ECE-305: Spring 2018
BJT and HBT Nonidealities

Pierret, *Semiconductor Device Fundamentals* (SDF)
Chapters 10 and 11 (pp. 371-385, 389-403)

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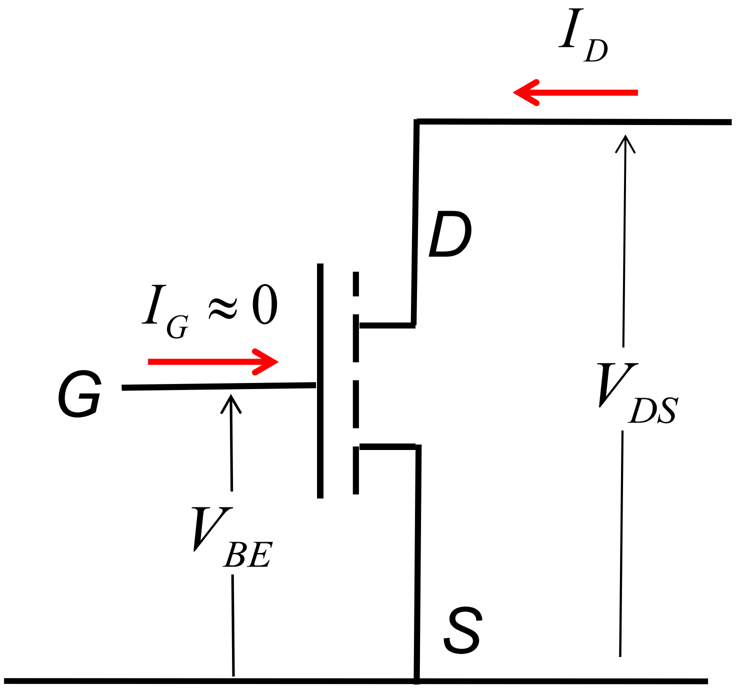
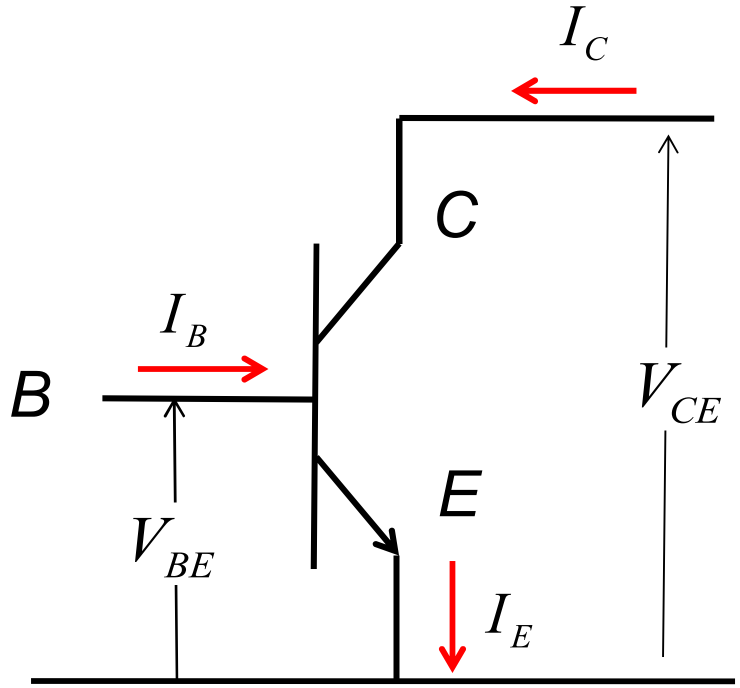
MOSFETs vs. BJTs



MOSFET characteristics:

- simple to make
- no gate current
- moderate gm
- low capacitance



BJT characteristics:

- more complex to make
- base current
- large gm
- high capacitance

active region example 1 (NPN)

$$A_E = 10\ \mu\text{m} \times \mu\text{m}$$

$$I_C = 50\ \mu\text{A}$$

$$N_{DE} = 1.5 \times 10^{19}\ \text{cm}^{-3} \qquad W_B = 0.50\ \mu\text{m} \qquad \tau_{pE} = 0.1\ \text{ns}$$

$$N_{AB} = 1.0 \times 10^{17}\ \text{cm}^{-3} \qquad W_B = 0.25\ \mu\text{m} \qquad \tau_{nB} = 75\ \text{ns}$$

$$N_{DC} = 2.0 \times 10^{16}\ \text{cm}^{-3} \qquad W_C = 1.50\ \mu\text{m} \qquad \tau_{pC} = 150\ \text{ns}$$

Ebers-Moll parameters summary

$$I_C(V_{BE},V_{BC}) = \alpha_F I_{F0}\left(e^{qV_{BE}/k_BT}-1\right) - I_{R0}\left(e^{qV_{BC}/k_BT}-1\right)$$

$$I_E(V_{BE},V_{BC}) = I_{F0}\left(e^{qV_{BE}/k_BT}-1\right) - \alpha_R I_{R0}\left(e^{qV_{BC}/k_BT}-1\right)$$

$$\alpha_R = \alpha_F \frac{I_{F0}}{I_{R0}}$$

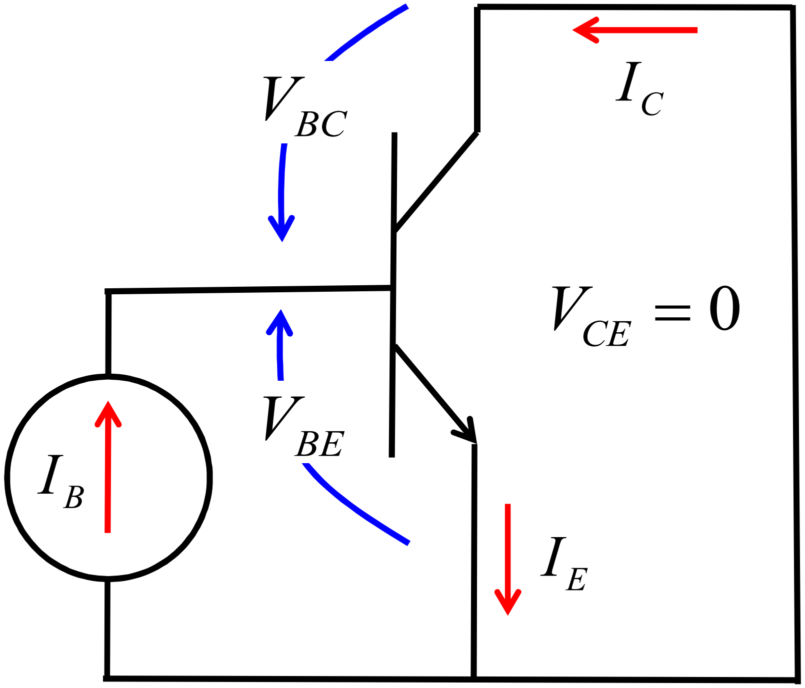
$$\alpha_F = 0.9987$$

$$I_{F0} = 1.33\times 10^{-16}\,\mathrm{A}$$

$$\alpha_R = 0.70 \qquad \beta_R = \frac{\alpha_R}{1-\alpha_R} = 2.3$$

$$I_{R0} = 1.91\times 10^{-16}\,\mathrm{A}$$

What is I_C?



$$I_B = 50\ \text{nA}$$

$$I_C = \alpha_F I_{F0}\left(e^{qV_{BE}/k_BT} - 1\right) - I_{R0}\left(e^{qV_{BC}/k_BT} - 1\right)$$

$$I_E = I_{F0}\left(e^{qV_{BE}/k_BT} - 1\right) - \alpha_R I_{R0}\left(e^{qV_{BC}/k_BT} - 1\right)$$

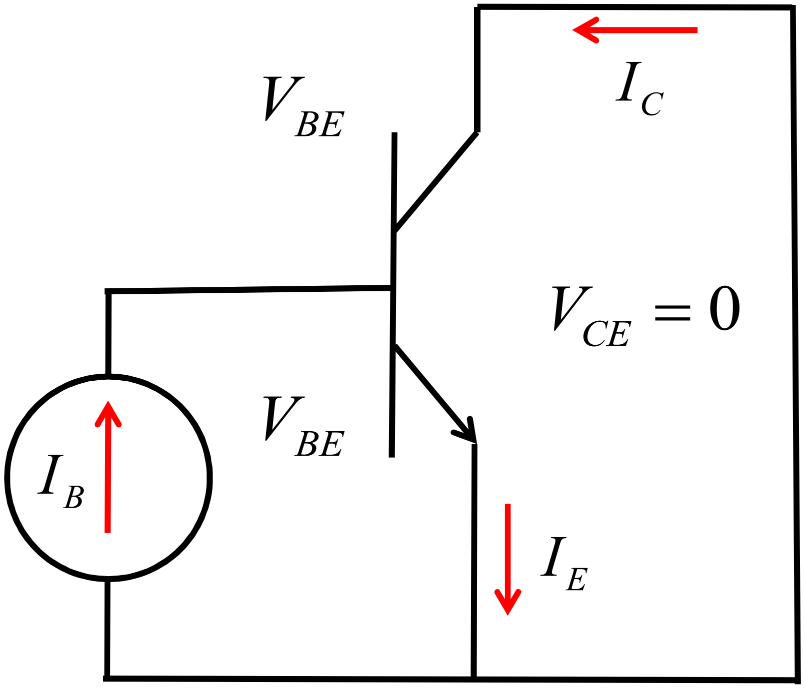
$$V_{CE} = V_{BE} - V_{BC} = 0$$

$$V_{BC} = V_{BE}$$

$$I_C = \left(\alpha_F I_{F0} - I_{R0}\right)\left(e^{qV_{BE}/k_BT} - 1\right)$$

$$I_E = \left(I_{F0} - \alpha_R I_{R0}\right)\left(e^{qV_{BE}/k_BT} - 1\right)$$

What is I_C?



$I_B = 50 \text{ nA}$

$$I_C = \left(\alpha_F I_{F0} - I_{R0}\right)\left(e^{qV_{BE}/k_BT} - 1\right)$$

$$I_E = \left(I_{F0} - \alpha_R I_{R0}\right)\left(e^{qV_{BE}/k_BT} - 1\right)$$

$$I_B = I_E - I_C$$

$$I_B = \left[\left(1-\alpha_F\right)I_{F0} + \left(1-\alpha_F\right)I_{R0}\right]\left(e^{qV_{BE}/k_BT} - 1\right)$$

$$\left(e^{qV_{BE}/k_BT} - 1\right) = \frac{I_B}{\left[\left(1-\alpha_F\right)I_{F0} + \left(1-\alpha_F\right)I_{R0}\right]}$$

What is I_C?

$$I_C = \left\{ \frac{\left(\alpha_F I_{F0} - I_{R0}\right)}{\left(1-\alpha_F\right) I_{F0} + \left(1-\alpha_F\right) I_{R0}} \right\} I_B$$

$$I_B = 50 \text{ nA}$$

$$I_{F0} = 1.33 \times 10^{-16} \text{ A}$$

$$I_C = -1.01 \times I_B$$

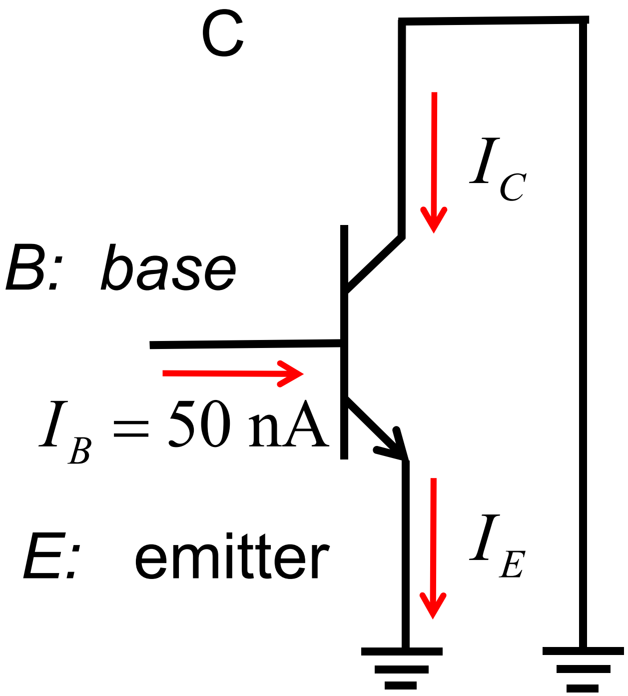
$$I_{R0} = 1.91 \times 10^{-16} \text{ A}$$

