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A Novel Low-bias Charge Concept for HBT/BJT Models Including Heterobandgap and Temperature Effects –Part I: Theory and Model Implementation

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Outline

- BJT/HBT transfer current and (hole) charge
- the *principal* low bias charge formula
- overview of the AC linked model approaches
- the *generic* low bias charge concept
- AC linked & bandgap feature temperature dependences
- model implementation

Note: fully rigorous treatments are included in [1]

Transfer Current and Charge

$$I_T = q \cdot A_E \cdot V_T \cdot \frac{\exp\left(\frac{vbiei}{V_T}\right) - \exp\left(\frac{vbici}{V_T}\right)}{\int_{xE}^{xC} \frac{p(x)}{\mu_n(x) \cdot n_i^2(x)} \cdot dx}$$

Derived by Moll-Ross [2] for low injection, generalized to all injection conditions by Gummel [3] as ICCR (each at Bell, but [2] not cited in [3]!)

$$Q_{pT} = q \cdot A_E \cdot \int_{xE}^{xC} \frac{\mu_n(x_R) \cdot n_i^2(x_R)}{\mu_n(x) \cdot n_i^2(x)} \cdot p(x) \cdot dx$$

$$c10 = q^2 \cdot V_T \cdot A_E^2 \cdot \mu_n(x_R) \cdot n_i^2(x_R)$$

$$I_T = c10 \cdot \frac{\exp\left(\frac{vbiei}{V_T}\right) - \exp\left(\frac{vbici}{V_T}\right)}{Q_{pT}}$$

Extending by constants in x_R the Hicum form is obtained with the Q_{pT} hole charge in denominator

Space charge neutrality for low injection implies $p(x) \approx N_A(x) = N(x)$

Low bias hole charge: (see figure on slide #5)

$$Q_{pT\_low} = q \cdot A_E \cdot \int_{xdEb}^{xdCb} \frac{\mu_n(x_R) \cdot n_i^2(x_R)}{\mu_n(x) \cdot n_i^2(x)} \cdot N(x) \cdot dx$$

Low bias hole charge

The effective doping density has been suggested in [4] as

$$N_{eff}(x) = \frac{\mu_n(x_R)\cdot n_i^2(x_R)}{\mu_n(x)\cdot n_i^2(x)}\cdot N(x) = m(x,T)\cdot N(x)$$

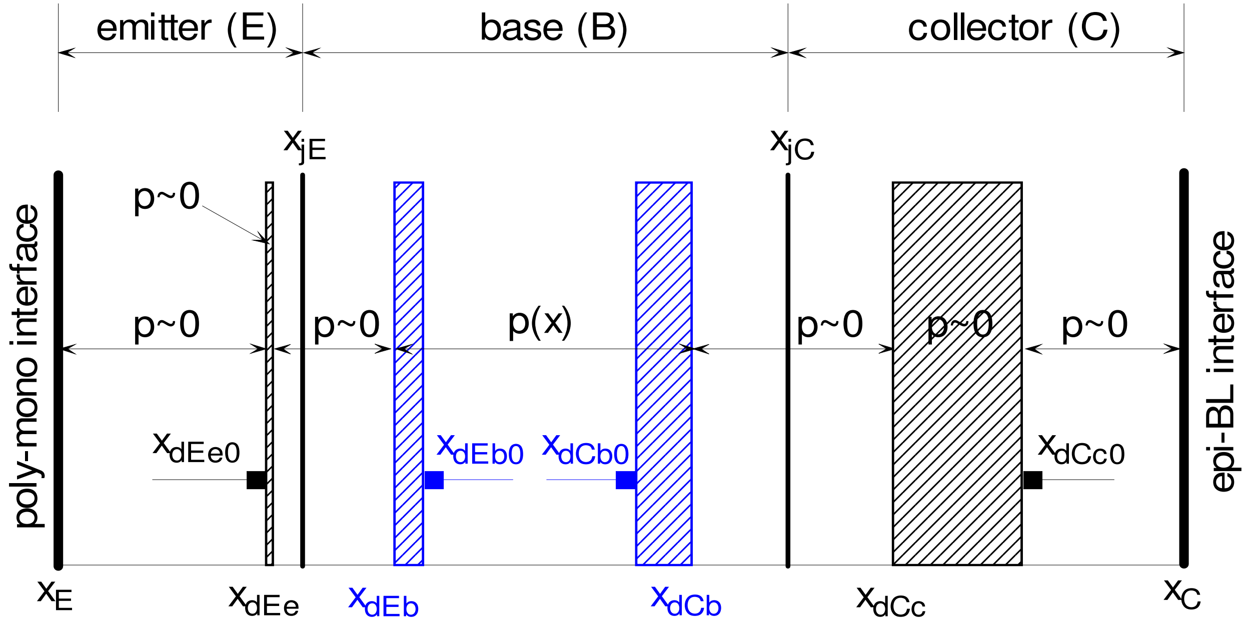
The Moll-Ross-Gummel or *MRG* function is introduced by

$$m(x,T) = m_\mu(x)\cdot \exp\left[-\frac{T_0}{T}\cdot\frac{\Delta V_G(x)-\Delta V_G(x_R)}{V_{T0}}\right] \qquad m_\mu(x) = \frac{\mu_n(x_R,T_0)}{\mu_n(x,T_0)}$$

Variable bandgap in the base makes the MRG function temperature dependent.

An analytic technique – not used so far - will be adopted for model construction enabling a consistent discussion of the bias and temperature controlled operation modes

Low bias hole charge, cont.'d



holes are only in $[x_{dEb}, x_{dCb}]$

$$Q_{pT\_low} = q \cdot A_E \cdot \int_{xdEb}^{xdCb} N_{eff}(x) \cdot dx$$

$$Q_{p0} = q \cdot A_E \cdot \int_{xdEb0}^{xdCb0} N_{eff}(x) \cdot dx$$

At low bias in the forward active mode the hole density is negligible in the emitter and collector *n*-type quasineutral regions. Shaded rectangles represent the electrostatic (**ES**) charge of the doping centers when the depletion layer boundaries are displaced from their equilibrium (zero subscripted) positions.

