Solar Cells, 20 (1987) 229 - 236

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BACK-SURFACE FIELD DESIGN FOR n^+p GaAs CELLS

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(Received January 22, 1986; accepted August 14, 1986)

Summary

Back-surface field (BSF) design issues for n^+p GaAs solar cells are addressed. An expression for the effective back-surface recombination velocity, S_{pp^+}, valid for both homojunction and heterojunction BSFs, is derived. Computations for a typical n^+p shallow junction cell demonstrate: (1) the importance of so-called bandgap narrowing effects in p^+ GaAs and (2) that pp^+ homojunction BSFs cannot attain the low (less than about 10^3 cm s^{-1}) effective surface recombination velocities required for very high efficiency. AlGaAs/GaAs heterojunction BSFs are shown to be capable of nearly zero effective surface recombination velocity. Comparison of n^+p shallow junction cells with homojunction BSFs to similar cells with heterojunction BSFs reveals an advantage of approximately 20 mV in open-circuit voltage for the heterojunction BSF. Theoretical estimates are in approximate agreement with the increase of about 30 mV that has been observed experimentally, and suggest that heterojunction BSFs may be required in order to reach the efficiency limits of n^+p GaAs cells.

1. Introduction

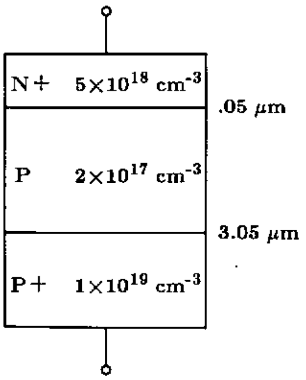
Recent studies have shown that GaAs solar cells have the potential to reach 30% conversion efficiency at high concentration [1], which corresponds to 24% at 1 sun. Improved materials and new device designs are two paths by which this potential may be reached. This paper is focused on the design of both homojunction and heterojunction back-surface fields for n^+p GaAs cells. We demonstrate that the performance of a p^+ homojunction back-surface field is substantially degraded by heavy doping effects but that heterojunction back-surface fields offer the potential for nearly zero surface recombination velocity.

Previous studies of back-surface fields (BSFs), dealing mostly with silicon cells, have shown that the open-circuit voltage increases when a built-in electric field is used at the back surface [2, 3]. The built-in field is typically produced by varying the doping near the back surface to form a high–

0379-6787/87/$3.50

low junction. In GaAs cells there is an additional degree of freedom for producing this field, namely the heterojunction, which is formed by an $Al_xGa_{1-x}As$ region at the back of the cell. GaAs cells with a heterojunction back-surface field have shown higher open-circuit voltages than similar cells with a doping back-surface field [4]. These studies showed that a 1 sun air mass (AM) 1 open-circuit voltage of 1.01 V could be attained with a heterojunction back-surface field —30 mV greater than the open-circuit voltage of previous designs which used doping back-surface fields.

To illustrate the need for a back-surface field in GaAs cells, consider the n^+p shallow-homojunction cell in Fig. 1 (the design is similar to that reported by Gale *et al.* [4]). A front surface recombination velocity of 10^6 cm s^{-1} is assumed since this is typical for GaAs. The back surface of the cell was assumed to be located 3.0 μm from the emitter–base junction and the high–low junction was modeled by an effective surface recombination velocity S_{pp^+}. Figure 2 shows modeling results (using a numerical model to be described in Section 4) of the open-circuit voltage, V_{oc}, *vs.* S_{pp^+} at 1 sun AM 1. Two cases were considered: (1) a base lifetime of 40 ns (to produce the 20 μm diffusion length expected in the base of this cell [5]), and (2) a more conservative value of 10 ns. The graph demonstrates the importance of S_{pp^+} for both cases and shows that open-circuit voltage declines sharply as S_{pp^+} is raised above 10^4 cm s^{-1}. If we are to reach the potential of this cell, we require that the effective surface recombination velocity be less