$$I_B = -50 \text{ nA}$$

$$\alpha_F = 0.9987$$

$$\alpha_R = 0.70$$

result



C

B: *base*

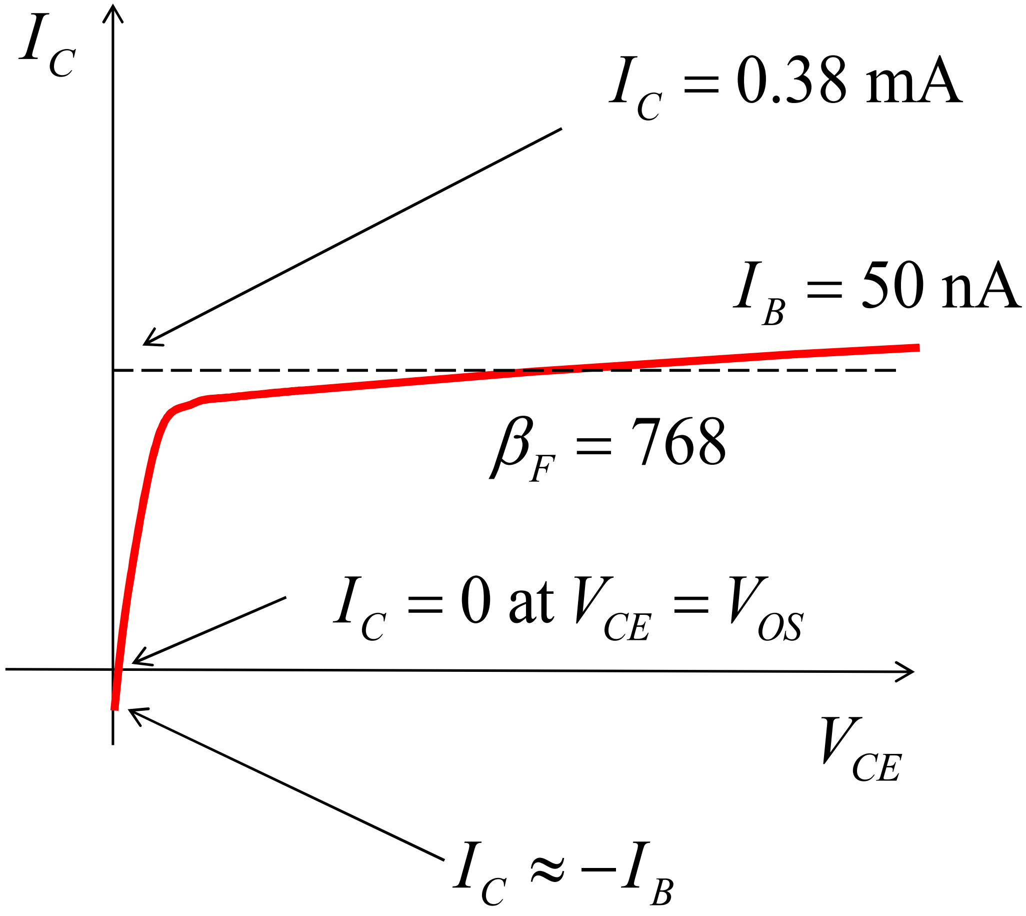
$I_B = 50\text{ nA}$

E: emitter

I_C

I_E

NPN BJT



I_C

V_{CE}

$I_C = 0.38\text{ mA}$

$I_B = 50\text{ nA}$

$\beta_F = 768$

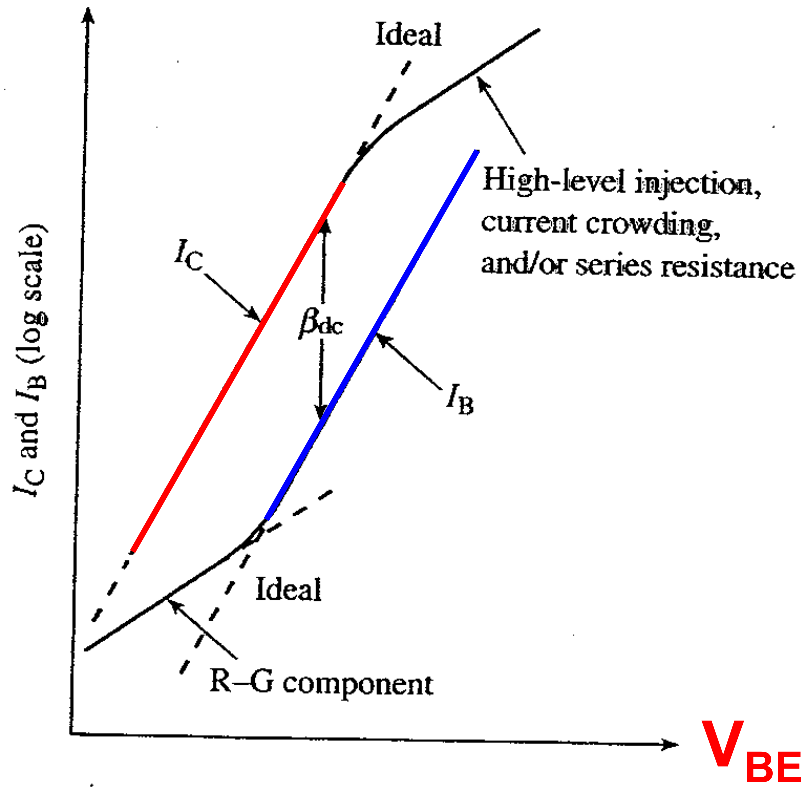
$I_C = 0 \text{ at } V_{CE} = V_{OS}$

$I_C \approx -I_B$

Why?

Gummel Plot and Output Characteristics

$$\frac{I_C}{A} = -\frac{qD_n}{W_B}\frac{n_{i,B}^2}{N_B}(e^{qV_{BE}/kT}-1) + \frac{qD_n}{W_B}\frac{n_{i,B}^2}{N_B}(e^{qV_{BC}/kT}-1)$$



$$\frac{I_B}{A} = \frac{qD_p}{W_E}\frac{n_{i,E}^2}{N_E}(e^{qV_{BE}/kT}-1)$$

$$\beta_{DC} = \frac{I_C}{I_B}$$

$\beta_{DC} \longrightarrow$ Common emitter Current Gain

How to make a Good Silicon Transistor

~1, same material

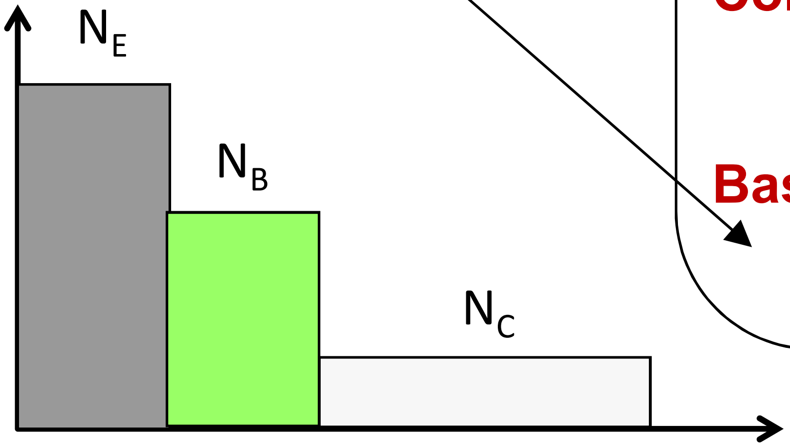
$$\beta_{DC} \approx \frac{D_n}{W_B}\frac{W_E}{D_p}\cancel{\frac{n_{i,B}^2}{n_{i,E}^2}}\frac{N_E}{N_B}$$

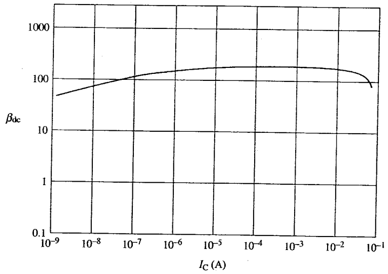
Emitter doping: As high as possible without *band gap narrowing*

Base doping: As low as possible, without *current crowding, Early effect*

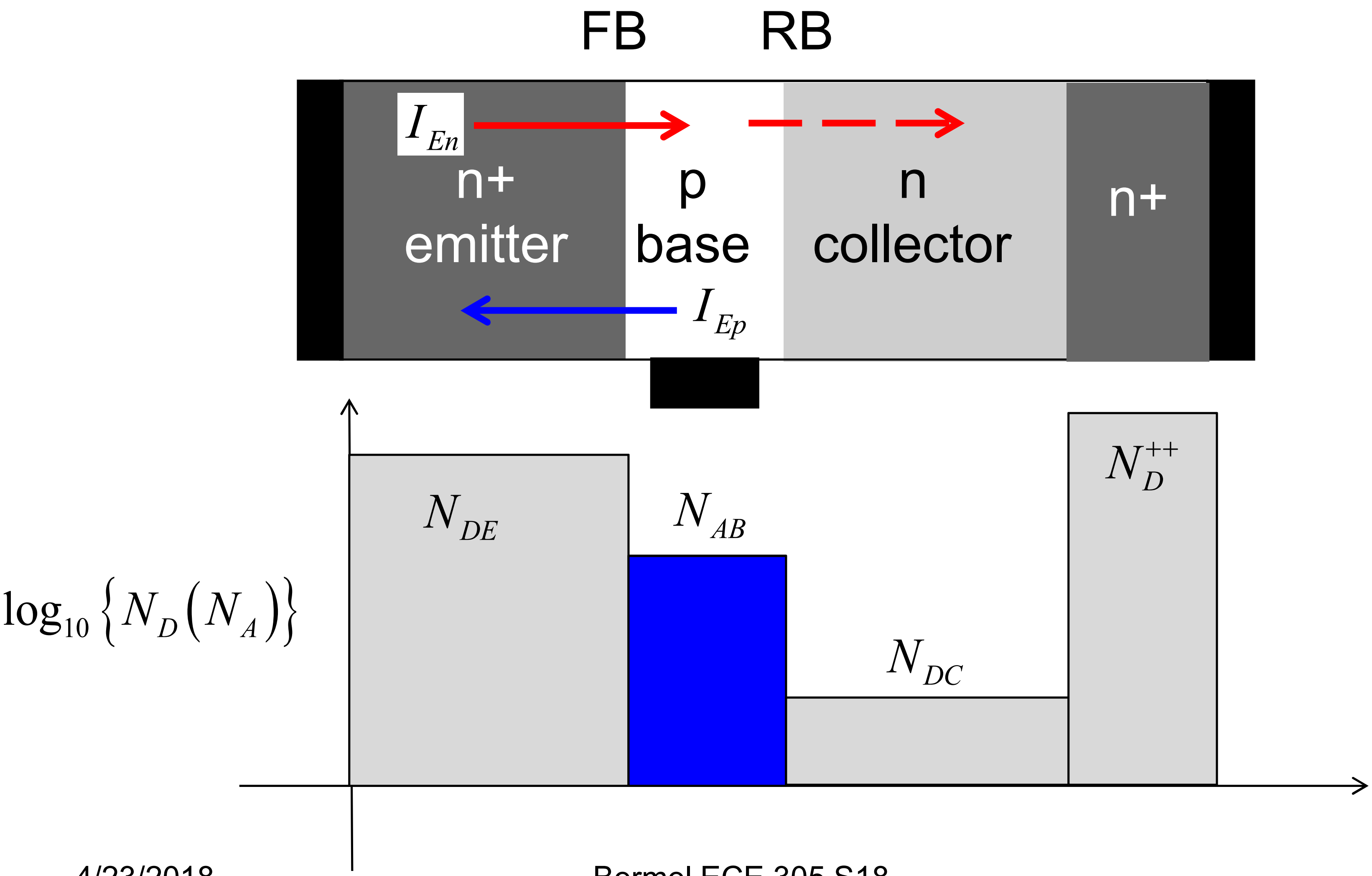
Collector doping: Lower than base doping *without Kirk Effect*

Base Width: As thin as possible without *punch through* (~1 mm in ‘50s, 200 Å now)

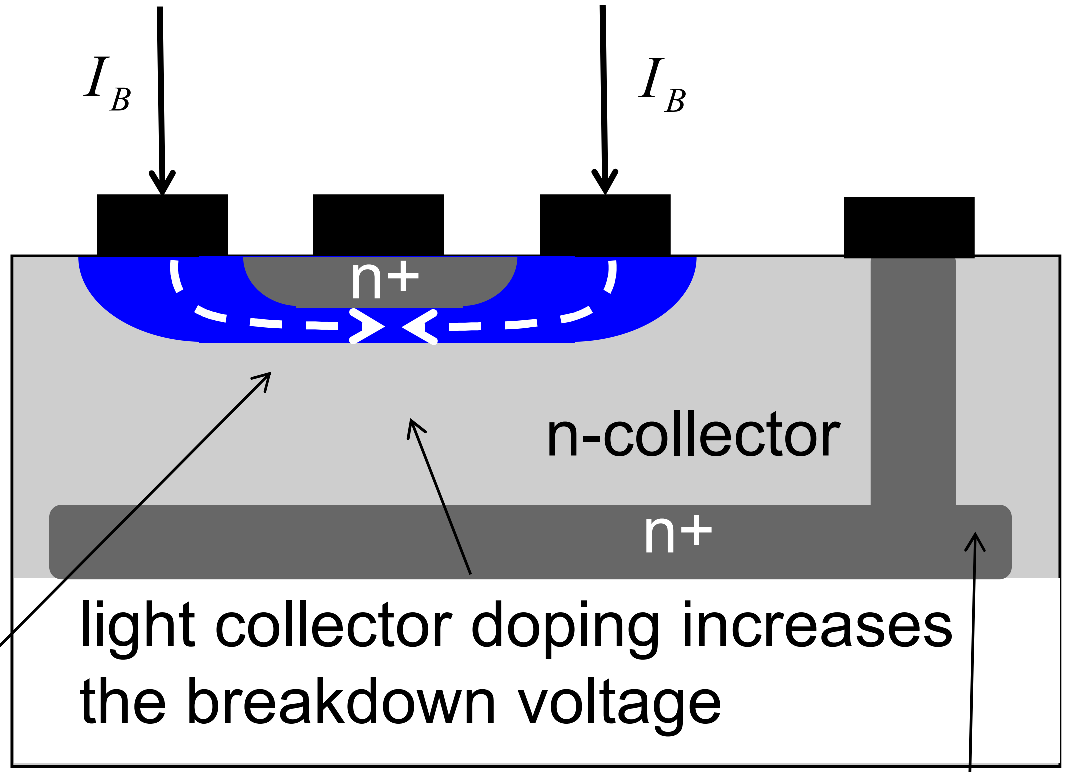




doping for maximum gain



doping for maximum gain



light collector doping increases the breakdown voltage

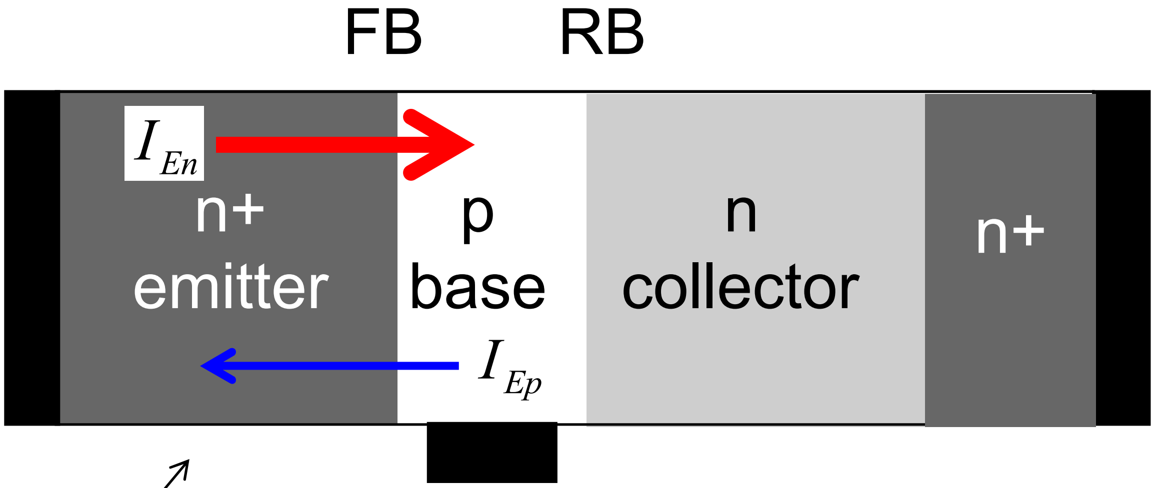
high base doping lowers the base resistance

high sub-collector doping lowers collector series resistance

emitter-base doping

$$I_{En} \propto \frac{n_i^2}{N_{AB}}$$

$$I_{Ep} \propto \frac{n_i^2}{N_{DE}}$$



High emitter doping increases the emitter injection efficiency.