The *principal* low bias charge formula

Apply a small forward bias increment to the BE junction

$$\frac{\partial Q_{pT\_low}}{\partial vbiei} = -q \cdot A_E \cdot \frac{\partial x_{dEb}}{\partial vbiei} \cdot N_{eff}(x_{dEb}) = -m(x_{dEb}) \cdot \frac{A_E \cdot \Delta x_{dEb} \cdot [-q \cdot N_A(x_{dEb})]}{\Delta vbiei} = m(x_{dEb}) \cdot \frac{\Delta \tilde{Q}_{jEi}}{\Delta vbiei}$$

$$\frac{\partial Q_{pT\_low}}{\partial vbiei} = m(x_{dEb}(vbiei)) \cdot \tilde{C}_{jEi}(vbiei)$$

~ denotes AC related quantities

Similarly for the BC side

$$\frac{\partial Q_{pT\_low}}{\partial vbici} = m(x_{dCb}(vbici)) \cdot \tilde{C}_{jCi}(vbici)$$

pair of PDEs has the solution

$$Q_{pT\_low} = q \cdot A_E \cdot \int_{xdEb}^{xdCb} N_{eff}(x) \cdot dx \Longleftrightarrow Q_{pT\_low} = Q_{p0} + \int_{o}^{vbiei} m(x_{dEb}(u)) \cdot \tilde{C}_{jEi}(u) \cdot du + \int_{o}^{vbici} m(x_{dCb}(u)) \cdot \tilde{C}_{jCi}(u) \cdot du$$

As long as the depletion approximation is accepted the two forms are equivalent

Junction related charges: terminology and implication

$$\tilde{Q}_{jEi} = q \cdot A_E \int_{xdEb}^{xdEb0} N(x) \cdot dx = \int_{o}^{vbiei} \tilde{C}_{jEi}(u) \cdot du$$

Emitter AC (ES) charge

$$\tilde{Q}_{jCi} = q \cdot A_E \int_{xdCb0}^{xdCb} N(x) \cdot dx = \int_{o}^{vbici} \tilde{C}_{jCi}(u) \cdot du$$

Collector AC (ES) charge

$$\overline{Q}_{jE} = q \cdot A_E \int_{xdEb}^{xdEb0} N_{eff}(x) \cdot dx = \int_{o}^{vbiei} m(x_{dEb}(u)) \cdot \tilde{C}_{jEi}(u) \cdot du$$

Emitter MRG charge

$$\overline{Q}_{jC} = q \cdot A_E \int_{xdCb0}^{xdCb} N_{eff}(x) \cdot dx = \int_{o}^{vbici} m(x_{dCb}(u)) \cdot \tilde{C}_{jCi}(u) \cdot du$$

Collector MRG charge

The MRG charges are the *weighted* integrals of the capacitances.

A *linear* MRG to AC charge relationship assumed in all present models is *not a mandatory approximation!*

Approximation of the *MRG* charges by averages

Second mean value theorem of integrals yields

$$\overline{m}_J = \frac{\overline{Q}_{jJ}}{\overline{Q}_{jJi}} = \int_o^{vbiJi} m(x_{dJb}(u)) \cdot \tilde{C}_{jJi}(u) \cdot du \Bigg/ \int_o^{vbiJi} \tilde{C}_{jJi}(u) \cdot du \qquad J = E, C$$

$$Q_{pT\_low} = Q_{p0} + \overline{m}_E \cdot \tilde{Q}_{jEi}(vbiei) + \overline{m}_C \cdot \tilde{Q}_{jCi}(vbici)$$

Normalized charge function at *nominal temperature*

$$\Phi_{JT0} = \frac{1}{1 - zJi} \cdot \left[1 - \left(1 - \frac{vbiJi}{vdJi_0} \right)^{1-zJi} \right]$$

implies $Q_{pT\_low}(T_0) = Q_{p0} + \overline{m}_E \cdot \tilde{C}_{jEi0}(T_0) \cdot \tilde{v}dei_0 \cdot \tilde{\Phi}_{ET0} + \overline{m}_C \cdot \tilde{C}_{jCi0}(T_0) \cdot \tilde{v}dci_0 \cdot \tilde{\Phi}_{CT0}$

GPM, VBIC and MEXTRAM use normalized formulations

AC linked approaches

Transition voltages: $v_E(vbiei) = \tilde{v}dei_0 \cdot \tilde{\Phi}_{ET0} \quad v_C(vbici) = \tilde{v}dci_0 \cdot \tilde{\Phi}_{CT0}$

Early voltages: $ver = \dfrac{Q_{p0}}{\overline{m}_E \cdot \tilde{C}_{jEi0}(T_0)} \quad vef = \dfrac{Q_{p0}}{\overline{m}_C \cdot \tilde{C}_{jCi0}(T_0)}$

Normalized charge: $Q_{pT\_low} = Q_{p0} \cdot q_{pT} \quad q_{pT} = 1 + \dfrac{v_E(vbiei)}{ver} + \dfrac{v_C(vbici)}{vef}$

Hicum looks different: $\boxed{Q_{pT\_low} = Q_{p0} + hjei \cdot \tilde{Q}_{jEi}(vbiei) + hjci \cdot \tilde{Q}_{jCi}(vbici)}$

$$hj_{Ji} = q \cdot A_E \int_{xdJb}^{xdJb0} m(x) \cdot N(x) \cdot dx \Bigg/ q \cdot A_E \int_{xdJb}^{xdJb0} N(x) \cdot dx = \frac{\overline{Q}_{jJ}}{\tilde{Q}_{jJi}} = \overline{m}_J$$

From Q_{pT_low} aspect GPM==VBIC==MEXTRAM ==HICUM

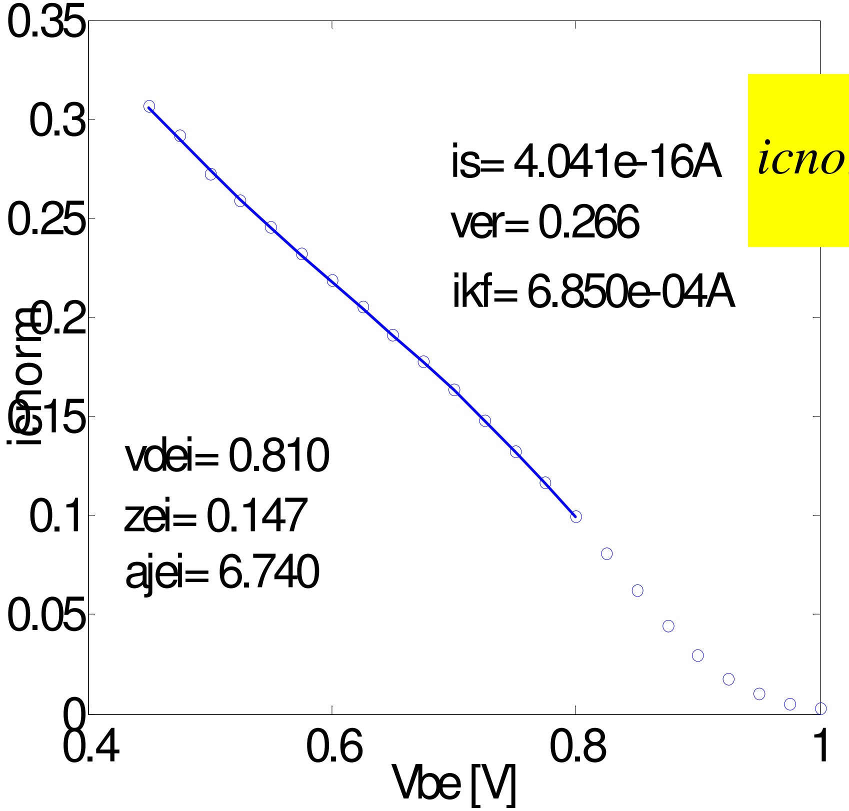
It is justified to term these approaches „*AC linked*“

