InAs-Based Bipolar Transistors

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Motivation for Work in InAs bipolar transistors

Historical Trend – Increase the amount of indium in the base of a heterojunction bipolar transistor (HBT)

- ⇨ Higher electron mobility & saturation velocity
- ⇨ Improved base resistance/base contact resistance
  - ⇨ Faster Device

Evolution of Base Compositions in HBTs

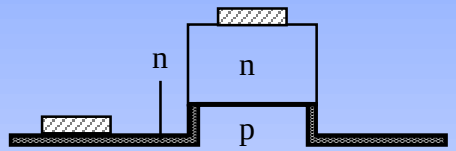
Increasing In composition in InGaAs base ↓

- GaAs base (0% indium) – AlGaAs/GaAs structures on a GaAs substrate
- $Ga_{1-x}In_xAs$ (x ~ 10%) – Pseudomorphic GaInAs base on a GaAs substrate
- $Ga_{.47}In_{.53}As$ – GaInAs base lattice-matched to an InP substrate
- $Ga_{1-x}In_xAs$ (x > 53%) – Pseudomorphic GaInAs base on an InP substrate
- Metamorphic growth for increased In content
- Final Frontier -- 100% InAs in the Base

This Work – Examine the Feasibility of Making InAs-Based Bipolar Transistors

Initial Concerns/Issues

- Early work (Mead & Spitzer, 1963) states that the Fermi level of InAs is pinned in the conduction band at the surface.
  - ➢This suggests that there is an (n-type) inversion layer at the surface of the p-type InAs.
    - ⇨Effect: Possibility of shorting out the pn junction due to the high conductivity (n-type) surface layer.



⇨ The Standard III-V Heterojunction Bipolar Transistor (HBT):

- ⇨ Emitter is lattice-matched, or nearly lattice-matched, to the substrate.
- ⇨ Type I, wide-gap emitter-base heterojunction.
- ⇨ Large valence-band discontinuity (? E_v).
  - ⇨ Result: No practical material fits these criteria.

⇨ No Semi-insulating (SI) substrate in 6.1Å materials.