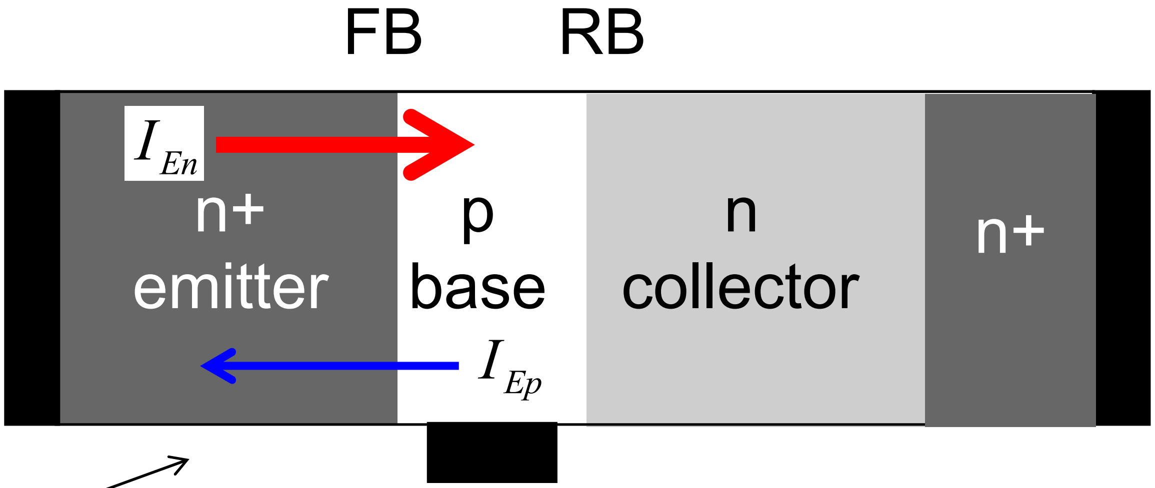
$$\gamma_F = \frac{1}{1 + \frac{D_{pE}}{D_{nB}} \frac{W_B}{W_E} \frac{N_{AB}}{N_{DE}}}$$

$$N_{DE} >> N_{AB}$$

High emitter doping benefits

$$I_{En} \propto \frac{n_i^2}{N_{AB}}$$

$$I_{Ep} \propto \frac{n_i^2}{N_{DE}}$$



High emitter doping increases the emitter injection efficiency.

$$\gamma_F = \frac{1}{1 + \frac{D_{pE}}{D_{nB}} \frac{W_B}{W_E} \frac{N_{AB}}{N_{DE}}}$$

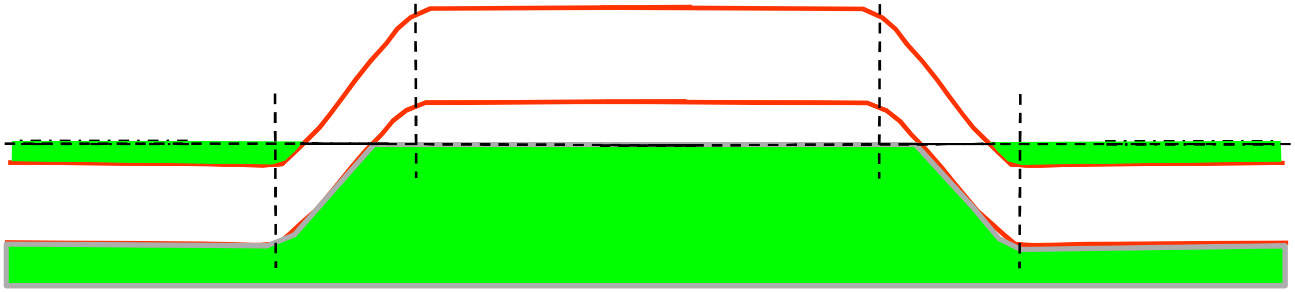
$$N_{DE} >> N_{AB}$$

high emitter doping → bandgap narrowing

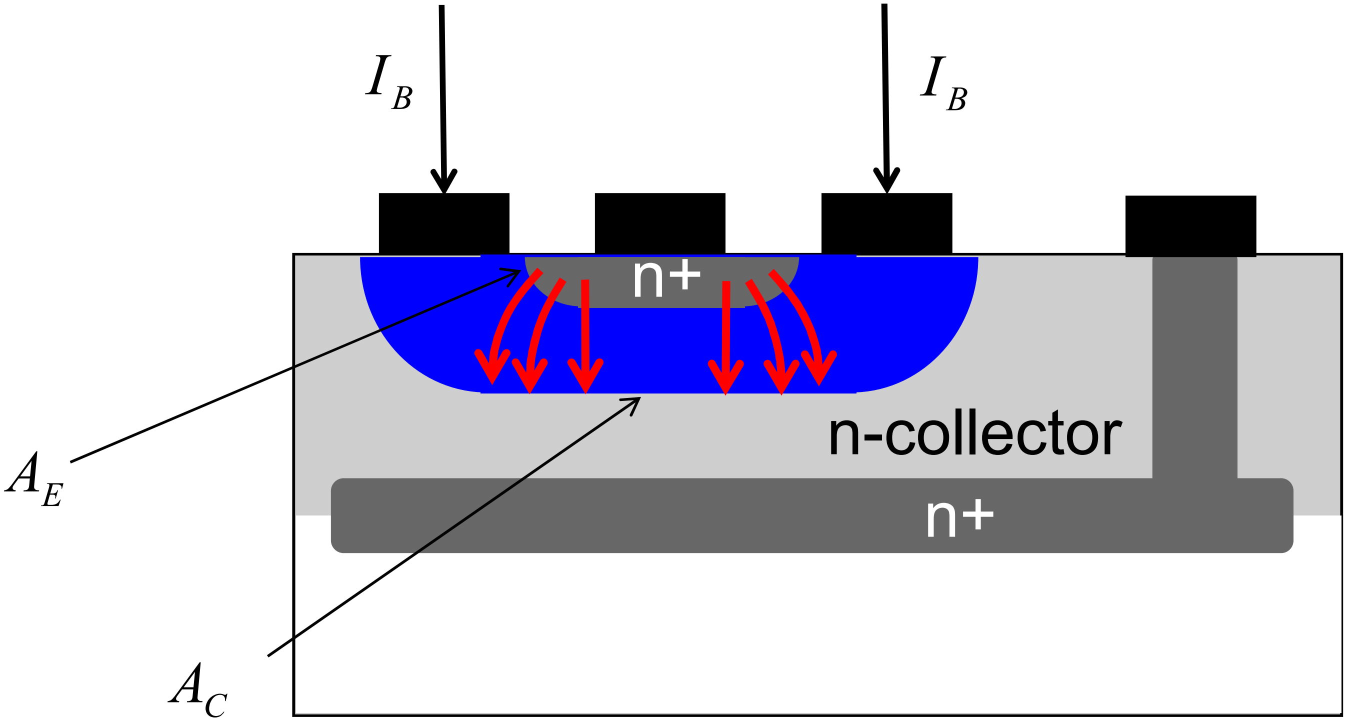
Band-gap narrowing reduces gain significantly …

$$\beta \approx \frac{D_n}{W_B}\frac{W_E}{D_p}\frac{n_{i,B}^2}{n_{i,E}^2}\frac{N_E}{N_B} = \frac{D_n}{W_B}\frac{W_E}{D_p}\frac{N_C N_V e^{-E_{g,B}/kT}}{N_C N_V e^{-E_{g,E}/kT}}\frac{N_E}{N_B} \approx e^{-\Delta E_g/kT}\frac{N_E}{N_B}$$

(Esaki-like) tunneling cause loss of base control …

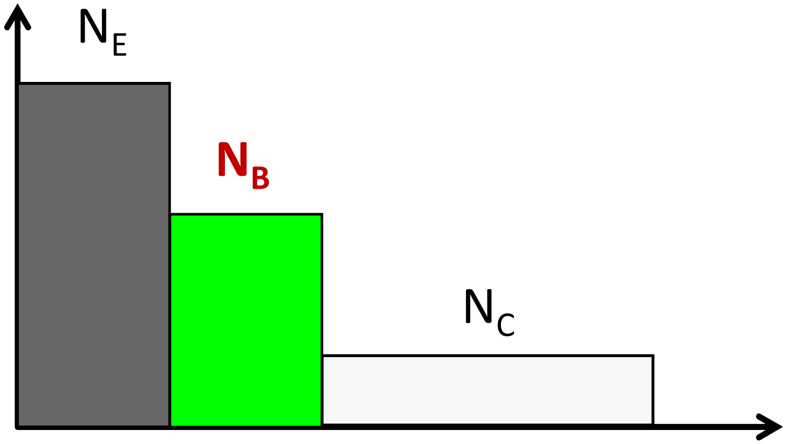


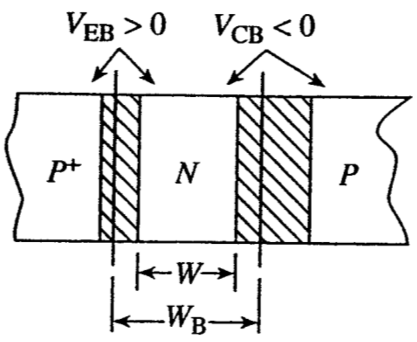
Low base doping → emitter current crowding

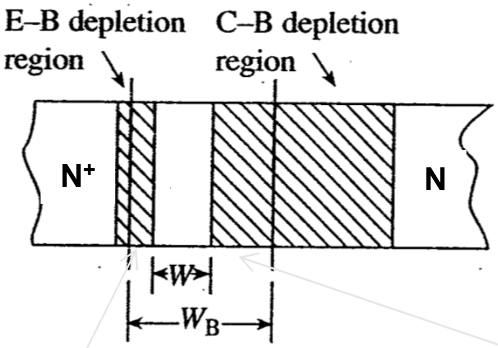


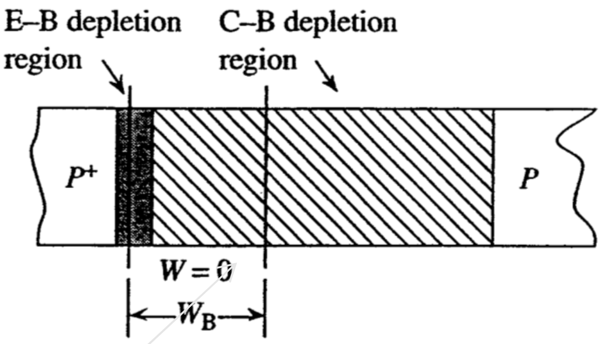
$$A_C >> A_E$$

Low Base Width → punch-through





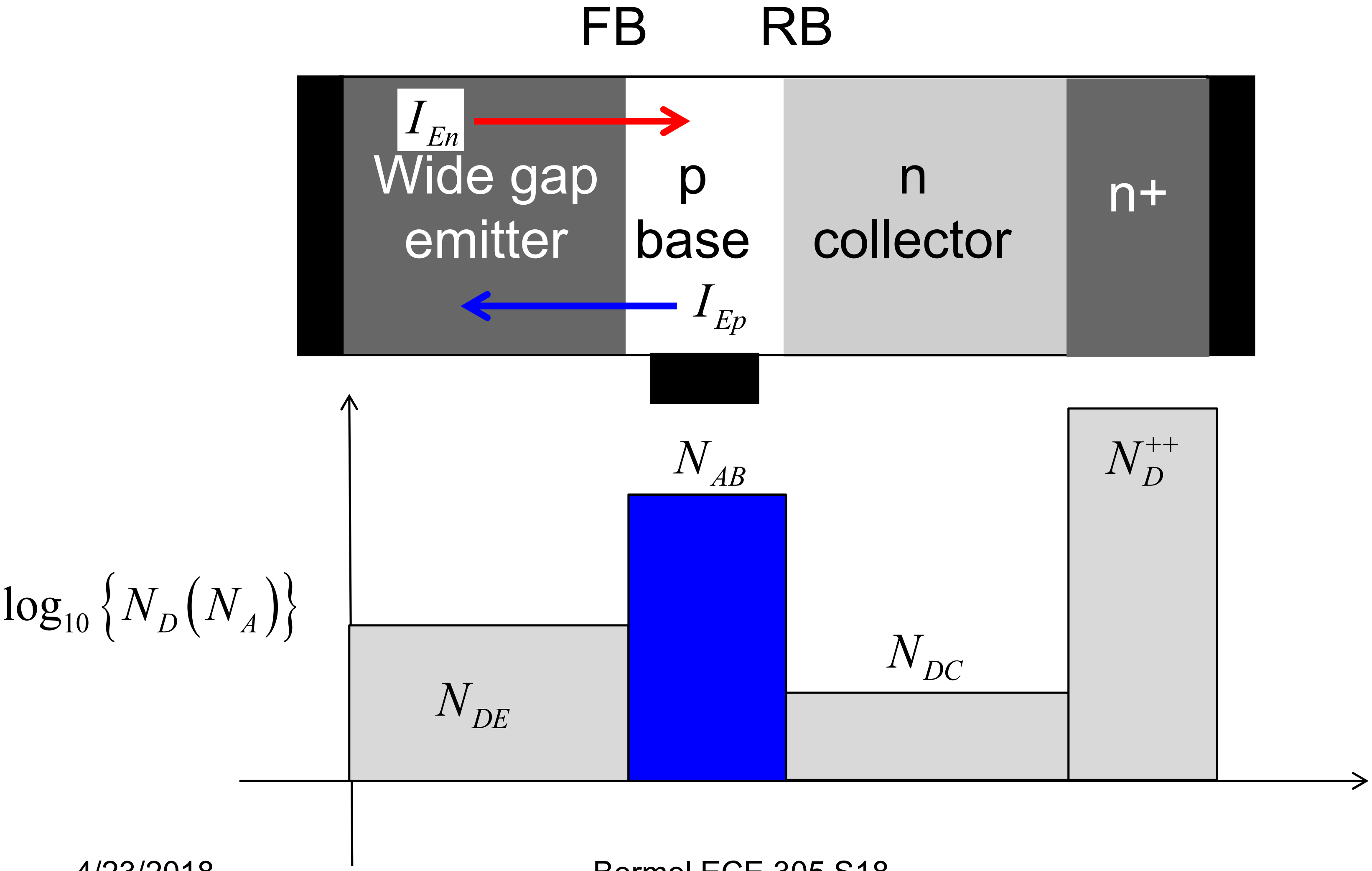




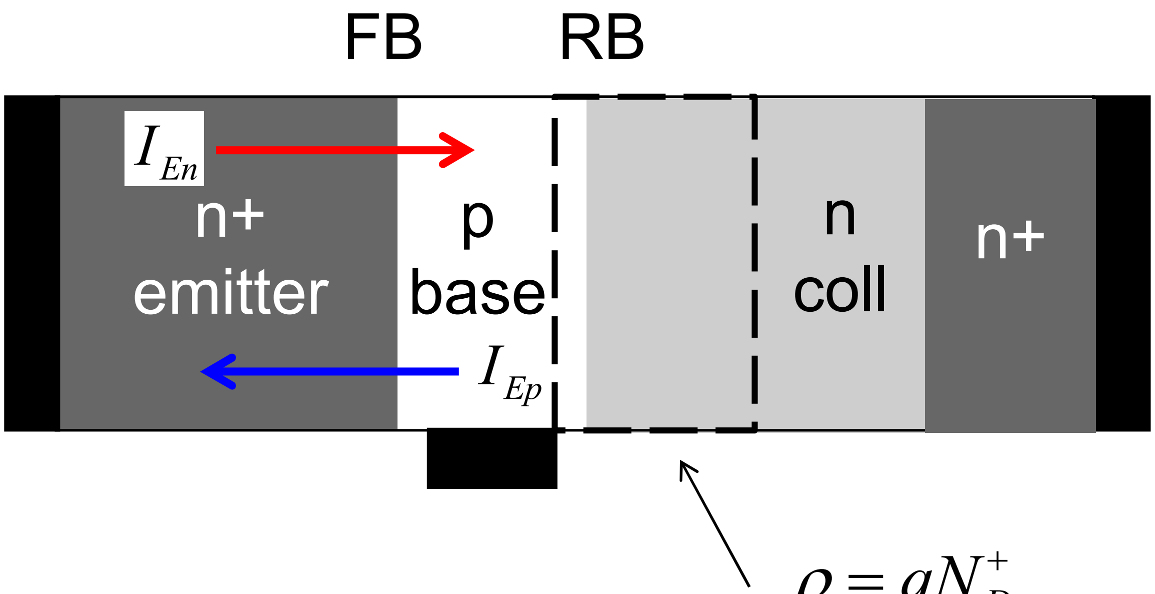
$$x_{p,BE} = \sqrt{\frac{2k_s\varepsilon_0}{q}\frac{N_E}{N_B(N_E+N_B)}(V_{bi}-V_{BE})}$$

$$x_{p,BC} = \sqrt{\frac{2k_s\varepsilon_0}{q}\frac{N_C}{N_B(N_C+N_B)}(V_{bi}-V_{BC})}$$

