Mextram 504
experimental results

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Willy Kloosterman

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Outline (1)

- Status of Mextram 504
- Short overview of changes for Mextram 504
- Main results with Mextram 504

Changes in Mextram 504 (2)

Smoother epilayer modeling (1 new parameter)

- See CMC Dec '99

Decoupling of DC/AC/scaling modeling (4)

- Charge parameters decoupled from DC
- Scaling parameters decoupled from DC
- Introduction of more transit time parameters

SiGe features (2)

Self-heating (2)

Thorough review of the model (8 removed, 9 new)

- Unnecessary details removed
- Avalanche model rewritten and decoupled
- Temperature model rewritten

Process A (3)

Single Poly BiCMOS process

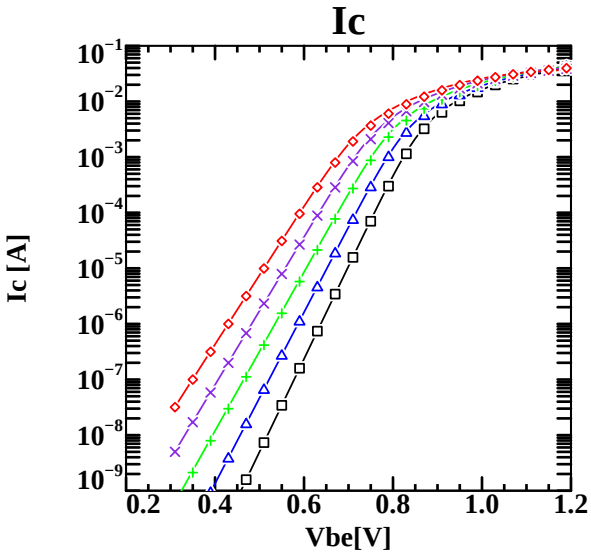
Emitter size: $0.6 \times 5.4\,\mu\mathrm{m}^2$

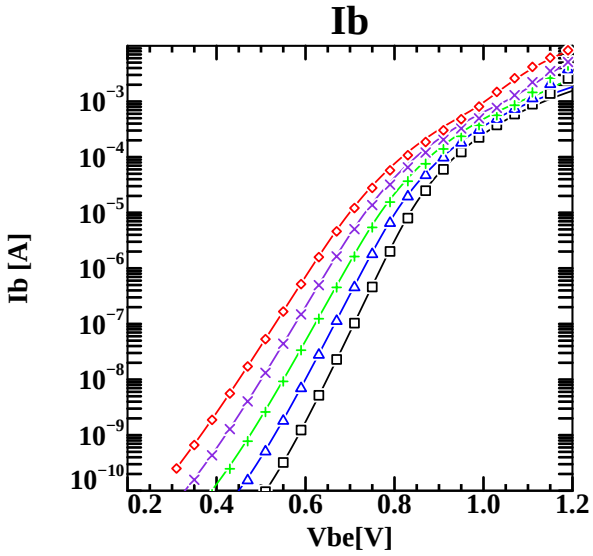
Double base contact: $\rho_{\square} = 10\,\mathrm{k}\Omega$

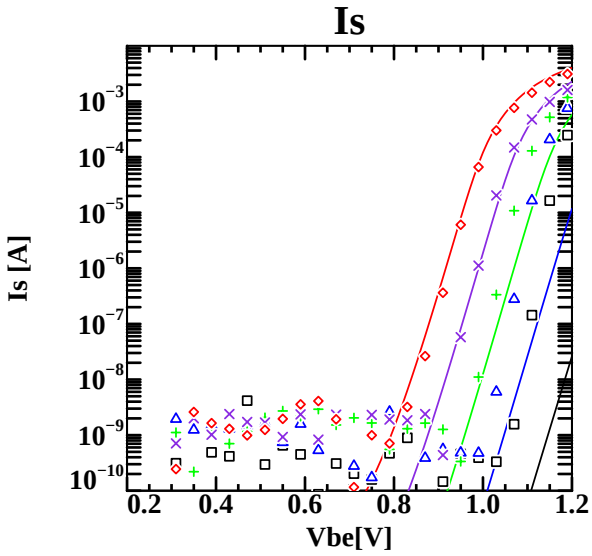
Maximum cut off frequency f_T
f_T: 10 GHz @ $V_{CE} = 5\,\mathrm{V}$
f_T: 6 GHz @ $V_{CE} = 0.5\,\mathrm{V}$

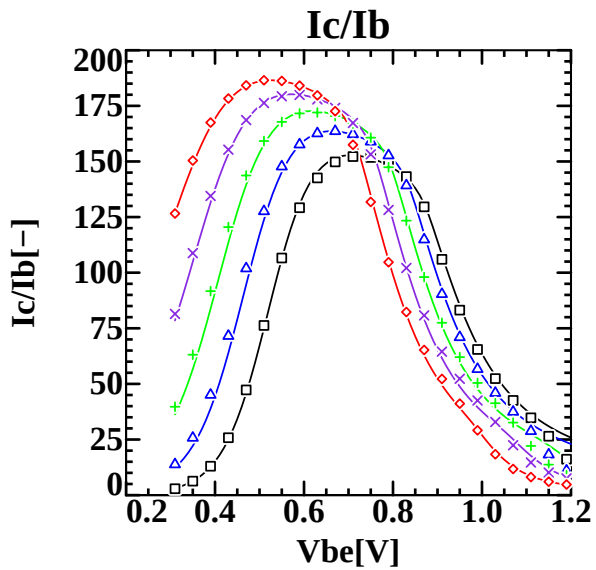
Problem for modeling:
Thick and low-doped epilayer

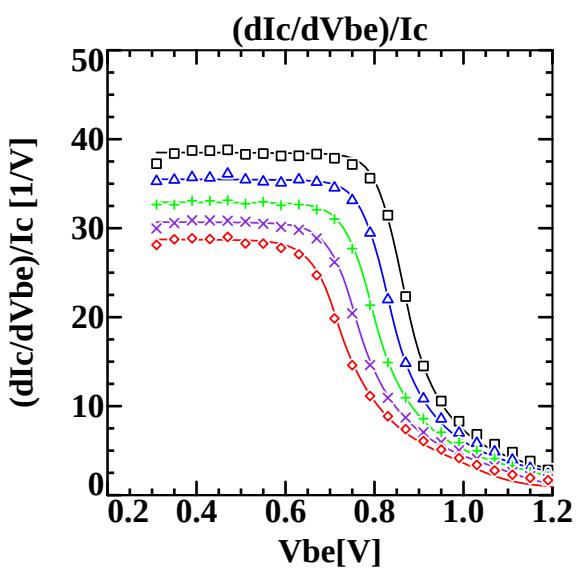
NPN A fgummel Vbc=0 Temp=25, 50, 75, 100, 125 Mextram 504.0

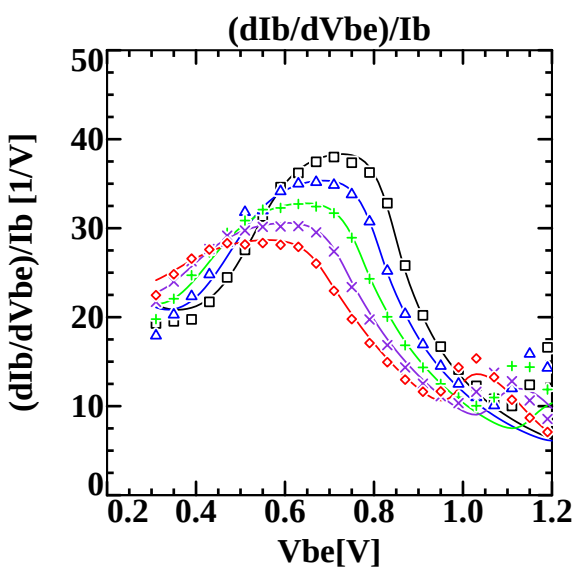


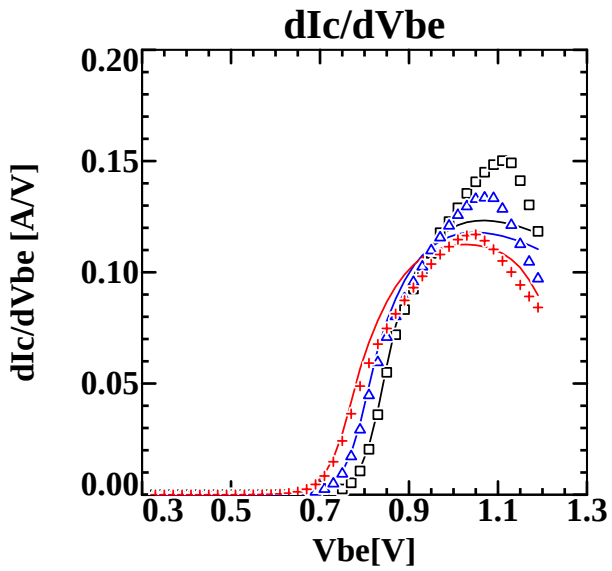


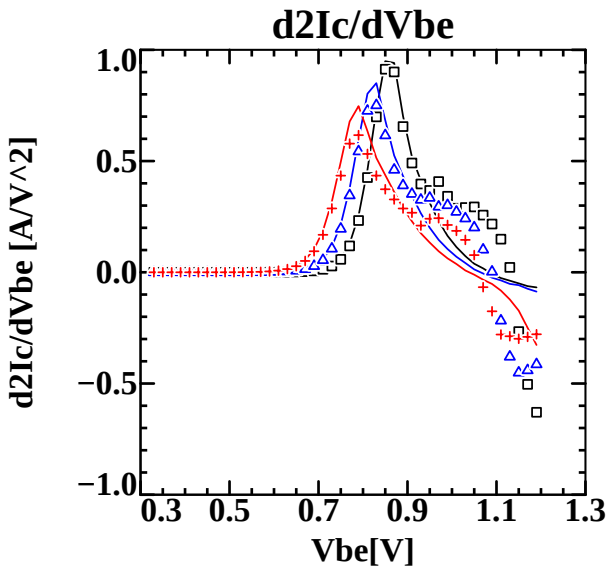


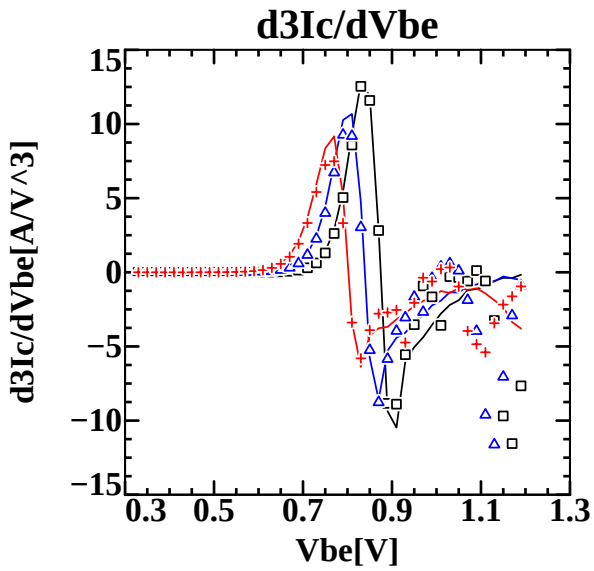


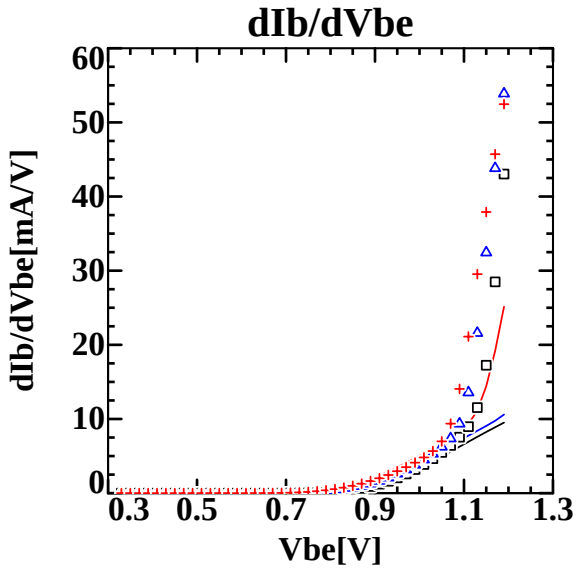


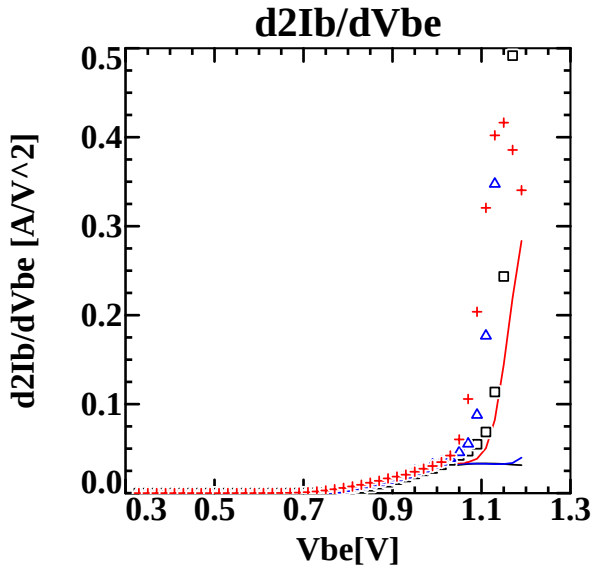


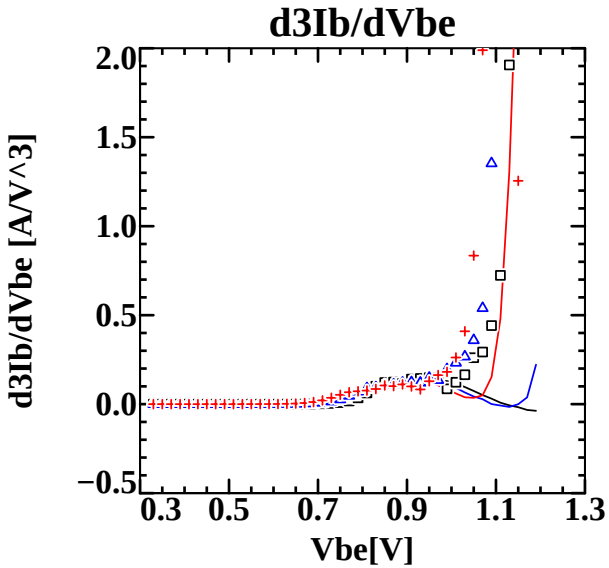

dIc/dVbe
dIc/dVbe [A/V]
0.20
0.15
0.10
0.05
0.00
0.3 0.5 0.7 0.9 1.1 1.3
Vbe[V]


d2Ic/dVbe
d2Ic/dVbe [A/V^2]
1.0
0.5
0.0
−0.5
−1.0
0.3 0.5 0.7 0.9 1.1 1.3
Vbe[V]

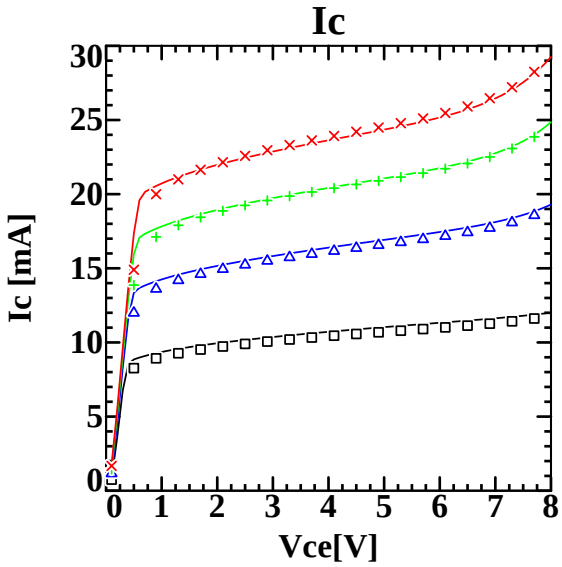

d3Ic/dVbe
d3Ic/dVbe[A/V^3]
15
10
5
0
−5
−10
−15
0.3 0.5 0.7 0.9 1.1 1.3
Vbe[V]

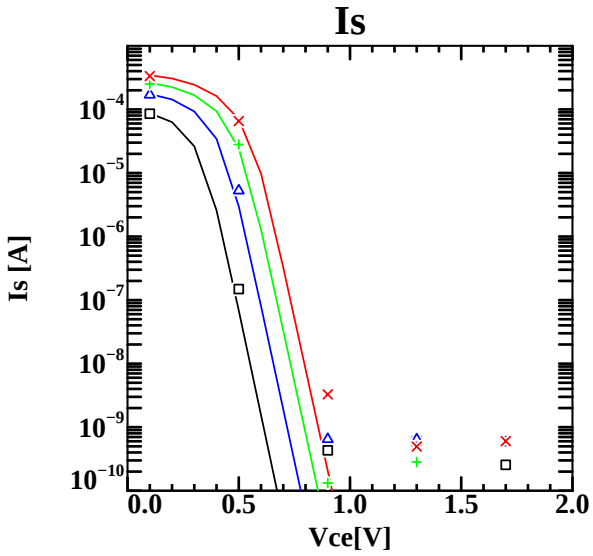

dIb/dVbe
dIb/dVbe[mA/V]
60
50
40
30
20
10
0
0.3 0.5 0.7 0.9 1.1 1.3
Vbe[V]

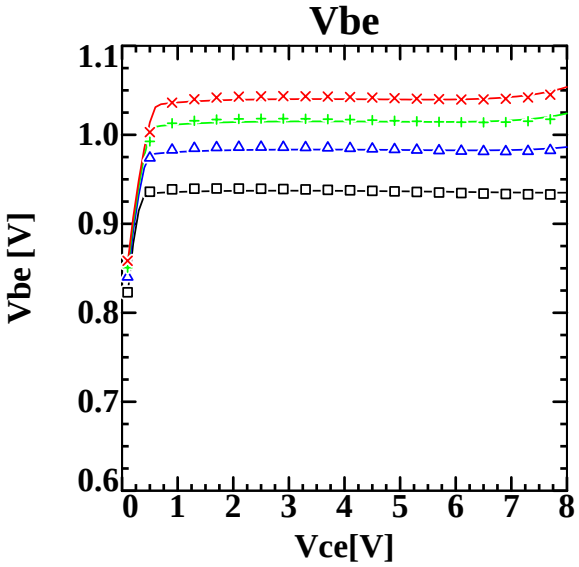

d2Ib/dVbe
d2Ib/dVbe [A/V^2]
0.5
0.4
0.3
0.2
0.1
0.0
0.3 0.5 0.7 0.9 1.1 1.3
Vbe[V]

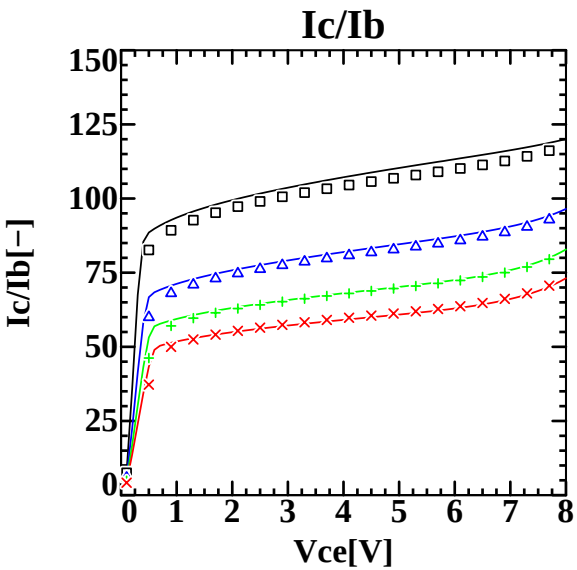

d3Ib/dVbe
d3Ib/dVbe [A/V^3]
2.0
1.5
1.0
0.5
0.0
−0.5
0.3 0.5 0.7 0.9 1.1 1.3
Vbe[V]

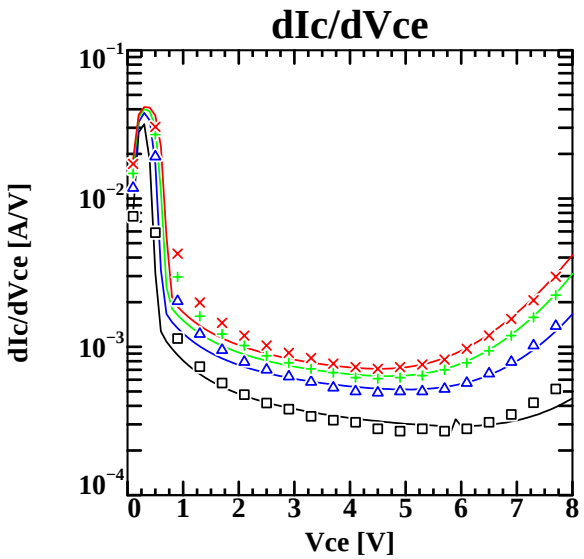
NPN A foutput_ib Temp=25 Ib= 100, 200, 300, 400 uA Mextram 504.0

