DC and Small-Signal Numerical Simulation of Graphene-Base Transistor for Terahertz Operation

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Outline

- Introduction and motivation
- Device concept
- Numerical model and simulated structure
- DC operation
- Small-signal model and RF performance
- Conclusions

Introduction and motivation

GRAPHENE: candidate for improving RF devices performances

- 2-D nature
- High-speed massless-like carriers
- Group velocity around 10^8 cm/s
- Long mean free path → quasi-ballistic transport at CMOS sizes

2004: Graphene Field-Effect Transistor (GFET)

- Cut-off frequencies in the range of hundreds of GHz
- Various RF applications (RF mixers, frequency multipliers...)

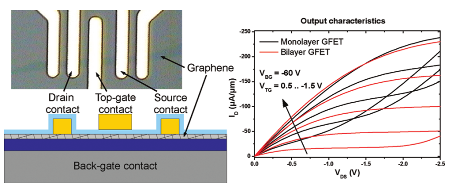
Introduction and motivation

DRAWBACK: Graphene has no bandgap!

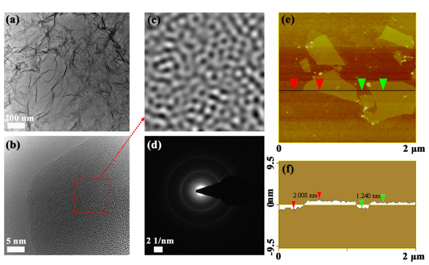
- Lack of current saturation
- Poor I_{ON}/I_{OFF} ratios

→ **SOLUTIONS ?**

Open a bandgap
(*bilayer, trilayer, fluorination*)

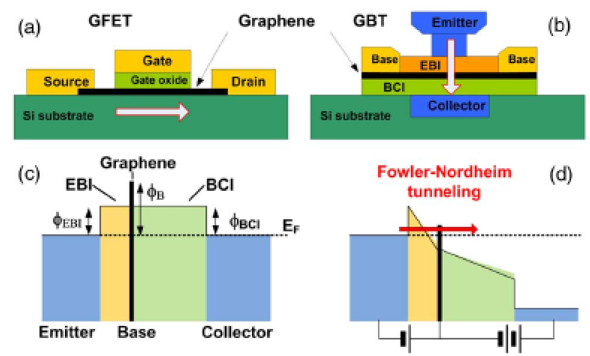


R. Szafranek et al., *Nano Lett.*, 2012, 12 (3), pp. 1324–1328



Z. Wang et al., *Carbon*, vol. 50, no. 15, Dec. 2012, pp. 5403–5410

Alternative approaches (GBT)



W. Mehr et al., *IEEE Electron Device Lett.*, vol. 33 no. 5, May 2012, pp. 691–693

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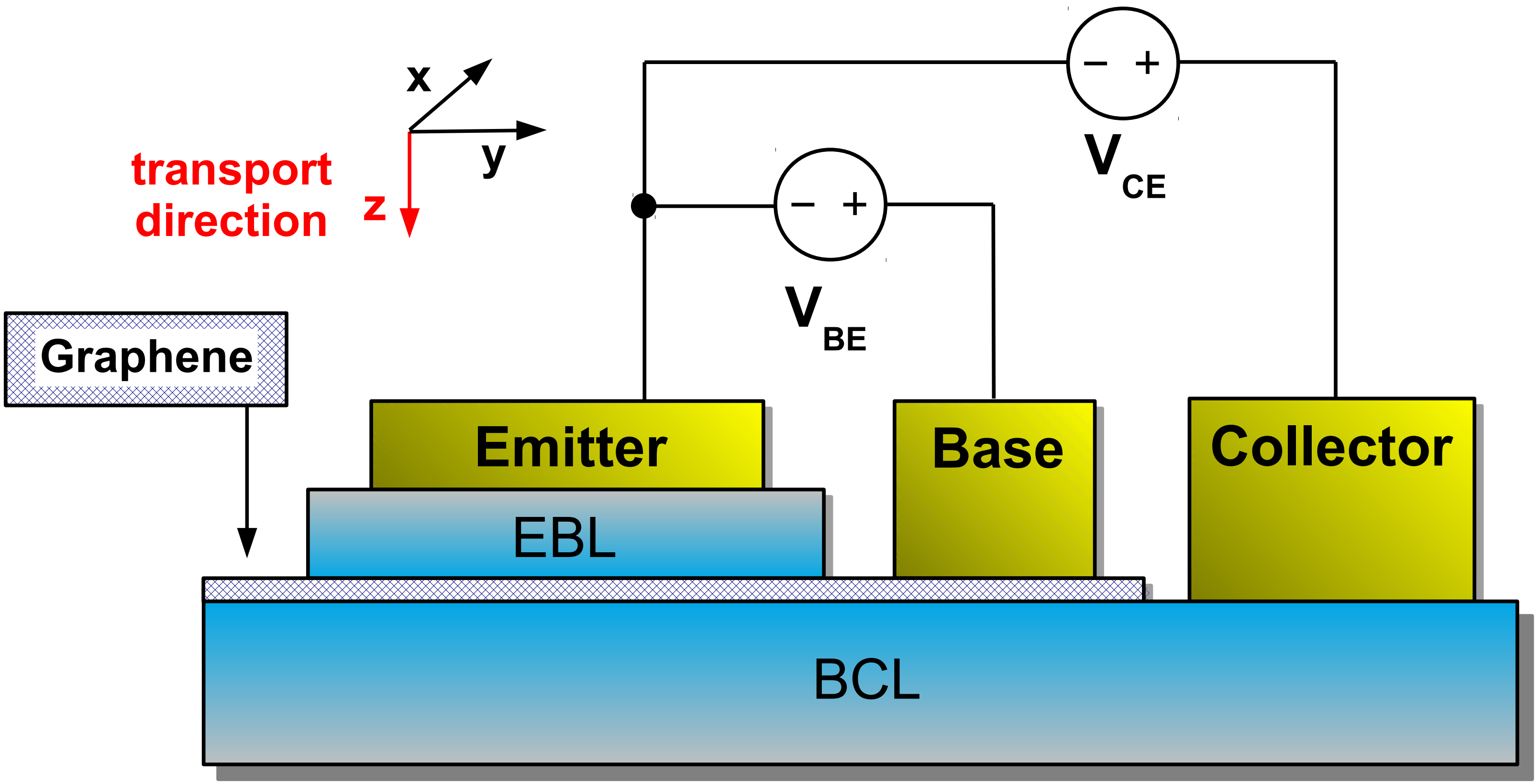
GBT device concept: structure

VERTICAL DEVICE

(Common emitter configuration shown)

W. Mehr et al., *IEEE Electron Device Lett.*, vol. 33 no. 5, May 2012, pp. 691–693



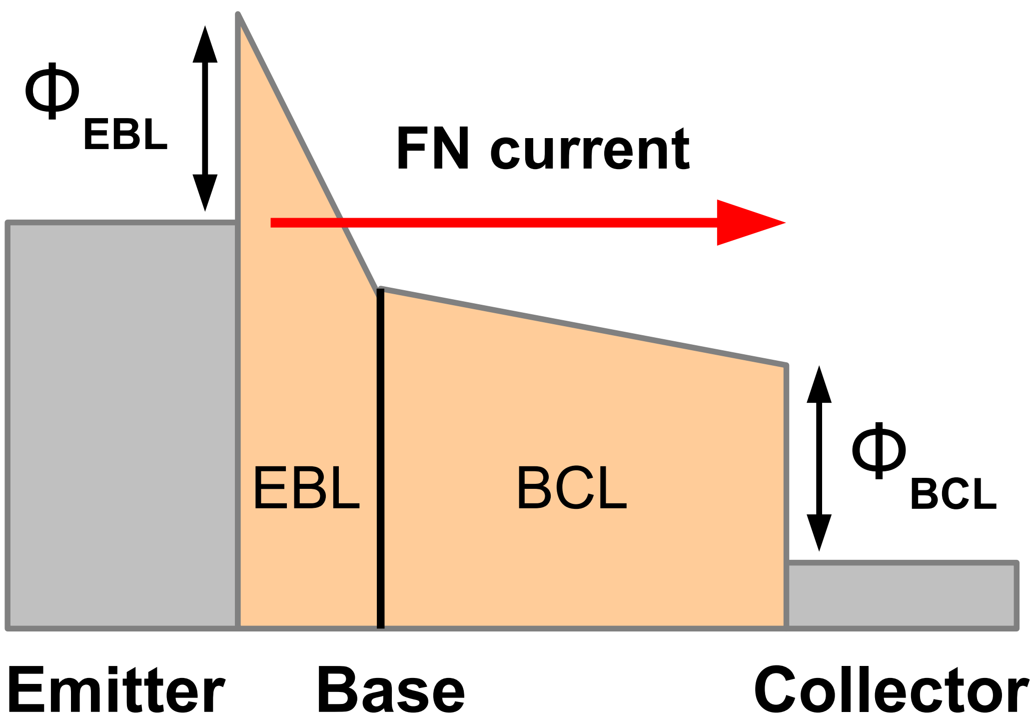
GBT device concept: principle

Hot Electron Transistor with graphene base
(similar to *n-p-n* BJT)

- Low off current
- Drain current saturation
- Ballistic transport across base → ***fast!***
- Power amplification

EBL and BCL:

- Oxides (historically)
- Semiconductors (more suitable)

