Electrical characteristics and hot carrier effects in quantum well solar cells

Long abstract

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We report on opto-electrical studies of hot carrier solar cells based on a quantum well/barriers architecture, giving access to electrical characteristics and carrier thermodynamic properties under same illumination conditions.

Sample design and fabrication Quaternary $In_xGa_{1-x}As_yP_{1-y}$ is chosen for lattice-matching with the InP substrate, and optimized from the results of our previous work [Rodière2015], which optically showed the evidence of hot carrier effects in a quantum well/barriers absorber. The multilayer wafer contains an intrinsic InGaAsP-based quantum well/barriers region, playing the role of absorber which generates charge carriers. For electric contact, this absorber is sandwiched between two p- and n-doped InP layers. The layers composition and thicknesses have been designed to minimize the number of energy levels in the quantum well and to spectrally separate absorption of the quantum well and the barriers.

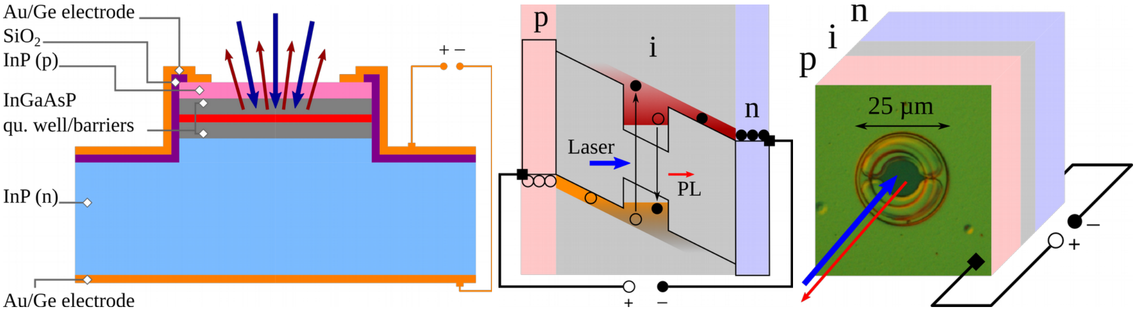


Figure 1 : Device structure and electric contact.

Our study consists of three experiments. **Electrical characteristics under laser illumination** To compare hot carrier effects with electrical performance, an experimental setup has been built. The strong point of this setup is the capacity to select microcells individually and characterize them both electrically and optically under the same conditions of laser illumination. Current-voltage characteristics are presented in Figure 2. Short-circuit current density *J*sc is linear with laser intensity over 4 orders of magnitude, which is the signature of a good generation and collection of charge carriers (in short-circuit regime). The open-circuit voltage remarkably exceeds the well's fundamental transition energy, which is 0.82 eV.

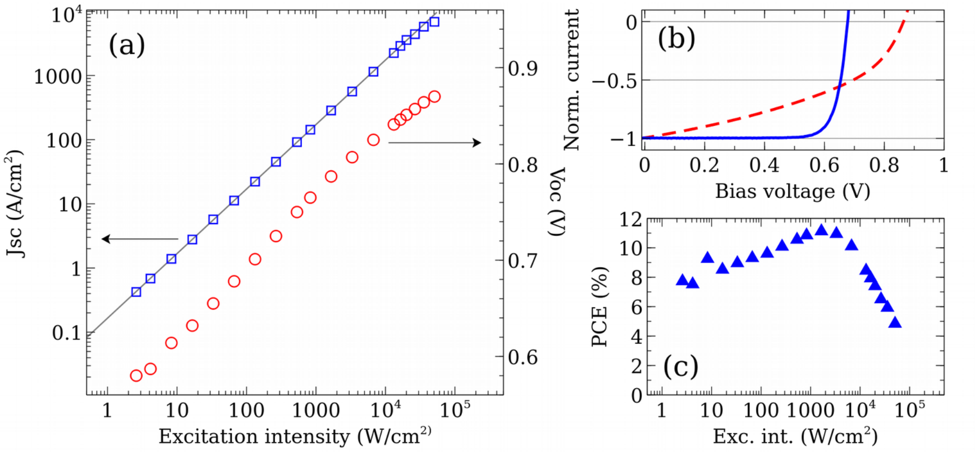


*Figure 2 : Electrical properties under different laser illumination. Figure (b) shows two normalized current-voltage curves at low (~80 W/cm², blue continuous line) and high (~4*10⁴ W/cm², red dashed line) laser powers.*

Under laser excitation in open-circuit The calibrated spectra are fitted to extract thermodynamic quantities of photo-generated carriers, i.e. T and $\Delta\mu$, using the generalized Planck's law of radiation [Lasher1964, DeVos1981, Würfel1982] :

$$I_{\mathrm{pl}}(E) = A(E)\cdot\frac{2n^2E^2}{h^3c^2}\frac{1}{\exp\left(\dfrac{E-\Delta\mu}{kT}\right)-1}$$

