“IGICCR Part II: Full HicumL2 Extraction Flow with Self Heating”

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in Device Characterization and Modeling
Outline

• recall and summarize formerly introduced IGICCR concept
• alternative normalized and convenience HL2 parameters
• the (G)ICCR crash condition
• rescue scheme to preserve HL2 functionality
• extraction flow with SH, determination of RTH
• extraction snapshots
• resolving temperature coefficient conflict
• concluding full HL2 extraction
Introduction of IGICCR

The classical GICCR charge in Hicum L2 (HL2) reads

\[ Q_T = Q_{p0,T} + hjei \cdot C_{jEi0} \cdot v_{jE} + hjci \cdot C_{jCi0} \cdot v_{jC} + Q_{FB} + Q_r + hfe \cdot Q_{FE} + hfc \cdot Q_{FC} \]

[1] suggested an improved (IGICCR) formulation

\[ Q_T = Q_{p0,T} + C_{jEh0} \cdot v_{jEh} + C_{jCh0} \cdot v_{jCh} + Q_{FB} + Q_r + hfe \cdot Q_{FE} + hfc \cdot Q_{FC} \]

The new junction related (or Early) charge components

\[ Q_{jEh} = C_{jEh0} \cdot v_{jEh} (V_{biei}, v\text{deh}, z\text{eh}) \]
\[ Q_{jCh} = C_{jCh0} \cdot v_{jCh} (V_{bici}, v\text{dch}, z\text{ch}) \]

are extracted from the DC characteristics assuming the same capacitance and charge formulas as used in HL2 with GICCR

That time it was suggested an improvement but by now it turned out to be an escape route from GICCR model crash situations
Normalized and convenience parameters

Alternative model card entries, NOT NEW PARAMETERS!
(cje0m, cjc0m are the measured or smoothed BE and BC zero bias capacitances)

\begin{align*}
    \text{is} &= \frac{c10}{qp0} \\
    \text{ver} &= \frac{qp0}{hjei \cdot C_{jEi0}} \\
    \text{vef} &= \frac{qp0}{hjci \cdot C_{jCi0}} \\
    \text{ikf} &= \frac{qp0}{t0} \\
    \text{ikr} &= \frac{qp0}{tr}
\end{align*}

$$
\begin{align*}
    \text{favln} &= \text{favl} \cdot \text{vdc}\text{i} \\
    \text{qavln} &= \frac{\text{qavl}}{\text{cjci0} \cdot \text{vdc}\text{i}}
\end{align*}
$$

\[ k\text{perie} = \frac{\text{cjep0}}{\text{cje0m} - \text{cbepar}} \]
\[ k\text{peric} = \frac{\text{cjcx0}}{\text{cjc0m} - \text{cbcpar}} \]

Conversion to original L2 parameters

\begin{align*}
    \text{qp0} &= \text{ikf} \cdot t0 \\
    \text{c10} &= \text{is} \cdot \text{qp0} \\
    \text{hjei} &= \frac{qp0}{\text{ver} \cdot C_{jEi0}} \\
    \text{hjci} &= \frac{qp0}{\text{vef} \cdot C_{jCi0}} \\
    \text{tr} &= \frac{qp0}{\text{ikr}} \\
    \text{favl} &= \frac{\text{favln}}{\text{vdc}\text{i}}
\end{align*}

\[ \text{cjep0} = k\text{perie} \cdot (\text{cje0m} - \text{cbepar}) \]
\[ \text{cjcx0} = k\text{peric} \cdot (\text{cjc0m} - \text{cbcpar}) \]
\[ \text{cjei0} = \text{cje0m} - \text{cbepar} - \text{cjep0} \]
\[ \text{cjci0} = \text{cjc0m} - \text{cbcpar} - \text{cjcx0} \]

Back transformation is done before model computation with no change in any of the official equations.
Low-Medium bias DC extraction equation

Transfer current in normalized form:

\[ i_T = \frac{\text{is} \cdot \left[ \exp\left(\frac{\text{vbiei}}{\text{mcf} \cdot V_T}\right) - \exp\left(\frac{\text{vbici}}{V_T}\right)\right]}{1 + \frac{V_{jEi}}{\text{ver}} + \frac{V_{jCi}}{\text{vef}} + \frac{Q_{fT} + Q_{rT}}{q0}} \]