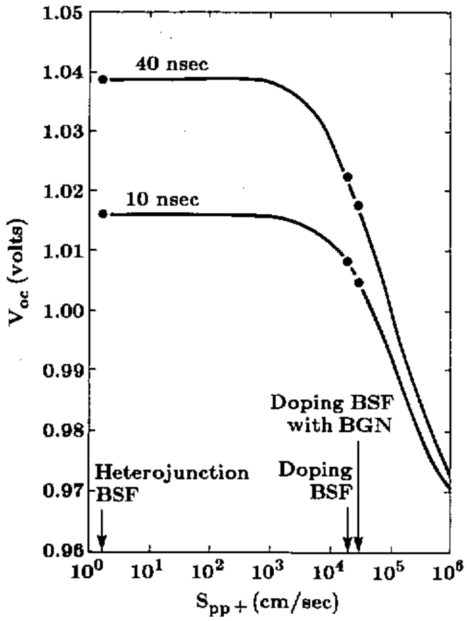


Fig. 1. Shallow-homojunction cell with back-surface field.

Fig. 2. Open-circuit voltage *vs.* effective back-surface recombination velocity for 10 and 40 ns base lifetimes.

than 10^3 cm s^{-1}. Our objective in this paper is to compare effective surface recombination velocities for homojunction and heterojunction back-surface fields to determine whether or not this criterion is met.

The paper is organized as follows. In Section 2 we derive a theoretical expression for the effective surface recombination velocity of both homojunction and heterojunction back-surface fields. In Section 3 we compare doping *vs.* heterojunction back-surface fields and assess the role of bandgap narrowing effects. Optimization of heterojunction BSFs is considered in Section 4 where a numerical simulation program is used to study cell efficiency as the placement of the heterojunction BSF is varied.

2. Theory of back-surface fields

Previous work on the theory of back-surface fields concentrated on homojunction back-surface fields and did not consider compositionally varying material [6]. Our goal is to extend the derivation of Hauser and Dunbar [6] so that S_{pp^+} can be calculated for a heterojunction back-surface field. To do this we make two assumptions: (1) the minority carrier quasi-Fermi level is constant across the back-surface field (which has been verified by numerical simulation for the heterojunctions addressed in this paper), and (2) the cell is not in high level injection (which is the case for typical GaAs cells even at high concentration). Possible interface recombination is not addressed since previous work suggests that the AlGaAs/GaAs interface is of high quality (see for example ref. 7 and references cited therein).

With the above-listed assumptions, we can readily relate the excess electron concentration on the lightly doped and heavily doped edges of the space charge region (denoted as n_p^- and n_p^+ respectively). For heterojunction BSFs, the doping ratio is of minor concern; however, for the purposes of discussion, we retain the convention that the lightly doped side of the junction comprises the base of the cell. By letting N_c^+ be the effective density of states of the conduction band in the heavily doped material (N_c^- being the same for the lightly doped material) and using assumption (1) we can write

$$\frac{n_p^+}{n_p^-} = \frac{N_c^+}{N_c^-} \exp\left\{-\frac{(E_c^+ - E_c^-)}{kT}\right\} \tag{1}$$

Since we have assumed low-level injection, $E_c^+ - E_c^- = qV_{bi} - (\chi^+ - \chi^-)$ where $\chi^+ - \chi^-$ is the difference in electron affinity of the two materials and V_{bi} is the built-in potential of the high–low junction

$$-qV_{bi} + \chi^+ - \chi^- = E_g^- - E_g^+ + kT \ln\left(\frac{N_v^+ N_a^-}{N_v^- N_a^+}\right) \tag{2}$$

From (1) and (2) we obtain

$$\frac{n_p^+}{n_p^-} = \frac{N_a^-}{N_a^+}\,\frac{N_c^+ N_v^+ \exp(-E_g^+/kT)}{N_c^- N_v^- \exp(-E_g^-/kT)} = \frac{N_a^-}{N_a^+}\left(\frac{n_i^+}{n_i^-}\right)^2 \tag{3}$$

where E_G is the bandgap, N_a is the acceptor doping, N_v the effective density of states of the valence band, and n_i is the intrinsic carrier concentration.

