AlSb/InAs HEMTs for Low-Voltage, High-Speed Applications

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Low-Power Sensor Devices

- **Objective:** Develop advanced HEMTs featuring high In-content channels on GaAs substrates to lower noise figure, increase gain, and reduce power consumption of microwave amplifiers.

- **Technical Approach:** Resolve fundamental material and design issues which are unique to the AlSb/InAs material system. Develop design and fabrication methods to fully realize the performance potential of the system.

Outline

- **Motivation**
- **Fabrication**
- **HEMT design runs**
  – 0.1 µm HEMTs with an InAlAs/AlSb barrier
  – 60 nm HEMTs
  – HEMTs with an InAs subchannel
- **Summary**

AlSb/InAs HEMT Motivation

- **Attractive Material Properties**
  - High electron mobility
  - High electron velocity
  - Large conduction-band offset
  - High 2-DEG sheet-charge density

→ **Potential for High Speed and Low Noise at Low Drain Voltage**

- **Design Issues**
  - Impact ionization
  - High gate leakage current
  - High output conductance
  - High reactivity of AlSb
  - Kink effect

HEMT Material System Properties

	Band Offset ΔE_c (eV)	Sheet Density n_s (cm^{-2})	Mobility μ (cm^2/V-sec)	Sheet Resistance R_{sh} (Ω/sq)
$AlGaAs/In_{0.2}Ga_{0.8}As/GaAs$ PHEMT	0.45	2.5×10^{12} —	6000	400
$InAlAs/In_{0.53}Ga_{0.47}As/InP$ HEMT	0.55	3.2×10^{12} —	11,000	180
$InAlAs/In_{0.8}Ga_{0.2}As/InP$ PHEMT	—	3.6×10^{12} —	12,700	140
AlSb/InAs HEMT	1.35	6.5×10^{12} —	12,000	80
		3.8×10^{12} —	21,000	80
		8.0×10^{12} —	19,000 (DH)	40

Hall measurements made at 300K on single-doped heterojunctions unless noted.

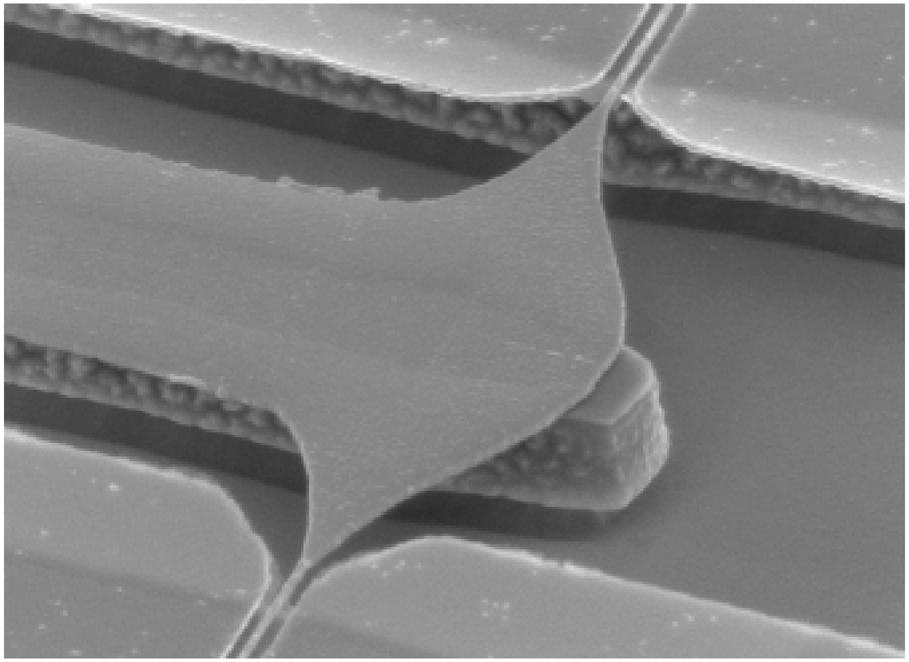
Potential Applications

Low-voltage, low-power consumption electronics is critical in applications which require light-weight power supplies and extension of battery lifetimes due to the environment in which they must operate.

- **Low-noise receivers**
  - T/R modules for space-based communications
  - mm-wave imaging arrays (aircraft landing guidance in adverse weather)
  - remote earth sensing/weather pattern prediction (X-band through 180 GHz)
  - portable communications (hand-held, vehicle remote sensing)
  - micro-air-vehicle (μAV) missions
- **High-speed logic**
  - high $f_{T,}$ high g_m, and large current drive capability
  - potential for lowest power-delay product
- **Integration with 6.1Å-based RTD’s, optoelectronic, and nanoelectronic devices**

