Device Research Conference 2011

1.0-THz f_{max} InP DHBTs in a refractory emitter and self-aligned base process for reduced base access resistance

Vibhor Jain, Johann C. Rode, Han-Wei Chiang, Ashish Baraskar, Evan Lobisser, Brian J Thibeault, Mark Rodwell

ECE Department, University of California, Santa Barbara, CA 93106-9560

Miguel Urteaga

Teledyne Scientific & Imaging, Thousand Oaks, CA 91360

D Loubychev, A Snyder, Y Wu, J M Fastenau, W K Liu

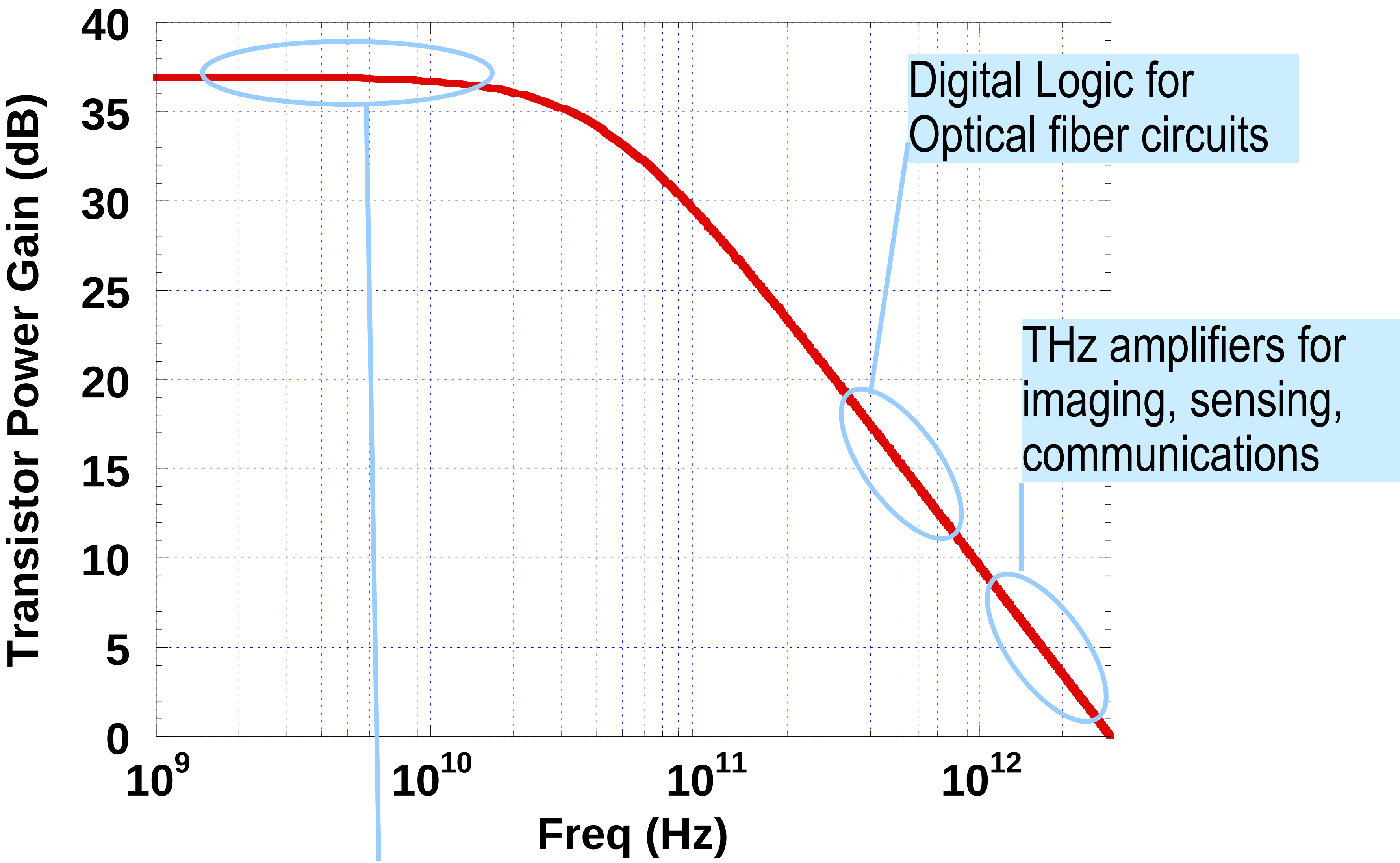
IQE Inc., 119 Technology Drive, Bethlehem, PA 18015

vibhor@ece.ucsb.edu, 805-893-3273

Outline

- Need for high speed HBTs
- Fabrication
  - Challenges
  - Process Development
- DHBT
  - Epitaxial Design
  - Results
- Summary

Why THz Transistors?



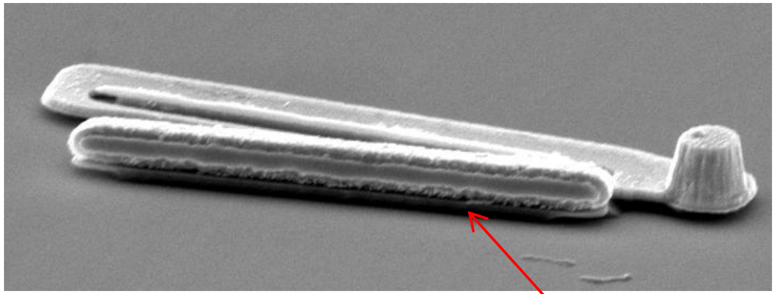
High gain at microwave frequencies → precision analog design, high resolution ADC & DAC, high performance receivers

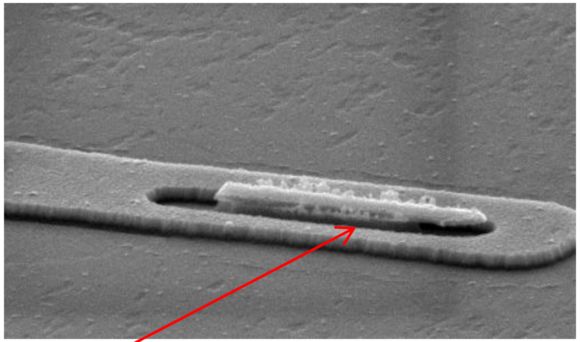
HBT process requirements

- Refractory emitter contact and metal stack
  - To sustain high current density operation
- Low stress emitters
  - For high yield
- Low base access resistance
  - For improved device f_{max}
- Thin emitter semiconductor
  - To enable a wet etched emitter process for reliability and scalability

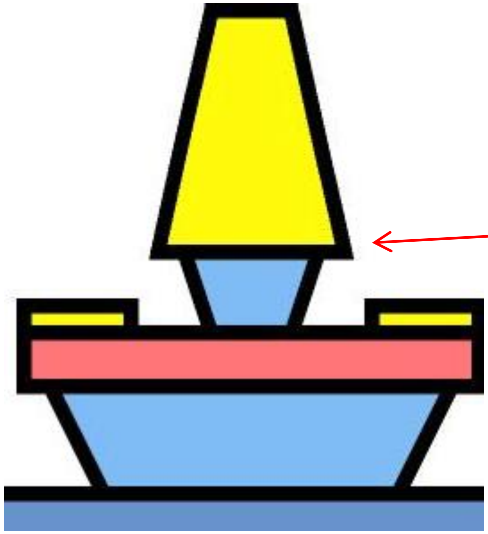
Fabrication Challenges – Stable refractory emitters