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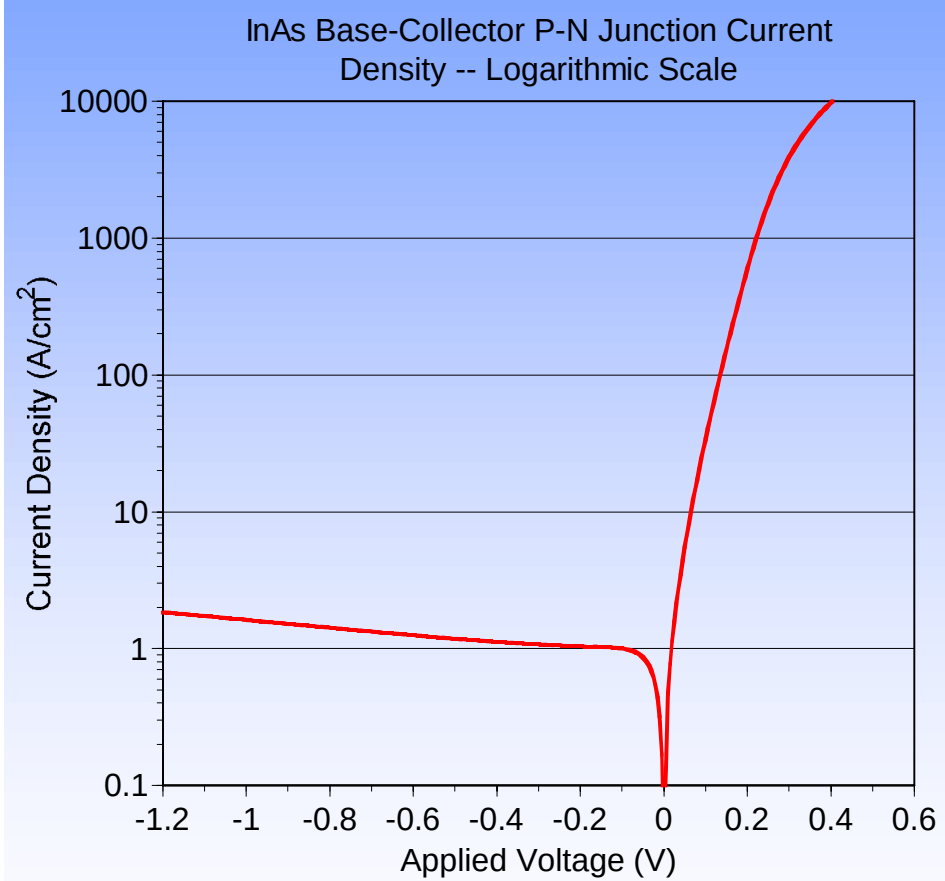
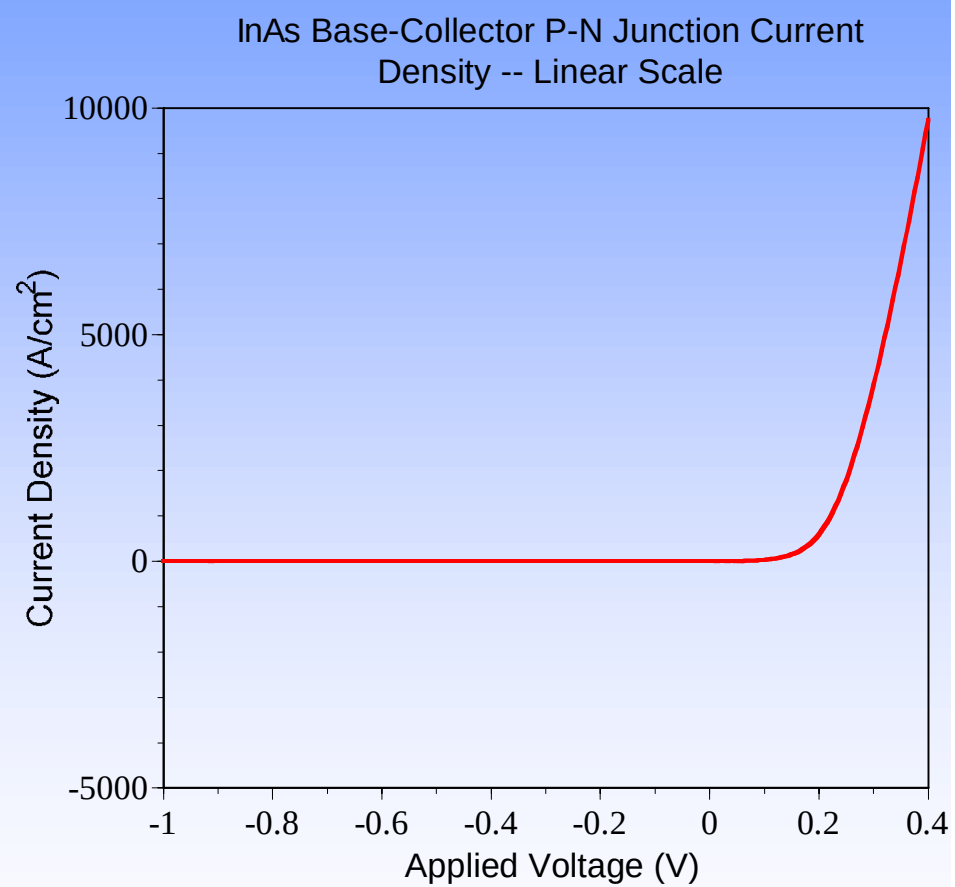
Surface Fermi Level Pinning in