MINIMIZATION OF IMPACT IONIZATION IN SILICON BJTs

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Introduction

Recent developments in silicon bipolar technology made it possible to achieve major breaktroughs in device speed and current gain. The metallurgical base width has been reduced down to 50 nm, and further shrinking is expected to occur in the near future [1 and references therein]. As a result, the base transit time can be kept well below 1 psec, and it is not expected to provide the major contribution to the total delay of the carriers in future-generation devices. The collector transit time, on the other hand, is emerging as the dominant contribution to the above delay [2]. Hence, a suitable design of the collector impurity profile is mandatory if further performance improvement is aimed at.

One of the major problems associated with further reduction of the collector transit time, however, is the impact ionization effect which occurs within the collector space charge region [3]. As the latter is shrunk according to the scaling rules, the electric field is deemed to increase by the scaling factor: hence, increased impact ionization is expected to occur. Holes generated within the collector space charge region drift to the base neutral region and subtract to the base current. For large current gain devices, the base current eventually reverses, and instability occurs in common-emitter configuration.

In this work we address the problem of minimizing impact ionization within the collector space charge region of a bipolar transistor. The analysis is carried out based on a simplified version of the energy balance equation which, however, retains the basic ingredients to account for non-local effects [4]. The latter are especially important when the high-field region is confined to distances of the order of the energy relaxation length, as it happens to occur within the collector space-charge region of a BJT. A major result of the present analysis is that impact ionization is minimized by a uniform temperature profile, as discussed in what follows.

Description of the model

The energy-balance equation can be regarded as the second-order moment of the Boltzmann transport equation (BTE). In one-dimensional form, the former reads

$$\frac{\mathrm{d}}{\mathrm{d}x}\left(\frac{5}{2}nvk_BT\right) = -qnvF - \frac{3}{2}k_Bn\frac{T-T_o}{\tau_w} \qquad (1)$$

where T and T_o are the electron and lattice temperature, respectively, τ_w is the energy relaxation time, n is the electron concentration, v is the carrier drift velocity and F is the electric field.

For any given field profile, eq. (1) allows the carrier-temperature to be determined as a function of position. Next, the temperature dependence for the ionization coefficient can be derived from the Chynoweth expression [5], accounting for (1) in static conditions. The result is

$$\alpha_{ii}(T) = A\ \exp(-E_{th}/k_B\Delta T) \qquad (2)$$

where E_{th} is related to the impact-ionization threshold energy and $\Delta T = T - T_o$.

Figure 1-a shows a comparison between the model and experimental measurements of the multiplication factor

$$(M-1) = \int_0^{x_d} \alpha_{ii}(T)\mathrm{d}x \qquad (3)$$

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for three different impurity concentrations within the collector space-charge region. The agreement is clearly very satisfactory. Figure 1-b compares instead the present model with the local-field model. The latter predicts a far too large multiplication factor.

The temperature model is then used to minimize the multiplication factor for a given potential drop across the collector region. From the mathematical standpoint, the multiplication factor $M - 1$ can be regarded as a functional of the temperature profile $T(x)$. The problem of minimizing impact ionization within the collector space-charge region, is equivalent to minimizing the functional (3) subject to the constraint

$$\psi_o + V_{cb} = - \int_0^{x_d} F(x)\, \mathrm{d}x \qquad (4)$$

where ψ_o and V_{cb} are the built-in potential and the collector-base voltage, respectively.

The result of such a treatment is a delta-shaped field at the base-collector junction, followed by a constant field within the collector space-charge region. Figure 2-a shows the temperature profile for a 0.1 μm collector space charge region corresponding to a triangular field, a uniform field, and the optimized field. Figure 2-b shows the corresponding impact ionization profiles. The suggested procedure minimizes the peak carrier temperature and, due to the exponential dependence of the ionization coefficient, a considerable improvement is achieved in terms of impact ionization. From a practical standpoint, an approximately-ideal field can be obtained by suitably profiling the impurity concentration within the collector space-charge region.

Conclusions

In conclusion, a new strategy is suggested to minimize the impact ionization effects which occur within the collector space charge region of a bipolar transistor. Two options are available for the designer: if maximum speed performance is sought for a given breakdown voltage V_{CEO}, the suggested method allows the depletion width to be reduced to a minimum compatible with the allowable generation rate; alternatively, one can improve the breakdown voltage for a given device speed. The maximum value of the voltage drop V_o at the base-collector metallurgical junction must be chosen well below the silicon bandgap. The increase of V_{CEO} will be of the same order and thus will be limited to less than 1 Volt. However, since high-frequency transistors for logic applications are often characterized by breakdown values $V_{CEO} \simeq 2 - 2.5$ V, the allowable improvement is worth pursuing.