Emitter yield drops during base contact, subsequent lift-off steps





Fallen emitters



High stress in emitter metal stack

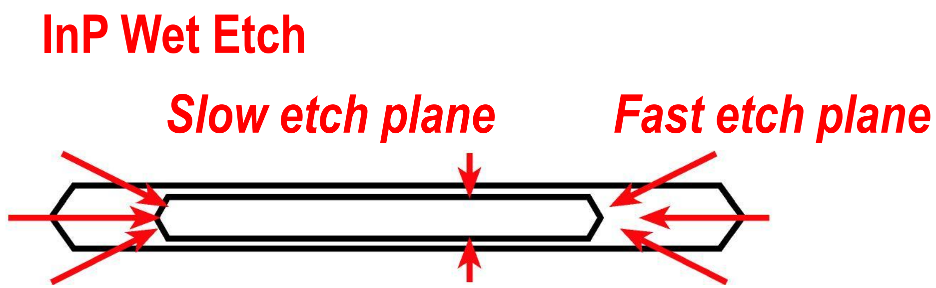
Poor metal adhesion to InGaAs

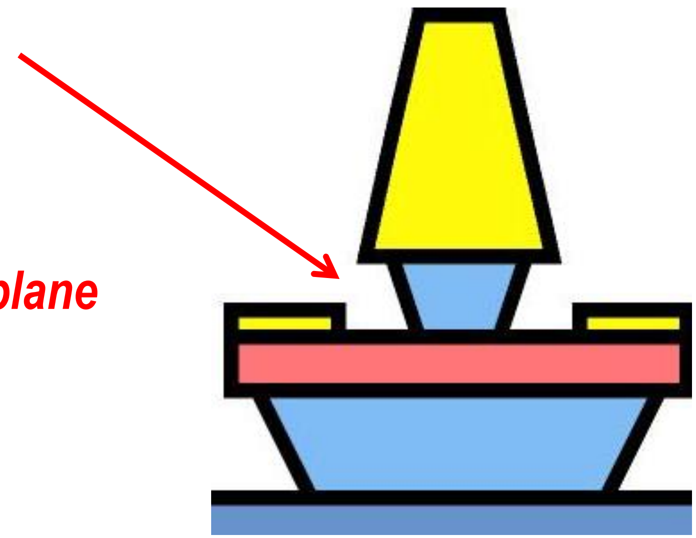
Need for low stress, high yield emitters

Fabrication Challenges – Base-Emitter Short

Undercut in thick emitter semiconductor

Helps in Self Aligned Base Liftoff





For controlled semiconductor undercut

→ Thin semiconductor

To prevent base – emitter short

→ Vertical emitter profile and line of sight metal deposition

→ Shadowing effect due to high emitter aspect ratio

Fabrication Challenges – Base Access Resistance

$$f_{\max} = \sqrt{\frac{f_\tau}{8\pi R_{bb} C_{cb}}}$$

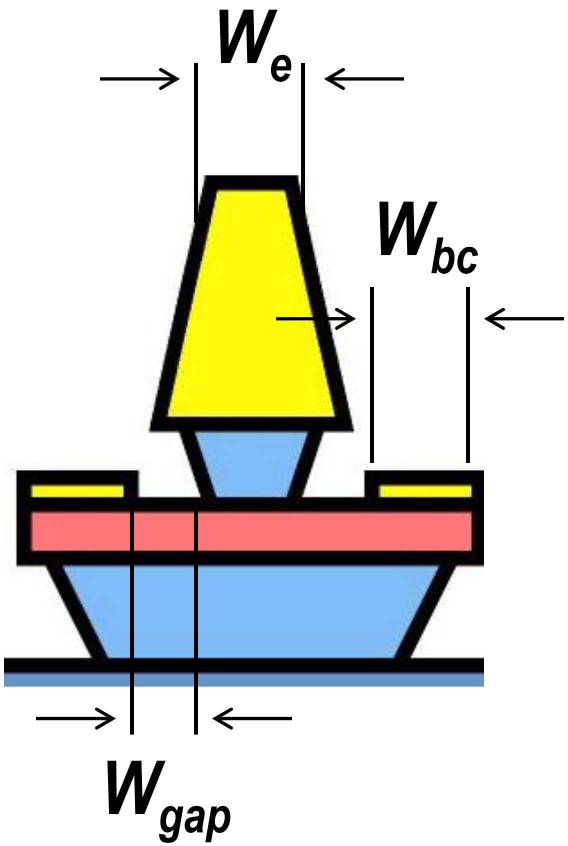
$$R_{bb} = \rho_{sh,e} \cdot \frac{W_e}{12 L_e} + \rho_{sh,bc} \cdot \frac{W_{bc}}{6 L_e} + \rho_{sh,gap} \cdot \frac{W_{gap}}{2 L_e} + \frac{\rho_{contact}}{A_{contacts}}$$

$$\rho_{sh,gap} >> \rho_{sh,e}, \rho_{sh,bc}$$

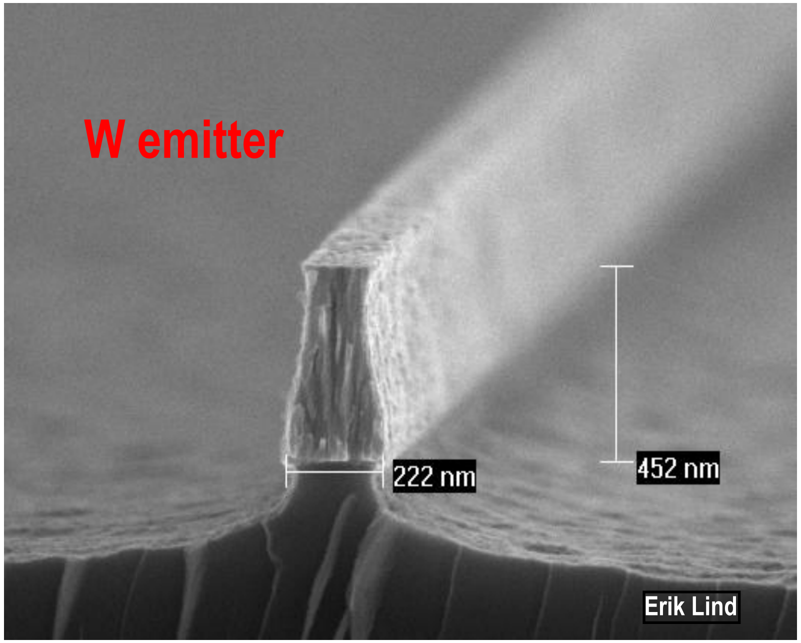
- Surface Depletion
- Process Damage

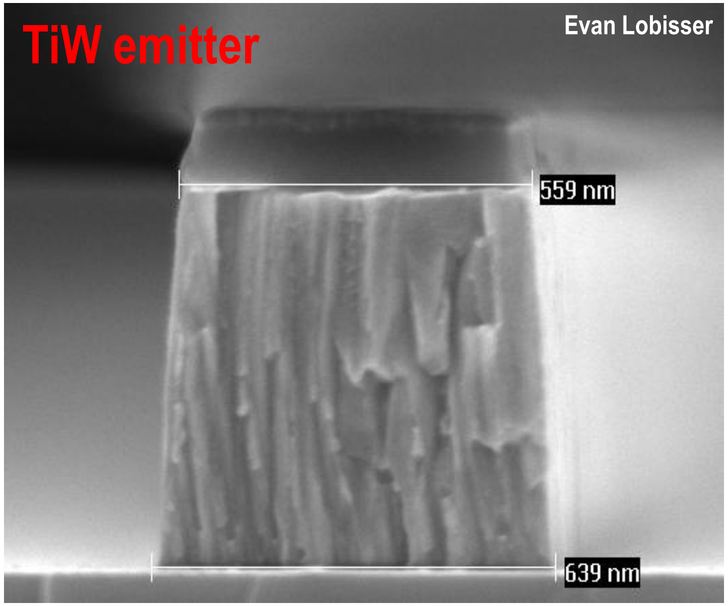
→ Need for very small W_{gap}

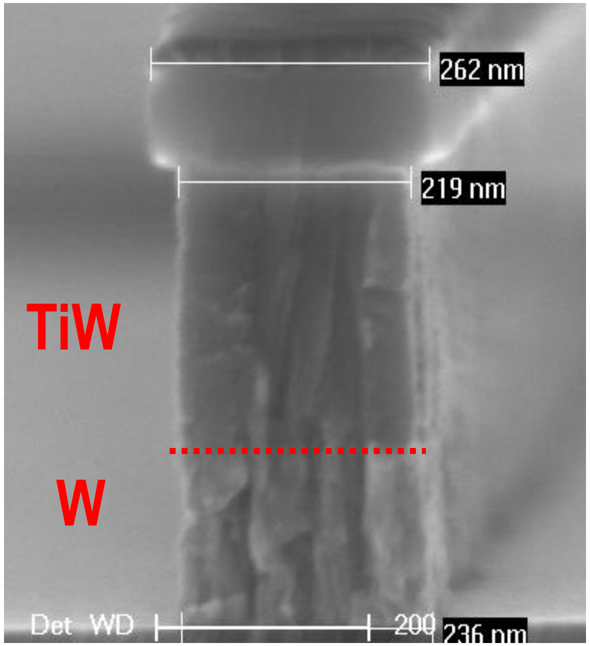
- Small undercut in InP emitter
- Self-aligned base contact