the Conduction Band -- No Problem





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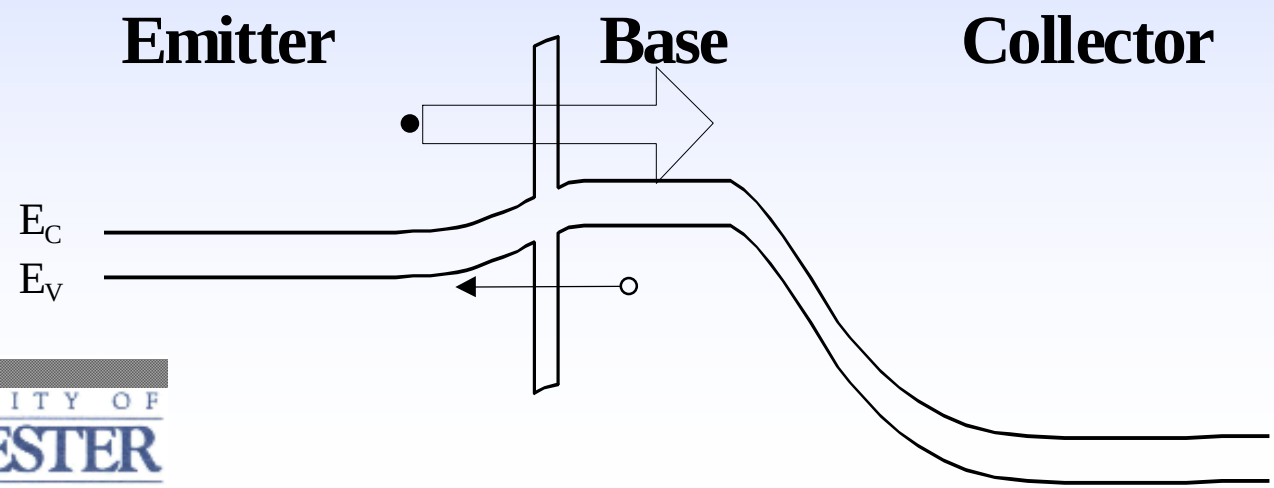
Bipolar Device Types Investigated

