values of some parameters used in calculating the current flowing through the PMOS transistor, for example, the effective mobility of hole and the bulk effect factor are different from that of the experiment in [1]. Other reasons are that the effect of the parameters of the experimental device on the characteristics of the CIGBT, especially at the high current flowing through the PMOS transistor with the larger W_P/L_P, is neglected in the analysis calculation and that the short channel effects in the actual experimental PMOS transistor have not been accounted for in the analytical model.

IV. Conclusion

The transient turnoff characteristics of the CIGBT transistor are obtained from the charge-based analytical model, which is supported by the experimental data and the simulated results by the enhanced SPICE3 program, in which the new network model of the CIGBT is implemented. The dependences of the transient turnoff time T_0 on the device design parameters, W_p/L_p, W_b, τ_H, and I_{N0}, demonstrate that T_0 decreases rapidly with W_p/L_p increasing and is weakly related to the two important parameters τ_H and I_{N0} in the IGBT at the larger W_p/L_p. The charge-based model can be also conveniently used to analyze the transient characteristics of the new device LIGBT/LDMOS [9], [10] and the enhanced SPICE3 can be effectively used to simulate the behaviors of the smart-power integrated circuits including the CIGBT.

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Miller's Approximation in Advanced Bipolar Transistors Under Nonlocal Impact Ionization Conditions

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***Abstract*—Using a modified ionization model based on nonlocal impact ionization conditions, Miller's relationship is reexamined for doping concentrations ($\geq 10^{17}/\mathrm{cm}^3$) used in advanced bipolar transistors. For the useful range of current gains ($0.1 > 1 - 1/\mathrm{M} > 0.005$), the empirical parameter n in Miller's relationship, evaluated under nonlocal impact ionization conditions is shown to be considerably different from that obtained using standard ionization rates.**

I. Introduction

Miller's relationship [1], used to approximate the avalanche multiplication factor M, is widely known in literature [2]–[6] and is given by

$$M = \frac{1}{1 - \left(\dfrac{BV_{\mathrm{ceo}}}{BV_{\mathrm{cbo}}}\right)^n} \tag{1}$$

where BV_{ceo} is the common-emitter breakdown voltage, BV_{cbo} is the collector-base breakdown voltage and n is an empirical parameter. It should be noted that in practice the actual BV_{cbo} is less than the theoretical one dimensional breakdown value because of sidewall breakdown. This study, therefore, concerns the ideal law, which would be achieved in practice using mesa or guard ring technologies [4]. Moll *et al.* [7] have shown that the logarithmic plot of $(1-1/M)$ versus the normalized breakdown voltage $BV_{\mathrm{ceo}}/BV_{\mathrm{cbo}}$ is well approximated by a straight line for $0.1 > 1 - 1/M > 0.005$ which corresponds to the useful range of current gain β for most bipolar transistors. Taking into account the influence of carrier generation within the space-charge regions of silicon p-n junctions upon their breakdown characteristics [8], [9], it has been shown that the avalanche multiplication factor M can be approximated by Miller's relationship with exponent n between 7 and 3 for one-sided $\mathrm{p}^+-\mathrm{n}$ junctions with bulk impurity concentrations between 10^{13} and $10^{17}/\mathrm{cm}^3$. In these calculations, the ionization coefficients are approximated as functions of the local electric field and the standard ionization models [10], [11] are used.

In advanced bipolar transistors, such as the SiGe heterojunction devices, itis now very common to use collector dopings well in excess of $10^{17}/\mathrm{cm}^3$ [12]–[14]. At these doping concentrations, the breakdown voltage is no longer a function of the local electric field as the ionization coefficients now really depend on the electron energy [15]. When the space-charge region is narrow due to high collector dopings, the electron energy profile does not coincide with the local electric field distribution. This leads to lower than otherwise expected multiplication factors. At higher collector dopings, it is therefore important to consider the nonlocal properties of the avalanche multiplication [16]–[18] to evaluate the multiplication factor M. The aim of this paper is to find the value of n in Miller's relationship under the conditions of nonlocal impact ionization for doping concentrations of interest in advanced bipolar transistors. Our

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results are, therefore, valid only for narrow depletion region widths where nonlocal impact ionization is dominant. We present the n values as a function of collector doping obtained using a modified impact ionization formulation based on [15], [19], [20] and compare with the values of n obtained using the standard ionization models [10], [11].