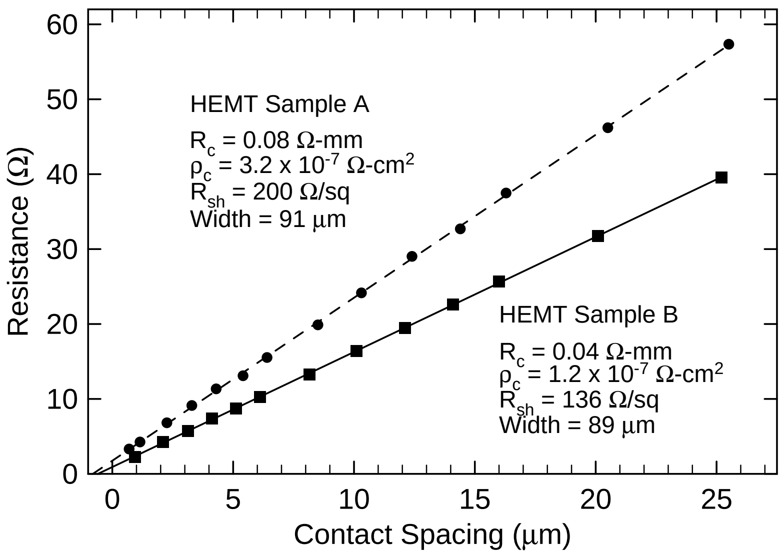
AlSb/InAs HEMT Fabrication

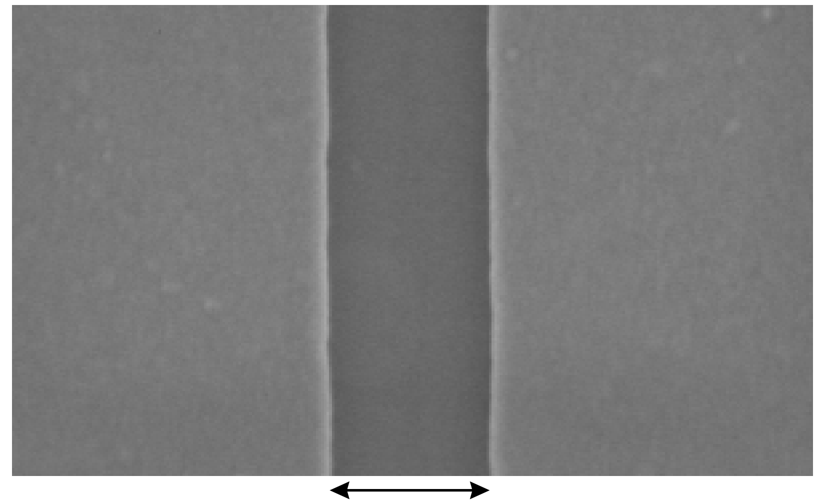
- **Pd/Pt/Au ohmic contacts**
  - Heat-treated at 175°C for 3 hours
  - Pt diffusion barrier
- **Cr/Au Schottky gate**
  - Tri-level resist e-beam lithography
  - Citric acid-based surface treatment
- **Mesa isolation**
  - Hydrofluoric acid-based etch
  - Gate air-bridge at mesa edge



L_G = 0.2 μm, L_{DS} = 1.0 μm

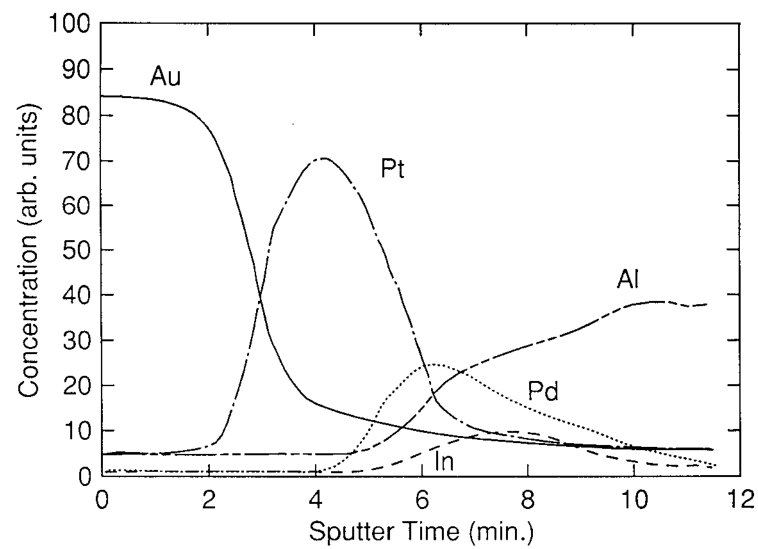
Pd/Pt/Au Ohmic Contacts for AlSb/InAs HEMTs





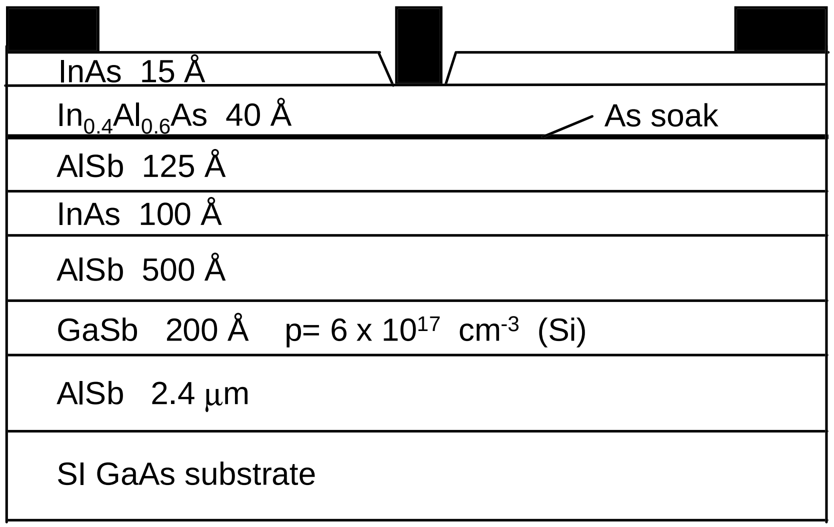
L_{DS} = 1.0 µm

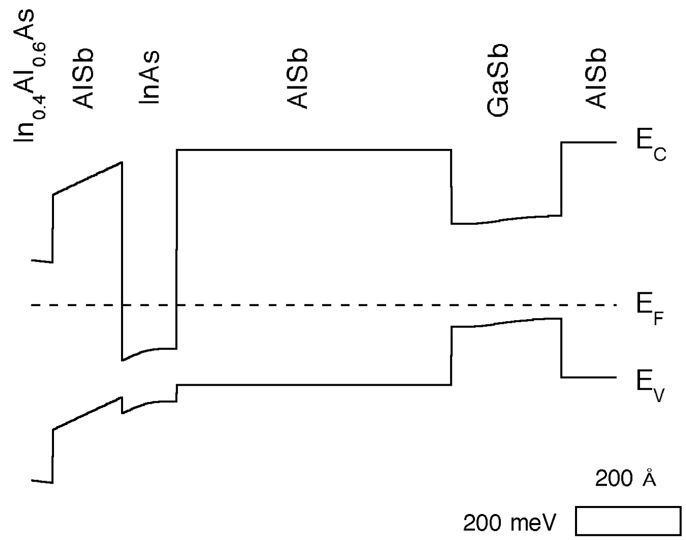
- Heat-treated at 175°C for 3 hours
- Pt diffusion barrier
- Sharp edge definition
- Smooth surface morphology
- R_c < 0.1 Ω-mm
- HEMT on-resistance as low as 0.4 Ω-mm



Auger profile of a Pd/Pt/Au contact after heat treatment.

