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Lowering Perimeter Recombination Losses in Micro-Concentrator Solar Cells: A Simulation Study

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Abstract. A device simulation study regarding perimeter recombination losses in micro-concentrator solar cells is presented. Perimeter losses for traditional and heterojunction designs were computed under dark and illuminated conditions for different solar cell sizes and surface state densities. A 2D device simulation model based on SRH recombination has shown that the use of heterojunction designs could help mitigate perimeter recombination for micro-CPV solar cells.

INTRODUCTION

The use of submillimeter concentrator photovoltaic solar cells may offer an alternative route to decrease the cost of a CPV system [1]. The main advantages rely on the lower temperature to be handled, the reduced Joule losses due to the lower current generated that may not require the use of heatsinks, among others. Besides the important challenges at the system level (see [2] and references therein), there are also challenges at the device level where perimeter recombination plays an important role, even under high concentrations.

As devices approach the Shockley–Queisser limit, the relative importance of other recombination mechanisms such as interface or perimeter recombination start to become hindrances for improved device performance. In fact, excellent bulk material quality has already been demonstrated in many III-V multijunction devices indicating that the path for improvements relies on the use of different device geometries or other electrical strategies that mitigate the remaining losses, among which perimeter and/or interface recombination are important. Moreover, perimeter recombination not only limits the open circuit voltage in single and multijunction solar cells with high P/A (perimeter to area) ratios, but also degrades the fill factor [1]. Typically, passivation of surfaces is employed to reduce surface recombination. However, for III-V materials (especially GaAs), the complete removal of surface states is complex and although improvements have been measured after passivation, the surface state density after passivation treatments is still significant (see for example [3], [4] and references therein). In addition, it should be noted that the passivation of surfaces involves additional steps in the processing of devices.

Accordingly, in this work we attempt to provide a pathway to minimize such losses by using solar cell designs different from traditional ones. We study the influence of perimeter recombination losses as a function of size (square geometry) and current density for traditional (i.e., homojunction) and heterojunction designs –by using thick n-type emitters without base layer (rear heterojunction, RHJ, similar to [5]) or in the absence of the emitter with thick p-type layers (front heterojunction, FHJ)–. We quantitatively discuss losses and show that heterojunction designs are possible candidates for perimeter recombination mitigation in micro-CPV solar cells.

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SIMULATION DETAILS

A traditional GaInP/Ga(In)As/Ge 3J solar cell is used as the baseline structure for 2D TCAD device simulations performed with Atlas from Silvaco. The analysis has been carried out for two different solar cell structures: a traditional design with n/p homojunction and a front heterojunction (N/p) design whose main difference with respect to the traditional design is the absence of a so called emitter, thus the pn junction is formed at the window/base interface (see Fig. 1). We are modeling and simulating the effect of a heterojunction design only in the Ga(In)As middle cell. This is because of two reasons: 1) we use previous knowledge indicating that both Ge and GaInP are dominated by bulk losses rather than perimeter recombination even at high P/A ratios [6] and 2) it helps introduce the concept in a simpler analysis.

Perimeter recombination is included in SRH recombination statistics, and is mainly dependent on the surface state density (N_{ss}), capture cross sections as well as energy levels of the surface states. This model has been previously applied successfully to a set of GaAs pn diodes for different sizes –including the submillimeter range– where a given midgap surface state density (assuming σ_n=σ_p) was characterized [7].

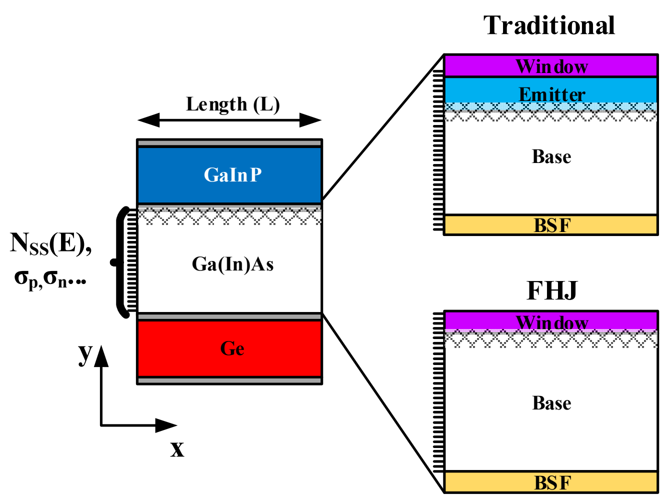

FIGURE 1. Sketch of the simulated structures: 3J and Ga(In)As subcells for traditional and FHJ designs. Shaded region indicate the depletion region of the Ga(In)As subcell.

