Key Factors Limiting the Open Circuit Voltage of $n^+pp^+$ Indium Phosphide Solar Cells

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Introduction

Solar cells made from gallium arsenide (GaAs), with a room temperature bandgap of $E_g = 1.43$ eV have exhibited the best measured open circuit voltage ($V_{oc}$) of 1.05 V at 1 AM0, 25°C [ref. 1]. The material InP is in many ways similar to GaAs. A simple calculation comparing InP to GaAs then shows that solar cells made from InP, with $E_g = 1.35$ at 300K, should exhibit the best measured $V_{oc}$ of $\approx 950$ mV at 1 AM0, 300K. However, to date, the best measured $V_{oc}$ for InP solar cells made by any fabrication method is 899 mV at AM1.5, 25°C [ref. 2], which would translate to 912 mV at 1 AM0, 25°C.

The $V_{oc}$ of an $n^+pp^+$ InP solar cell is governed by several factors. Of these, some factors, such as the thickness and doping of the emitter and base regions, are easily controlled and can be adjusted to desired values dictated by a good performance-optimizing model. Such factors have not been considered in this investigation. There are other factors which also govern $V_{oc}$, and their values are not so easily controlled. The primary ones among these are 1) the indirect or Hall-Shockley-Read lifetimes in the various regions of the cell, 2) the low-doping intrinsic carrier concentration $n_i$ of the InP material, 3) the heavy doping factors in the emitter and BSF regions, and 4) the front surface recombination velocity $S_F$. We have investigated the influence of these latter factors on the $V_{oc}$ of the $n^+pp^+$ InP solar cell and have used the results to produce a near-optimum design of the $n^+pp^+$ InP solar cell.

Theoretical Approach

We have developed a fairly comprehensive, one dimensional, closed form solution, computerized model of the shallow homojunction InP space solar cell. This model assumes a cell with three homogeneously doped regions, an $n^+$ emitter, a p-type base and a $p^+$ BSF region. Details of the model have been presented elsewhere [ref. 3]. In our earlier near-optimum design of the $n^+pp^+$ shallow-homojunction InP solar cell using this model [refs. 3,4] no accounting was made of the heavy-doping effects in the
heavily doped emitter and BSF regions. As of this day, to the best of our knowledge, measured heavy doping factors or equivalent bandgap narrowing values as functions of doping for n-type and p-type InP have not been published in the literature, as they have been for GaAs [ref. 5]. This lack of information makes it difficult to take into account heavy doping effects in InP cell modeling. Even so, it is now realized that it is very important to take these into account in order for the modeling to be of much value. Hence, some way must be found to reasonably estimate the heavy doping effects. A prior attempt [ref. 6] at this has been to represent the heavy doping effects, including Fermi-Dirac statistics, by an equivalent effective bandgap narrowing \( \Delta E_g \) in each heavily doped cell region (emitter, BSF) and to estimate the amount of \( \Delta E_g \) in these regions by matching the calculated and measured internal spectral response in the short and long wavelength region of the incident light spectrum. We feel that a less roundabout and more accurate method is to lump all the heavy doping effects into an effective intrinsic carrier concentration \( n_{ie} \) and to thereby define a heavy doping factor \( HD \) in each heavily doped region as, for example in the emitter, by

\[
HD_E = \frac{n_{ieE}}{n_{i0}}
\]

where \( n_{ieE} \) is the the effective value of \( n_i \) in the emitter and \( n_{i0} \) is the low-doping value of \( n_i \) in InP. A similar heavy doping factor \( HD_{BSF} \) is defined for the BSF region. The values of \( HD_E \) and \( HD_{BSF} \) are then estimated by matching the calculated and measured curves of not only the internal spectral response but also the illuminated I-V and log \( I_{sc} - V_{oc} \).

The above approach still leaves one major problem. It allows the estimation of \( HD_E \) and \( HD_{BSF} \), each for only one value of doping, that of the experimental cell whose measured curves were matched. However, what is needed for general modeling purposes is \( HD_E \) and \( HD_{BSF} \) as functions of their respective dopings: in other words, curves of \( HD_E^2 \) and \( HD_{BSF}^2 \) vs. their respective dopings, as are available for GaAs at 300K [ref. 5], as shown in figure 1. In the absence of available measured data on InP, we made the reasonable assumption, as a first approximation, that for both n-type and p-type InP, the nature of the \( HD^2 \) versus doping curve is similar to that of GaAs. With this assumption, the curve for InP can be obtained from that of GaAs if one point on the curve could be determined. As stated earlier, this can indeed be done by matching the calculated and measured curves of illuminated I-V, log \( I_{sc} - V_{oc} \) and internal spectral response.

