InGaAs/InP DHBTs using MOCVD Selective Emitter Regrowth

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Outline

THz InP HBTs demonstrated

- *TSC* ***f_t/f_{max} 525/1150 GHz*** *– Urteaga et. al; DRC, 2011*
- *UCSB* ***f_t/f_{max} 480/1070 GHz*** *– Rode et. al; TED, 2015*

Challenges for next generation

- **Low base contact resistivity**
- **Drop in current gain with emitter scaling**

Propose MOCVD Emitter Regrowth

- **Good base contact resistivity**
- **Demonstrate moderate current gain**

InP bipolar transistor scaling roadmap

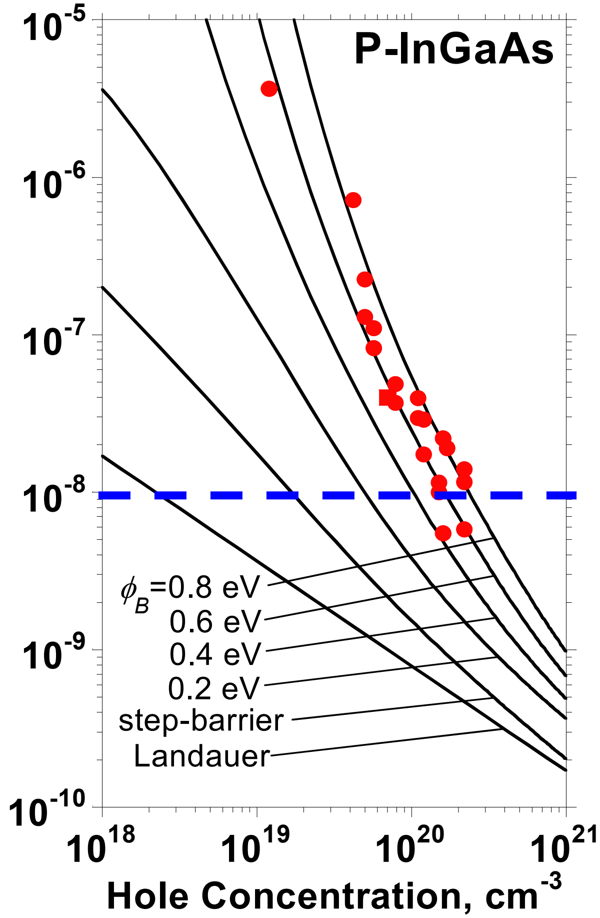
Design	Emitter	*256*	*128*	*64*	*32*	Width (nm)
		8	4	2	1	Access ρ ($\Omega \cdot \mu m^2$)
	Base	175	120	60	30	Contact width (nm)
		10	5	2.5	1.25	Contact ρ ($\Omega \cdot \mu m^2$)
	Collector	106	75	53	37.5	Thickness (nm)
Performance	Current density	9	18	36	72	$mA/\mu m^2$
	Breakdown voltage	4	3.3	2.75	2-2.5	V
	f_τ	*520*	*730*	*1000*	*1400*	GHz
	f_{max}	*850*	*1300*	*2000*	*2800*	GHz

Need for better base contacts!

Rodwell, Le, Brar, Proceedings of IEEE, 2008

Refractory Contacts to In(Ga)As

Baraskar *et al*, Journal of Applied Physics, 2013

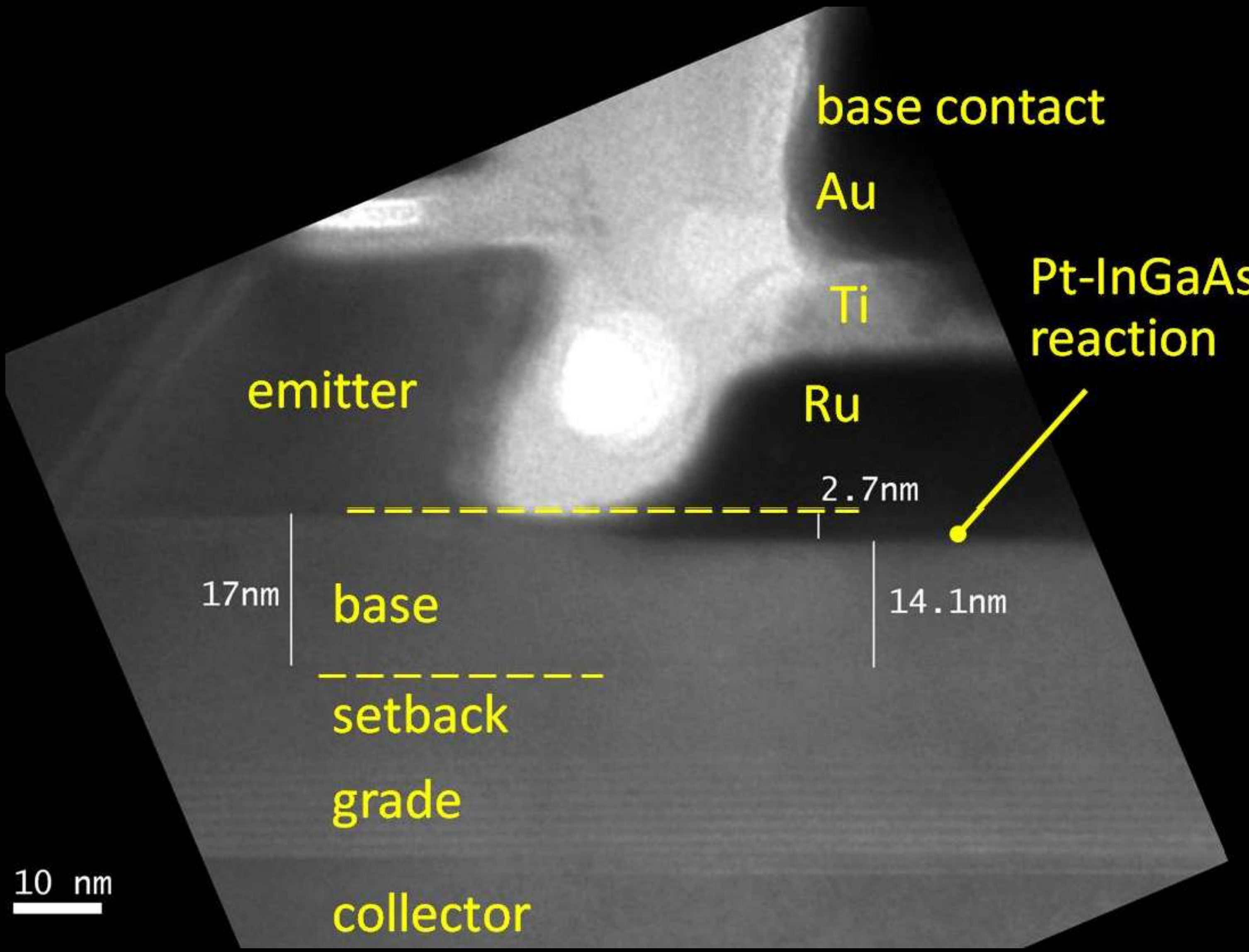


requirements
for 3 THz HBTs,
7nm III-V CMOS

Refractory: robust under high-current operation / Low penetration depth: ~ 1 nm / Performance sufficient for 32 nm /2.8 THz node.

Problem – Reproducing data on HBT process flow

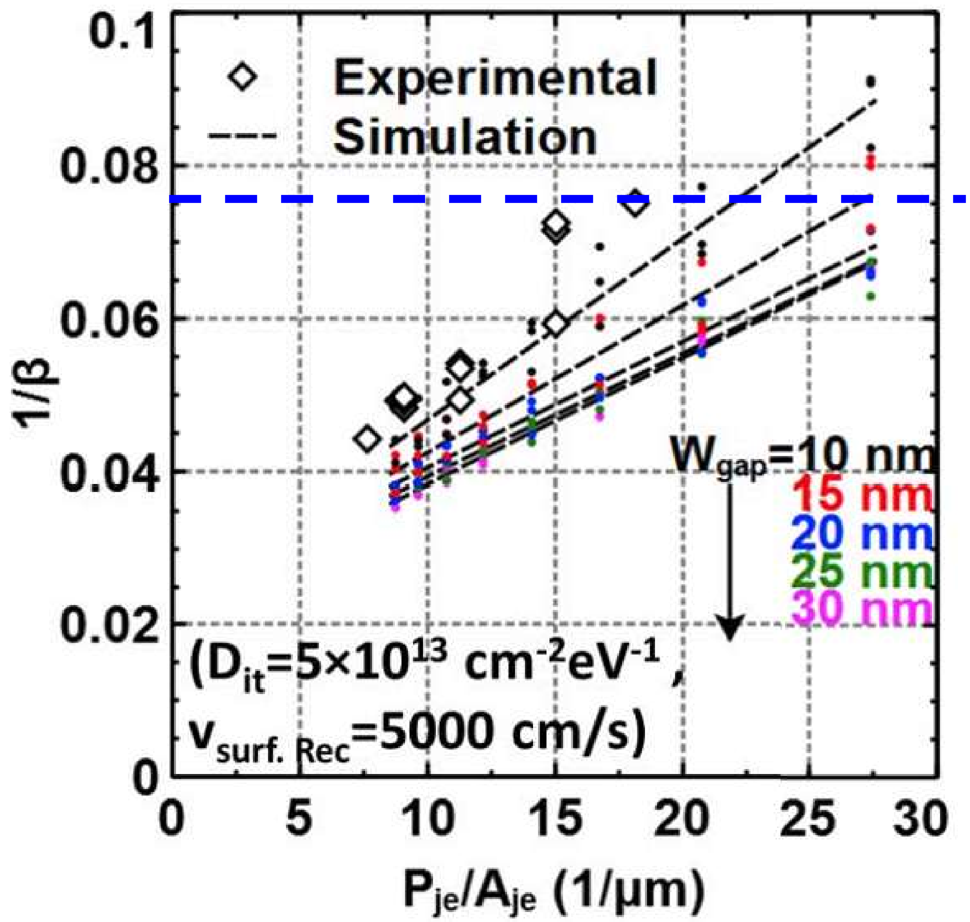
Blanket Base Metal Process



Partial solution
Need something better!