“inverted” base doping



High collector doping → Kirk effect



$$\rho = qN_D^+$$

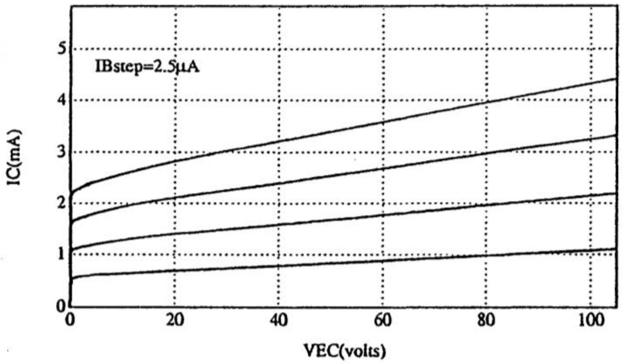
$$I_{Cn} = qA_E \frac{D_n}{W_B} \Delta n(0)$$

“base push out”/ Kirk effect implies cannot reduce base doping arbitrarily

$$I_C = qA_W n \upsilon_{sat} \qquad n \approx N_D$$

Low base doping → early effect

$$\beta_{DC} \approx \frac{D_n}{W_B - x_{p.B} - x_{p.C}} \frac{W_E}{D_p} \frac{\cancel{n^2_{i,B}}}{\cancel{n^2_{i,E}}} \frac{N_E}{N_B}$$

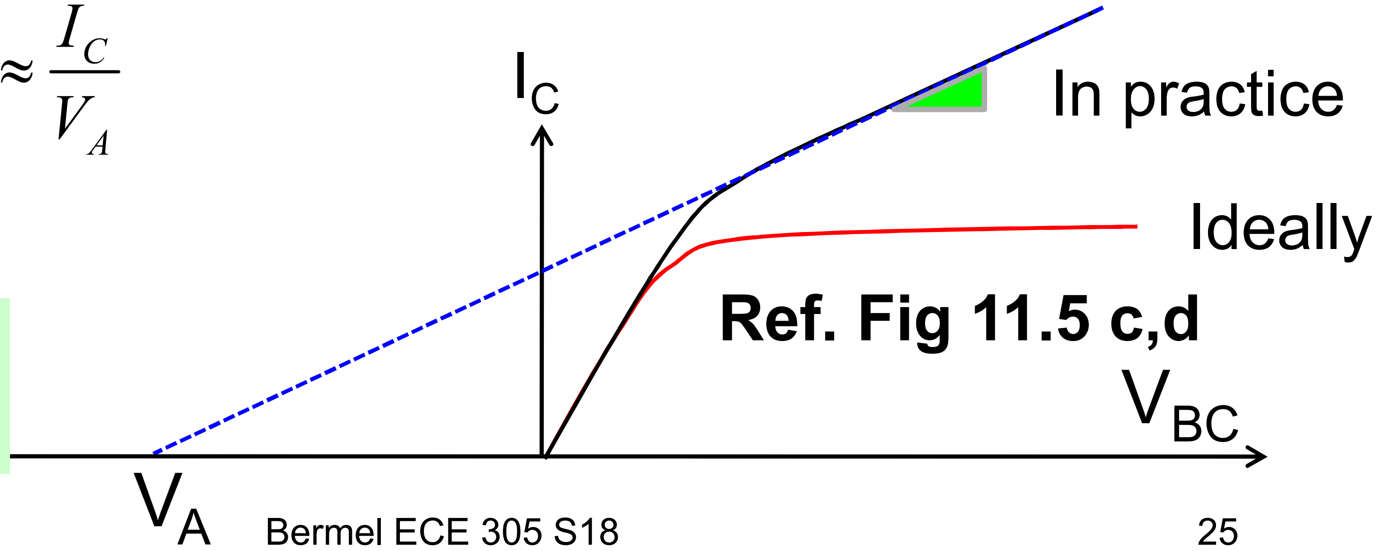


$$I_{n,C} = -\frac{qD_n}{W_B'} \frac{n^2_{i,B}}{N_B}\left(e^{(qV_{BE}/kT)} - 1\right) + \frac{qD_n}{W_B'} \frac{n^2_{i,B}}{N_B}\left(e^{(qV_{BC}/kT)} - 1\right)$$

$$\frac{dI_C}{dV_{BC}} = \frac{I_C}{V_{BC} + V_A} \approx \frac{I_C}{V_A}$$

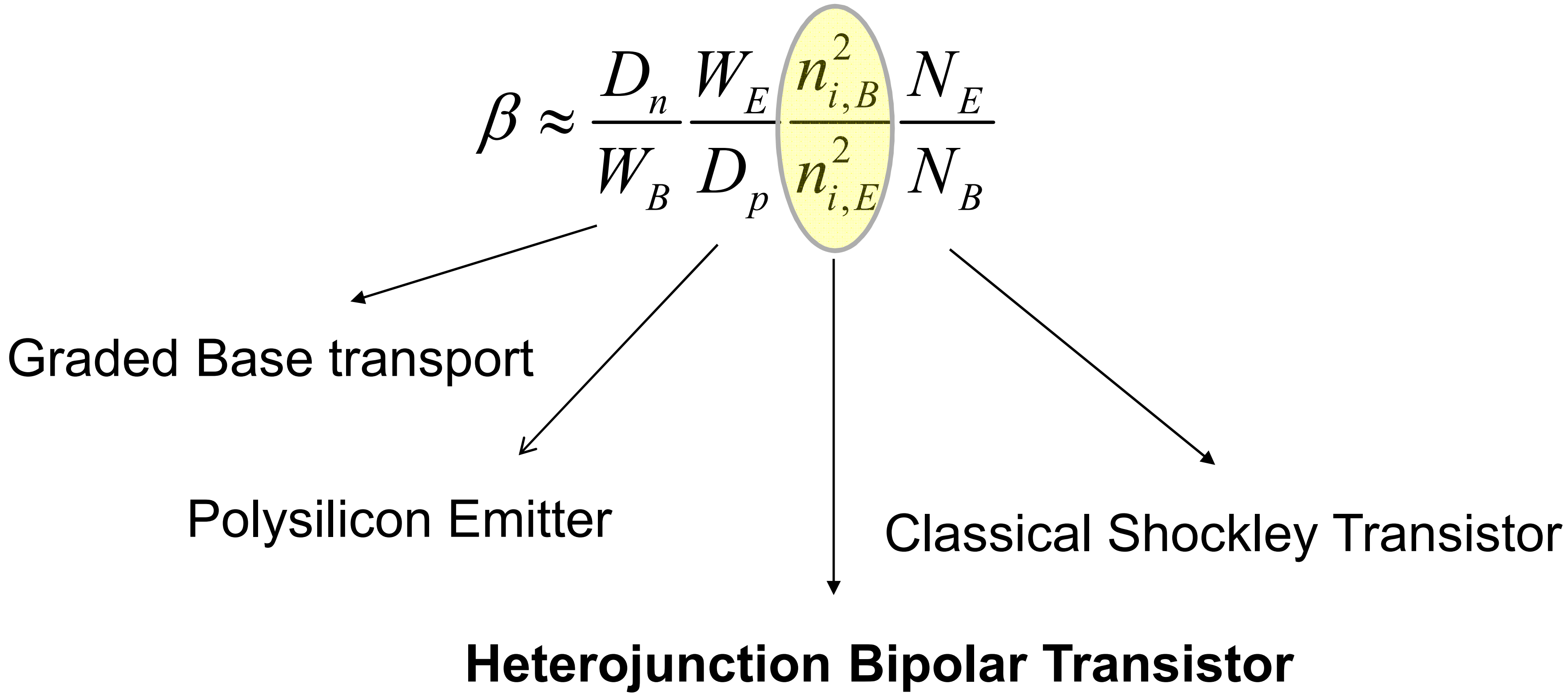
$$\Rightarrow V_A = -\frac{qN_B W_B}{C_{CB}}$$

Gain depends on collector voltage (bad) …



Ref. Fig 11.5 c,d

how to make better transistors



$$\beta \approx \frac{D_n}{W_B}\frac{W_E}{D_p}\frac{n_{i,B}^2}{n_{i,E}^2}\frac{N_E}{N_B}$$

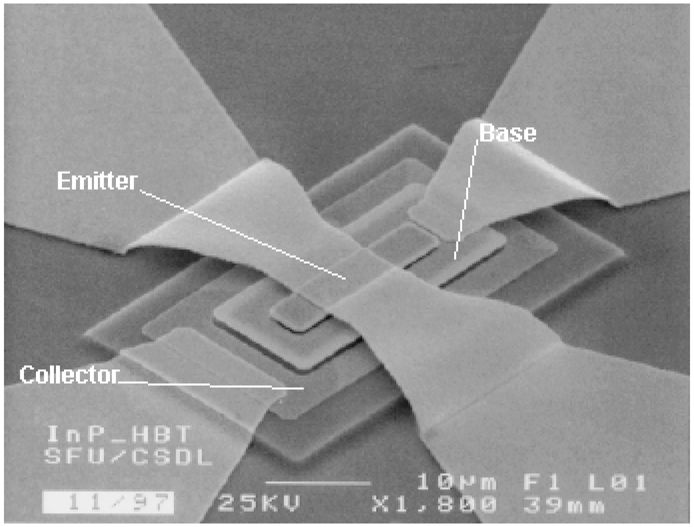
Graded Base transport

Polysilicon Emitter

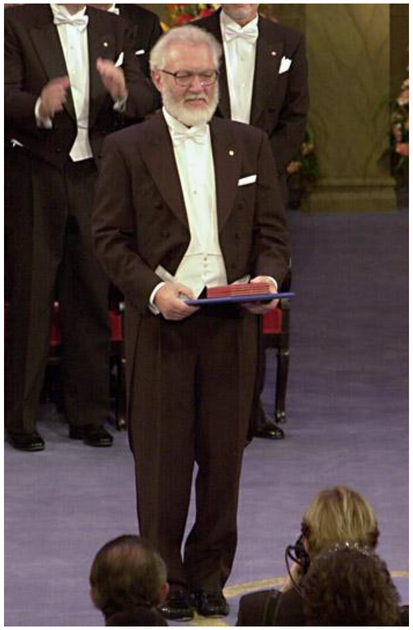
Classical Shockley Transistor

Heterojunction Bipolar Transistor

heterojunction bipolar transistors (HBTs)



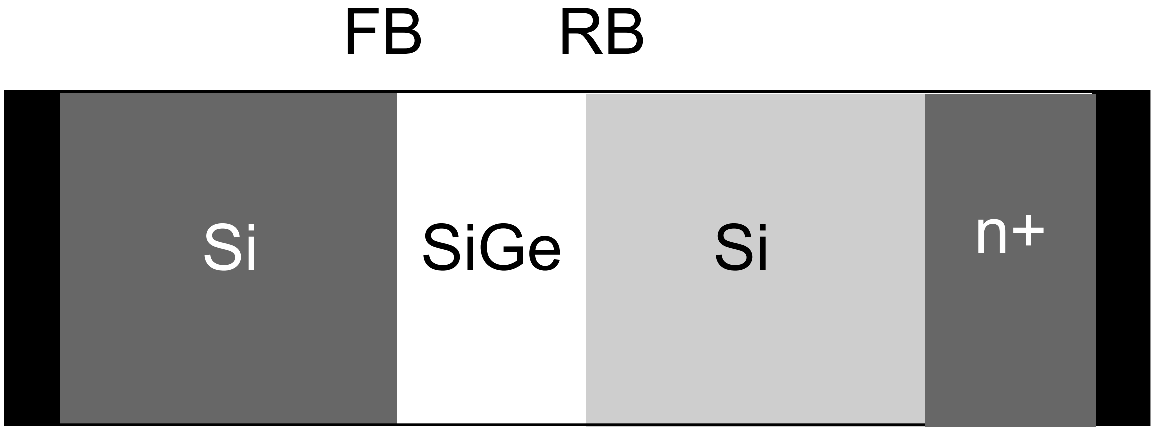
A heterojunction bipolar transistor



Kroemer

Shockley realized that HBT is possible, but Kroemer really provided the foundation of the field and worked out the details.

SiGe HBTs



$$E_G(\text{Si}) = 1.12\ \text{eV}$$

$$E_G(\text{Si}) = 1.12\ \text{eV}$$

$$E_G(\text{Ge}) = 0.66\ \text{eV}$$

SiGe HBT applications

1) **optical fiber communications**

   -40Gb/s…….160Gb/s

2) **Wideband, high-resolution DA/AD converters and digital frequency synthesizers**