Composite Emitter Metal Stack

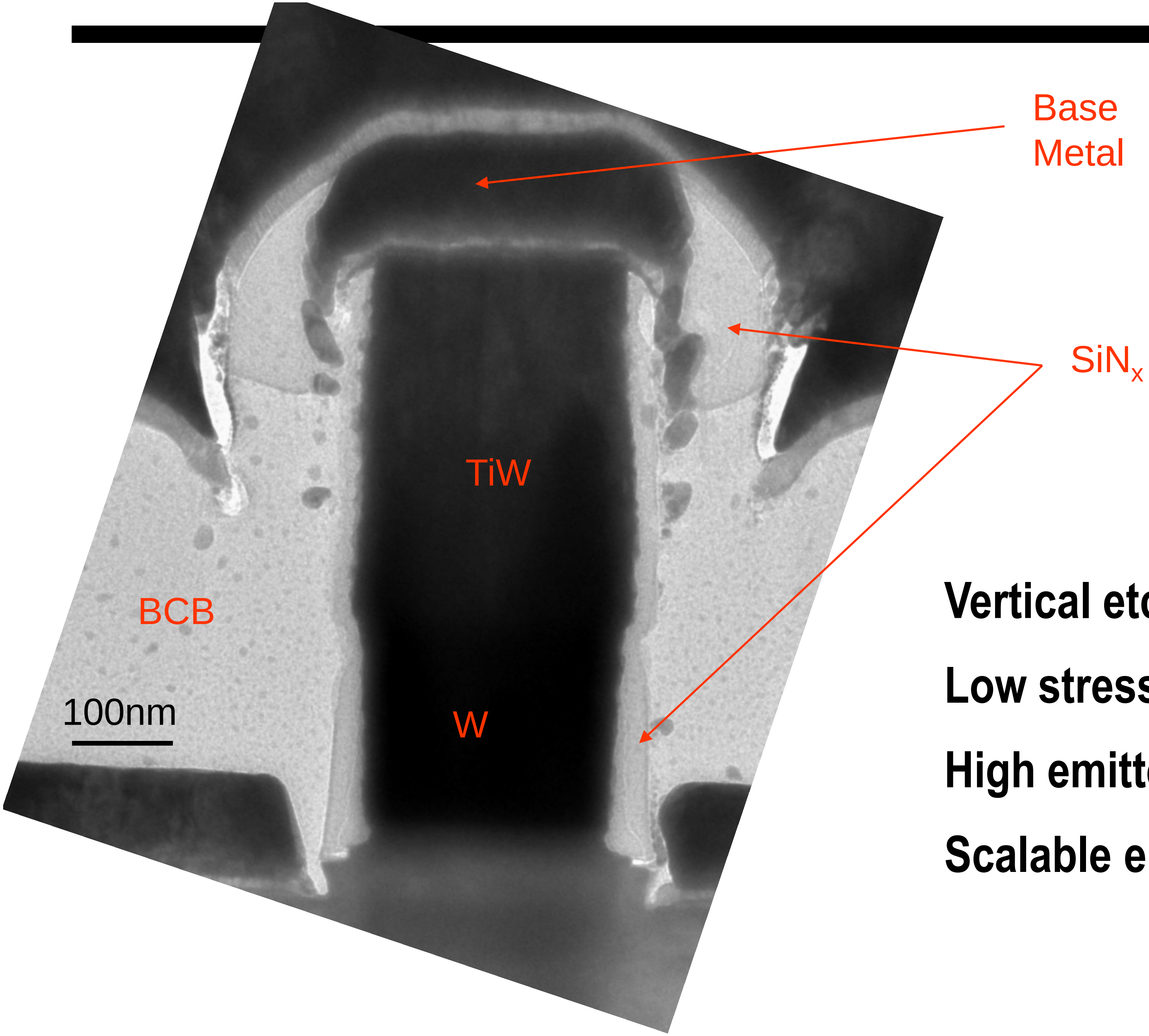






- W/TiW metal stack
- Low stress
- Refractory metal emitters
- Vertical dry etch profile