Figure 3 shows the structure of the back-surface field and defines its parameters; the dotted line represents the junction. The electron current at the junction is

$$J_n = q n_p{}^+ \frac{D_n{}^+}{L_n{}^+} \coth\left(\frac{W_{p^+}}{L_n{}^+}\right) \tag{4}$$

where D_n and L_n are the diffusion constant and diffusion length of electrons and W_{p^+} is the width of the p^+ material. Using (3), we find that J_n is proportional to $n_p{}^-$ so that an effective surface recombination velocity may be defined as

$$S_{pp^+} = \frac{D_n{}^+}{L_n{}^+}\frac{N_a{}^-}{N_a{}^+}\left(\frac{n_i{}^+}{n_i{}^-}\right)^2 \coth\left(\frac{W_{p^+}}{L_n{}^+}\right) \tag{5}$$

Equation (5) is the desired expression for the surface recombination velocity of a back-surface field. It is valid for both homo- and heterostructures.

If we extend this derivation to include degenerate statistics on the heavily doped side of the junction, then eqn. (5) becomes

$$S_{pp^+} = \frac{D_n{}^+}{L_n{}^+}\frac{N_a{}^-}{N_a{}^+}\left(\frac{n_i{}^+}{n_i{}^-}\right)^2 \frac{\mathcal{F}_{1/2}(\eta_v{}^+)}{e^{\eta_{v^+}}} \coth\left(\frac{W_{p^+}}{L_n{}^+}\right) \tag{6}$$

where $\mathcal{F}_{1/2}$ is the Fermi–Dirac integral of order one-half.

Equation (6) illustrates the various factors that influence the effective surface recombination velocity of a back-surface field. The ratio of intrinsic carrier concentrations in (6) was assumed to be unity in the derivation of Hauser and Dunbar [6]. For very heavy impurity doping, however, bandgap narrowing may occur [9] and, as a result, the ratio can be substantially greater than unity. Bandgap narrowing effects are seen to increase S_{pp^+}, but if a wide bandgap AlGaAs layer is used, the n_i ratio may be made very low to produce low effective surface recombination velocities. The ratio $\mathcal{F}(\eta)/\exp(\eta)$ describes the influence of Fermi–Dirac statistics on BSF performance. For non-degenerate semiconductors this ratio is unity, but when the heavily doped

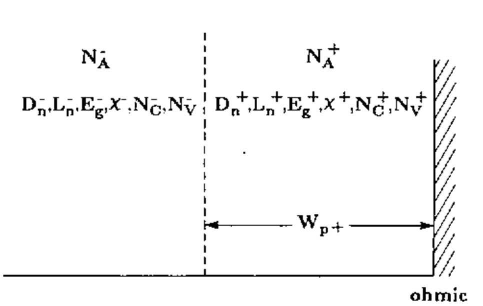


Fig. 3. A back-surface field which allows for two material compositions. The dotted line represents the junction.

region is degenerate, the ratio is less than unity. The effect of degenerate carrier statistics, therefore, is to reduce S_{pp^+} in opposition to bandgap narrowing effects. In the following section we demonstrate that predictions of cell performance based on (6) are in approximate agreement with reported results [4]. Precise quantitative agreement should not be expected at this stage because of uncertainties in the magnitude of bandgap narrowing in GaAs and in the value of the minority carrier diffusion coefficient.