AlSb/InAs HEMT with InAlAs/AlSb Barrier



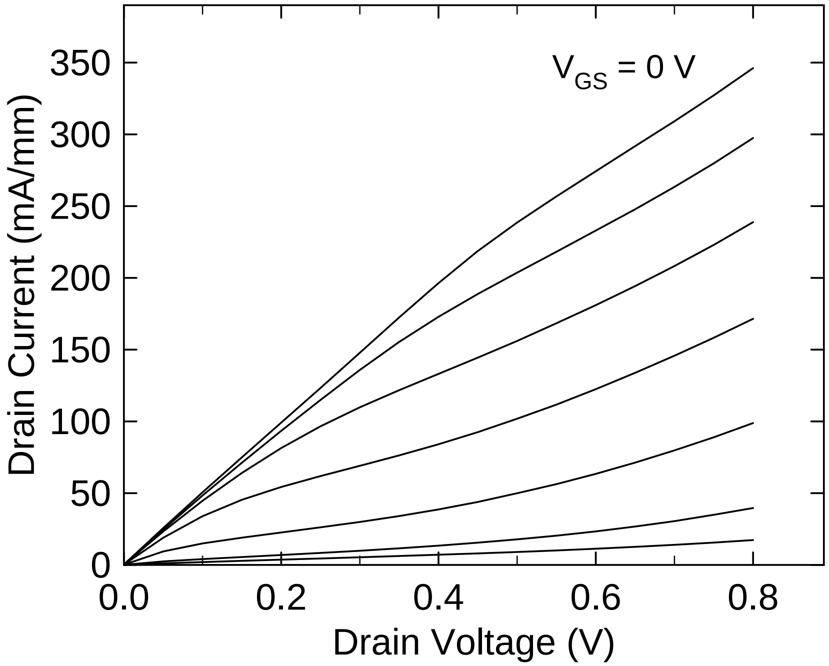


μ = 16,000 cm^2/V-s, n_s = 1.5 x 10^{12} cm^{-2}

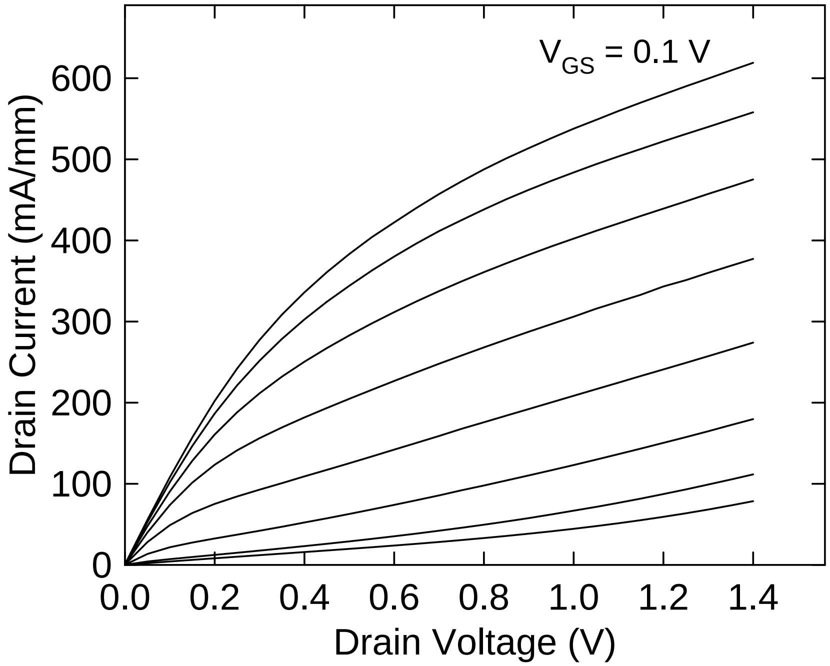
- **$In_{0.4}Al_{0.6}As$/AlSb composite barrier layer**
  - Enables gate recess, reduces kink effect, lowers gate leakage
- **p$^+$ GaSb Layer within buffer**
  - Reduces kink effect, lowers gate leakage.