Vertical Emitter



Vertical etch profile

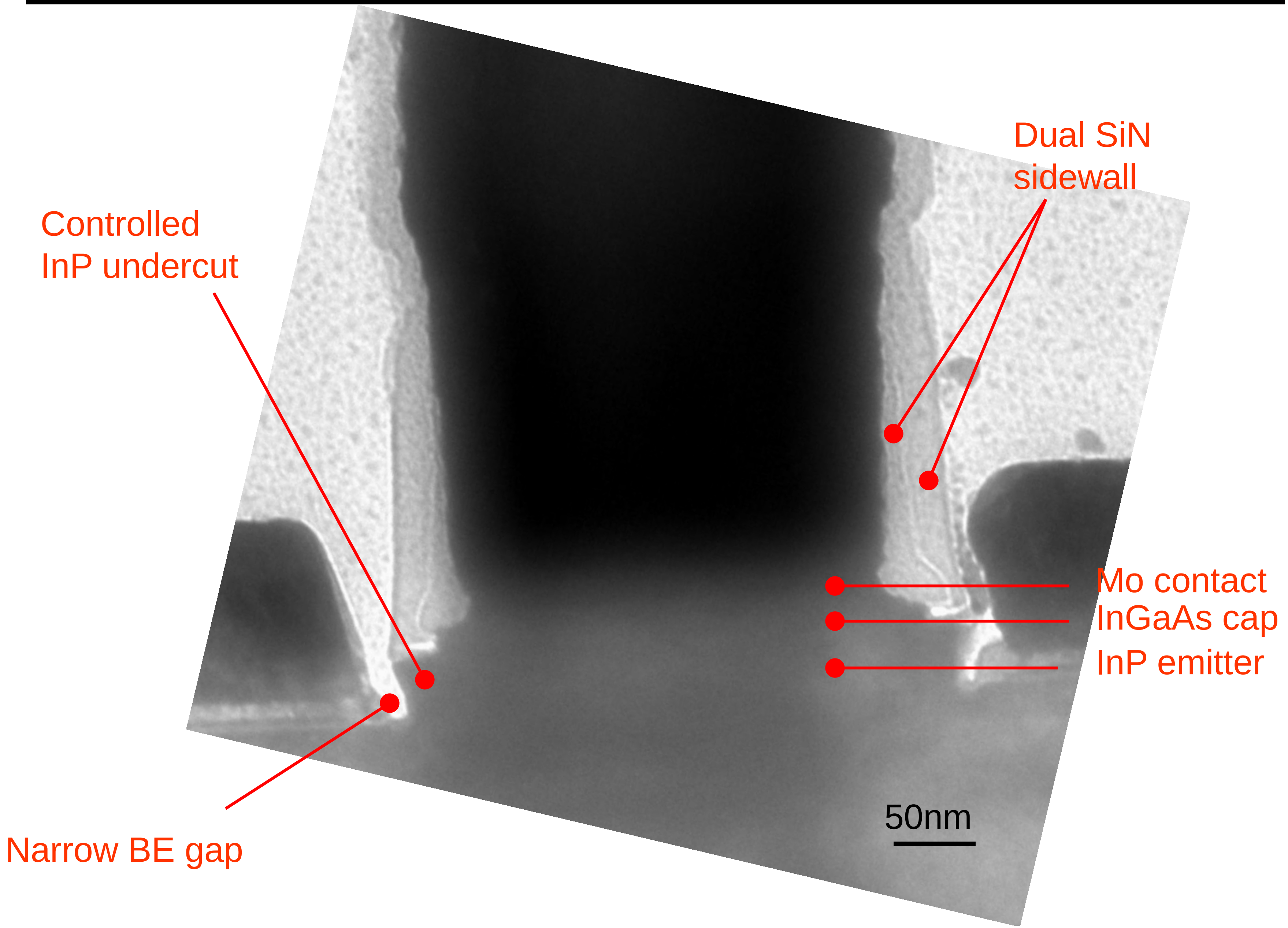
Low stress

High emitter yield

Scalable emitter process

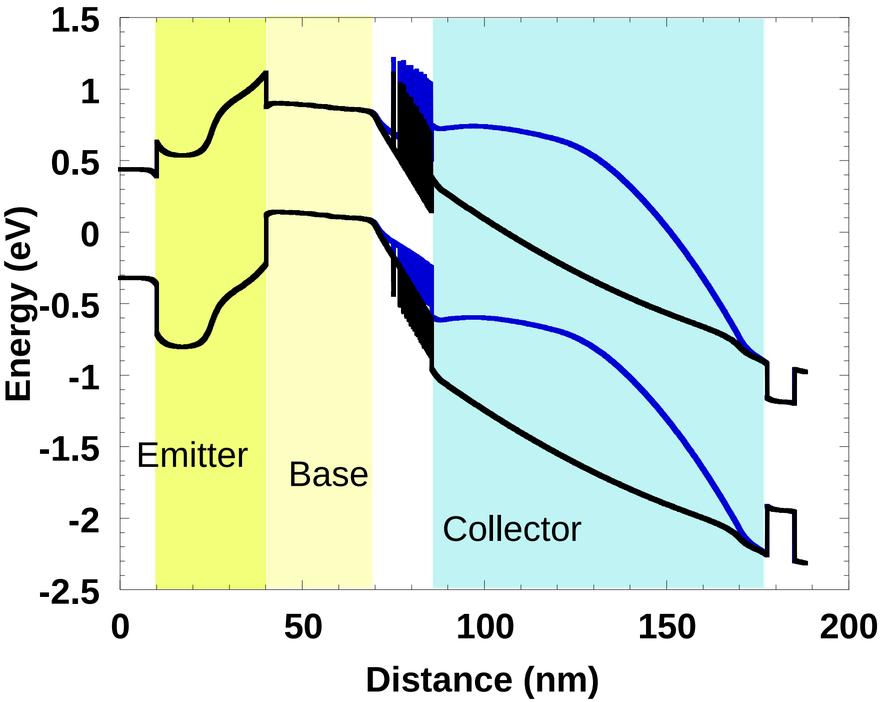
Narrow Emitter Undercut

FIB/TEM by E Lobisser



Epitaxial Design

T(nm)	Material	Doping (cm^{-3})	Description
10	$In_{0.53}Ga_{0.47}As$	$8 \cdot 10^{19}$: Si	Emitter Cap
20	InP	$5 \cdot 10^{19}$: Si	Emitter
15	InP	$2 \cdot 10^{18}$: Si	Emitter
30	InGaAs	$9\text{-}5 \cdot 10^{19}$: C	Base
13.5	$In_{0.53}Ga_{0.47}As$	$5 \cdot 10^{16}$: Si	Setback
16.5	InGaAs / InAlAs	$5 \cdot 10^{16}$: Si	B-C Grade
3	InP	$3.6 \cdot 10^{18}$: Si	Pulse doping
67	InP	$5 \cdot 10^{16}$: Si	Collector
7.5	InP	$1 \cdot 10^{19}$: Si	Sub Collector
5	$In_{0.53}Ga_{0.47}As$	$4 \cdot 10^{19}$: Si	Sub Collector
300	InP	$2 \cdot 10^{19}$: Si	Sub Collector
Substrate	SI : InP		



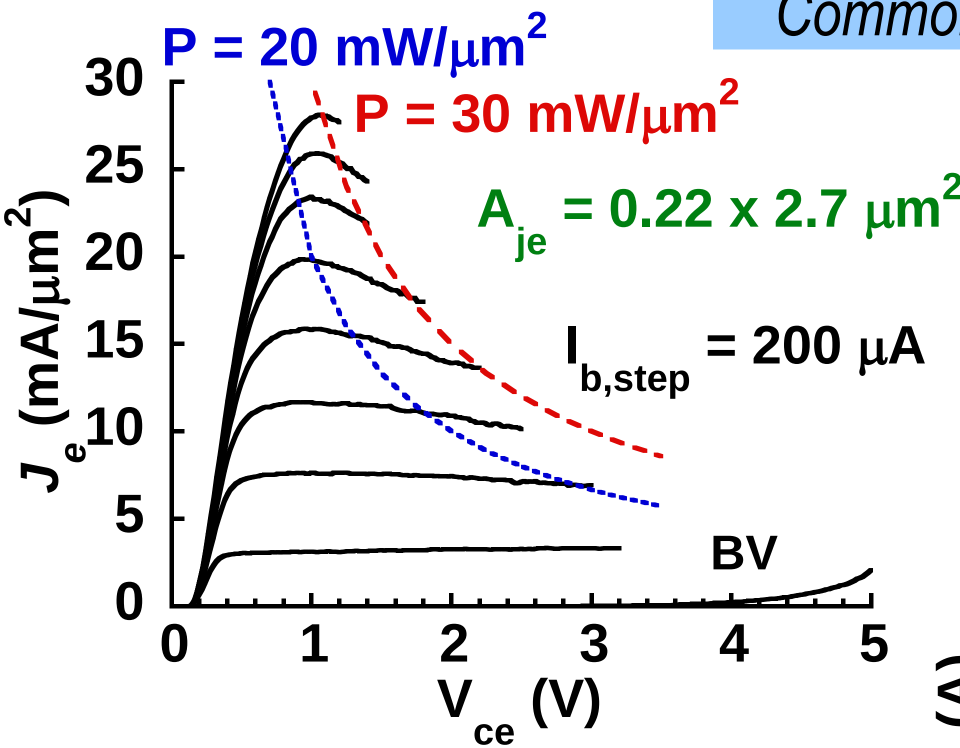
$V_{be} = 1$ V, $V_{cb} = 0.7$ V, $J_e = 24$ mA/μm^2