3. Homojunction *vs.* heterojunction back-surface fields

Using (6), we calculate S_{pp^+} for the shallow-homojunction cell in Fig. 1 for three cases: (1) a homojunction back-surface field with neither bandgap narrowing effects nor carrier degeneracy considered, (2) a homojunction back-surface field with bandgap narrowing effects and carrier degeneracy included, and (3) a heterojunction back-surface field with an $Al_xGa_{1-x}As$ p^+ region of AlAs mole fraction $x = 0.2$. The width of the p^+ region W_{p^+} was assumed to be 0.5 μm for each case. We assumed the following relation for bandgap shrinkage in p^+ GaAs

$$\Delta E_G = 1.6 \times 10^{-8} p^{1/3} \qquad (7)$$

which was deduced from optical absorption measurements [8]. In eqn. (7) p is the hole concentration and ΔE_G is measured in electron volts. The results are

(1) $S_{pp^+} = 2.0 \times 10^4$ cm s^{-1} (homojunction BSF, no BGN)

(2) $S_{pp^+} = 3.2 \times 10^4$ cm s^{-1} (homojunction BSF, with BGN)

(3) $S_{pp^+} = 1.6$ cm s^{-1} (heterojunction BSF)

These three values were then used to compute V_{oc}. Figure 2 labels the three cases and shows that a heterojunction back-surface field achieves the desired back-surface recombination velocity ($S_{pp^+} < 10^3$ cm s^{-1}), while the homojunction back-surface field does not. The figure also demonstrates that heavy doping effects substantially degrade the open-circuit voltage through an increase in S_{pp^+}. Degraded performance is a result of the sensitivity of V_{oc} to back-surface recombination velocities greater than 10^4 cm s^{-1}.

Table 1 shows the decrease (from the case of the heterojunction back-surface field) in open-circuit voltage for both 10 ns and 40 ns base lifetimes. It is apparent that a heterojunction back-surface field has more benefit for cells with high base lifetimes. The table also shows that bandgap narrowing effects are significant (even with the offsetting effect of carrier degeneracy). Although bandgap shrinkage dominates carrier degeneracy at the doping level used here (p^+, 10^{19} cm s^{-1}), the effects of degeneracy may be more considerable in heavily doped n^+ GaAs.

We conclude that a heterojunction back-surface field may be necessary to achieve maximum performance from n^+p cells with very high base life-

TABLE 1

Open-circuit voltage difference from heterojunction back-surface field case

	Homojunction BSF (no BGN) (mV)	*Homojunction BSF (with BGN)* (mV)
10 ns	−7	−12
40 ns	−15	−22
Measured	−30	−30

times. For base lifetimes of 40 ns, the use of a heterojunction back-surface field increases V_{oc} by about 20 mV and raises the cell's efficiency by about half a percentage point. Although quoted values may be uncertain due to uncertainties in bandgap narrowing effects and minority carrier mobilities, the benefit of a heterojunction back-surface field is clearly demonstrated.

4. Optimization of heterojunction back-surface fields

Having demonstrated the effectiveness of heterojunction back-surface fields, we now consider the optimization of cell design. In this section, we use a numerical simulation program to optimize the performance of the cell in Fig. 1, with the p^+ region replaced by an $Al_xGa_{1-x}As$ region. The numerical device model solves Poisson's equation simultaneously with the hole and electron continuity equations within a one-dimensional compositionally nonuniform semiconductor. For details of the numerical solution procedures, the reader is referred to ref. 8. A graphical analysis package, which enables the user to observe the internal carrier densities, electric fields, recombination rates, and other physical parameters, aids in identifying loss mechanisms. The various physical parameters of the model are also described in ref. 8.

Since S_{pp^+} is already near zero with a 20% AlAs mole fraction, no benefits should be expected from the use of higher aluminum fractions. We consider, therefore, the optimum placement of the heterojunction. By varying the position of the heterojunction, we find the design that maximizes the efficiency. For a cell like that shown in Fig. 1 but with a heterojunction back-surface field (Al mole fraction $x = 0.2$, $W_{p^+} = 0.5$ μm), the simulation computes an efficiency of 24.4%. A base lifetime of 40 ns was assumed and the heterojunction was placed 3.0 μm beyond the emitter-base junction. Shadowing and reflective losses at the front surface were not considered. We then varied the placement of the heterojunction to find the location that would maximize efficiency. We started with the heterojunction 1 μm beyond the emitter-base junction and moved it towards the back of the cell. Figure 4 shows the open-circuit voltage, short-circuit current, and efficiency as a function of heterojunction placement ($X_{hj} - X_j$ is the distance in microns from the emitter–base junction to the heterojunction). Figure 4(a) shows