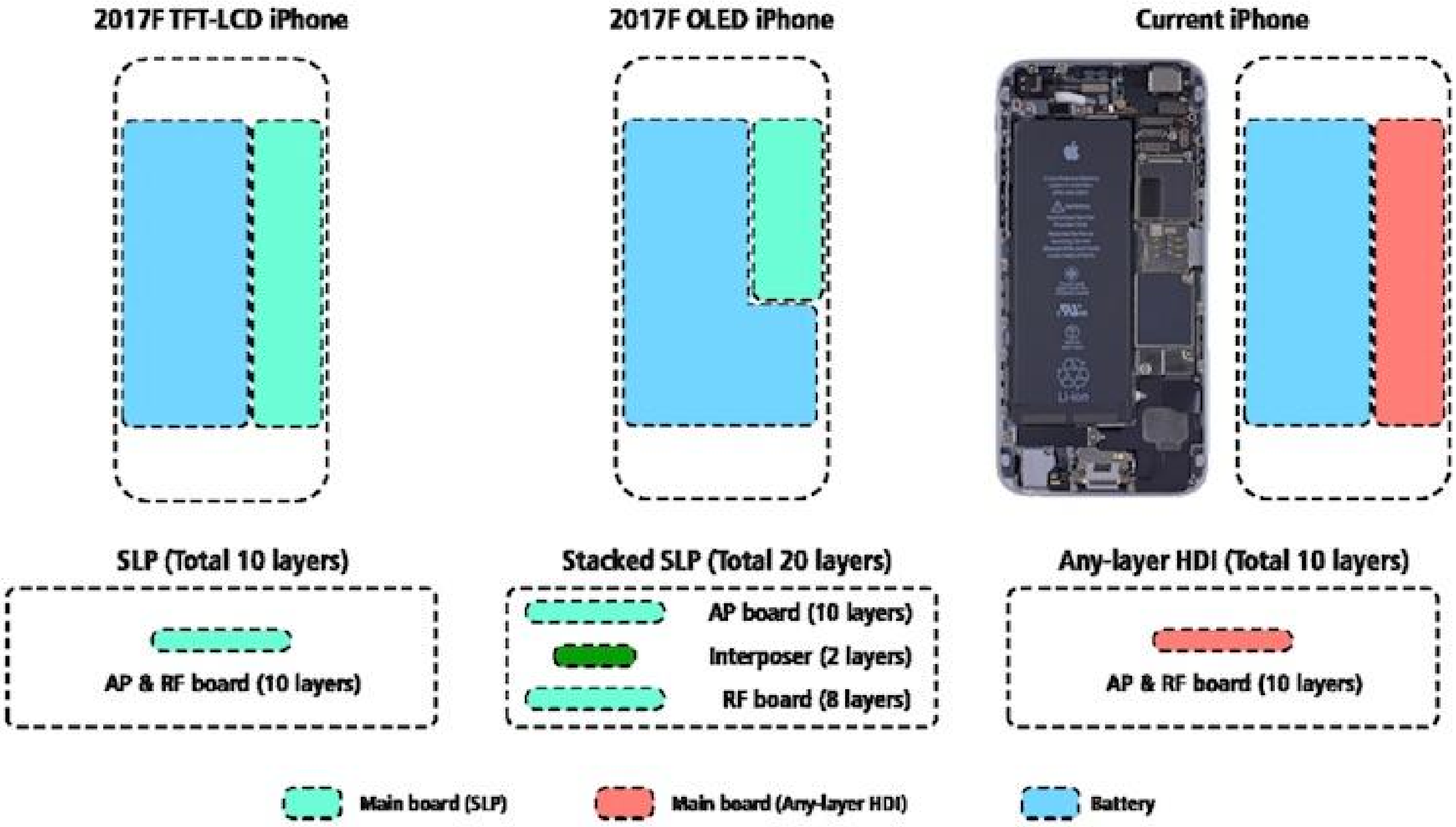
   -military radar and communications

3) **Monolithic, millimeter-wave IC's (MMIC's)**

   -front ends for receivers and transmitters

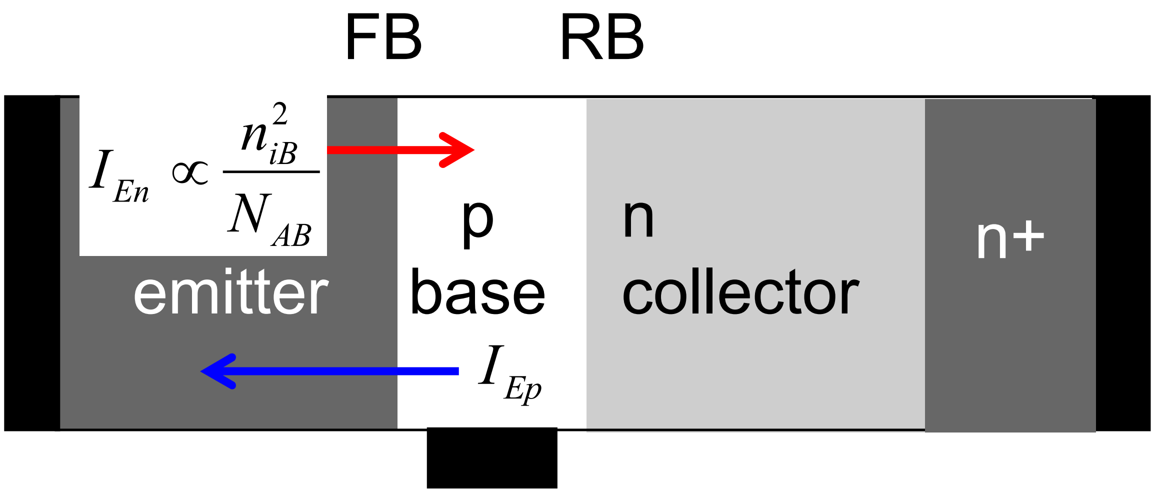
future need for transistors with
1 THz power-gain cutoff freq.

SiGe HBTs



https://www.macrumors.com/2017/11/02/fight-for-space-iphone-x/

HBT (wide gap emitter)



E_{GE} E_{GB} E_{GC}

$$I_{En} \propto \frac{n_{iB}^2}{N_{AB}}$$

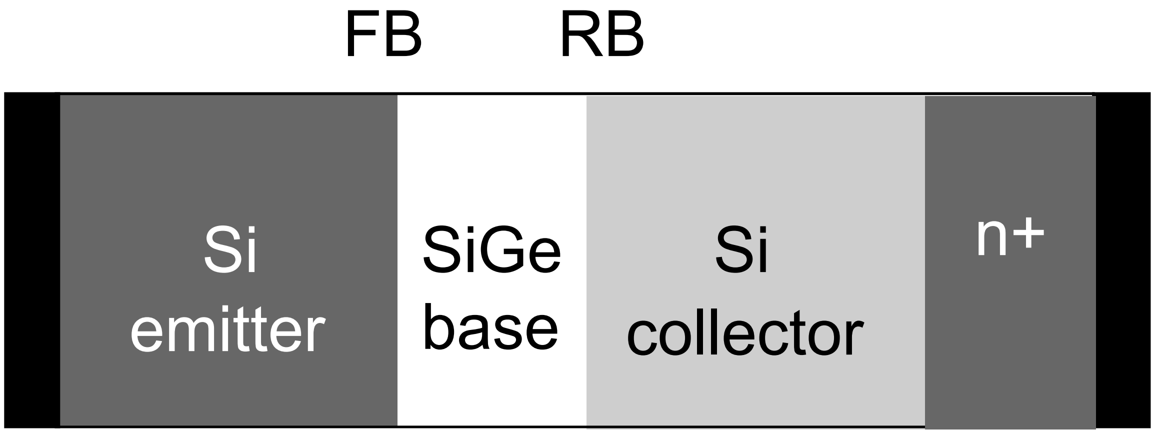
$$\gamma_F = \frac{1}{1 + \frac{D_{pE}}{D_{nB}} \frac{W_B}{W_E} \frac{N_{AB}}{N_{DE}} \frac{n_{iE}^2}{n_{iB}^2}}$$

$$n_i^2 \propto e^{-E_G/k_B T}$$

$$I_{Ep} \propto \frac{n_{iE}^2}{N_{DE}}$$

Choose an emitter with a higher bandgap than the base

SiGe HBTs



$E_G(\mathrm{Si}) = 1.12\ \mathrm{eV}$

$E_G(\mathrm{Si}) = 1.12\ \mathrm{eV}$

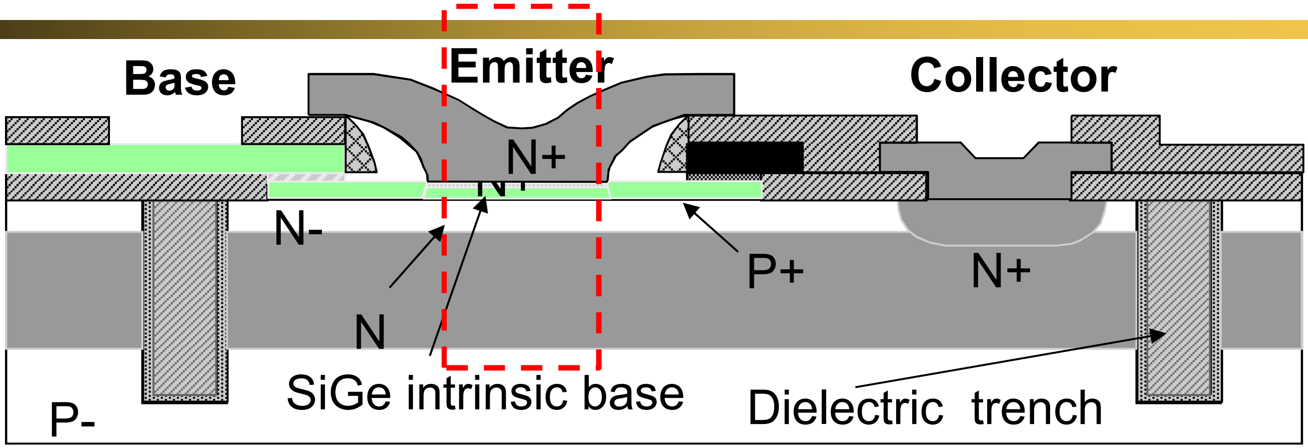
$E_G(\mathrm{Ge}) = 0.66\ \mathrm{eV}$

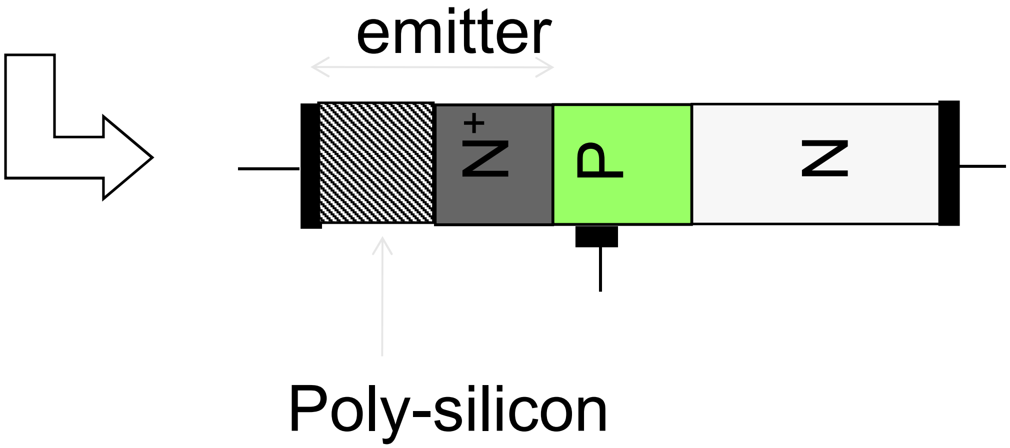
$$\gamma_F = \frac{1}{1 + \frac{D_{pE}}{D_{nB}} \frac{W_B}{W_E} \frac{N_{AB}}{N_{DE}} \frac{n_{iE}^2}{n_{iB}^2}}$$

$$n_i^2 \propto e^{-E_G/k_B T}$$

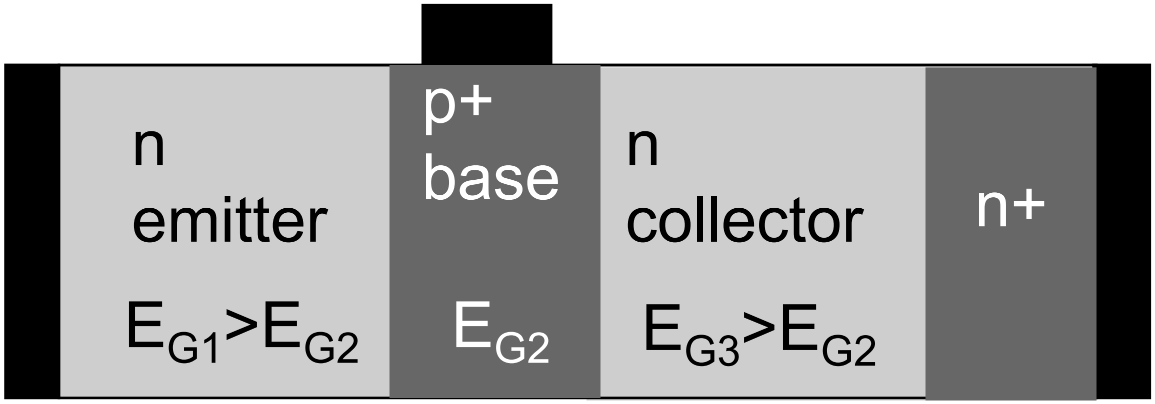
Choose an emitter with a higher bandgap than the base

poly-silicon HBT emitter





mesa HBTs



n emitter

$E_{G1}>E_{G2}$

p+ base

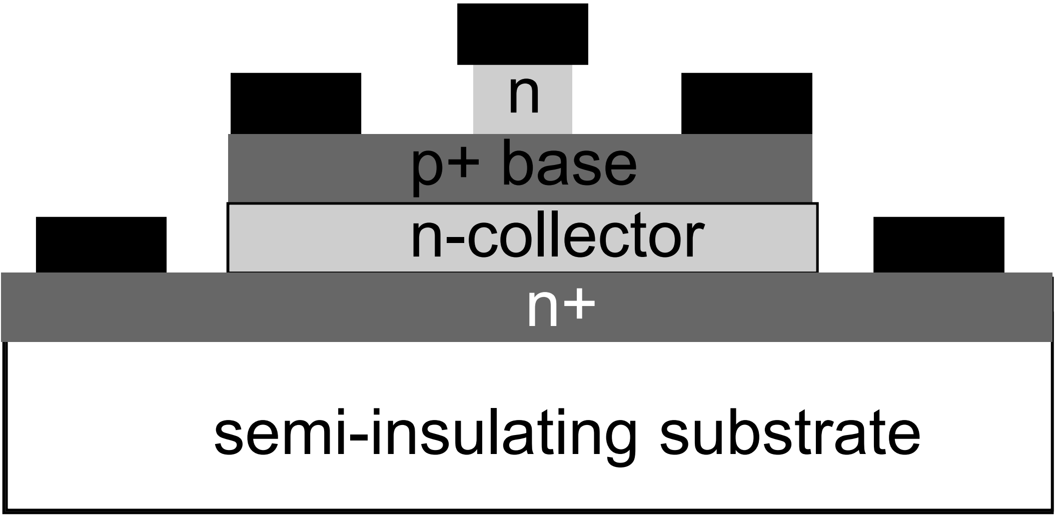
E_{G2}

n collector

$E_{G3}>E_{G2}$

n+

mesa HBT



n

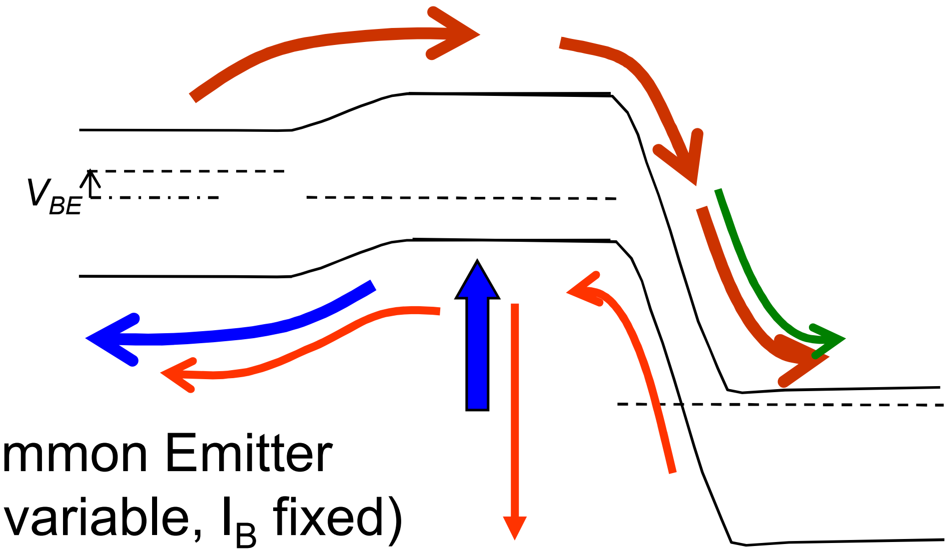
p+ base

n-collector

n+

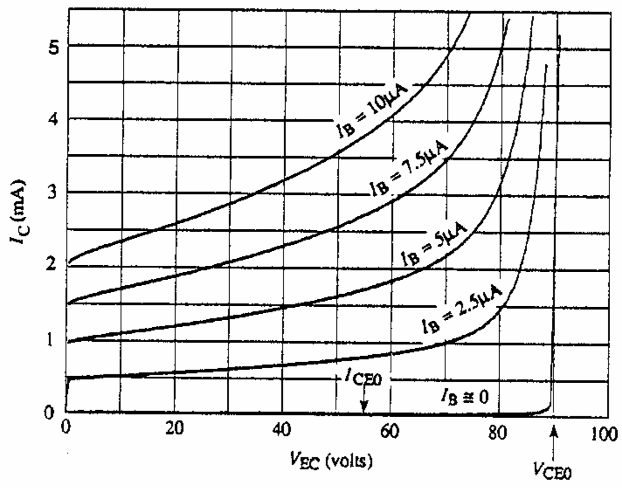
semi-insulating substrate

collector breakdown



Common Emitter
(I_E variable, I_B fixed)

Common Base
(I_E fixed, I_B variable)



Common emitter breakdown voltage is smaller than common base breakdown voltage.

conclusions

- There are many non-ideal effects of bipolar junction transistors that give rise to design constraints
- Classical (MSM or Shockley) BJTs are almost nonexistent today.
- Modern BJTs use poly-Silicon emitter, graded based, hetero E-B junction, etc., to enhance performance.