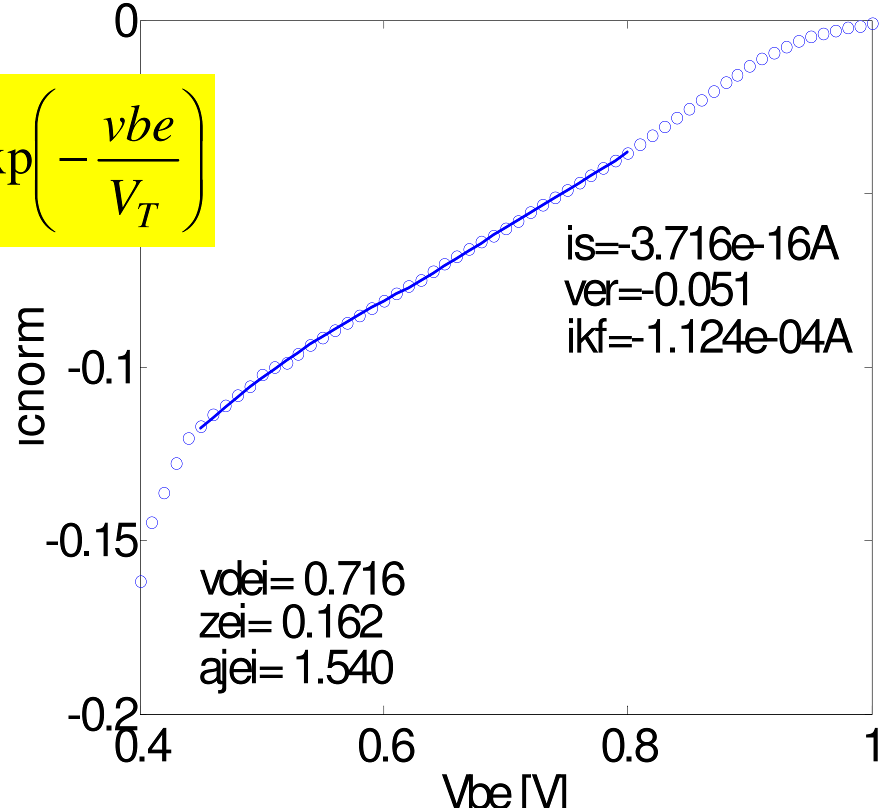
since ES capacitances & charges are measured by *AC* methods

Problems with AC linked approaches, all models

Negative IS, VER were reported in [4] for a 250GHz device

$$icnorm = \frac{ic}{is} \cdot \exp\left(-\frac{vbe}{V_T} \right)$$





70GHz device, falling curve
is, ver can be extracted

250 GHz device, rising curve
is, ver can not be extracted

The *generic* low bias charge approach, primitives

No theoretical coercion exists which should demand an AC charge term in the related MRG charge expression

- Maxwell equation div(**D**)=σ linking electrical displacement to space charge is valid for any kinds of spatial charge distributions
- 1D integral form –Gauss‘ theorem - implies depletion capacitance and charge relations
- Semi-empirical capacitance relations do not restrict the shape of the charge distribution i.e. shape of the doping concentration N(x)
- **Consequently C-Q type functions can be constructed to any N(x) incl. the effective doping concentration Neff(x) as well [4]**

$$\frac{Q_{pT}}{c10} = \frac{1}{I_T}\left[\exp\left(\frac{vbiei}{V_T}\right) - \exp\left(\frac{vbici}{V_T}\right)\right]$$

parameters incorporated in Q_{pT} can be extracted from the known RHS

The *generic* low bias charge approach, formulation

$$Q_{pT\_low} = Q_{p0} + q \cdot A_E \cdot \int_{xdEb}^{xdEb0} N_{eff}(x) \cdot dx + q \cdot A_E \cdot \int_{xdCb0}^{xdCb} N_{eff}(x) \cdot dx$$

$$Q_{pT\_low} = Q_{p0} + \overline{Q}_{jE} + \overline{Q}_{jC}$$

- MRG charge parameters are extracted from the DC data
- Moderate V_B shift by Ge content directly addressed at extraction
- MRG „depletion boundaries“ differ from AC ones but this is indifferent from DC point of view (positions do not control anything)

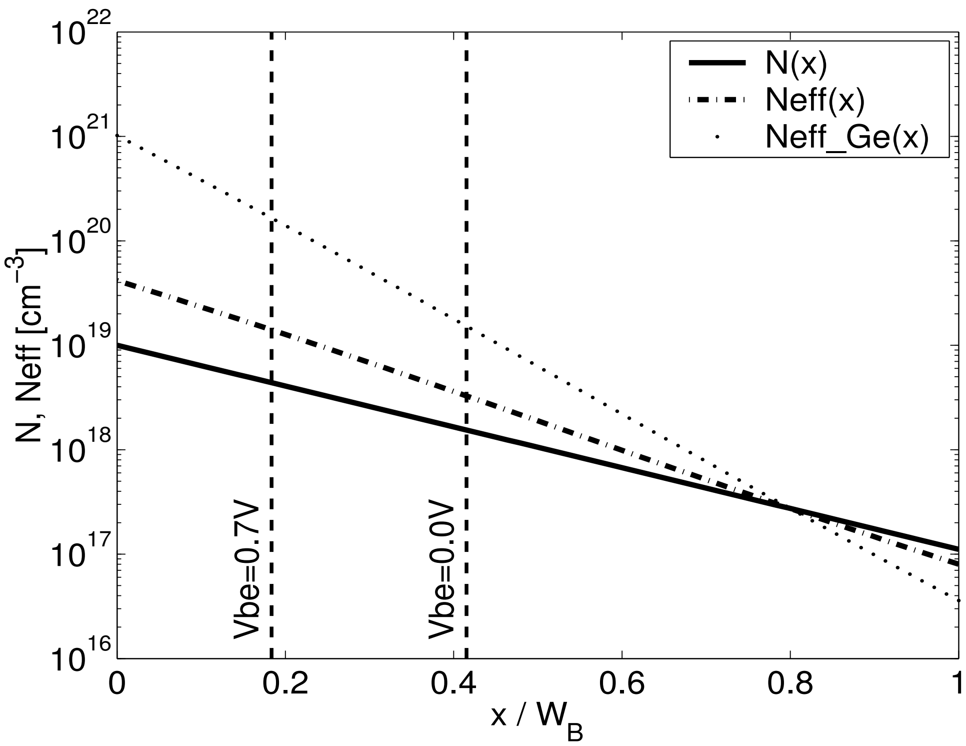
Each junction shall be attributed a pair of independent MRG and AC charge component to, the former responsible for the DC, the latter for the AC behaviour

