TECHNISCHE UNIVERSITÄT DRESDEN

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Physics-based Analytical Modeling of SiGe- Heterojunction Bipolar Transistors for High-speed Integrated Circuits

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Motivations

- SiGe-HBTs become mainstream and offer competitive r.f. performance
- de-facto SGPM fails to keep up with advanced Si- and SiGe- bipolar transistors
- Exploding costs for manufacturing

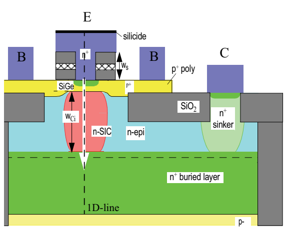
Methodology

- Behavioral device study with numerical device simulations based on practical device profiles
- In-depth device analysis of physical effects with charge partitioning schemes
- Identify important characteristics to be modeled
- Physics-based analytical modeling of measureable electrical elements such as charges and transit times.

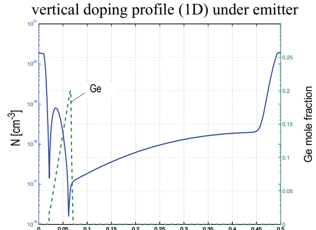
One-dimensional Generalized Integral Charge-Control Relation

An accurate yet compact relation describing the transfer current is crucial for developing a compact model. The Integral Charge-Control Relation (ICCR) was the keystone of the SGPM. ICCR was too simple and failed to address new effect found in HBTs. The GICCR was developed to address ICCR's shortfalls as an approach for analysing device's d.c. behavior and as a compact relation for modeling the transfer current.

schematic cross-section of CED SiGe-HBT



vertical doping profile (1D) under emitter



The Master GICCR relation is

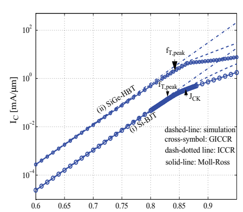
$$J_T = \frac{I_T}{A_{E0}} = (q^2 V_T \mu_{n0} n_{i0}^2)\frac{\exp(V_{BEi}/V_T) - \exp(V_{BCi}/V_T)}{Q_{p,T}}$$ with the weighted hole charge $Q_{p,T} = q\int_0^{x_C} h_g h_j h_v p\,dx$ and

corresponding weighting factor $h_g(x, J_C) = \frac{\mu_{n0} n_{i0}^2}{\mu_n n_i^2}$, $h_j(x, J_C) = \frac{J_{nx}(x)}{J_T}$, $h_v(x, J_C) = \exp\left(\frac{V_{BEi} - \varphi_p(x)}{V_T}\right)$.

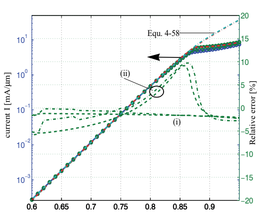
The "regional-approach" compact relation

$$J_T = C_{10}\frac{\exp(V_{BEi}/V_T) - \exp(V_{BCi}/V_T)}{Q_{p0} + h_{jE}^* Q_{jE} + h_{jC}^* Q_{jC} + h_{fB}^* Q_{fB} + h_E^* Q_{pE} + h_C^* Q_{pC}}$$

The results:



Comparison with other theories

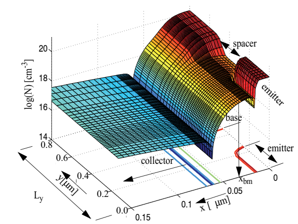


Results of compact modeling

The one-dimensional GICCR relation is a powerful theory to describe and model the transfer current. It is applicable for both SiGe- and "compound" HBTs. In its aggressively simplified form, the compact relation derived from GICCR yields good agreements with numerical device simulations.

Multi-dimensional Generalized Integral Charge-Control Relation

Two-/three- dimensional GICCR was developed in complement to 1D-GICCR to address the needs of dimension-related analysis and modeling such as parameter scaling, device optimization and to model those such as silicon-on-insulator based HBTs. The theory was derived for 2D profiles but also applicable for 3D ones.