Our computer model was designed from the start to correctly take into account heavy doping effects in all three regions of the cell, if necessary, by means of appropriate boundary conditions involving the heavy doping factors in each region. The boundary condition at the emitter-base junction is that of the generalized 'law of the junction', valid at all injection levels, while that at the base-BSF interface is that of the low-injection effective interface recombination velocity \( S_{pp+} \) given by
\[ S_{pp+} = \frac{N_{a,\text{base}}}{N_{a,\text{BSF}}} \cdot \left( \frac{\text{HD}_{\text{BSF}}}{\text{HD}_{\text{base}}} \right)^2 \cdot \frac{D_{n,\text{BSF}}}{L_{n,\text{BSF}}} \cdot \frac{1}{\tanh\left( \frac{W_{\text{BSF}}}{L_{n,\text{BSF}}} \right)} \]  

where \( N_a \) is the doping, HD is the heavy doping factor, as defined earlier (e.g. \( \text{HD}_{\text{BSF}} = \frac{n_{i_e,\text{BSF}}}{n_{i_0}} \)), and \( D, L, w \) are the minority carrier diffusivity, diffusion length and width of the region, respectively. For a base doping of less than \( 10^{17} \text{ cm}^{-3} \), \( \text{HD}_{\text{base}} = 1 \), and it is seen in equation [1] that the net effect of heavy doping in the BSF region is to increase the effective base-BSF interface recombination velocity \( S_{pp+} \) by a factor of \( (\text{HD}_{\text{BSF}})^2 \). As we shall see from the calculated results in the following section, the overall effect of heavy doping in the BSF region is to increase the minority carrier recombination in the base at the base-BSF interface, thereby increasing the dark saturation current in the base and reducing the open circuit voltage of the cell.

As to the task at hand, that of finding \( \text{HD}_E \) and \( \text{HD}_{\text{BSF}} \) at one doping, we chose to match theoretical and measured curves of illuminated I-V, \( \log I_{sc} - V_{oc} \) and internal spectral response for a 17.9\% efficient \( n^+p^+ \) solar cell labeled Spire 6 [ref. 7], made by the Spire Corporation, for which such measured curves were available. All measurements on this cell were made at the NASA Lewis Research Center in Cleveland, Ohio, and were made available to us by courtesy of Mr. Russell E. Hart.

We obtained excellent matches between the calculated and measured curves of Spire 6 for specific values of \( \text{HD}_E = 1.4 \) for the n-type emitter doping of \( 1 \times 10^{18} \text{ cm}^{-3} \) and \( \text{HD}_{\text{BSF}} = 4.87 \) for the p-type BSF doping of \( 5 \times 10^{18} \text{ cm}^{-3} \). By noting that each of the two \( \text{HD}^2 \) versus doping curves had to pass through its corresponding specific point indicated above and also that each HD has to become unity at dopings of \( 10^{17} \text{ cm}^{-3} \) and below, we were able to express the general variations of \( \text{IID}_E \) and \( \text{HD}_{\text{BSF}} \) versus their respective dopings in equation form as:

\[ \text{HD}_E^{2, n-InP} = 1.92 \cdot [\text{HD}_{n-GaAs}^{2} - 1] + 1 \]  

except when \( \text{HD}_{n-GaAs} \) drops below unity, in which case, for simplicity, we used the approximation

\[ \text{HD}_E^{2, n-InP} = \text{IID}_{n-GaAs} \]  

Also,

\[ \text{HD}_{\text{BSF}, p-InP}^{2} = 6.1 \cdot [\text{HD}_{p-GaAs}^{2} - 1] + 1 \]  

The +1 on the right-hand side of equations [2] and [4] ensures that HD in InP becomes unity when IID in GaAs becomes unity, at the lower dopings.
The above equations were incorporated into the computer model so that, for any
doping concentration in the emitter and BSF, the corresponding heavy doping factor
could easily be calculated. This capability to calculate the heavy doping factors
$H_{DE}$, $H_{BSF}$ as functions of doping was the only new addition that our computer
model required. The computer model was already capable of calculating all other
geometrical and material parameters needed to simulate the solar cell, as in the past
[refs. 3,4].