HEMT Drain Characteristics

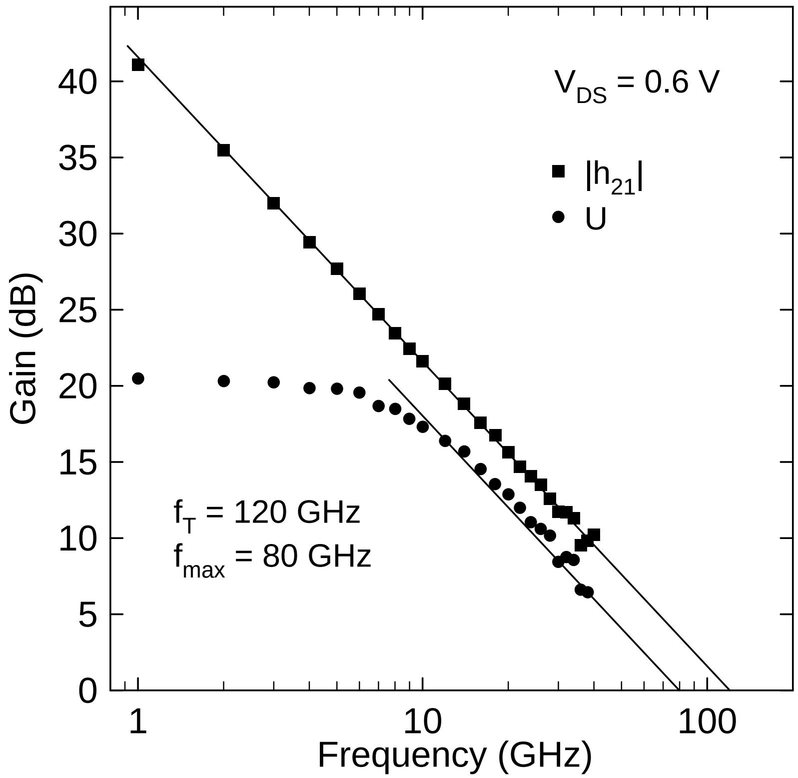
0.1 μm HEMT

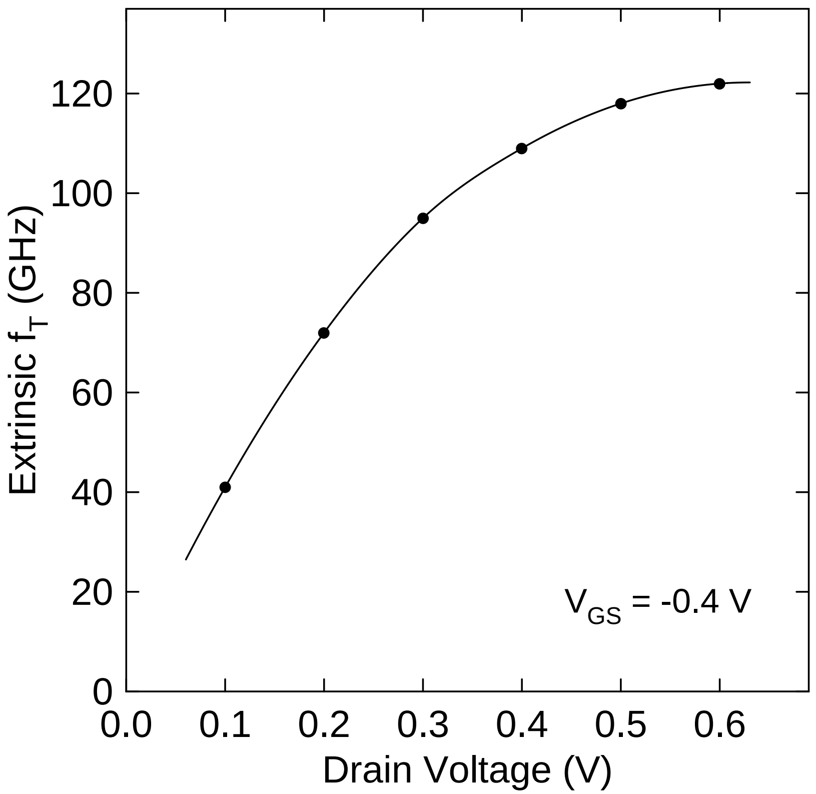


0.5 μm HEMT

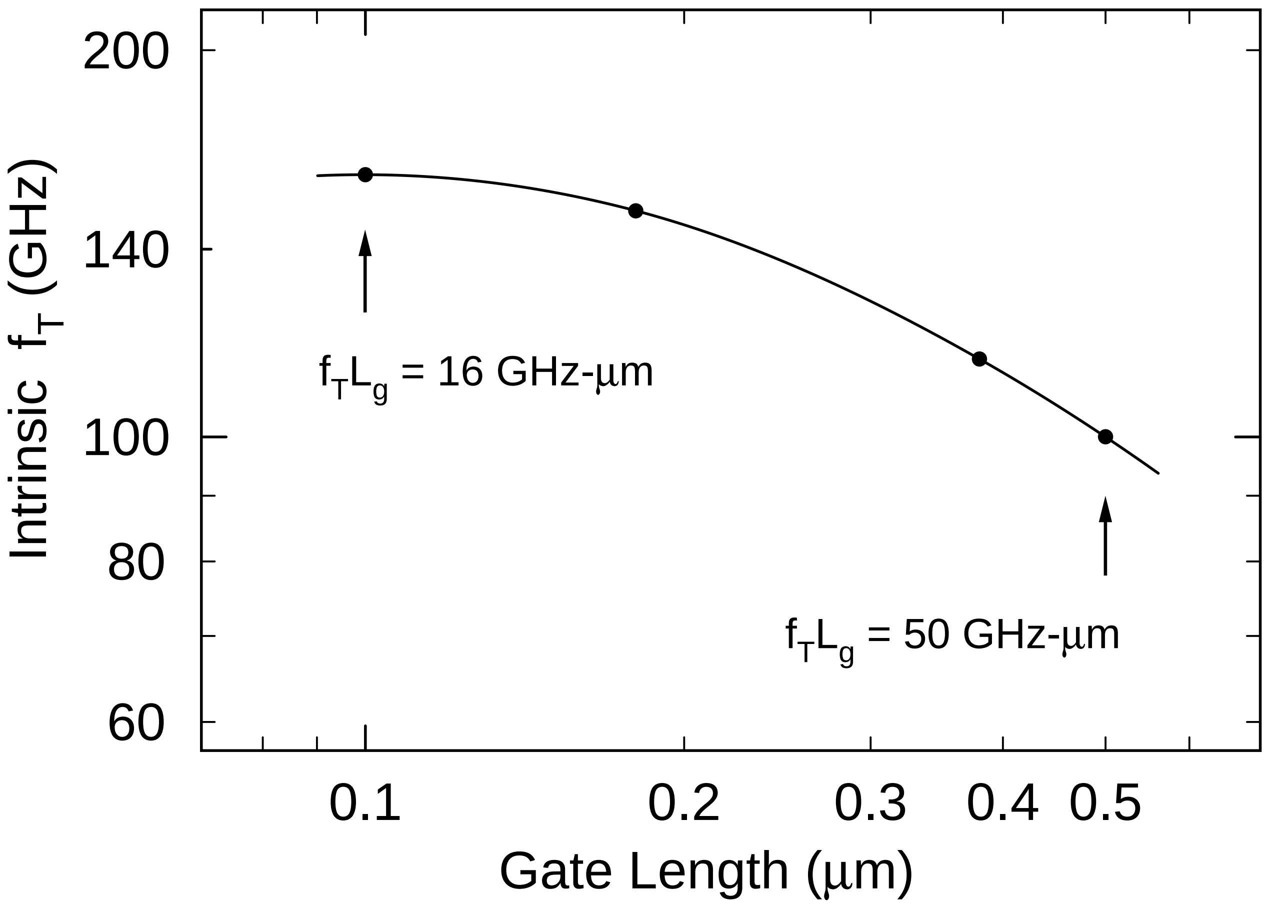


0.1 μm HEMT Microwave Characteristics



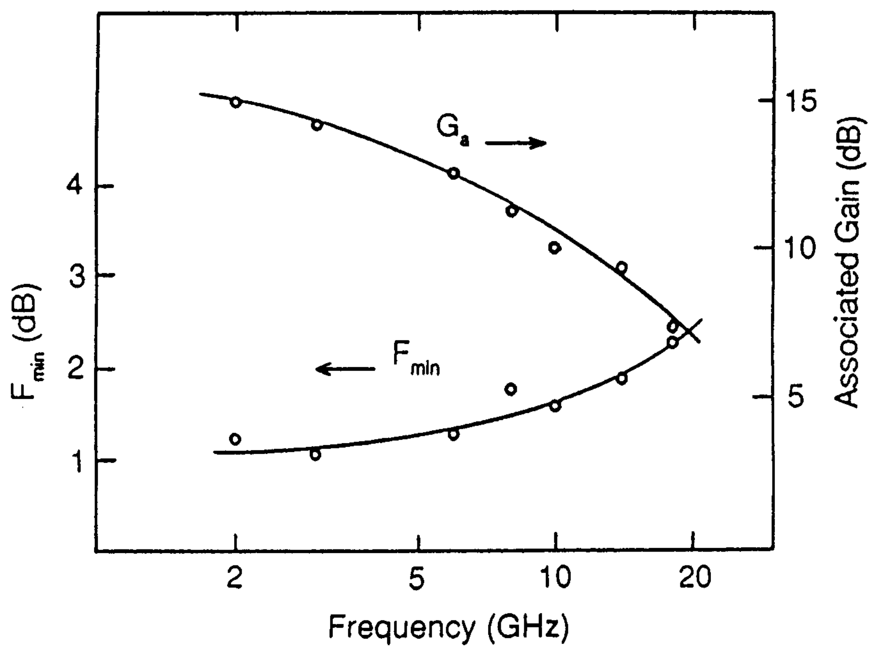