- Bipolar Junction Transistor (BJT) – All junctions are homojunctions.
- Heterojunction Bipolar Transistor (HBT) – Pseudomorphic $Al_{0.09}In_{0.91}As$ wide-gap emitter.
- Tunneling Emitter Bipolar Transistor (TEBT) – $Al_{0.4}In_{0.6}As$ barrier. Designed to incorporate the advantages of an HBT without the stringent requirement of lattice-matched wide-gap emitter.



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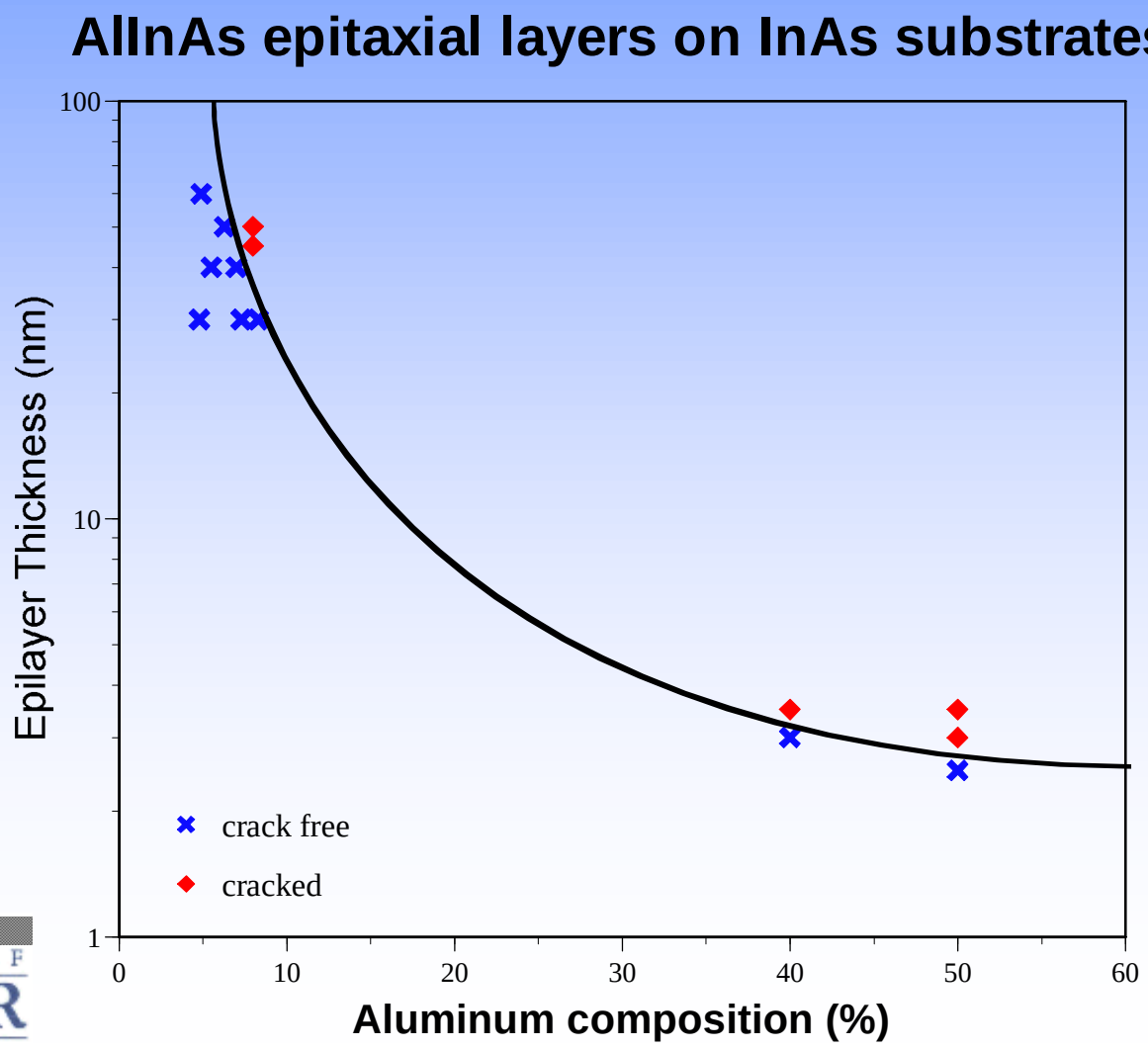
AlInAs Cracking Study