**Calculated Results and Discussion**

In order to see how the $V_{oc}$ varied with each of the individual parameters expected
to affect it, we first chose a somewhat modified version of the Spire 6 cell design to
serve as a baseline cell. The primary modifications were: a) a reduced grid shadowing
from 4.8% of Spire 6 to 4.0% of the baseline design, b) a thinner emitter, from 400 Å
of Spire 6 to 200 Å of the baseline cell, c) a heavier emitter doping, $5 \times 10^{18}$ cm$^{-3}$ from
$1 \times 10^{18}$ cm$^{-3}$ of Spire 6, d) a thinner base, 2 µm instead of 3 µm, and e) a lighter BSF
doping of $2 \times 10^{18}$ cm$^{-3}$ for the baseline cell instead of $5 \times 10^{18}$ cm$^{-3}$ for Spire 6. These
modifications reflected current practice in cell design and resulted in an improved cell
efficiency of 19.23% from the 17.9% of Spire 6. The baseline design also resulted in
a somewhat larger $V_{oc}$ of 873 mV from the 868 mV of Spire 6. Table 1 shows all the
geometrical and material parameters of the Spire 6 and the baseline solar cells. Note
that the numbers in the baseline cell column are for 300 K as opposed to 298 K for
Spire 6. This results in a significantly longer radiative lifetime in the base for the
baseline cell, since the base radiative lifetime is extremely sensitive to temperature.

In our model, the indirect or Hall Shockley-Read (HSR) lifetime in any cell region
is assumed to be inversely proportional to the doping in that region. This assumption
is tantamount to the assumption that indirect recombination in InP occurs via a single
dominant recombination level whose density is proportional to doping density. Thus,
in any cell region,

$$\tau_{HSR} = \frac{\Gamma_{HSR}}{N}$$

where $\Gamma_{HSR}$ is the constant of proportionality between $\tau_{HSR}$ and the reciprocal of the
doping concentration $N$. Only two different values of $\Gamma_{HSR}$ are needed, one for n-type
and one for p-type InP. These were obtained from our matching the calculated and
measured curves for Spire 6, as were the values of $H_{DE}$, $H_{BSF}$ and $S_F$. For the
baseline value of $n_i$, we chose the prevalent value of $n_i(300 \text{ K}) = 1.2 \times 10^7\text{cm}^{-3}$, which
may be on the high side according to current thinking [ref. 2].

Thus, knowing the baseline values of $H_{DE}$, $H_{BSF}$, $\Gamma_{HSR,p}$, $\Gamma_{HSR,n}$, $S_F$ and $n_i$,
all except $n_i$ being derived from the Spire 6 match, we could calculate the complete
performance of the baseline cell at 300 K. The second column of Table 1 gives the
geometrical, material and performance parameters of the baseline cell. Note that the
baseline cell has a thinner, more heavily doped emitter, a thinner base and a less
heavily doped BSF layer than the Spire 6 cell.

Next, we made a large number of parametric variation runs of our computer
model simulating the baseline cell, varying one parameter at a time from among
HD_{E}, HD_{BSF}, \Gamma_{HSR,p} and \Gamma_{HSR,n} (in the form of relative HSR or indirect lifetime
\tau_{i}/\tau_{0} in the n-type emitter and p-type base and BSF regions), the low-doping intrinsic
carrier concentration \textit{n}_{i0} and finally the front surface recombination velocity \textit{S}_{F}. It
should be noted that in our model, \textit{S}_{F} is the area-weighted average effective surface
recombination velocity over both the part of the front surface which is not in actual
physical contact with the front grid metallization and the part which is in such contact
[ref. 3].

The results of the parameter variation runs are shown in Figs. 2, 3, 4 and 5, which
show, respectively the variation of \textit{V}_{oc} versus 1) the HSR relative lifetime \tau_{i}/\tau_{0} in
the emitter, base and BSF, 2) the low-doping intrinsic carrier concentration \textit{n}_{i0}, 3) the
BSF heavy doping factor HD_{BSF} and 4) the effective front surface recombination
velocity \textit{S}_{F}.