Current gain (β) drops with scaling

H.W. Chiang *et al*, DRC, 2014



β = 15 @ 120nm Emitter width

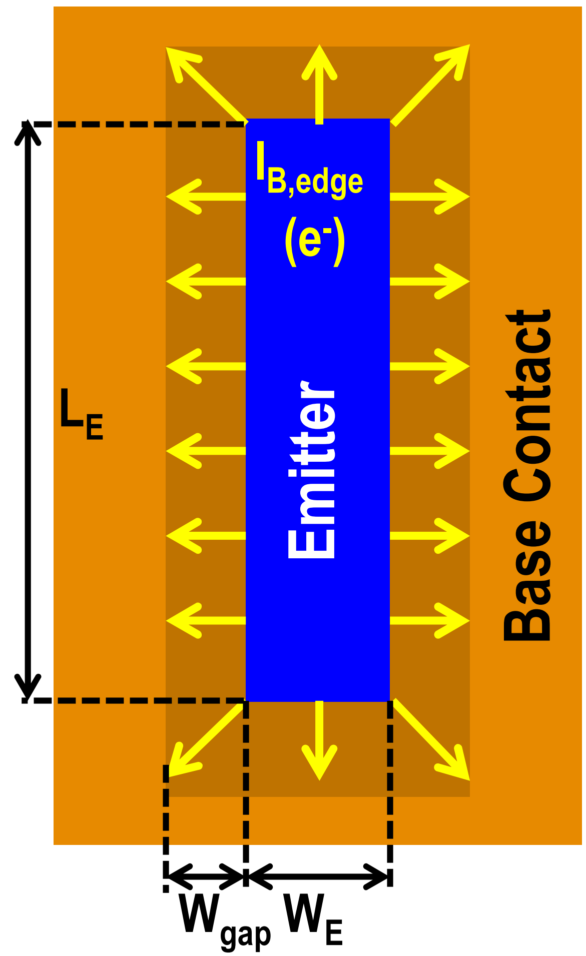
Need higher β for PA, DAC, Mixers …

Causes of Low β

Lateral Diffusion (bulk and surface)

- $I_{B,edge}$ α $1/W_E$

BE diode, top-down view



Causes of Low β

Lateral Diffusion (bulk and surface)

- $I_{B,edge} \propto 1/W_E$

High base doping (N_A)

- High Auger recombination

- **RF HBTs need**
  - **Small emitter width - β_{edge} decreases**
  - **High base doping - β_{bulk} decreases**

Need to increase β

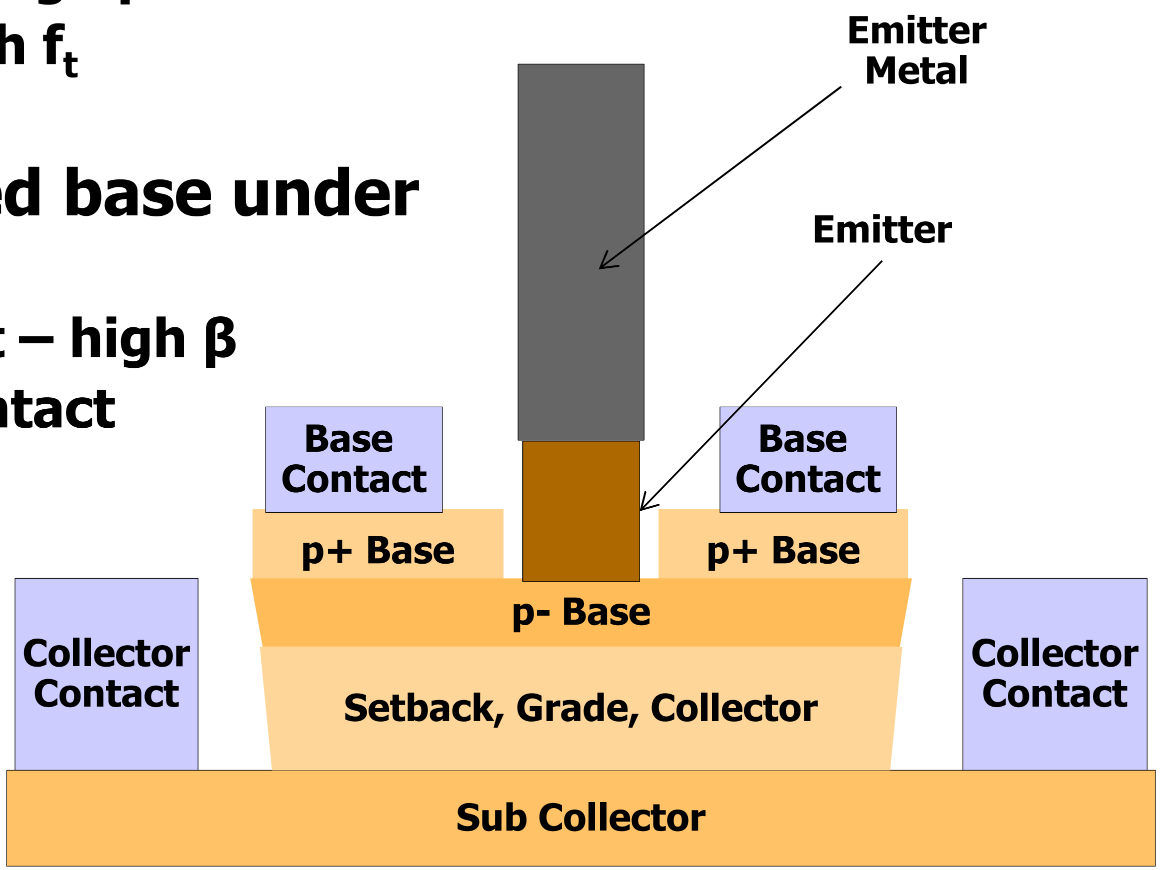
Improving HBT Base Design

Thin, lightly doped base under emitter

- Low recombination – high β
- Low transit time – high f_t

Thick, heavily doped base under base contact

- Repels e^- from contact – high β
- Allows ~5nm base contact metal penetration



Possible via MOCVD Emitter Regrowth

MOCVD Emitter Regrowth

Is it feasible?

MOCVD Regrowth - Issues

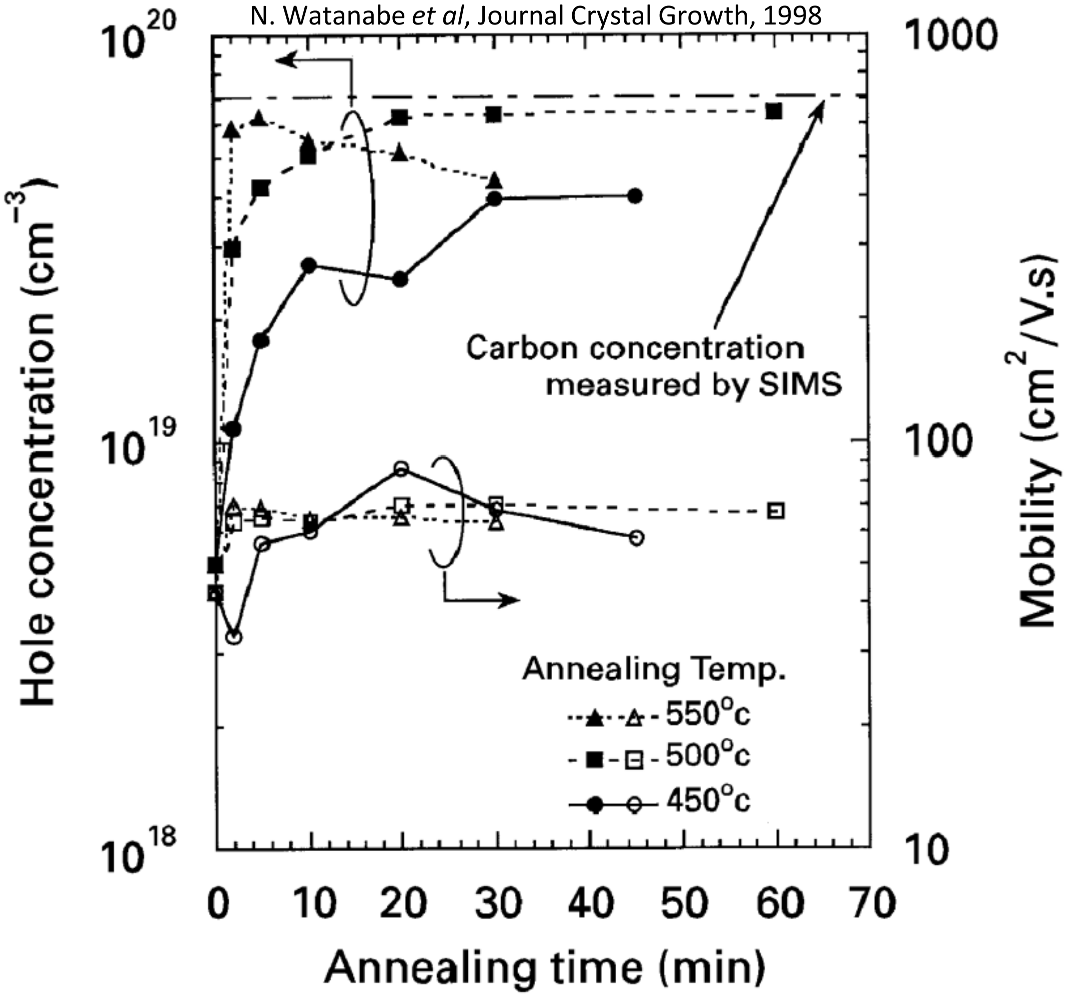
- MOCVD introduces H^+
  - Passivates p-InGaAs carbon doping
  - Can the carbon be reactivated?

- Good base contacts with emitter regrowth?

p-InGaAs Carbon Reactivation

H^+ passivates carbon p-dopant in InGaAs base

N. Watanabe *et al*, Journal Crystal Growth, 1998



Annealing reactivates C dopants

p-InGaAs Carbon Reactivation - Partial

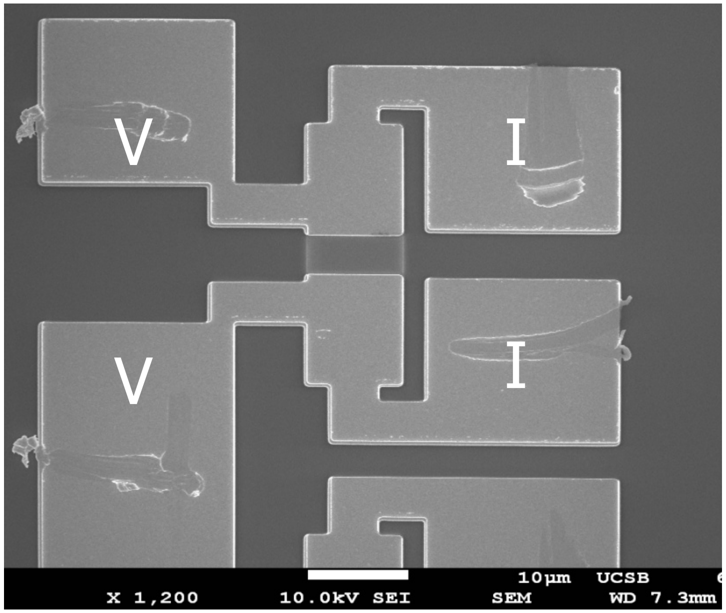
Limited success so far

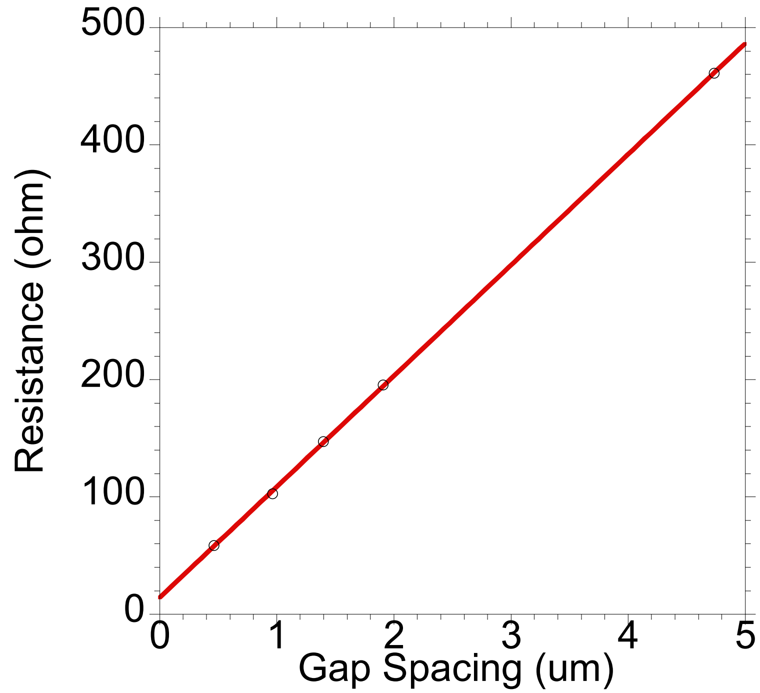
*All samples annealed with oxide cap ** Hall Measurement

