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M. E. Klausmeier-Brown
Purdue University

Mark S. Lundstrom
Purdue University, lundstro@purdue.edu

Michael R. Melloch
Purdue University, melloch@purdue.edu

S. P. Tobin
Spire Corporation

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M. E. Klausmeier-Brown, M. S. Lundstrom, and M. R. MellochS. P. Tobin

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M. E. Klausmeier-Brown, M. S. Lundstrom, and M. R. Melloch
School of Electrical Engineering, Purdue University, West Lafayette, Indiana 47907

S. P. Tobin
Spire Corporation, Patriots Park, Bedford, Massachusetts 01730

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Measurements of electron injection currents in p^+-n diodes are presented for a range of p-type dopant concentrations. A successive etch technique was used to characterize the electron injection current in terms of the product $(n_o D_n)$. Measurements are presented for Zn-doped GaAs solar cells with p-layer hole concentrations in the range $6.3\times 10^{17} - 1.3\times 10^{19}$ cm^{-3}. The results demonstrate that so-called band-gap narrowing effects substantially increase the injected electron current in heavily doped p-type GaAs. These heavy doping effects must be accounted for in the modeling and design of GaAs solar cells and heterostructure bipolar transistors.

The efficiency of silicon solar cells and the gain of silicon bipolar transistors are profoundly influenced by changes in the energy-band structure associated with heavy impurity doping.[1] The measurements of Slotboom and DeGraaff showed that heavy doping effects greatly enhance electron injection currents in silicon p^+-n junctions,[2] but corresponding measurements for p^+-n GaAs have not yet been reported. In this letter we characterize electron injection currents in p^+-GaAs doped from 6.3×10^{17} to 1.3×10^{19} cm^{-3}. The results show heavy doping effects in p^+-GaAs that are analogous to those observed in p^+-Si and comparable in magnitude. This work demonstrates that heavy doping effects must be treated in order to accurately model GaAs bipolar devices.

The current density versus applied voltage for a forward-biased p-n diode can be represented by

$$J = J_{01}[\exp(qV_A/k_B T) - 1] + J_{02}[\exp(qV_A/2k_B T) - 1], \tag{1}$$

where J_{01} and J_{02} are the saturation current densities associated with carrier recombination in the quasi-neutral and space-charge regions, respectively. All diodes studied in this work were found to be well described by (1). For a diode with a thin, unpassivated p-layer, the saturation current component due to electron injection in the quasi-neutral p-region can be written

$$J_{01e} = \frac{q(n_o D_n)}{W_p} \frac{S}{S + (D_n/W_p)}, \tag{2}$$

where n_o is the equilibrium minority-carrier concentration, D_n is the minority-carrier electron diffusion coefficient, S is the recombination velocity at the surface of the p-type layer, and W_p is the width of the quasi-neutral p-type layer. An effective intrinsic carrier concentration, n_{ie}^2, is often introduced to relate n_o to the ionized dopant density by

$$n_o \equiv n_{ie}^2/p_o, \tag{3}$$

where p_o is the hole concentration in the p-layer. Measurements have shown that n_{ie} in heavily doped silicon substantially exceeds n_{io}, the intrinsic carrier concentration in lightly doped silicon. For device modeling purposes, this effect is often described by relating n_{ie} to n_{io} with a nonphysical, apparent band-gap shrinkage.[1]

In this letter we make use of a recently described successive etch technique to quantify the electron saturation current density, J_{01e}, as a function of the p-layer hole concentration, p_o.[3] The results are reported in terms of the parameter most directly obtained from the measurement, the $(n_o D_n)$ product. Translation of these results into the form of apparent band-gap shrinkage data for use in numerical simulations is briefly discussed.