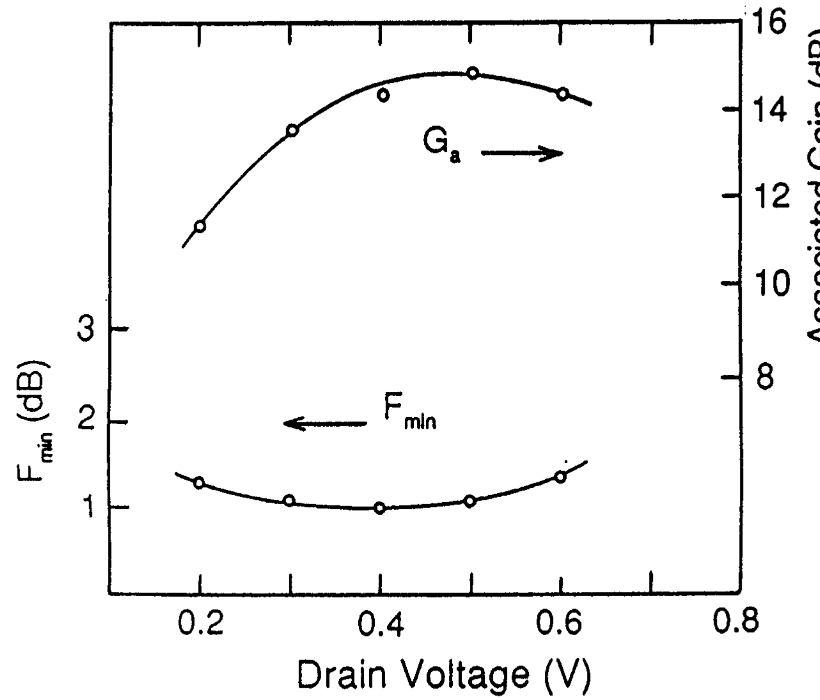
Intrinsic f_T versus Gate Length



50 GHz-µm intrinsic $f_T L_G$ on 0.5 µm HEMTs equal to highest reported for any FET in this gate-length region.

0.1 μm AlSb/InAs HEMT
Microwave Noise Characteristics



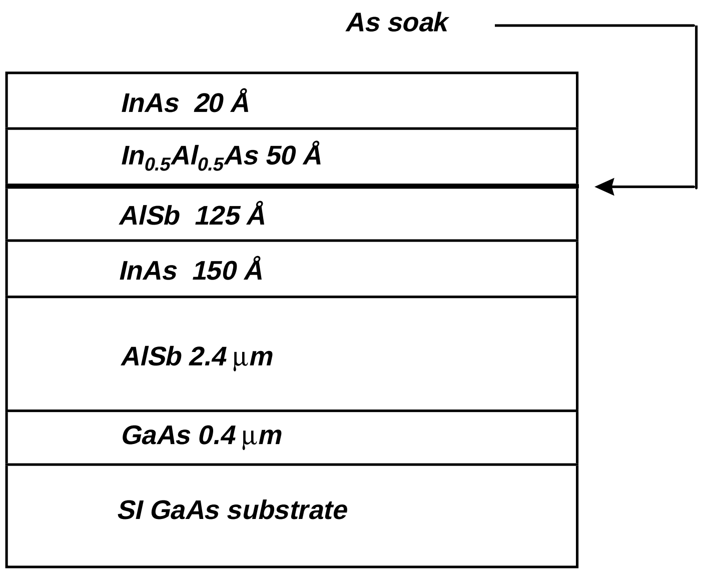