Summary of ECE 305

Semiconductor Devices
Fundamentals

Drift-diffusion model for semiconductors

$$\nabla \bullet D = q\left(p - n + N_D^+ - N_A^-\right)$$

$$\frac{\partial n}{\partial t} = \frac{1}{q}\nabla \bullet \mathbf{J}_N - r_N + g_N$$

$$\mathbf{J}_N = qn\mu_N\mathcal{E} + qD_N\nabla n$$

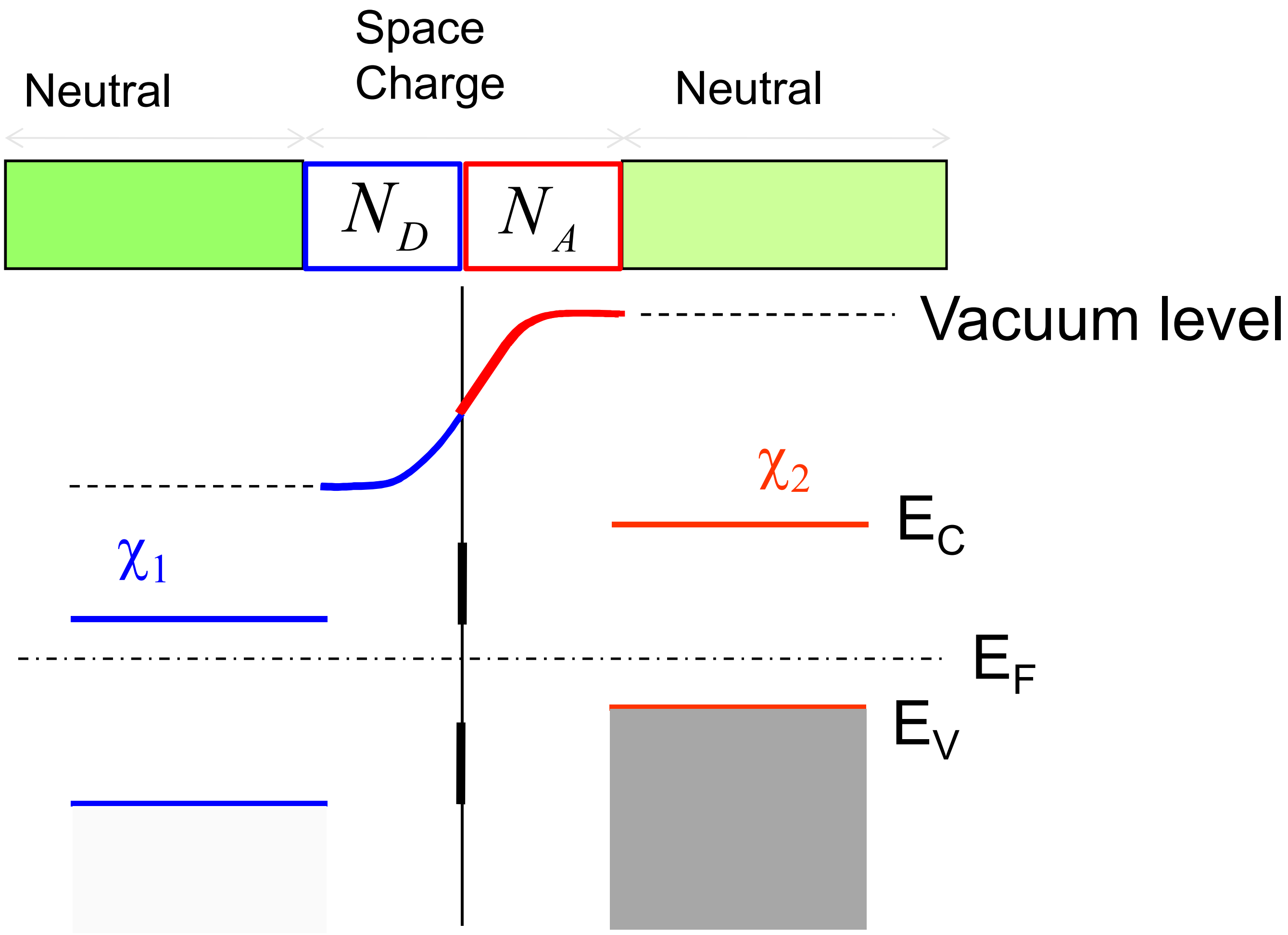
$$\frac{\partial p}{\partial t} = \frac{-1}{q}\nabla \bullet \mathbf{J}_P - r_P + g_P$$

$$\mathbf{J}_P = qp\mu_P\mathcal{E} - qD_P\nabla p$$

← Band-diagram

← Diffusion approximation,
Minority carrier transport,
Ambipolar transport

Short-cut to Band-diagram



… is equivalent to solving the Poisson equation

Minority Carrier Diffusion

$$n(x=0^+) = n_i\, e^{(F_n - E_i)\beta}$$

$$p(x=0^+) = n_i\, e^{-(F_p - E_i)\beta}$$

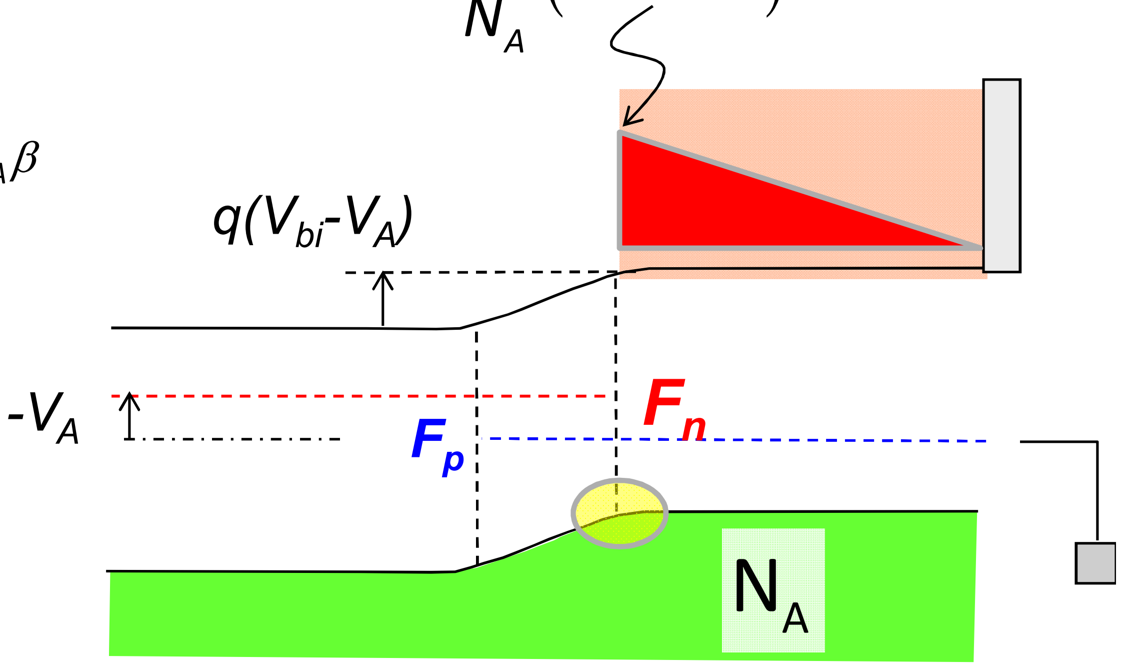
$$np = n_i^2 e^{(F_n - F_p)\beta} = n_i^2 e^{qV_A\beta}$$

$$p(0^+) = N_A$$

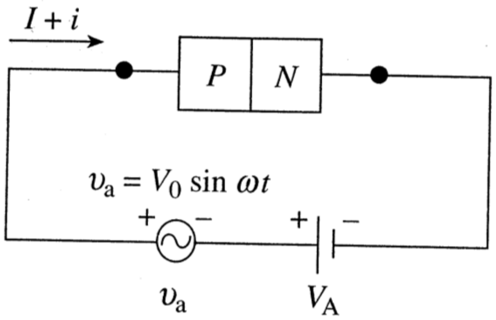
$$n(0^+) = \frac{n_i^2}{N_A} e^{qV_A\beta}$$

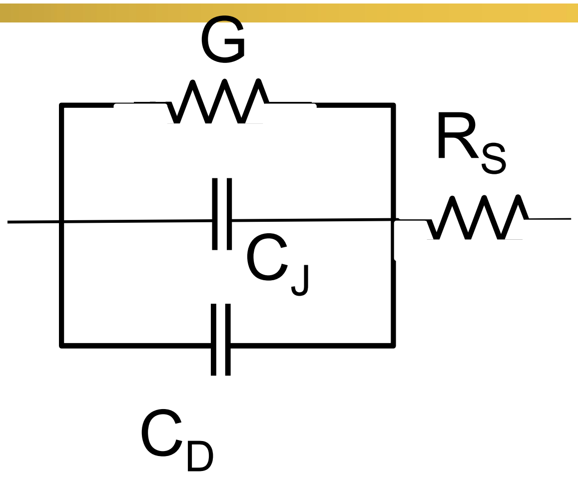
$$\Delta n(0^+) = n(0^+)_{V_G} - n(0^+)_{V_G=0}$$

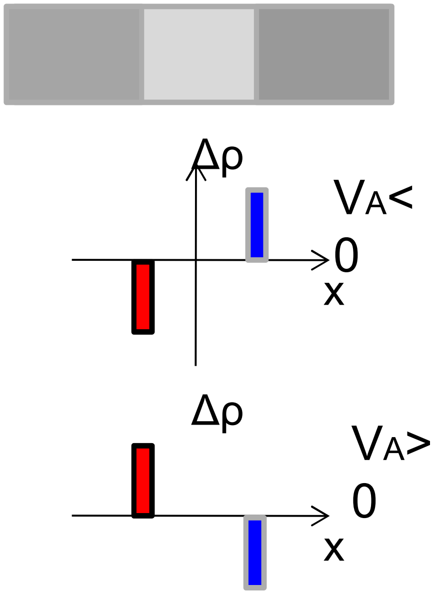
$$= \frac{n_i^2}{N_A}\left(e^{qV_A\beta} - 1\right)$$

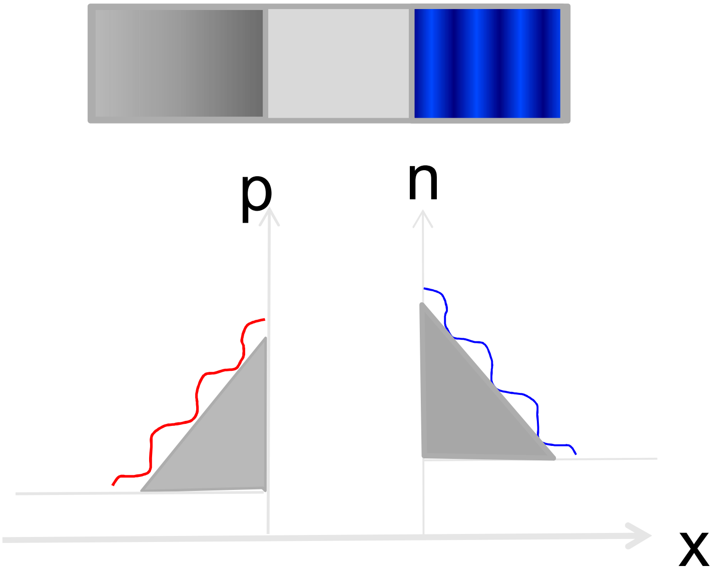


Small Signal AC Response









Concepts for Device Analysis

	Equilibrium	DC	Small signal	Large Signal
Diode	Band-diagram	diffusion	dn/dt~jωn	Charge-control
Schottky	Band-diagram	TE	Junction capacitance	Majority transport
BJT/HBT	Band-diagram	diffusion/TE	dn/dt~jωn	Charge-control
MOSCAP MOSFET	2D band-diagram	Drift/TE	MOS capacitance	Charge-control

Major Questions for Semiconductor Researchers

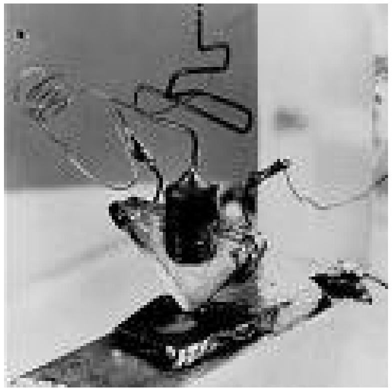
- Can we achieve computing power equivalent to or greater than that of the human brain?
- Can we create and deploy sustainable energy technologies to transition away from fossil fuel usage?
- Can we integrate electronics with biology to detect and fix debilitating diseases?

Grand Challenges in Electronics

Vacuum Tubes

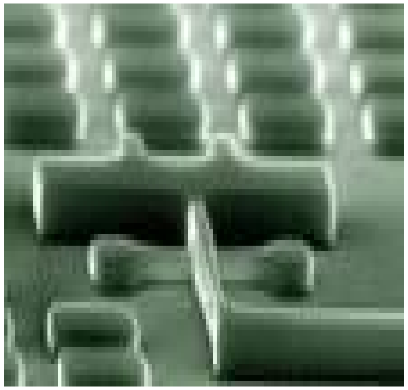
1906-1950s

Bipolar



1947-1980s

MOSFET



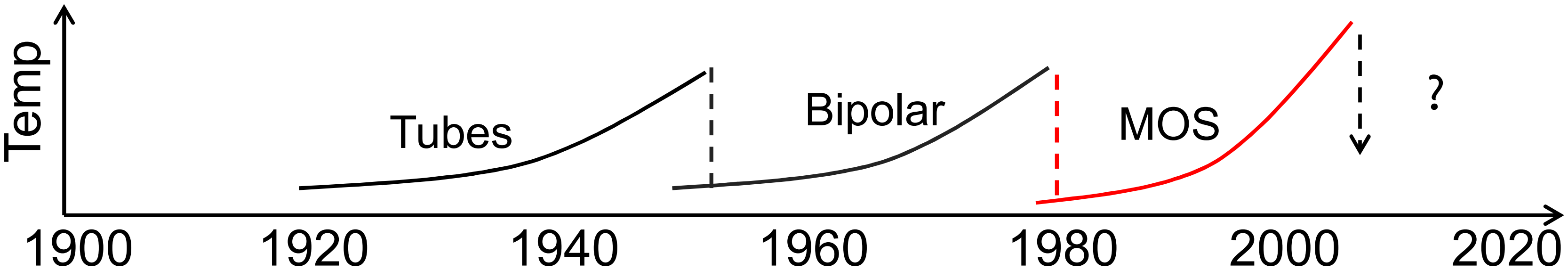
1980-until now

Now ??

Spintronics

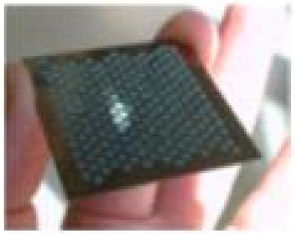
Bio Sensors

Displays ....