A cross section of the GaAs solar cells used for these experiments is displayed in Fig. 1. All cells were grown by metalorganic chemical vapor deposition (MOCVD) in a commercial, five-wafer reactor (Spire Corporation model MO-450). Four percent of each cell's top surface was covered by a metal grid pattern which formed an ohmic contact to the p^+-GaAs cap layer. The layer of interest in this study is the Zn-doped, p-type GaAs layer which lies just below the passivating p-$(Al_{0.9}Ga_{0.1})As$ heteroface layer. Five cells, nominally identical except for the p-layer doping density, were studied. Details of the film growth and cell processing have been described by Tobin *et al.*[4]

The cells were first characterized by fitting the mea-

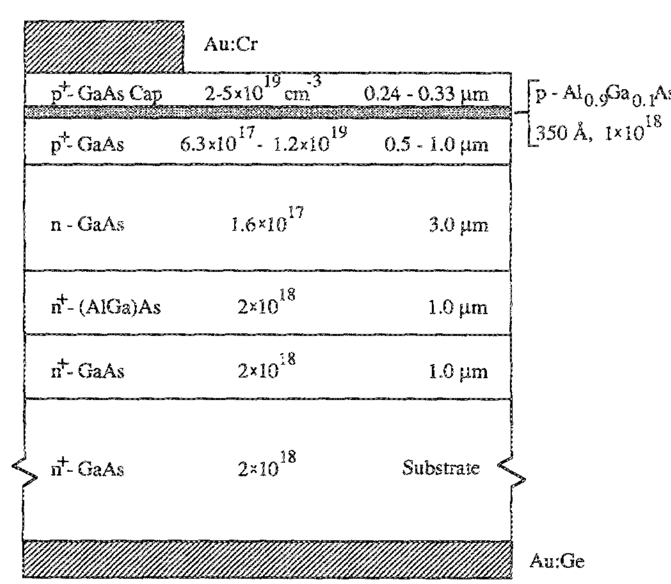

FIG. 1. Cross section of the solar cells used in this study (before etching).

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sured dark current-voltage (I-V) characteristics to (1). The resulting J_{01} values were independent of the emitter doping density, which suggests that the initial $n = 1$ dark current component was dominated by hole injection into the quasi-neutral n-region. After removing the p-GaAs cap and the p-$(Al_{0.9}Ga_{0.1})As$ heteroface layers by chemical etching, J_{01} was observed to increase. The magnitude of the increase, from a factor of 3 for cells with the most heavily doped emitters to a factor of 22 for cells with the most lightly doped emitters, demonstrates that the $n = 1$ dark current of unpassivated cells was controlled by electron injection into the quasi-neutral p-layer. A successive etch technique was then used to characterize the electron injection current.[3] In brief, the technique consists of successive 20 s etches of the p-layer in a solution of $(2H_2SO_4{:}1H_2O_2{:}96H_2O)$ at 25 °C, followed by measurement of the forward-biased, dark I-V characteristic and extraction of J_{01}. During the etching process, J_{01} was observed to increase as the p-layer was thinned. The electron injection component, J_{01e}, was deduced as a function of emitter thickness, W_p, by subtracting J_{01} of the passivated cell (which was thought to be dominated by hole injection into the n-region) from the value of J_{01} measured after each etch. Because J_{01} was so low in the passivated cells, this subtraction had a minor influence on the value of J_{01e} deduced.

The current associated with electron injection into the quasi-neutral p-layer is described by (2) if the minority-carrier diffusion length exceeds the width of the p-region, W_p (0.5 μm in all but sample No. 3, for which $W_p = 1.0\,\mu$m). From a detailed analysis of the internal quantum efficiency and dark current of similar cells grown in the same reactor with an emitter doping of 2×10^{18} cm^{-3}, an electron diffusion length of $\approx$3–5 μm was deduced.[4] Because all cells used for this study had comparable internal quantum efficiencies and dark currents, we conclude that (2) should accurately describe J_{01e}. Equation (2) may be rearranged to show how the electron injection current varies with etch time t during the experiment:

$$J_{01e}^{-1} = \left(\frac{W_{p0}}{q(n_oD_n)} + \frac{1}{qn_oS}\right) - \left(\frac{R}{q(n_oD_n)}\right)t, \qquad (4)$$

where R is the etch rate. According to (4), a plot of J_{01e}^{-1} versus etch time should be linear; the experimental results confirm this prediction. From the slope of the line, $R/q(n_oD_n)$, the product (n_oD_n) was deduced. The result is independent of the surface recombination velocity, S.