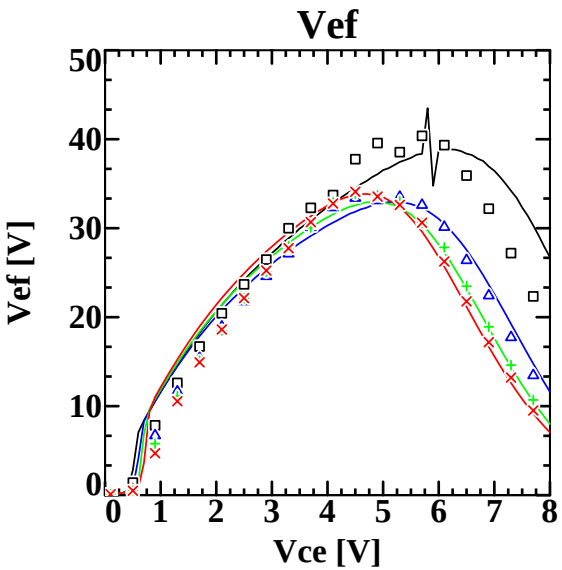


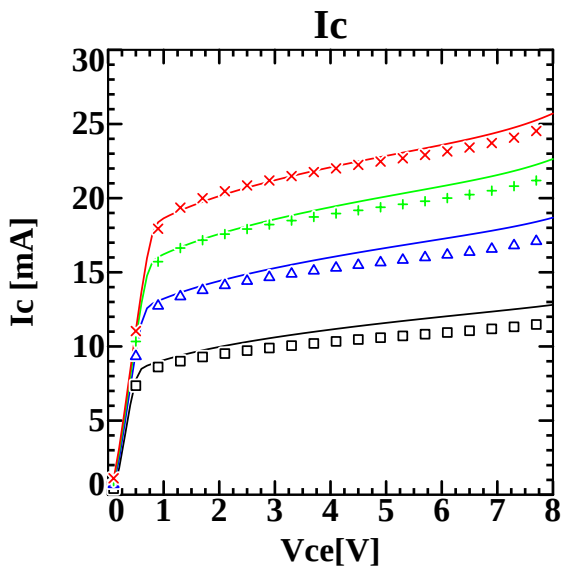


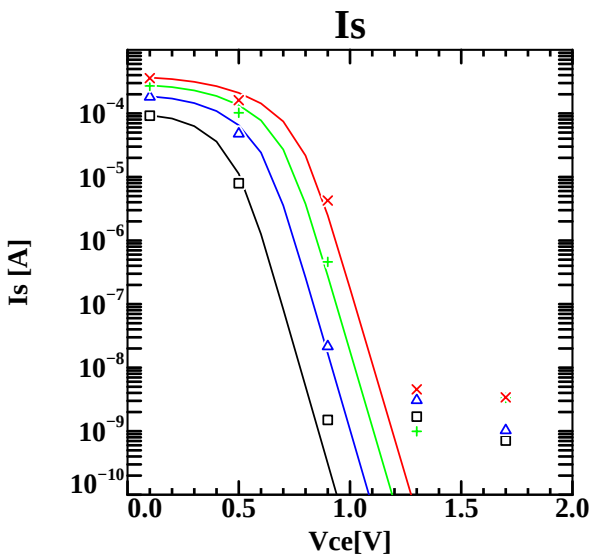


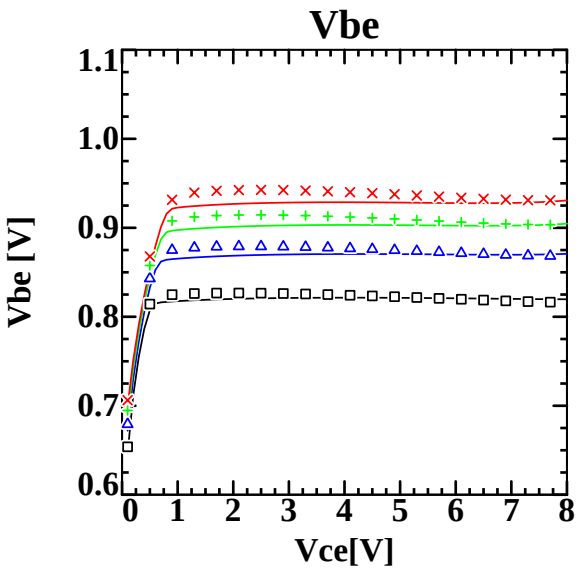


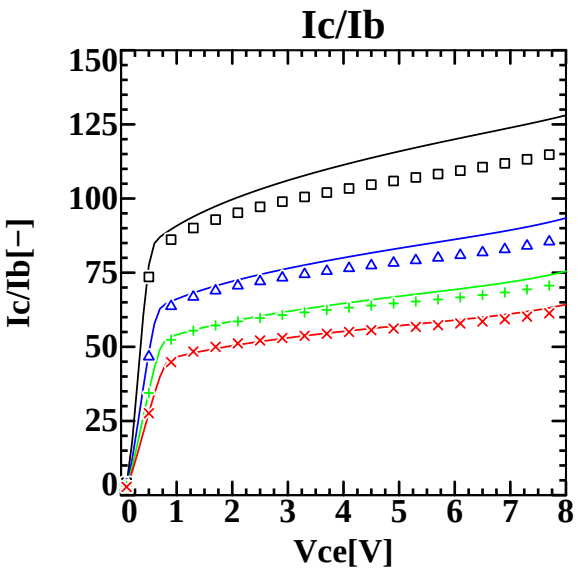


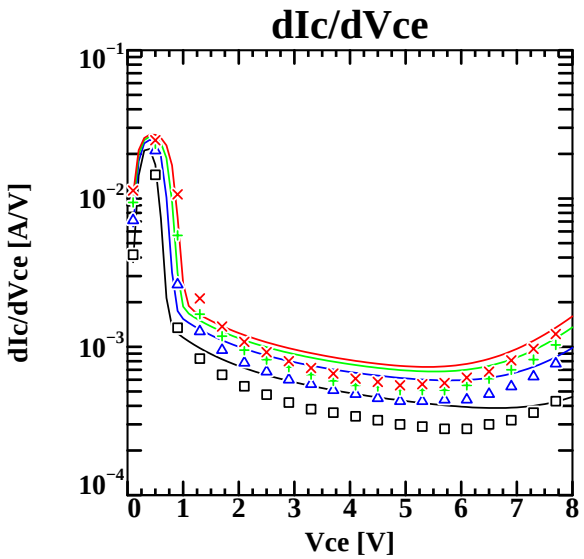


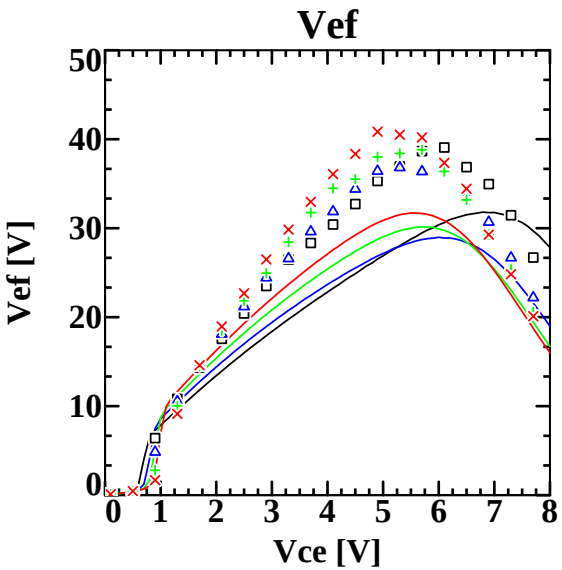

Ic
Ic [mA]
Vce[V]

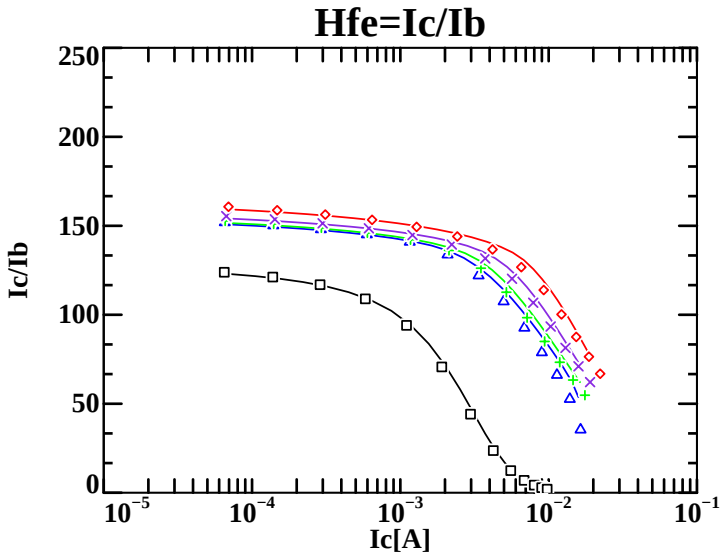

Is
Is [A]
Vce[V]

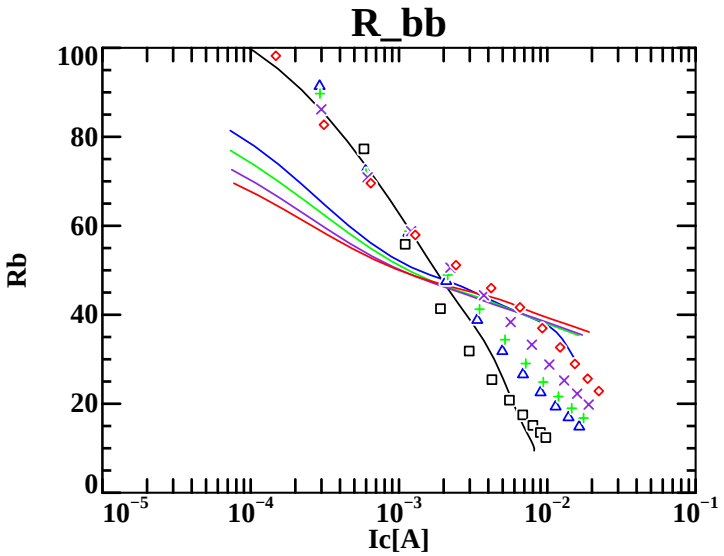

Vbe
Vbe [V]
Vce[V]

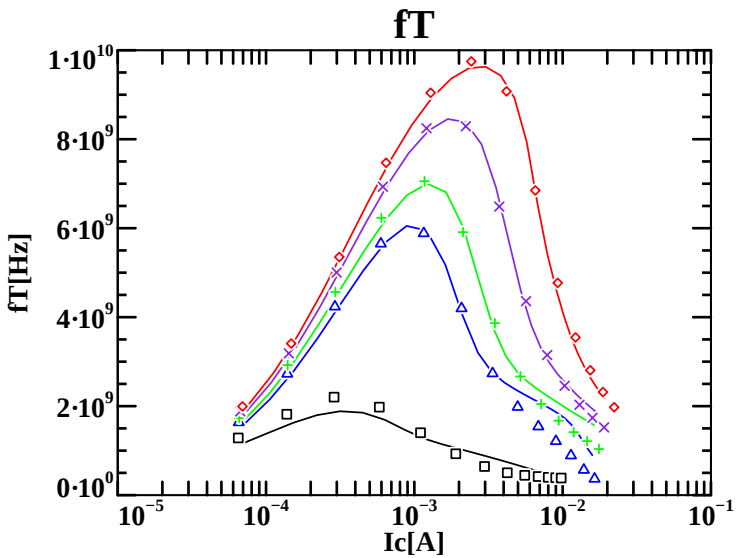

Ic/Ib
Ic/Ib[−]
Vce[V]

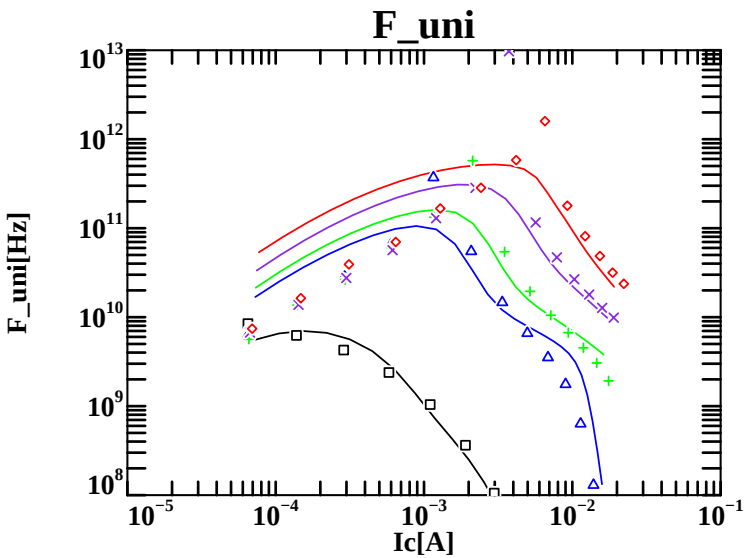

dIc/dVce
dIc/dVce [A/V]
Vce [V]


Vef
Vef [V]
Vce [V]

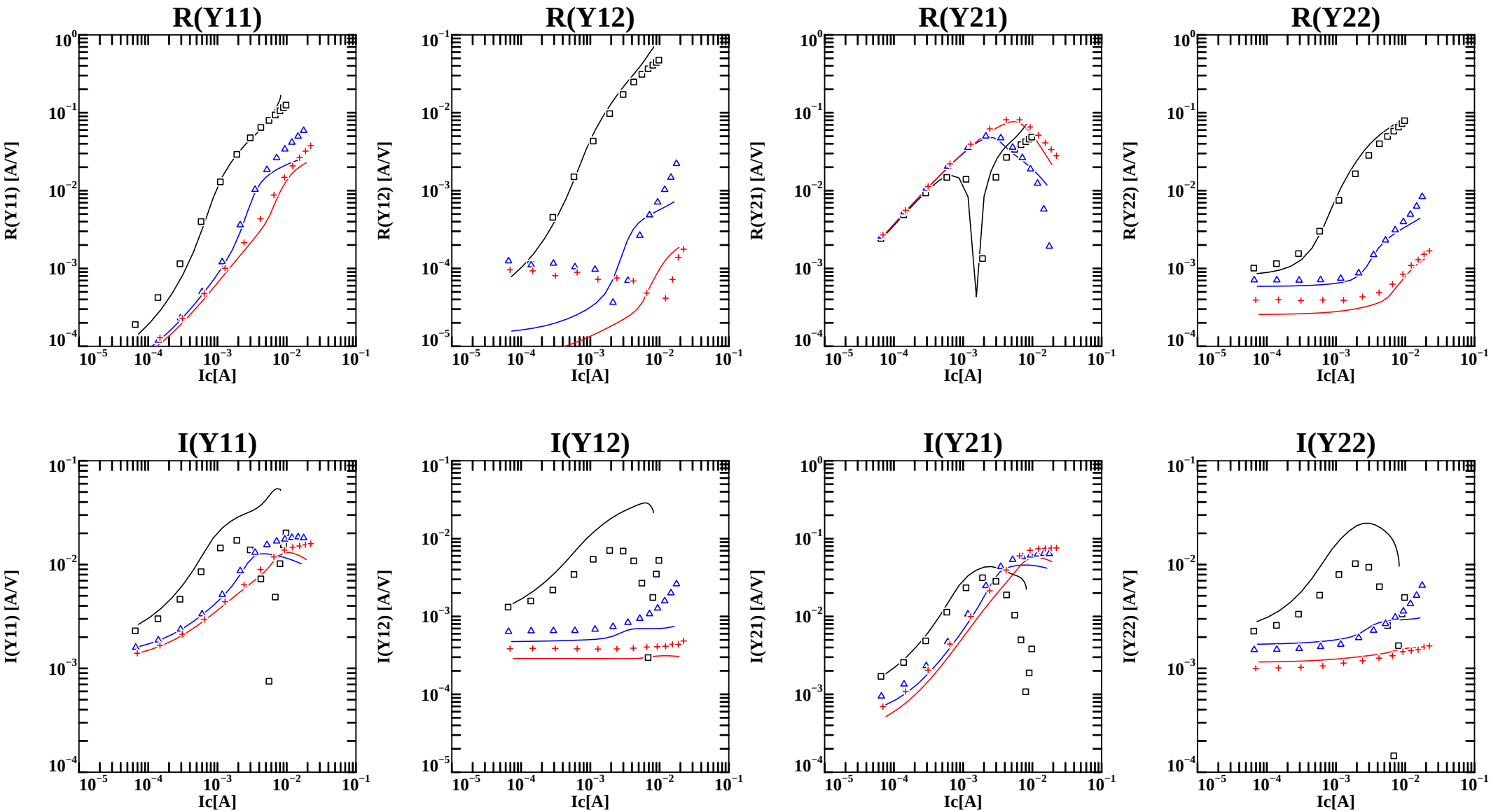

Hfe=Ic/Ib
Ic/Ib
Ic[A]


R_bb
Rb
Ic[A]


fT
fT[Hz]
Ic[A]


F_uni
F_uni[Hz]
Ic[A]

NPN A Temp=25 Freq=1Ghz Vce=0.2, 0.8, 5 V Mextram 504.0



Process B (10)