$Al_xIn_{1-x}As$ grown on an InAs substrate is tensile strained, and there exists a critical thickness for the epilayer to form cracks to relieve strain.



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Structures of devices in this work

BJT Structure

3000 Δ InAs:Si	cc ~ 2 E 18 cm^{-3}
50 Δ InAs spacer	NID
300 Δ InAs:Be	cc ~ 1 E 18 cm^{-3}
700 Δ InAs:Be	cc ~ 1 E 19 cm^{-3}
1 micron InAs	NID (cc ~ 1 E 17 cm^{-3})
InAs:S substrate	

HBT Structure

500Δ InAs:Si	cc ~ 2 E 18 cm^{-3}
1000 Δ InAs:Si	cc ~ 5 E 17 cm^{-3}
500Δ AlInAs:Si	Al = 9 - 0 %
400Δ AlInAs:Si	Al = 0 - 9 %
50 Δ InAs spacer	NID
300 Δ InAs:Be	cc ~ 1 E 18 cm^{-3}
600 Δ InAs:Be	cc ~ 1 E 19 cm^{-3}
1 micron InAs	NID (cc ~ 1 E 17 cm^{-3})
InAs:S substrate	

TEBT Structure

3000 Δ InAs:Si	cc ~ 2 E 18 cm^{-3}
50 Δ InAs spacer	NID
Al(0.4)In(0.6)As	NID
50 Δ InAs spacer	NID
300 Δ InAs:Be	cc ~ 1 E 18 cm^{-3}
700 Δ InAs:Be	cc ~ 1 E 19 cm^{-3}
1 micron InAs	NID (cc ~ 1 E 17 cm^{-3})
InAs:S substrate	

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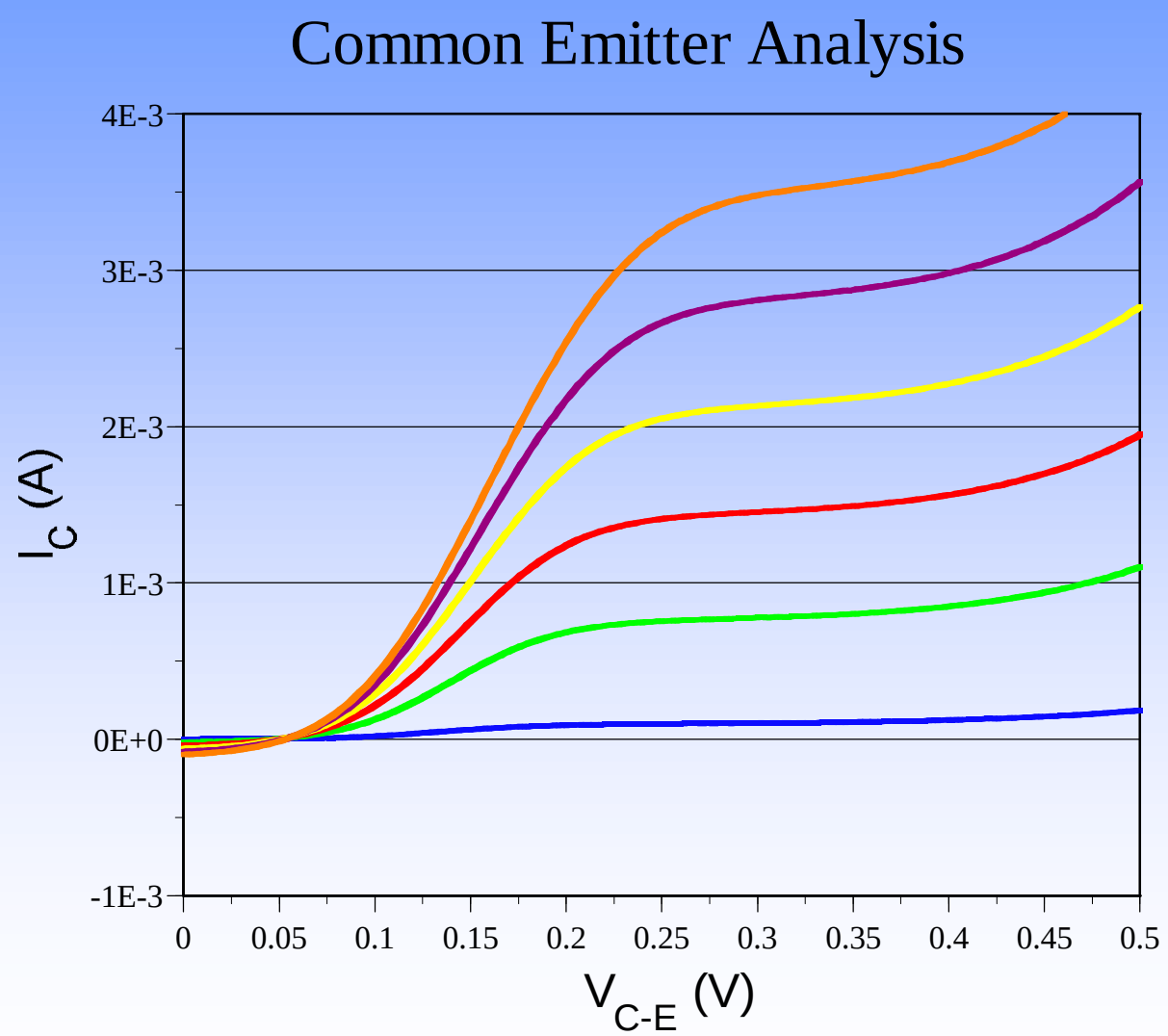
Common Emitter Results