RESULTS AND DISCUSSION

The main motivation for the use of heterojunction structures comes from the fact that previous knowledge has shown that perimeter recombination peak occurs at the intersection of the pn junction with the perimeter (see [7] and references therein). The recombination at this region peaks because it is the zone where the maximum pn product is found. Indeed, this recombination peak is the main source of losses regarding perimeter recombination. The reason of this could be attributed to a significantly different built in potential at the perimeter. For instance, surface states at the p-region (base) bend the conduction and valence bands downwards, and the potential developed is opposite to the built-in potential of the bulk p-n junction. This reduces the built-in potential at the perimeter where additional carriers can be injected. This is observed in Fig. 2 (a) where the band diagrams at equilibrium for a traditional design is depicted at two different parts of the structure: one corresponding to a bulk region (x=L/4) where no influence of perimeter is observed and a second band diagram corresponding to a cross section along the perimeter (x=0µm). As can be seen, in the bulk (red lines) there is a high built in potential while at the perimeter (black lines), the built-in potential has been highly reduced due to the presence of surface states. This means that electrons and holes find an additional path at the perimeter (and surroundings) where they can be injected more easily (rather than going through the bulk where high built-in potential is found), enhancing recombination. This is the most dominant current path for recombination, however, recombination along the perimeter through midgap states (not shown) also takes place.

By looking at the heterojunction case in Fig. 2 (b), there is also a high built-in potential at the bulk and an easy injection of electrons to the base side. The difference with the homojunction case is that additional barriers are developed at both bands, being higher at the valence band. This high barrier (>3000meV) is capable of rejecting a significant amount of holes from the pn junction intersection with the perimeter. This is the key factor that suggests why a lower recombination could be expected for the heterojunction case. In fact, for the SRH statistics assumed, the probability of an electron to recombine with a hole in the valence band is reduced due to the lower population of holes in that region where the additional barrier is rejecting them. In other words, hole rejection results in lower minority carrier recombination, i.e., electrons at the base region reducing pn product, thus the recombination rate.

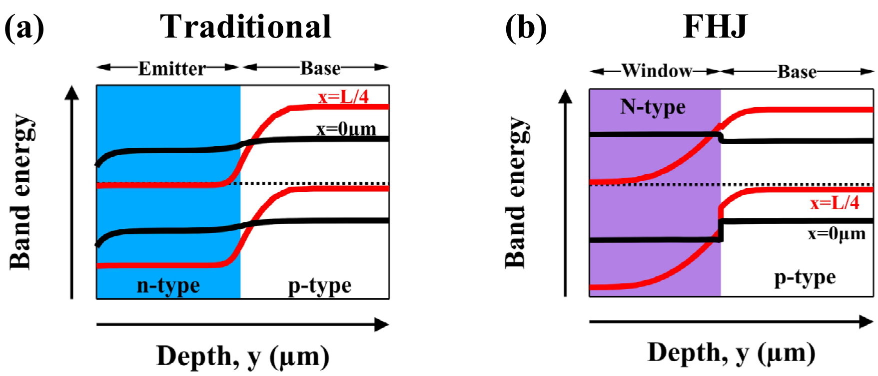

FIGURE 2. Band diagrams at x=L/4 µm (along the bulk, red line) and x=0µm (along the perimeter, black line) of both designs: (a) Traditional and (b) FHJ under equilibrium conditions (dashed line: quasi-Fermi levels).

To shed more light on the hole rejection and lowering recombination through the reduction of the pn product at the perimeter intersection with the pn junction, Fig. 3 shows 3D maps of the recombination distribution in each design at 1V. A high recombination peak is found in the vicinity of the n/p junction of traditional designs (where the n·p product peaks), as expected, the recombination distributes along the full perimeter for FHJ reducing substantially the peak at the junction (~1 order of magnitude lower). This recombination peak reduction translates directly into lower voltage losses due to perimeter.