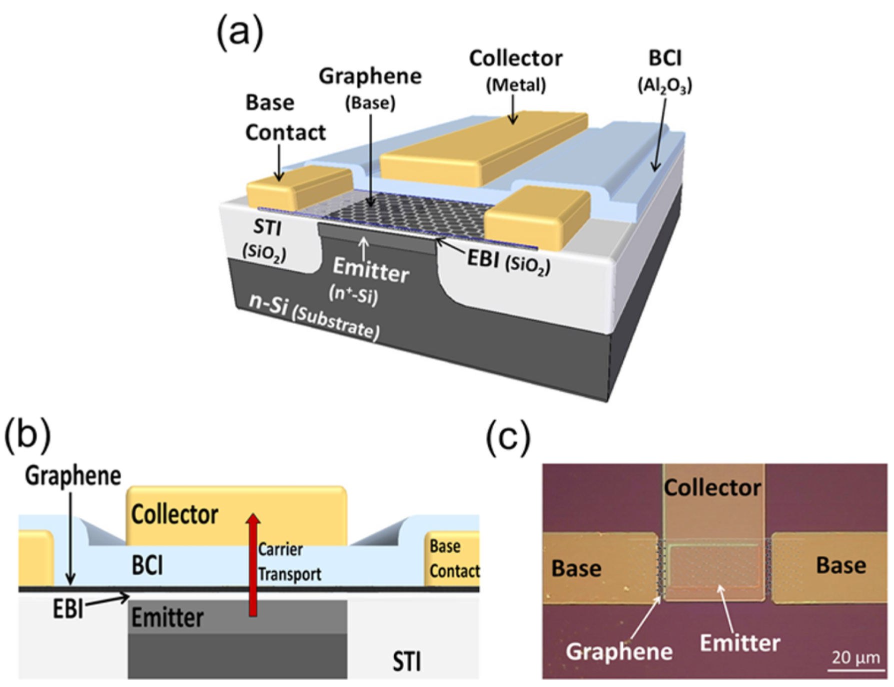


Experimental works

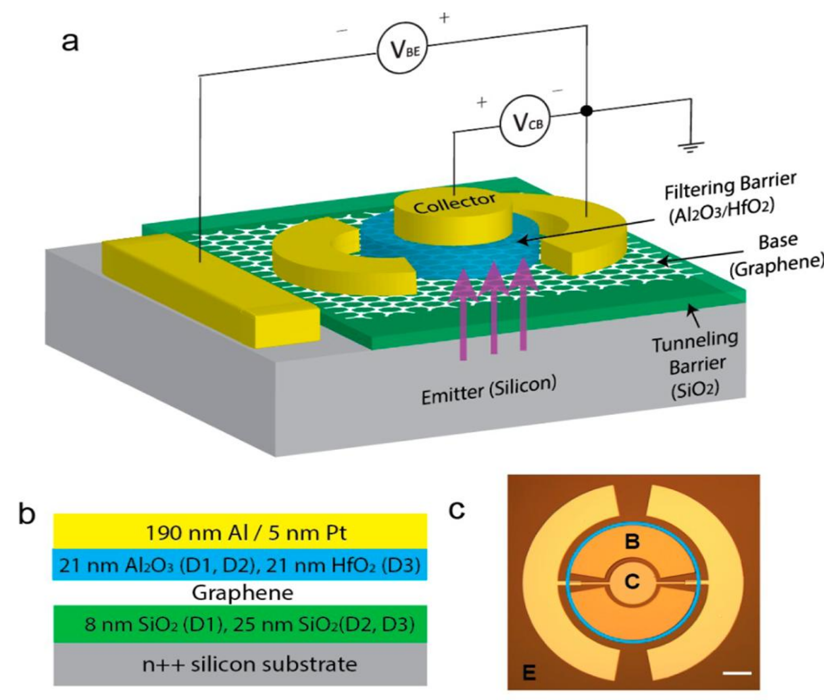
DC functionality

Very low currents (< 1 µA/cm^2)

Poor common-base gain α (< 0.1)



S. Vaziri et al., *Nano Letters*, vol. 13 no. 4, pp. 1435-1439, 2013.



C. Zeng et al., *Nano Letters*, vol. 13 no. 6, pp. 2370-2375, 2013.

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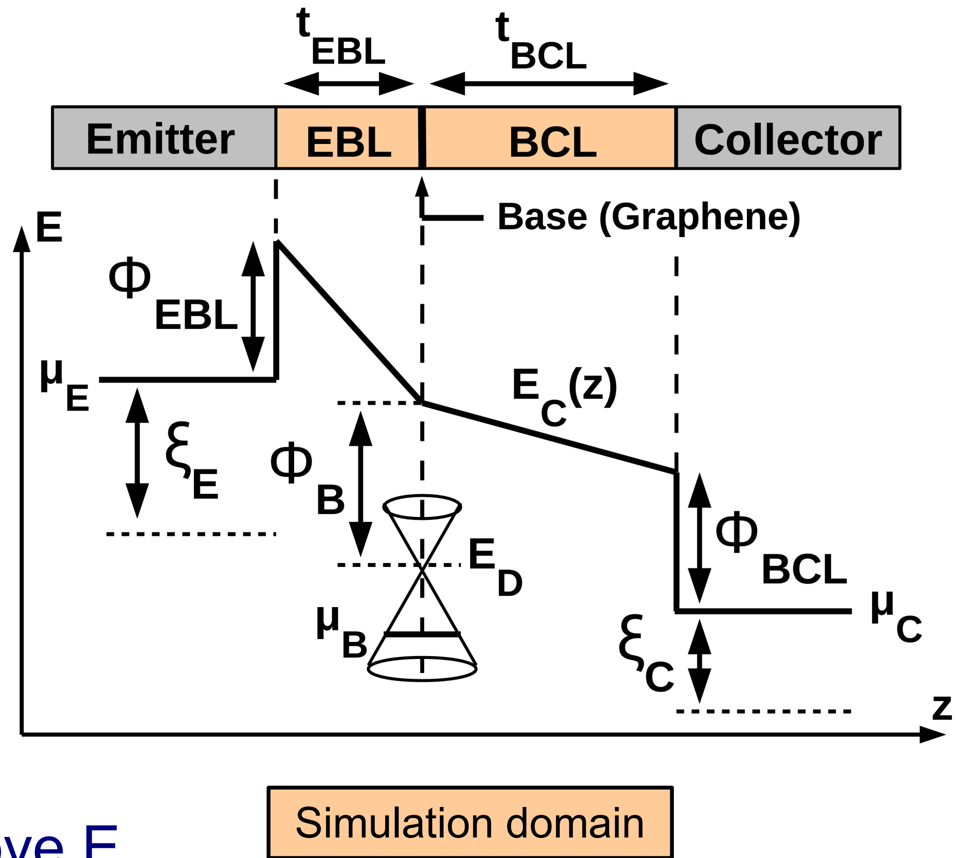
Numerical model and simulated structure

Assumptions:

- Silicon for EBL and BCL
- 1-D transport model
- No valence band (max V_{BE}/V_{CE} = 1.3/1.5 V)



Electron transport:

- NEGF formalism
- Ballistic approximation
- Eff. mass Hamiltonian
- Non-parabolic correction above E_C
- Self-consistent with Poisson's equation

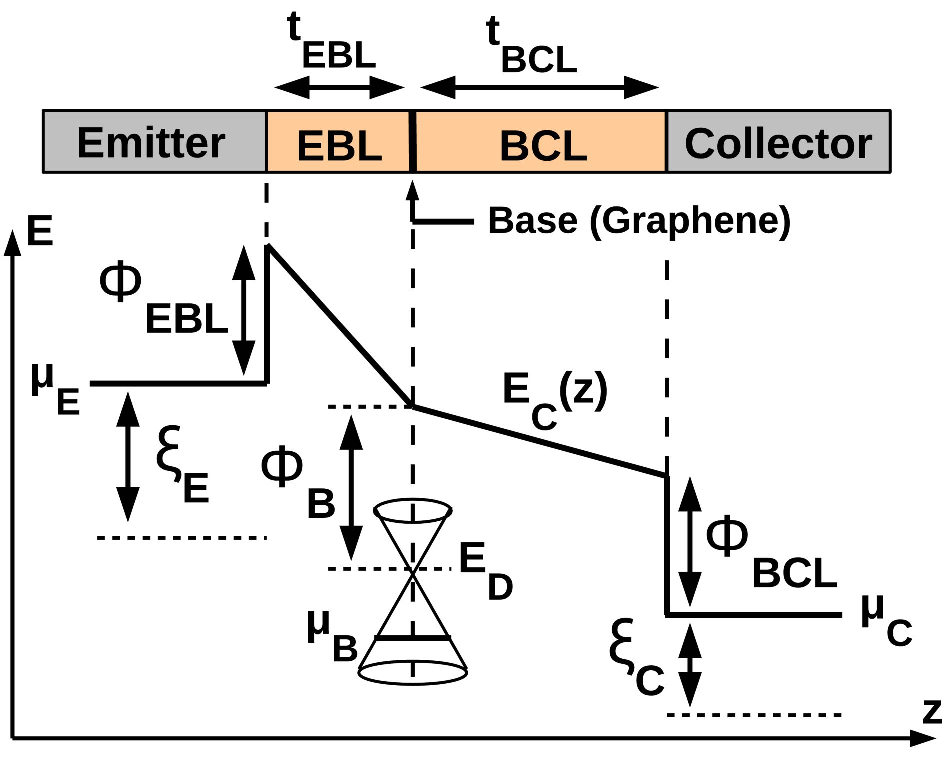
Numerical model and simulated structure

Simulation domain: EBL (silicon) + base + BCL (silicon)

Contacts: semi-infinite Si leads

- $E_C = \mu_{E/C} - \xi_{E/C}$
- $\xi_{E/C} = 0.8/0.06$ eV (degeneracy)

- $\Phi_{EBL} = \Phi_{BCL} = 0.2$ eV (no IFL)
- GBT1: $t_{EBL/BCL} = 3/20$ nm
- GBT2: $t_{EBL/BCL} = 3/10$ nm
- $\Phi_B = 0.5$ eV



Treatment of the graphene layer

Potential barrier or well?