Emitter mesa area = 4.00×10^{-6} cm^2

Emitter & Base contact areas = 1.69×10^{-6} cm^2

Collector contact area = 4.7×10^{-4} cm^2



I_B = 0 uA	I_B = 60 uA
I_B = 20 uA	I_B = 80 uA
I_B = 40 uA	I_B = 100 uA

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Analysis of Common Emitter Current Gain

BJT gives respectable results for the common emitter current gain (ß) -- ß ~ 100.

Relative to other III-Vs, InAs has inherent advantages for producing large ß:

- The ratio of electron to hole mobility is quite large – $\frac{\mu_{electron}}{\mu_{hole}} = 50 - 100$
  Result: devices with higher ß.

- Pseudo HBT effect due to bandgap narrowing in the base (Jerry Woodall, Michael Melloch, Michael Lovejoy, Paul Dodd, Mark Lundstrom, and David Pettit) can also contribute to large ß.

BJT ß ~ HBT ß

$$\beta = \frac{\alpha_T \ \gamma}{1 - \alpha_T \ \gamma}$$

a_T is the limiting factor in the equation for ß.
Thinner base layers should increase ß.

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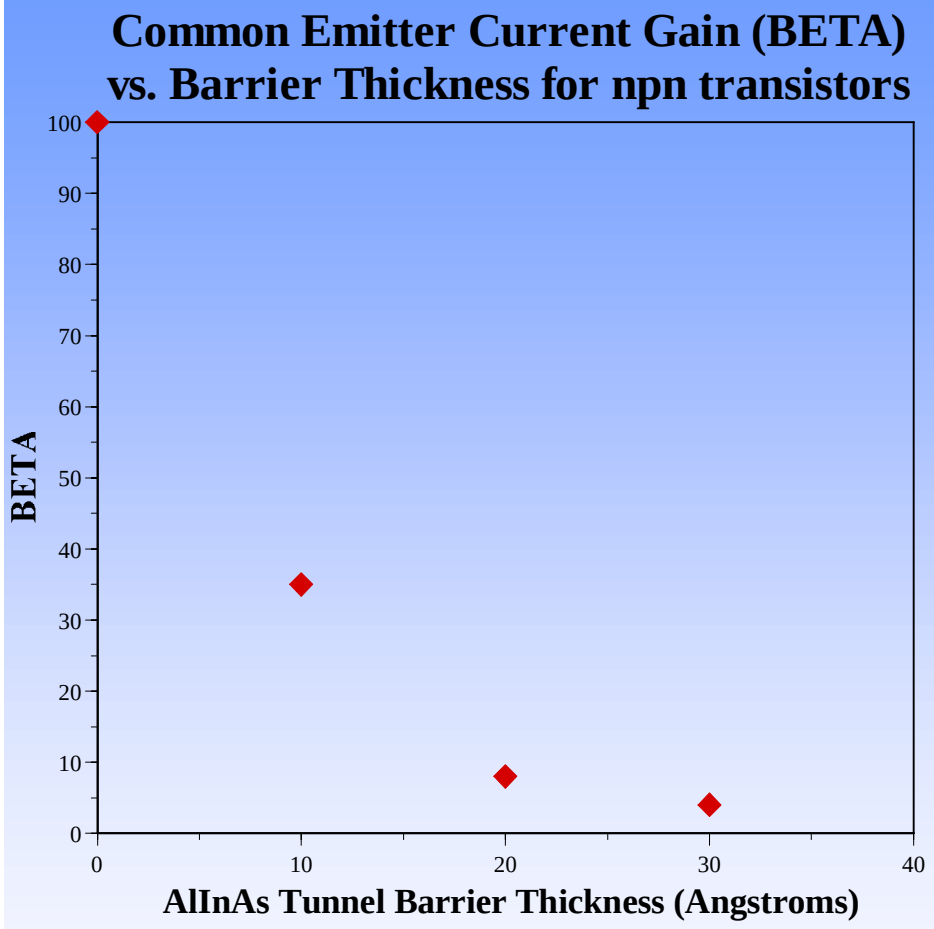
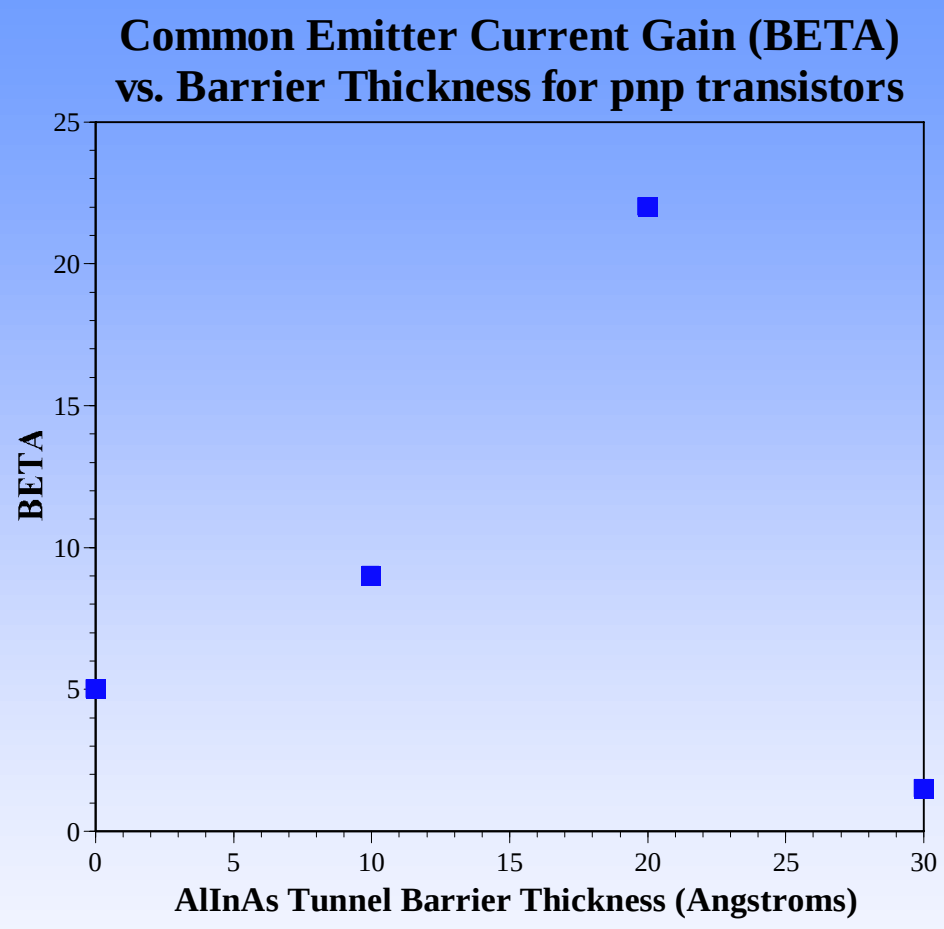
TEBT Results





Conclusion: Holes tunnel easier than electrons through AlInAs barriers.