Sample prep	***Anneal condition @ 500°C***	*****Carrier Concentration (before regrowth) ($10^{19} cm^{-3}$)***	*****Carrier Concentration (after regrowth) ($10^{19} cm^{-3}$)***
p-InGaAs->regrow n-InP ->etch InP	No anneal	10	**0.7**
p-InGaAs->regrow n-InP ->etch InP	20min, N_2	10	**5.5**
p-InGaAs->NO regrowth	20min, N_2	10	**5.5**

The anneal lowers p-doping by 45%!

Good p-InGaAs Contacts With Emitter Regrowth



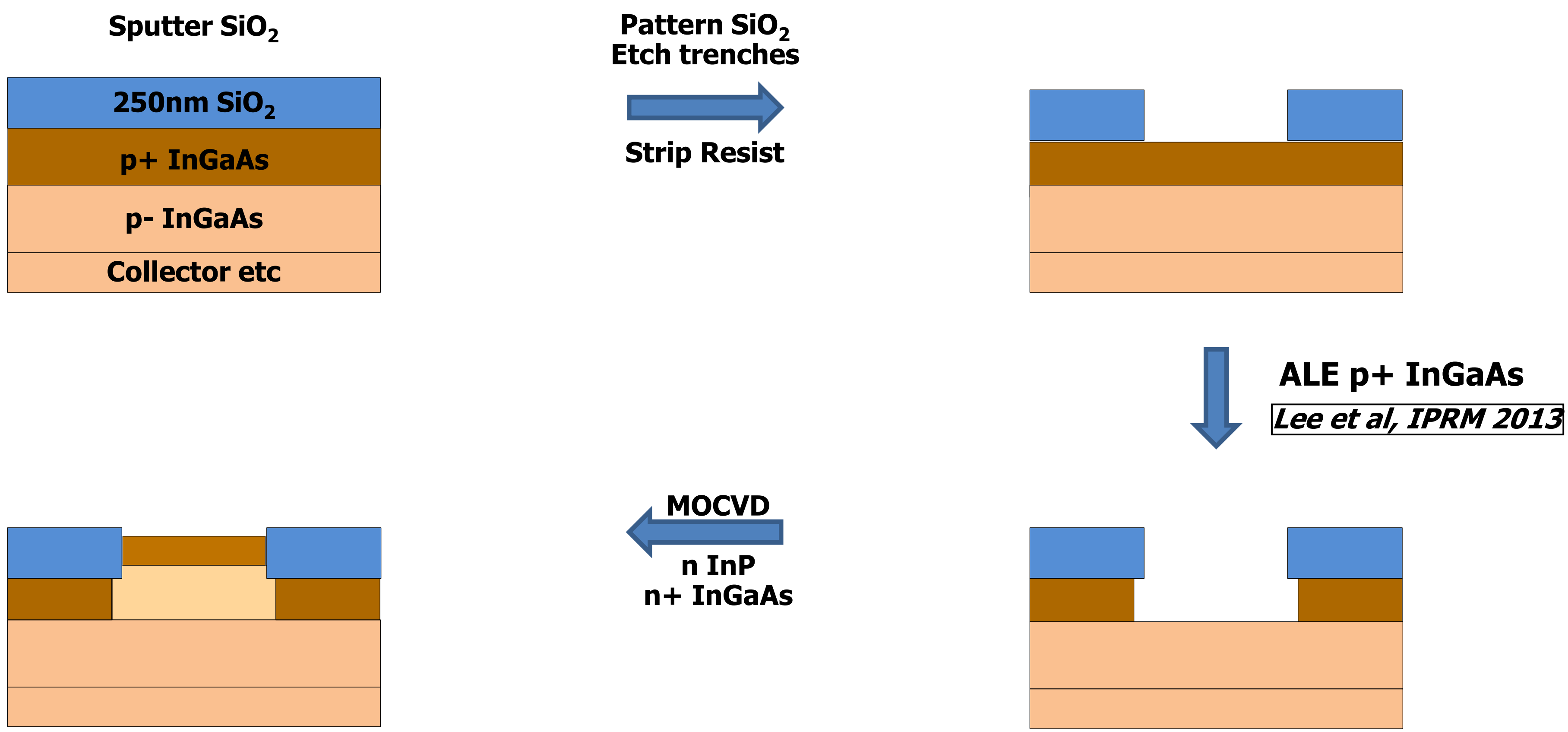


p-InGaAs doping before RG ($10^{19}/cm^3$)	*RG*	*RG Mask*	*Anneal Temp (^oC)*	*Contact Metal*	*Contact Resistivity ($\Omega.um^2$)*
10	N	–	–	W/Ti/Au	**2.9**
10	Y	W/SiO_2	500	W/Ti/Au	**5.47**

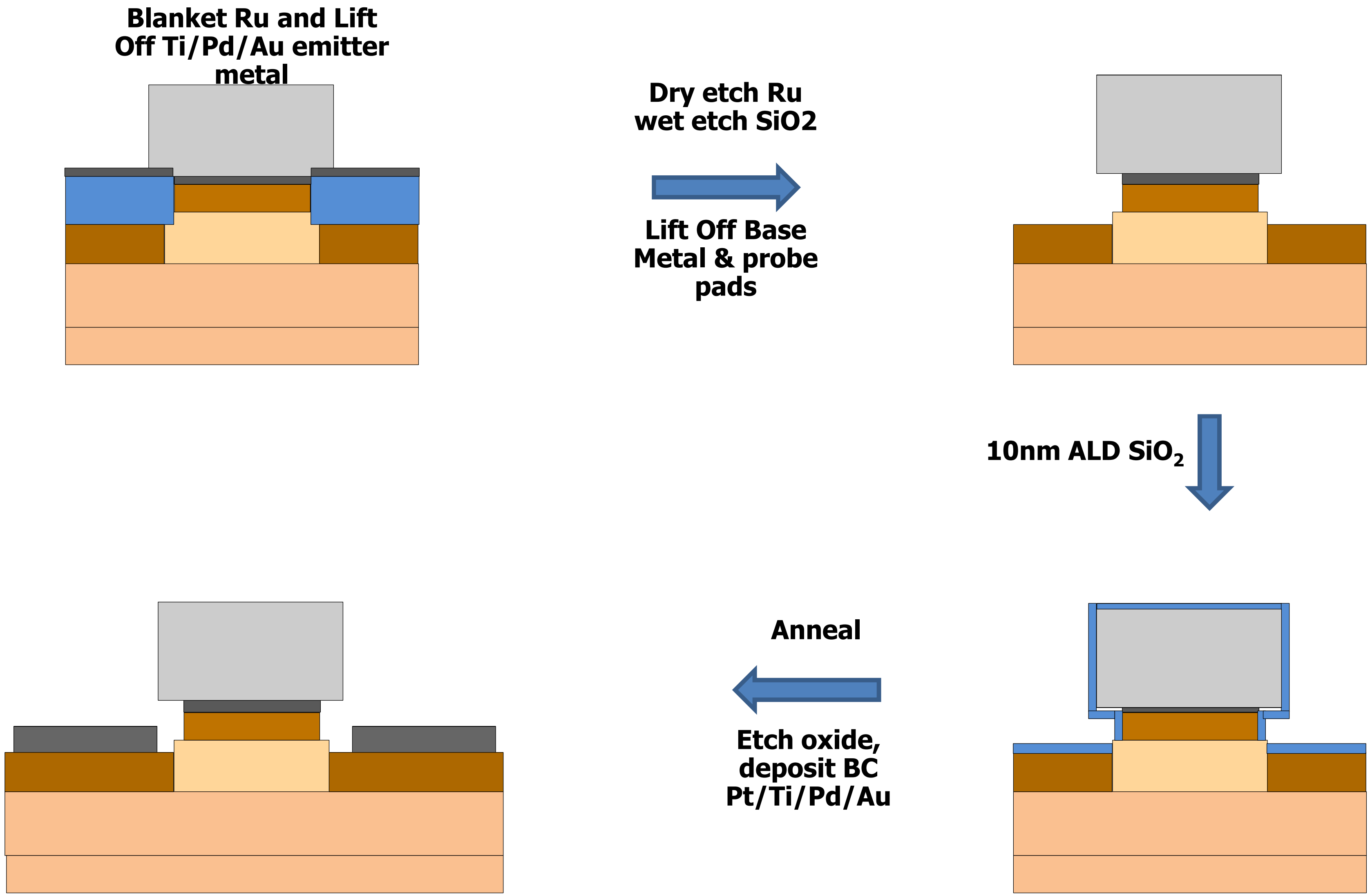
Base contacts sufficient for 100nm Emitter width

Emitter Regrowth Large Area Devices (LAD)