We now discuss each of these figures in turn. In Fig. 2, we see that if, by using
better material and device processing, we can make the indirect or HSR lifetimes in
all regions of the cell to be ten times longer than their current-technology values in
Spire 6, then \textit{V}_{oc} can be improved by slightly over 10 mV, which, while not being a
very large gain in \textit{V}_{oc} still is a significant gain. Fig. 2 also shows that \textit{V}_{oc} begins
to level off as the HSR lifetime is made even longer. This is because when the IISR
lifetime becomes very long, the overall lifetime is controlled by the radiative lifetime
which, for a given doping and temperature, is an inherent property of the material InP
and is independent of the quality of the starting material or of the device processing
parameters. Thus, it appears from Fig. 2 that by making the IISR lifetime in each
region indefinitely long by using the highest quality starting material and using the
cleanest possible device processing, the most to be gained in \textit{V}_{oc} is about 15 mV or
so.

Next considering Fig. 3, we see the variation in \textit{V}_{oc} as the 300 K, low-doping
intrinsic carrier concentration \textit{n}_{i0} decreases from $1.2 \times 10^{7}$ cm$^{-3}$ to a hypothetical value
of $5 \times 10^{6}$ cm$^{-3}$, to show the nature and extent of variation of \textit{V}_{oc} with \textit{n}_{i0}. If \textit{n}_{i0}
were somehow halved from its presently used value of $1.2 \times 10^{7}$ cm$^{-3}$ to $6 \times 10^{6}$ cm$^{-3}$,
then Fig. 3 shows that \textit{V}_{oc} would increase by \textasciitilde 25 mV. The values of \textit{n}_{i0} and \textit{V}_{oc}
indicated by the two arrows in Fig. 3 are as follows. The one corresponding to \textit{n}_{i0} = $1.2 \times 10^{7}$ cm$^{-3}$ represents the prevalent value of \textit{n}_{i} based on both the density of
states functions \textit{N}_{c}, \textit{N}_{v}, and the bandgap \textit{E}_{g} corresponding to InP. The other point
is the value of \textit{n}_{i0} that would be obtained by using the density of states values of
GaAs but the bandgap of InP—in other words, the value of \textit{n}_{i} that InP would have if
its \textit{N}_{c}\textit{N}_{v} product were the same as that for GaAs. The difference in \textit{V}_{oc} between the
two points is about 18 mV, and it indicates that, in comparison with GaAs, InP has an 18 mV $V_{oc}$ disadvantage merely because its $N_cN_v$ product is too large compared to that of GaAs.

There is some uncertainty about the value of $n_i$ in InP. Yahia and Coutts have done an extensive investigation of this problem, and believe that $n_i$ in InP at 300 K should be around 8 to $9 \times 10^6$ cm$^{-3}$ [ref. 8]. If this is true, then the expected maximum $V_{oc}$ of InP would be higher by about 10 mV.

In Fig. 4, we show the calculated variation of $V_{oc}$ for the baseline InP cell with the BSF heavy doping factor $HD_{BSF} = n_{i,BSF}/n_{i0}$ The point corresponding to the heavy doping factor calculated using equation (4) is indicated by the arrow. It is seen that the lower the heavy doping factor, the higher the $V_{oc}$.

If the qualitative behavior of heavy doping factor versus doping in p-type and n-type InP is indeed similar to that for GaAs, as we have assumed, then it would appear at first sight that it would be advantageous to have an n-based cell with n$^+$ BSF. However, only detailed calculations would show whether that would be the case or not, for the following reasons: First, in a p$^+$nn$^+$ InP cell, the p$^+$ emitter would have to be relatively thick in order for the low hole mobility in it to not cause an excessively large emitter sheet resistance component of series resistance. With a thicker emitter, a significant portion of the total cell photocurrent would now come from the emitter, as would the dark saturation current. In that case, any gain due to a low (lower than one) $HD_{BSF}$ could be more than counteracted by the high $HDE$ in the p$^+$ emitter. We are in the process of doing such detailed calculations for the p$^+$nn$^+$ cell.