Determining the spectral absorptivity A(E) is crucial to minimize fit uncertainty [Tedeschi2016, Gibelli2017]. To this purpose we developed an absorption model taking into account electron bands observed in PL spectra:

$$\alpha_{w0}(E) = A_x\cdot\exp\left[-\frac{(E-E_x)^2}{2\Gamma_x^2}\right] + A_1\cdot\frac{1}{1+\exp\left(-\dfrac{E-E_1}{\Gamma_1}\right)}\cdot\frac{2}{1+\exp\left(-2\pi\sqrt{\dfrac{R_y}{|E-E_c|}}\right)} + A_2\cdot\frac{1}{1+\exp\left(-\dfrac{E-E_2}{\Gamma_2}\right)}$$

for the well, and

$$\alpha_{b0}(E) = A_b \cdot \frac{1}{1+\exp\left(-\frac{E-E_b}{\Gamma_b}\right)}$$

for the barriers. Also for more accurate analysis, the band-filling induced photobleaching is included $\alpha \propto \alpha_0 \cdot (f_e - f_h)$ [Würfel2009 p.90]. Amplitude of absorption is determined from a quantification of absorption, predicted by theory and supported by experiments [Fang2013, Skolnic1987, Stolz1987]. With these developments, fit quality is visually very good in all the laser excitation intensity range (Figure 3(a)). The resulting well carrier temperature (figure 3(b)) increases from 300 K to about 550 K, which is physically more *reasonable* than that obtained with the high-energy tail linear fit, as pointed out in Ref. [Gibelli2017]. The fitted barrier carrier electrochemical potential (figure 3(c)) describes well the electrically measured open-circuit voltage [refer to Figure 2(a)].

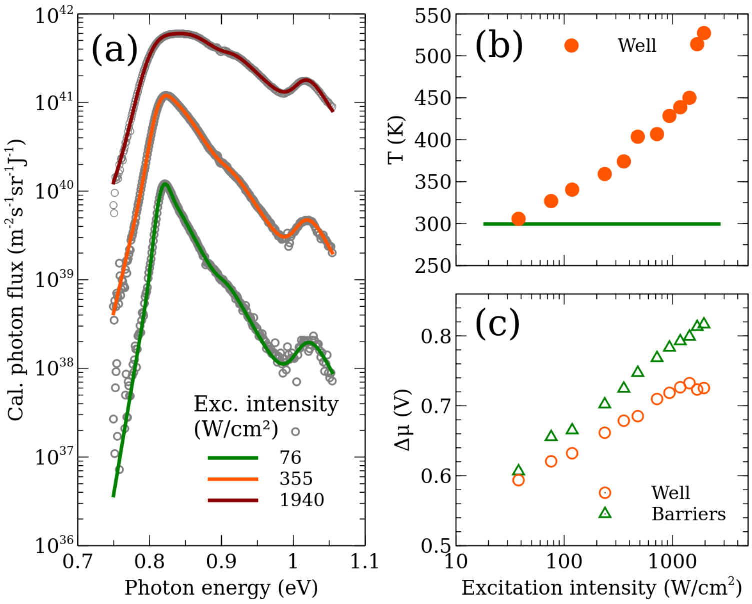
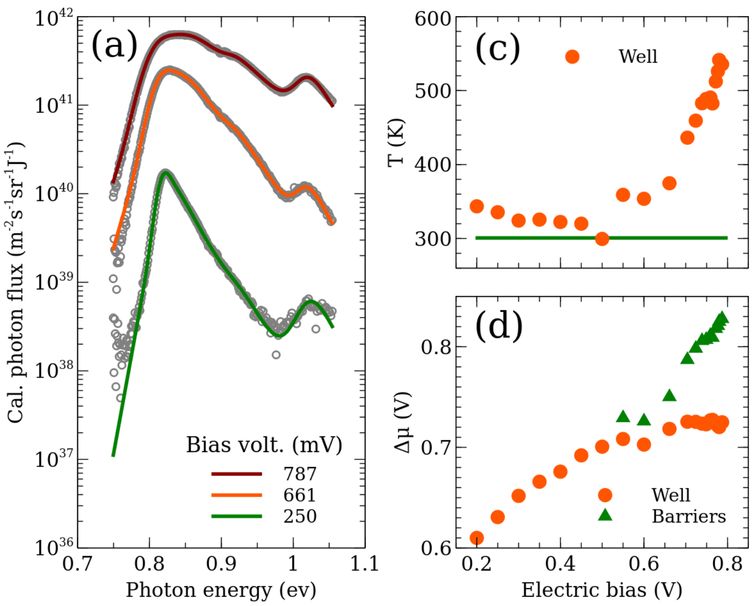


Figure 3 : Variation of carrier thermodynamic properties with laser intensity.

Extraction of photo-generated carriers by electric bias In this third experiment, we tried tuning carrier thermodynamic properties T and $\Delta\mu$ with a bias voltage. Fixing the laser intensity to a high value and starting from the open-circuit point, one expects T and $\Delta\mu$ of the carriers in the well with decreasing bias voltage. That is indeed the case as illustrated by the results presented in Figure 4.



Figures 4 : Variation of carrier thermodynamic properties with bias voltage at fixed laser intensity.

In perspective, we are working on a new device generation which aims to enhance the hot carrier footprint, both optically and electrically.

Reference

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