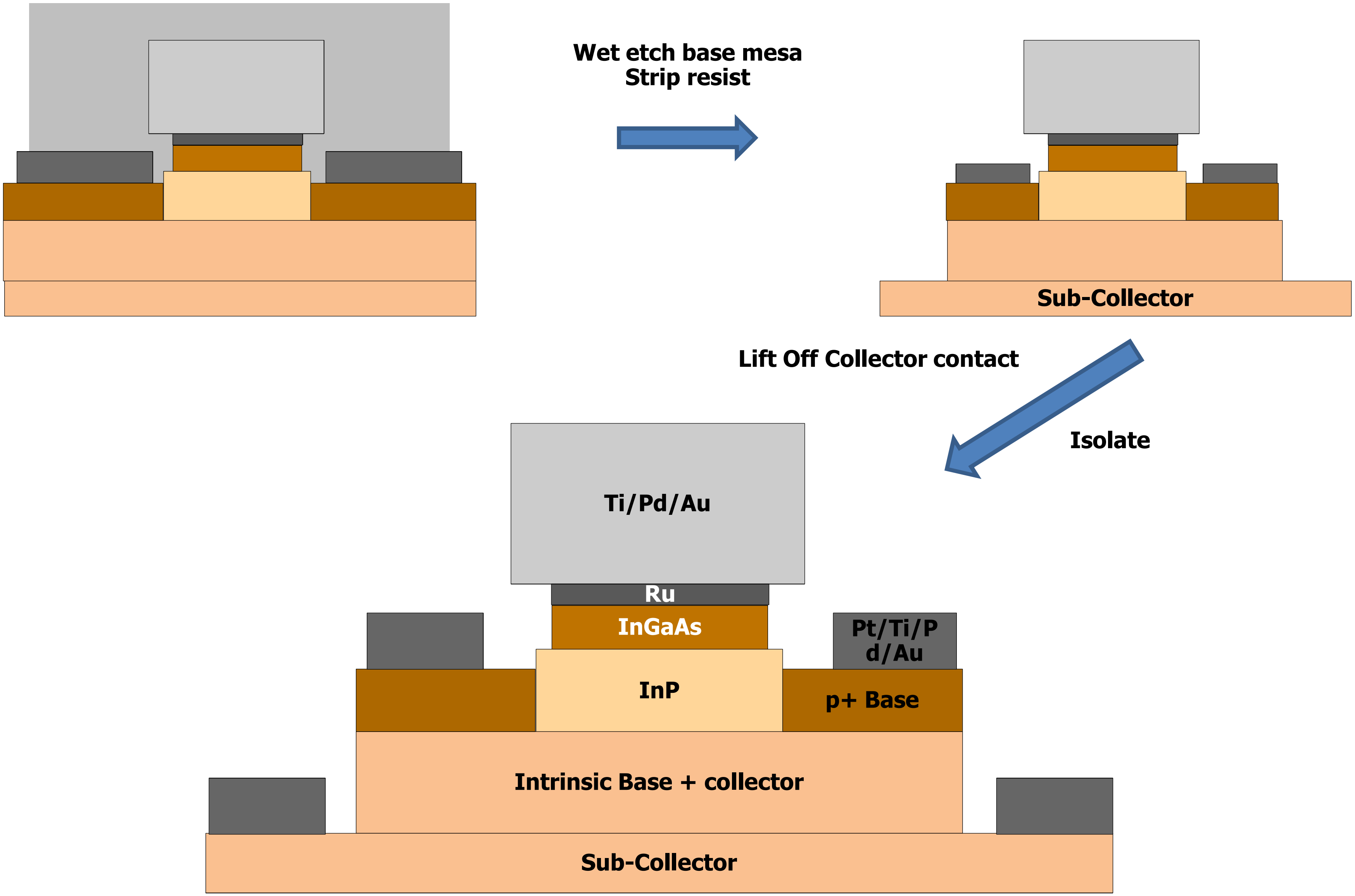
Process Flow



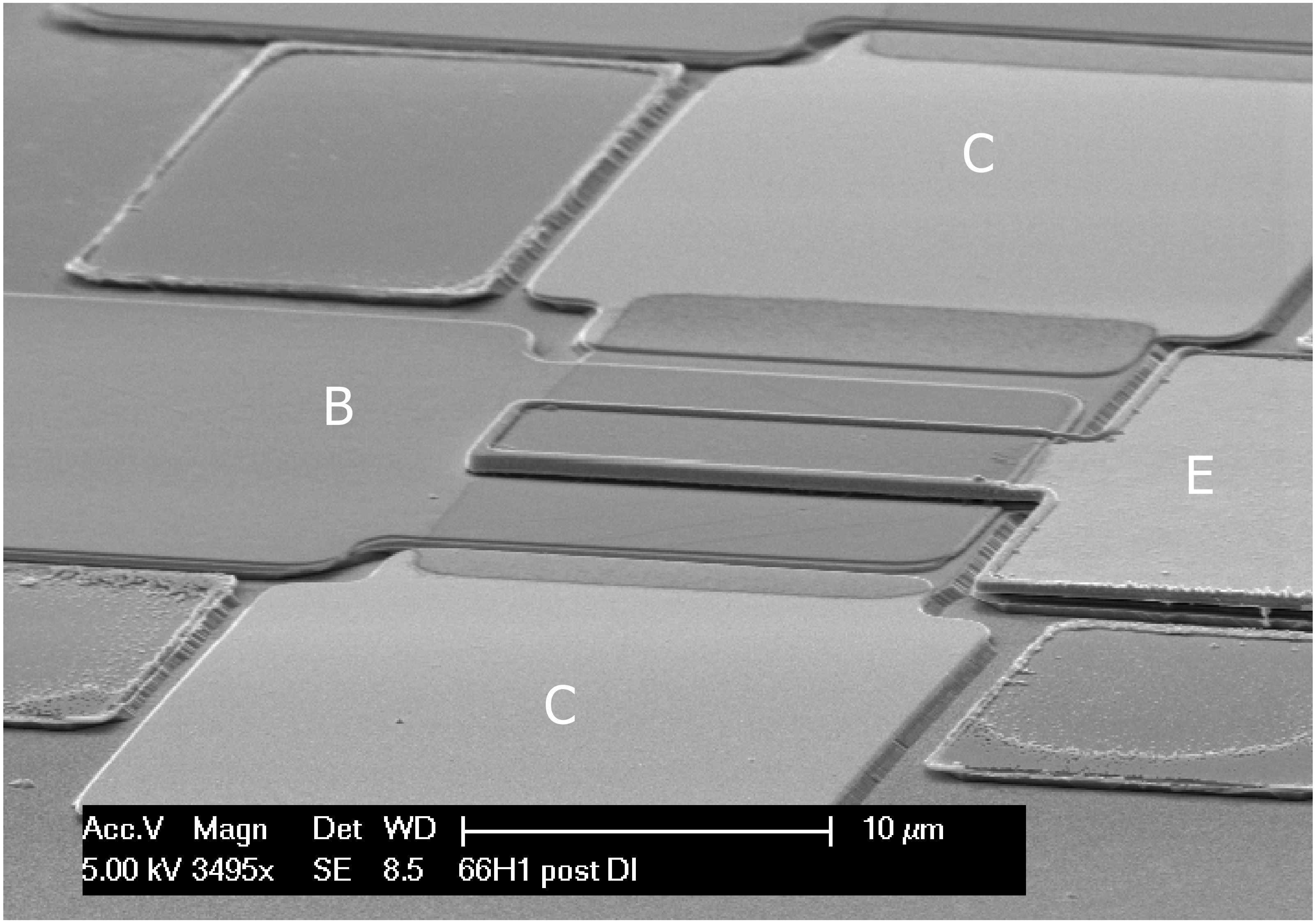
Process Flow



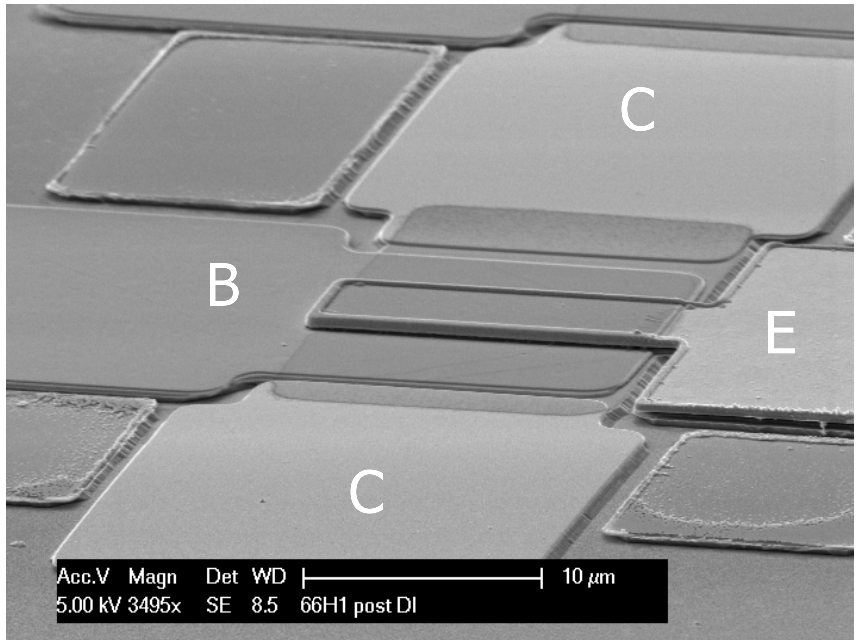
Process Flow

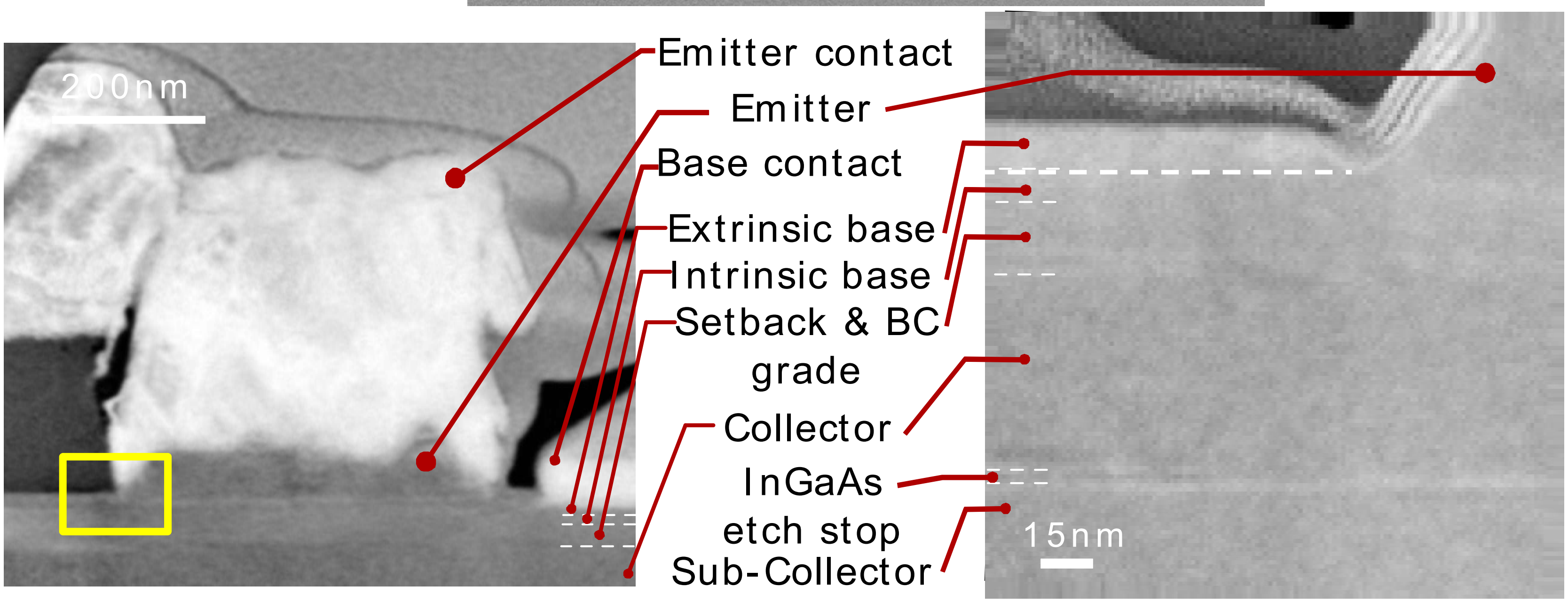


Regrowth LAD



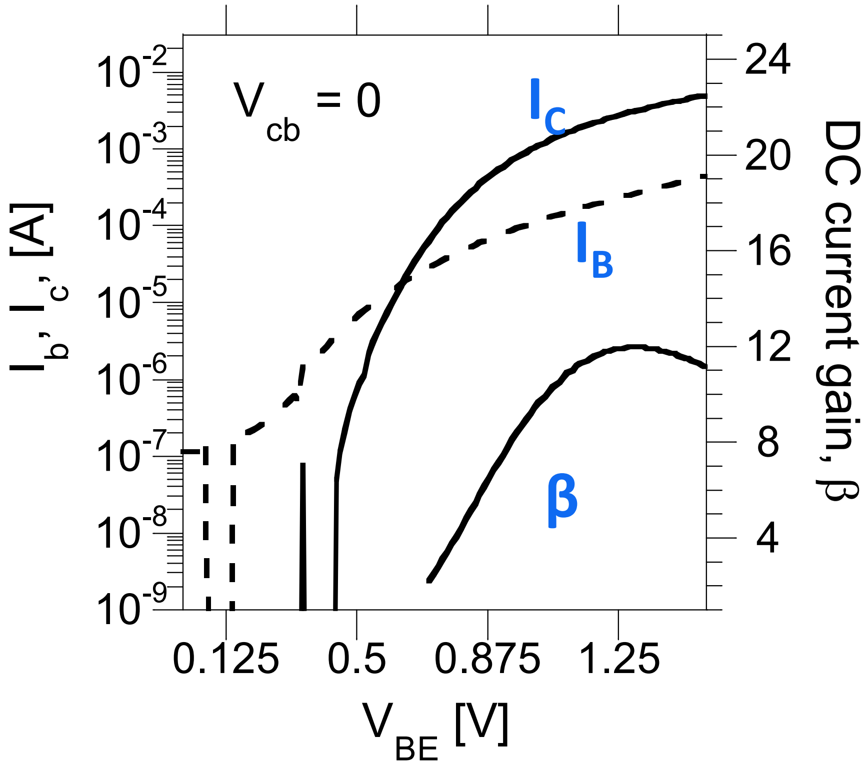
Regrowth LAD





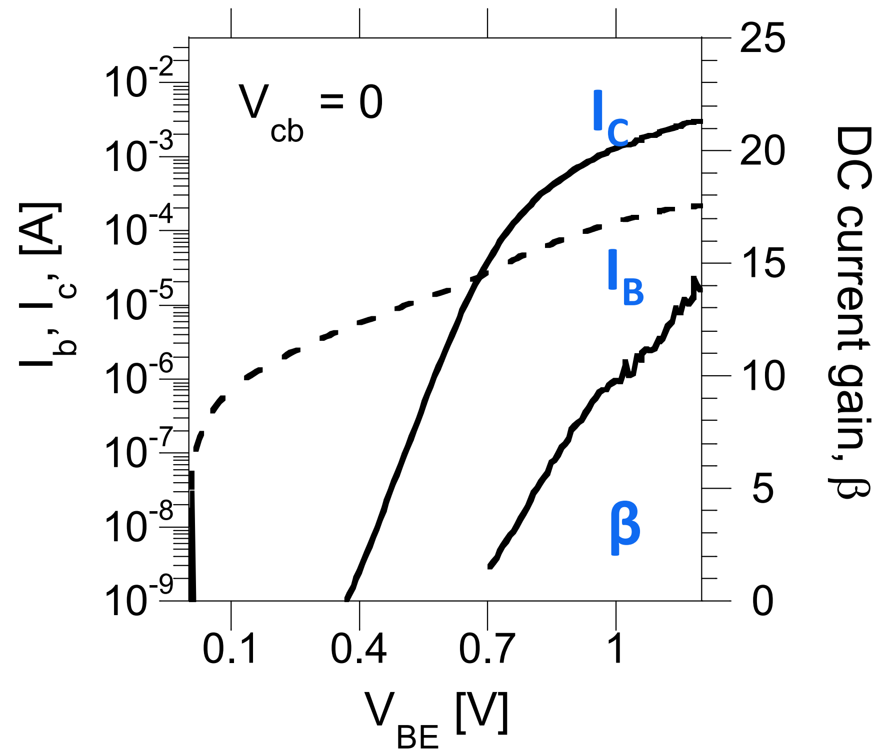
Emitter Regrowth – Initial Results

Regrown emitter



A_E = 0.4 um^2

No regrowth



A_E = 0.4 um^2

Regrown transistors show moderate gain

Emitter Regrowth – Current Issues

- Large BC leakage

- Cannot measure common emitter