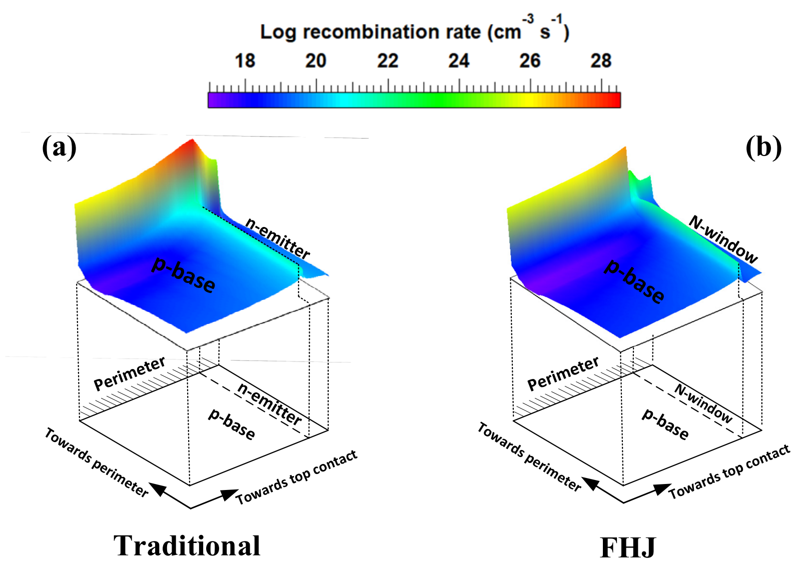

FIGURE 3. 3D maps of recombination rate (in logarithmic scale) within the Ga(In)As subcell (125x125µm) at 1V of traditional (a) and FHJ (b) designs.

The electrical impact of the different recombination maps of Figure 3 is shown in Fig. 4 where the voltage difference (extracted from their dark J-V curves) between the case considering perimeter recombination and the case neglecting it ($\Delta V_{per}=V(N_{ss}=0)-V(N_{ss})$) as a function of the current density (J) is depicted for both designs and different cell sizes. As can be seen, the voltage loss in FHJ designs is low for any size analysed and almost independent on the N_{ss} considered. For $N_{ss}=3\cdot10^{12}$ cm^{-2} (typical value for devices subjected to conventional wet chemical etching processes [3]), if FHJ is used the voltage gain is ~95mV for the lowest size considered (125x125µm) at 1-sun operation (AM1.5d) and ~15 mV at 1000 suns. For a 500x500µm size, the gain is ~50mV at 1-sun and ~3 mV at 1000 suns while for a 1000x1000 µm size the influence of perimeter recombination is almost negligible (<10mV) above 100 suns for any case.

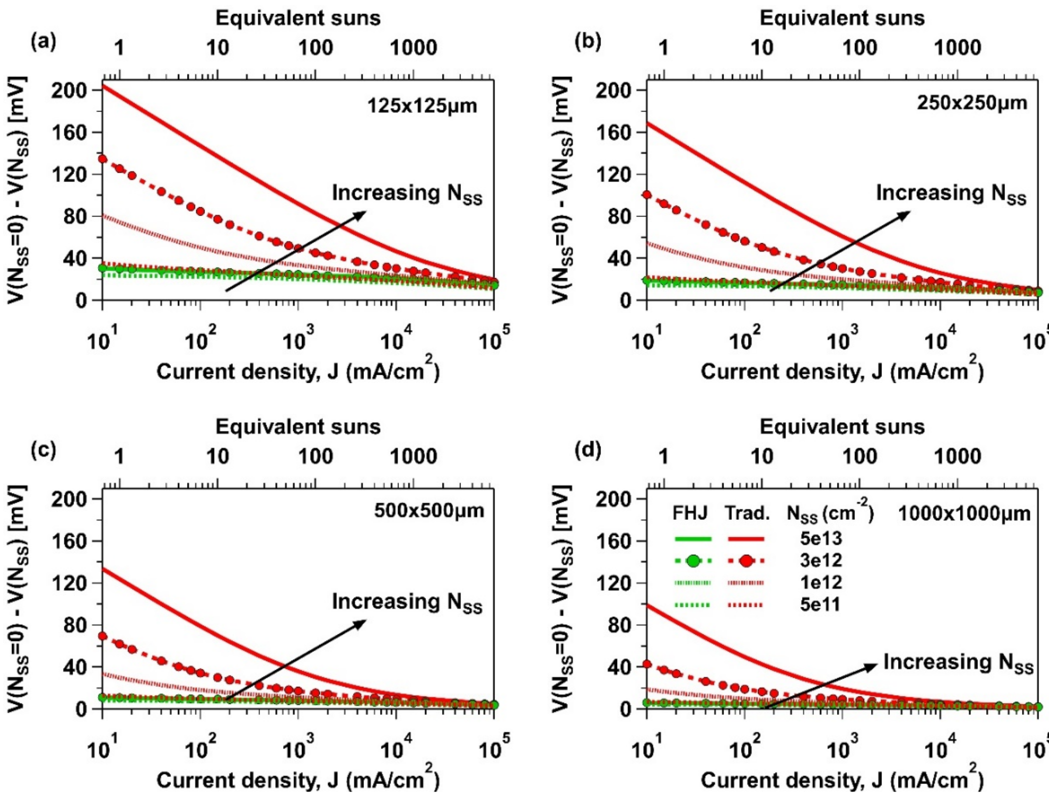

FIGURE 4. Voltage difference between the cases of perimeter with variable N_{SS} and zero perimeter losses, for different solar cell sizes as a function of the injected current (J) for each design: Traditional (red) and FHJ (green). Normalized equivalent suns on the top axis is calculated by $J/J_{SC}(1sun)$. Lines with symbols correspond to the case using the surface states density typically achieved in our GaAs devices.