- **Well**:
  H. Yang *et al.*, "Graphene barristor: a triode device with a gate-controlled Schottky barrier", *Science*, vol. 336, no. 6085, pp. 1140-1143, 2012
- **Barrier**:
  W. Mehr *et al.*, "Vertical Graphene Base Transistor", *IEEE Electron Device Lett*., vol. 33 no. 5, May 2012, pp. 691-693

Transport approximation

- $\boldsymbol{\Sigma^R_B = -j\,\Delta_B\,\delta(z - z_B)}$ added to [H] at $z = z_B$ ($t_B = 0$)
- $\boldsymbol{\Delta_B}$ is a fitting parameter: here, $\Delta_B = 10^{-13}$ eV·cm ($\beta_F \approx 10^5$)

Electrostatics

- $\boldsymbol{n(z) = n_{SC}(z) + \delta(z - z_B)n_{GR}}$ with n_{GR} from the Dirac band model

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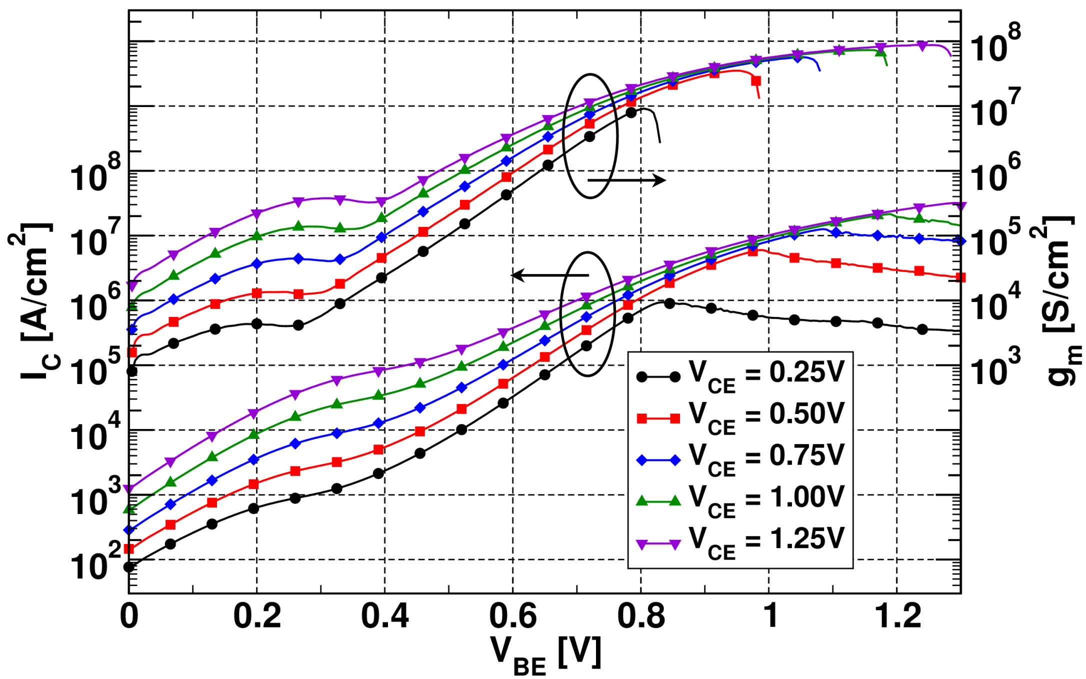
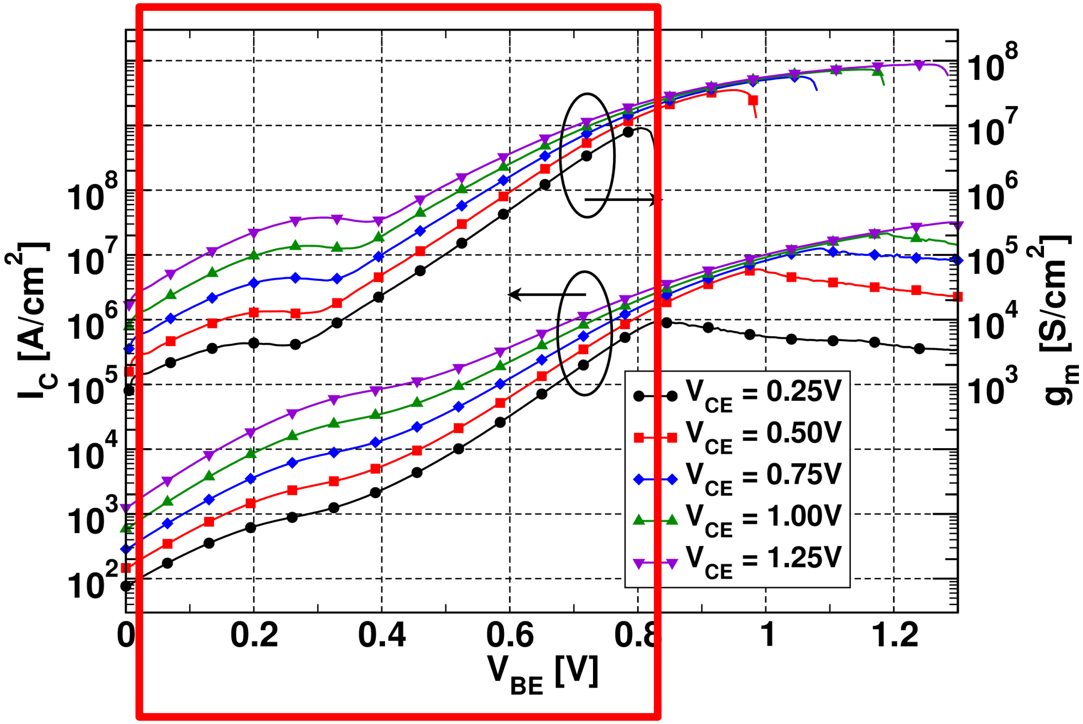
Turn-on characteristics (GBT1)



Turn-on characteristics (GBT1)

V_{BE} < 0.8 V:

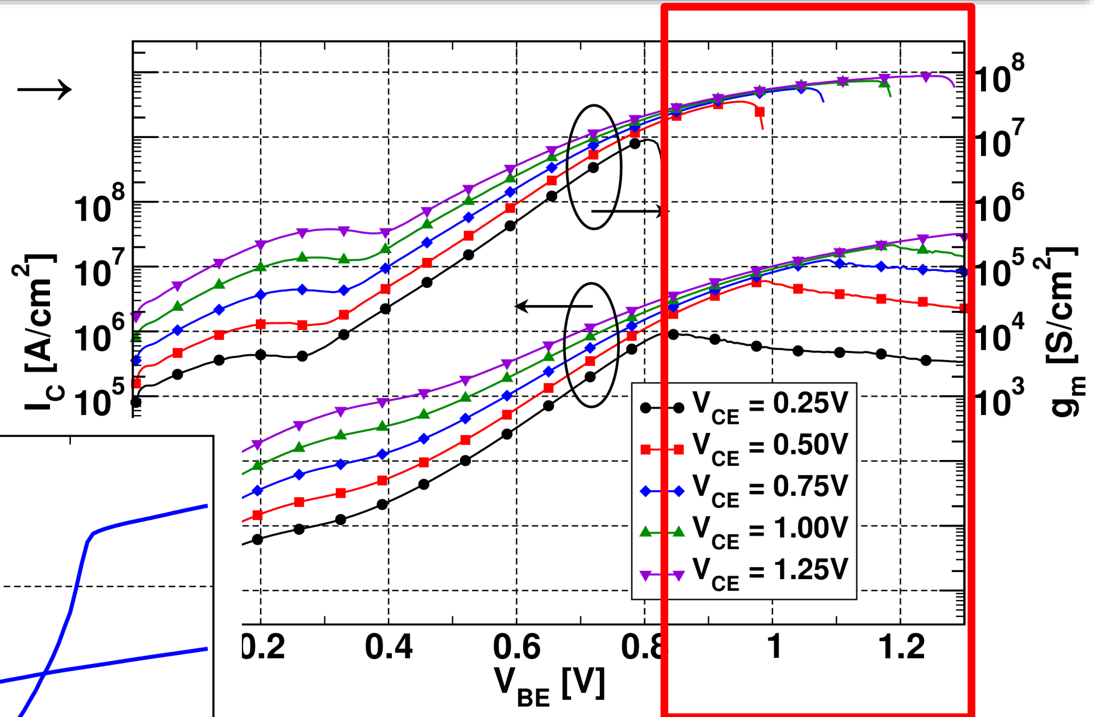
$I_C \approx \exp(V_{BE}, V_{CE})$



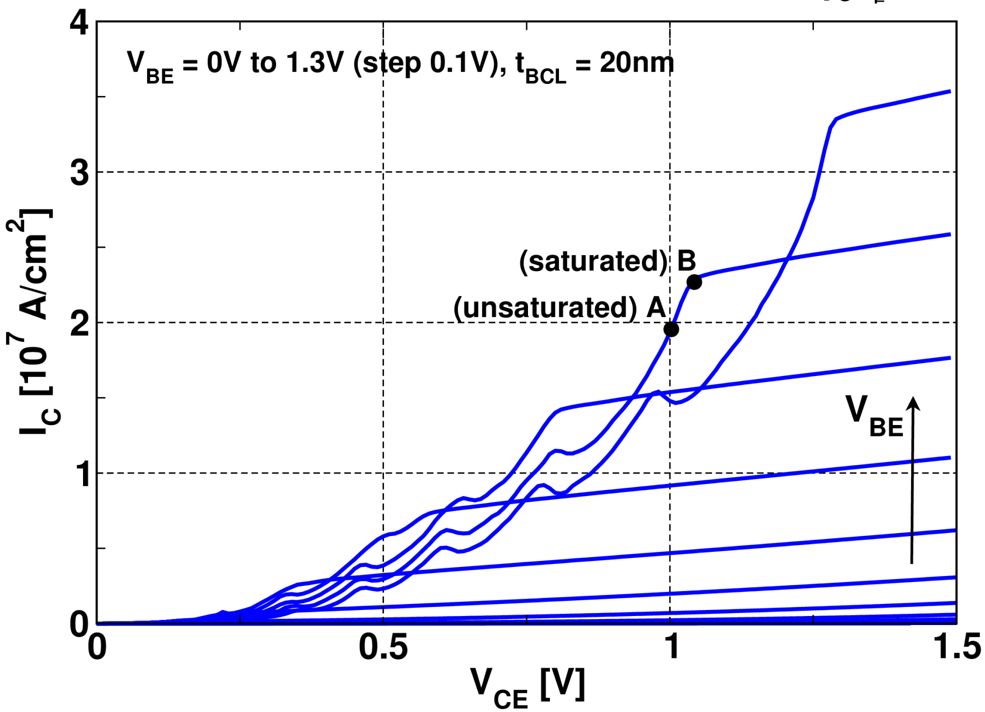
Turn-on and output characteristics (GBT1)