- High base sheet resistance after anneal

Base doping before RG (10^{19} cm^{-3})	**Sheet Resistance (Ω/sq)**	**Sheet Resistance after RG(Ω/sq)**
9-5	1250	2392

Incomplete p-InGaAs C reactivation

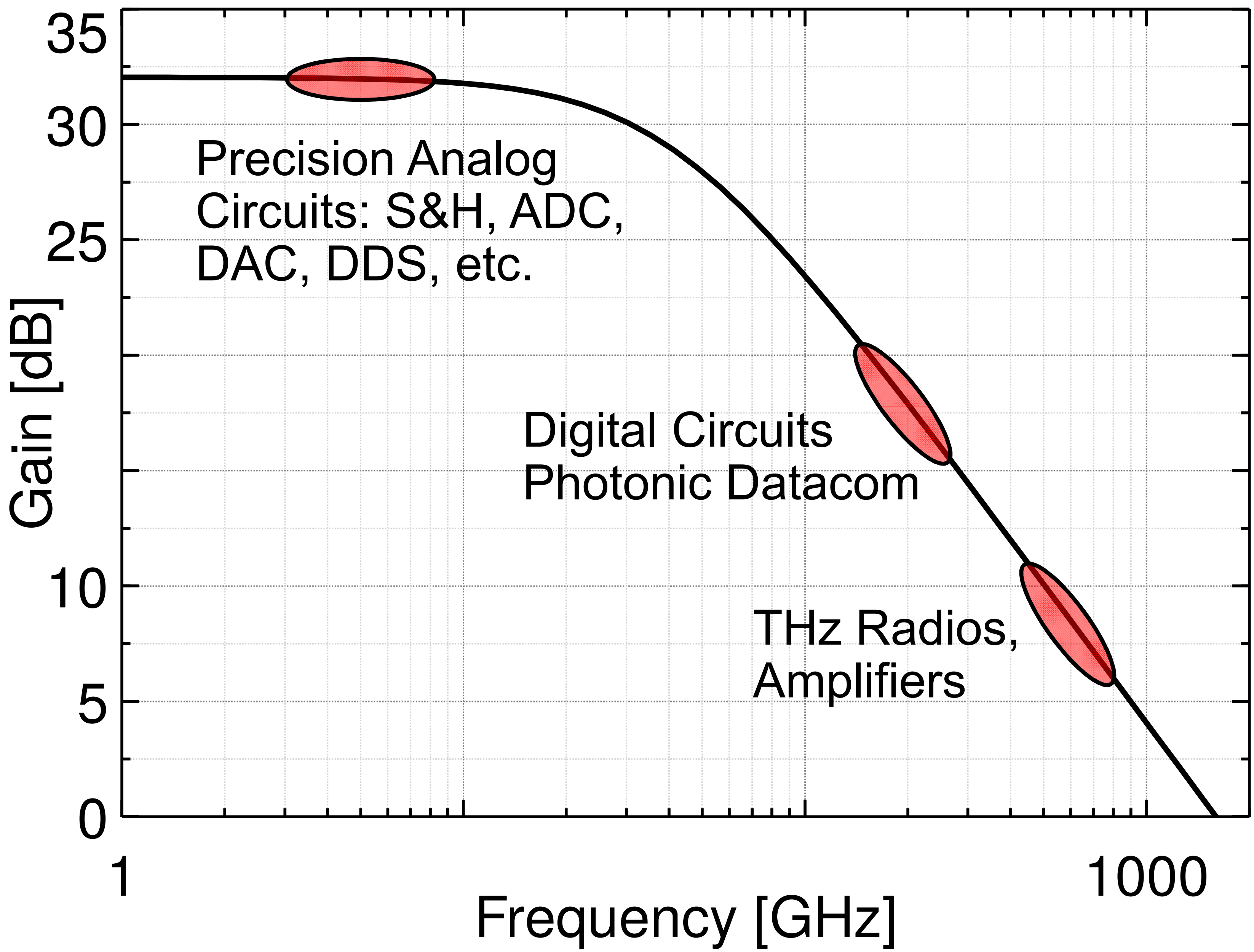
Summary

- Emitter regrowth is feasible
  - partial p-InGaAs carbon reactivation shown
  - contact resistivity sufficient for 100nm node
- Low base doping affecting device performance
- Future work
  - higher base doping
  - regrowth with W/SiO_2 mask
  - scaling emitter width/thicker base