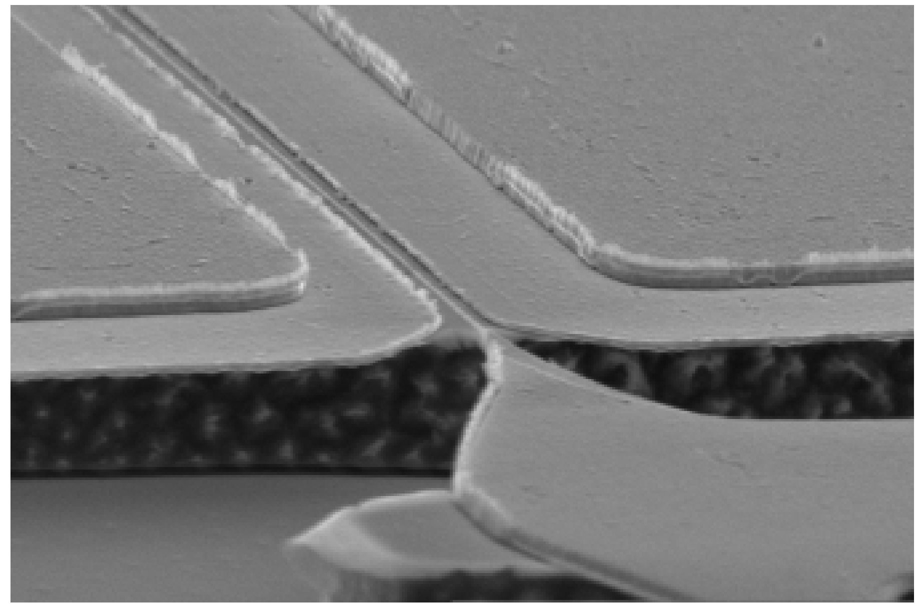
First report of microwave noise figure in this material system.

Noise modeling indicates gate leakage current is primary performance limitation.

Noise modeling predicts 0.3 dB noise figure at 4 GHz with expected technological improvements.