Thin emitter semiconductor

→ Enables wet etching

Results - DC Measurements

Common emitter I-V



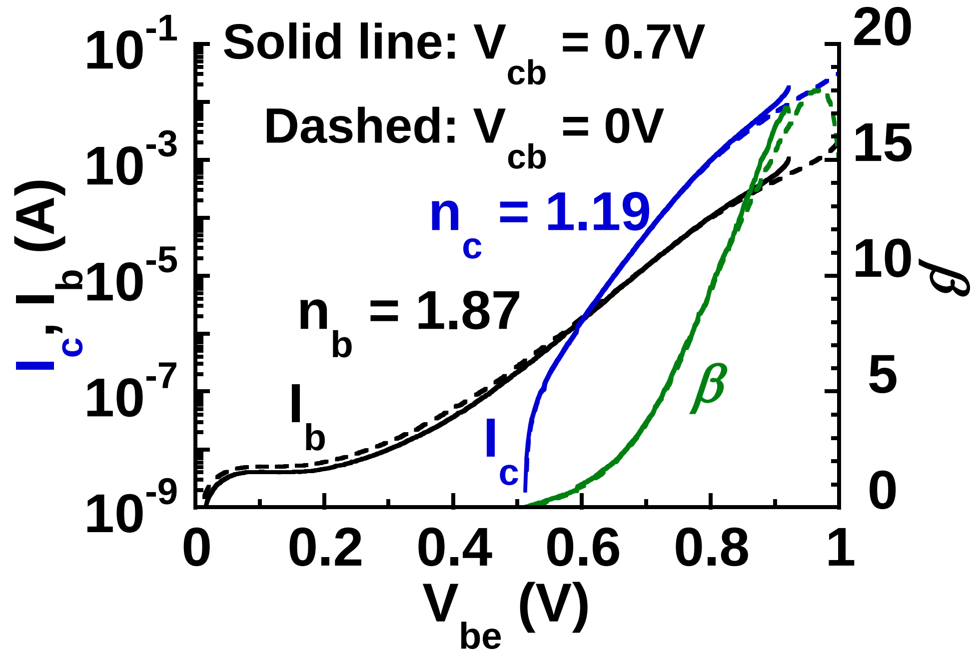
@Peak f_τ, f_{max}

J_e = 20.4 mA/μm²

P = 33.5 mW/μm²

BV_{ceo} = ***3.7 V*** @ J_e = 0.1 mA/cm²

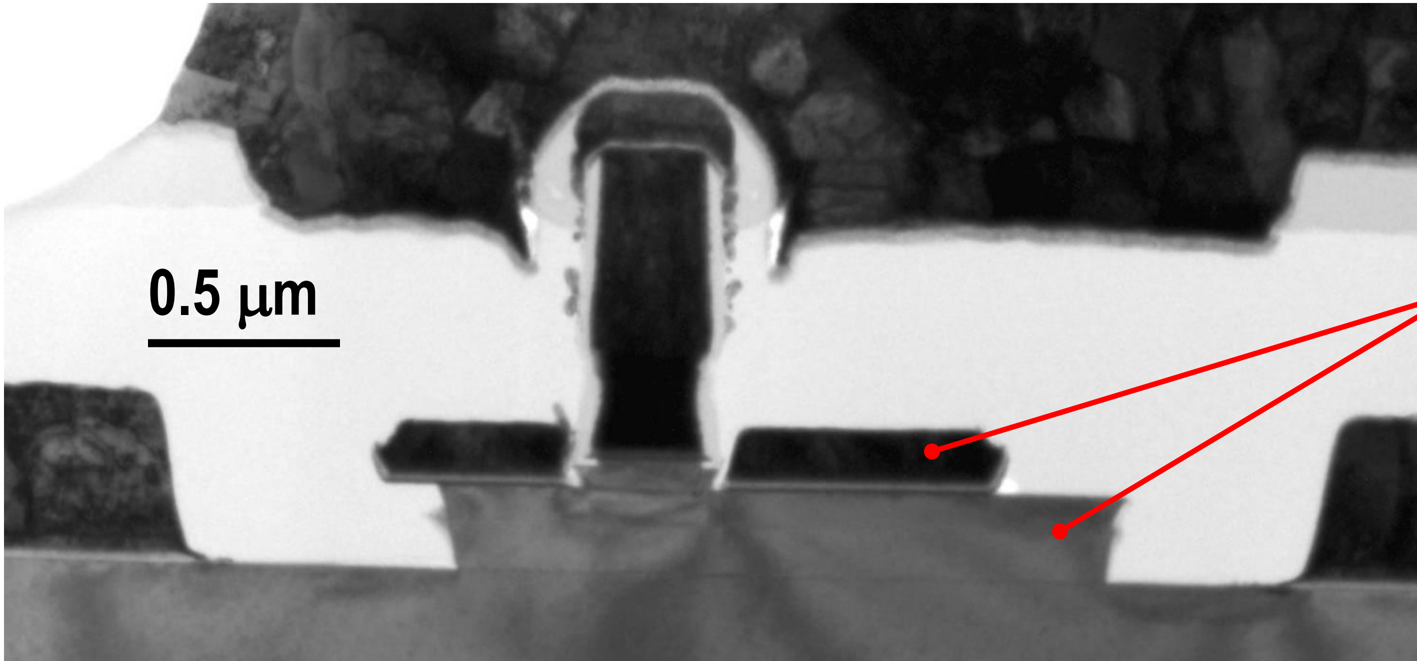
β = ***17***



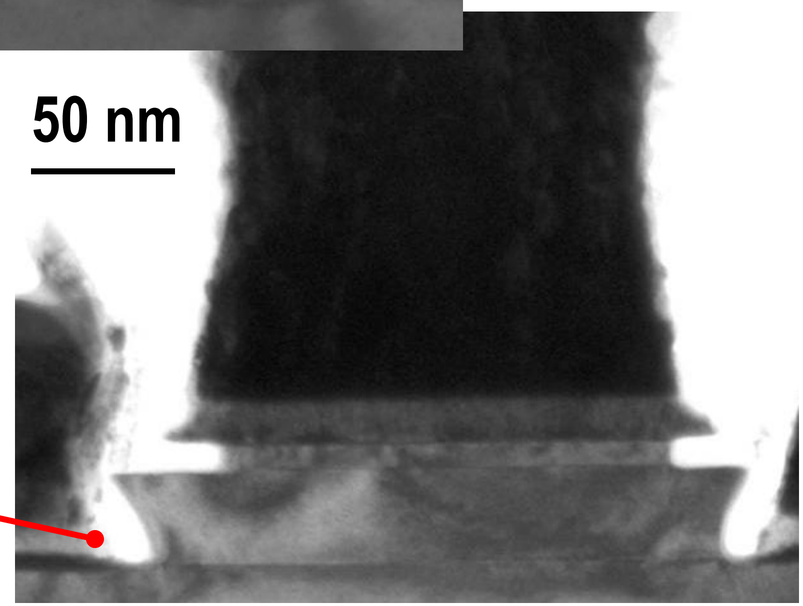
Gummel plot

FIB/TEM by H. Chiang

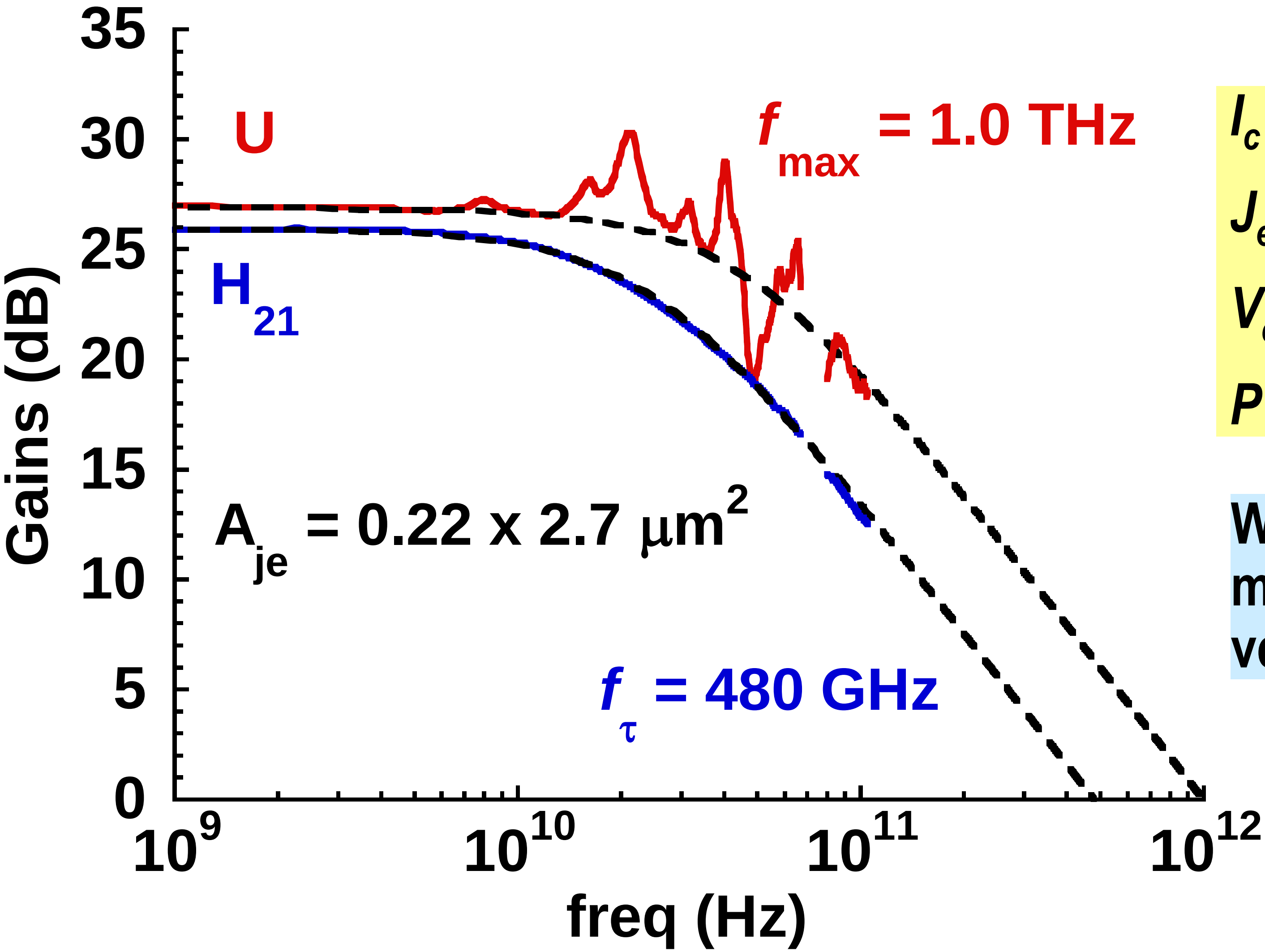
TEM – Wide, misaligned base mesa



- 220 nm emitter-base junction
- 1.1 µm wide base-collector mesa



RF Data



I_c = 12.1 mA

J_e = 20.4 mA/μm²

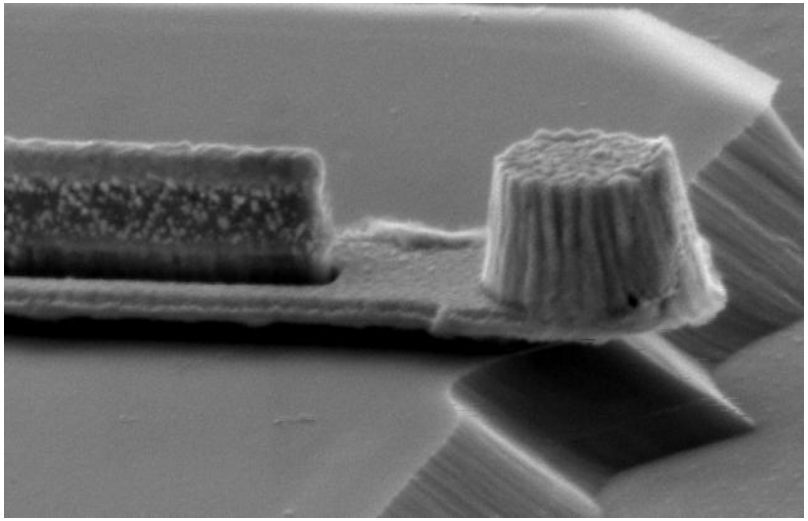