Turn-on characteristics →

V_{BE} > 0.8 V: two regimes



↓ I_C-V_{CE} curves



Low V_{CE}: unsaturated

High V_{CE}: saturated

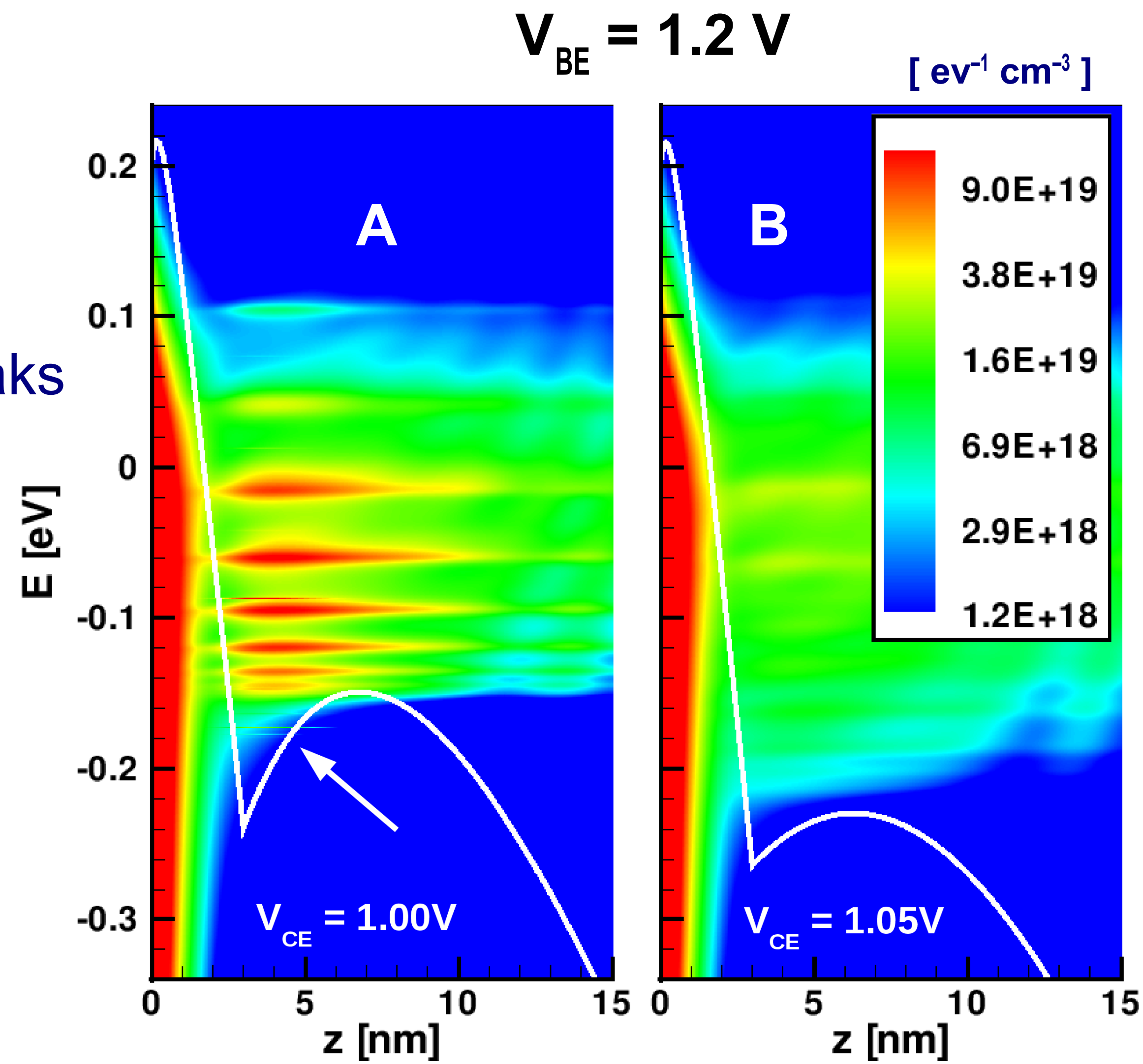
Electron density spectra (GBT1)

A (unsaturated):

- Potential well at z_B
- BCL barrier
- Quasi-bound states arrow→subband peaks

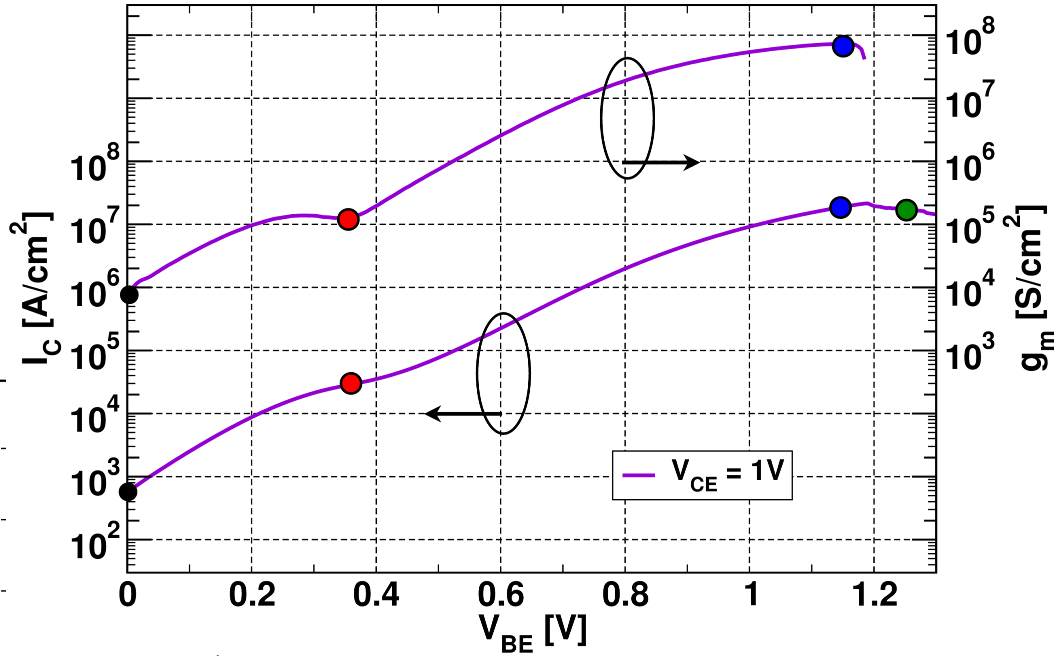
B (saturated):

- States suppressed
- Positive charge ↓
- Dirac point energy ↓
- BCL barrier lowered

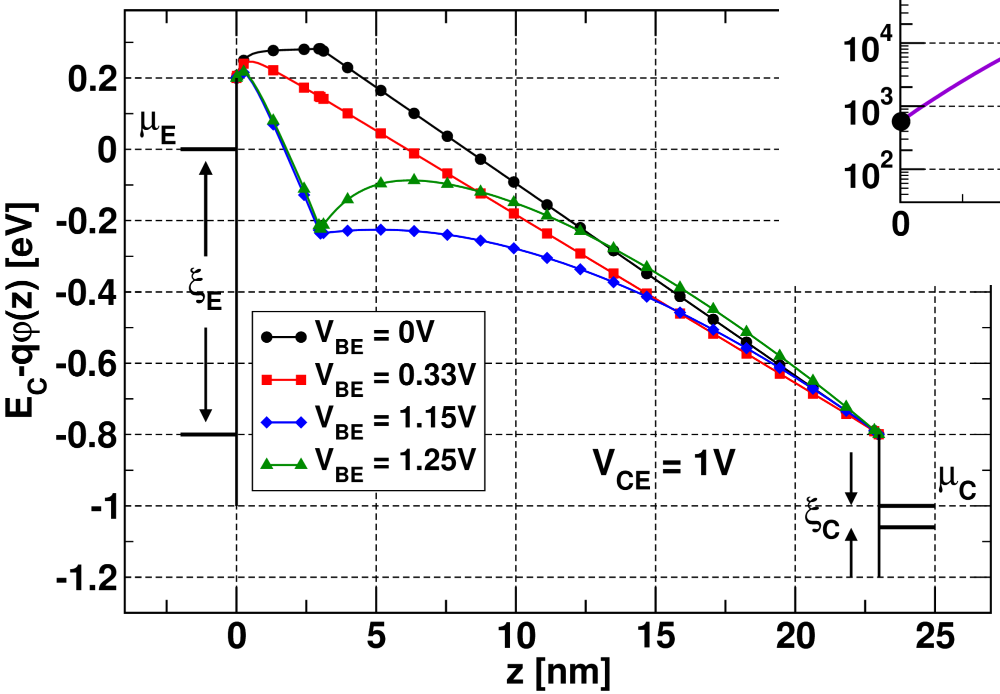


Transconductance dip (GBT1)

Turn-on characteristics →



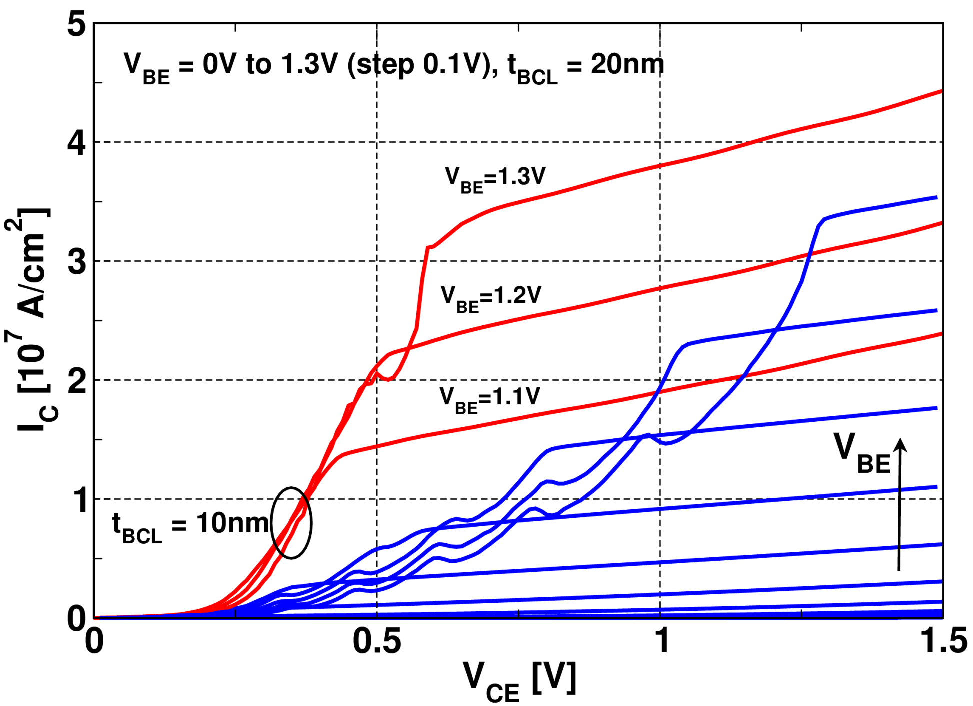
↓ Band diagram (E_C)



← **V_{BE} = 0.33V**: Q_{GR} = 0

Minimum C_Q → g_m dips

Output conductance (GBT1 and GBT2)



Even if BCL barrier is low or absent, V_{CE} still affects I_C through the electrostatic influence on Q_{GR} and V_{Dirac}.