Thank You

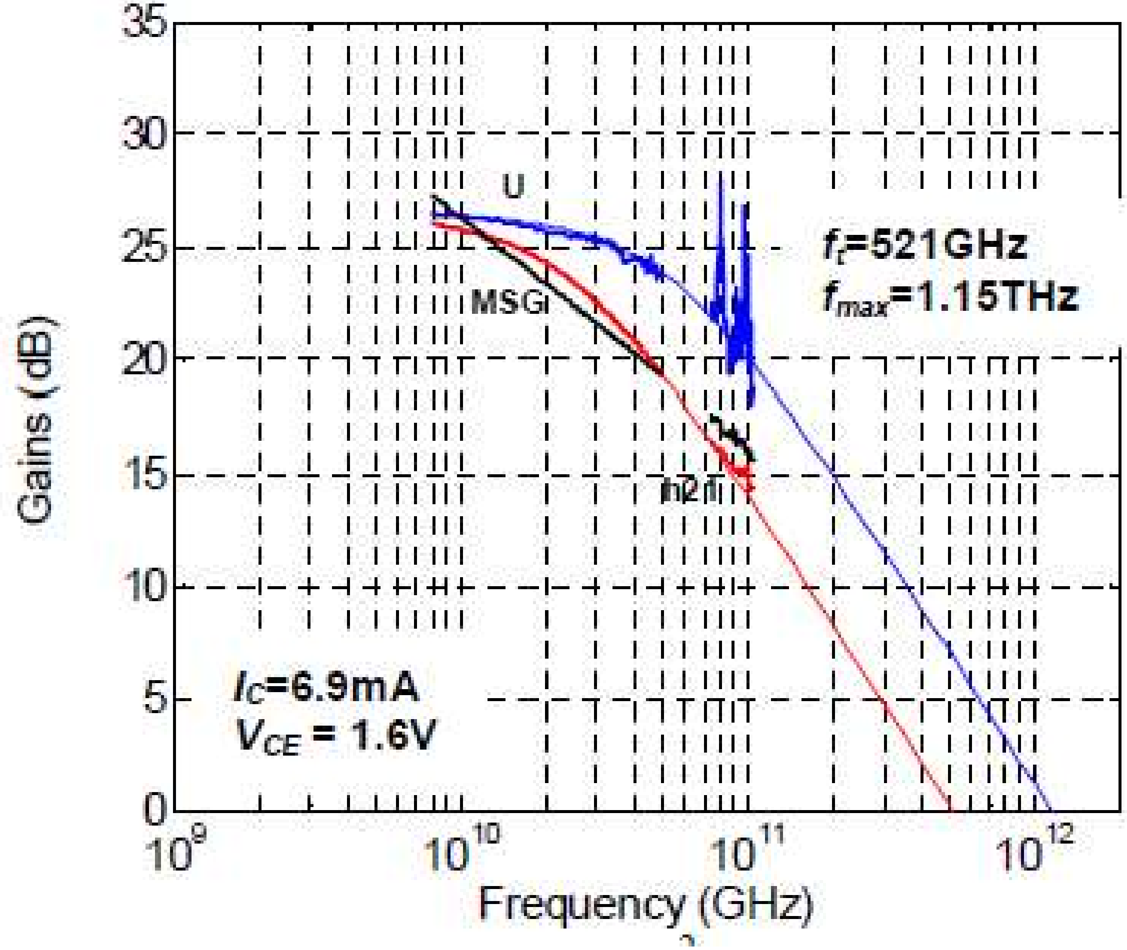
Backup

THz Transistors



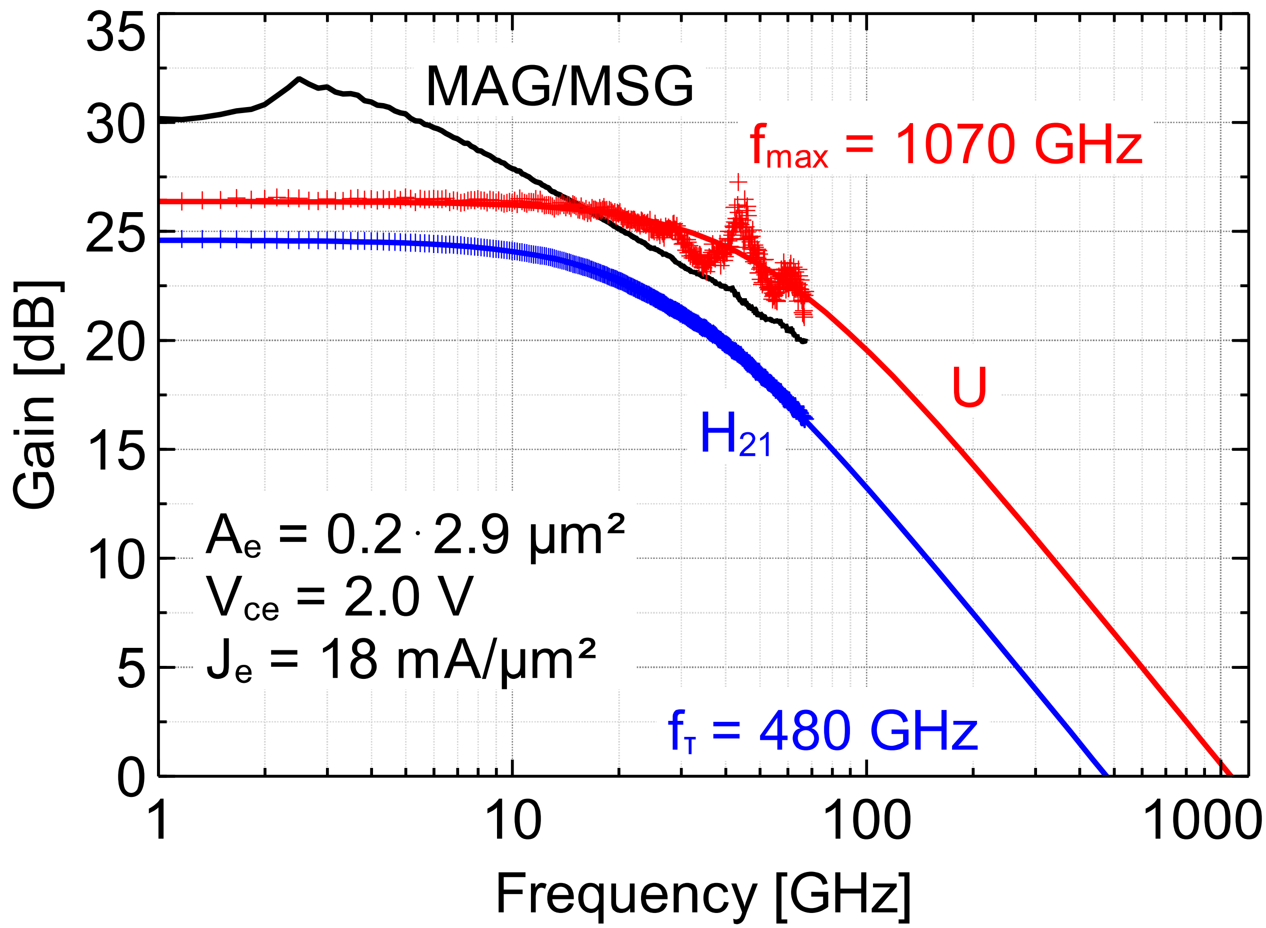
THz InP HBTs: Performance @ 130 nm Node

Teledyne: M. Urteaga *et al*: 2011 DRC



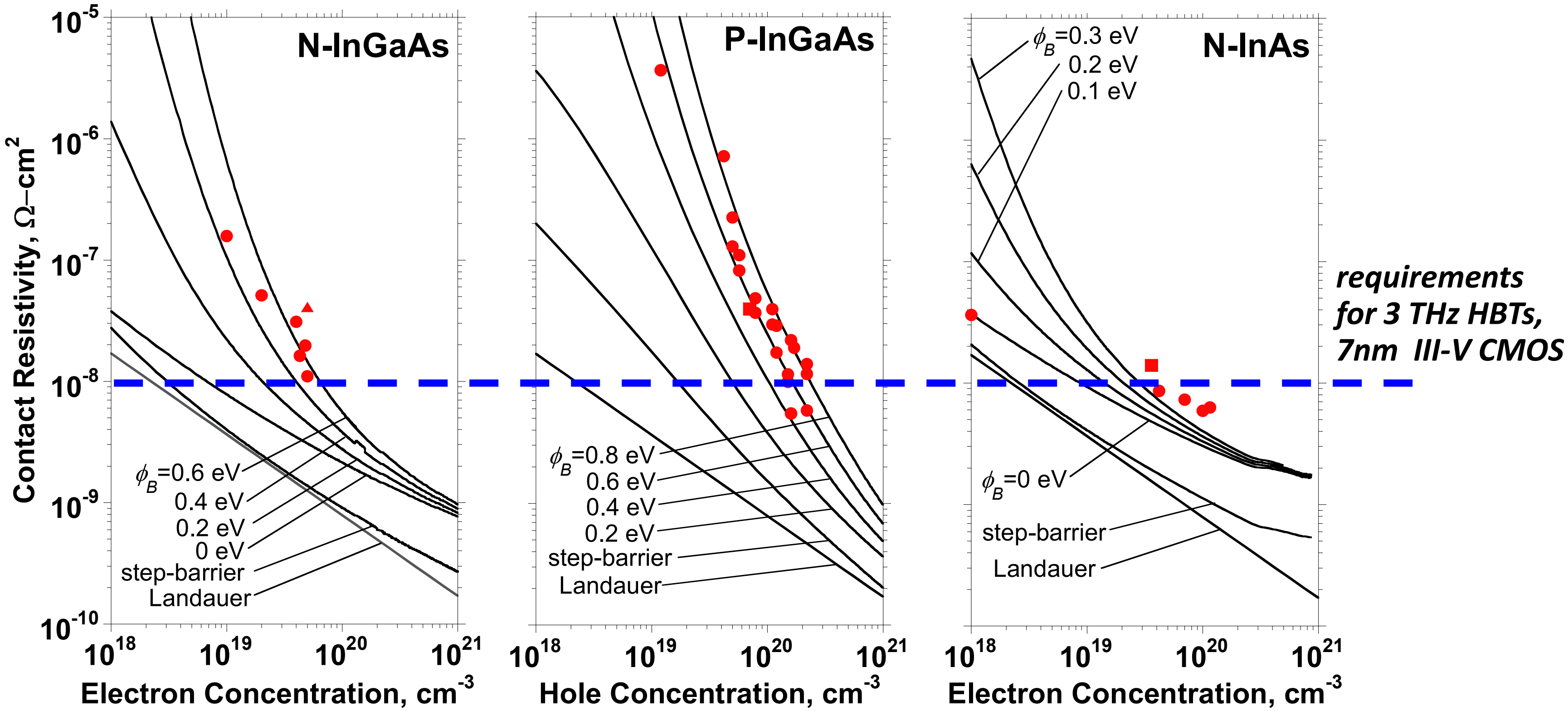
THz InP HBTs: Performance @ 130 nm Node

UCSB: J. Rode *et al*: 2015 IEEE TED



Refractory Contacts to In(Ga)As

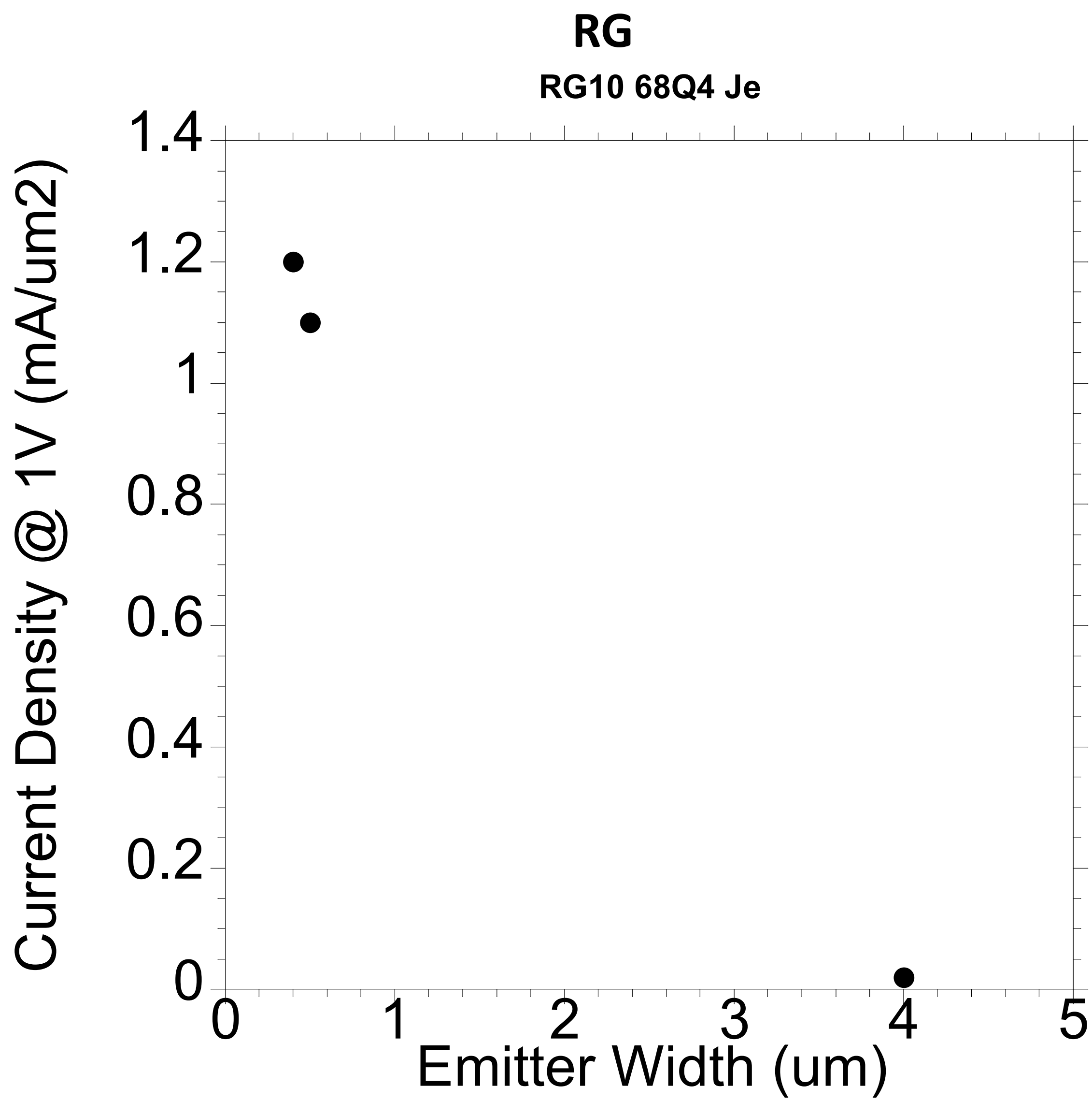