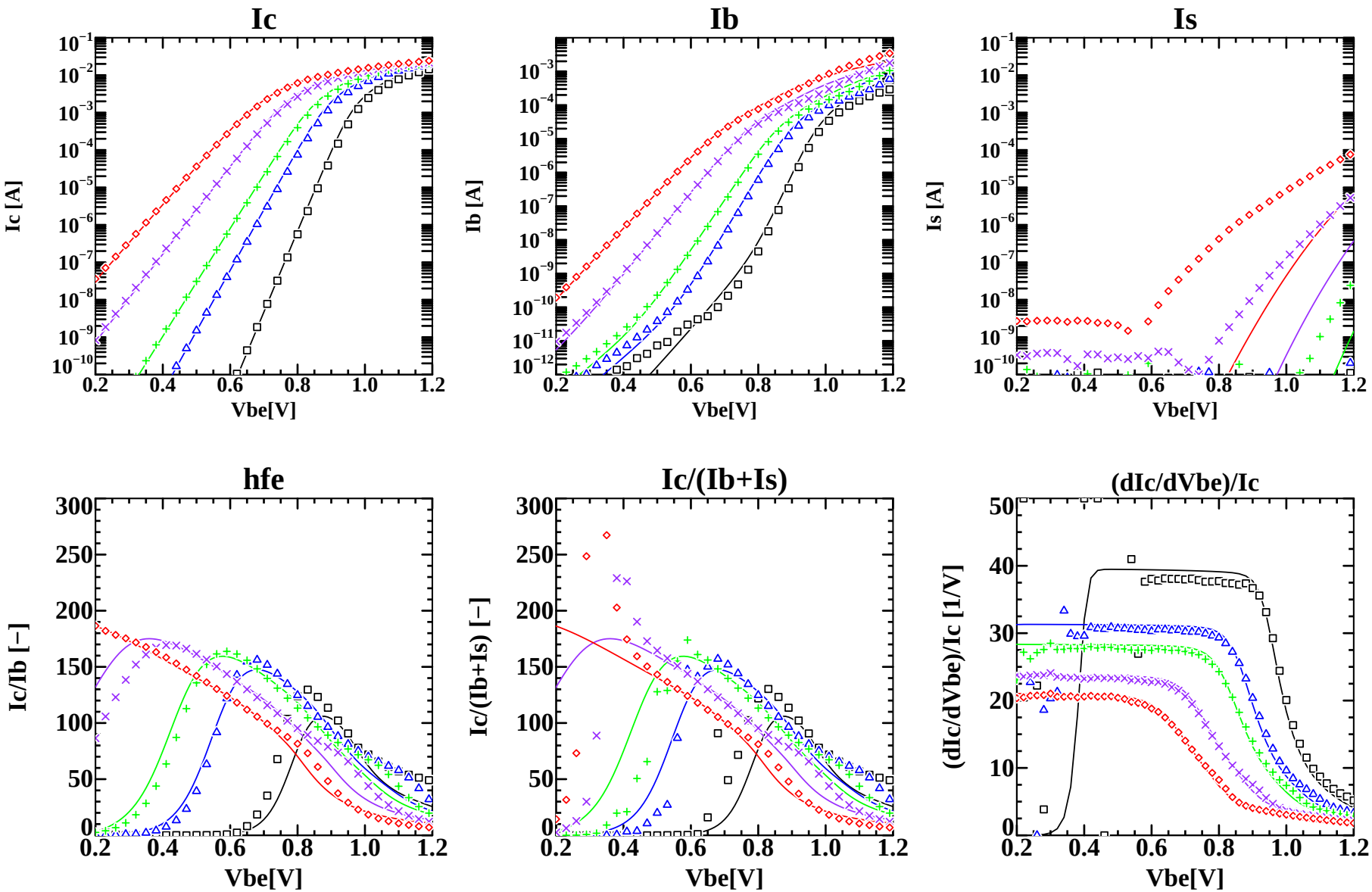
SiGe BiCMOS process

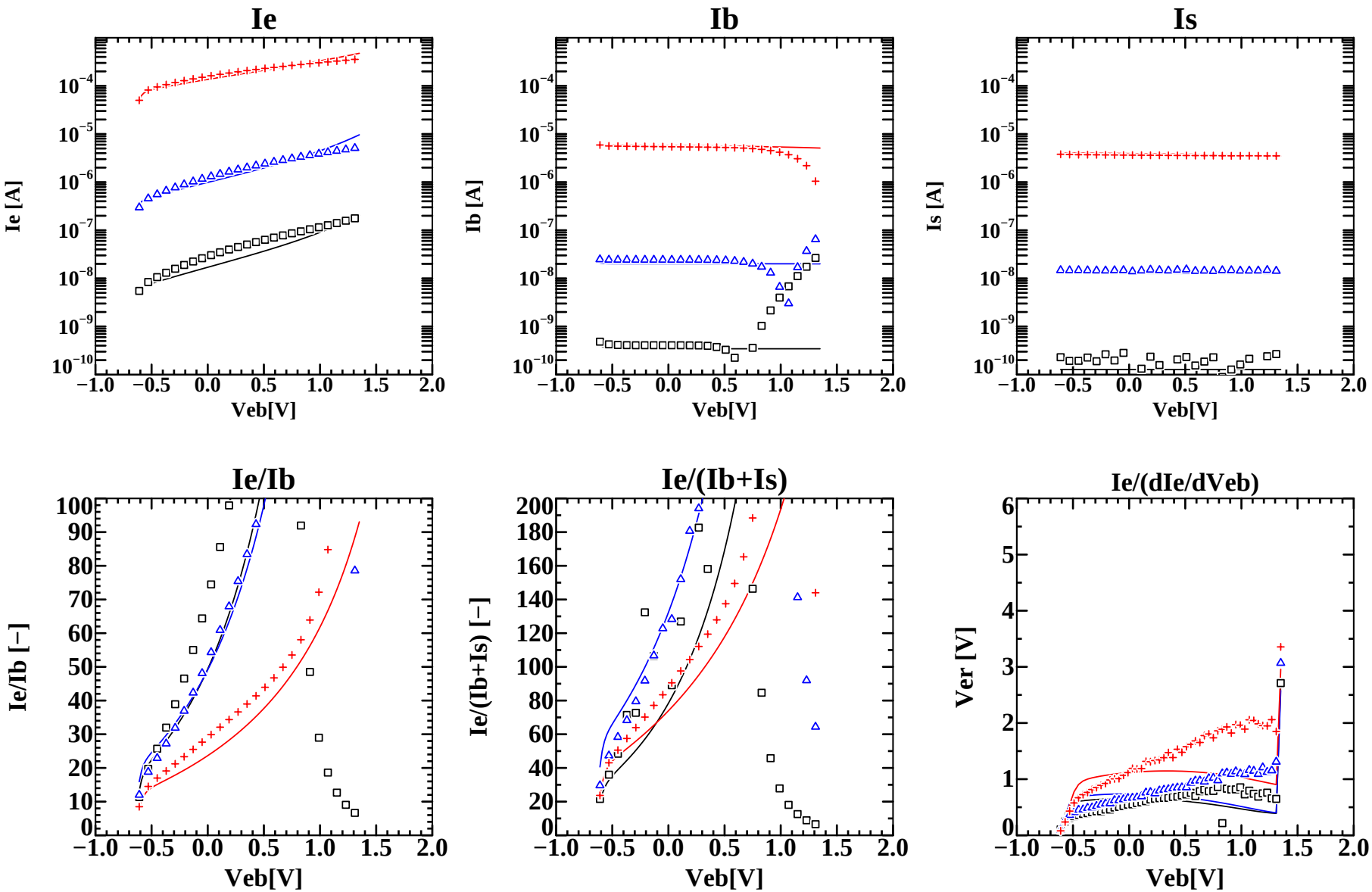
Emitter size: $0.25 \times 5.75\,\mu\mathrm{m}^2$

Single base contact: $\rho_{\square} = 6.5\,\mathrm{k}\Omega$

Maximum cut off frequency f_T
f_T: 97 GHz @ $V_{CE} = 2\,\mathrm{V}$
f_T: 85 GHz @ $V_{CE} = 0.75\,\mathrm{V}$

Problem for modeling:
Graded Ge concentration
$\rightarrow$ Difficult to model reverse Early effect
both in forward and in reverse


Ic
Ic [A]
Vbe[V]
Ib
Ib [A]
Vbe[V]
Is
Is [A]
Vbe[V]
hfe
Ic/Ib [–]
Vbe[V]
Ic/(Ib+Is)
Ic/(Ib+Is) [–]
Vbe[V]
(dIc/dVbe)/Ic
(dIc/dVbe)/Ic [1/V]
Vbe[V]


Ie
Ie [A]
Veb[V]
Ib
Ib [A]
Veb[V]
Is
Is [A]
Veb[V]
Ie/Ib
Ie/Ib [−]
Veb[V]
Ie/(Ib+Is)
Ie/(Ib+Is) [−]
Veb[V]
Ie/(dIe/dVeb)
Ver [V]
Veb[V]

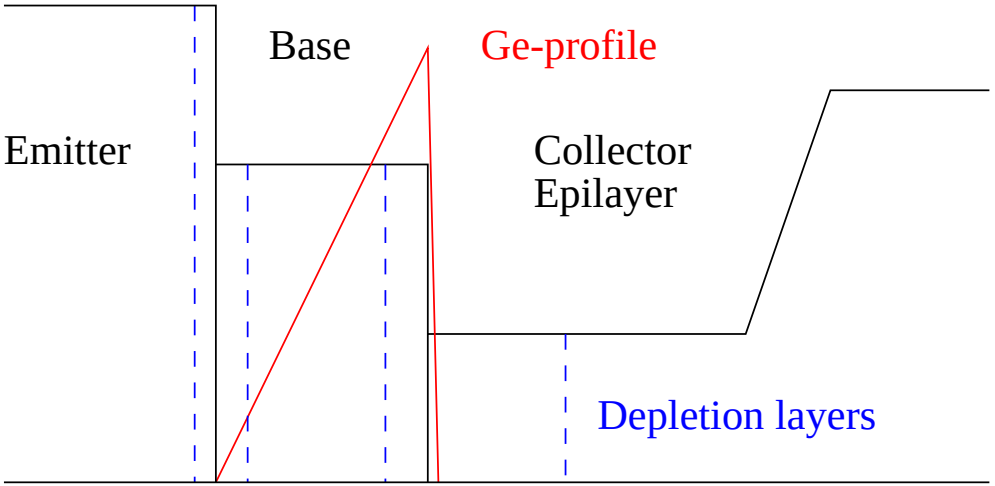
Graded Ge-profile modeling (13)

→ High forward Early voltage

→ Low reverse Early voltage

For reverse output characteristics this leads to punchtrough.

Extra model feature, based on 'ideal' profiles in base



Graded Ge-profile modeling (14)

Main current:

$$I_C \simeq I_S \, e^{V_{BE}/V_T} \, / q_B$$

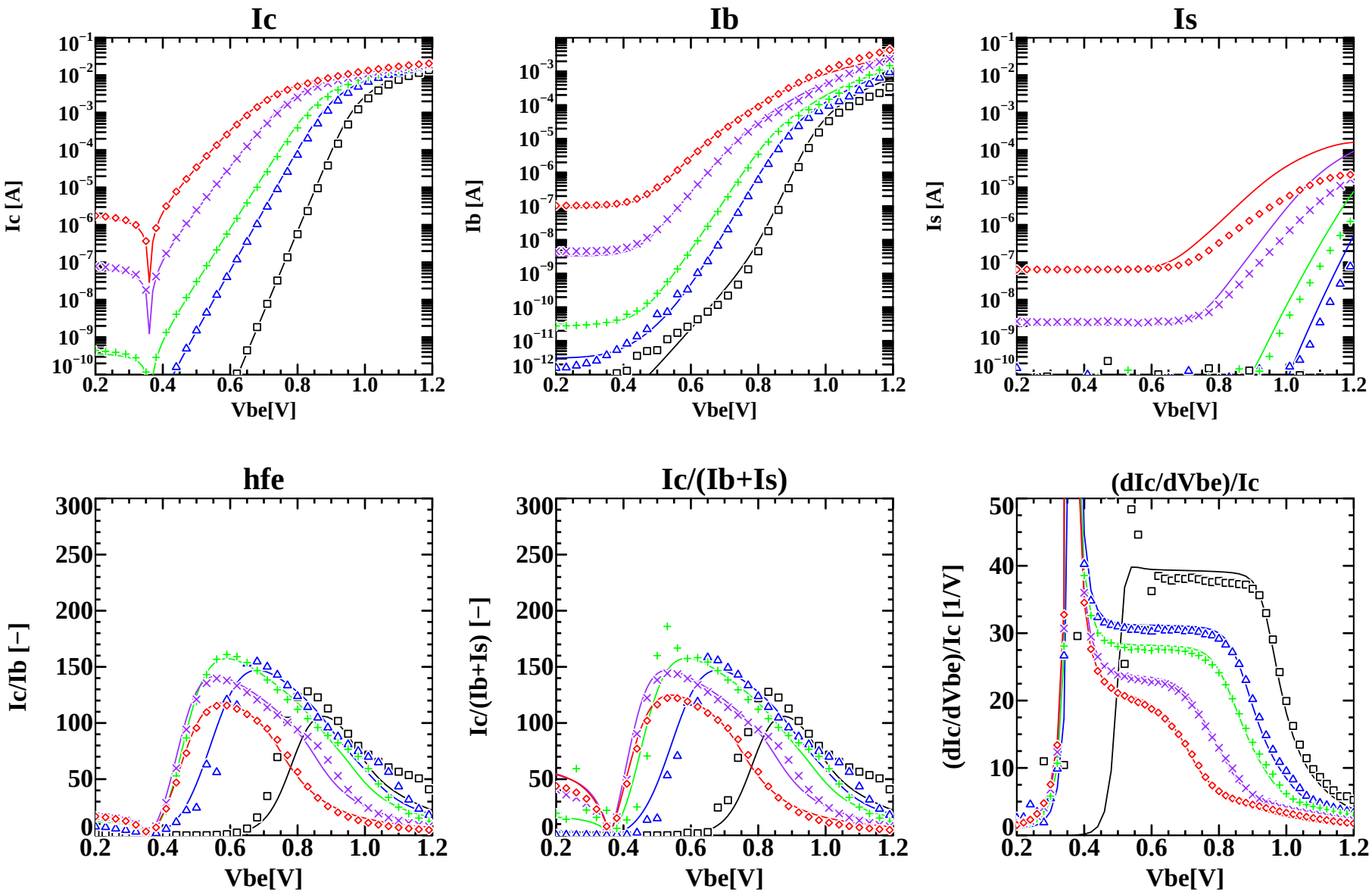
For Si and for charges:

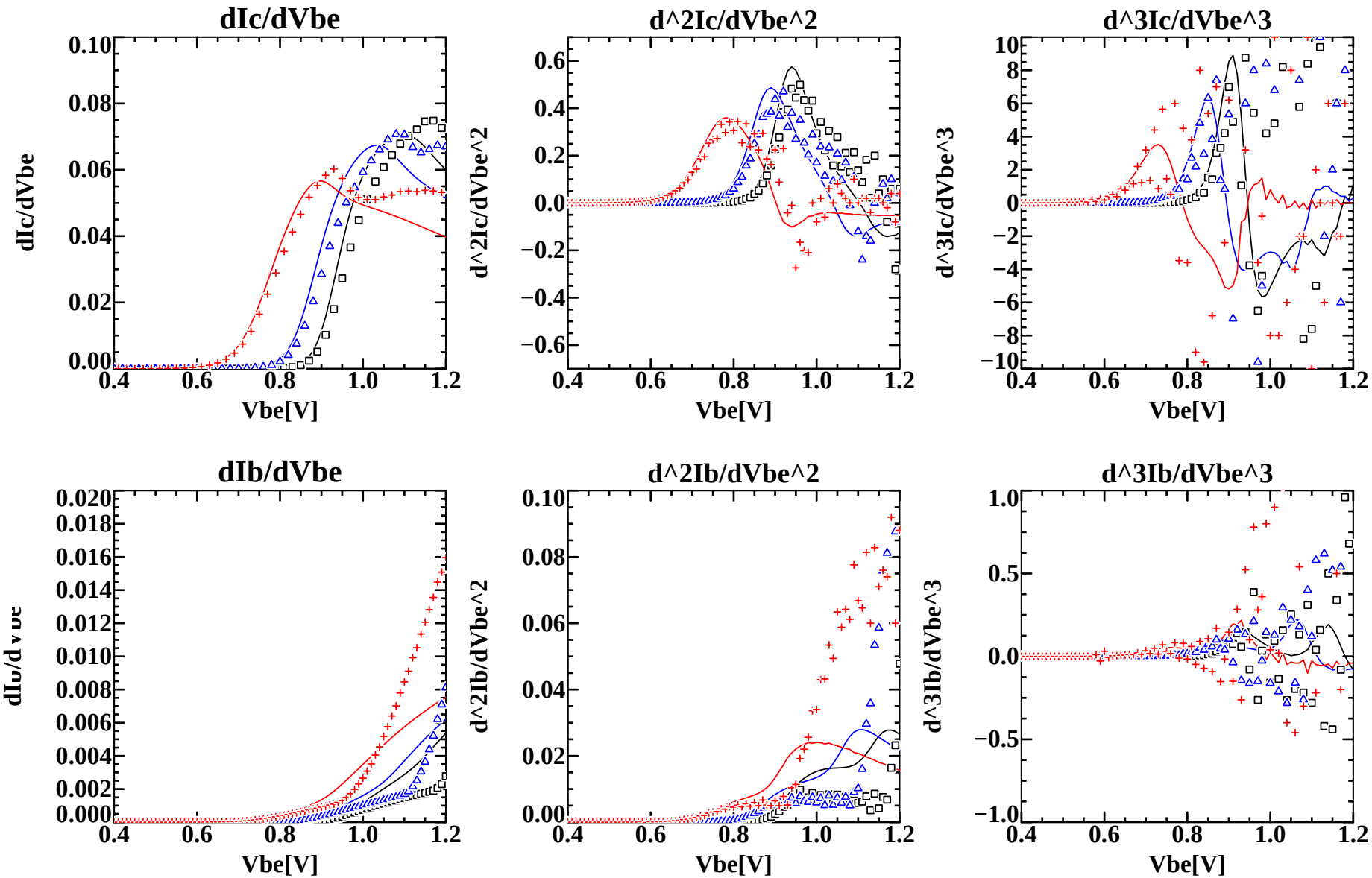
$$q_B \simeq 1 + \frac{V_{BE}}{V_{ER}} + \frac{V_{BC}}{V_{EF}}$$

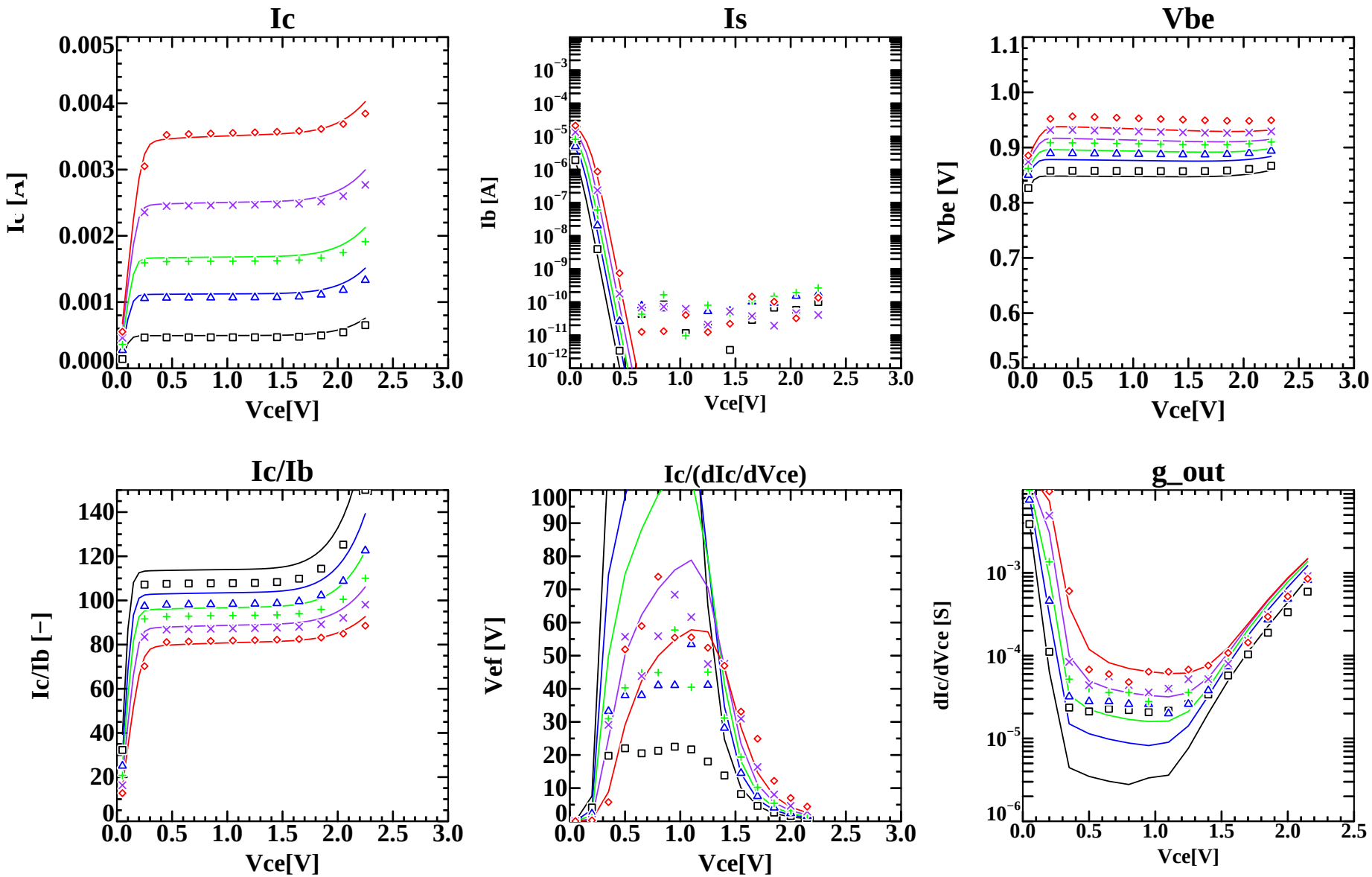
For SiGe:

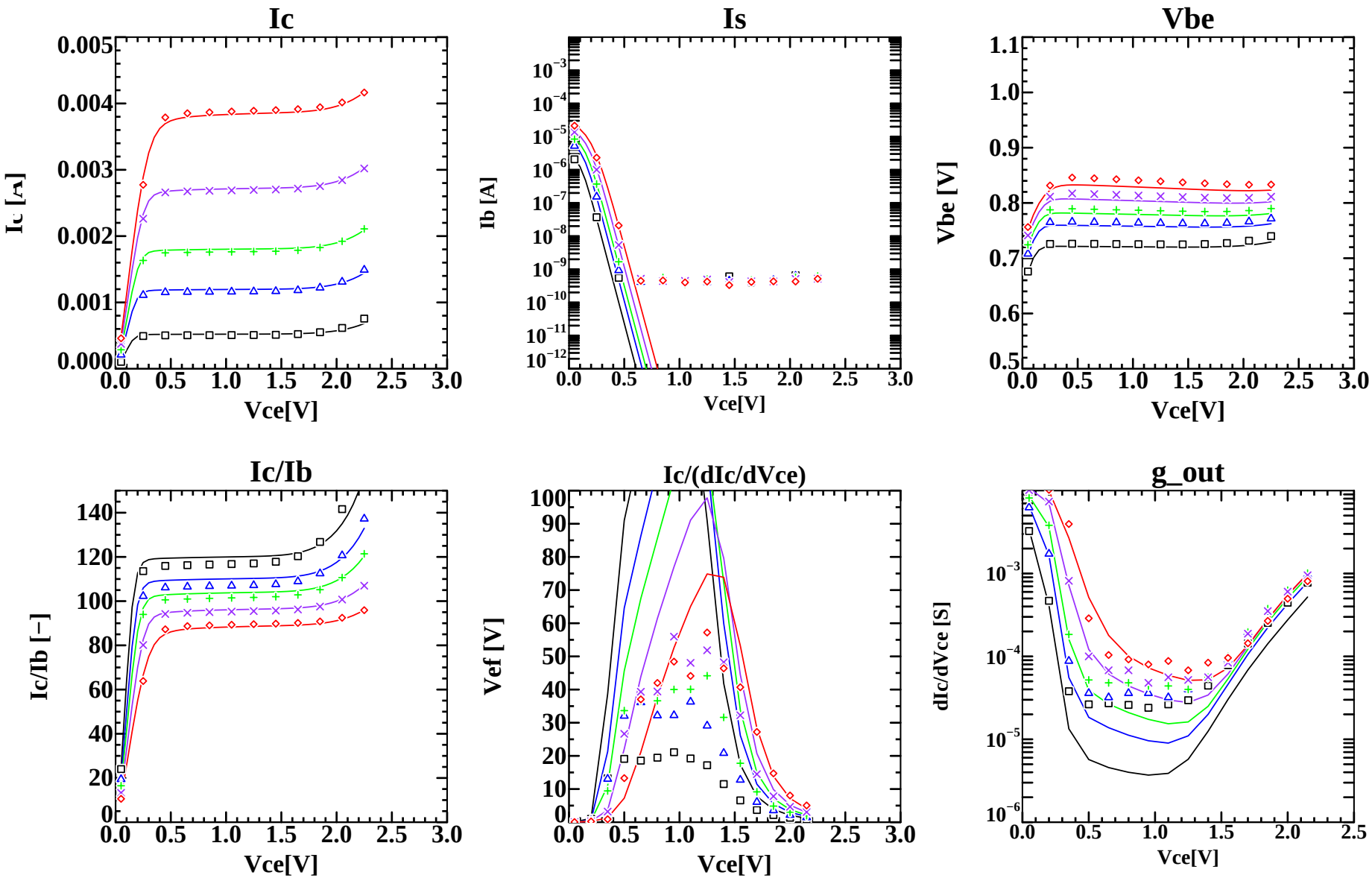
$$q_B \simeq \frac{\exp\left[\left(1 + \frac{V_{BE}}{V_{ER}}\right) \frac{dV}{V_T}\right] - \exp\left[-\frac{V_{BC}}{V_{EF}} \frac{dV}{V_T}\right]}{\exp\left[\frac{dV}{V_T}\right] - 1}$$