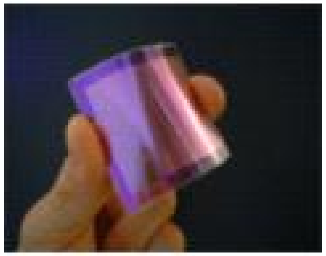


Emergence of Macroelectronics

Biosensors Energy Flexible Electronics



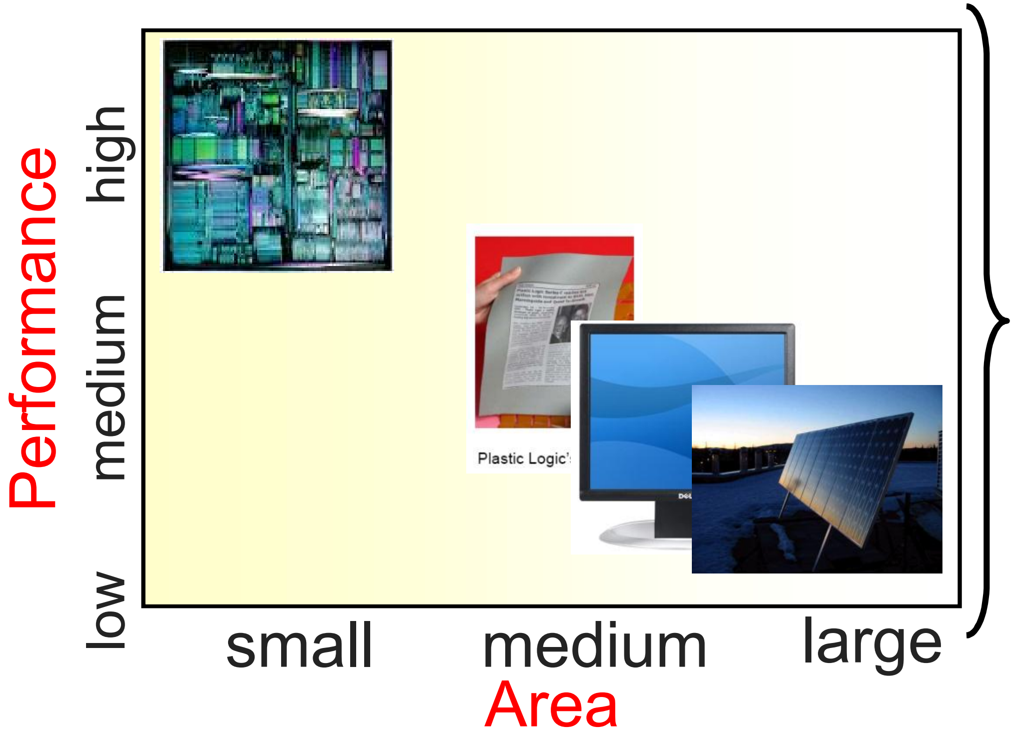
Drug Discovery Substrates



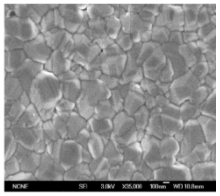
Conformal Solar Cells

nature
nanotechnology
High-performance
nanotube devices

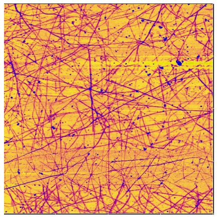
Flexible Electronics



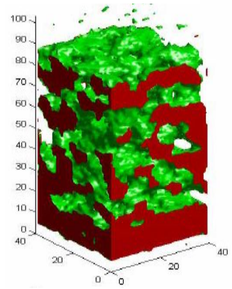
Poly-Si



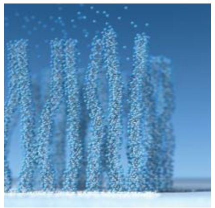
NanoNet



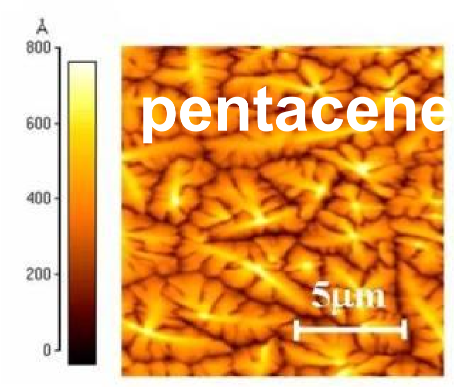
Polymers



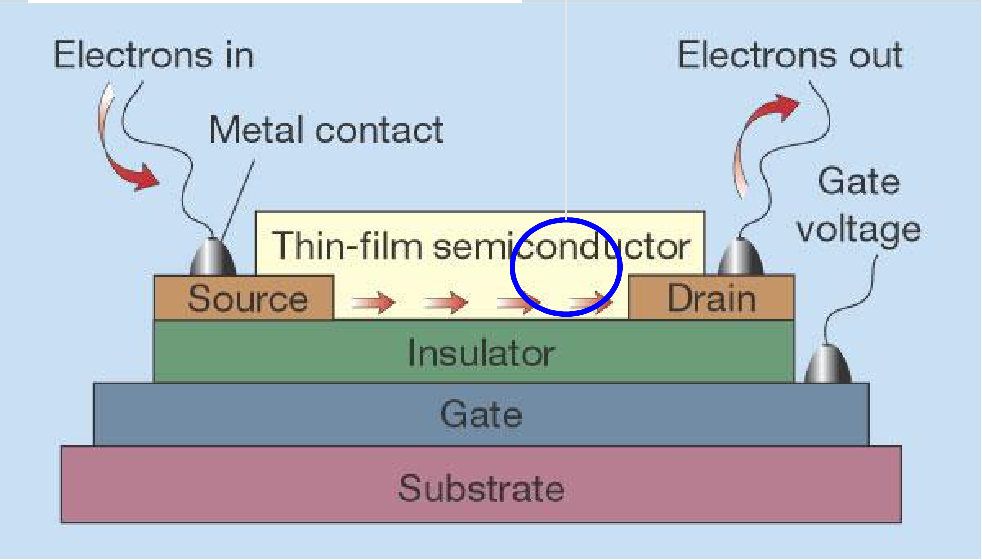
mesoporous



Thin Film Organic Transistors



- Can you draw the band-diagram?
- What type of transport theory would you use?
- Would you be able to use numerical simulators from nanohub.org to explore the TFT?

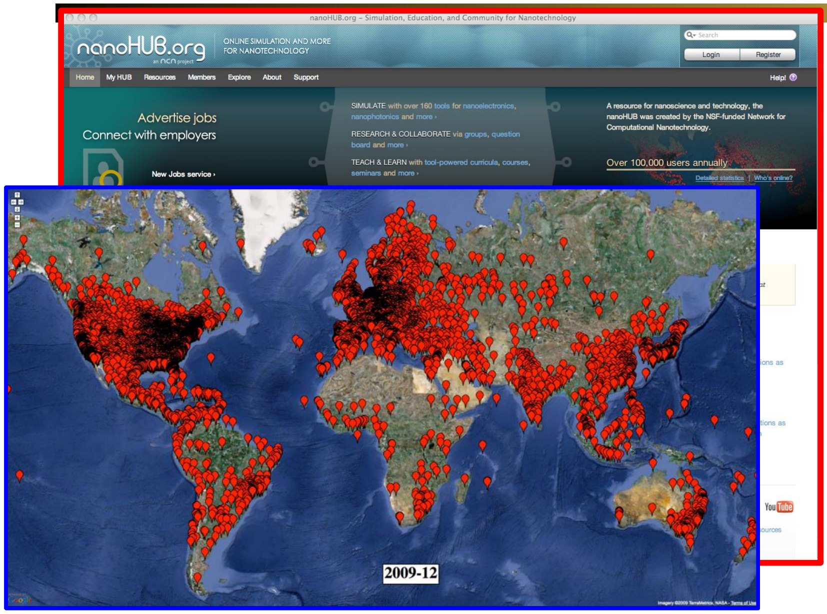


Samsung flexible phone

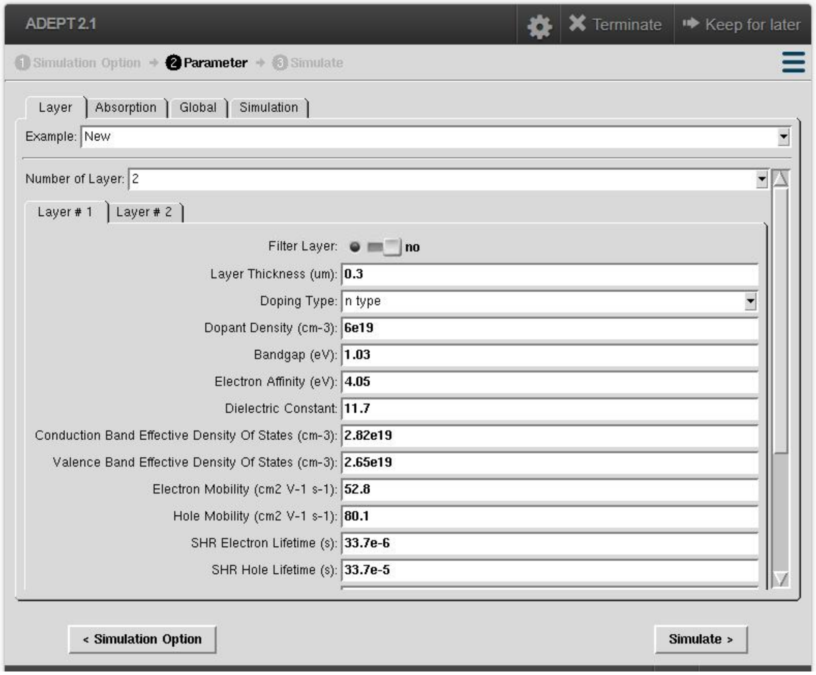
www.faculty.iu-bremen.de/dknipp/group/research.htm
M.G. Kanatzidis, Nature, 428, 2004.

PV Simulations on nanoHUB.org

a major resource for computational nanotechnology



enabled by the HUBzero platform for simulation, learning, and collaboration



Example: New

Number of Layer: 2

Filter Layer: ● no

Layer Thickness (um): 0.3

Doping Type: n type

Dopant Density (cm-3): 6e19

Bandgap (eV): 1.03

Electron Affinity (eV): 4.05

Dielectric Constant: 11.7

Conduction Band Effective Density Of States (cm-3): 2.82e19

Valence Band Effective Density Of States (cm-3): 2.65e19

Electron Mobility (cm2 V-1 s-1): 52.8

Hole Mobility (cm2 V-1 s-1): 80.1

SHR Electron Lifetime (s): 33.7e-6

SHR Hole Lifetime (s): 33.7e-5

- *25 Hubs operating or under construction*
- *open source platform*
- *6,144 dedicated cores with over 17,000 on standby*

Multijunction Photovoltaics

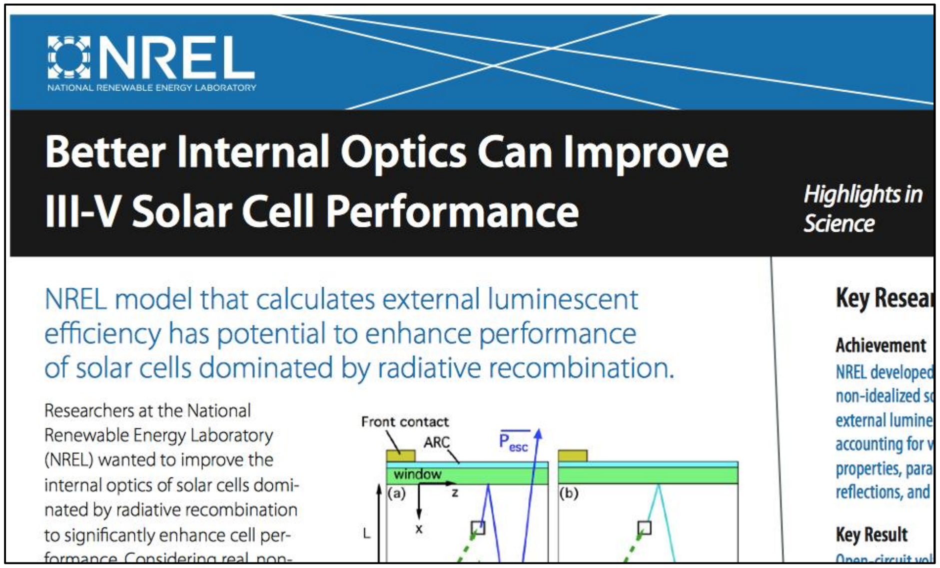
- The new record obtain in June 2013, at 31.1%, is a significant jump from 29.5% prior record
- Enhanced **photon recycling** is believed to cause this improvement.

News Release NR-3913

NREL Reports 31.1% Efficiency for III-V Solar Cell

Conversion-efficiency mark is a world record for a two-junction solar cell measured under one-sun illumination

June 24, 2013



Better Internal Optics Can Improve III-V Solar Cell Performance

NREL model that calculates external luminescent efficiency has potential to enhance performance of solar cells dominated by radiative recombination.

Researchers at the National Renewable Energy Laboratory (NREL) wanted to improve the internal optics of solar cells dominated by radiative recombination to significantly enhance cell performance. Considering real non-

Key Resear

Achievement

NREL developed
non-idealized s
external lumine
accounting for v
properties, para
reflections, and

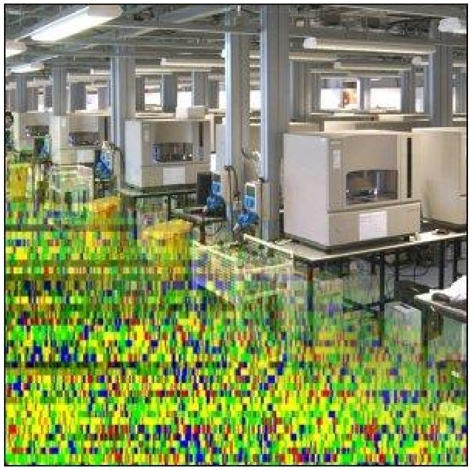
Key Result

“ The NREL researchers improved the cell’s efficiency by enhancing the photon recycling in the lower, gallium-arsenide junction by using a gold back contact to reflect photons back into the cell, and by allowing a significant fraction of the luminescence from the upper, GaInP junction to couple into the GaAs junction. Both the open-circuit voltage and the short-circuit current were increased.”