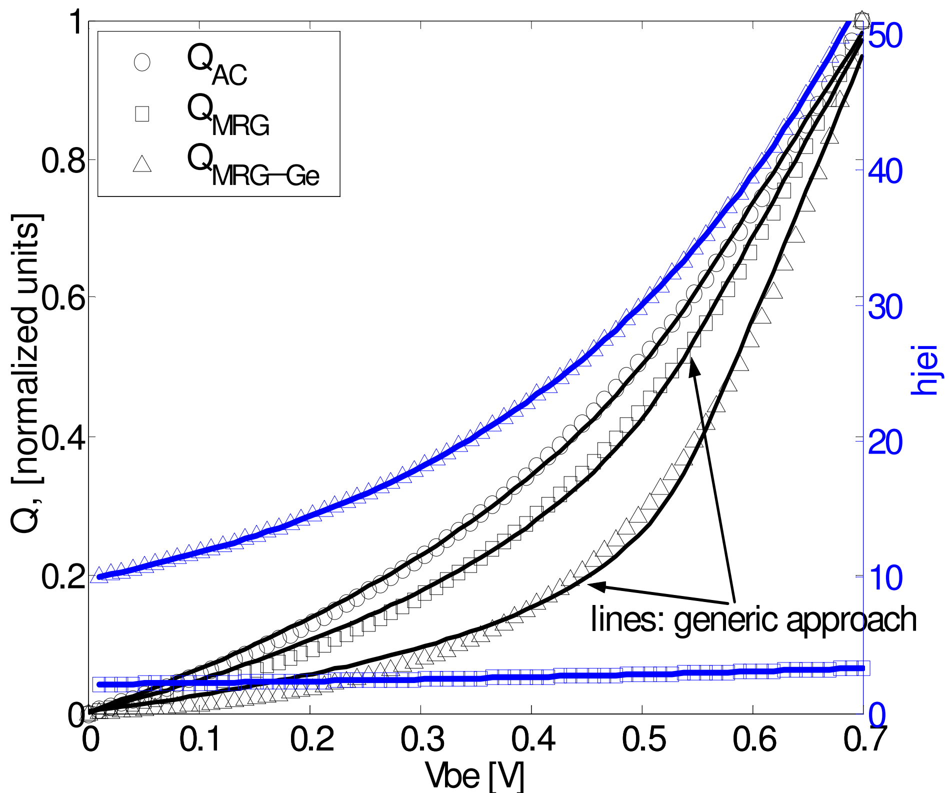
The *generic* low bias charge approach, example

Abrupt exponential EB junction was numerically computed with

$N_{D0} = 2.10^{20} cm^{-3} N_A(x) = N_{A0} \cdot \exp(-\eta \cdot x / W_B) N_{A0} = 1.10^{19} cm^{-3} \; \eta = 4.5 \; W_B = 50nm$

$x_R = 0.8W_B \;\; \Delta V_G / V_{T0} = 4$, linear ramp





Charge curves on RHS plot should overlap by AC linked theory!

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Temperature dependence: homobandgap

$$C_j(T) = C_{j0}(T_0)\cdot\left(\frac{v_{tot}}{vd_0}\right)^{-z} \qquad Q_j(T) = Q_{jnom}\cdot\Phi_T \qquad \Phi_T = \frac{1}{1-z}\left[\left(\frac{vd}{vd_0}\right)^{1-z} - \left(\frac{v_{tot}}{vd_0}\right)^{1-z}\right]$$

$$v_{tot} = vd - v \qquad Q_{jnom} = C_{j0}(T_0)\cdot vd_0$$ to be used below without verification

Total derivative w.r.t. temperature: $$\frac{dQ_{pT\_low}}{dT} = \frac{\partial Q_{jE}}{\partial T} + \frac{\partial Q_{jC}}{\partial T}$$

The emitter part from the AC linked approach reads

$$\frac{\partial Q_{jE}}{\partial T} = -q\cdot A_E\cdot\frac{\partial x_{dEb0}}{\partial T}\cdot N_{eff}(x_{dEb0}) + \overline{m}_E\cdot\int_o^{vbiei}\frac{\partial\tilde{C}_{jEi}(u)}{\partial T}\cdot du$$

Integrand:

$$\frac{\partial\tilde{C}_{jEi}}{\partial T} = \frac{\partial\tilde{C}_{jEi}}{\partial vbiei}\cdot\frac{\partial vbiei}{\partial v_{tot}}\frac{\partial v_{tot}}{\partial T} = -\frac{\partial\tilde{C}_{jEi}}{\partial vbiei}\cdot\frac{d(vdei)}{dT}$$

Temperature dependence: homobandgap, cont.'d

First term:

$$-q \cdot A_E \cdot \frac{\partial x_{dEb0}}{\partial T} \cdot N_{eff}(x_{dEb0}) = m(x_{dEb0}) \cdot \frac{\partial \tilde{Q}_{jE0}}{\partial vbiei} \cdot \frac{\partial vbiei}{\partial v_{tot}} \cdot \frac{\partial v_{tot}}{\partial T} =$$

$$-m(x_{dEb0}) \cdot \tilde{C}_{jEi0} \cdot \frac{d(vdei)}{dT}$$

Substitution reveals a new model parameter and a PDE w.r.t. *vdei*

$$\delta_E = \frac{m(x_{dEb0})}{\overline{m}_E} \qquad \frac{\partial Q_{jE}}{\partial(vdei)} = -\overline{m}_E \cdot (\delta_E \cdot \tilde{C}_{jEi0} + \tilde{C}_{jEi} - \tilde{C}_{jEi0})$$

Similarly for the collector side

$$\delta_C = \frac{m(x_{dCb0})}{\overline{m}_C} \qquad \frac{\partial Q_{jC}}{\partial(vdci)} = -\overline{m}_C \cdot (\delta_C \cdot \tilde{C}_{jCi0} + \tilde{C}_{jCi} - \tilde{C}_{jCi0})$$

Solution of the pair of PDEs must contain a bias ***and*** temperature independent constant Q_{p0} redefined to

„quiescent hole charge“

Temperature dependence: final result

Integrals can be performed w.r.t. the built in voltages yielding

$$Q_{pT\_low} = Q_{p0} + \overline{m}_E \cdot \tilde{Q}_{jEnom} \cdot \tilde{\Gamma}_{ET} + \overline{m}_C \cdot \tilde{Q}_{jCnom} \cdot \tilde{\Gamma}_{CT}$$

$$\Gamma_{JT} = \frac{\delta_J}{1-zji} \cdot \left[1 - \left(\frac{vdji_T}{vdji_0} \right)^{1-zji} \right] + \Phi_{JT}$$

Hicum/L2v24: $Q_{pT\_low} = Q_{p0} \cdot \left[2 - \left(\frac{vdei_T}{vdei_0} \right)^{zei} \right] + hjei \cdot \tilde{Q}_{jEnom} \cdot \tilde{\Phi}_{ET} + hjci \cdot \tilde{Q}_{jCnom} \cdot \tilde{\Phi}_{CT}$

Neither the *E* nor the *C* terms agree. Inserting an additional segment in the undepleted base region, Q_{p0} should change but its temperature dependence should not since the added segment is *T*-independent

The *generic* approach yields with $\overline{m}_E = \overline{m}_C = 1$

$$Q_{pT\_low} = Q_{p0} + \overline{Q}_{jEnom} \cdot \overline{\Gamma}_{ET} + \overline{Q}_{jCnom} \cdot \overline{\Gamma}_{CT}$$

