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# Internal voltages in GaInP/GaInAs/Ge multijunction solar cells determined by electroluminescence measurements

Thomas Kirchartz,[1,a)] Uwe Rau,[1] Martin Hermle,[2] Andreas W. Bett,[2] Anke Helbig,[3] and Jürgen H. Werner[3]

[1]*IEF5-Photovoltaik, Forschungszentrum Jülich, 52425 Jülich, Germany*
[2]*Fraunhofer Institut für Solare Energiesysteme, Heidenhofstr. 2, 79110 Freiburg, Germany*
[3]*Institut für Physikalische Elektronik, Pfaffenwaldring 47, 70569 Stuttgart, Germany*

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We analyze electroluminescence spectra of a GaInP/GaInAs/Ge triple-junction solar cell at different injection currents. Using the reciprocity theorem between electroluminescent emission and external quantum efficiency of solar cells allows us to derive the current/voltage curves and the diode quality factors of all individual subcells. © *2008 American Institute of Physics*.
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Multijunction solar cells based on III-V semiconductors on Ge substrate have the highest efficiency among today's solar cell technologies.[1] The possibility to epitaxially grow high quality semiconductor layers on top of each other allows a better adaptation of the absorber materials to the solar spectrum.[2] Characterization of these devices, however, is challenging, especially for multijunction cells designed for use in concentrator systems. For instance, the experimental access to information about individual subcells, as well as the device characteristics at high illumination conditions, are of interest yet difficult to assess with common methods.

This letter introduces a method to derive the individual current/voltage curves of all subcells in a stacked multijunction cell by combining electroluminescence (EL) and quantum efficiency measurements. We measure the EL spectra of a lattice mismatched $Ga_{0.35}In_{0.65}P/Ga_{0.83}In_{0.17}As/Ge$ solar cell at currents ranging from 100 $\mu$A to 150 mA and over a range of wavelengths λ from 600 to 1800 nm. The solar cell of an area $A=0.032$ cm$^2$ was prepared by metal organic vapor phase epitaxy.[3] The current is applied with a dc source and the EL emission is chopped in order to allow the use of lock-in amplifiers. The spectra are then recorded with a Ge detector attached to a single stage monochromator and are subsequently corrected for the relative sensitivity of the setup. Figure 1(a) shows three exemplary EL measurements at currents $I=2$, 20, and 150 mA. The spectra feature two pronounced peaks of the direct semiconductors GaInAs ($E \approx 1.20$ eV) and GaInP ($E \approx 1.72$ eV). The Ge peak is hardly visible since the sensitivity of the Ge detector is already very low at the peak around $E \approx 0.70$ eV.

The basic theoretical ingredient for our analysis is the spectral reciprocity relation (RR) between solar cell and light emitting diode, as described in Ref. 4, and experimentally verified for the case of *pn*-junction solar cells made of Si and $Cu(In,Ga)Se_2$.[5,6] The RR relates the external solar cell quantum efficiency $Q_e(E)$ to the spectral emission $\phi_{em}$ via[4]

$$\phi_{em}(E) = Q_e(E)\phi_{bb}(E)\left[\exp\left(\frac{qV}{kT}\right) - 1\right], \quad (1)$$

where $\phi_{bb}(E)$ is the black body photon flux, $V$ is the internal voltage applied to the *pn* junction, and $kT/q$ is the thermal voltage. Equation (1) connects the spectral EL emission with two quantities of high relevance for photovoltaics: the quantum efficiency $Q_e(E)$ and the junction voltage $V$. In the following, we determine the three junction voltages $V_j$ ($j=1$, 2, and 3) of the three individual subcells of our GaInP/GaInAs/Ge stack. Therefore, we directly use measured external quantum efficiencies $Q_e^{dir}$ to scale EL emission of each subcell with the help of Eq. (1).

Figure 1(b) shows $Q_e^{dir}$ of the three subcells directly measured (using the method described in Ref. 7) in comparison with the quantum efficiency $Q_e^{EL}$ extracted from the EL spec-

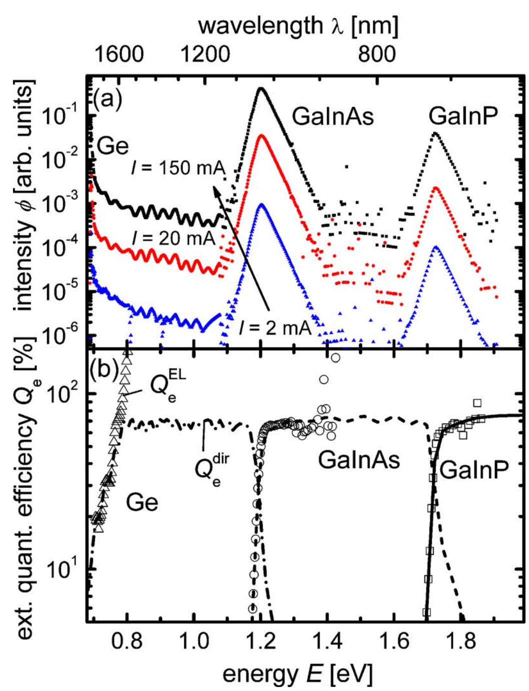


FIG. 1. (Color online) (a) EL spectra of the multijunction cell at three different injection currents. (b) Comparison of the directly measured quantum efficiency (lines) to the quantum efficiencies derived from the EL spectrum (symbols) using Eq. (1).