Because the objective of this study was to determine the product, (n_oD_n), as a function of doping density, it was important to thoroughly characterize the doping of the p-type layer. First, carrier concentration (from Hall effect measurements, assuming a Hall factor of unity) was plotted versus resistivity for a series of p-type GaAs films grown in the same MOCVD reactor. For each solar cell used in the present study, the resistivity of the p-layer was measured using an adjacent test resistor. The hole concentration p_o was then deduced for each cell from the measured resistivity, using the previously constructed plot. The results are displayed in Table I. Next, Schottky barrier capacitors were formed by depositing aluminum on the p-layer of each cell, and the quantity $(N_A - N_D)$ was deduced from reverse-biased capacitance-voltage (C-V) profiling measurements. The results of the C-V measurements are displayed in Table I. Finally, secondary ion mass spectroscopy (SIMS) confirmed that the p-layer of each sample was uniformly doped. SIMS analysis measured the Zn concentration, N_{Zn}. (However, the absolute accuracy of SIMS analysis was deemed to be only a factor of 2.)

Results of the measurements for cells with five different p-layer dopings are summarized in Table I. The quantity (n_oD_n) was obtained from the slope of J_{01e} versus etch time according to (4). The temperature during the experiment is also listed in Table I. Following del Alamo, we have scaled all (n_oD_n) products to 300 K by using the known temperature dependence of n_{io}.[5] The maximum error introduced by this temperature scaling should not exceed 4%.

Figure 2 is a plot of (n_oD_n) at 300 K versus dopant density. To highlight the effects of heavy impurity doping, we also indicate the (n_oD_n) product computed without considering heavy doping effects (except for degeneracy of the hole gas). The dashed line was evaluated from

$$n_o = \frac{n_{io}^2}{p_o}\,\frac{\mathscr{F}_{1/2}(\eta_c)}{e^{\eta_c}}, \qquad (5)$$

using the minority-carrier electron mobilities predicted by Walukiewicz *et al.*[6] for uncompensated p-GaAs, with $n_{io} = 2.25\times10^{6}$ cm^{-3}.[5] Since measured minority-carrier electron mobilities in MOCVD-grown GaAs[7] are less than those predicted by Walukiewicz *et al.* for uncompensated material, the dashed line in Fig. 2 should be regarded as an upper limit for (n_oD_n) in the absence of heavy doping effects. Comparison of the dashed line with the experimental results shows that a substantial increase in (n_oD_n) can be associated with heavy doping effects. The increase is a factor of 10 at $p_o \approx 10^{19}$ cm^{-3}, and underscores the importance of correctly modeling these phenomena in order to accurately

TABLE I. Summary of the measurements. The product (n_oD_n) is listed both at the measurement temperature T and at 300 K. C-V measurements could not be obtained for the highest doped sample, No. 5.

Sample	T (°C)	Resistivity (Ω cm)	p_0 (cm^{-3}) (Hall effect)	$N_A - N_D$ (cm^{-3}) (C-V)	N_{Zn} (cm^{-3}) (SIMS)	(n_oD_n) at T (10^{-4} cm^{-1} s^{-1})	(n_oD_n) at 300 K (10^{-4}cm^{-1} s^{-1})
1	24.0	0.062	6.3×10^{17}	6×10^{17}	1.1×10^{18}	5.5	10
2	25.0	0.040	1.0×10^{18}	1×10^{18}	1.7×10^{18}	4.5	6.7
3	22.4	0.018	3.0×10^{18}	3×10^{18}	3.0×10^{18}	1.4	3.5
4	23.4	0.014	4.6×10^{18}	5×10^{18}	5.8×10^{18}	1.1	2.3
5	23.3	0.0079	1.3×10^{19}	···	1.2×10^{19}	0.70	1.5