Finally, Fig. 5 shows the variation of $V_{oc}$ versus the effective front surface recombination velocity $S_F$. Here, it is seen that over its entire range of values from $S_F \ll D_{pE}/L_{pE}$, the diffusion velocity of minority carriers in the emitter, to $S_F \gg D_{pE}/L_{pE}$, $V_{oc}$ degrades by only about 3 mV. The reason why $V_{oc}$ is relatively insensitive to $S_F$ is that in any relatively well-designed InP solar cell, as in the baseline cell, the $V_{oc}$ is controlled primarily by the dark saturation current $J_0$ in the base, which is several times (~10 or more) larger than the $J_0$ from the emitter. Thus, the $S_F$ variation, which may affect $J_{0,emitter}$ by a factor of a few, does not affect the overall $J_0$, and therefore $V_{oc}$, significantly. It is to be noted, however, that $S_F$ has a significant effect on the short circuit current $J_{sc}$ and on the efficiency; therefore, it is most desirable to reduce $S_F$ to a very low value ($S_F \ll D_{pE}/L_{pE}$) by means of front surface passivation or the use of an appropriate higher bandgap window layer.

Near–Optimum Cell Design

Having investigated the individual variation of $V_{oc}$ with each of the parameters $\Gamma_{HSR,n}$ and $\Gamma_{HSR,p}$, $n_{i0}$, $HD_{BSF}$ and $S_F$ and some other variations ($V_{oc}$ vs. base thickness, base doping, emitter thickness, emitter doping and $HDE$) not shown here,
we next proceeded to design a near-optimum InP n+pp+ solar cell for 1 AM0, 300 K operation with a view to maximizing its efficiency (not $V_{oc}$).

Our approach to the near-optimum design was to ignore limitations imposed by current technology on such parameters as $\Gamma_{HSR,p}$, $\Gamma_{HSR,n}$ and $S_F$. With improved technology, in the near future, $\Gamma_{HSR,p}$ and $\Gamma_{HSR,n}$ could realistically be about ten times the values obtained in the Spire 6 match, while $S_F$ could very likely be $\sim 10^4$ cm/s or less. Thus we have used values for $\Gamma_{HSR,p}$ and $\Gamma_{HSR,n}$ that are ten times the values obtained in the Spire 6 match and used in the baseline cell. This is tantamount to assuming that in the near future, material and processing quality is likely to improve to the extent that at moderate and high dopings, the overall lifetime in InP will be limited by the radiative lifetime. We have also used $S_F = 10^4$ cm/s, again assuming that the significant amount of research on surface passivation and searching for an appropriate window material will result, in the near future, in an effective front SRV of $S_F = 10^4$ cm/s or less. As to the technology-independent parameters, such as $H_{DE}$, $H_{BSF}$ and $n_{i0}$ we have used the same values as used earlier, namely, $H_{DE}$ and $H_{BSF}$ based on equations [2], [3] and [4], and $n_{i0} = 1.2 \times 10^7$ cm$^{-3}$ at 300 K.

Table 2 gives the complete geometrical, material and performance parameters of the near optimum cell. Note that this optimized cell has a realistic expected efficiency of 22.61% and a $V_{oc}$ of 901.6 mV. According to our model, higher $V_{oc}$ values are obtainable at some sacrifice in $J_{sc}$ and efficiency.

Because of heavy doping effects, our near-optimum design has relatively lighter dopings in the BSF and base. It may seem at first sight that with a BSF doping only ten times the base doping, the base/BSF interface would not be an effective reflector of minority carriers. However, higher BSF dopings result in the base/BSF interface being an even worse reflector of minority carriers because of heavy doping effects in the BSF.

**Concluding Remarks**

1. The primary factor limiting the $V_{oc}$ in an n+pp+ solar cell is the heavy-doping factor in the p+ BSF.

2. In a well-designed n+pp+ InP solar cell, the effective front SRV $S_F$ has a significant effect on $I_{sc}$ and $\eta$ but a relatively minor effect on $V_{oc}$.

3. If the effective front SRV is reduced to $\sim 10^4$ cm/s and the HSR lifetime coefficients $\Gamma_{HSR,p}$, $\Gamma_{HSR,n}$ are increased by a factor of 10, then it is theoretically possible to obtain a $V_{oc}$ of 902 mV and $\eta = 22.6\%$ at 1 AM0, 300 K, for an n+pp+ InP solar cell. Even higher $V_{oc}$ values should be obtainable at a sacrifice in $I_{sc}$ and $\eta$. 

