out}^{ul} >\tau_{out} >\tau_{ph}\), and (iii) \(\tau_{out} <\tau_{ph}\). For example, with large extraction time for (i), the chemical potential separation in the cell becomes larger than that in the bath, i.e. \(\mu_{cell}^0 - \mu_{cell}^V > \mu_{C} - \mu_{V}\). The boundary extraction time, \(\tau_{out}^{ul}\), depends on the material parameters (effective mass, and indirect/direct gap), and linearly on the cell thickness \(w\). We found \(\tau_{out}^{ul}\) to be sub-millisecond for 100-\(\mu\)m thick Si cells. In Figure 1(d), maximum conversion efficiency \(\eta_{max}\) is plotted as a function of \(\tau_{out}\) between regime (i) and (ii) for 100-\(\mu\)m thick Si cell. As expected, \(\eta_{max}\) starts to decrease significantly from the SQ limit (29.5%) as \(\tau_{out}\) increases and enters the regime (i). From the \(I-V\) characteristics (not shown), the short-circuit current \(I_{SC}\) and fill factor \(FF\) decrease with \(\tau_{out}\) while the open-circuit voltage \(V_{OC}\) is unchanged in this regime (i). Device performance in the slow-extraction regime (i) could be understood similarly with the equivalent circuit model in presence of large series resistance. Device characteristics in the fast-extraction regime (iii) [2] will be discussed elsewhere.


Figure 1: (a) Non-equilibrium model for our theory; (b) three different regime in terms of carrier extraction time, (c) the upper boundary extraction time, \(\tau_{out}^{ul}\), as a function of cell thickness \(w\) for a planer Si and GaAs solar cell, (d) maximum conversion efficiency as a function of \(\tau_{out}\) for 100 \(\mu\)m thick Si cell. All plots are obtained for planer single junction solar cells under 1 sun illumination at AM0 condition.