Simplify notations by:

\[ h_{vbc} = 1 + \frac{d t 0 h}{t0} \cdot (c - 1) + \frac{t b y l}{t0} \cdot \left(\frac{1}{c} - 1\right); \quad w_{E\Delta}^2 = \frac{1}{1 + gte} \cdot \left(\frac{i_{ff}}{i_{ck}}\right)^{gte} \]

\[ i_T = \frac{\text{is} \cdot \left[ \exp\left(\frac{\text{vbiei}}{\text{mcf} \cdot V_T}\right) - \exp\left(\frac{\text{vbici}}{V_T}\right)\right]}{1 + \frac{V_{jEi}}{\text{ver}} + \frac{V_{jCi}}{\text{vef}} + \frac{i_{Tr}}{\text{ikr}} + \frac{i_{ff}}{\text{ikf}} \cdot \left\{ h_{vbc} + \frac{t e f 0}{t0} \cdot h f e \cdot w_{E\Delta}^2 + \frac{t h c s}{t0} \cdot \left[(1 - f t h c) \cdot w_{B\Delta}^2 + h f c \cdot f t h c \cdot w_{C\Delta}^2\right] \right\}} \]

Low- medium bias (Vbe<=0.85V, Vbc=0V):

\[ i_{icwz} = \frac{Q_{p,T}}{c 10} = \text{ic}^{-1} \cdot \exp\left(\frac{\text{vbe}}{V_T}\right) = \frac{1 + \frac{V_{jEi}}{\text{is} \cdot \text{ver}} + \frac{ic}{\text{is} \cdot \text{ikf}}}{\text{is} \cdot \text{ikf}} \]
(G)ICCR crash condition, theory

is and ver can be extracted in low bias Vbe<=0.70V:

either from (A) \[ iicw_z(vbe) = \frac{1}{is} + \frac{1}{is \cdot ver} \cdot v_{jEi}(vbe) \]
or from (B) \[ \frac{iicw_z(vbe)}{v_{jEi}(vbe)} = \frac{1}{is \cdot ver} + \frac{1}{is} \cdot \frac{1}{v_{jEi}(vbe)} \]

Both (A) and (B) must have positive slopes to have is>0

For regression (B):

\[
\frac{\partial(iicw_z/v_{jEi})}{\partial(1/v_{jEi})} = \frac{1}{v_{jEi}} \cdot \frac{\partial(iicw_z)}{\partial(1/v_{jEi})} = \frac{1}{v_{jEi}} \cdot \left[ \frac{\partial \ln(iicw_z)}{\partial V_{be}} \right] = \frac{iicw_z}{\partial \ln(Q_{jEi})} \cdot \frac{\partial \ln(iicw_z)}{\partial V_{be}} = \frac{iicw_z}{\partial \ln(Q_{jEi})} \cdot \frac{\partial \ln(iicw_z)}{\partial V_{be}}
\]

Declining \[ Q_{jEi} \cdot ic \cdot \exp \left( -\frac{vbe}{V_T} \right) \] is indicating (G)ICCR crash when VBIC, HL2, and HL0 can not be directly used for modeling
(G)ICCR crash condition, examples

(G)ICCR crash test

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

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

Junction related (static) and actual (dynamic) charges have different physical origin as considered in IGICCR
Regression of $i_{s}$, $v_{e}$, $i_{kf}$ (70GHz device)

\[ i_{icw_{z}}(v_{be}) = \frac{1}{i_{s}} + \frac{v_{jE_{i}}(v_{be}, v_{de}, z_{e})}{i_{s} \cdot v_{e}} + \frac{i_{c}(v_{be})}{i_{s} \cdot i_{kf}} \]

\[ i_{cnorm} = \frac{i_{c}}{i_{s}} \cdot \exp\left( -\frac{v_{be}}{V_{T}} \right) \]

\[
\begin{vmatrix}
  v_{be} [V] \\
  \hline
  0.4 & 0.6 & 0.8 & 1 & 1.2 & 1.4 \\
  0 & 0.2 & 0.4 & 0.6 & 0.8 & 1 \\
\end{vmatrix}
\]

\[
\begin{vmatrix}
  i_{cnorm} \\
  \hline
  0.4 & 0.6 & 0.8 & 1 & 1.2 & 1.4 \\
  0 & 0.2 & 0.4 & 0.6 & 0.8 & 1 \\
\end{vmatrix}
\]

(G)ICCR see also [2]  