InAs HEMTs with a 60 nm Gate Length

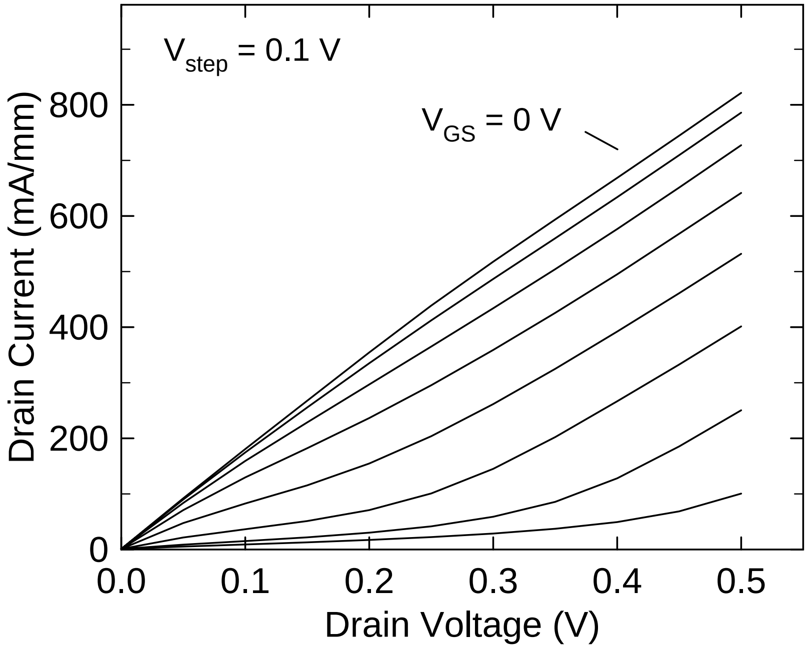


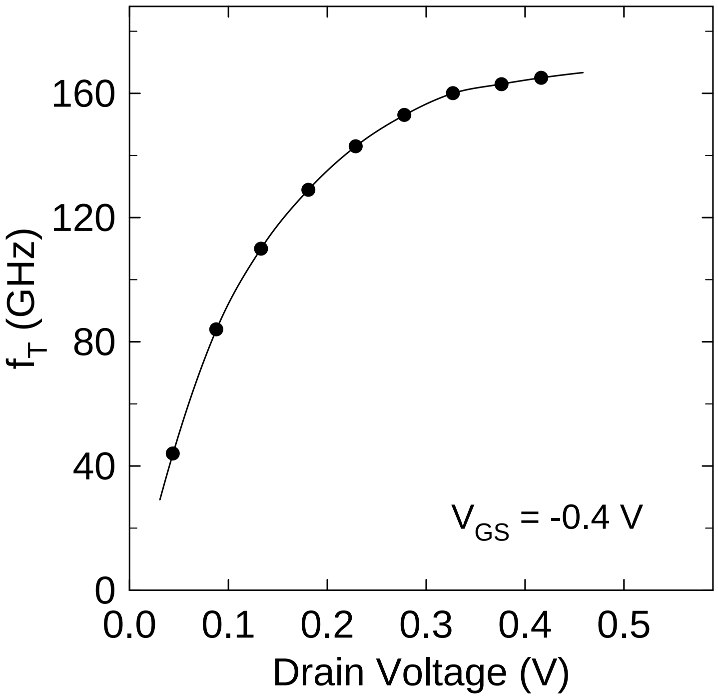


Sheet Density = 1.6 x 10^{12} cm^{-2}
Mobility = 21,300 cm^2/Vsec

Modulation Doping using an As-soak

60 nm InAs HEMT Characteristics





Microwave Performance at V_{DS} = 0.35 V

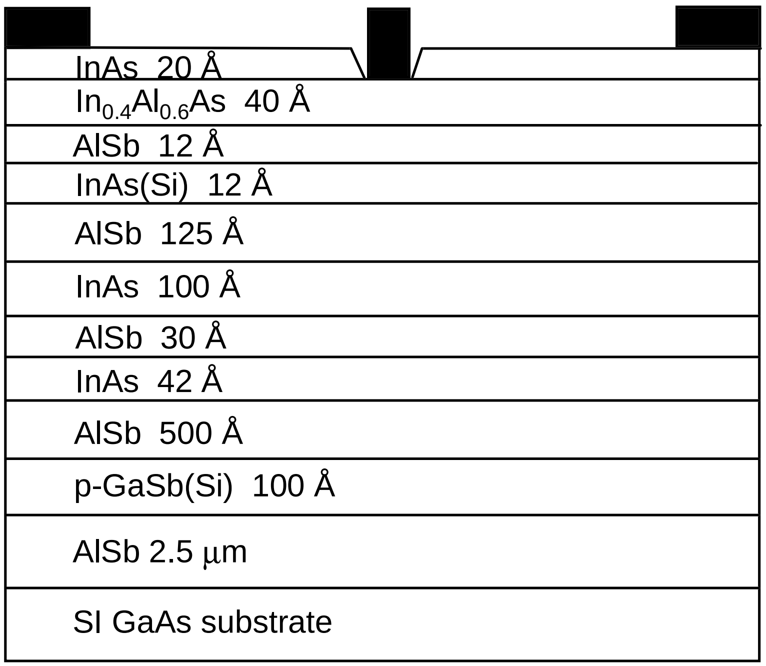
g_m(rf) = 1 S/mm

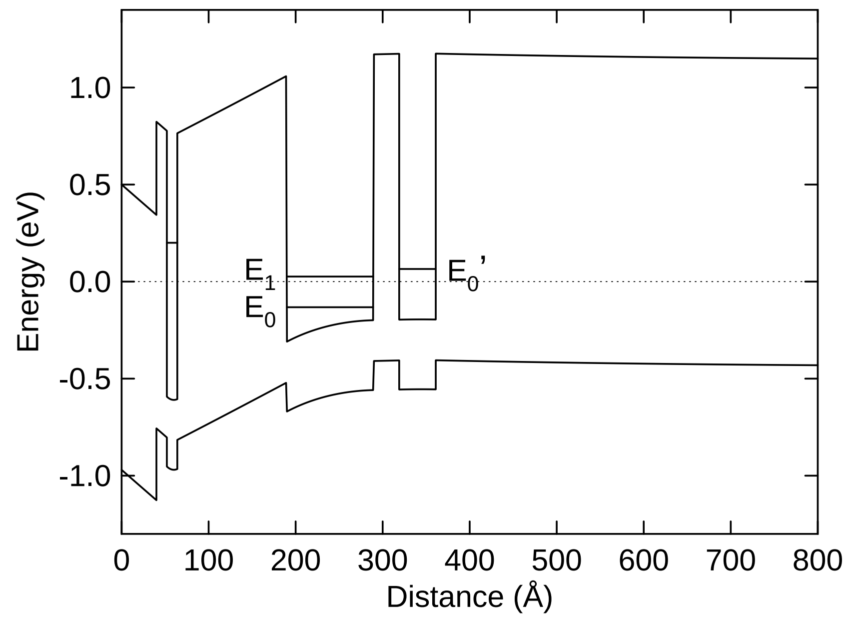
f_T = 160 GHz

f_{max} = 80 GHz

f_T = 90 GHz at 100 mV is highest reported for a FET at this drain bias.