V_{cb} = 0.7 V

P = 33.5 mW/μm²

W-Band measurements to verify f_τ/f_{max}

Base Post Cap

$$C_{cb,post} = \frac{\varepsilon_0 \varepsilon_r \cdot A_{post}}{T_c}$$



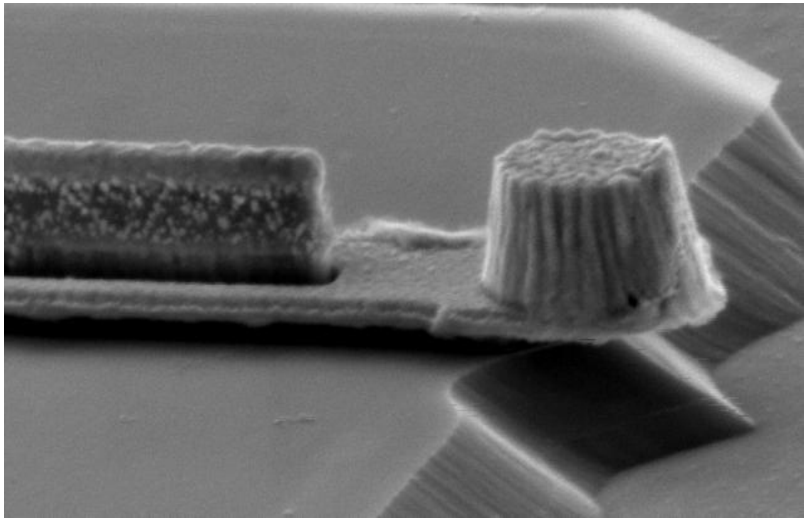
$C_{cb,post}$ does not scale with L_e

→ Adversely effects f_{max} as $L_e \downarrow$

→ Need to minimize the $C_{cb,post}$ value

Base Post Cap

$$C_{cb,post} = \frac{\varepsilon_0 \varepsilon_r \cdot A_{post}}{T_c}$$



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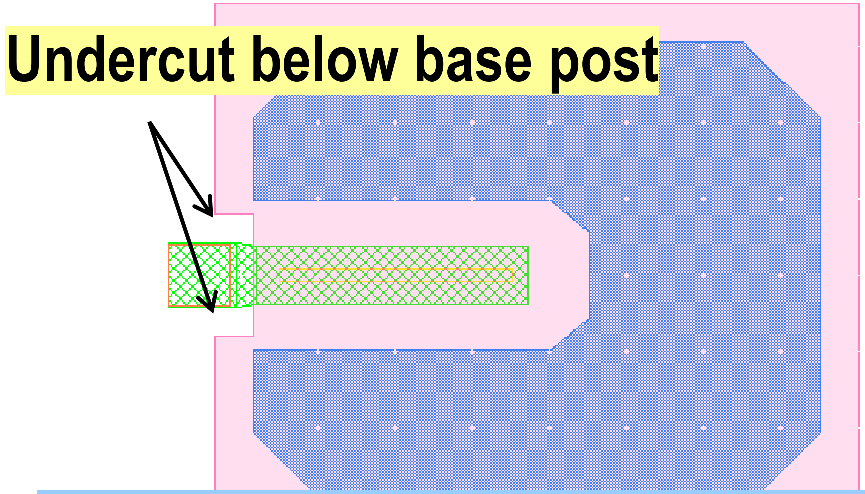
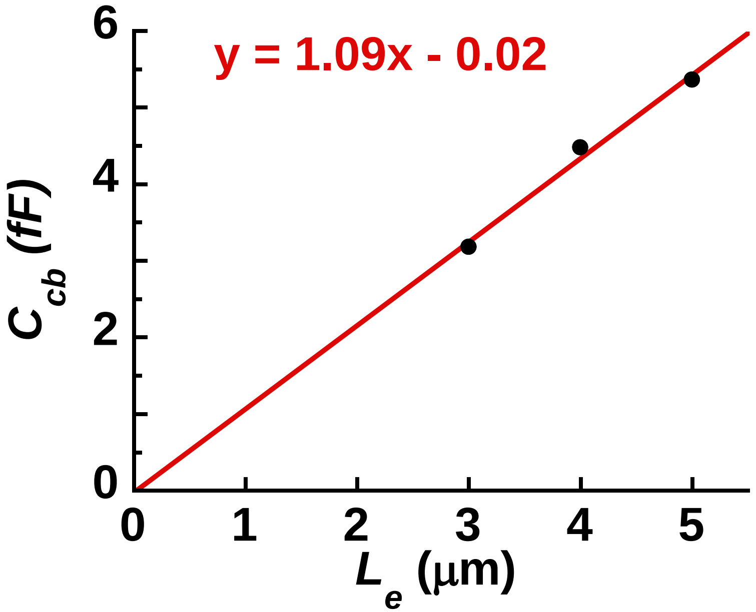
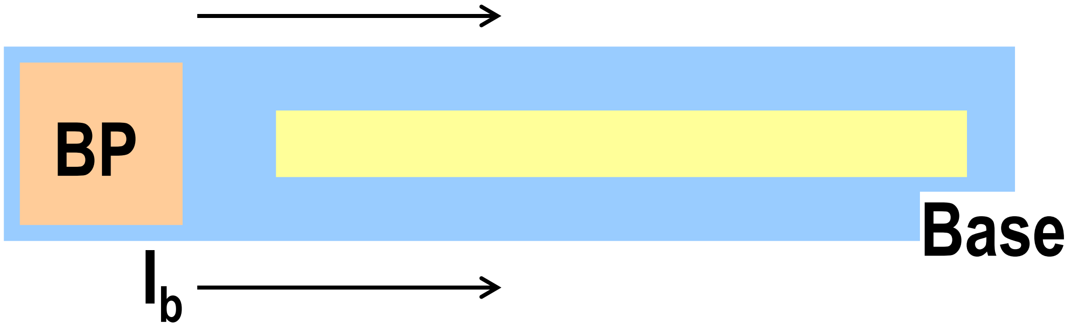