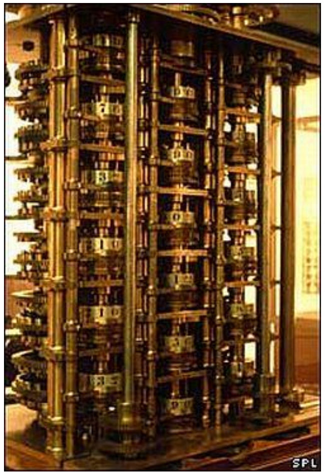
—NREL News Release, June 24, 2013

Technology: Sequencing by Synthesis

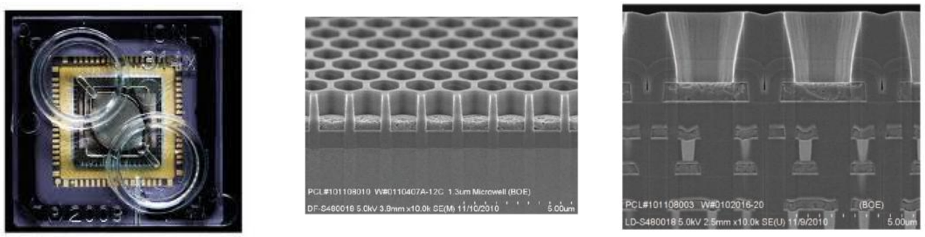
Sanger method (1990s)



Babbage computer (~1830s)

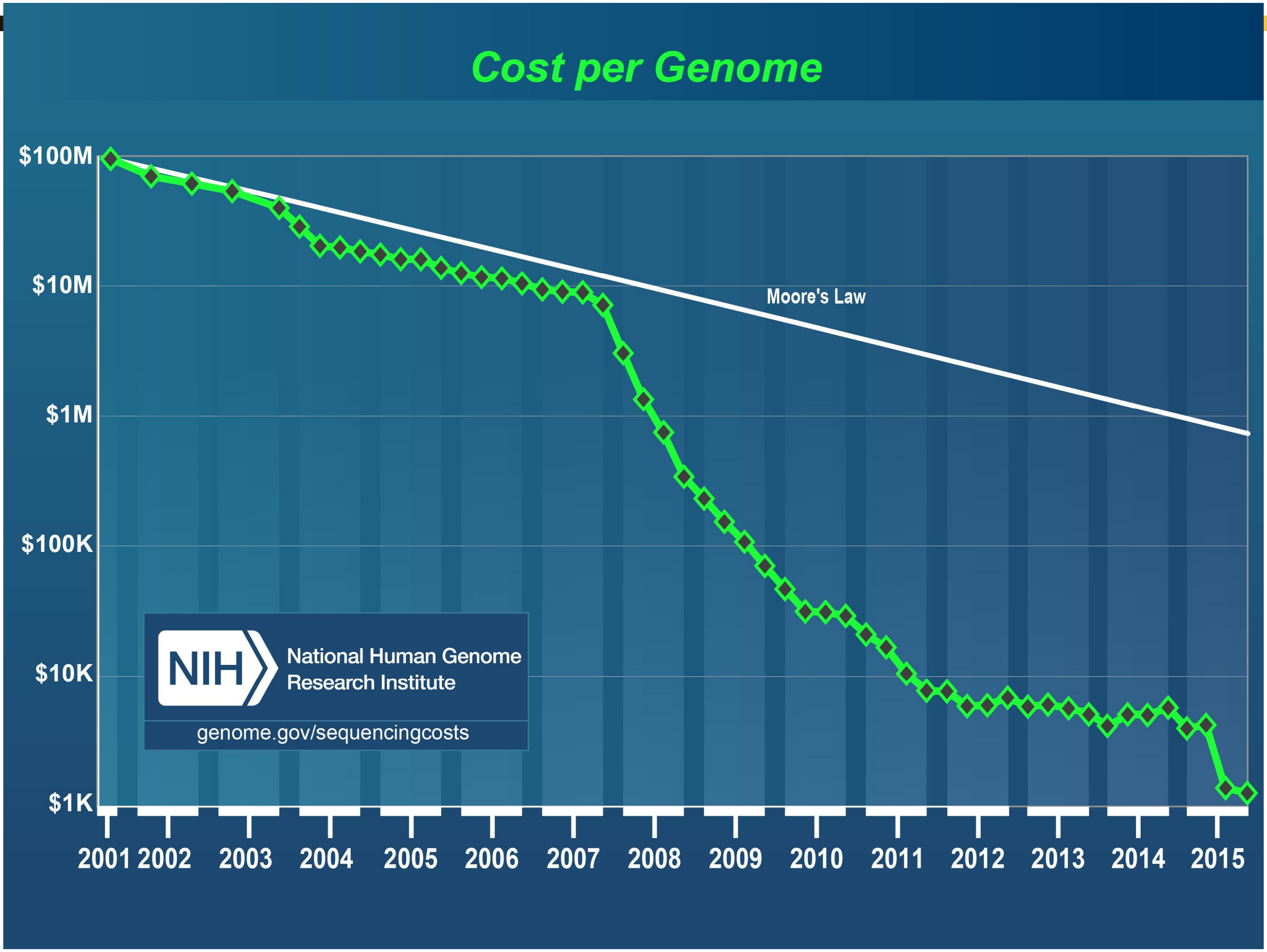


Ion-torrent system (2011)



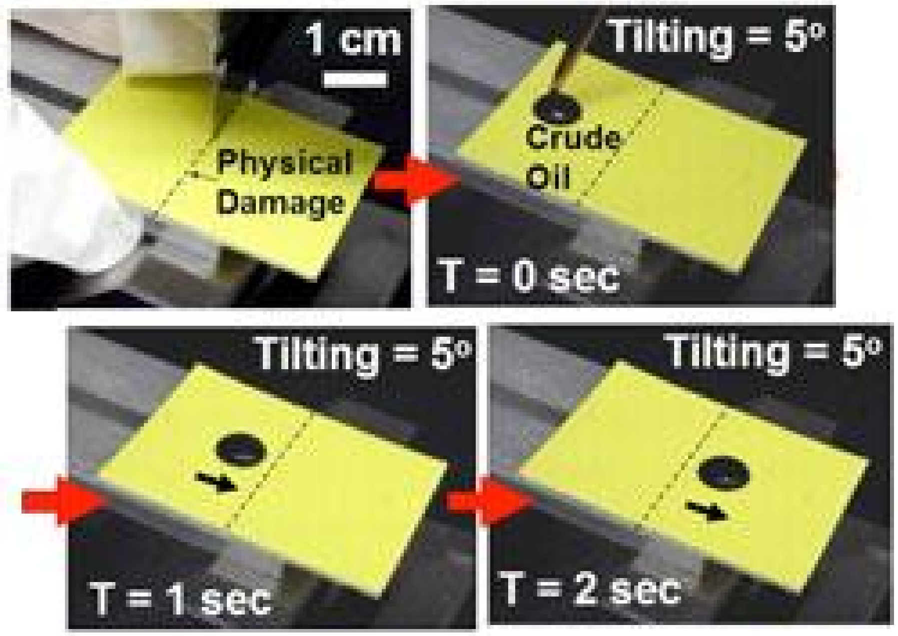
Intel Chip Today

Technology: Sequencing by Synthesis



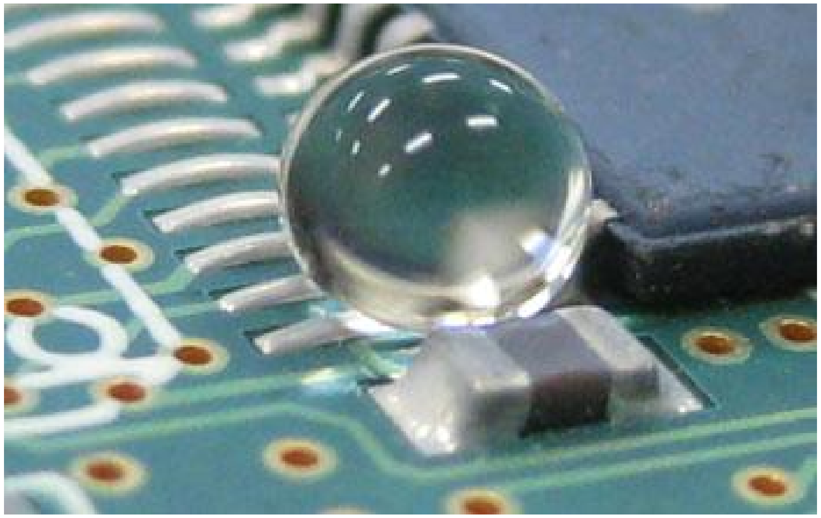
Superhydrophobic coatings

SLIPS Coatings



http://wyss.harvard.edu/viewpage/316

‘Waterproof’ circuit boards



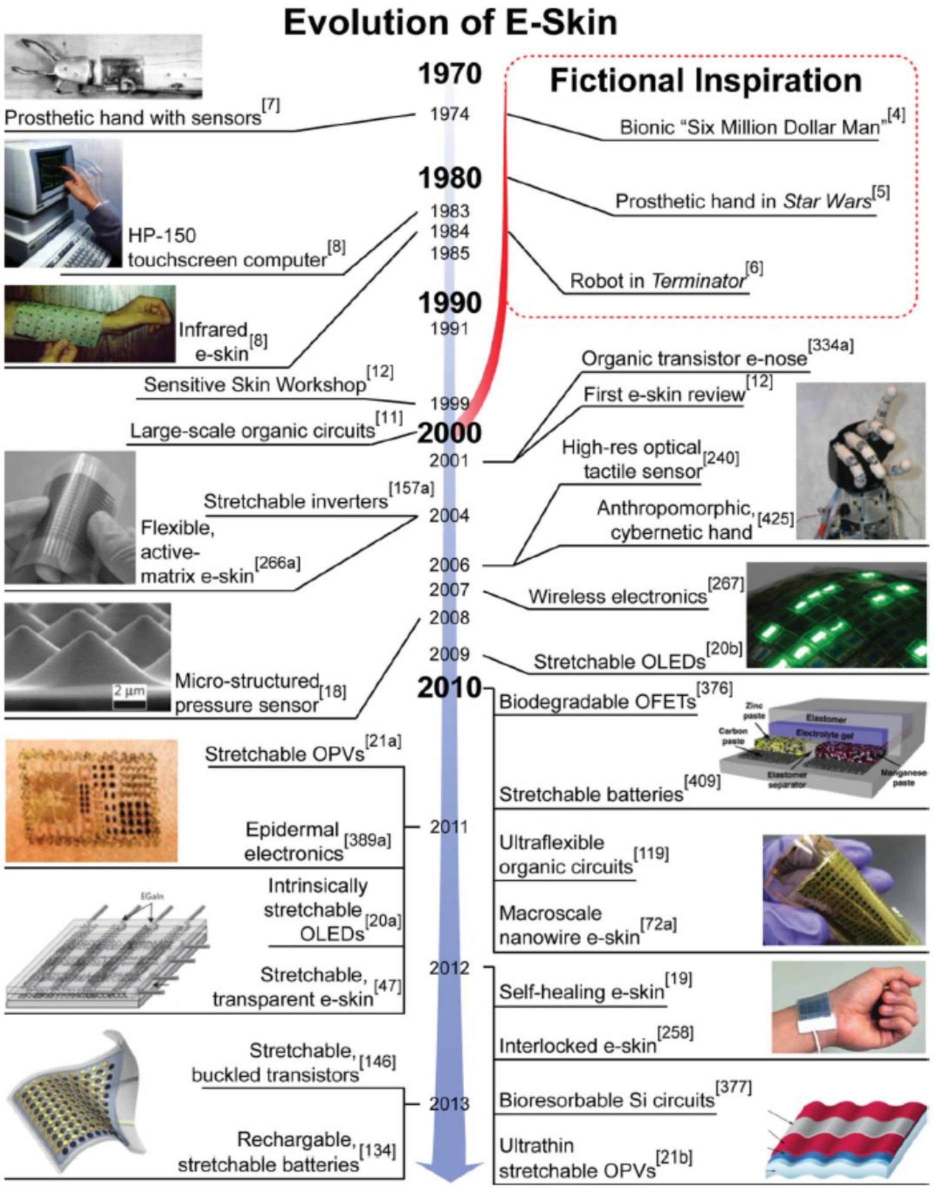
http://www.cytonix.com/conformal-coating-s/1872.htm

Superhydrophobic coatings

Anti-soiling coatings for photovoltaic modules

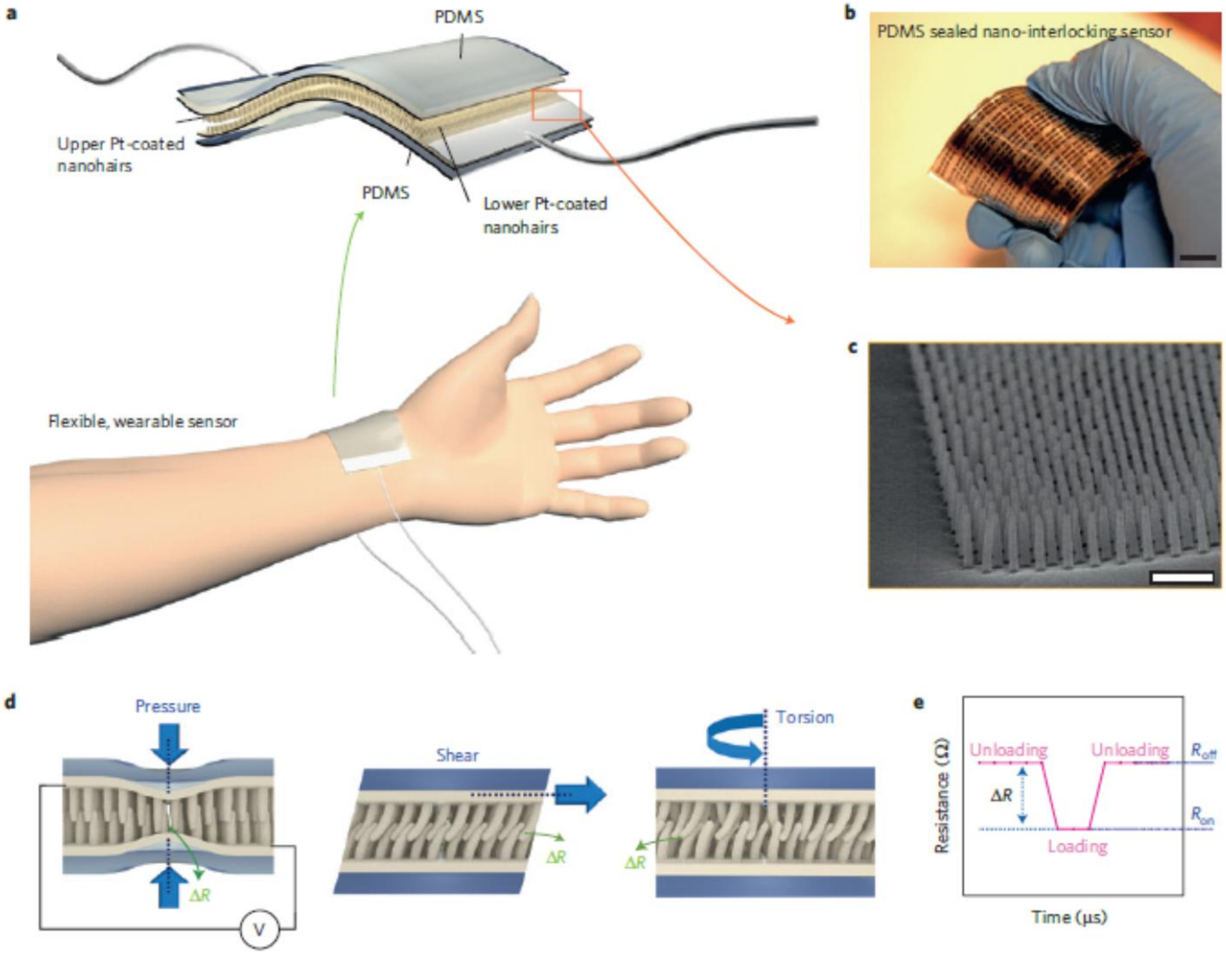
https://www.youtube.com/watch?v=16RcYoXOvRM

Artificial Skin



M.L. Hammock et al., "25th Anniversary Article: The Evolution of Electronic Skin (E-Skin): A Brief History, Design Considerations, and Recent Progress." *Advanced Materials* **25**, 5997-6038 (2013).

Artificial Skin



Multiplex, flexible strain-gauge sensor based on the reversible interlocking of Pt-coated polymer nanofibres. Image: *Nature Materials* (2012) http://dx.doi.org/10.1038/nmat3380

Developing New Ideas

“New ideas pass through three periods:

1) It can't be done.
2) It probably can be done, but it's not worth doing.
3) I knew it was a good idea all along!”

“I don't pretend we have all the answers. But the questions are certainly worth thinking about.”

-- Sir Arthur C. Clarke