[a)]Author to whom correspondence should be addressed. Electronic mail: t.kirchartz@fz-juelich.de.

 

trum taken using Eq. (1). For the GaInAs and GaInP solar cells, we find a good agreement of the respective low-energy portions of $Q_e^{\mathrm{dir}}$ and $Q_e^{\mathrm{EL}}$ including a part of the region where the quantum efficiency saturates. At higher photon energies, $Q_e^{\mathrm{EL}}$ becomes noisy because of the low intensity of the underlying EL signal [Fig. 1(a)]. For the Ge cell, the spectral region, where $Q_e^{\mathrm{dir}}$ and $Q_e^{\mathrm{EL}}$ correspond to each other, is restricted to the low-energy slope; whereas at higher photon energies ($>0.76$ eV), the original EL is distorted by small amounts of stray light. Due to the exponential energy dependence of the black body spectrum in Eq. (1), the increased luminescence signal strongly affects the $Q_e^{\mathrm{EL}}$ leading to the discrepancy to $Q_e^{\mathrm{dir}}$, visible in Fig. 1(b).

In order to determine the internal junction voltages, we have to consider the fact that the EL intensity is measured in arbitrary units and, thus, reformulate Eq. (1) using the Boltzmann approximation for $\phi_{\mathrm{bb}}$ as

$$\phi_{\mathrm{em}}(E) = CQ_e(E)E^2 \exp\left(\frac{-E}{kT}\right)\exp\left(\frac{qV}{kT}\right), \tag{2}$$

with $C$ being an unknown energy independent proportionality factor. Solving for the internal voltage $V_j$ at any of the three junctions $j=1$, 2, and 3 leads to

$$V_j = V_T \ln(\phi_{\mathrm{em}}) + E/q - 2V_T \ln(E) - V_T \ln(Q_e^j) - V_T \ln(C), \tag{3}$$

with $V_T=kT/q$. Except for the constant additive term $\delta V=V_T \ln(C)$, Eq. (3) enables us to determine the voltage that internally drops over each of the three *pn* junctions.

Figures 2(a)–2(c) show the result of performing the operation given by Eq. (3) on the measured spectra of Fig. 1. The three spectral regions highlighted by vertical lines in Figs. 2(a)–2(c) correspond to the ranges, where the EL of each subcell yields a maximum signal and where $Q_e^{\mathrm{dir},j} \approx Q_e^{\mathrm{EL},j}$ in Fig. 1(b). Since the internal voltages are the quasi-Fermi-level splittings at the three internal junctions, the application of Eq. (3) in these regions must lead to a result for $V_j$ being independent of energy. This is verified by Figs. 2(a)–2(c).

The constant offset voltage $\delta V$ is determined from a separately measured current/voltage ($J/V$) curve under about 25 suns illumination, as depicted in Fig. 2(d). Then, we adjust the sum $\Sigma V_j$ of the junction voltages (measured at a dark current density $J_D$) to the open circuit voltage $V_{\mathrm{OC}}$ at the illumination condition leading to the corresponding short circuit current density $J_{\mathrm{SC}}=J_D$. Note that this scaling must only be performed once for the total series of EL measurements because the offset voltage $\delta V$ is the same for all spectra. Adjusting the voltages to $V_{\mathrm{OC}}$ and not to an arbitrary voltage is necessary since neither the internal voltages from EL nor the $V_{\mathrm{OC}}$ contain resistive effects as any other directly measured voltages do.

Having determined the offset voltage, we can rescale the voltage axis in Figs. 2(a)–2(c) and finally receive the internal voltages of the individual subcells, shown in Fig. 2(d) for a wide range of injection currents. From the semilogarithmic slope of the $J/V$ curves, we determine the diode quality factors $n_{\mathrm{id}}$ with the relation $n_{\mathrm{id}}=q/kT \times \partial V/\partial \ln J$, receiving the values $n_{\mathrm{id}}=1.14$, 1.61, and 1.37 for the Ge, GaInAs, and GaInP cell, respectively. Summing up the individual voltages leads to $\Sigma V_j$ as a function of injection current. This curve nicely corresponds to the directly measured $J/V$ curve over the whole range and not only at the point $V=V_{\mathrm{OC}}$ (which is the case by design).