No contribution of Base post to C_{cb}

Base Metal Resistance

$$R_{bb,metal} = \rho_{\mathrm{sh,metal}} \cdot \frac{L_e}{6W_{bc}}$$

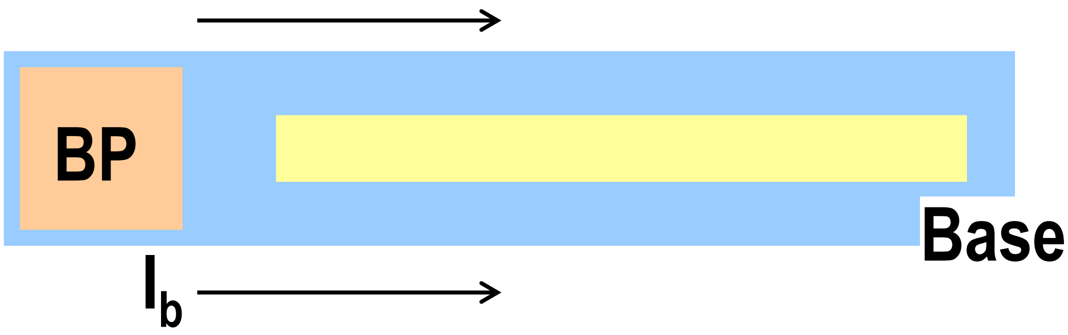


- $R_{bb,metal}$ increases with emitter length

→ $f_{\max}$ decreases with increase in emitter length

Base Metal Resistance

$$R_{bb,metal} = \rho_{\text{sh,metal}} \cdot \frac{L_e}{6W_{bc}}$$



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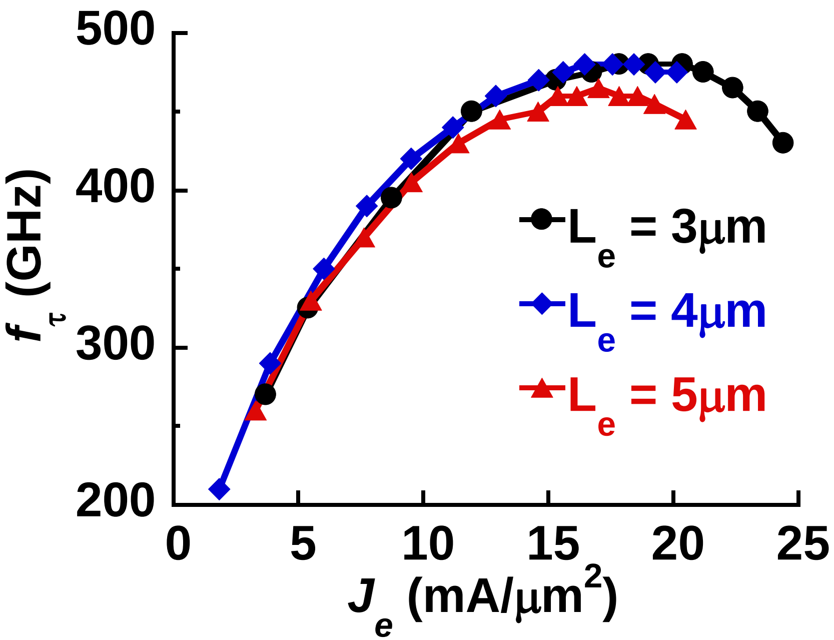
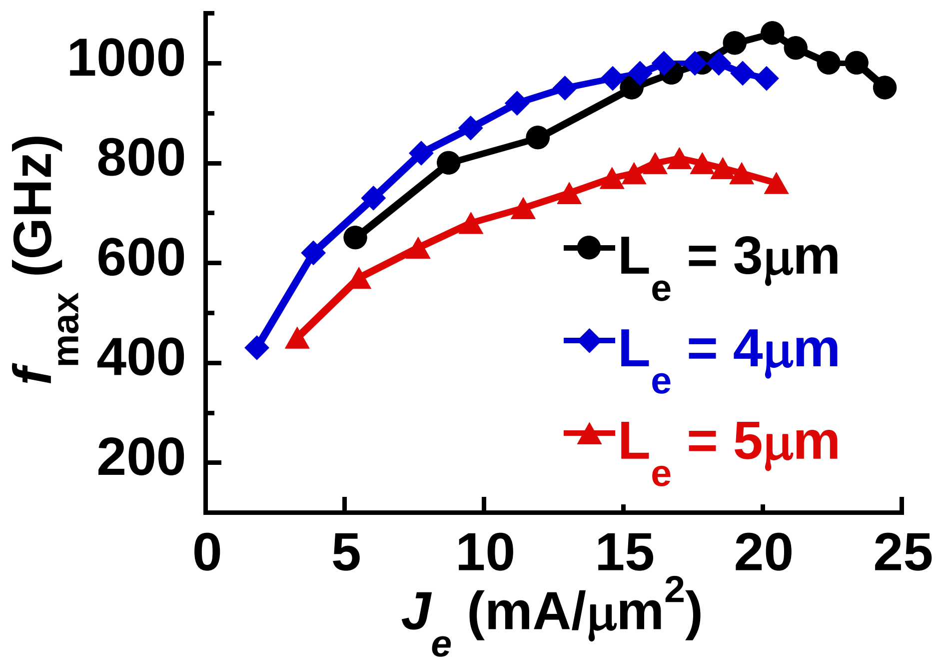
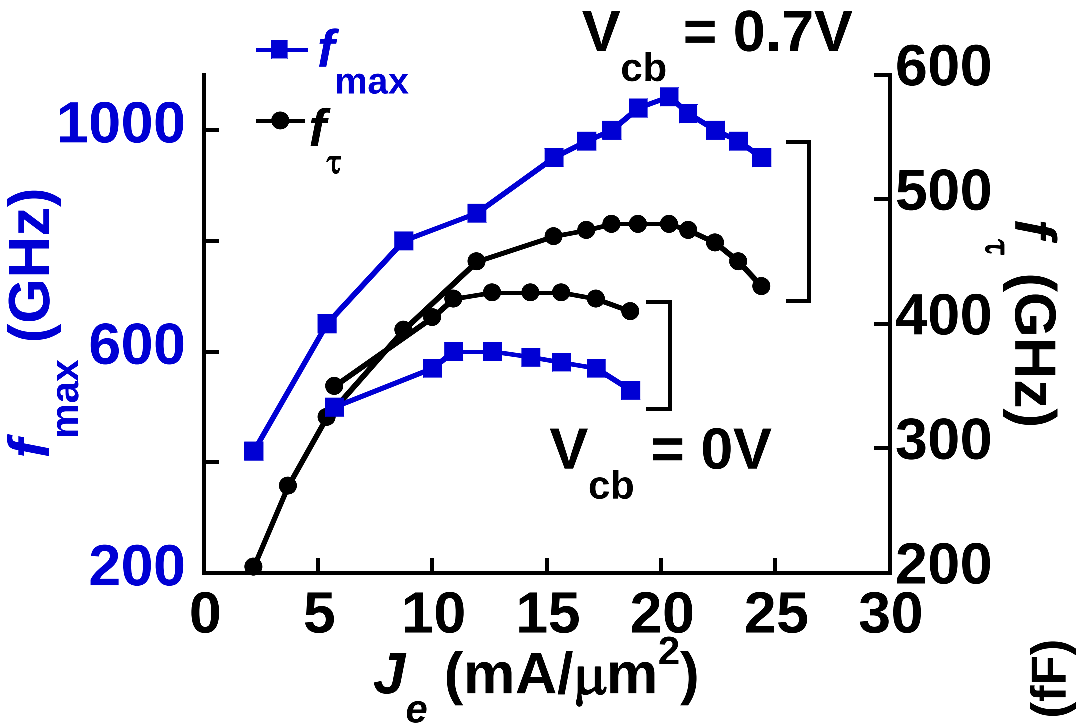
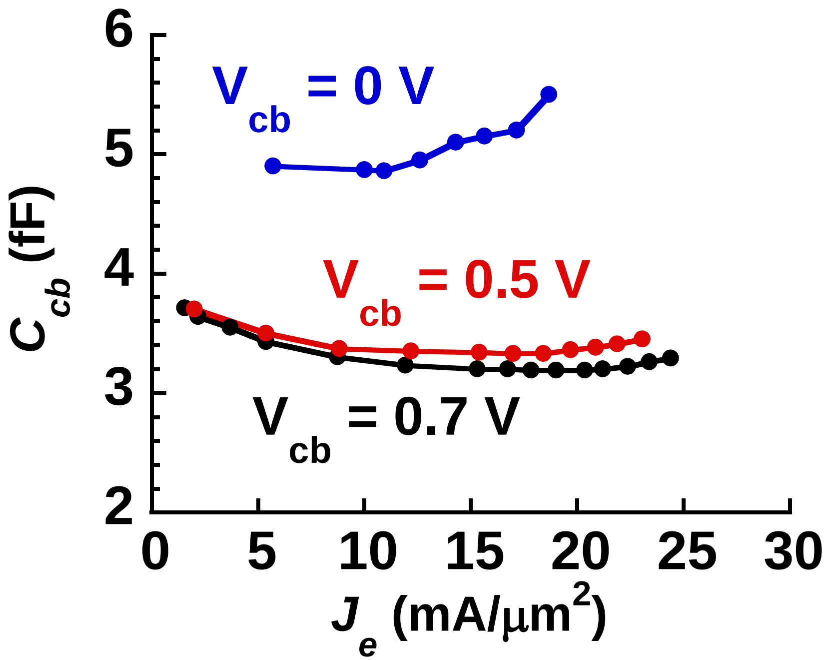