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References


Table 1

<table>
<thead>
<tr>
<th></th>
<th>Spire 6 Match (298 K)</th>
<th>Baseline Cell (300 K)</th>
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<tbody>
<tr>
<td><strong>Grid Shadow</strong></td>
<td>4.8%</td>
<td>4.0%</td>
</tr>
<tr>
<td>*Front SRV (cm/sec)</td>
<td>$3.3 \times 10^6$</td>
<td>$3.3 \times 10^5$</td>
</tr>
<tr>
<td>$w_E, \text{Å}$</td>
<td>400</td>
<td>200</td>
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<tr>
<td>$N_{D,\text{emitter}}, \text{cm}^{-3}$</td>
<td>$1.0 \times 10^{18}$</td>
<td>$5.0 \times 10^{18}$</td>
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<tr>
<td>$\tau_{\text{HSR}}, \text{ns}$</td>
<td>1.4</td>
<td>0.632</td>
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<td>$\tau_{\text{Rad}}, \text{ns}$</td>
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<tr>
<td>$\tau_p, \text{ns}$</td>
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<td>0.161</td>
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<td>$L_{pE}, \mu\text{m}$</td>
<td>0.355</td>
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<td>150</td>
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<td>$\tau_{\text{Rad}}, \text{ns}$</td>
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<td>$L_{n,\text{BSF}}, \mu\text{m}$</td>
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<td>0.477</td>
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<td>$V_{oc}, \text{mV}$</td>
<td>868</td>
<td>873</td>
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<tr>
<td>$\eta$</td>
<td>17.9%</td>
<td>19.23%</td>
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* Value obtained from Spire 6 match
Table 2

**Best Theoretical Cell Design**

<table>
<thead>
<tr>
<th>Grid Shadow</th>
<th>4.0%</th>
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<tr>
<td>Front SRV</td>
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<th>$w_E$</th>
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<td>$N_{D,\text{emitter}}$</td>
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<tr>
<td>$H_{D,E} = \frac{n_E}{n_0}$</td>
<td>0.837</td>
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<tr>
<td>* $\tau_{\text{HSR}}$</td>
<td>6.667 ns</td>
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<tr>
<td>$\tau_{\text{rad}}$</td>
<td>0.478 ns</td>
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<tr>
<td>$\tau_p$</td>
<td>0.431 ns</td>
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<tr>
<td>$L_pE$</td>
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<th>$w_{\text{base}}$</th>
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<td>171 ns</td>
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<td>$L_n,\text{base}$</td>
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<table>
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<th>$w_{\text{BSF}}$</th>
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<td>$7.5 \times 10^{16}$ cm$^{-3}$</td>
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<tr>
<td>$H_{D,\text{BSF}}$</td>
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<td>$\tau_n$</td>
<td>18.24 ns</td>
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<tr>
<td>$L_n,\text{BSF}$</td>
<td>12.57 μm</td>
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$J_s = 39.94$ mA/cm$^2$
$V_{oc} = 901.6$ mV
$J_{max} = 38.59$ mA/cm$^2$
$V_{max} = 804.4$ mV
$FF = 86.21$ %
$\eta = 22.61$ %
Effective intrinsic carrier concentration in n- and p-type GaAs.
Figure taken from M.E. Klausmeier-Brown et al., Proc. of the 20th PVSC [5].

$V_\infty$ vs. Relative HSR Lifetime

$V_\infty$ vs. Relative HSR Lifetime ($\tau_1/\tau_0$)
Figure 3

$V_{oc}$ vs. $n_{i0}$

Density of States of GaAs

Density of States of InP

Intrinsic Carrier Concentration $n_{i3}$

Figure 4

$V_{oc}$ vs. BSF Heavy Doping Factor

BSF Heavy Doping Factor for InP as determined from Spire 6

BSF Heavy Doping Factor ($n_{i0}/n$)
Figure 5

$V_{oc}$ vs. Effective Front SRV

Surface Recomb. Velocity $S_p$ (cm/sec)

Front SRV from Spire 6 match