Shorter BCL:

Wider saturation region / Worse output conductance

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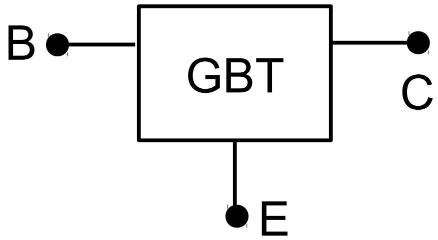
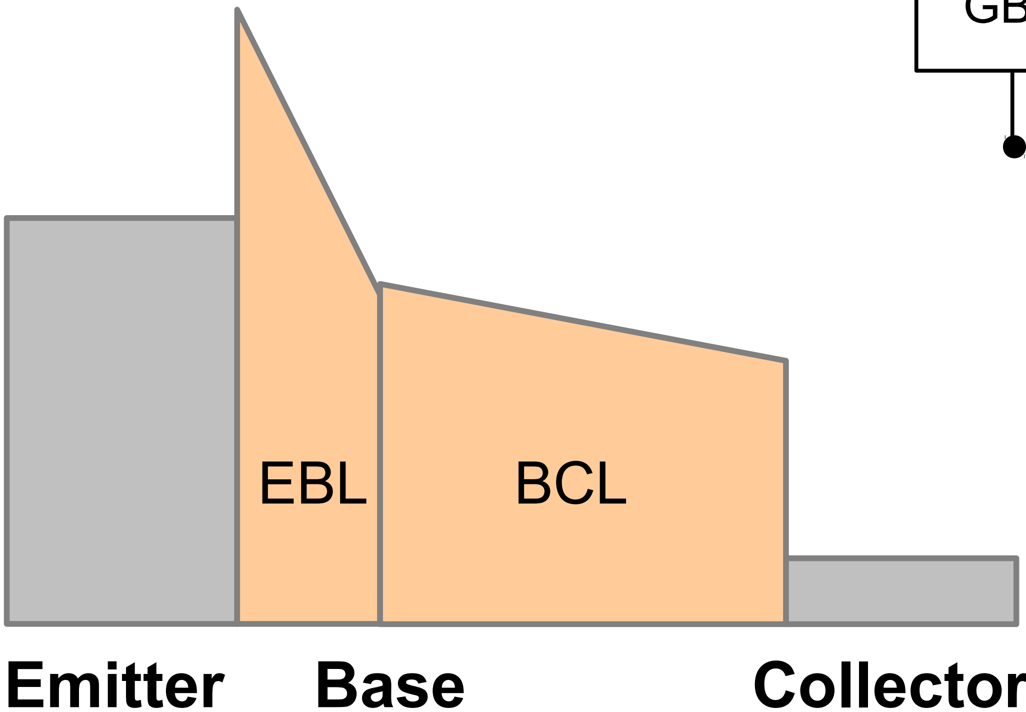
Small-signal model