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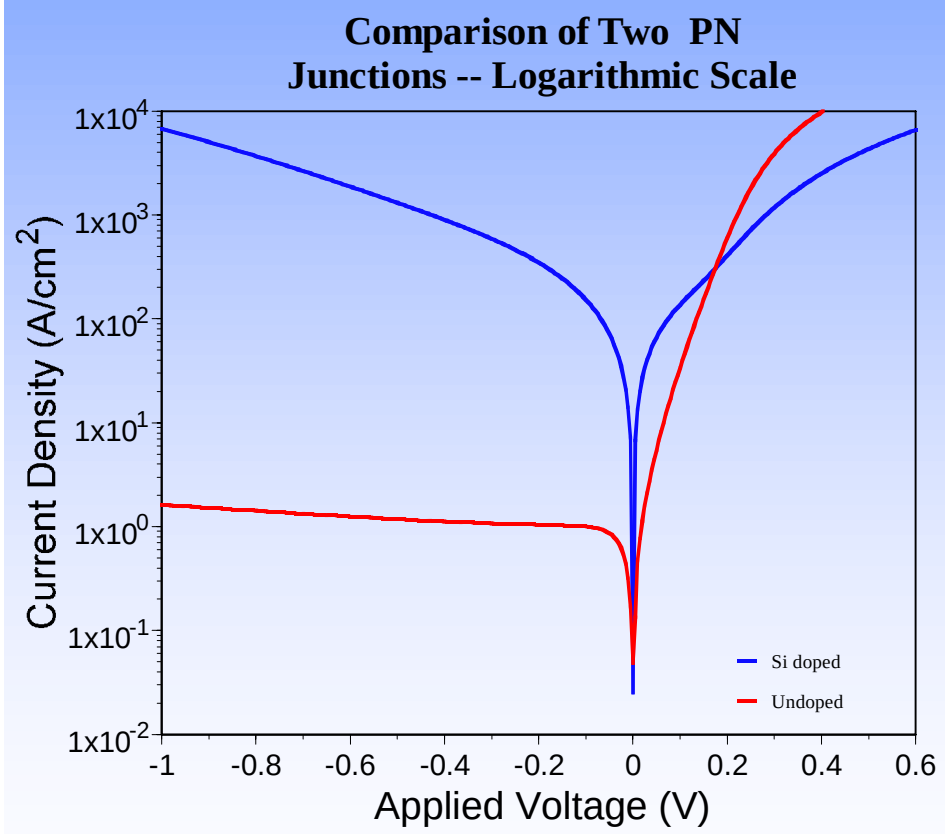
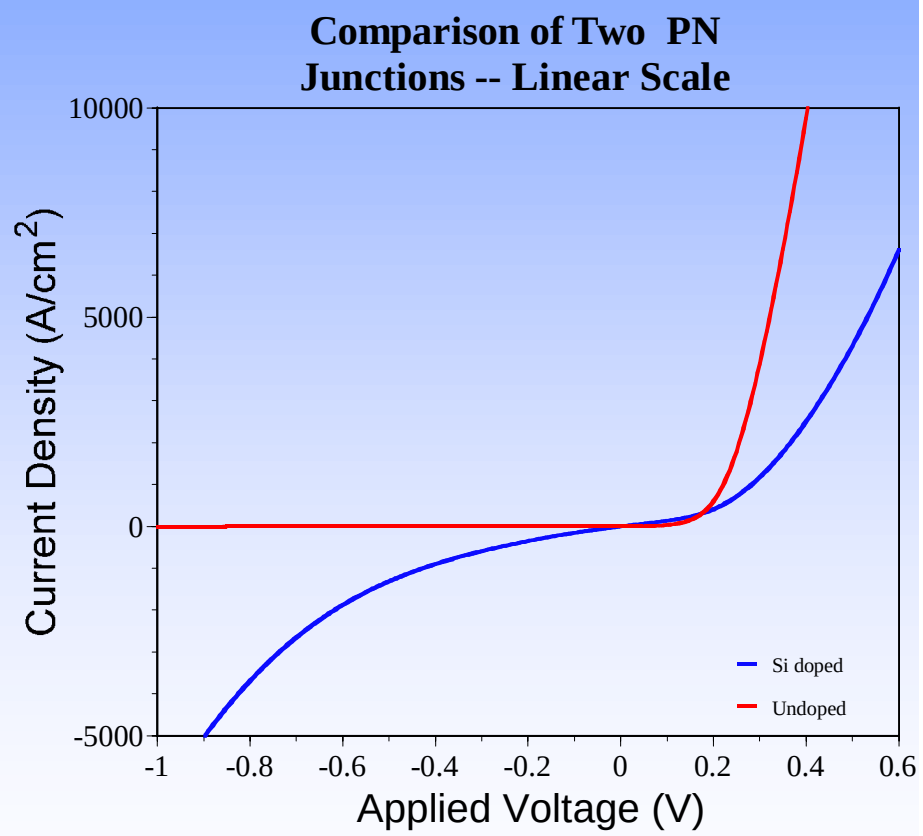
Remaining Issues to Investigate/Overcome