II. Simulation Results and Discussion

We have used the BIPOLE3 device simulator [21] to estimate the multiplication factor M by numerically integrating the ionization integral (S_e) from the electric field solution to Poisson's equation [22]. In the numerical integration, an abrupt base-collector ($p^+ - n$) junction is assumed with a uniform base doping at $3 \times 10^{19}/\mathrm{cm}^3$ and different collector dopings up to $10^{18}/\mathrm{cm}^3$ are considered. The ionization integral S_e is related to the multiplication factor M by the classical expression [22]:

$$S_e = 1 - \frac{1}{M} = \int_{x_1}^{x_2} \alpha_e(E) \cdot \exp\left[-\int_{x_1}^{x} (\alpha_e(E) - \alpha_h(E))\,dz\right] dx \quad (2)$$

where $\alpha_e(\alpha_h)$ is the ionization rate and is a function of the electric field E and x_1 is the *dead space* [10] and is equal to the distance the particle must travel to gain the energy E_i which is related to the effective electric field $F_{\mathrm{eff}}(x)$ as follows:

$$E_i = q \int_0^{x1} F_{\mathrm{eff}}(x)\,dx. \quad (3)$$

The effective electric field is a measure of the actual kinetic energy of the particle. The profile of the particle kinetic energy distribution does not coincide with the actual electric field distribution when the width of the high electric field region is comparable to the energy relaxation length λ_w [15]. In the modified impact ionization formulation [15], this effective electric field $F_{\mathrm{eff}}(x)$, which coincides with the real electric field for homogeneous silicon, is first calculated from [23]:

$$F_{eff}(x) = \frac{1}{\lambda_w} \int_0^x F(z) \exp\left(\frac{x - z}{\lambda_w}\right) dz. \quad (4)$$

The ionization integral S_e is then calculated by substituting the effective electric field F_{eff} into the $\alpha(E)$ dependence and using the published data on ionization coefficients by Marsland [20] with $\lambda_w = 55$ nm [15]. This modified ionization formulation has been shown to predict the breakdown voltages very accurately when the collector doping is $\geq 10^{17}/\mathrm{cm}^3$ [17].

Fig. 1 shows the normalized breakdown voltage plotted as a function of $(1 - 1/M)$ computed by BIPOLE3 using the standard ionization rates [10], [11] and the modified ionization formulation [15] for two different collector dopings. We note from here that normalized breakdown voltage versus $(1-1/M)$ can be approximated by a straight line in the useful range of $0.1 > 1 - 1/M > 0.005$ independent of the ionization model used. The value of n is obtained by calculating the slope of this straight line.

Fig. 2 shows the n values as a function of collector doping concentration for the standard and the modified ionization models. The values of n reported in literature [9] are also shown for a comparison with n values obtained by BIPOLE3 using the standard ionization rates. It may be noted that the BIPOLE3 computed values of n using the standard ionization rates are identical to those reported in literature and in this case as one would predict, for collector dopings $\geq 10^{17}/\mathrm{cm}^3$, the value of n decreases as the doping increases. However, it is interesting to note that when nonlocal impact ionization conditions are applied for calculating n, its value is considerably larger than the values of n obtained using the standard

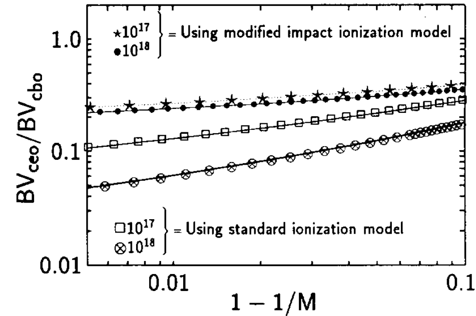

Fig. 1. Normalized breakdown voltage as a function of $(1 - 1/M)$ obtained using standard and modified ionization models.