IIGICCR

\[ i_{s} = 1.466e-17A \]
\[ v_{e} = 19.027 \]
\[ i_{kf} = 4.568e-03A \]

\[ v_{de} = 0.725 \]
\[ z_{e} = 0.587 \]
Regression of $i_{s}$, $v_{er}$, $i_{kf}$ (250GHz device)

$$i_{icw_{z}}(v_{be}) = \frac{1}{i_{s}} + \frac{V_{jEi}(v_{be}, v_{de}, z_{e})}{i_{s} \cdot v_{er}} + \frac{i_{c}(v_{be})}{i_{s} \cdot i_{kf}}$$

$$i_{cnorm} = \frac{i_{c}}{i_{s}} \cdot \exp\left(-\frac{v_{be}}{V_{T}}\right)$$

$$(G)ICCR$: model crash: $i_{s}<0$

$\begin{align*}
    i_{s} &= 1.813 \times 10^{-16} A \\
    v_{er} &= 0.192 \\
    i_{kf} &= 3.386 \times 10^{-4} A \\
    v_{deh} &= 0.807 \\
    z_{eh} &= 0.791 \\
    a_{jei} &= 1.540
\end{align*}$$

$\begin{align*}
    i_{s} &= -3.716 \times 10^{-16} A \\
    v_{er} &= -0.051 \\
    i_{kf} &= -1.124 \times 10^{-4} A \\
    v_{dei} &= 0.716 \\
    z_{ei} &= 0.162 \\
    a_{jei} &= 1.540
\end{align*}$$
Rescue scheme for preserving HL2 functionality

- extract *is, ver, ikf* along with IGICCR parameters *vdeh, zeh, ajeh* by a 3-variable nonlinear optimization

- Save RF extracted *vdei, zei, ajei* in the perimeter entries, *vdeh, zeh, ajeh* in the internal ones; same for *cjc* (see later)

- allocate separate (new) *cx*-function with *cjcx* parameters for computing dynamic *Tf0x* for FT, noise etc. while leaving the original *c*-function as it is

- use compatibility parameter *alb* for missing *zetarth*
Rescue scheme, parameter partitioning summary

This work applied HL2v2.0 $r_{bi}$ to escape a relevant formulation problem in the HL2v2.22 update [4]

two redundant parameters are omitted with the constraints $cje0m$ and $cjc0m$
Extraction flow I. (flsh=0)

- extract and freeze (E&F) capacitance parameters, record $cje0m$ and $cjc0m$, select estimated $kperie$ and $kperic$
- E&F IGICCR group, avalanche and $ibe$ parameters and $re$, guess $rcx$
- E&F $ibcxs$, $mbcx$, $itss$, $msf$, $iscs$, $msc$, $rsu$, $ikr$
- tempcos $vgb$, $zetact$, $vge$, $zerabet$. E&F: $rth$, $zetarth$
- estimate transit time parameters whichever method, former card etc. providing just startup values due to self heating
Extraction flow II. (flsh=1 in preconditioned HL2)

- \( t_0, \text{cbepar}, \text{ajei} \) \( V_{be}=0.70-0.85\text{V} \), \( V_{bc}=0 \) then \( dt0h, \text{tbvl} \), \( \text{kperic} \) (see also [2]), reextract \( cje \)

- \( \text{tef}0, \text{gtfe}, \text{thcs}, \text{ahc}, \text{rci}0, \text{vlim}, \text{vces} \): FT roughly O.K.

- \( \text{re}, \text{zetare}, \text{zetact}, (\text{zetabet}) \) over high end of \( \text{rfdc} \) data

- \( \text{rcx}, \text{zci}, \text{alt}0, \text{kt}0, \text{zetare}, \text{zetact}, \text{ikf} \) on joint \( \text{foi} \) and \( \text{rfdc} \)

- Reoptimize \( \text{zetact}, \text{vgb}, \text{zetabet}, \text{vge} \) on temperature \( \text{fg} \) measurement, \( V_{be}>=0.7\text{V} \), \( V_{bc}=0\text{V} \), joint IC and IB

- Recycle with new tempcos, add \( \text{hfe}, \text{hfc} \) to fine tune high IC
Preconditioning HL2 for fast, efficient extraction at SH

Put off collector spreading by \( \text{latl} = \text{latb} = 0 \) and set \( \text{fthc} = 1 - 10^{-5} \)

\[
i_T = \frac{is \cdot \left[ \exp \left( \frac{vbiei}{V_T} \right) - \exp \left( \frac{vbici}{V_T} \right) \right]}{1 + \frac{v_{jEi}}{ver} + \frac{v_{jCi}}{vef} + \frac{i_T}{ikr} + \frac{i_T}{ikf} \cdot \left\{ hvbc + hfe \cdot \frac{tef}{t0} \cdot w_{E\Delta}^2 + \frac{thcs}{t0} \cdot w_{C\Delta}^2 + 1e - 5 \cdot \frac{thcs}{t0} \cdot w_{C\Delta}^2 \right\}}
\]