Model parameters δ_J change accordingly but all functional forms stay the same

Temperature dependence: heterobandgap

Temperature variation of the quiescent hole charge:

$$\frac{\partial Q_{p0}}{\partial T} = q \cdot A_E \cdot \int_{xdEb0}^{xdCb0} \frac{\partial \ln(m(x))}{\partial T} \cdot N_{eff}(x) \cdot dx = \frac{d}{dT}\left(-\frac{T_0}{T}\right) \cdot q \cdot A_E \cdot \int_{xdEb0}^{xdCb0} \frac{\Delta V_G(x) - \Delta V_G(x_R)}{V_{T0}} \cdot N_{eff}(x) \cdot dx$$

Approximately 7mV bandgap reduction can be achieved in Si by adding 1% Ge contaminant. A typical Ge ramp of 15% yields approximately $\Delta V_G / V_{T0} = 4$ what is small to $N_{eff}(x)$ allowing a separation

$$\zeta_{G0} = \int_{xdEb0}^{xdCb0} \left[\frac{\Delta V_G(x) - \Delta V_G(x_R)}{V_{T0}}\right] \cdot N_{eff}(x) \cdot dx \Bigg/ \int_{xdEb0}^{xdCb0} N_{eff}(x) \cdot dx$$

Resulting solution of the PDE $\frac{\partial Q_{p0}}{\partial T} = \frac{d}{dT}\left(-\frac{T_0}{T}\right) \cdot \zeta_{G0} \cdot Q_{p0}$ reads

$$\boxed{Q_{p0}^{G} = Q_{p0} \cdot \exp\left[\left(1 - \frac{T_0}{T}\right) \cdot \zeta_{G0}\right]}$$

Temperature dependence: heterobandgap, cont.'d

Temperature variation of the emitter MRG charge is approximately:

$$\frac{\partial \overline{Q}_{jE}}{\partial T} \approx q \cdot A_E \int_{xdEb}^{xdEb0} \frac{\partial \ln(m(x))}{\partial T} \cdot N_{eff}(x) \cdot dx$$

As before, it yields for the *E* and *C* nominal MRG charges

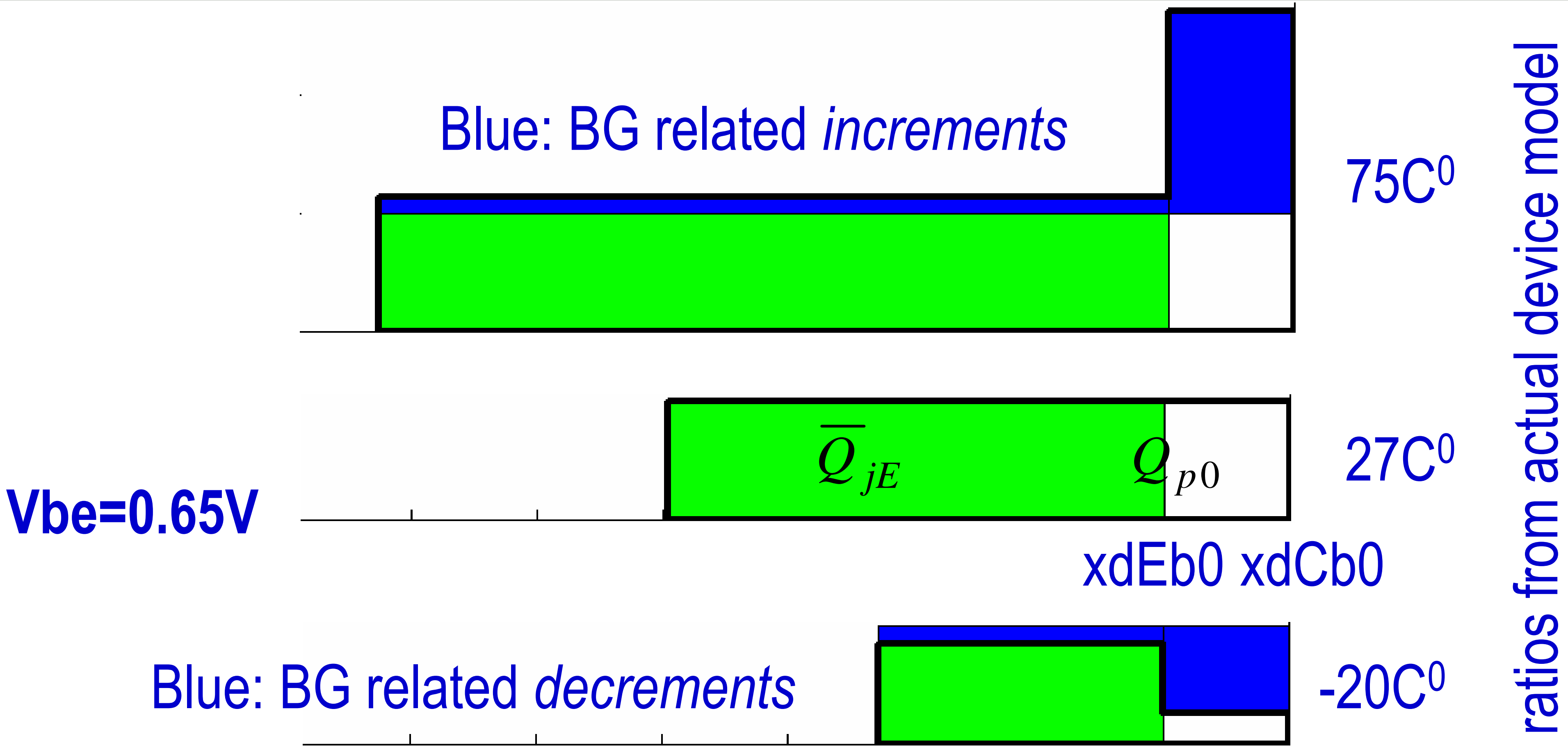
$$\boxed{Q_{jEnom}^{G} = \overline{Q}_{jEnom} \cdot \exp\left[\left(1-\frac{T_0}{T}\right)\cdot \zeta_{GE}\right]} \qquad \boxed{Q_{jCnom}^{G} = \overline{Q}_{jCnom} \cdot \exp\left[\left(1-\frac{T_0}{T}\right)\cdot \zeta_{GC}\right]}$$

The integration limits x_{dEb} and x_{dCb} also change in the PDEs what have been neglected here as second orders. It is proven in [1] though that the above temperature variations are exact for $\overline{C}_{jE0}$ and $\overline{C}_{jC0}$

$$\boxed{Q_{pT\_low}^{G} = Q_{p0}^{G} + Q_{jEnom}^{G} \cdot \overline{\Gamma}_{ET} + Q_{jCnom}^{G} \cdot \overline{\Gamma}_{CT}}$$

This general result has been achieved w/o assuming any specific Ge profile as opposed to [6]

Temperature dependence: illustration



Net Q_{pT_low} resides in black frames (Q_{jC} was negligible this case)