References

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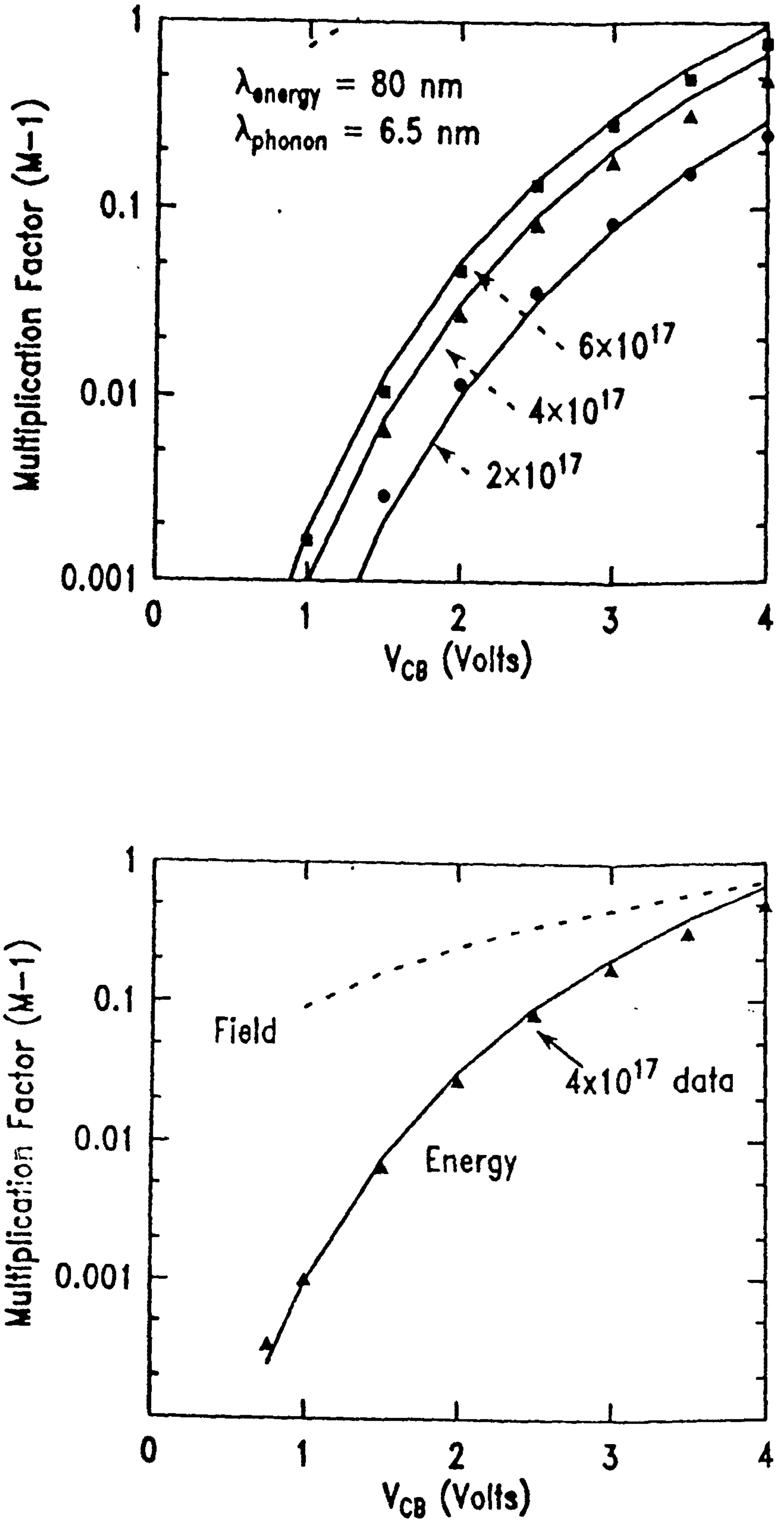
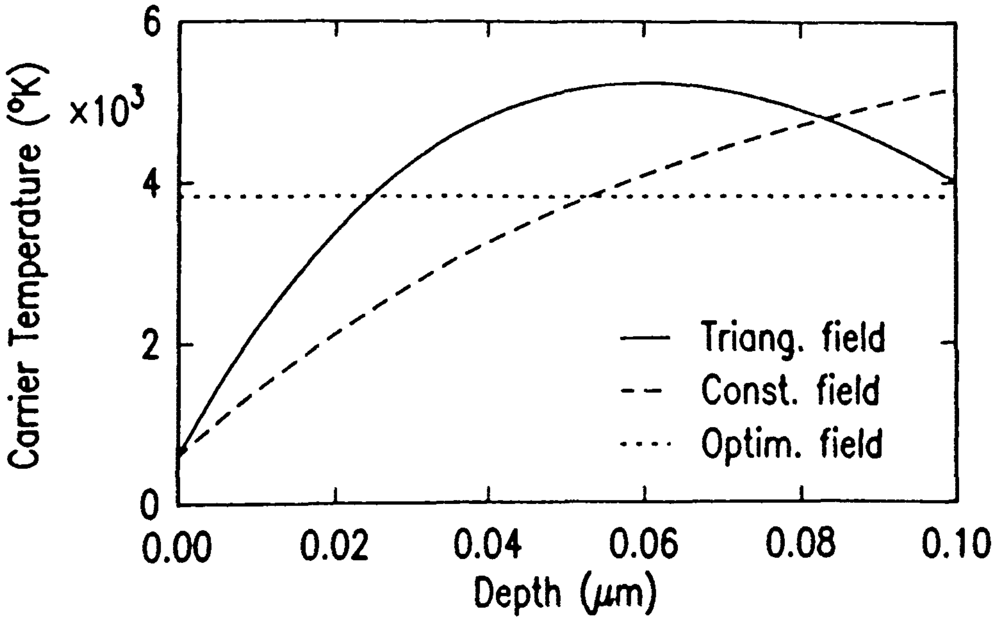
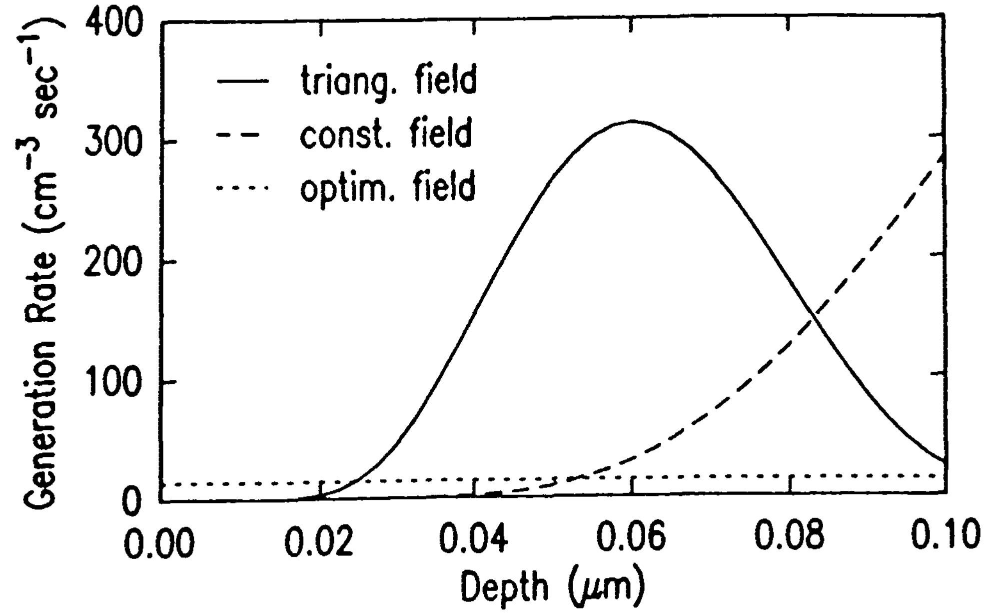


Figure 1. Multiplication factor against collector-base voltage; a) Comparison between theory and experiments for three different collector voltages; b) comparison between the temperature model (solid line) and the field model (dotted line).



Carrier temperature profile



Impact-Ionization Rate Profile

Figure 2. a) Temperature profile within the collector space-charge region for three different field shapes: triangular field (solid line), constant field (dashed line) and opimized filed (dotted line). b) Generation rate within the collector space-charge region for three different field shapes: triangular field (solid line), constant field (dashed line) and opimized filed (dotted line).