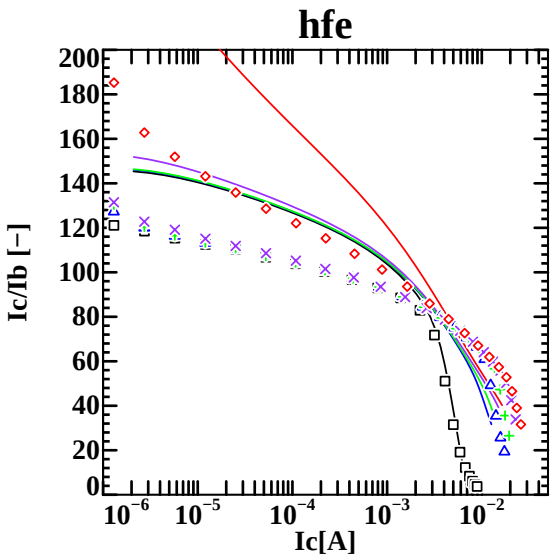
Parameter: dV: band-gap narrowing over neutral base

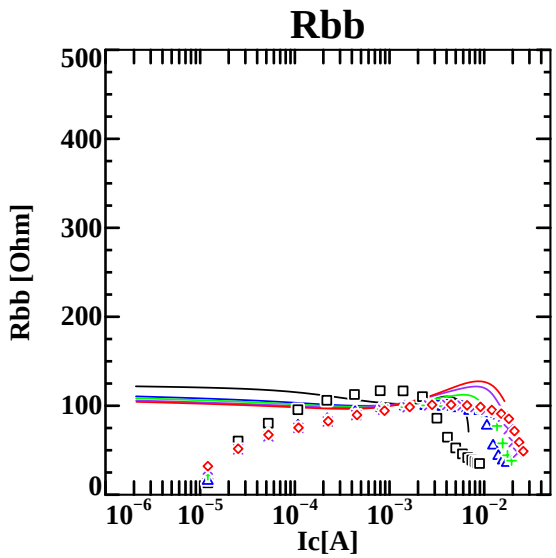

Ic
Ic [A]
Vbe[V]
Ib
Ib [A]
Vbe[V]
Is
Is [A]
Vbe[V]
hfe
Ic/Ib [−]
Vbe[V]
Ic/(Ib+Is)
Ic/(Ib+Is) [−]
Vbe[V]
(dIc/dVbe)/Ic
(dIc/dVbe)/Ic [1/V]
Vbe[V]

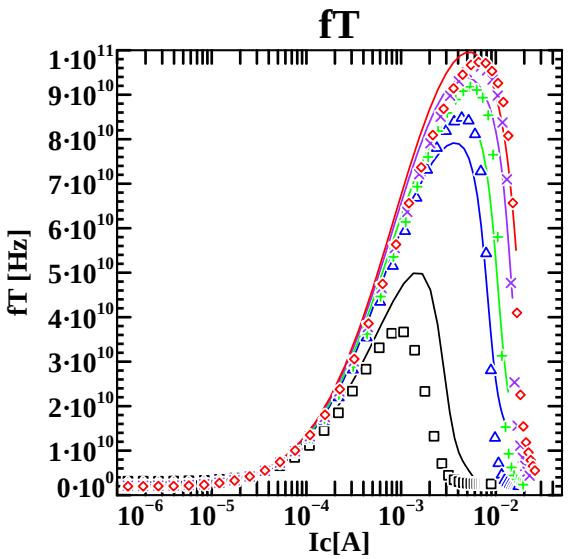

dIc/dVbe
d^2Ic/dVbe^2
d^3Ic/dVbe^3
dIb/dVbe
d^2Ib/dVbe^2
d^3Ib/dVbe^3
Vbe[V]

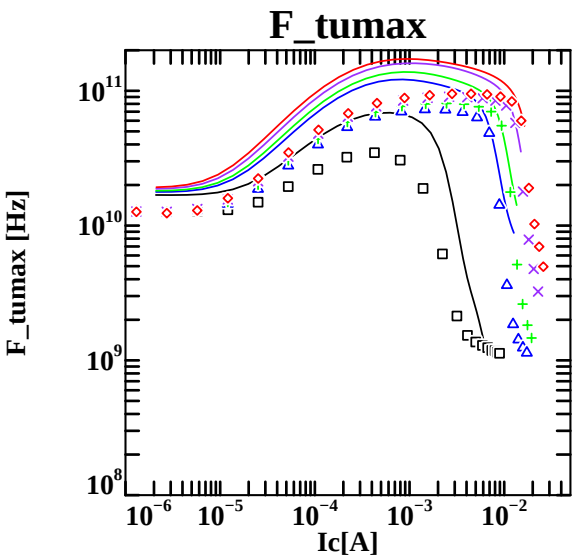

Ic
Ic [A]
Vce[V]
Is
Ib [A]
Vce[V]
Vbe
Vbe [V]
Vce[V]
Ic/Ib
Ic/Ib [–]
Vce[V]
Ic/(dIc/dVce)
Vef [V]
Vce[V]
g_out
dIc/dVce [S]
Vce[V]

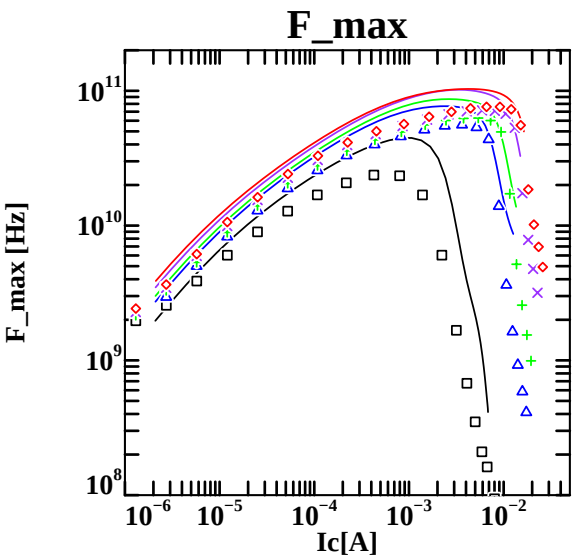

Ic
Ic [A]
Vce[V]
Is
Ib [A]
Vce[V]
Vbe
Vbe [V]
Vce[V]
Ic/Ib
Ic/Ib [–]
Vce[V]
Ic/(dIc/dVce)
Vef [V]
Vce[V]
g_out
dIc/dVce [S]
Vce[V]


hfe
Ic/Ib [–]
Ic[A]

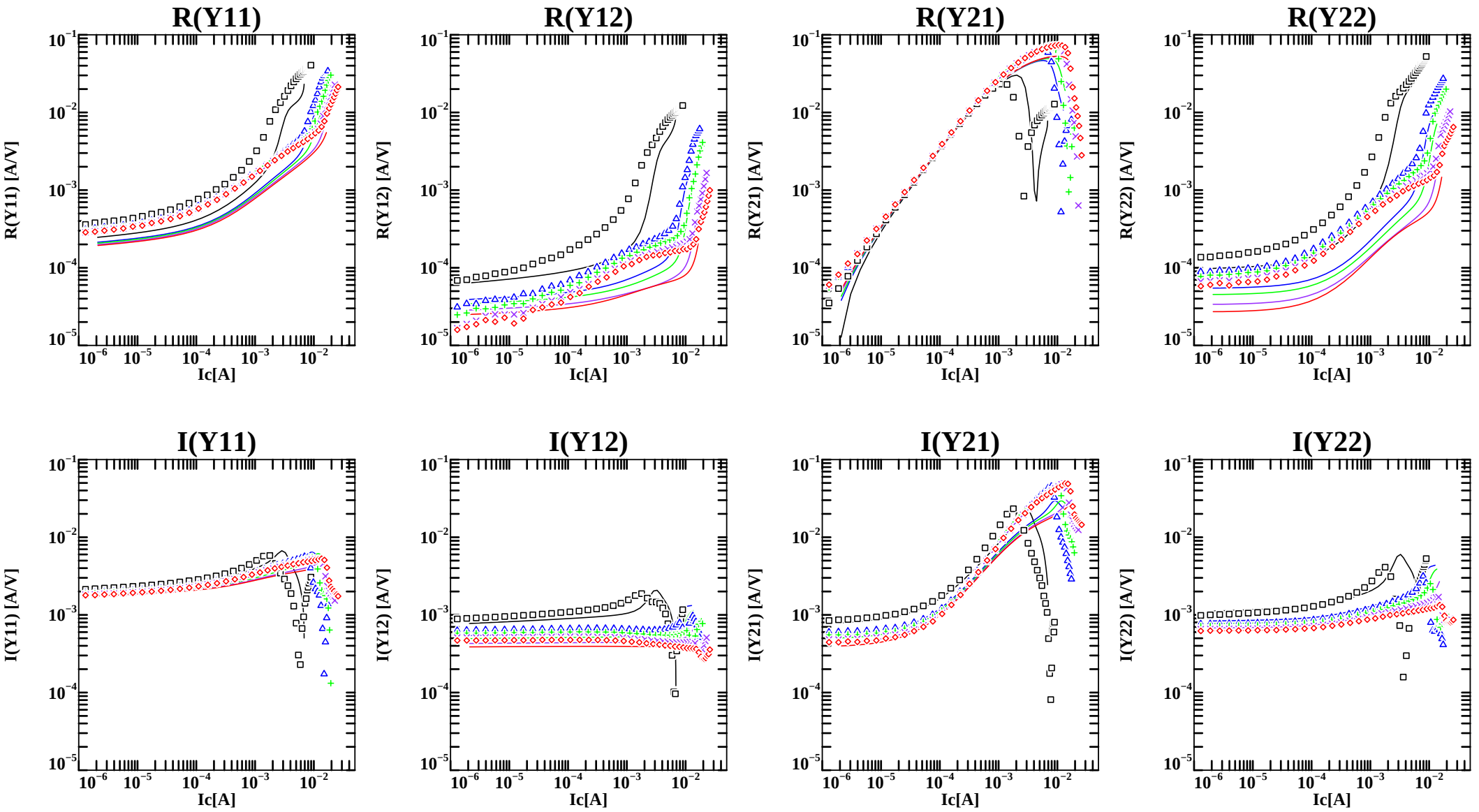

Rbb
Rbb [Ohm]
Ic[A]


fT
fT [Hz]
Ic[A]


F_tumax
F_tumax [Hz]
Ic[A]


F_max
F_max [Hz]
Ic[A]

NPN B1 temp=22 freq=8GHz Vce=0.25, 0.75, 1.0, 1.5, 2.0



Process C

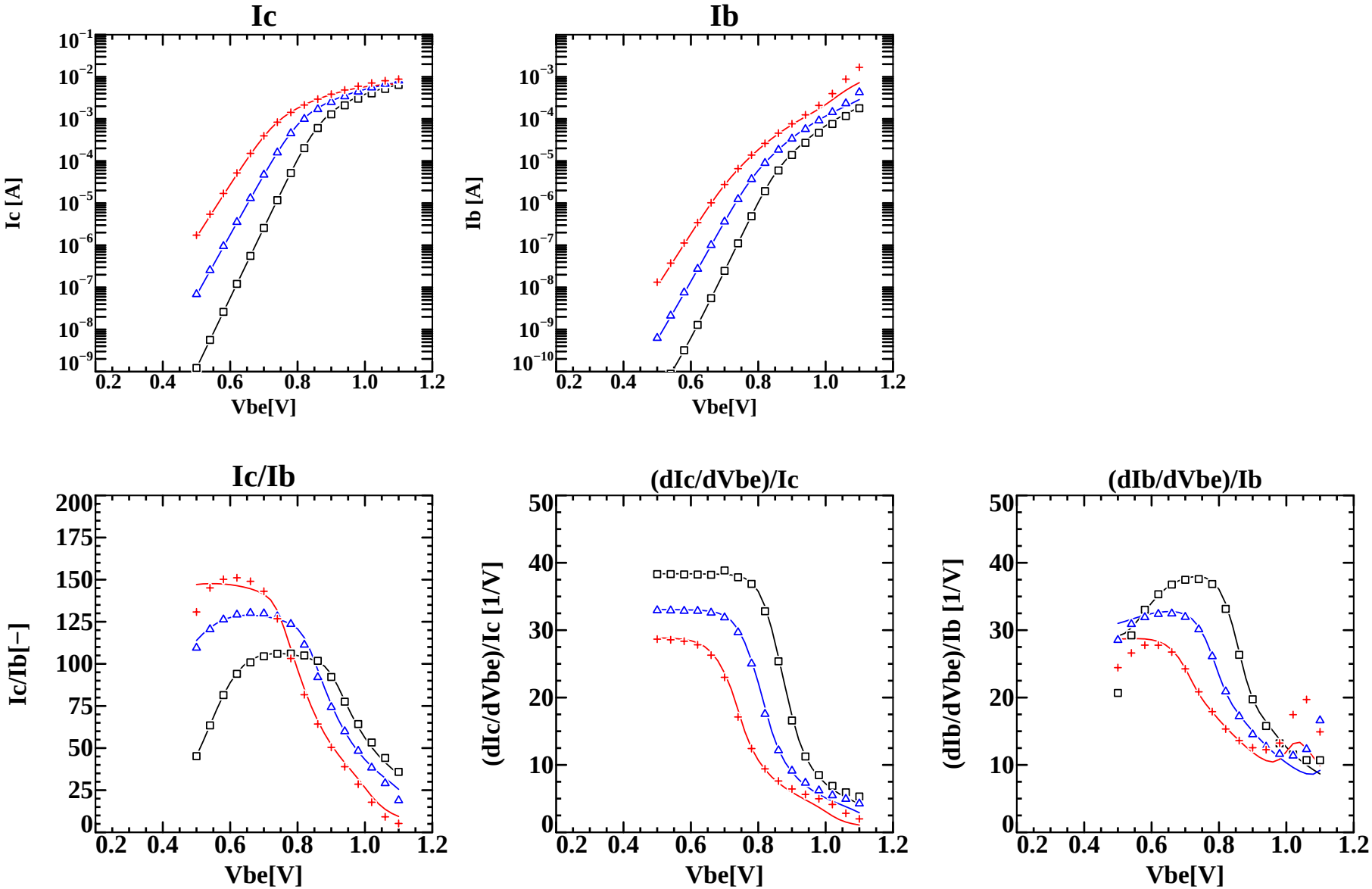
NPN on SOI

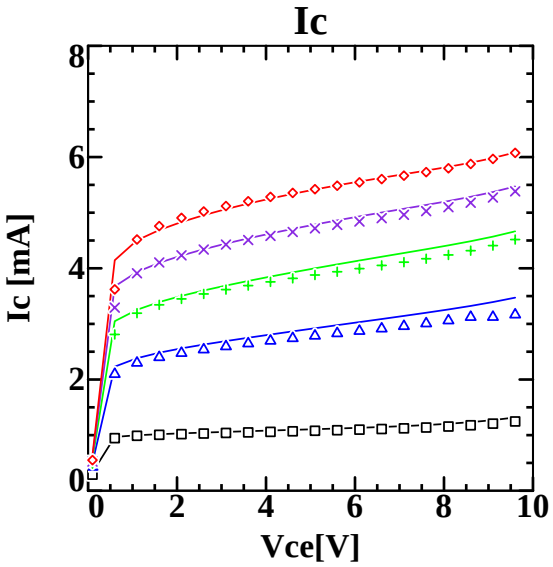
Emitter size: $1.0 \times 5.0\,\mu\mathrm{m}^2$

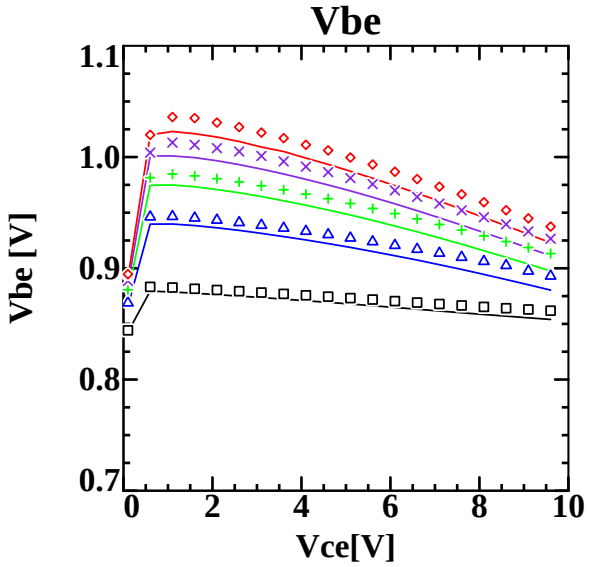
Base: $\rho_{\square} = 12\,\mathrm{k}\Omega$

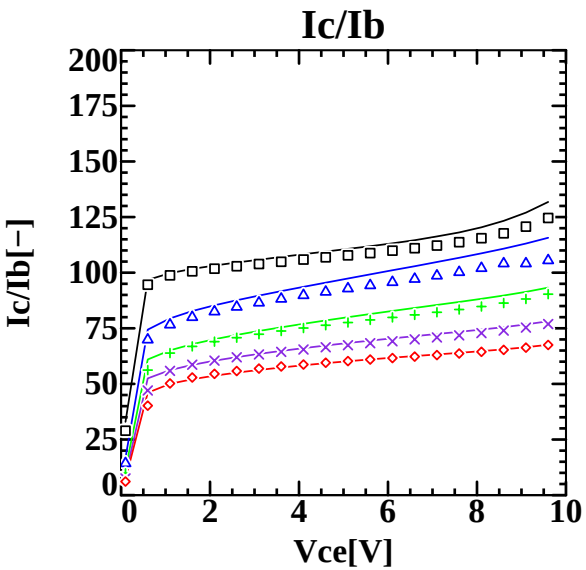
Maximum cut off frequency f_T
f_T: 10 GHz @ $V_{CE} = 6\,\mathrm{V}$

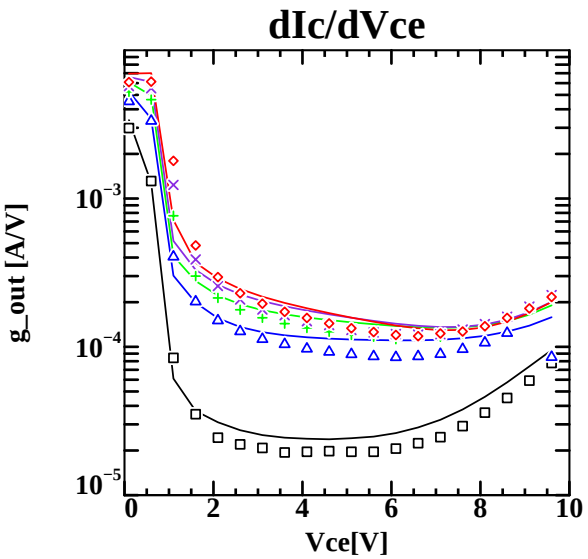
Problem for modeling: self-heating ($R_{th} = 2500^{\circ}\mathrm{C/W}$)

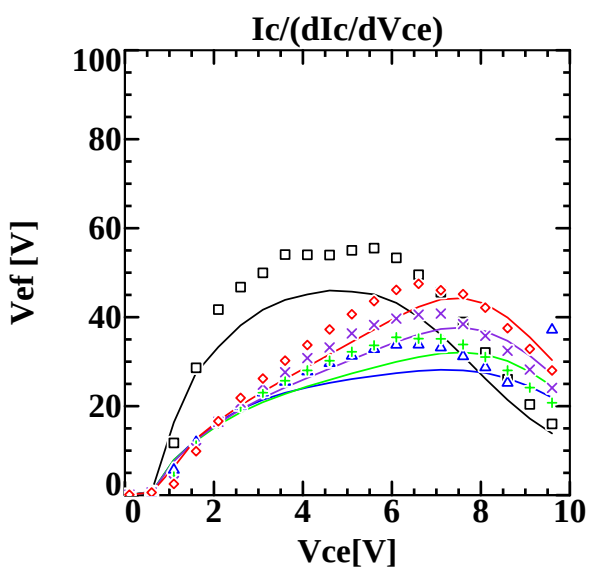

Ic
Ic [A]
Vbe[V]
Ib
Ib [A]
Vbe[V]
Ic/Ib
Ic/Ib[–]
Vbe[V]
(dIc/dVbe)/Ic
(dIc/dVbe)/Ic [1/V]
Vbe[V]
(dIb/dVbe)/Ib
(dIb/dVbe)/Ib [1/V]
Vbe[V]