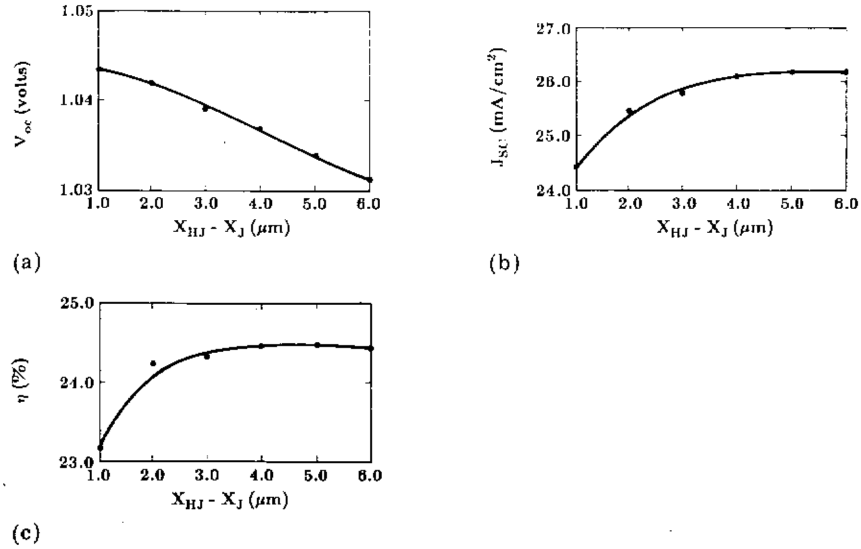


Fig. 4. Open-circuit voltage, short-circuit current, and efficiency as a function of heterojunction placement.

that V_{oc} increases as the heterojunction is moved closer to the emitter–base junction. An increase in V_{oc} is expected since the heterojunction is reducing the total recombination in the base which results in a lower dark current. The increase in V_{oc} would be favorable were it not accompanied by a reduction in short-circuit current as shown in Fig. 4(b).

The decrease in J_{sc} is caused by a loss of generated carriers in the active region of the base due to the wide-gap $Al_xGa_{1-x}As$ region. Optimum cell design involves a tradeoff: the heterojunction BSF must be placed near the pn junction in order to increase V_{oc}, but it must also be far enough away from the junction so that the light-generated current does not suffer. The modeling results show that the efficiency peaks when the heterojunction is approximately 5 μm beyond the emitter–base junction. The improvement from 24.4% to 24.7% suggests that a cell with a heterojunction back-surface field is relatively insensitive to the position of the heterojunction.

5. Conclusion

It has been shown experimentally that heterojunction back-surface fields improve open-circuit voltage in GaAs solar cells [4]. The results of this paper suggest that this improvement is due to the lower surface recombination velocity of the heterojunction BSF. A theoretical expression for S_{pp^+} was derived and was used to calculate V_{oc} for homojunction and heterojunction back-surface fields. As with measured cells, we found that cells with heterojunction back-surface fields produce higher open-circuit voltages than those with homojunction back-surface fields. Since pp^+ homojunction BSFs cannot achieve the required surface recombination velocity of less than about 10^3 cm s^{-1}, the use of heterojunction BSFs may be necessary for maximum performance.

For homojunction back-surface fields, bandgap narrowing effects in p^+ GaAs must be addressed because such effects adversely, and substantially, affect cell performance. For nn^+ BSFs, however, this conclusion may not apply because carrier degeneracy effects, which oppose bandgap narrowing, are much stronger in n^+ GaAs [10]. The results of this paper should provide useful guidelines for the design of BSFs in GaAs cells. The demonstration of the importance of heavy doping effects on GaAs cell performance underscores the need for accurate experimental characterization of transport parameters in heavily doped GaAs.

Acknowledgment

We wish to acknowledge Sandia National Laboratories for sponsoring this research under Contract 21-0931.

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