Due to significance at very high currents only, set \( \text{hfe} = \text{hfc} = 0 \) term retained for barrier recombination: negligible at \( i_T \) computation

\[
i_T = \frac{is \cdot \left[ \exp \left( \frac{vbiei}{V_T} \right) - \exp \left( \frac{vbici}{V_T} \right) \right]}{1 + \frac{v_{jEi}}{ver} + \frac{v_{jCi}}{vef} + \frac{i_T}{ikr} + \frac{i_T}{ikf} \cdot \left[ hvbc + 1e - 5 \cdot \frac{thcs}{t0} \cdot w_{C\Delta}^2 \right]}
\]

\( i_T \) is given in 1 iteration cycle, DC coupled to AC by only \( dt0h, \ tbvl \). Comparable speed but superior to HL0
It was recognized in [3] that several ambient and SH temperatures can produce identical junction temperatures. [3] will be refined in this work by an analysis providing accuracy improvement by a correction term.
Extraction of the thermal resistance cont.'d

\[
\ln \left( \frac{T_j}{T_0} \right) = \ln \left( \frac{T_j}{T_0} \right) + \frac{E}{V_{T_0}} - \frac{E - (vbe - ie \cdot re - ib \cdot rb)}{V_{Tj}} \quad T_j = T_A + rth \cdot P
\]

\[
P = vbe \cdot ie + vcb \cdot (ie - ib)
\]

At junction temperatures \( T_{j1}, T_{j2} \):

\[
\ln \left( \frac{ibei(T_{j2})}{ibei(T_{j1})} \right) = X \cdot \ln \left( \frac{T_{j2}}{T_{j1}} \right) + \frac{E - (vbe - iem \cdot re - ibm \cdot rb)}{V_{Tj1}} \cdot \left(1 - \frac{T_{j1}}{T_{j2}}\right) - \frac{\Delta i e \cdot re + \Delta i b \cdot rb}{V_{Tj1}} \cdot \left(1 + \frac{T_{j1}}{T_{j2}}\right)
\]

Taylor expansions

\[
\ln \left( \frac{T_{j2}}{T_{j1}} \right) = \ln \left( \frac{1 + h}{1 - h} \right) \approx 2h \cdot \left[1 + \frac{h^2}{3}\right] \; ; \; \frac{T_{j1}}{T_{j2}} = \frac{1 - h}{1 + h} \approx 1 - 2h \cdot [1 + h]
\]

with \( T_{jm} = \frac{T_{j2} + T_{j1}}{2} \); \( \Delta T_j = \frac{T_{j2} - T_{j1}}{2} = \frac{\Delta T_A + rth \cdot \Delta P}{2} \); \( h = \frac{\Delta T_j}{T_{jm}} \)

yield

\[
rth(V_{Tjm}) = -\frac{\Delta T_A}{\Delta P} \cdot \left[ \frac{2\Delta i e \cdot re + 2\Delta i b \cdot rb}{V_{Tj1}} + \frac{2\Delta i be i}{ibeim} \right] \cdot \left[1 - \frac{T_{jm}}{\Delta T_A} \cdot \frac{V_{Tj1}}{E - (vbe - iem \cdot re - ibm \cdot rb)} \cdot \frac{X}{\Delta T_A} \cdot \frac{V_{Tj1}}{E - (vbe - iem \cdot re - ibm \cdot rb)} \right]
\]

\( E = vge \); \( X = zetabet \)
Extraction of the thermal resistance cont.'d

At the IB intercept
omitting the rb term

\[
rth(V_{Tjm}) = rth_0 \cdot \left[ 1 - \frac{T_{jm}}{\Delta T_A} \cdot \frac{ie(T_{j2}) - ie(T_{j1})}{vbe - iem \cdot re} \right]_{ib(T_j1)=ib(T_j2)=ibm}
\]

\[
P_2 = vbe \cdot ie(T_{j2}) + vcb_2 \cdot [ie(T_{j2}) - ibm] \quad P_1 = vbe \cdot ie(T_{j1}) + vcb_1 \cdot [ie(T_{j1}) - ibm]
\]

\[
\Delta T_A = T_{A2} - T_{A1} \quad \Delta P = P_2 - P_1 \quad rth0 = -\Delta T_A / \Delta P
\]