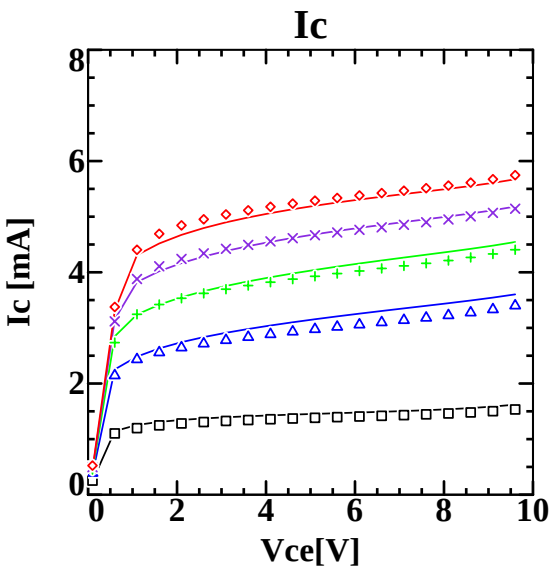

Ic
Ic [mA]
Vce[V]
0
2
4
6
8
0
2
4
6
8
10

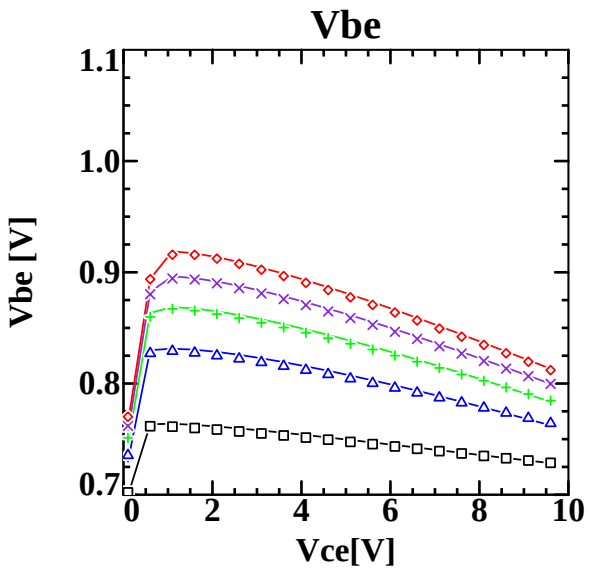

Vbe
Vbe [V]
Vce[V]
0.7
0.8
0.9
1.0
1.1
0
2
4
6
8
10

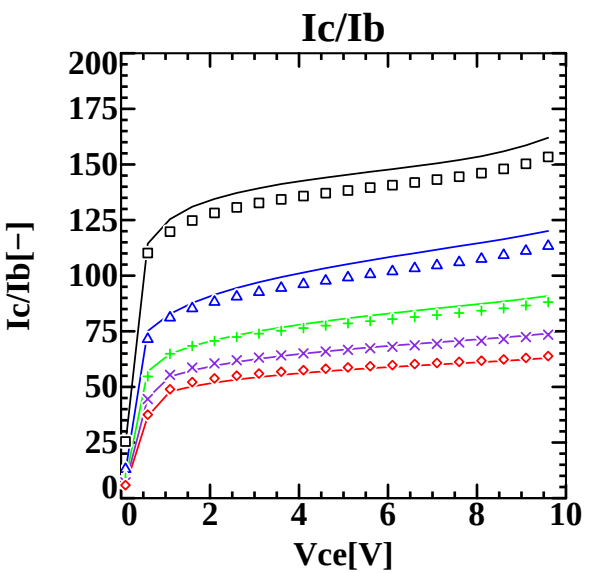

Ic/Ib
Ic/Ib[–]
Vce[V]
0
25
50
75
100
125
150
175
200
0
2
4
6
8
10

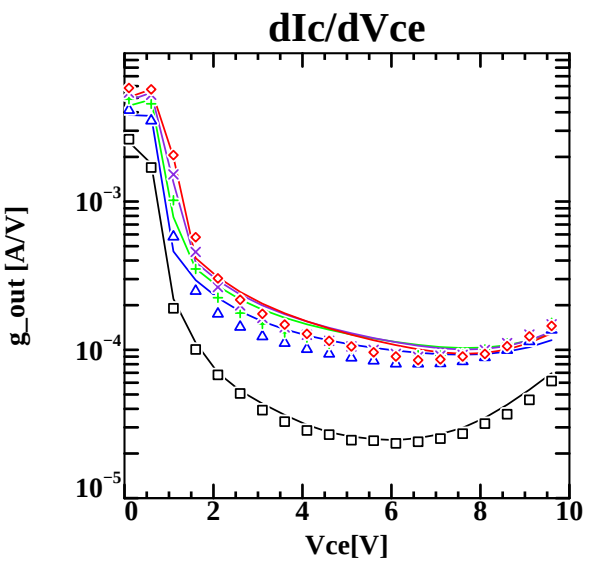

dIc/dVce
g_out [A/V]
Vce[V]
10^{-3}
10^{-4}
10^{-5}
0
2
4
6
8
10

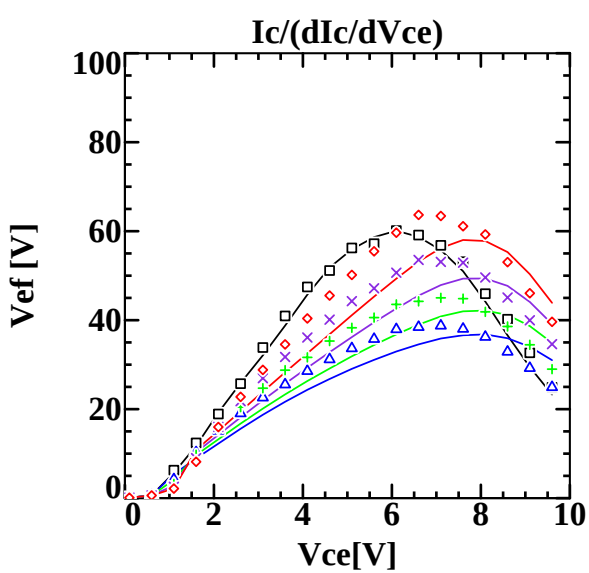

Ic/(dIc/dVce)
Vef [V]
Vce[V]
0
20
40
60
80
100
0
2
4
6
8
10

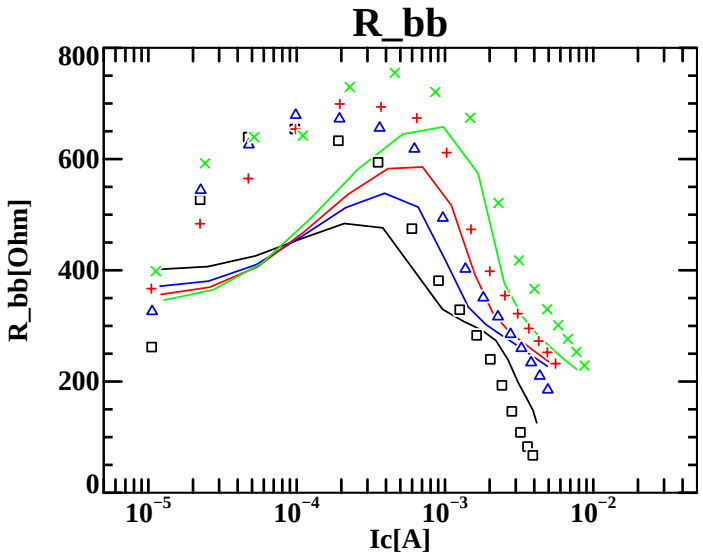

Ic
Ic [mA]
Vce[V]
0
2
4
6
8
0
2
4
6
8
10

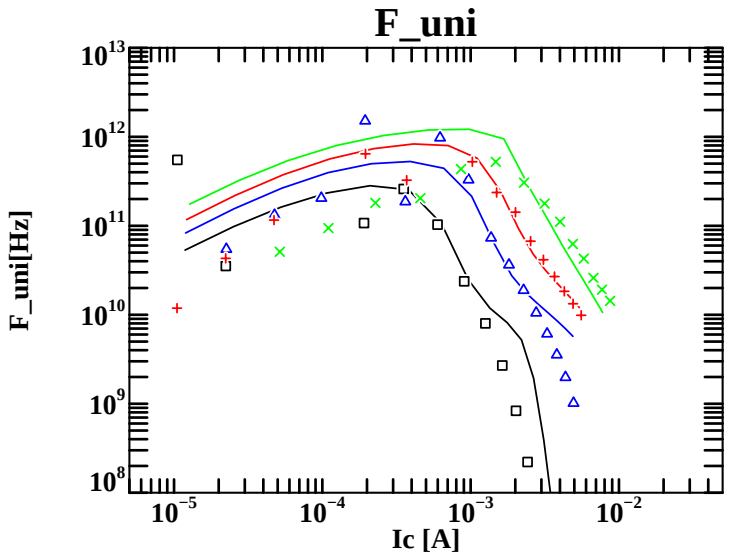

Vbe
Vbe [V]
Vce[V]
0.7
0.8
0.9
1.0
1.1
0
2
4
6
8
10

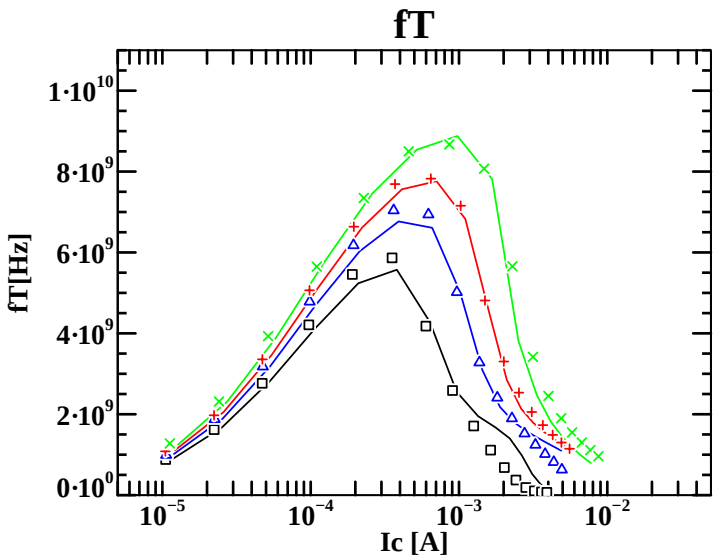

Ic/Ib
Ic/Ib[−]
Vce[V]
0
25
50
75
100
125
150
175
200
0
2
4
6
8
10

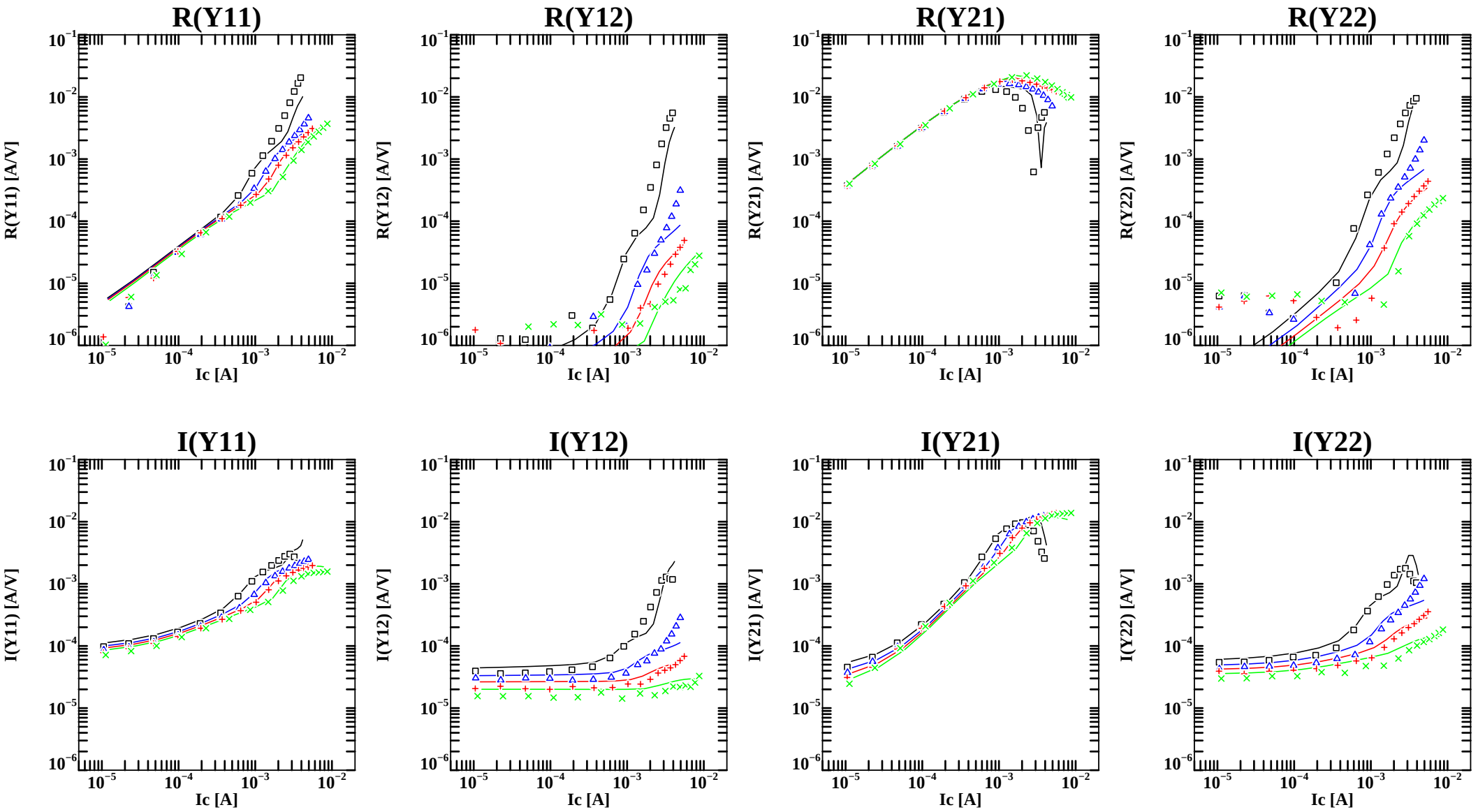

dIc/dVce
g_out [A/V]
Vce[V]
10^{-3}
10^{-4}
10^{-5}
0
2
4
6
8
10


Ic/(dIc/dVce)
Vef [V]
Vce[V]
0
20
40
60
80
100
0
2
4
6
8
10


R_bb
R_bb[Ohm]
800
600
400
200
0
10^{-5}
10^{-4}
10^{-3}
10^{-2}
Ic[A]


F_uni
F_uni[Hz]
10^{13}
10^{12}
10^{11}
10^{10}
10^{9}
10^{8}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
Ic [A]


fT
fT[Hz]
$1{\cdot}10^{10}$
$8{\cdot}10^{9}$
$6{\cdot}10^{9}$
$4{\cdot}10^{9}$
$2{\cdot}10^{9}$
$0{\cdot}10^{0}$
10^{-5}
10^{-4}
10^{-3}
10^{-2}
Ic [A]


R(Y11)
R(Y12)
R(Y21)
R(Y22)
I(Y11)
I(Y12)
I(Y21)
I(Y22)
R(Y11) [A/V]
R(Y12) [A/V]
R(Y21) [A/V]
R(Y22) [A/V]
I(Y11) [A/V]
I(Y12) [A/V]
I(Y21) [A/V]
I(Y22) [A/V]
Ic [A]
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
10^-5
10^-4
10^-3
10^-2

Process D

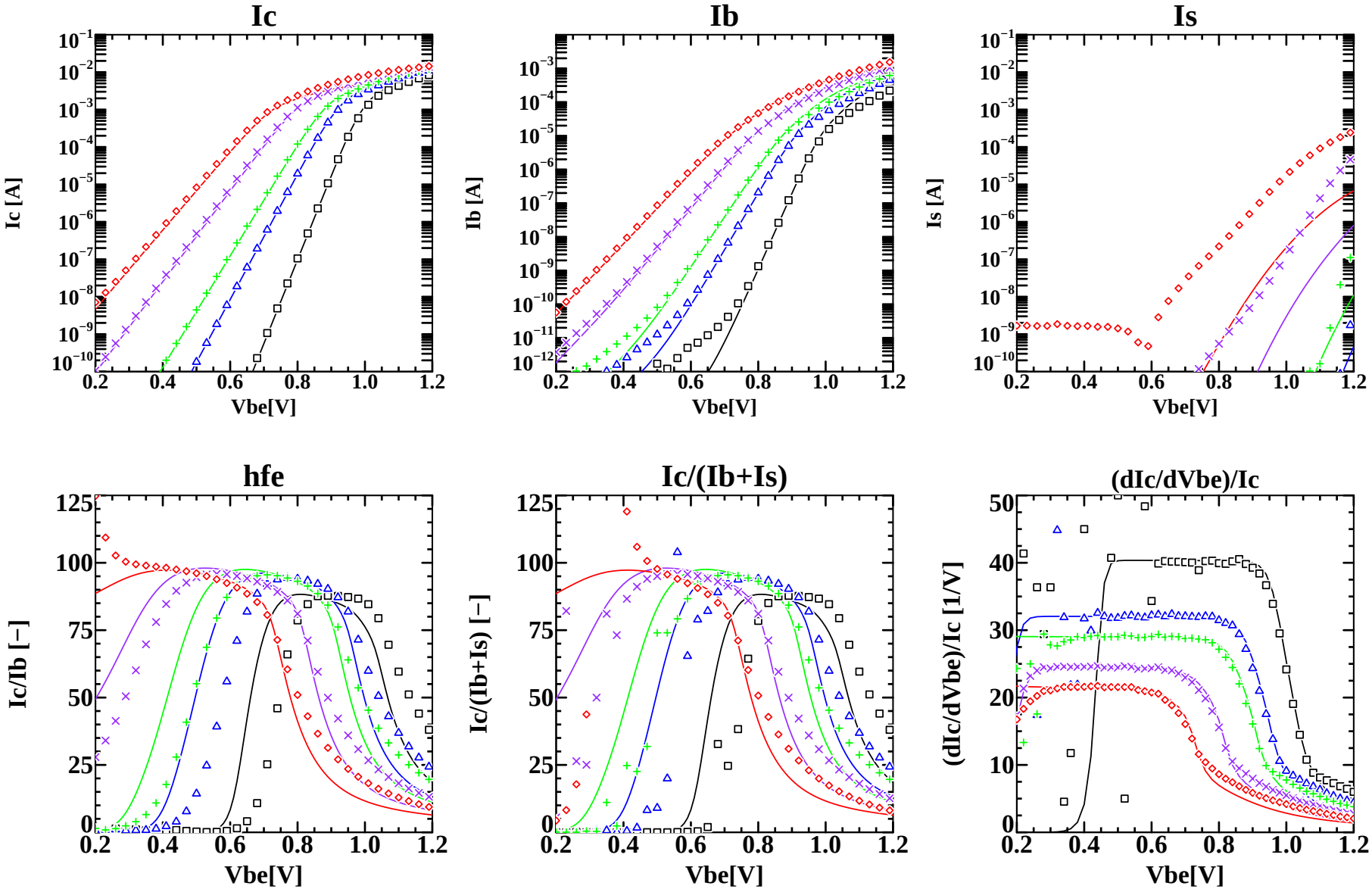
Double Poly BiCMOS process

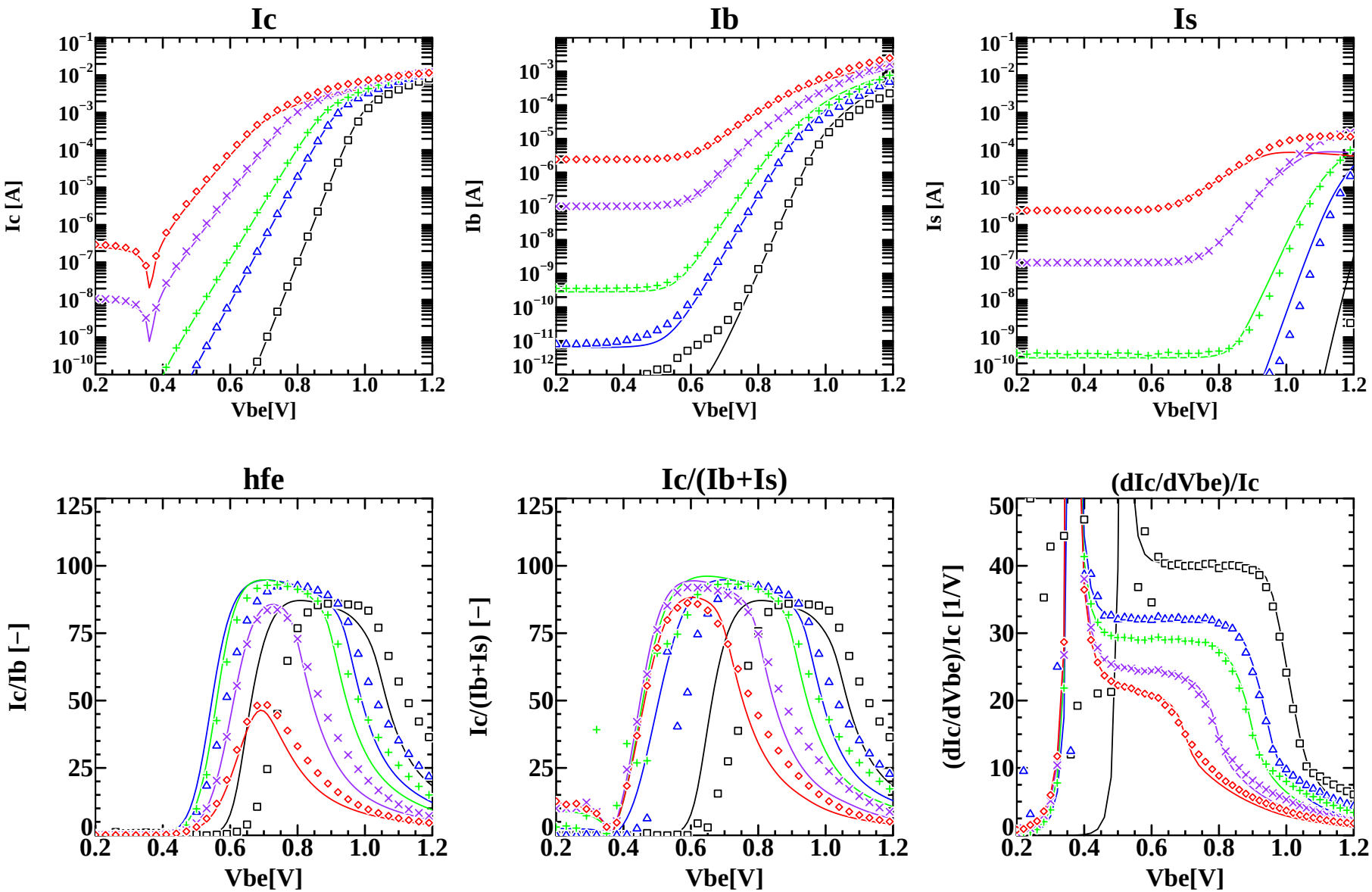
Emitter size: $0.55 \times 3.45\,\mu\mathrm{m}^2$