– Effect of Si doping on pn junctions





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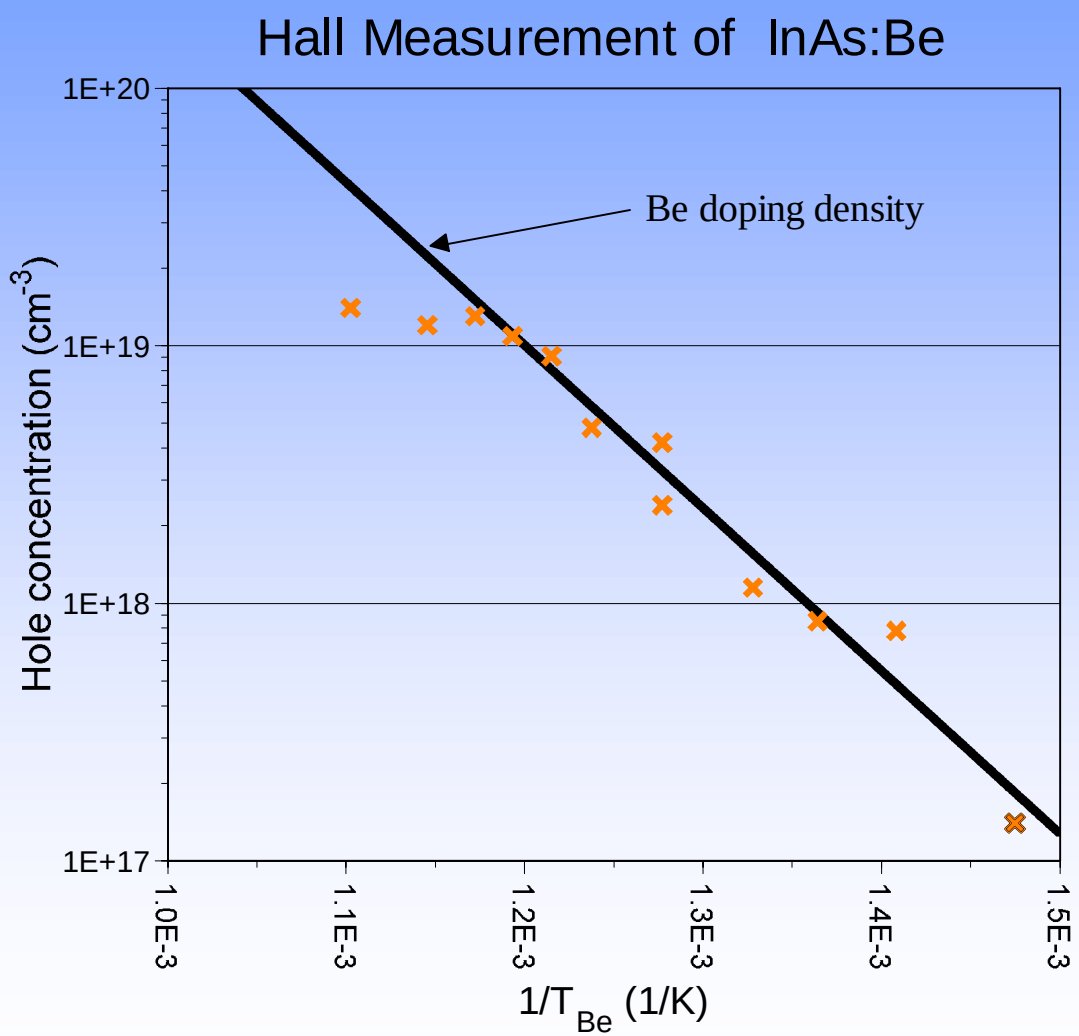
Remaining Issues to Investigate/Overcome

– P-type doping of InAs with Be has an upper limit of $p \sim 1 \times 10^{19}$ cm^{-3}



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Summary -- Conclusions

- BJT, HBT, & TEBT structures have been grown, processed, and characterized in our laboratory.
- Pinning of the surface fermi level in the conduction band of InAs is either nonexistent or not important.
- Neither Si nor Be are ideal dopants for InAs-based pn devices.
- The study of AlInAs epilayers show maximum thicknesses for $Al_xIn_{1-x}As$ on InAs: ~ 40 nm (x=9%); ~ 3 nm (x=40%).
- AlInAs is not an effective material for the TEBT design.
- Room temperature common emitter current gains on the order of ß = 100 demonstrate the feasibility of InAs-based bipolar transistor. Thinner bases are expected to further increase ß.

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