- **W X L = 0.27 X 3um**
  - rth = 3577.61
  - zetarth = 0.95
  - rth_unc = 3706.28
  - zetarth_unc = 0.82

- **W X L = 0.27 X 5um**
  - rth = 2539.36
  - zetarth = 0.84
  - rth_unc = 2592.68
  - zetarth_unc = 0.77
Extraction of the reverse parameter group

ibcx, mbcx, itss, msf, iscs, msc, rsu, ikr

ikr extracted from the Vce<0 part of foi (next slide)
kink created by an improper dt0h, tbvl (AC) and/or by wrong vdcx, zcx (DC) combination. (IGICCR: cx(vdcx,zcx) for FT)

foi is a sensitive indicator: check it each extraction step!
Reextract CJE by FT-determined \textit{cbepar, aje}
Concluding 1st main extraction cycle

Results are apparently good but **inconsistent** because \( z_{\text{act}} \) has been departed from its low bias extracted value.
Redefining temp cos

At high ambient temperatures SH is in effect even at low bias implying false results from conventional extraction.

$\text{zetact}=3.555 \Rightarrow 7.868$

global reoptimization
Tuning for nominal temperature: FT

\[ \text{FT} \text{ [GHz]} \]

\[ \text{Vbe [V]} \]

\[ \text{Ic [mA]} \]

- \( V_{cb} = -0.50 \text{V} \)
- \( V_{cb} = -0.30 \text{V} \)
- \( V_{cb} = -0.15 \text{V} \)
- \( V_{cb} = 0.00 \text{V} \)
- \( V_{cb} = 0.15 \text{V} \)
- \( V_{cb} = 0.30 \text{V} \)
- \( V_{cb} = 0.50 \text{V} \)

- \( \text{vgb} = 0.9970 \Rightarrow 1.018 \)
- \( \text{zetact} = 3.555 \Rightarrow 5.033 \)
- \( \text{vge} = 1.133 \Rightarrow 1.336 \)
- \( \text{zetabet} = 2.787 \Rightarrow -5.658 \)

FT after 2\text{nd} tempco readjustment with hfe, hfc added
**Tuning for nominal temperature: DC**

*fg, foi after 2\(^{nd}\) tempco readjustment with hfe, hfc added*
Tuning for global temperature and bias space: FT (I)

Cross sections at medium temperature and Vcb
Cross sections at minimum and maximum $V_{cb}$

**Tuning for global temperature and bias space:** FT (II)

- **$V_{cb}=0.50V$**
  - $t=-40.00^\circ C$
  - $t=-20.00^\circ C$
  - $t=0.00^\circ C$
  - $t=27.00^\circ C$
  - $t=50.00^\circ C$
  - $t=75.00^\circ C$
  - $t=100.00^\circ C$
  - $t=125.00^\circ C$

- **$V_{cb}=-0.50V$**
  - $t=-40.00^\circ C$
  - $t=-20.00^\circ C$
  - $t=0.00^\circ C$
  - $t=27.00^\circ C$
  - $t=50.00^\circ C$
  - $t=75.00^\circ C$
  - $t=100.00^\circ C$
  - $t=125.00^\circ C$
Tuning for global temperature and bias space: FT (III)

Cross sections at minimum and maximum temperatures

Linear (neg.) $g_{tfe}$ temperature dependence was observed
Effect of zetarth

changing zetarth = 0.84 to 0

model shall incorporate temperature exponent zetarth
Summary

• (G)ICCR crash has been shown to be a real life problem
• a rescue path out of such situations has been suggested
• full extraction flow presented for the stiff crash&SH case
• highly robust RTH extraction of former Author refined
• preconditioned HL2 proved to be a highly efficient tool
• due to its flexible formulation HL2 is able for self-adopting to harsh conditions where HL0 and VBIC fail
• with proven operation at .25THz the proposed scheme is an option for .5THz (DotFive) or higher device speeds
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2. The Chapters allocated by Prof. M. Schröter from his book being written in co-authorship with Prof. A. Chakravorty provided a firm basis for a strict formulation of the IGICCR concept. His helpful remarks to the subject are also highly appreciated.
References

[1] Z. Huszka and E. Seebacher, “Removing Ambiguity from Hicum/L2 by an Improved GICCR,” 8th Hicum Workshop, 20-21 May, Böblingen, Germany


Temperature scaling of the FG (left) and the RFDC data