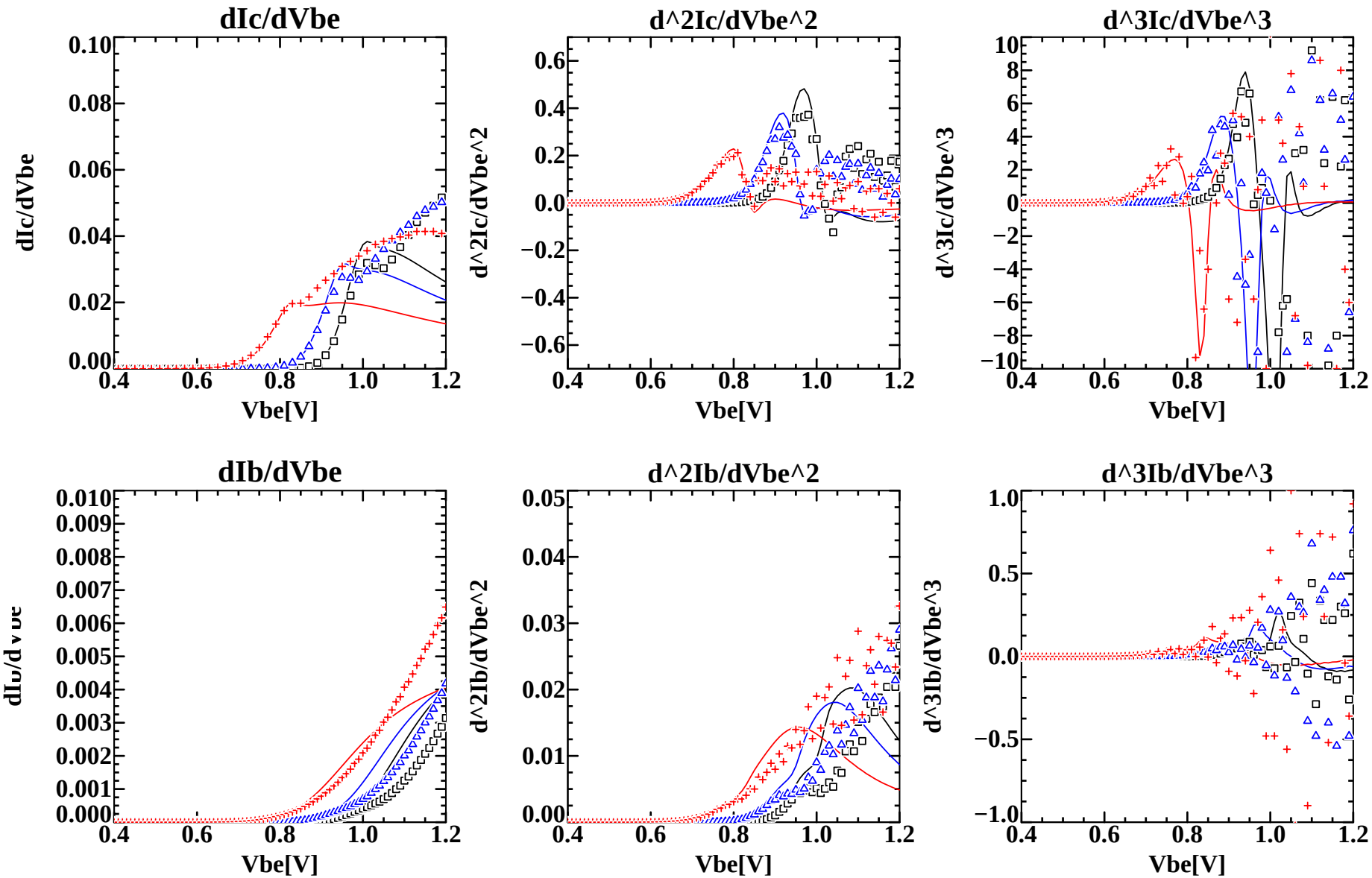
Single base contact: $\rho_{\square} = 9\,\mathrm{k}\Omega$

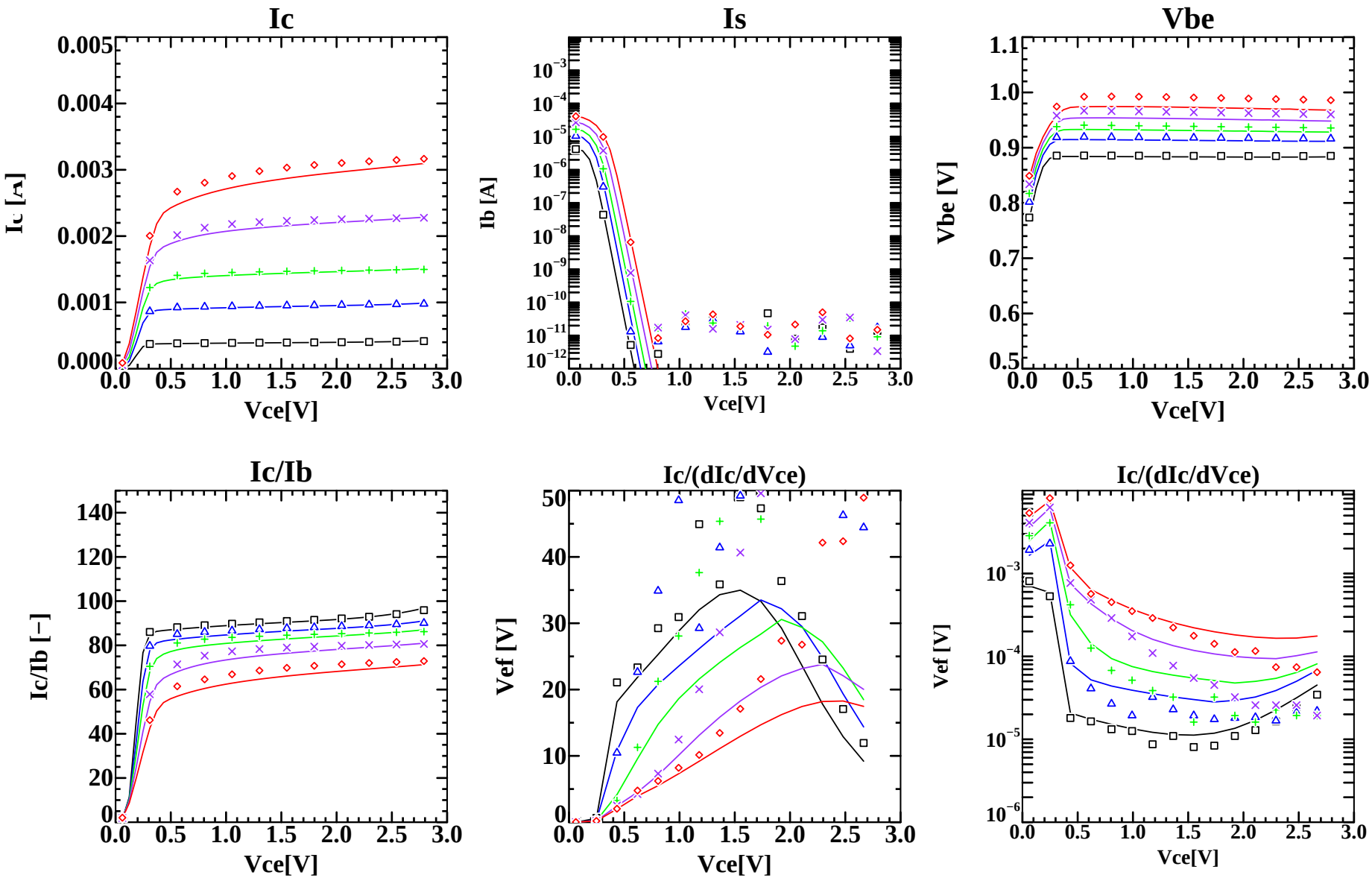
Maximum cut off frequency f_T

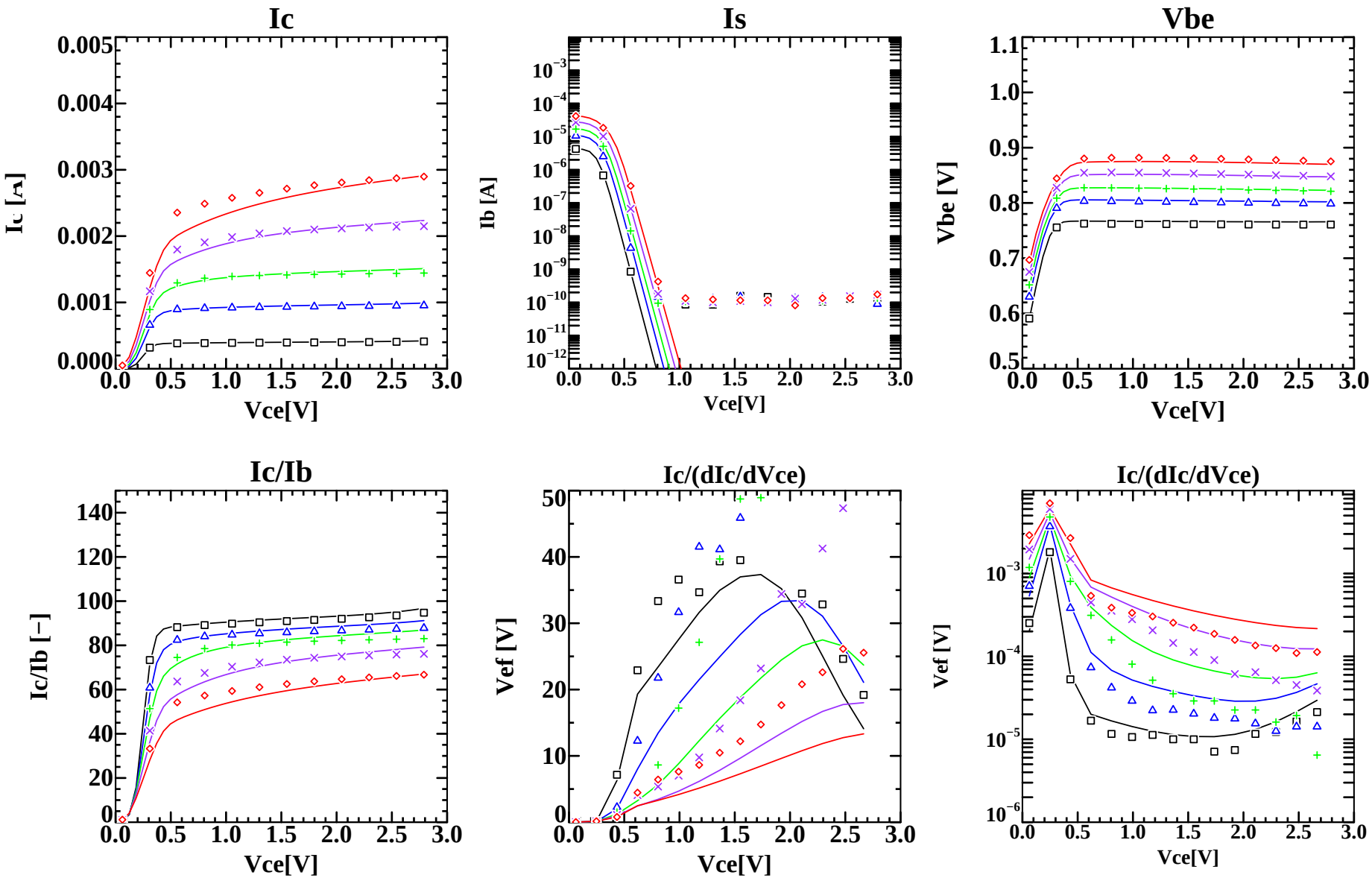
f_T: 25 GHz @ $V_{CE} = 1\,\mathrm{V}$

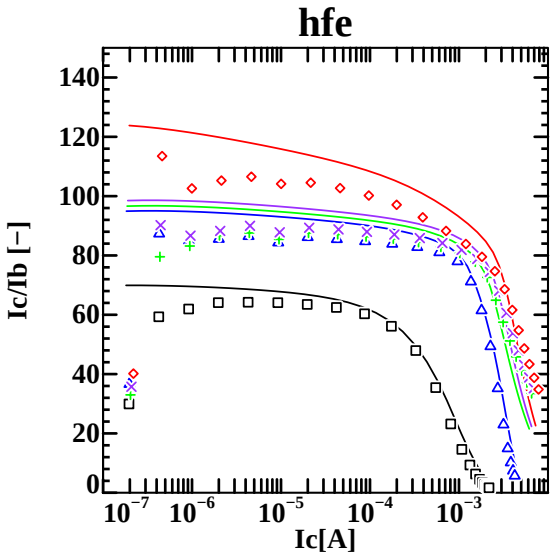

Ic
Ic [A]
Vbe[V]
Ib
Ib [A]
Vbe[V]
Is
Is [A]
Vbe[V]
hfe
Ic/Ib [−]
Vbe[V]
Ic/(Ib+Is)
Ic/(Ib+Is) [−]
Vbe[V]
(dIc/dVbe)/Ic
(dIc/dVbe)/Ic [1/V]
Vbe[V]

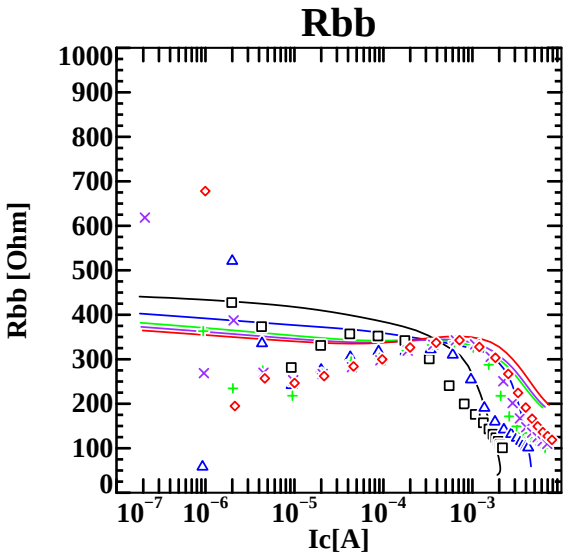

Ic
Ic [A]
Vbe[V]
Ib
Ib [A]
Vbe[V]
Is
Is [A]
Vbe[V]
hfe
Ic/Ib [–]
Vbe[V]
Ic/(Ib+Is)
Ic/(Ib+Is) [–]
Vbe[V]
(dIc/dVbe)/Ic
(dIc/dVbe)/Ic [1/V]
Vbe[V]

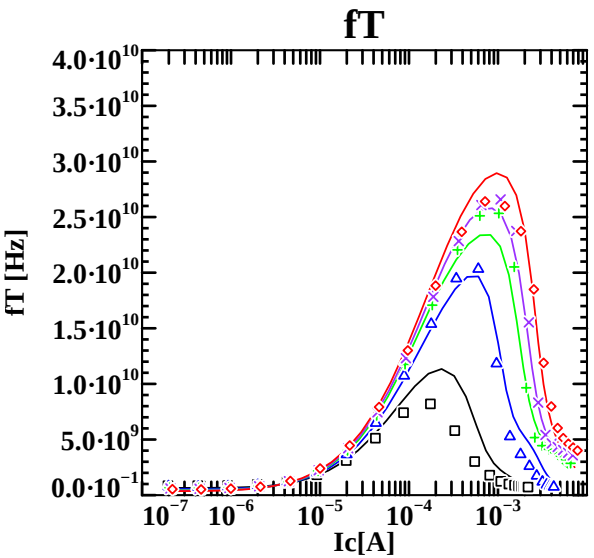

dIc/dVbe
dIc/dVbe
Vbe[V]
d^2Ic/dVbe^2
d^2Ic/dVbe^2
Vbe[V]
d^3Ic/dVbe^3
d^3Ic/dVbe^3
Vbe[V]
dIb/dVbe
dIb/dVbe
Vbe[V]
d^2Ib/dVbe^2
d^2Ib/dVbe^2
Vbe[V]
d^3Ib/dVbe^3
d^3Ib/dVbe^3
Vbe[V]

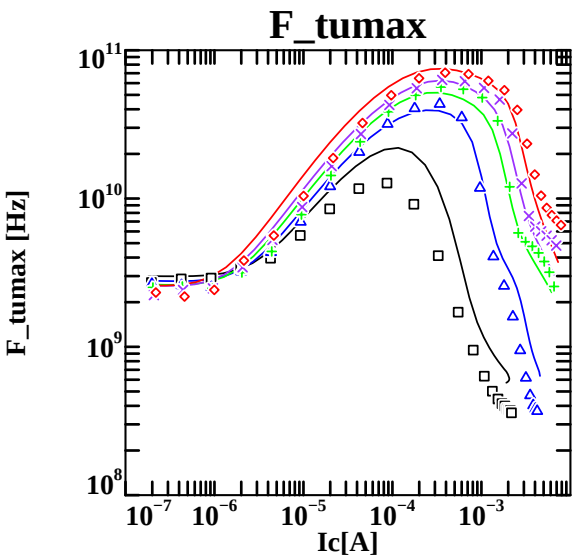

Ic
Ic [A]
Vce[V]
Is
Ib [A]
Vce[V]
Vbe
Vbe [V]
Vce[V]
Ic/Ib
Ic/Ib [–]
Vce[V]
Ic/(dIc/dVce)
Vef [V]
Vce[V]
Ic/(dIc/dVce)
Vef [V]
Vce[V]

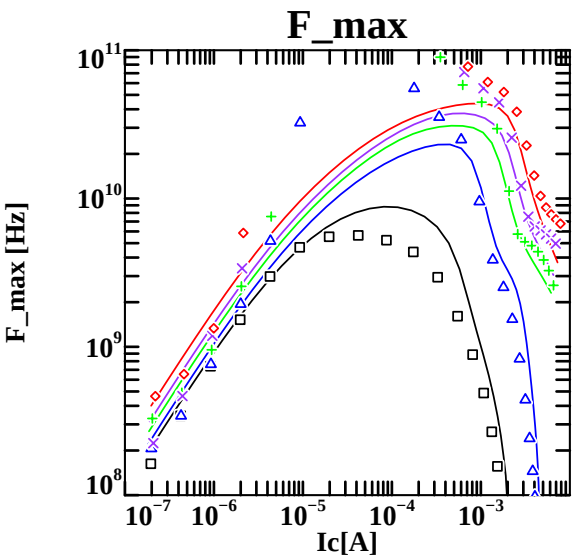

Ic
Ic [A]
Vce[V]
Is
Ib [A]
Vce[V]
Vbe
Vbe [V]
Vce[V]
Ic/Ib
Ic/Ib [–]
Vce[V]
Ic/(dIc/dVce)
Vef [V]
Vce[V]
Ic/(dIc/dVce)
Vef [V]
Vce[V]


hfe
Ic/Ib [–]
Ic[A]