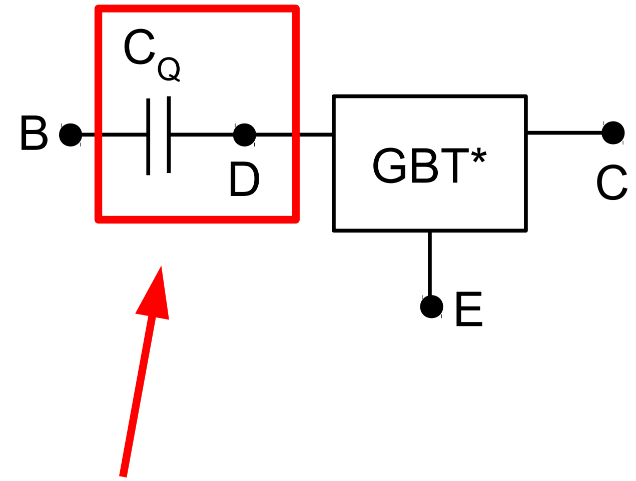
Valid in SATURATION

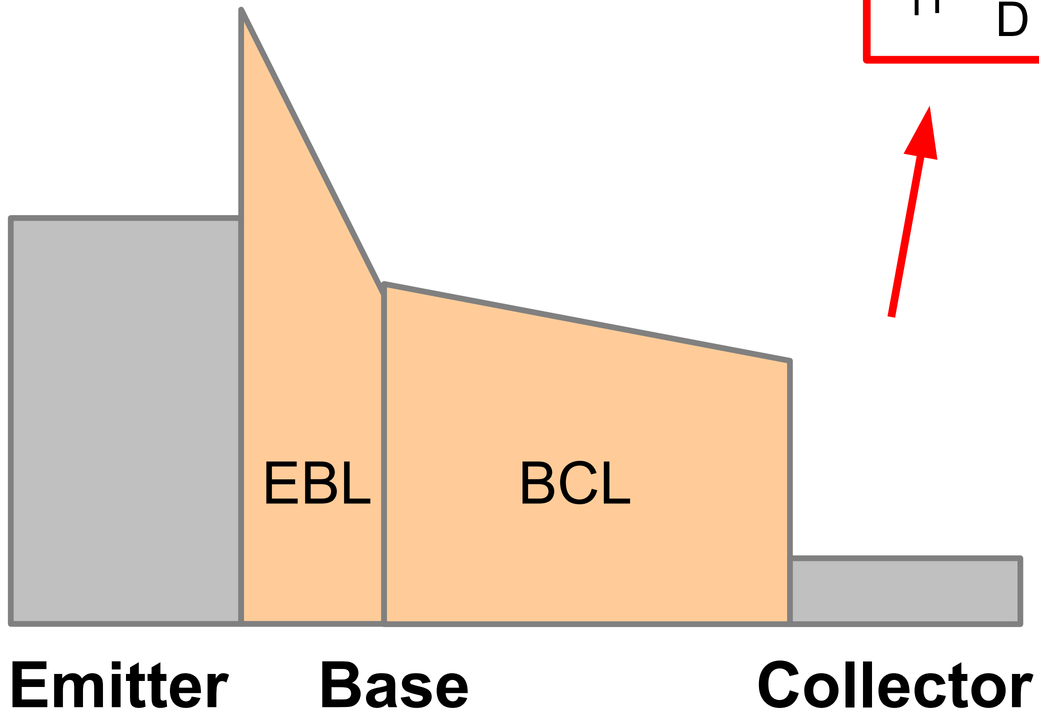




Small-signal model: Dirac point and C_Q

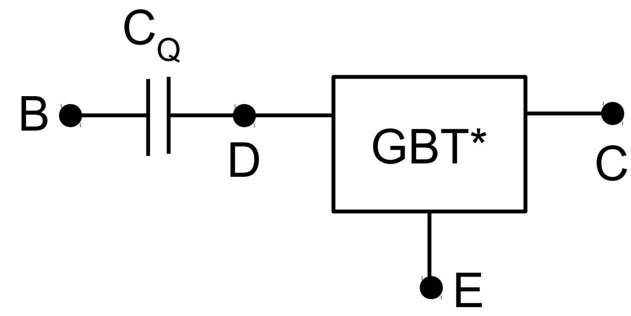
Valid in <u>SATURATION</u>

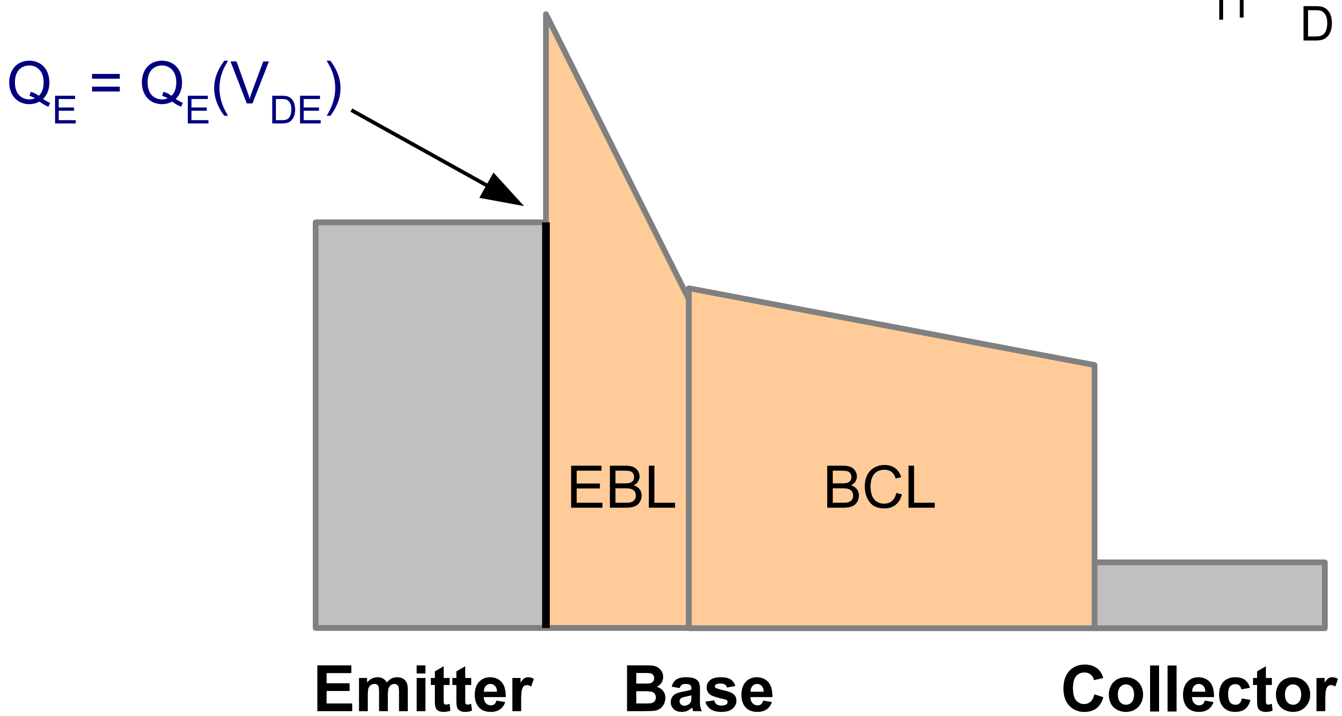




Small-signal model: definitions and assumptions

Valid in <u>SATURATION</u>





Small-signal model: definitions and assumptions

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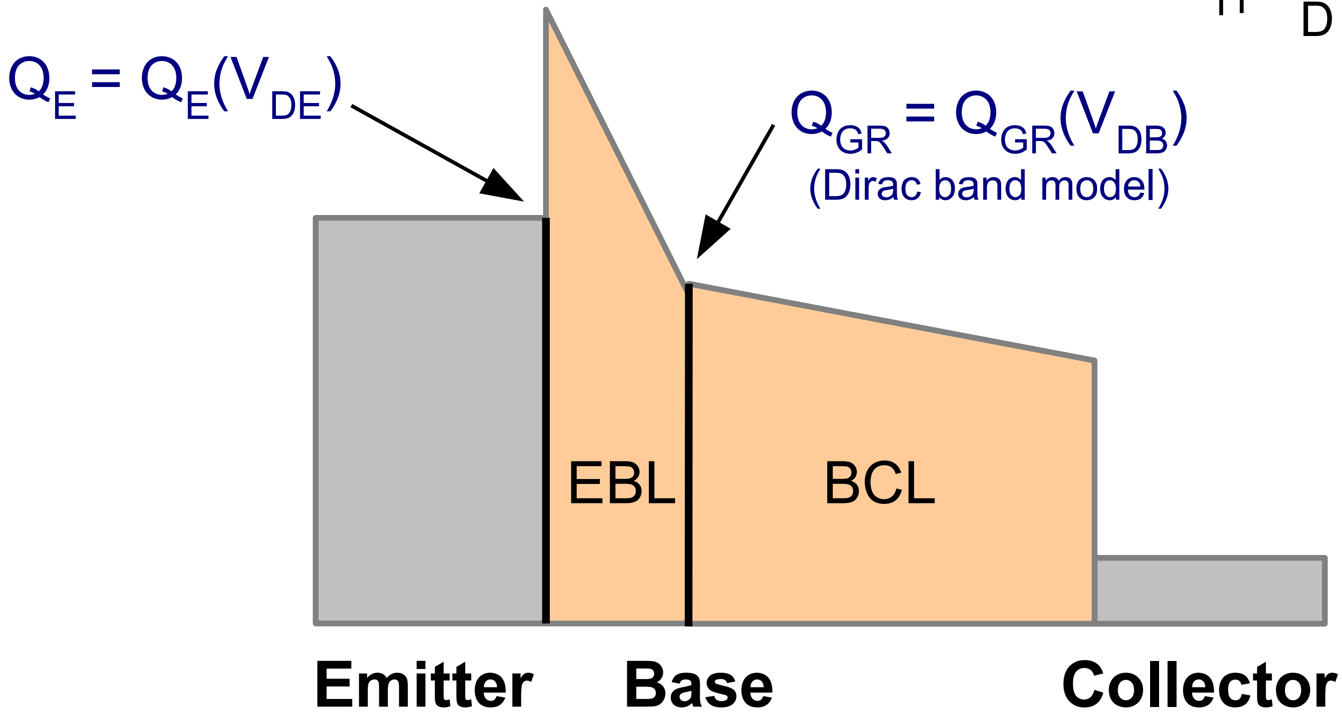

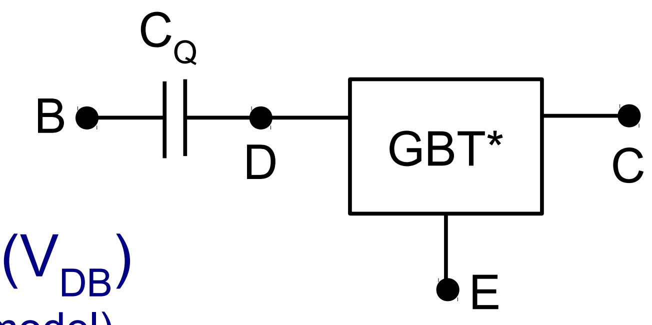

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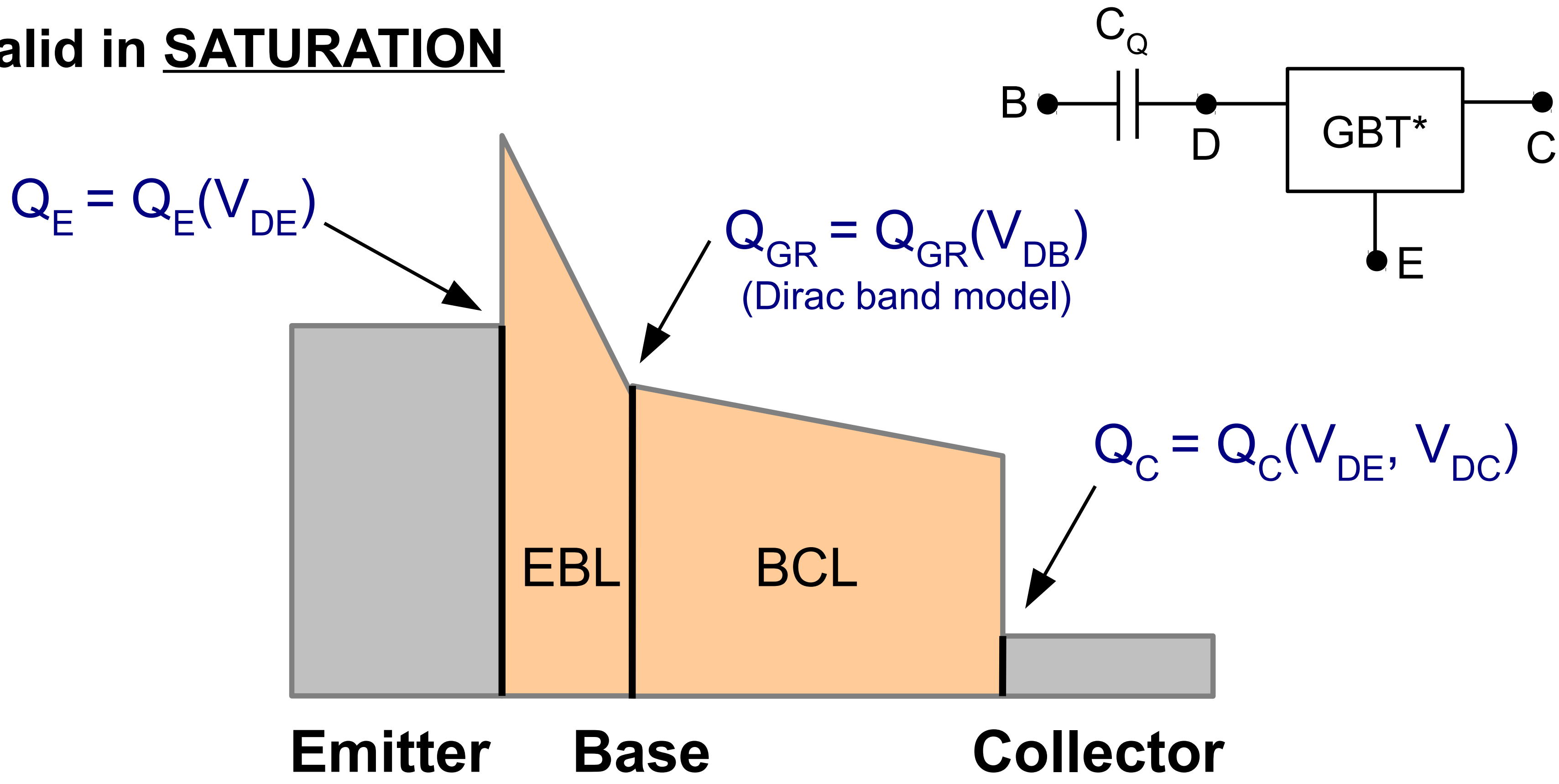
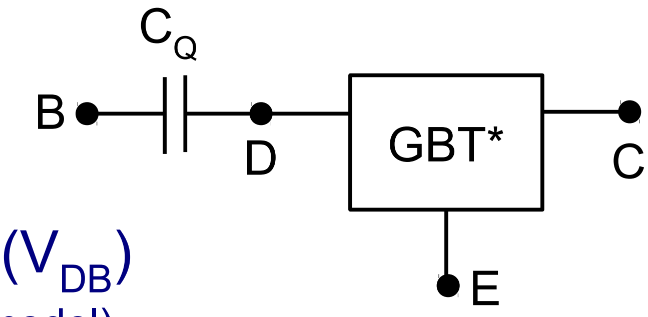


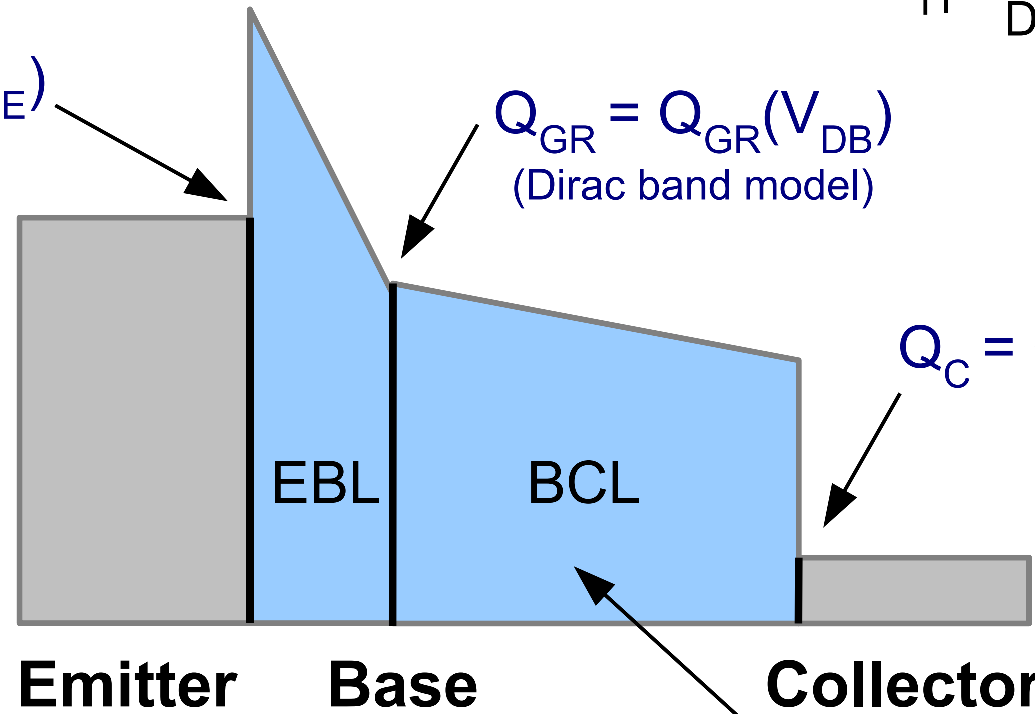
Small-signal model: definitions and assumptions