Baraskar *et al*, Journal of Applied Physics, 2013



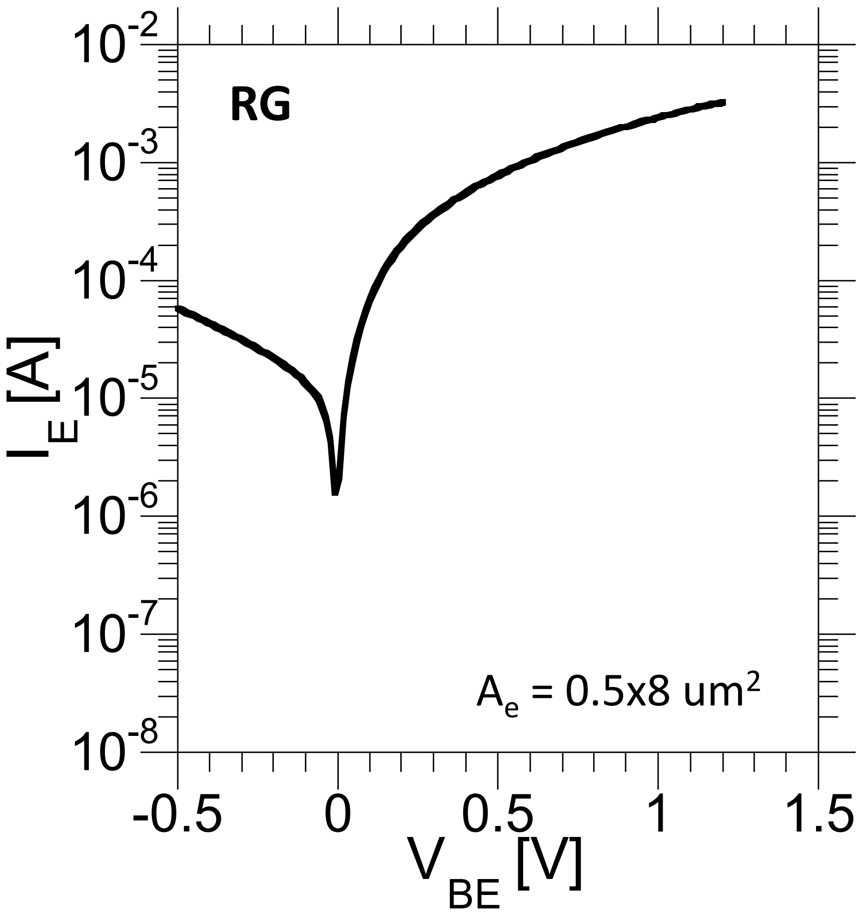
Refractory: robust under high-current operation / Low penetration depth: ~ 1 nm / Performance sufficient for 32 nm /2.8 THz node.

Problem – Reproducing data on HBT process flow

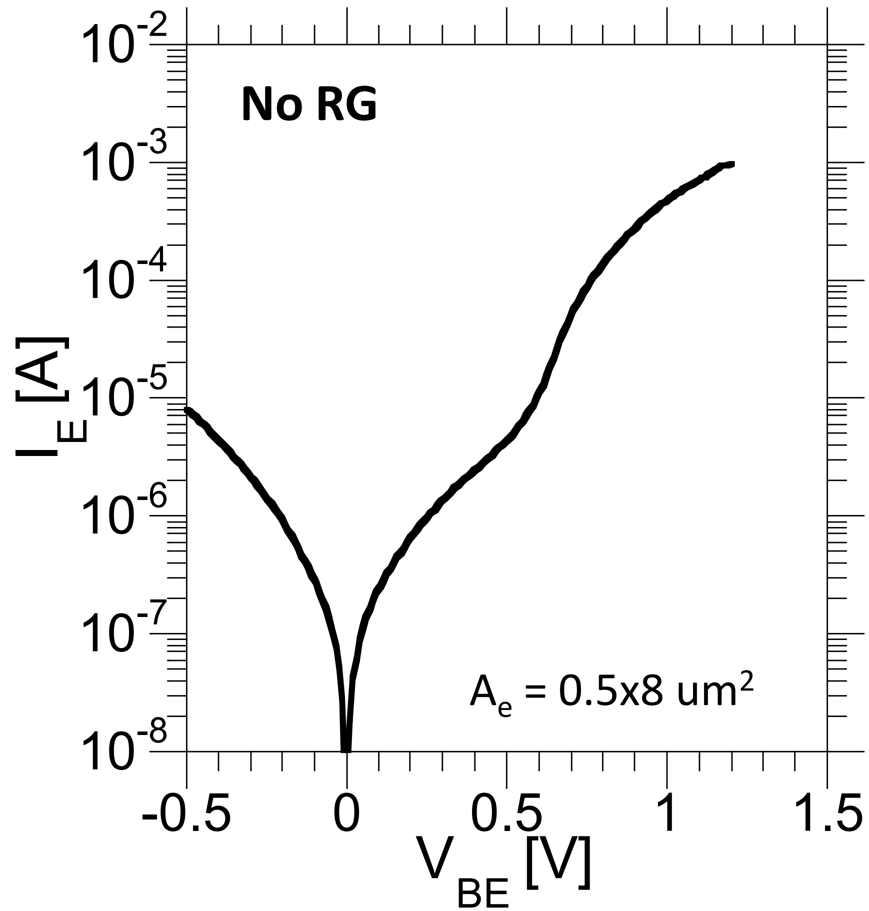
LAD – Current crowding due to high R_{bb}



