Theoretical Description of Quantum Efficiency Spectra of Thin Film $CuInSe_2$ and $Cu(In,Ga)Se_2$ Solar cells

Taras I. Mykytyuk[1], **Victoria Ya. Lytvynenko,**[1] **Leonid A. Kosyachenko,**[1] **Xavier Mathew**[2] **and Olena L. Maslyanchuk**[1]

[1] *Chernivtsi National University, Kotsyubinsky Str. 2, 58012 Chernivtsi, Ukraine*
[2] *Instituto de Energías Renovables, Universidad Nacional Autonoma de Mexico, Temixco, Morelos 62580, México*

During the last decade, thin-film technology as an alternative to solar modules based on mono- and poly-silicon wafers is developing rapidly. Together with amorphous silicon, the most common materials used in the mass production of thin-film modules are CdTe and $CuIn_xGa_{1-x}Se_2$ (CIGS). The efficiency of small area laboratory samples of CdS/CdTe solar cells increases year by year and now stands at 18.7% under AM1.5 solar radiation, whereas the efficiency of large area CdTe solar modules had reached 14.4 % in the early 2012. For a long time, solar modules based on CIGS keep a stable position among the promising materials for efficient thin-film photovoltaics. Their efficiency in the production conditions is in the range of 12-15%, and for laboratory samples, a record level of efficiency among thin-film solar cells 20.3% was achieved. Since this efficiency is much lower than the theoretical limit 28-30%, works to improve the CdTe module efficiency are extremely relevant. From this point of view, an analytical description of one of the key characteristics, which is the spectral distribution of the quantum efficiency of cells, can bring significant benefits. In fact, a comparison of the numerical results with the measured spectrum of the quantum efficiency allows determining the real parameters of the used materials and the solar cell structure, which may differ from those predicted by the fabrication technology.

In this paper, solar cells based on $CuIn_xGa_{1–x}Se_2$ with the band gap of 1.4 eV are considered, which is close to its optimal value for maximum efficiency of the device. Special attention is also paid to the most narrow band gap semiconductor $CuInSe_2$ (CIS), which is considered as a suitable material for a bottom sub-cell in tandem devices with the $Cd_{1–x}Mg_xTe$ top sub-cell, for example. Finding the drift and diffusion components of the CdS/$Cu(In,Ga)Se_2$ solar cell efficiency is based on solving the continuity equation for the $Cu(In,Ga)Se_2$ absorber layer with appropriate boundary conditions. At the interface between space-charge region and the neutral part of the $Cu(In,Ga)Se_2$ layer, the excess concentration of electrons can assumed to be zero, whereas recombination at the front and rear surfaces of the absorber is compensated by the influx of free carriers. The optical transmission of the ZnO and CdS layers is calculated using their optical constants, that is, the refraction indexes and the extinction coefficients. For the best matching the calculation results with measurements, we choose the concentration of the uncompensated impurity, the electron lifetime, the recombination velocity at the front surface of the $Cu(In,Ga)Se_2$ absorber, as well as the thickness of the CdS window layer. As a result, one can achieve quite good quantitative descriptions of the observed spectra. It turns out that for both devices under study, the concentration of the uncompensated impurity, determining the width of the space charge region, differ by more than an order of magnitude, while the lifetime of electrons in the CIS and CIGS layer differ by more than two orders of magnitude (it can be explained by different degrees of the crystal lattice disorder). The thicknesses of the CdS layers are also different, namely, they are 55 and 35 nm for the CIS and CIGS layers, respectively.

It follows that comparison of the calculation results with the measured spectra provides important and useful information about the parameters of the materials used.