Valid in <u>SATURATION</u>



$Q_E = Q_E(V_{DE})$

$Q_{GR} = Q_{GR}(V_{DB})$
(Dirac band model)



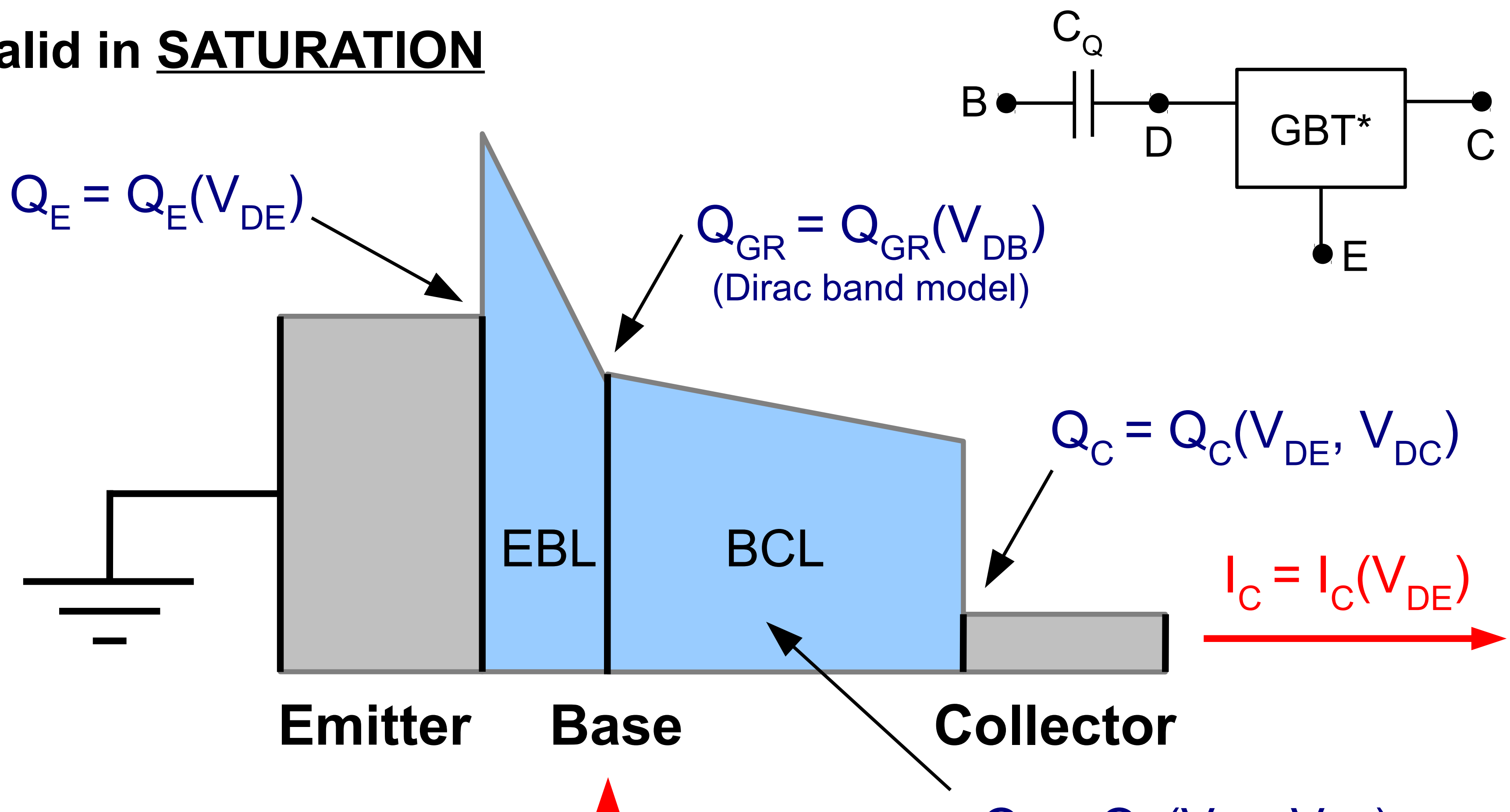
$Q_C = Q_C(V_{DE}, V_{DC})$

$Q_N = Q_N(V_{DE}, V_{DC})$
(arising from transport)

$Q_E + Q_{GR} + Q_C + Q_N = 0$

Small-signal model: definitions and assumptions

Valid in <u>SATURATION</u>



$$Q_E + Q_{GR} + Q_C + Q_N = 0$$

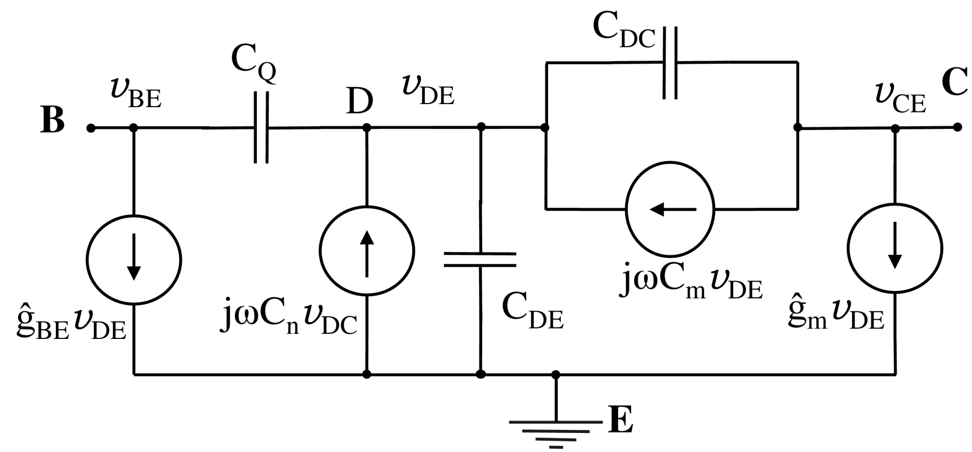
Small-signal model: differential parameters

$$\hat{g}_{\mathrm{BE}} = \frac{\mathrm{d}I_B}{\mathrm{dV_{DE}}}, \quad \hat{g}_m = \frac{\mathrm{d}I_C}{\mathrm{dV_{DE}}}$$

$$C_{\mathrm{DE}} = -\frac{\partial(Q_E + Q_N)}{\partial V_{\mathrm{DE}}}$$

$$C_{\mathrm{DC}} = -\frac{\partial Q_C}{\partial V_{\mathrm{DC}}}, \quad C_m = \frac{\partial Q_C}{\partial V_{\mathrm{DE}}}$$

$$C_Q = \frac{\mathrm{d}Q_{\mathrm{GR}}}{\mathrm{dV_{BD}}}, \quad C_n = \frac{\partial Q_N}{\partial V_{\mathrm{DC}}}$$



$$A_{\mathrm{v0}} = \frac{g_m}{g_{\mathrm{CE}}} = \frac{C_Q}{C_{\mathrm{DC}} - C_n}$$

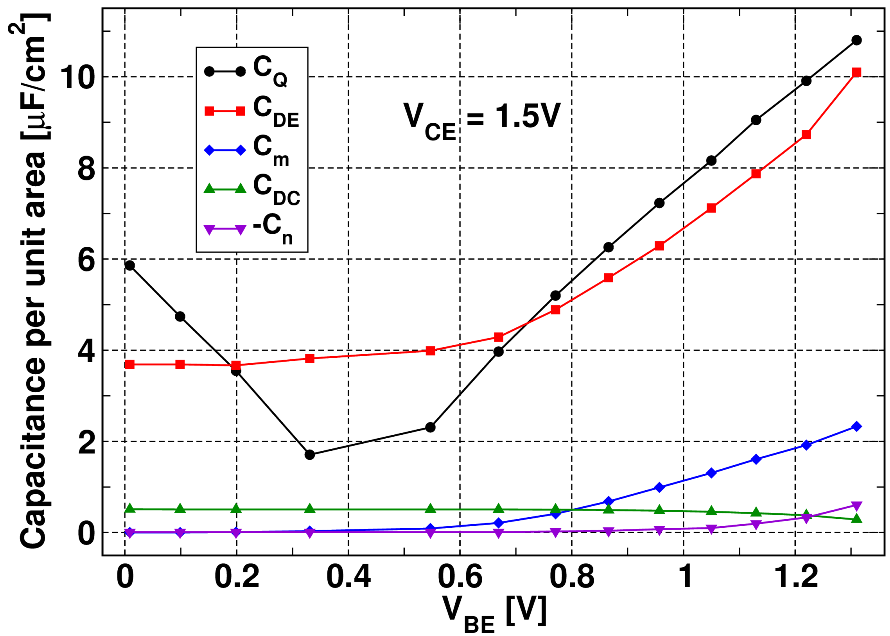
$$f_T = \frac{1}{2\pi}\frac{\mathrm{d}I_C}{\mathrm{d}Q_{\mathrm{GR}}} = \frac{1}{2\pi}\frac{\hat{g}_m}{C_{\mathrm{DE}} + C_{\mathrm{DC}} - C_m - C_n}$$

$C_{DC} - C_n \approx \varepsilon_{Si}/t_{BCL}$ → **g_{CE} and A_{v0}** depend on **t_{BCL}**!