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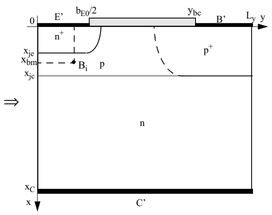


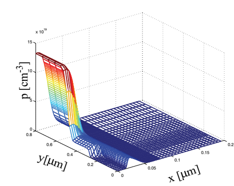
The Master GICCR relation for a 2D structure

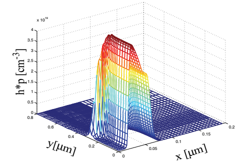
$$I_T = q b_E l_{E0} c_0 \frac{\exp(V_{B_iE'}/V_T) - \frac{2L_y}{b_E}\exp(V_{B_iC'}/V_T)}{Q_{p0h} + \Delta Q_{ph}}$$

- $Q_{p,T} = Q_{p0h} + \Delta Q_{ph}$ is two dimensional weighted hole charge
- $b_E = b_{E0} + 2\int_{b_{e0}/2}^{L_y} e^{-\varphi_n(0,y)/V_T} dy \approx b_{E0} + 2\gamma_C$ is the effective emitter width and $A_E = b_E l_{E0}$ is *effective* emitter area, $A_E > A_{E0}$.

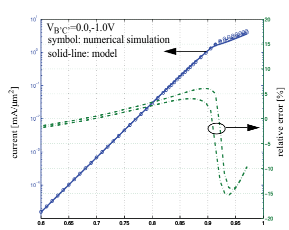
The "compact relation"

$$I_T = q b_E l_{E0} c_0 \frac{\exp(V_{B_iE'}/V_T) - \frac{2L_y}{b_E}\exp(V_{B_iC'}/V_T)}{Q_{p0h} + Q_{jEh} + Q_{jCh} + Q_{mh}}$$





Results



A multidimensional Generalized Integral Charge Control Relation was presented that accurately describes the transfer current of 2D Si- and SiGe transistors. As an exact and physics-based solution, the relation can be regarded as Master Equation that allows further considerations and simplifications, for compact model formulations to be made. A compact relation was demonstrated with good results.

Field-based charge and transit time model for SiGe-HBTs

The field model

- model equation: $E_{jc} = E_{\infty} + f_e E_{lim}$

with

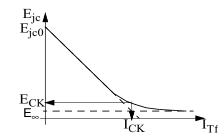
$$f_e(V_{BC}, I_{Tf}) = \frac{e_j + \sqrt{e_j^2 + g_{jc}\frac{E_{CK}}{E_{lim}}}}{2},$$

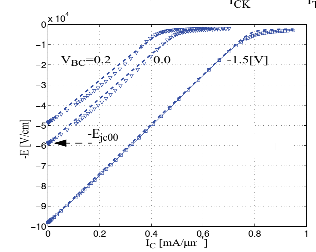
$$e_j = \frac{(E_{jC0} - E_{\infty}) - (E_{jC0} - E_{CK})\frac{I_{Tf}}{I_{CK}}}{E_{lim}}$$

$$E_{jc0}(V_{BC}, J_C \to 0) = E_{jC00} + \frac{\bar{Q}_{jC}(V_{BC}, J_C \to 0)}{\varepsilon}$$

- parameter: g_{jc} (all other parameters are already available in HICUM)
- depletion charge model provided in HICUM

- Approach ⇒



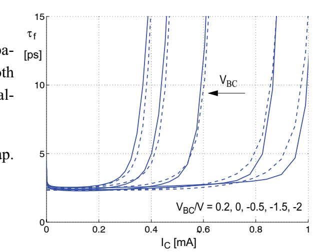


Modeling the carrier jam

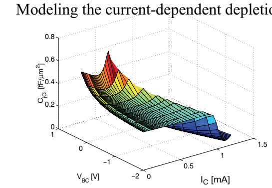
The base carrier jam model in HICUM

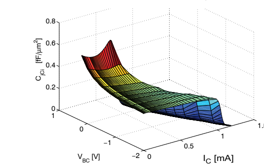
$$\Delta\tau_{Bfv} = \tau_{Bfvl} f_u\left[1 - \left(1 - \left(\frac{v_n}{v_{sn}}\right)^{\gamma_u}\right)^{\gamma_u}\frac{I_{Tf}}{u}\frac{du}{dI_{Tf}}\right]\exp(-b_{hc}u)$$

with $f_u(u)$ given in Diss., b_{hc} as new model parameter, and γ_u = 1(holes), 2(electrons) both transit time formulations depend on the normalized field $u = E_{jc}(V_{BC}, I_{Tf})/E_{lim}$



Modeling the current-dependent depletion cap.





A physics-based electric field model was presented and succesfully applied to model the base carrier jam component in SiGe-HBTs. It was also employed to model the current-dependent behavior of the BC depletion capacitance. The demonstrated results are in good agreements with numerical device simulations.

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