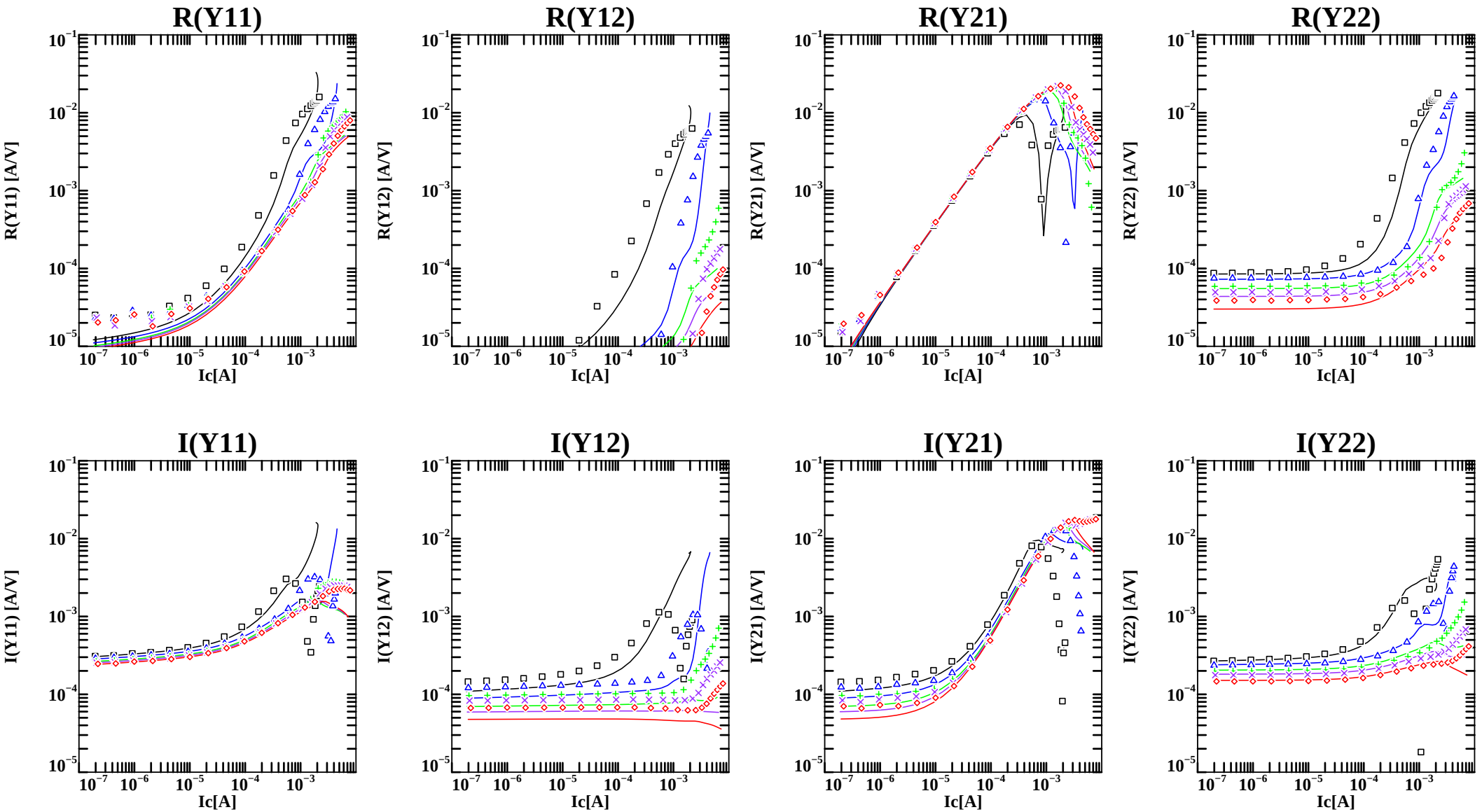

Rbb
Rbb [Ohm]
Ic[A]


fT
fT [Hz]
Ic[A]


F_tumax
F_tumax [Hz]
Ic[A]


F_max
F_max [Hz]
Ic[A]

NPN D temp=25 freq=1.8GHz Vce=0.2, 0.4, 0.9, 1.5, 3.0



Process E

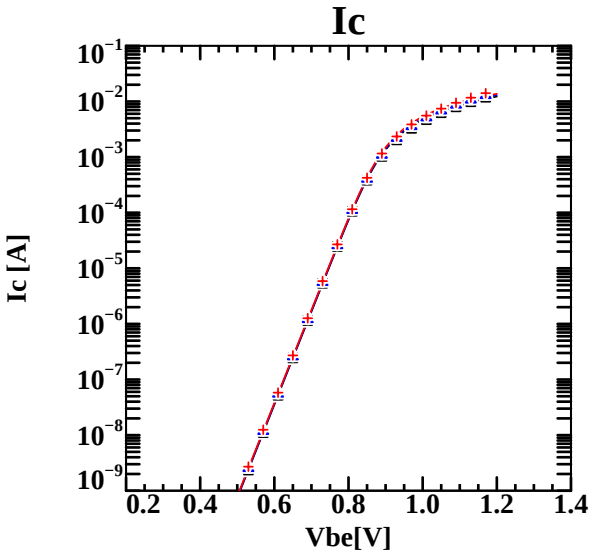
Si BiCMOS process

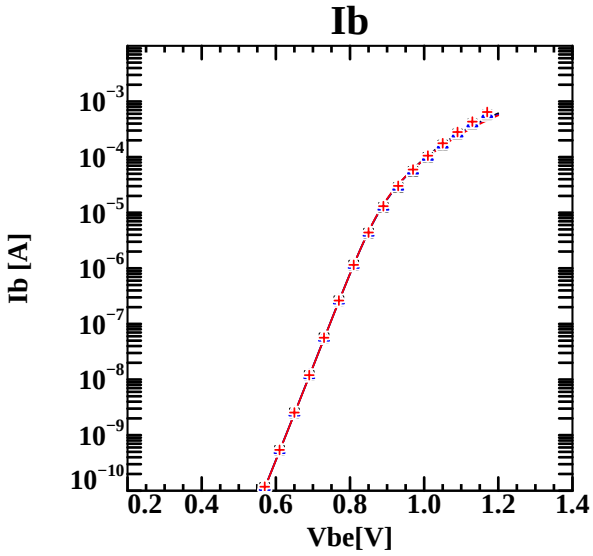
Emitter size: $0.6 \times 4.8\,\mu\mathrm{m}^2$

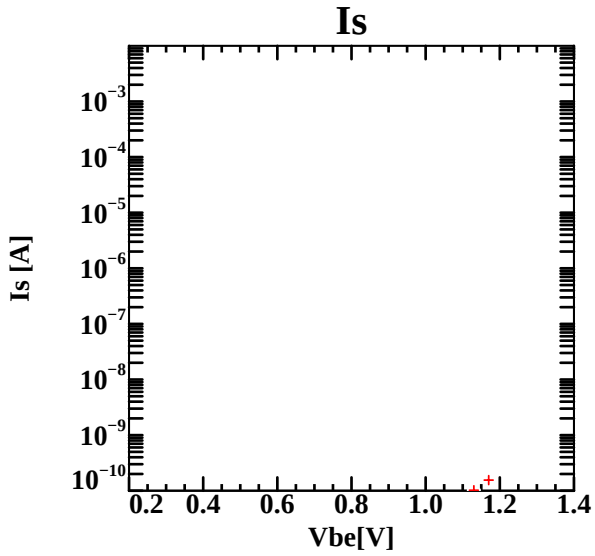
Base: $\rho_{\square} = 10\,\mathrm{k}\Omega$

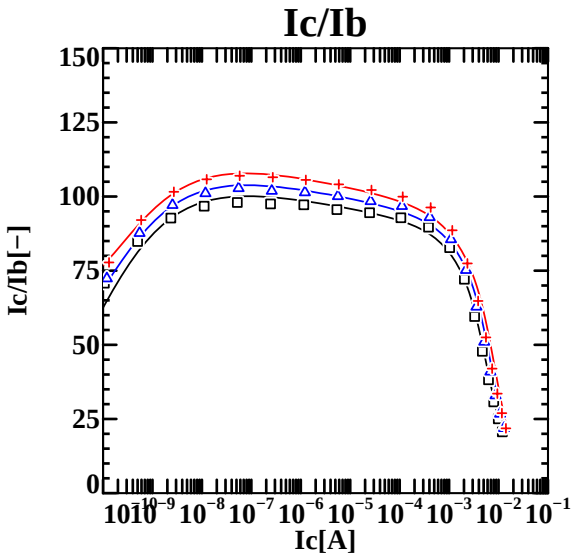
Maximum cut off frequency f_T

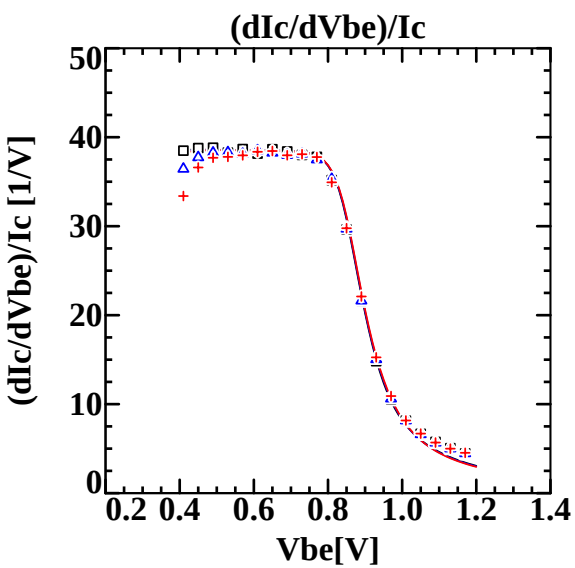
f_T: 25 GHz @ $V_{CB} = 4\,\mathrm{V}$

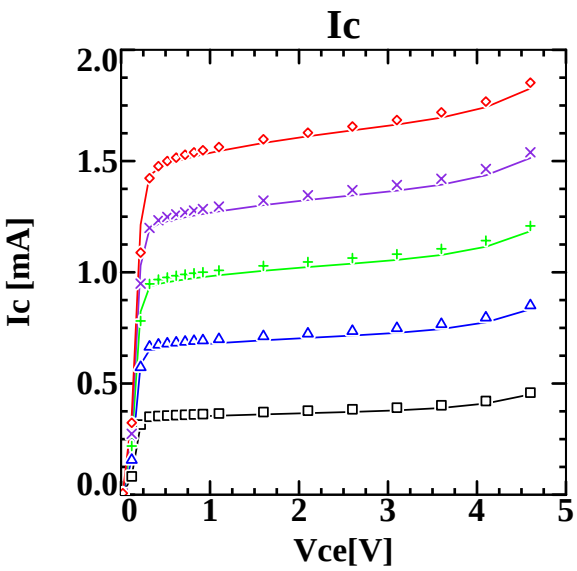

Ic
Ic [A]
Vbe[V]

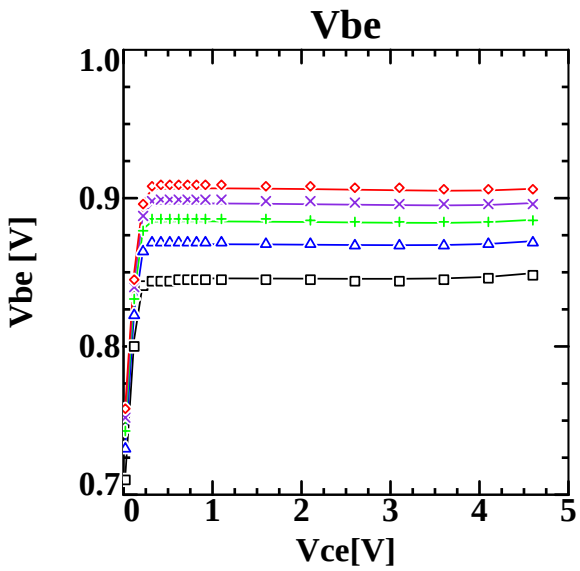

Ib
Ib [A]
Vbe[V]

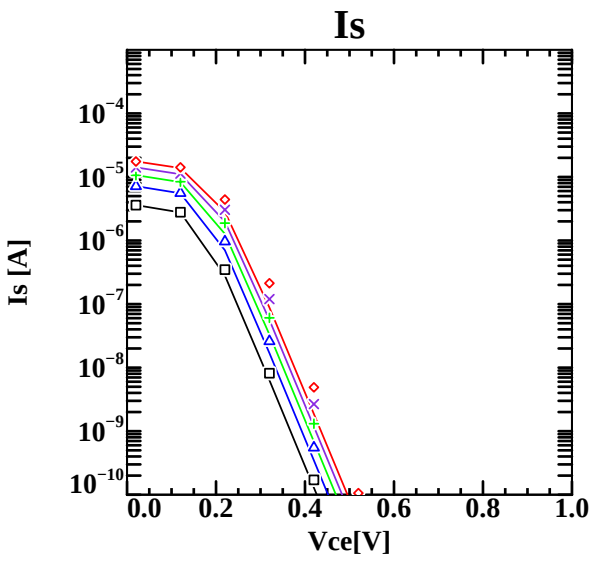

Is
Is [A]
Vbe[V]

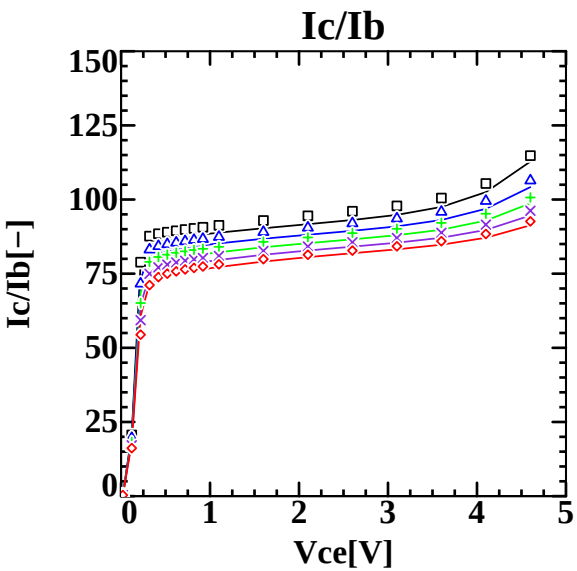

Ic/Ib
Ic/Ib[−]
Ic[A]

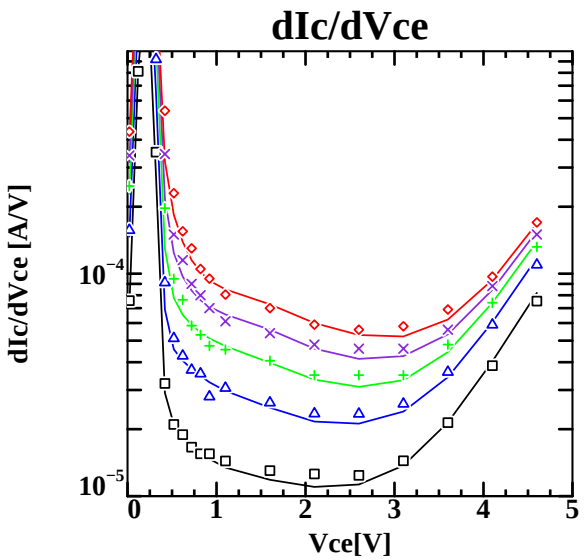

(dIc/dVbe)/Ic
(dIc/dVbe)/Ic [1/V]
Vbe[V]

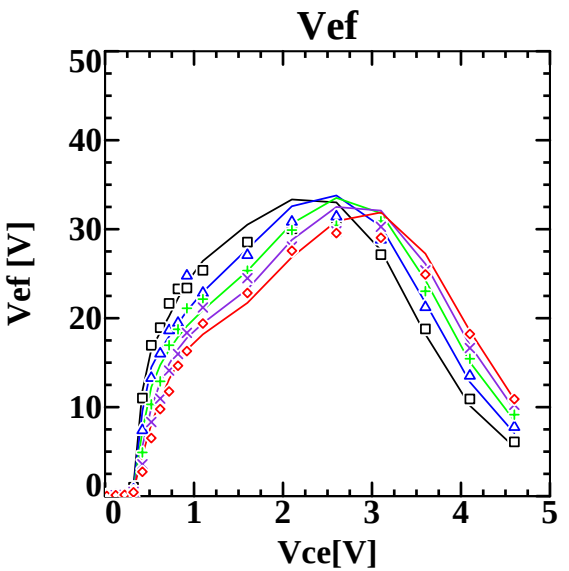

Ic
Ic [mA]
Vce[V]

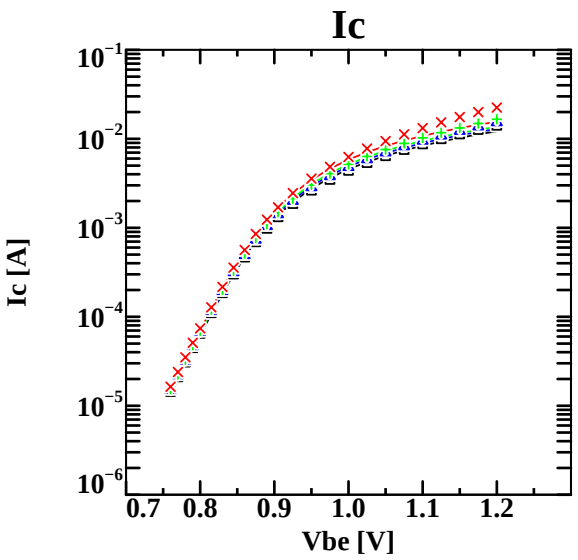

Vbe
Vbe [V]
Vce[V]

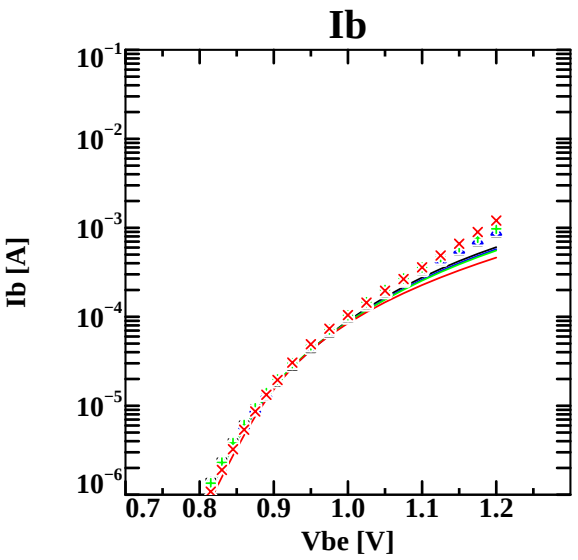

Is
Is [A]
Vce[V]

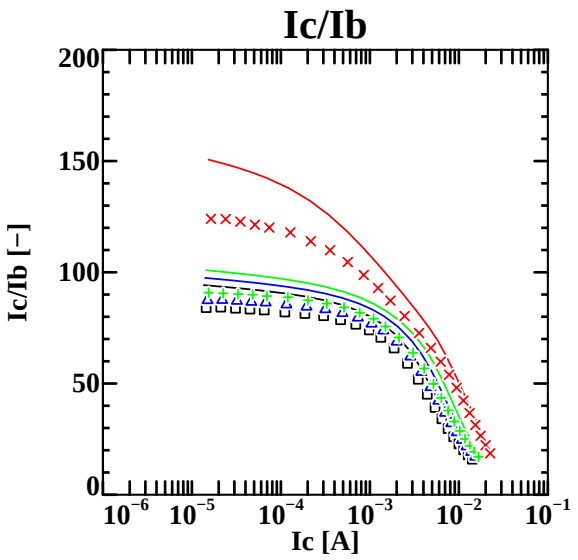

Ic/Ib
Ic/Ib[−]
Vce[V]

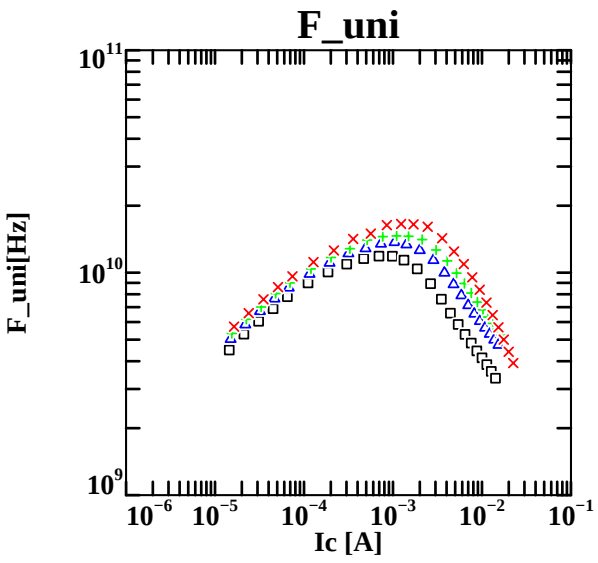

dIc/dVce
dIc/dVce [A/V]
Vce[V]