LAD – B-E diode



R_{ser} = 21 Ω/μm

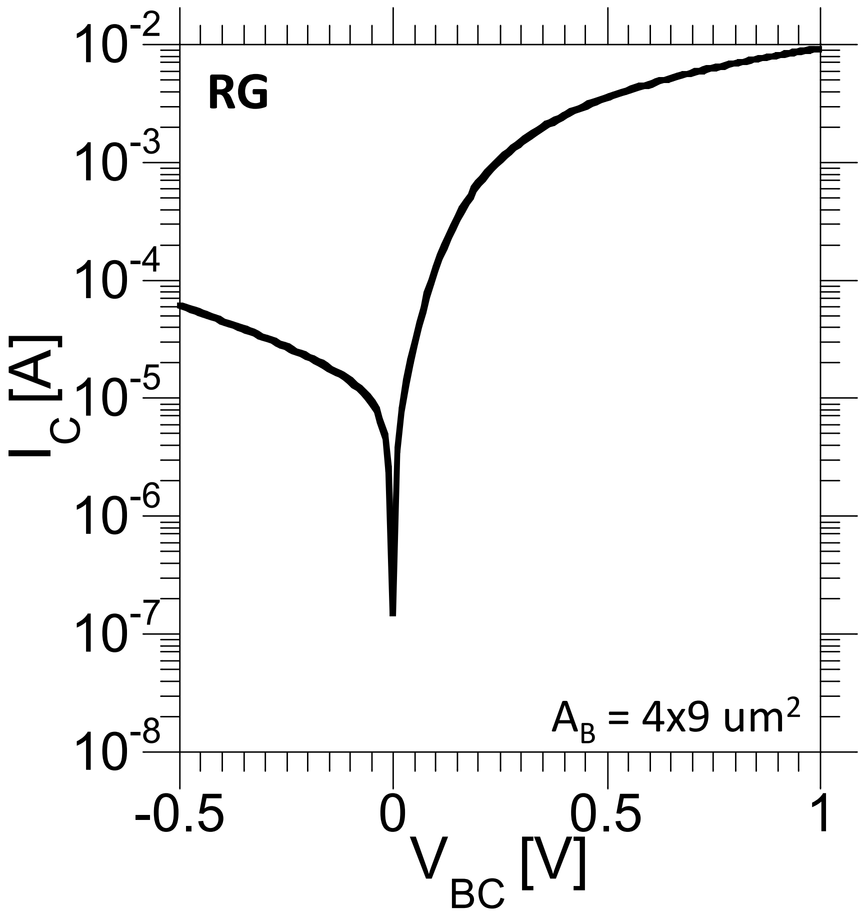


*R_{ser} = 49 Ω/μm

*B-E diode resistive due to excessive base mesa lateral undercut

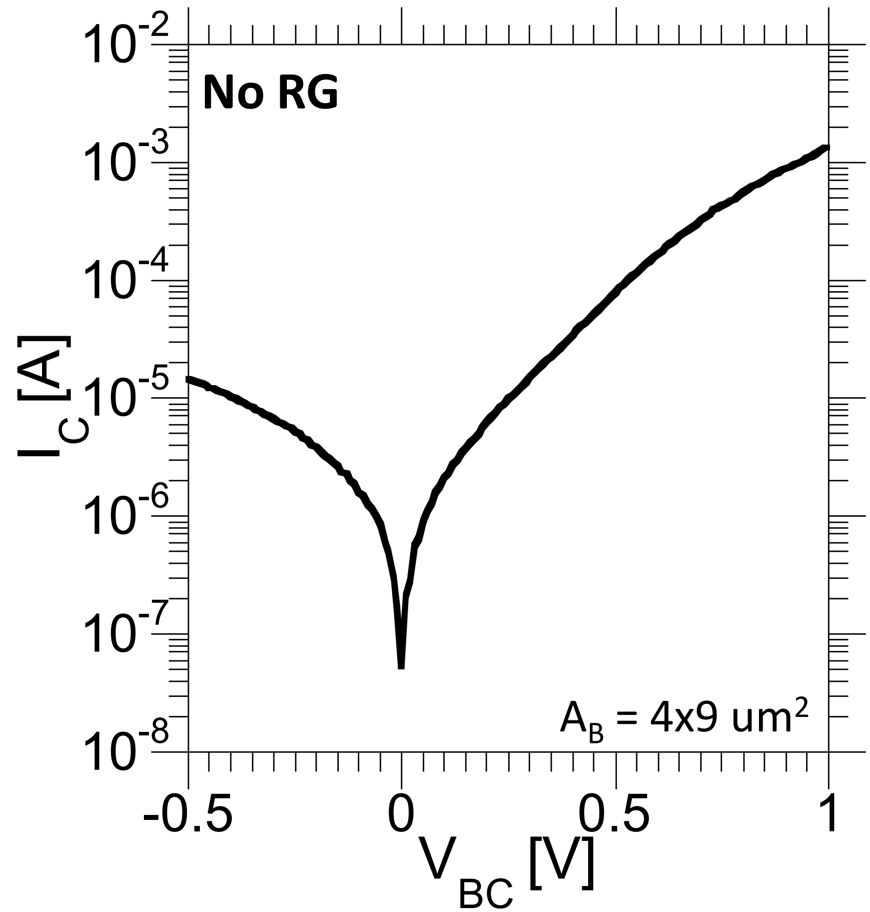
25nm base, doped 9-5e19 cm^{-3}
100nm collector

LAD – B-C diode



R_{ser} = 82 Ω/µm

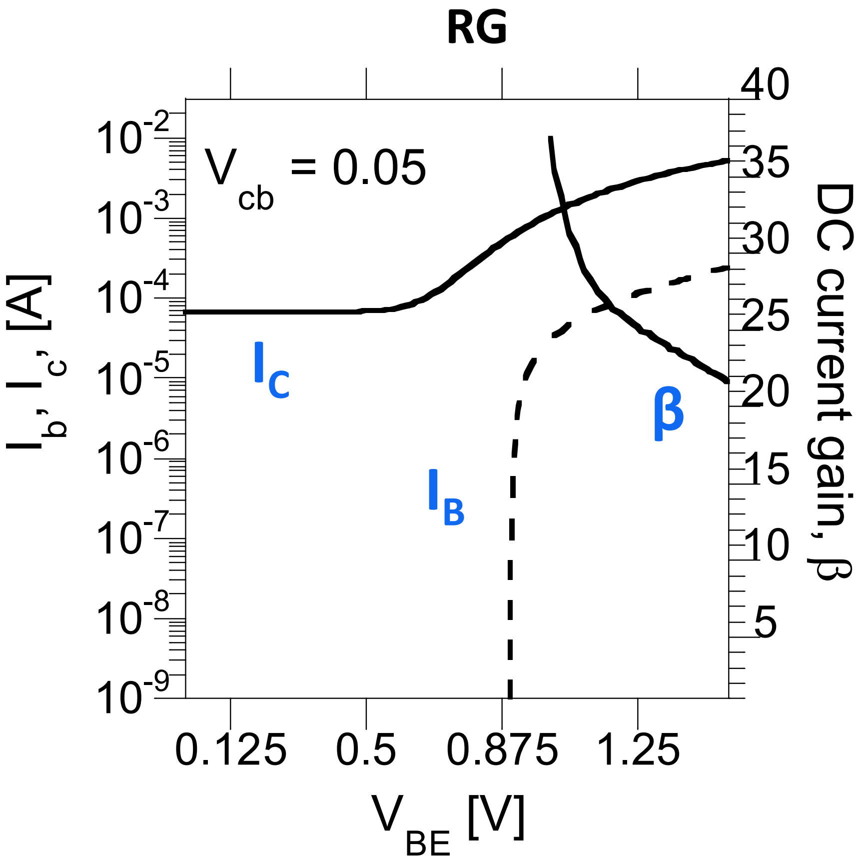
Large BC leakage!

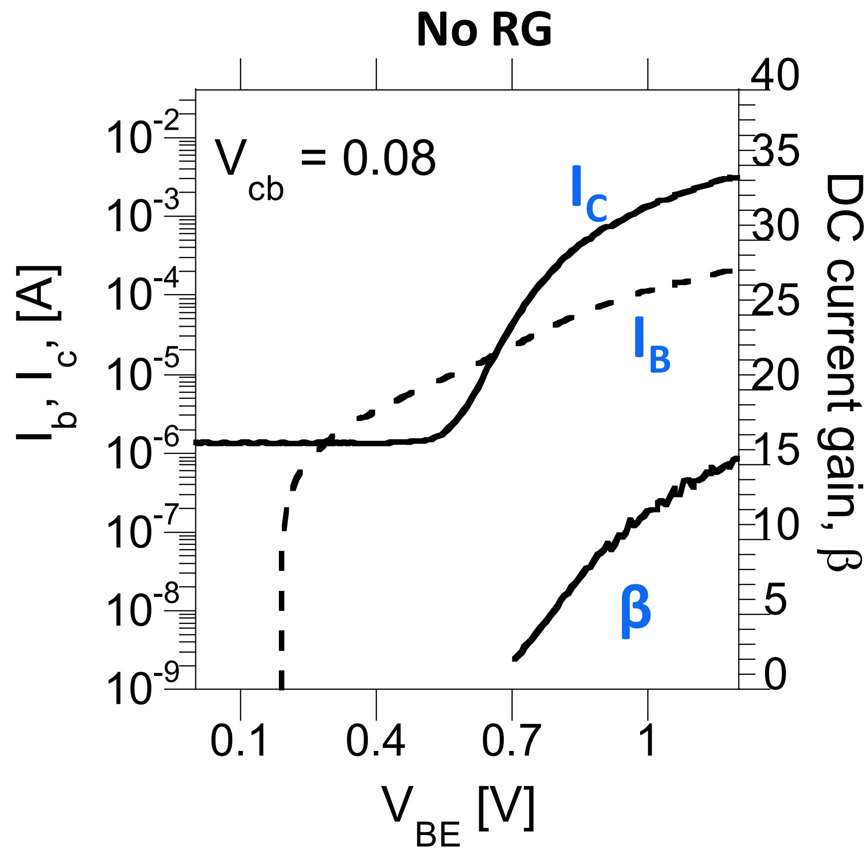


***R_{ser} = 253 Ω/µm**

*B-E diode resistive due to excessive base mesa lateral undercut

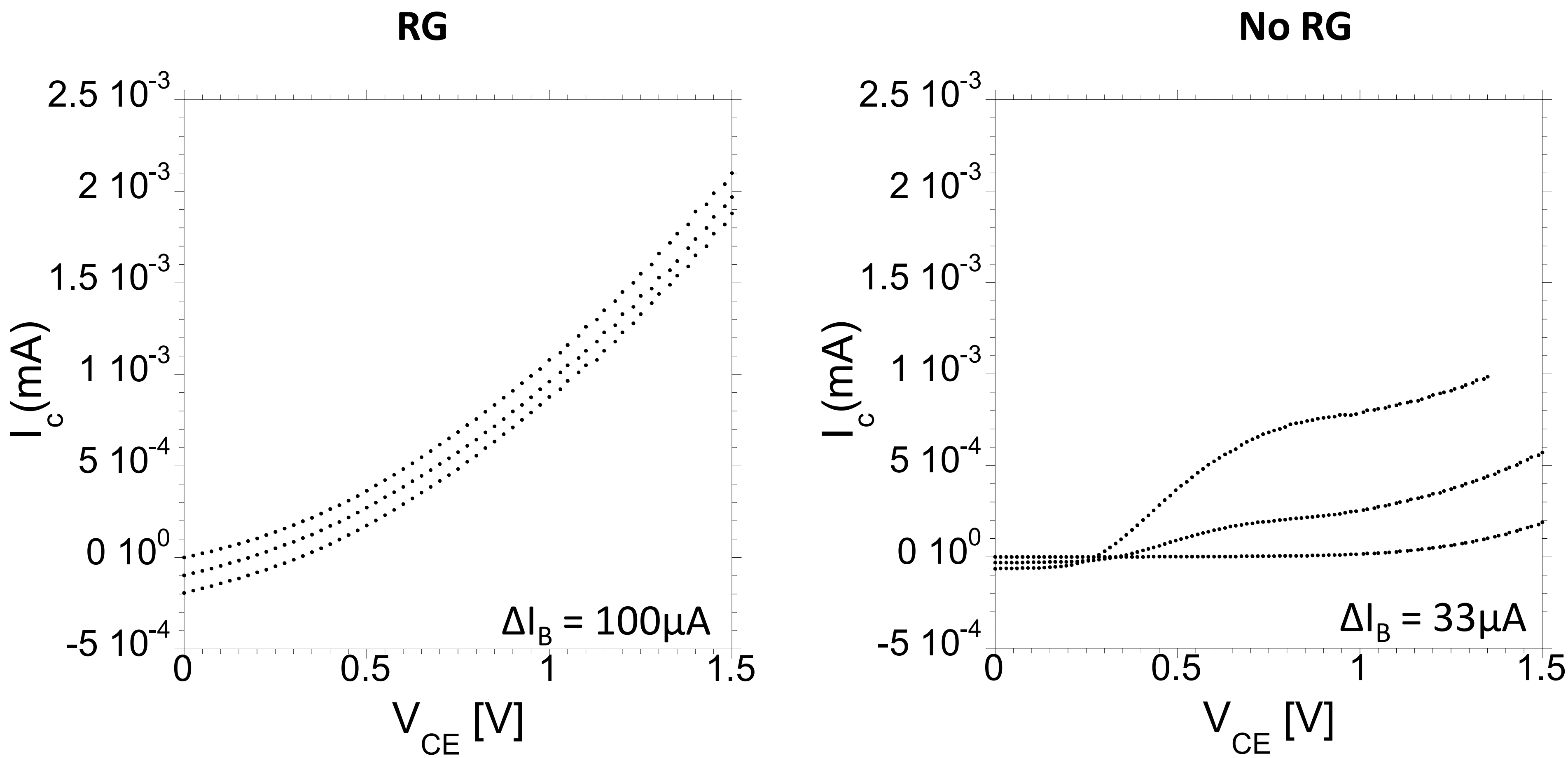
LAD – Gummel





Large BC leakage!

LAD – Common Emitter Characteristics



RG LAD sees no saturation

BE diode does not turn on

MOCVD Regrowth – Good Selectivity with Oxide