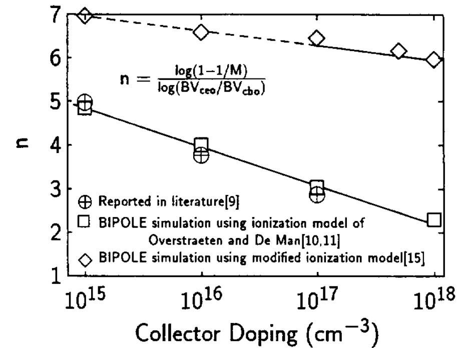

Fig. 2. The value of n as a function of collector doping concentration obtained using standard and modified ionization models.

ionization rates. It must be noted that in [15], [17] the ionization coefficient data was selected from [20] after studying available published data. When combined with the above described nonlocal impact ionization model, this was found to give excellent agreement with all available experimental data for structures with collector doping levels in the range of 10^{17}–$2 \times 10^{18}/\mathrm{cm}^3$. No experimental data has been found for the intermediate range of doping levels from 10^{16} to $10^{17}/\mathrm{cm}^3$ and it is expected that results will lie between the two curves in Fig. 2. It should be noted that the exact value of M depends critically on the ionization coefficient data actually used [20].

III. Conclusions

In conclusion, we have shown that Miller's relation is still valid for collector doping concentrations $\geq 10^{17}/\mathrm{cm}^3$ commonly used in high performance bipolar transistors. Our results, however, demonstrate that when nonlocal impact ionization conditions (used to extract accurate breakdown voltages at higher collector dopings) are employed for estimating n, its value is at least 2–3 times larger than that obtained using standard ionization rates.

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Simulation of High-Efficiency n^+p Indium Phosphide Solar Cell Results and Future Improvements

Raj K. Jain and Dennis J. Flood

***Abstract*— A simulation of the highest efficiency (19.1% AM0) n^+p indium phosphide (InP) solar cell was made using a computer code PC-1D in order to understand it and suggest future improvements to it. Available cell design and process data was used in the simulation. Minority carrier diffusion lengths in the emitter and base have been varied to match the experimental cell I-V characteristics with the calculated results. To further understand and improve the InP cell efficiency, simulations were performed using improved values of cell material and process parameters. We show that the efficiency of this cell could be increased to more than 23% AM0 by incorporating the suggested cell material, design and process improvements. At these high efficiencies InP cell technology will be very attractive for space use.**

I. Introduction

The superior radiation tolerance of indium phosphide (InP) solar cells has made them a strong candidate for space power applications [1], [2]. The highest efficiency homoepitaxial n^+p InP solar cells have been developed by metalorganic chemical vapor deposition (MOCVD) techniques [3] and have been measured at NASA Lewis at 19.1% efficiency under AM0, 1 sun, 137.2 mW/cm^2 conditions at 25°C. Although this achievement on 4 cm^2 cells is remarkable, cell efficiencies must be enhanced further to make InP cost competitive. With this goal a simulation study of the highest efficiency InP solar cell has been undertaken using a computer code PC-1D [4] in order to understand it and suggest future improvements to it.

InP solar cells have greatly increased radiation tolerance compared to the gallium arsenide and silicon solar cells [5] which are currently being used for space applications. By increasing the efficiency of InP solar cells, we will improve the array power density (W/kg) resulting in significant reduction in launch cost, and also increase the lifetime of solar arrays for orbits with high radiation, such as intermediate Earth orbit applications. Solar cells for such intermediate Earth orbits have important applications to NASA, military, and commercial use. Intermediate Earth orbit is the preferred positioning of next-generation small-aperture communication satellites, which will be used for portable telephone systems. This single application represents a share of a satellite market of $600 million to $3.4 billion to be launched over the next decade, with an even larger market in following years as portable telecommunications systems become global.

II. Modeling Approach and Solar Cell Details

PC-1D is a quasi-one-dimensional program based on finite-element approach and operated on a personal computer for investigating the transport of electrons and holes in semiconductor devices [4]. Available cell design and process data was used in the simulation. The intrinsic carrier concentration equal to the widely accepted value of 8×10^6 cm^{-3} was used for the modeling calculations [6].

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