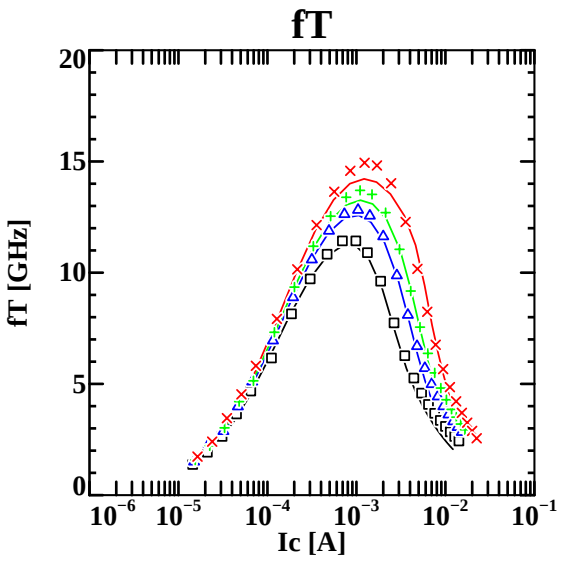

Vef
Vef [V]
Vce[V]

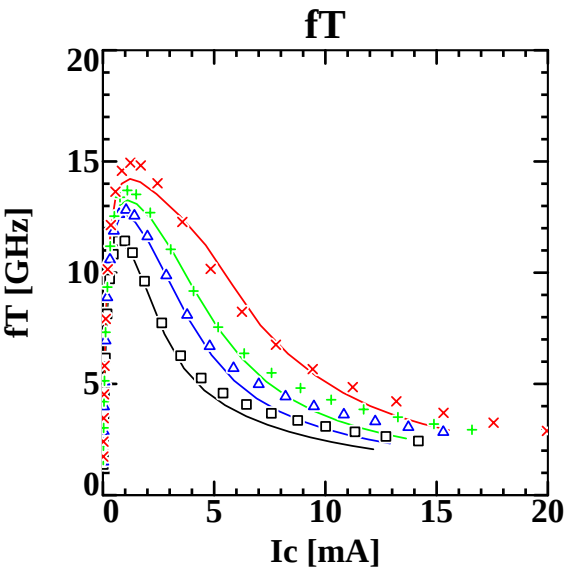

Ic
Ic [A]
Vbe [V]

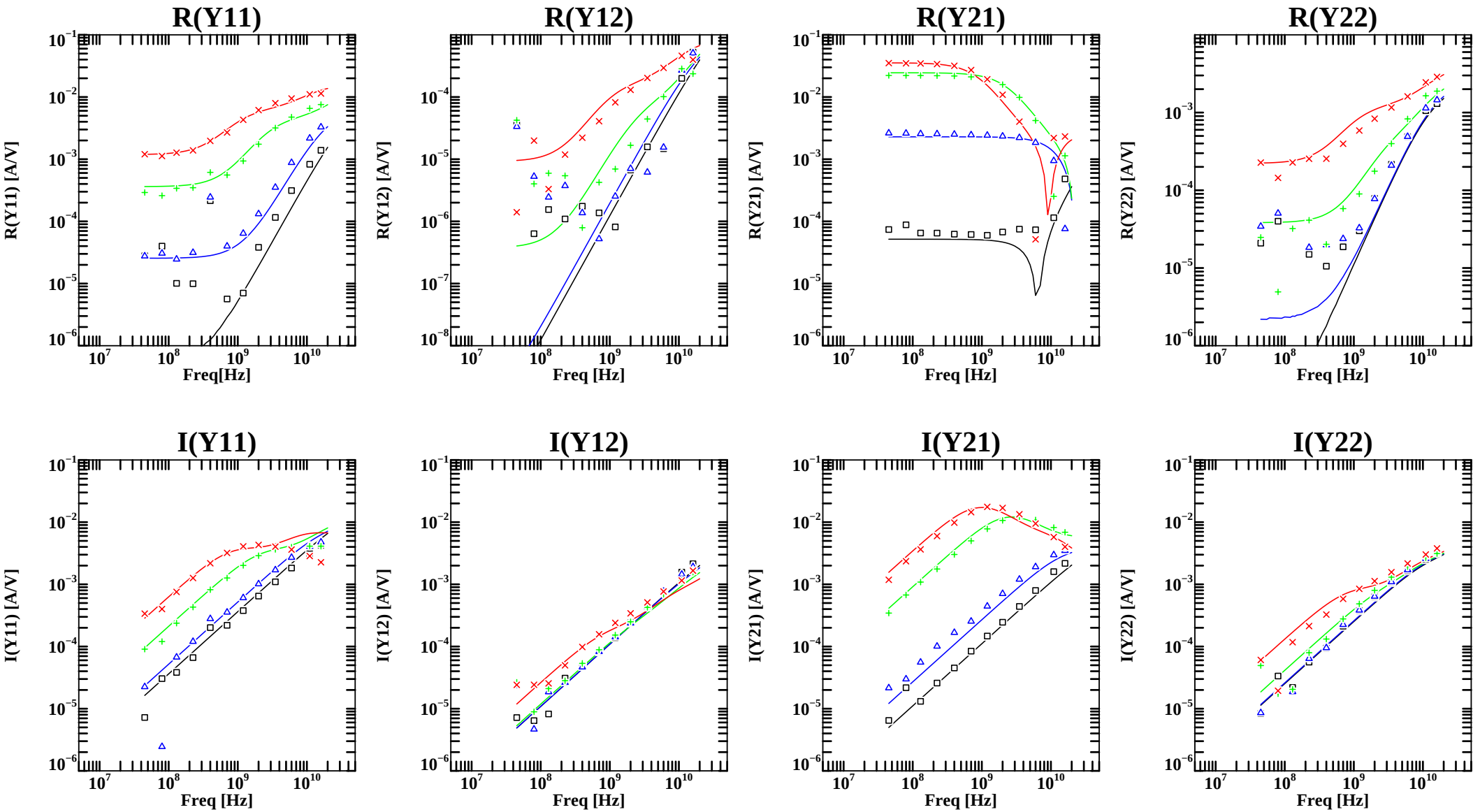

Ib
Ib [A]
Vbe [V]


Ic/Ib
Ic/Ib [–]
Ic [A]


F_uni
F_uni[Hz]
Ic [A]


fT
fT [GHz]
Ic [A]


fT
fT [GHz]
Ic [mA]

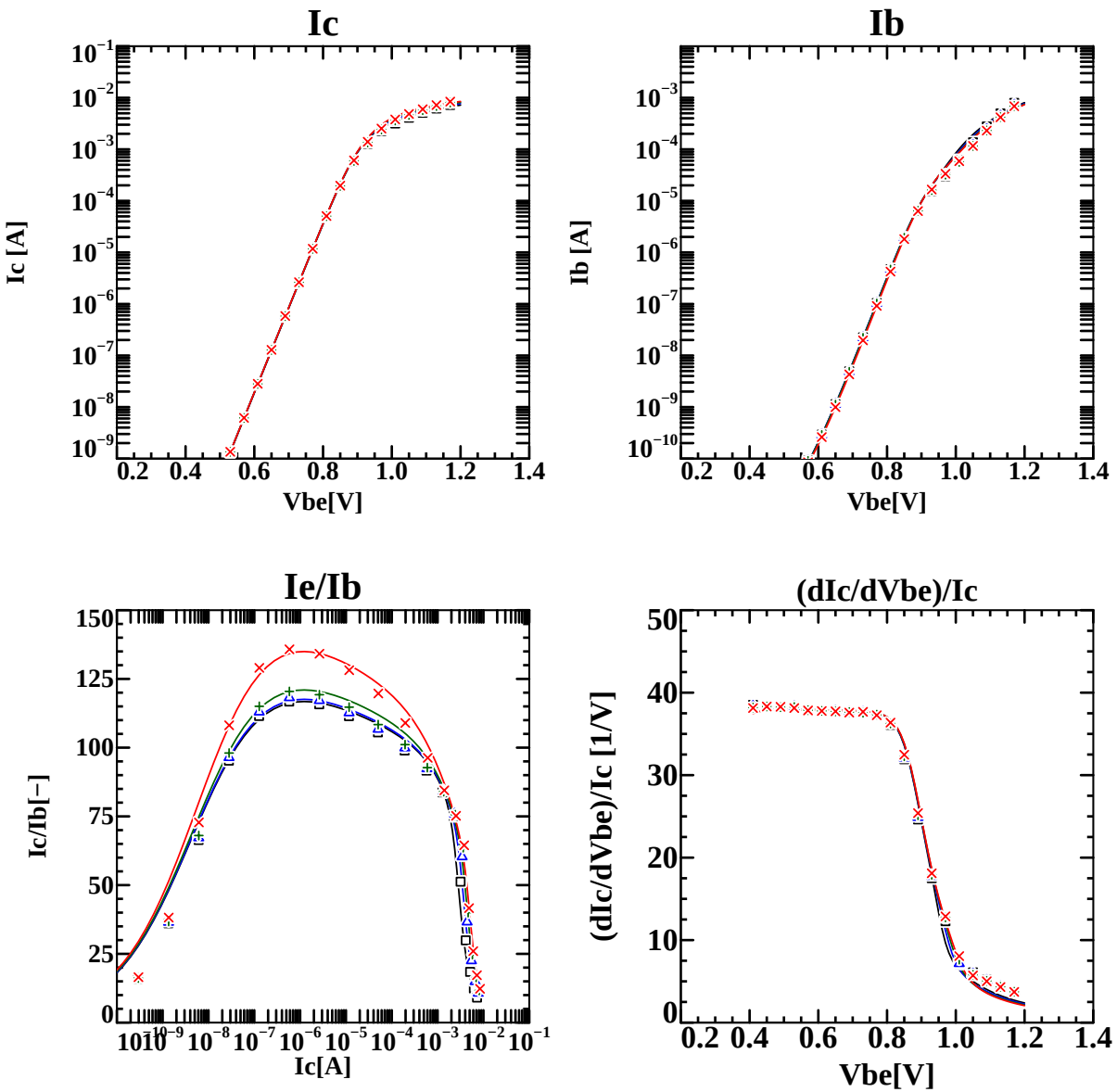

R(Y11)
R(Y11) [A/V]
Freq[Hz]
R(Y12)
R(Y12) [A/V]
Freq [Hz]
R(Y21)
R(Y21) [A/V]
Freq [Hz]
R(Y22)
R(Y22) [A/V]
Freq [Hz]
I(Y11)
I(Y11) [A/V]
Freq [Hz]
I(Y12)
I(Y12) [A/V]
Freq [Hz]
I(Y21)
I(Y21) [A/V]
Freq [Hz]
I(Y22)
I(Y22) [A/V]
Freq [Hz]

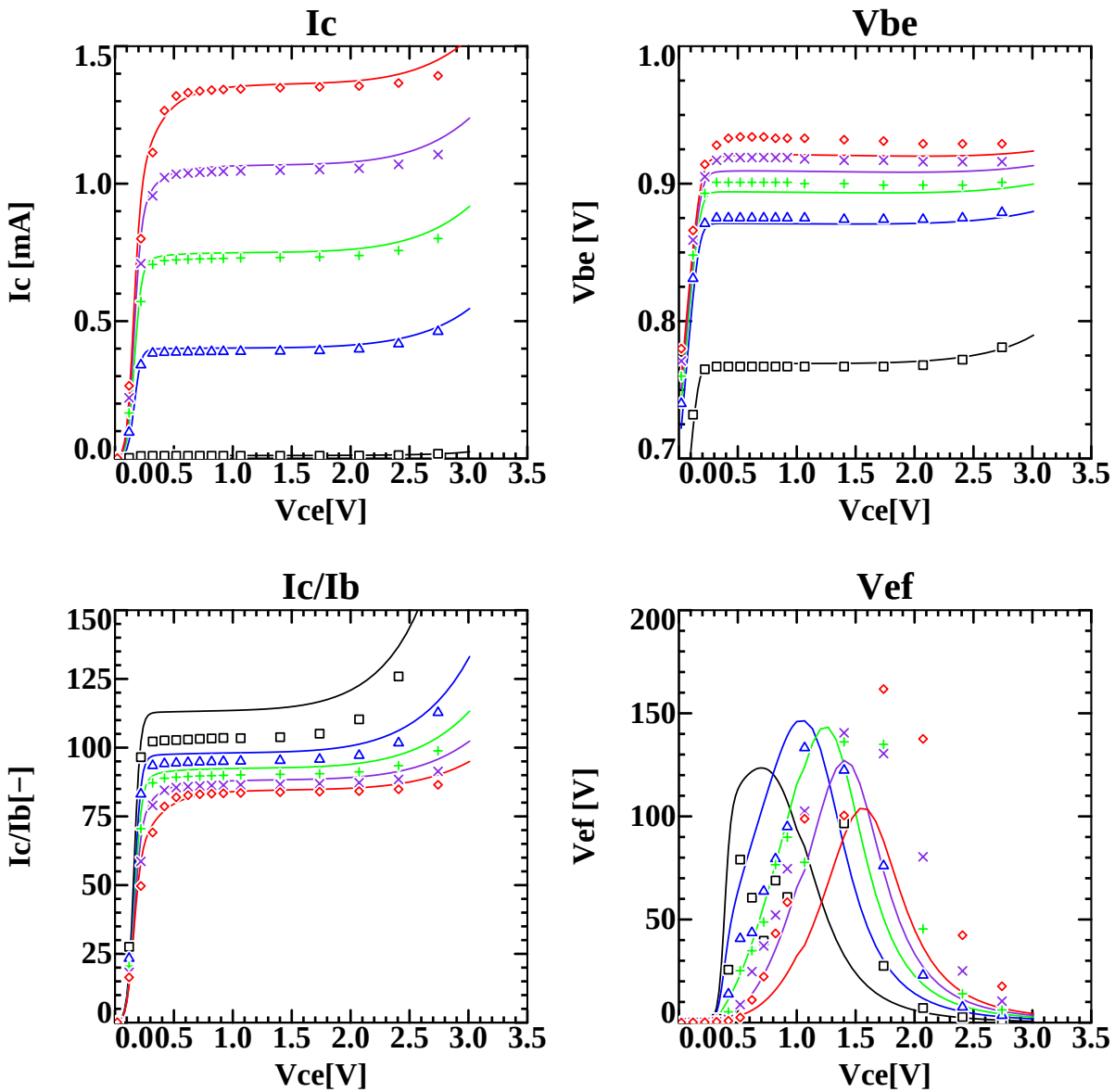
Process F

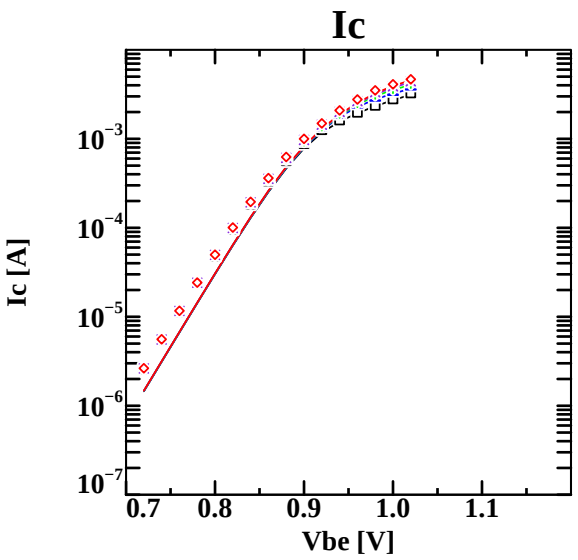
SiGe process

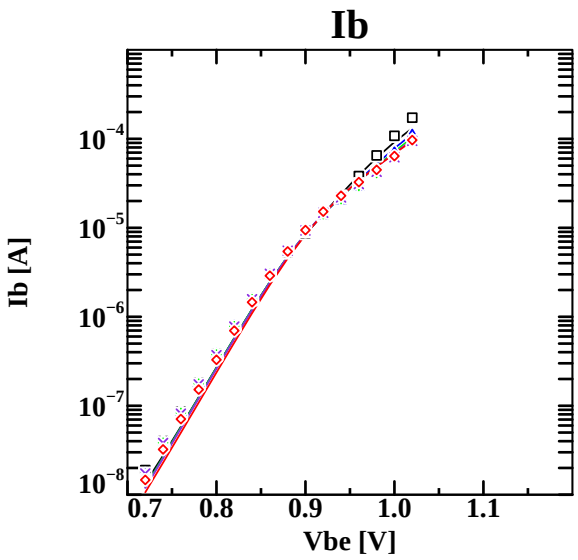
Maximum cut off frequency f_T

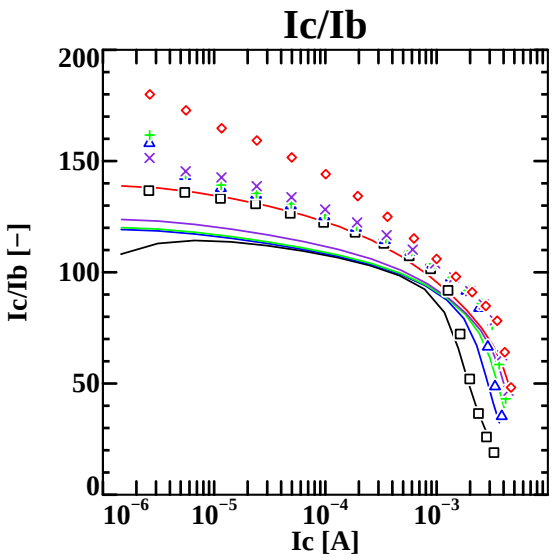
f_T: 50 GHz @ $V_{CB} = 1.5\,\mathrm{V}$

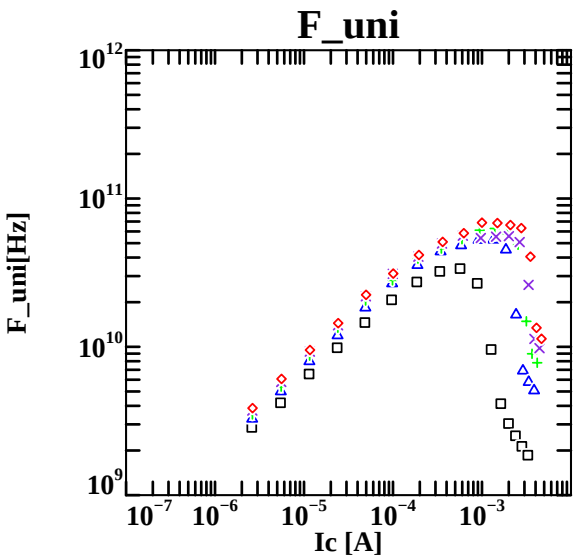

Ic
Ic [A]
Vbe[V]
Ib
Ib [A]
Vbe[V]
Ie/Ib
Ic/Ib[−]
Ic[A]
(dIc/dVbe)/Ic
(dIc/dVbe)/Ic [1/V]
Vbe[V]

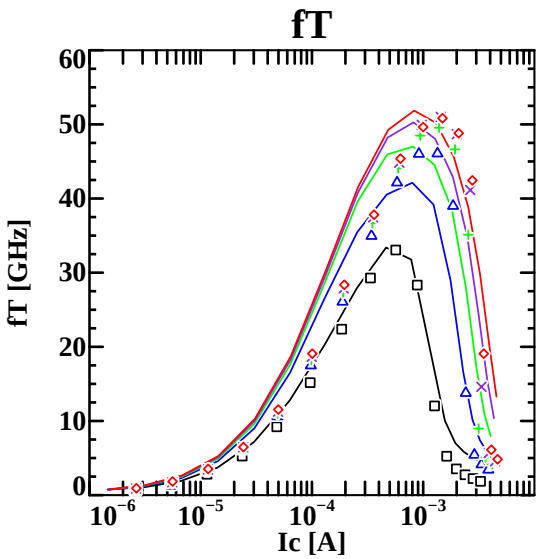

Ic
Ic [mA]
1.5
1.0
0.5
0.0
0.00.5 1.0 1.5 2.0 2.5 3.0 3.5
Vce[V]
Vbe
Vbe [V]
1.0
0.9
0.8
0.7
0.00.5 1.0 1.5 2.0 2.5 3.0 3.5
Vce[V]
Ic/Ib
Ic/Ib[–]
150
125
100
75
50
25
0
0.00.5 1.0 1.5 2.0 2.5 3.0 3.5
Vce[V]
Vef
Vef [V]
200
150
100
50
0
0.00.5 1.0 1.5 2.0 2.5 3.0 3.5
Vce[V]

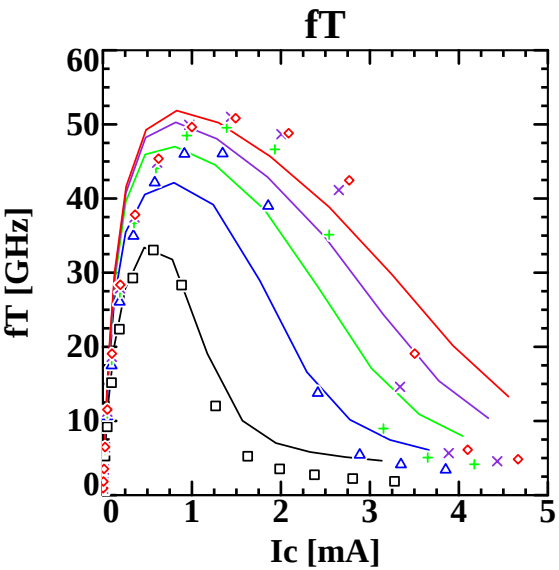

Ic
Ic [A]
Vbe [V]


Ib
Ib [A]
Vbe [V]


Ic/Ib
Ic/Ib [–]
Ic [A]


F_uni
F_uni[Hz]
Ic [A]


fT
fT [GHz]
Ic [A]


fT
fT [GHz]
Ic [mA]