Junction and BG related temperature variations are „orthogonal“

Temperature dependence: low bias transit time and Q_{f0}

Bandgap induced temperature variation affects the low bias transit time as well. With approximation for large drift factors

$$t_0 = \frac{W_B^2}{\mu_{n0} \cdot V_{T0}} \cdot \left(\frac{T_0}{T}\right)^{1-\zeta_n} \cdot f(\eta_{eff}) \approx \frac{W_B^2}{\mu_{n0} \cdot V_{T0}} \cdot \left(\frac{T_0}{T}\right)^{1-\zeta_n} \cdot \frac{1}{\eta_{eff}}$$

The effective drift factor at a linear Ge ramp reads

$$\eta_{eff} = \eta + \frac{T_0}{T} \cdot \frac{\Delta V_G}{V_{T0}}$$

This adds a mild further variation to the homobandgap case what can be conveniently absorbed by the existing quadratic temperature mapping

$$t_0(T) = t_0(T_0) \cdot \left[1 + alt0 \cdot (T - T_0) + kt0 \cdot (T - T_0)^2\right]$$

No change in t_0 and Q_{f0} is required

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Temperature dependence: weight of E minority charge

$$hfe(T) = \frac{\int_{x_E}^{x_{jE}} m_E(x,T)\cdot p_E(x)\cdot dx}{\int_{x_E}^{x_{jE}} p_E(x)\cdot dx} \approx \frac{\mu_n(x_R)}{\mu_n(\xi_E)}\cdot \exp\left[\frac{T_0}{T}\cdot\frac{\Delta V_G(x_R)-\Delta V_{GE}}{V_{T0}}\right] \quad x_E < \xi_E < x_{jE} \quad \Delta V_{GE} = BGN_E$$

$$tef\,0(T) = tef\,0(T_0)\cdot\left(\frac{T_0}{T}\right)^{-zetatef}\cdot\exp\left[-\frac{vgb-vge}{V_{T0}}\cdot\left(1-\frac{T_0}{T}\right)\right]$$ std. temperature dependence

$$hfe(T)\cdot\Delta Q_{Ef}(T) = hfe(T)\cdot tef\,0(T)\cdot\text{(other terms)} \propto \left(\frac{T_0}{T}\right)^{-zetatef}\cdot\exp\left[-\frac{vgb-vge_{eff}}{V_{T0}}\cdot\left(1-\frac{T_0}{T}\right)\right]$$

$$tef\,0(T) = tef\,0(T_0)\cdot\left(\frac{T_0}{T}\right)^{-zetatef}\cdot\exp\left[-\frac{vgb-vge_{eff}}{V_{T0}}\cdot\left(1-\frac{T_0}{T}\right)\right]$$

modified *vge*

hfe* stays constant with its *T*-dependence absorbed by *tef0(T)

Temperature dependence: weight of C minority charge

$$hfc(T) = \frac{\int_{x_{jC}}^{x_C} m_C(x,T) \cdot p_C(x) \cdot dx}{\int_{x_{jC}}^{x_C} p_C(x) \cdot dx} \approx \frac{\mu_n(x_R)}{\mu_n(\xi_C)} \cdot \exp\left[\frac{T_0}{T} \cdot \frac{\Delta V_G(x_R)}{V_{T0}}\right] \quad x_{jC} < \xi_C < x_C \quad BGN_C \approx 0$$

$$thcs(T) = thcs(T_0) \cdot \left(\frac{T_0}{T}\right)^{1-zetaci}$$

thcs(T) can only partially absorb the bandgap feature effects

$$thcs(T) = thcs(T_0)\left(\frac{T_0}{T}\right)^{1-zetaci} \cdot \exp\left[-\frac{\Delta V_{GR}}{V_{T0}} \cdot \left(1 - \frac{T_0}{T}\right)\right]$$

modified *thcs(T)* would allow leaving *htc* constant

Either *hfc* should be scaled as shown or the temperature dependence of *thcs* should be modified (preferred). Needs more experiment or TCAD to decide: no modification in this framework.

Temperature dependence: base resistance

The quiescent part of the stored *minority charge* with typically $f_{DQr0} < 0$

$$\tilde{Q}_0 = q \cdot A_E \int_{xdEb0}^{xdCb0} N(x) \cdot dx \le q \cdot A_E \int_{xdEb0}^{xdCb0} N_{eff}(x) \cdot dx = Q_{p0} \Longrightarrow \tilde{Q}_0 = (1 + f_{DQr0}) \cdot Q_{p0}$$

The conductivity modulation is to be re-written by the *total* AC junction related charges referenced to the **quiescent** depletion boundaries [5]

$$r_i = r_{Bi0} \cdot \frac{\tilde{Q}_0}{\tilde{Q}_0 + \tilde{Q}_{jEtot} + \tilde{Q}_{jCtot} + Q_f} \qquad Q_{jtot} = \frac{Q_{jnom}}{1-z} \cdot \left[1 - \left(\frac{v_{tot}}{vd_0}\right)^{1-z}\right]$$

Refines temperature dependence. *rbi* is overaddressed in the model:
change is justified only along with other due updates

Tetrode structures are not able to detect the bandgap related temperature variation of Q_{p0}

Model implementation: HICUM/L2v2.24G

$$n_i^2(x_R,T) = n_{i,Si}^2 \cdot \exp\left(\frac{\Delta V_G(x_R)}{V_{T0}}\frac{T_0}{T}\right)$$

The bandgap shrink in the reference point has been tacitly merged in *vgb* since the introduction of the model thus c_{10} will be kept as it is.

$$I_T = c_{10} \cdot \frac{\exp\left(\frac{vbiei}{mcf \cdot V_T}\right) - \exp\left(\frac{vbici}{V_T}\right)}{Q_{p0}^G + h_{jei}^G \cdot Q_{p0} \cdot \overline{\Gamma}_{ET} + h_{jci}^G \cdot Q_{p0} \cdot \tilde{\Gamma}_{CT} + Q_{fT}(I_{Tf}, I_{Tr})}$$

$$h_{jei} = \frac{\overline{Q}_{jEnom}}{Q_{p0}} \qquad h_{jci} = \frac{\tilde{Q}_{jCnom}}{Q_{p0}} \qquad h_{jei}^G = h_{jei} \cdot \exp\left[\left(1-\frac{T_0}{T}\right)\cdot \zeta_{GE}\right]$$

$$Q_{p0}^G = Q_{p0} \cdot \exp\left[\left(1-\frac{T_0}{T}\right)\cdot \zeta_{G0}\right] \qquad h_{jci}^G = h_{jci} \cdot \exp\left[\left(1-\frac{T_0}{T}\right)\cdot \zeta_{GC}\right]$$

Reverse active mode of operation is usually irrelevant hence the *C* side has been left AC linked. No other changes than indicated.

HICUM/L2v2.24G: alternative *IS* parameter

This model formulation allows for “pseudo-normalization” by specifying *is#0* which case *c10=is*qp0* is internally computed by the code.

nominal temperature:

$$I_T = \frac{is \cdot Q_{p0} \cdot \left[\exp\left(\frac{vbiei}{mcf \cdot V_T} \right) - \exp\left(\frac{vbici}{V_T} \right) \right]}{Q_{p0} + h_{jEi} \cdot Q_{p0} \cdot \overline{\Gamma}_{ET} + h_{jCi} \cdot Q_{p0} \cdot \tilde{\Gamma}_{CT} + Q_{fT}(I_{Tf}, I_{Tr})}$$

Q_{fT} vanishes at low currents implying Q_{p0} to cancel out. Extraction of or importing *is*, *hjei* and *hjci* becomes a straightforward procedure. This will be essential for bandgap features parameter extraction.