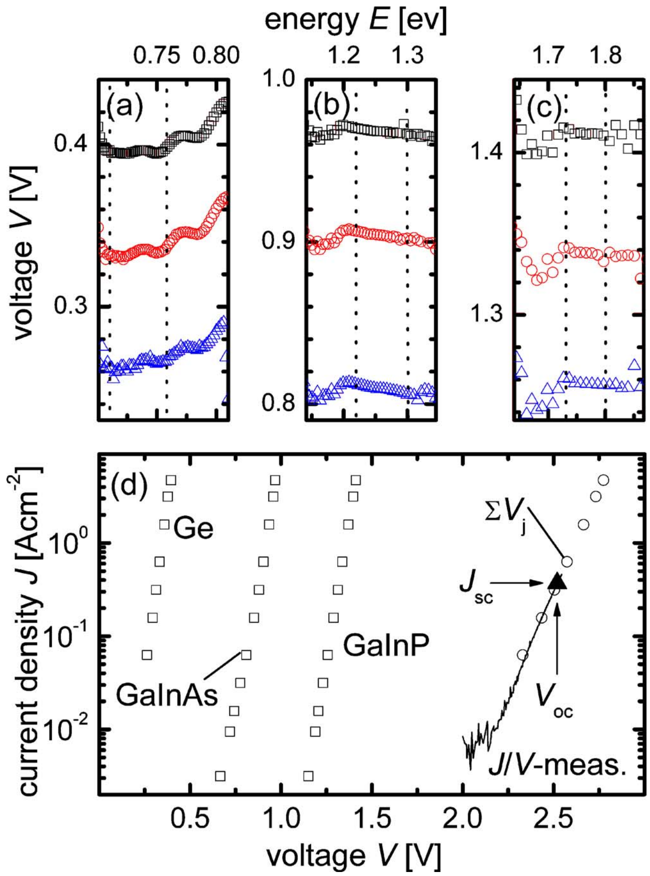


FIG. 2. (Color online) [(a)–(c)] Relative internal voltage derived from the EL spectra of Fig. 1 according to Eq. (3) for currents $I=2$ mA (open triangles), 20 mA (circles), and 150 mA (squares). The dotted vertical lines indicate the spectral intervals, where the voltages have been determined. (d) These voltages (open circles) are adjusted to the open circuit voltage $V_{\mathrm{OC}}$ (full triangle) of a $J/V$ curve under 25 suns illumination. The solid line represents this $J/V$ curve shifted by the short circuit current density $J_{\mathrm{SC}}$. We finally receive the $J/V$ curves of the three individual subcells (open squares) with a correctly scaled voltage axis.

Apart from measuring the internal voltages, we can also rate the quality of the subcells from the difference between these internal voltages and their respective radiative limits. The saturation value $J_{0,\mathrm{rad}}^j$ of the radiative recombination current of cell $j$ follows directly from Eq. (1) via[5,6]

$$J_{0,\mathrm{rad}}^j = q \int Q_e^j(E)\phi_{\mathrm{bb}}(E)dE. \tag{4}$$

Defining the radiative open circuit voltage by $V_{\mathrm{OC,rad}}^j = V_T \ln(J_{\mathrm{SC}}/J_{0,\mathrm{rad}}^j)$ allows us to determine $V_{\mathrm{OC,rad}}^j$ for each subcell. The difference $\Delta V_{\mathrm{OC}}=V_{\mathrm{OC,rad}}^j-V_j(J=J_{\mathrm{SC}})$ is then a measure for nonradiative recombination losses in the subcell.[5,6] The resulting values at the injection current of the $J/V$ measurement (25 suns) are $\Delta V_{\mathrm{OC}}=226$, 132, and 210 mV for the Ge, GaInAs, and GaInP cell, respectively. Hence, the GaInAs cell comes by far closest to its radiative limit.

In summary, the present method allows us by combining EL and quantum efficiency measurements not only to determine the internal voltages of stacked multijunction solar cells but also to evaluate the performance of each subcell with respect to the respective radiative limit.

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[1]M. A. Green, K. Emery, Y. Hisikawa, and W. Warta, Prog. Photovoltaics **15**, 425 (2007).
[2]F. Dimroth and S. Kurtz, MRS Bull. **32**, 230 (2007).
[3]F. Dimroth, Phys. Status Solidi C **3**, 373 (2006).
[4]U. Rau, Phys. Rev. B **76**, 085303 (2007).
[5]T. Kirchartz, U. Rau, M. Kurth, J. Mattheis, and J. H. Werner, Thin Solid Films **515**, 6238 (2007).
[6]T. Kirchartz and U. Rau, J. Appl. Phys. **102**, 104510 (2007).
[7]M. Meusel, C. Baur, G. Létay, A. W. Bett, W. Warta, and E. Fernandez, Prog. Photovoltaics **11**, 499 (2003).