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Modelling of perimeter recombination in GaAs solar cells

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Abstract

To investigate perimeter recombination current in heteroface GaAs solar cells, two models were proposed; the first concerned the analysis of recombination at the surface that intersects the space-charge layer and the second dealt with recombination at the quasi-neutral region. Recombination at the depleted layer surface has a $2kT$ character and was treated in a similar way to that of the bulk, using the model of Sah, Noyce and Shockley. The electric field at the surface due to Fermi level pinning is different from that of the bulk. We suggested a simple model to obtain an analytical form of the perimeter current at the space-charge region surface that yielded values of the product of the characteristic length by the surface recombination velocity (L_sS_0) that agreed well with experimental values. The recombination current outside the space-region is of two dimensional nature and has a kT behaviour, the model adopted consisted mainly of solving numerically the bidimensional continuity equation. An effective recombination velocity was introduced to account for bend bending caused by the charged surface states. As the ratio of perimeter to area (P/A) is increased the perimeter current acquired significant proportions, thus the expected $2kT$ current due to bulk deep levels existing in the depletion layer is two to three orders of magnitude too small to account for.

Keywords: Solar cell; Perimeter current; Surface recombination; Dark current

1. Introduction

Gallium arsenide solar cells have a number of advantages, including ideal direct band gap, good radiation resistance, low temperature coefficient and high conversion efficiency. On the other hand, GaAs surface is known to contain high densities of localized energy states or generation-recombination centres, which has a strong effect on the characteristics of many semiconductor devices. The surface recombination has a profound effect on the performance of a solar cell, at the illuminated surface reduces its photocurrent and along the cell's perimeter increases its dark current. The perimeter recombination increases considerably the dark current particularly for small area cells where the perimeter to area ratio is important. In the field of GaAs micro solar cells designed as best power sources for micro-electromechanical systems the effect of perimeter leakage current is extremely important [1]. Perimeter recombination is reported to be the cause of an efficiency loss of 3–4% (relative) even for 4 cm^2 PERL large solar cells [2].

Prior to modelling the effect of perimeter recombination current it is necessary to understand the mechanism of recombination at GaAs surface. The first model was proposed by Henry et al. [3] for AlGaAs double heterostructure p–n junction, it was found that the amplitude of the $2kT$ recombination current did not correlate with area and that this current is not primarily due to recombination occurring within the interior of the p–n junction, but instead due to recombination at the perimeter. They were able to obtain an analytical expression of the perimeter recombination current at the p–n surface based on a number of assumptions including Fermi level pinning, the density of donor and acceptor defects with energies uniformly distributed across the energy gap and the ratio of electron and hole density at the surface is constant. The perimeter recombination current was found to decrease away from the junction according to a simple diffusion equation with an average surface diffusion length L_s. The obtained L_s is of the same order of magnitude to the experimentally determined values taking the commonly assumed value of $S_0 = 4 \times 10^5$ cm/s.

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Later Dodd et al. [4] treated recombination at the p–n junction surface in a similar way to recombination in the junction depletion layer in the bulk using the Sah, Noyce and Shockley (SNS) [5] theory and found a $2kT$ recombination perimeter current with an effective width W_{eff}. This width has the same expression as the bulk effective width $W_{\mathrm{eff}}=(\pi kT/2eE)$, E is the electric field normal to the junction where the recombination rate is at its maximum, is very small fraction of the junction depletion layer width but very large compared to the value of the bulk characteristic length. The only difference being the amplitude of the electric field, it was found that electric field at the surface has the same direction but with a much reduced value. They suggested that the cause of this was the presence of charged states at the perimeter. In their model the diffusion of minority carriers along the junction surface is neglected. The calculated W_{eff} value is about one order of magnitude smaller than the surface diffusion length L_s obtained by Henry et al.[3]. Mazhari et al. [6] brought few corrections to the early model of Henry et al. [3], and concluded that the $2kT$ surface recombination current represents drift diffusion of carriers within the junction depletion region and not outside. It was found that this current was dominant at low bias, but at higher voltages it became comparable to recombination current resulting from injection outside the junction. The recombination current resulting from carriers injection into the quasi-neutral region surface has a kT behaviour and may tend towards $2kT$ type at higher biases. The carriers injection into the surface outside the p–n junction is of a two dimensional nature, Mazhari et al. [6] using a simplified analysis were able to reduce it to a one dimensional problem. They obtained an analytical expression for perimeter current outside the junction.