The correlation nightmare among *c10, qp0, hjei, hjci* existing in the stdandard Hicum/L2 formulations at low bias has been removed, making the model uniquely extractable for these parameters

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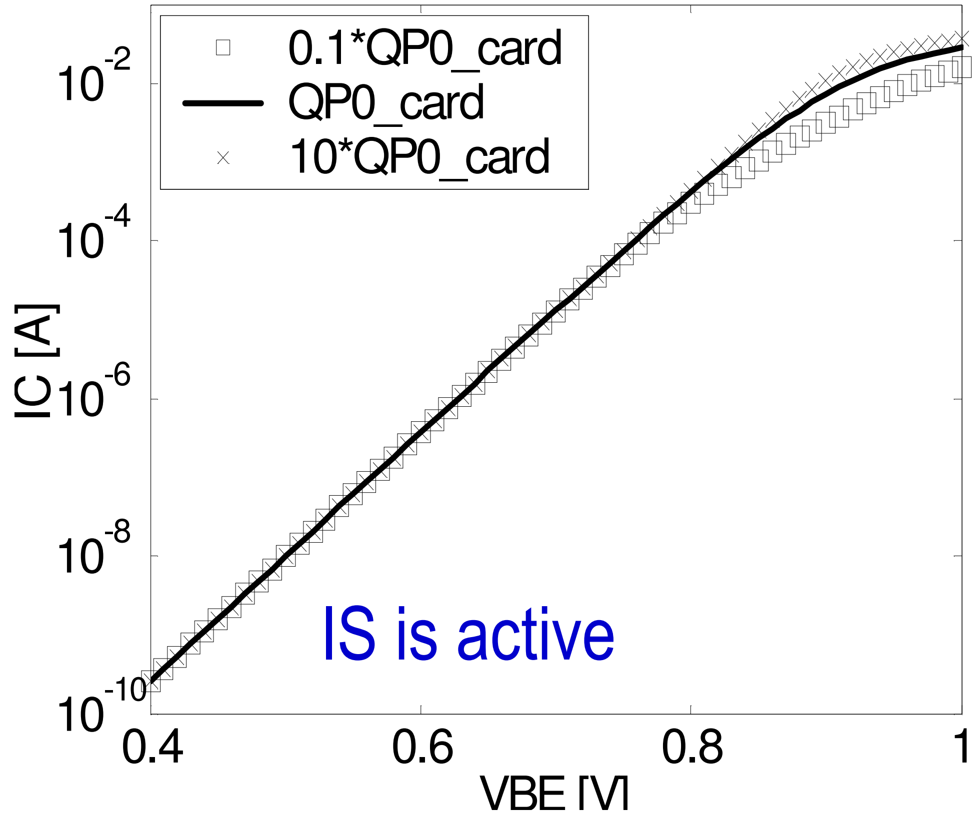
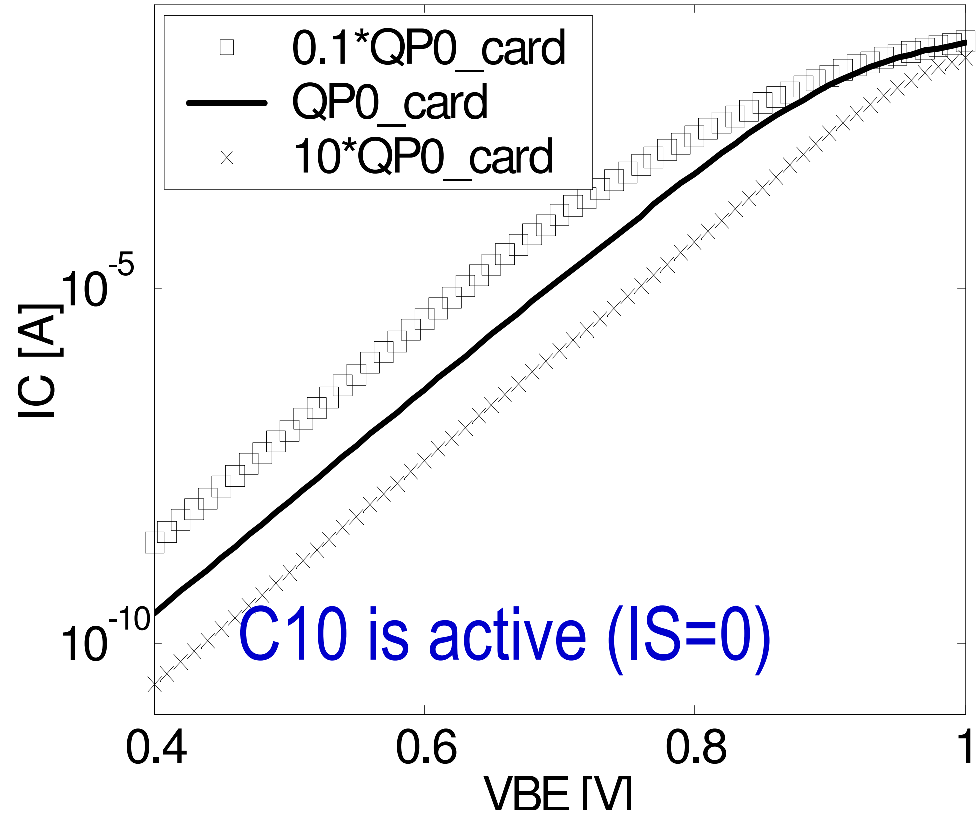
HICUM/L2v2.24G: pseudo-normalization





Vbe<= 0.7 interval is invariant to range of order qp0 variations. qp0 is a medium-current parameter: its extraction by low bias methods like using tetrode structures might be error prone

Additional model parameters, HICUM/L2v2.24G

no	name	description	default	range	unit	factor
1	delte	coefficient of the zero bias emitter MRG charge temperature variation	0	[0:Inf)	-	-
2	deltc	coefficient of the zero bias collector MRG charge temperature variation	0	[0:Inf)	-	-
3	zetag0	bandgap parameter of the quiescent hole charge	0	[-10:10]	-	-
4	zetage	bandgap parameter of the emitter MRG charge	0	[-10:10]	-	-
5	zetagc	bandgap parameter of the collector MRG charge	0	[-10:10]	-	-
6	zedc	grading factor of the emitter MRG charge	0.9	[0:1)	-	-
7	vdedc	built in potential of the emitter MRG charge	0.9	(0:10]	V	-
8	ajedc	ratio maximum to zero bias value of the B-E MRG charge voltage gradient	10	[0:Inf)	-	-
9	is	saturation current (alternative to c10)	0	[0:1]	A	M