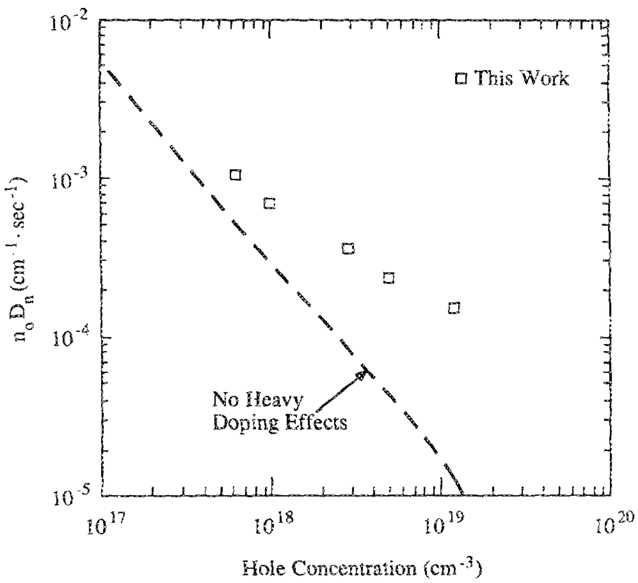

FIG. 2. Measured (n_oD_n) product plotted vs hole concentration p_o at $T=300$ K. The values of p_o used were those obtained from Hall-effect measurements. The dashed curve was obtained using the theoretical minority electron diffusion coefficient from Ref. 6 with Eq. (5), assuming no compensation.

predict the behavior of GaAs devices that contain heavily doped regions. Note that the behavior of the product (n_oD_n) versus hole concentration is quite similar to that observed in heavily doped silicon (see Fig. 7 of Ref. 1).

A nonphysical, apparent band-gap shrinkage parameter is often introduced for device modeling purposes.[1] The saturation current density for electrons injected across a GaAs p-n junction is modeled by the expression

$$J_{01e}^{\rm mod}=\frac{qn_{io}^2D_o}{p_oW_p}\,\frac{S}{S+(D_n/W_p)}\exp\left(\frac{\Delta E_g^{\rm app}}{k_BT}\right), \qquad (6)$$

where n_{io} is the intrinsic carrier concentration assumed in the device model, D_o is the assumed electron diffusion coefficient in p-GaAs for a hole concentration p_o, and $\Delta E_g^{\rm app}$ is the nonphysical apparent band-gap shrinkage. Equating (6) to (2) we find

$$\Delta E_g^{\rm app}\equiv k_BT\ln[(n_oD_n)p_o/n_{io}^2D_o], \qquad (7)$$

where (n_oD_n) is the measured product of the equilibrium electron concentration and the electron diffusion coefficient on the p-side. Use of this definition of $\Delta E_g^{\rm app}$ ensures that the modeled electron injection saturation current density, $J_{01e}^{\rm mod}$, will be equal to the measured J_{01e}. Equation (7) is the definition of apparent band-gap shrinkage implicitly assumed by Slotboom and DeGraaff[2] in their pioneering studies of heavy doping effects in p^+-Si. We do not quote apparent band-gap shrinkage values, because they depend on D_o, the assumed minority-carrier electron diffusion coefficient, which is not well known at present.

Measurements of electron current in p^+-n GaAs diodes were presented and analyzed. The large magnitude of the measured currents in cells doped greater than 10^{18} cm^{-3} on the p-side was attributed to heavy doping effects in the p^+-GaAs. These effects are analogous to so-called band-gap narrowing effects in silicon and were found to be comparable in magnitude to those observed in p^+-Si. To accurately model GaAs devices such as solar cells and bipolar transistors, heavy doping effects must be treated. Further work is needed to extend the measurements over a wider range of doping densities and dopant types, to separate out the effects of heavy doping on the minority-carrier diffusion coefficient, and to explore heavy doping effects in n-GaAs.

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