Fig. 5 also gives an estimate of how much efficiency is lost by perimeter recombination. For instance, for the lowest size analysed, the efficiency loss due to perimeter is in the range of 0.7-1.6% (see black dashed line) for the concentration range of 100-5000 suns. Our calculations estimate an efficiency gain in the 3JSC (through V_{OC} and FF) up to 0.87 absolute points for concentrations around 100 suns (see 125x125µm size in Fig. 4) and about 0.3% at 1000 suns by using FHJ rather than a traditional design. Overall, the enhancements depend strongly on a proper optimization of the heterojunction itself (i.e. heterojunction system, band offsets, doping concentrations and thicknesses) as well as the properties of the absorber. Important challenges are those regarding the development of a heterojunction system with proper band offsets as well as the growth of abrupt heterojunctions.

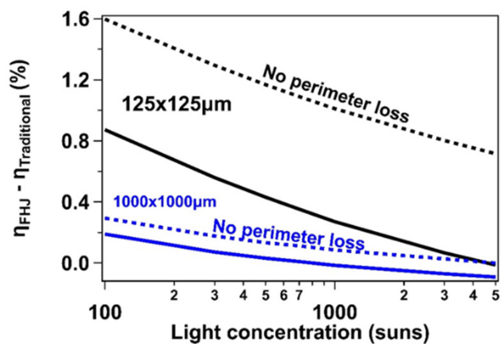

FIGURE 5. 3JSC efficiency difference between FHJ and traditional designs in the GaAs subcell as a function of light concentration for two different sizes: 125x125µm (black) and 1000x1000µm (blue). The cases neglecting perimeter recombination are depicted with dashed lines for each size.

Additionally, the distribution of surface states (i.e., density and energy levels) along the perimeter may be altered at the heterojunction itself, whose impact has not been considered here. The actual distribution of surface states at the perimeter can produce results quantitatively different than using the simplified distribution of surface states considered here. Experimental confirmation of these results is ongoing.

We have presented a front heterojunction design where the absorber is p-type. Similar voltage gains have been detected for the rear heterojunction case (n-type absorber). If n-type absorbers are used special precautions must be taken into consideration for thick absorbers in order to avoid any possible insufficient diffusion length (minority hole mobility is about 20 times lower than minority electron mobility) that reduces the overall photocurrent in this subcell. This n-type carrier collection reduction has been reported for solar cells on-substrate [8] and we also found such trend. To overcome this issue in RHJ designs, we have detected that a lower doping concentration (i.e. 10^{16} cm^{-3}) at the absorber is capable of providing similar current collection as the traditional designs. On the one hand, a reduction of doping also implies a possible reduction in V_{OC}, so the gains in terms of perimeter recombination by using a heterojunction structure could be obscured this way. On the other hand, n-type GaAs has been reported to exhibit slightly lower surface recombination velocity than p-type GaAs [9]. Moreover, hole minority carrier lifetimes in n-type layers have been reported to be higher than those of electrons in p-type layers (see [10] and references therein). Therefore, an analysis of such structures would also be of interest in terms of perimeter recombination.

SUMMARY AND CONCLUSIONS

Perimeter recombination in micro-CPV solar cells has been evaluated by means of 2D TCAD device simulations. The simulations consider empirical values of surface states density (located at midgap) previously characterized and the recombination losses have been calculated within the basis of SRH recombination. It has been shown that the impact of perimeter recombination in traditional solar cell designs is significant even at high concentrations. The efficiency loss in a GaInP/Ga(In)As/Ge 3J solar cell was calculated to be in the range of 0.7-1.6% for a concentration range of 100-5000 suns. The better performance of heterojunction designs relies on the fact that the additional barriers at the pn junction reject carriers from this region and thus the high recombination is lessened. This lower recombination at the pn junction intersection with the perimeter translates into moderate efficiency gains. For a GaInP/Ga(In)As/Ge 3J solar cell , the gains by using FHJ instead of a traditional structure are 0.3 and 0.87 absolute points at 100 and 1000 suns (where only Ga(In)As included perimeter recombination) for the lowest size considered (125x125µm). All in all, the enhancement is strongly dependent on the heterojunction design including a proper selection of band offsets as well as thicknesses and doping concentrations. Although there is no experimental confirmation of the concept, heterojunction solar cells have shown a possible pathway to mitigate perimeter recombination losses in micro-CPV solar cells.

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