Parameter Extraction

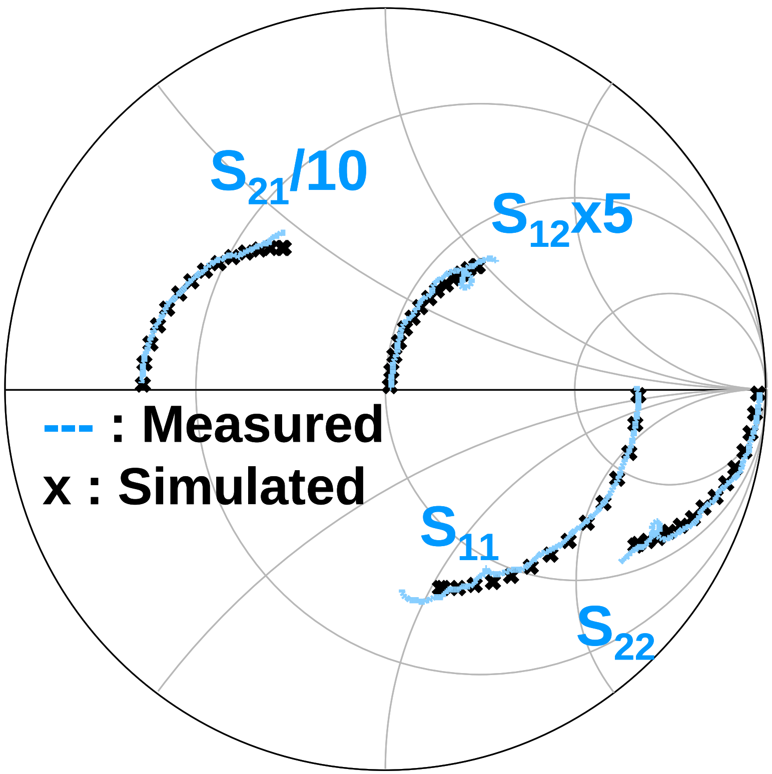


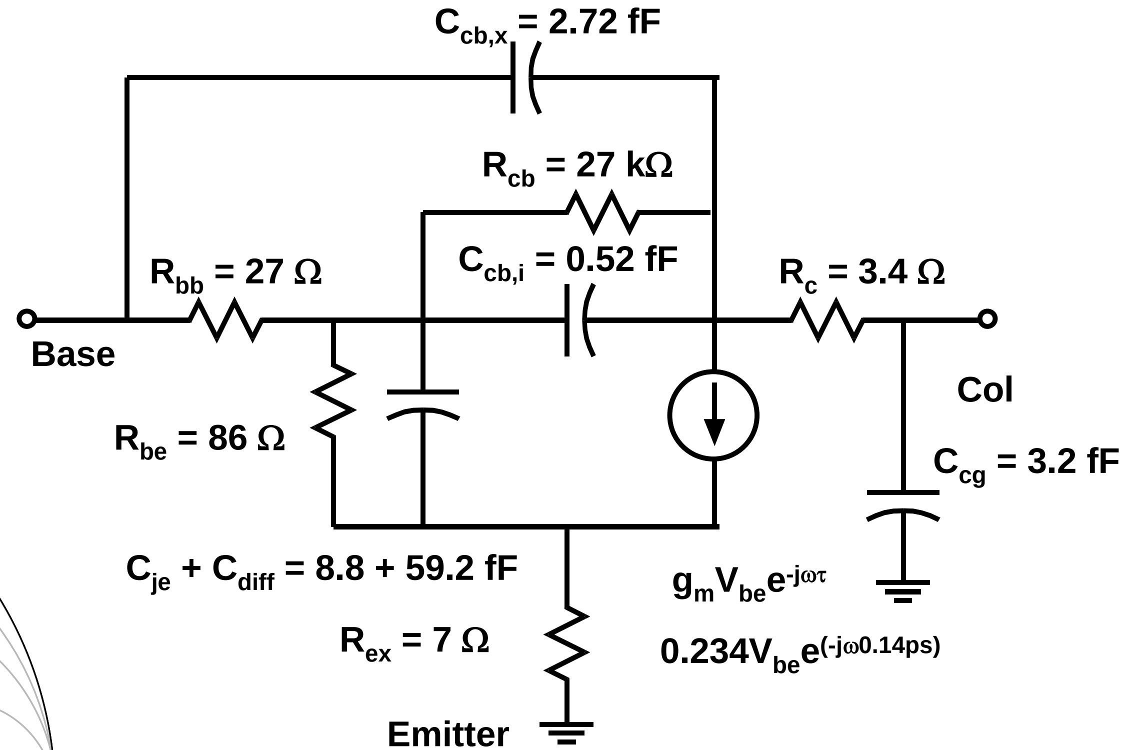


J_{kirk} = 23 mA/μm^2 (@V_{cb} = 0.7V)

Equivalent Circuit

R_{ex} ~ *4.2 Ω·μm²*

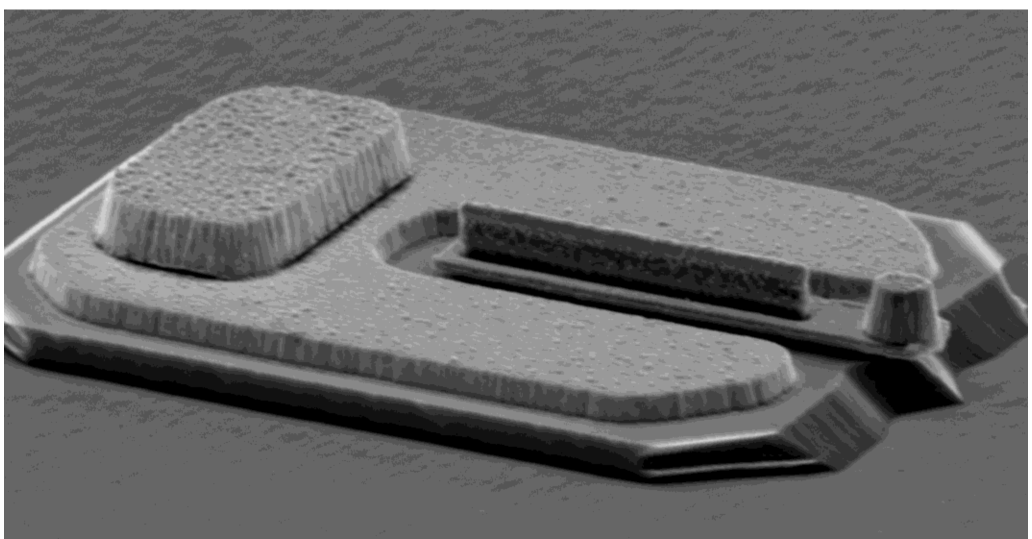


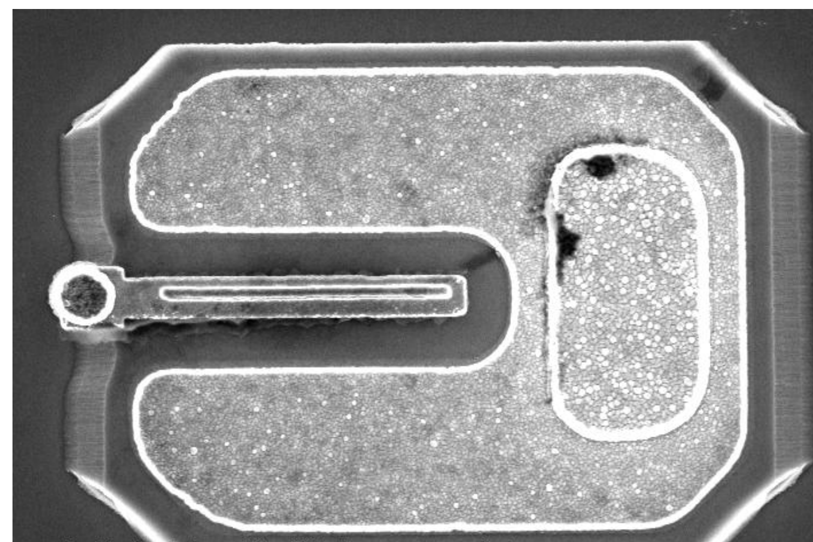


Hybrid-π equivalent circuit from measured RF data

Summary

- **Demonstrated DHBTs with peak f_τ / f_{max} = 480/1000 GHz**
- **Small W_{gap} for reduced base access resistance → High f_{max}**
- **Undercut below the base post to reduce C_{cb}**
- **Narrow sidewalls, smaller base mesa and better base ohmics** needed to enable higher bandwidth devices





Thank You

Questions?

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