Model implementation, HICUM/L0v1.2G

$$ver = \frac{Q_{p0}}{\overline{Q}_{jEnom}} = \frac{1}{hjei} \qquad ver^G = ver \cdot \exp\left[\left(1 - \frac{T_0}{T}\right) \cdot \zeta_{VER}\right] \qquad \zeta_{VER} = \zeta_{G0} - \zeta_{GE}$$

$$vef = \frac{Q_{p0}}{\tilde{Q}_{jCnom}} = \frac{1}{hjci} \qquad vef^G = vef \cdot \exp\left[\left(1 - \frac{T_0}{T}\right) \cdot \zeta_{VEF}\right] \qquad \zeta_{VEF} = \zeta_{G0} - \zeta_{GC}$$

$$\zeta_{IQF} = \zeta_{G0} \qquad \exp_T = \exp\left[\left(1 - \frac{T_0}{T}\right) \cdot \zeta_{IQF}\right]$$

$$iqf^G = iqf \cdot \exp_T \qquad iqr^G = iqr \cdot \exp_T \qquad iqfh^G = iqfh \cdot \exp_T \qquad iqfe^G = iqfe \cdot \exp_T \qquad (iqfe = iqfh / tfh)$$

$$is^G(T) = is(T_0) \cdot \left(\frac{T}{T_0}\right)^{\zeta_{CT}} \cdot \exp\left[\left(\frac{vgb}{V_{T0}} - \zeta_{IQF}\right) \cdot \left(1 - \frac{T_0}{T}\right)\right] \qquad \boxed{I_T = is^G \cdot \frac{\exp\left(\frac{vbiei}{mcf \cdot V_T}\right) - \exp\left(\frac{vbici}{mcr \cdot V_T}\right)}{q_{pT}^G}}$$

This looks fairly complicated: normalization smears the bandgap effects all over the model. **Theoretical advantage of the provident omission of normalization in HICUM/L2 is evident.**

Additional model parameters, HICUM/L0v1.2G

no	name	description	default	range	unit	factor
1	delte	coefficient of the zero bias emitter MRG charge temperature variation	0	[0:Inf)	-	-
2	deltc	coefficient of the zero bias collector MRG charge temperature variation	0	[0:Inf)	-	-
3	zetaver	bandgap parameter of the reverse Early coefficient	0	[-10:10]	-	-
4	zetavef	bandgap parameter of the forward Early coefficient	0	[-10:10]	-	-
5	ibhrec	specific BC barrier recombination current	0	[0:1]	A	M
	iqfe	roll-off current of the emitter charge component, 0 is Inf (replaces tfh by iqfe=iqfh/tfh)	0	[0:1]	A	M

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Summary

- a *principal* low bias charge expression has been derived relying on the widely accepted depletion approximation
- the AC linked approach has been shown to be only an option with the risk of implying model misfit at advanced SiGe devices
- a *generic* approach has been suggested for the MRG charges
- novel *quiescent* low bias charge concept and consistent *bandgap feature* temperature model have been proposed
- model was implemented in MATLAB and benchmarked to the modified VA codes Hicum/L2v2.24G and Hicum/L0v1.2G

Appreciation

It is honourable mention the vision of the Hicum originators

Prof. Dr.-Ing. H. M. Rein and Prof. Dr.-Ing. M. Schröter

for having proposed a model such that it seamlessly allows for extensions not relevant at the time of its native formulation

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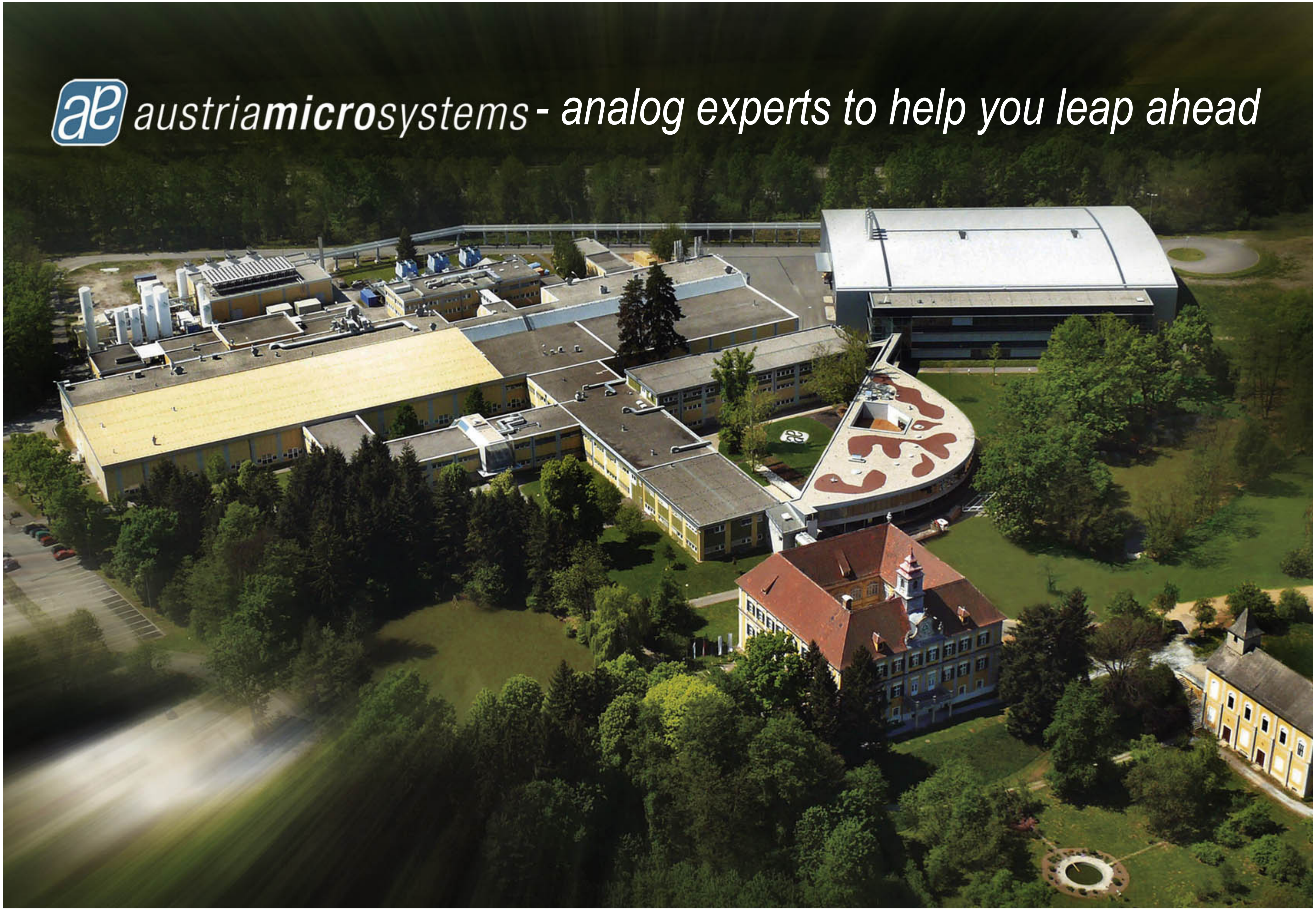
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