In the present work we analysed the perimeter recombination occurring at the surface of an heteroface GaAs solar cell. The perimeter surface recombination current can be decomposed into two components: one resulting from carriers injection where the space-charge region intersects the surface I_{PSCR} and the other due to injection from the bulk region outside the junction (quasi neutral region) I_{PQN}.

The maximum rate of carriers injection into the surface occurs close to the metallurgical junction then they drift along the surface channel created by band bending. For this current we adopted a similar approach to that of Dodd et al. [4], besides we were able to estimate the electric field at the surface of the depleted layer using a simple approach. We demonstrated that the Fermi level pinning could lead to a near uniform electric field throughout the p–n junction surface. Regarding the contribution of the quasi-neutral region to the perimeter current, a more accurate approach was adopted in the treatment of the lateral diffusion of minority carriers to the perimeter. Only the contribution of the quasi-neutral base was considered because the base counts over 75% of the whole cell thickness. However, to obtain the surface recombination current we should solve numerically the bidimonsional continuity equation to get the electron density at the surface. The experimental data used for comparison were those reported by Tobin et al. [7] using MOCVD and MBE grown GaAs thin film solar cells.

2. Model

The most significant property of surface states is that it generally introduces energy levels lying in the forbidden energy gap between the valence and the conduction bands, these levels are supposed to be uniformly distributed across the energy gap. They arise either from the effect of the boundary of the crystal or the adsorption of impurities on the surface. To obtain the recombination current at the diodes perimeter first we considered recombination at the perimeter of the p–n junction, where the active layer intersects the surface, then the contribution of the quasi-neutral base. Parameters of the simulated structure are shown in Table 1, the adopted structure was identical to that of Tobin et al. [7]. In this structure the emitter is highly doped compared to the base and extremely thin, therefore, the depleted region is almost entirely in the base and the quasi-neutral region of the emitter could be neglected.

The kinetics of surface recombination can be described by Shockley-Read-Hall statistics using a general expression of surface recombination rate expressed as:

$$R=N_{\mathrm{st}}\frac{\sigma_{\mathrm{n}}v_{\mathrm{n}}\sigma_{\mathrm{p}}v_{\mathrm{p}}(n_{\mathrm{s}}p_{\mathrm{s}}-n_{\mathrm{t}}p_{\mathrm{t}})}{\sigma_{\mathrm{n}}v_{\mathrm{n}}(n_s+n_t)+\sigma_{\mathrm{p}}v_{\mathrm{p}}(p_{\mathrm{s}}+p_{\mathrm{t}})} \quad (1)$$

where N_{st} is the density of surface states at level ε_{s}, σ_{n}, σ_{p}, v_{n} and v_{p} are the capture cross-section and thermal velocity of electron and hole, respectively, n_{t} and p_{t} are the electron and hole densities that would exist if their respective Fermi levels were at the surface state level ε_{s}, if we assume that ε_{s} is close to the middle of the band gap then, $n_{\mathrm{t}}=p_{\mathrm{t}}=n_{\mathrm{i}}$ (deep level defect are recombination centres). We also assume that: $\sigma_{\mathrm{n}}=\sigma_{\mathrm{p}}=\sigma$, $v_{\mathrm{n}}=v_{\mathrm{p}}=v$, we will take the density of surface states to be N_{s} and assume that the states are isolated deep levels having energies that are uniformly distributed across the energy gap, n_{s} and p_{s} are the densities of electrons and holes at the surface. The surface is assumed to be sufficiently far from equilibrium so that $n_{\mathrm{s}}p_{\mathrm{s}}\gg n_{\mathrm{i}}^2$ this allow Eq. (1) to be simplified to:

$$R=S_0\frac{n_{\mathrm{s}}p_{\mathrm{s}}}{n_{\mathrm{s}}+p_{\mathrm{s}}} \quad (2)$$

with $S_0=\sigma v N_{\mathrm{s}}$ represents the surface recombination velocity.

Table 1
parameters of the simulated heteroface GaAs solar cell [7]

	Cap	Window	Emitter	Base
Thickness (μm)	0.35	0.03	0.5	3
Doping (cm^{-3})	4×10^{19}	1×10^{18}	4×10^{18}	2×10^{17}