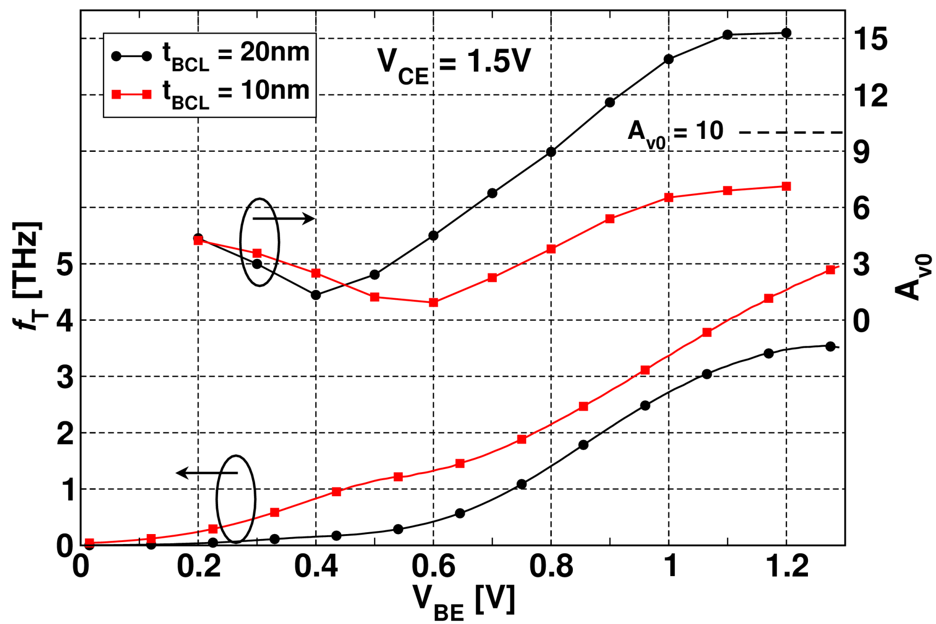
f_T does <u>NOT</u> depend on **C_Q**!

Device performance: simulation results

Capacitances (GBT1)



f_T and A_{v0} (GBT1 and GBT2)



Trade-off between f_T and A_{v0}

Limited C_Q → scalability issues (saturation region extension)

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Conclusions

- Silicon-based GBT investigated
  - Full-quantum **ballistic** transport model
  - Non-parabolicity and multiple valley band effects
  - **Transparent graphene** layer
- Space charge effects in BCL
  - Internal barrier → limited extension of sat. region
  - Limited C_Q → trade-off between sat. region extension and voltage gain
- Physical-based small-signal model developed
- Scalability issues ($A_{v0} > 10$ requires $t > 15\text{-}20$ nm)
- Bias window for THz operation *and* $A_{v0} > 10$ exists

>> Promising device even considering the approximations <<

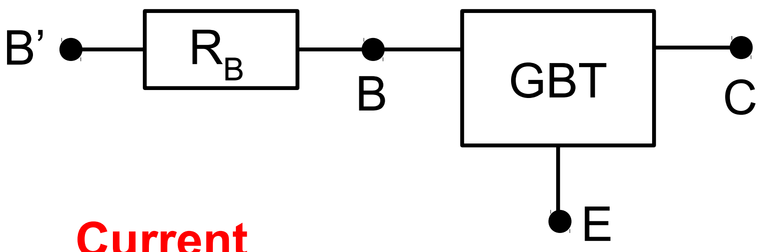
Thank you for your attention

This work has been supported by the EU Grant no. 317839 (GRADE)

Extra slides

Base resistance

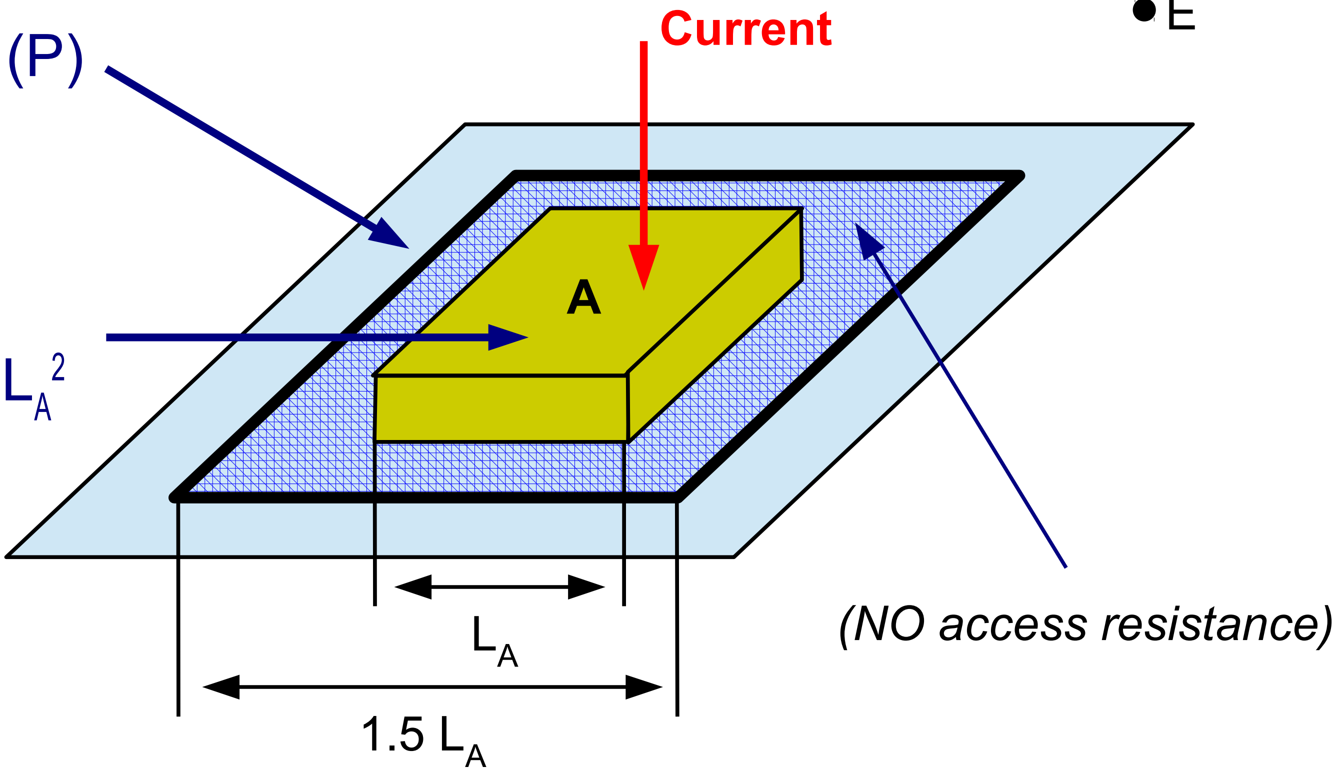
- $R_E = R_C = 0$
- $R_B' = 60\text{–}300\ \Omega\ \mu m$



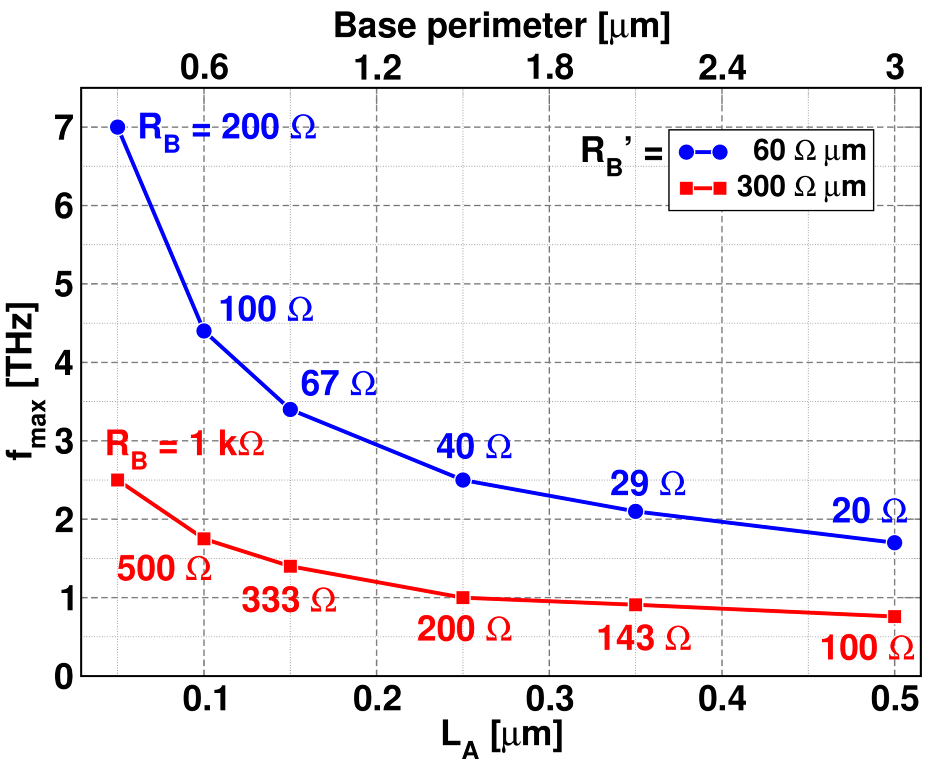
Base perimeter (P)

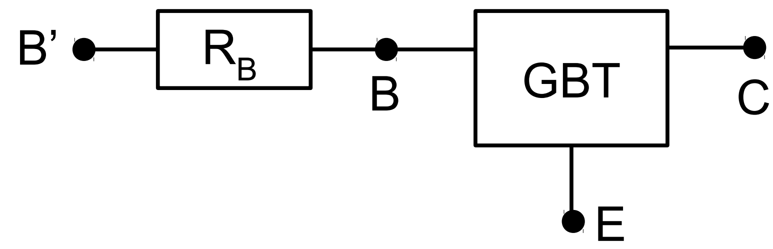
$$R_B = \frac{R_B'}{P}$$

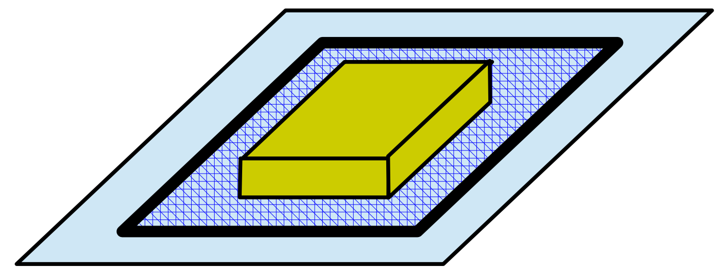
Active area $A = L_A^2$



Power gain and f_{max} (GBT1 @ V_{BE}=1.3V, V_{CE}=1.5V)







$$P = 4 \times (1.5 \times L_A)$$

$$R \propto \frac{1}{L_A} \qquad C \propto L_A^2 \qquad \tau = RC \propto L_A$$

$$G_u = \frac{|S_{21}|^2}{|(1 - |S_{11}|^2)(1 - |S_{22}|^2)|}$$

$$f_{max} = \frac{1}{2\pi\tau} \propto \frac{1}{L_A}$$