MINIMIZATION OF IMPACT IONIZATION IN SILICON BJTs

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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

\[
\frac{d}{dz} \left( \frac{5}{2} n v k_B T \right) = -q n v F - \frac{3}{2} k_B n \frac{T - T_e}{\tau_w}
\]

where \( T \) and \( T_e \) are the electron and lattice temperature, respectively, \( \tau_w \) 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

\[
\alpha_{ii}(T) = A \exp \left( -\frac{E_{th}}{k_B T} \right)
\]

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

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

\[
(M - 1) = \int_0^z \alpha_{ii}(T) \, dx
\]
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

$$\psi_0 + V_{cb} = - \int_0^{x_d} F(x) \, dx$$

where $\psi_0$ 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 $\mu$m 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 $V_{CEO} \approx 2 - 2.5$ V, the allowable improvement is worth pursuing.

References


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).
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 optimized field (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 optimized field (dotted line).