AlSb/InAs HEMTs with InAs(Si) Doping and an InAs Subchannel

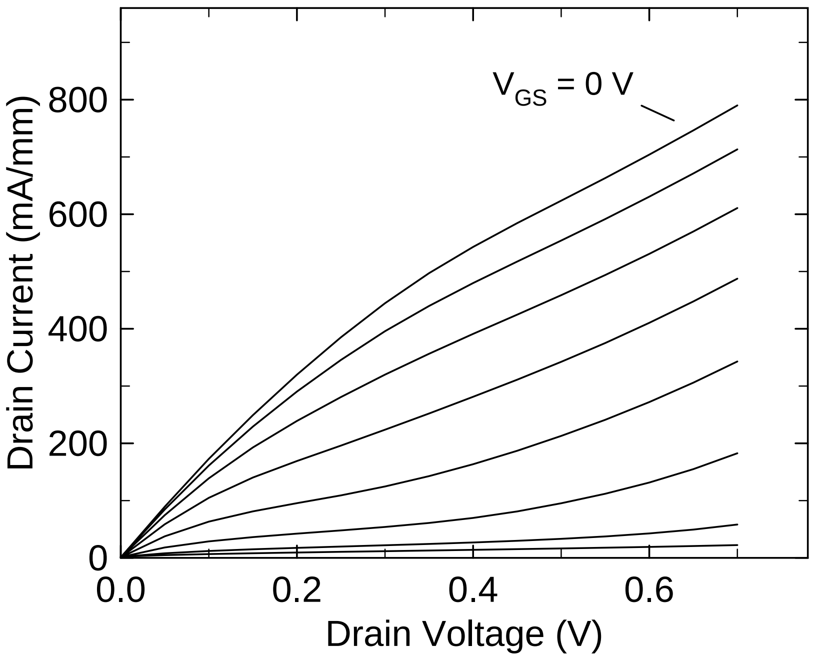


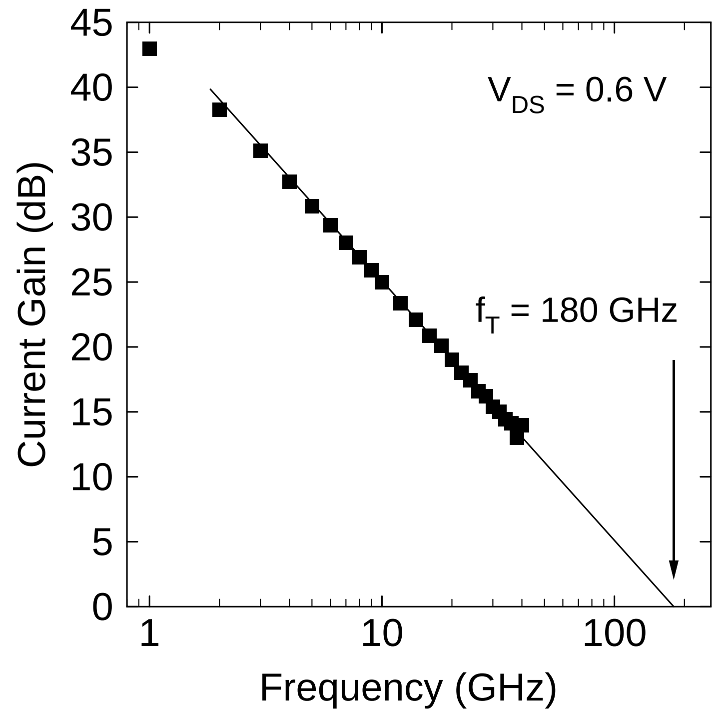


μ = 20,000 cm^2/V-s, n_s = 1.9 x 10^{12} cm^{-2}

- **Used Si doping in a thin (12 Å) InAs donor layer located above the InAs quantum well to achieve high sheet carrier density.**
- **42 A InAs subchannel reduces impact ionization by transfer of hot electrons to subchannel which has a larger effective bandgap due to quantization.**

0.1 μm InAs HEMTs with InAs Subchannel





Microwave Performance at V_{DS} = 0.6 V

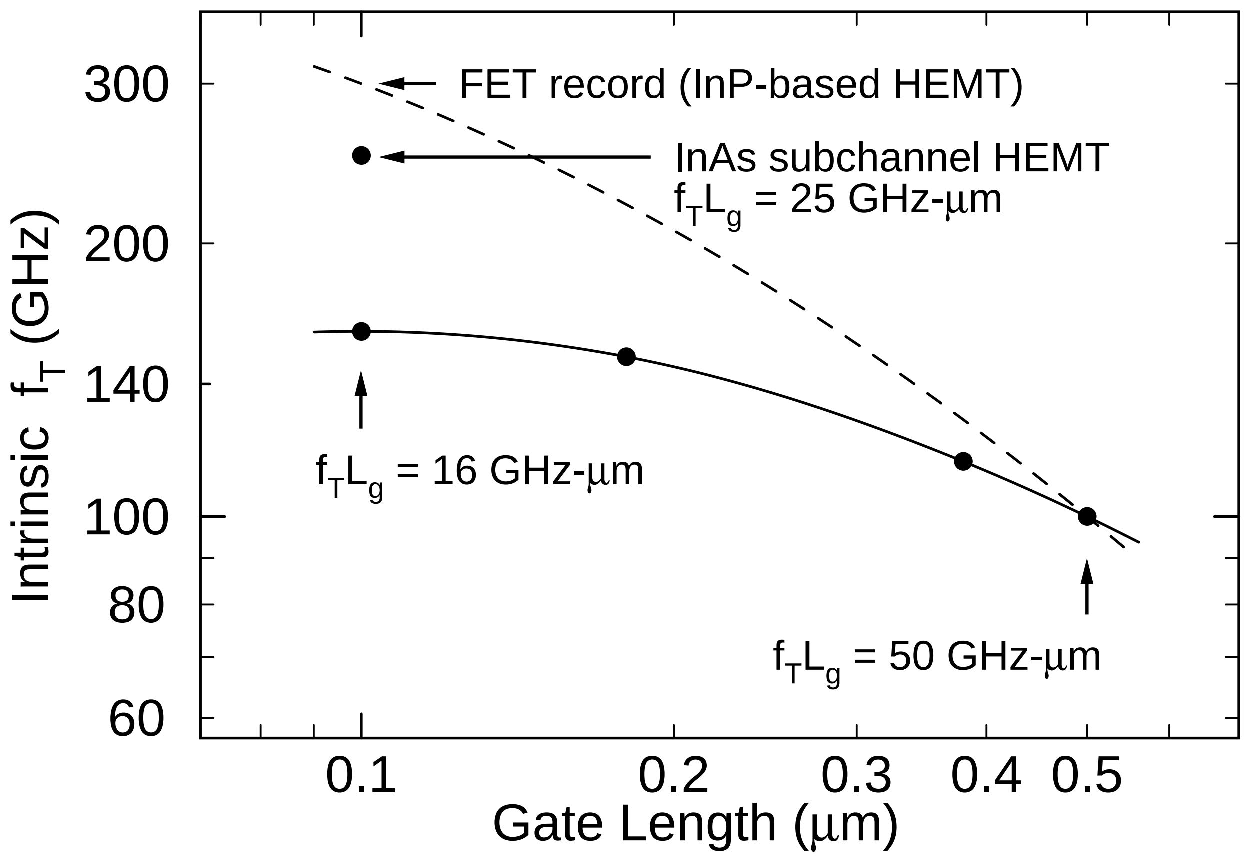
g_m(rf) = 850 mS/mm

f_T = 180 GHz, f_{max} = 80 GHz

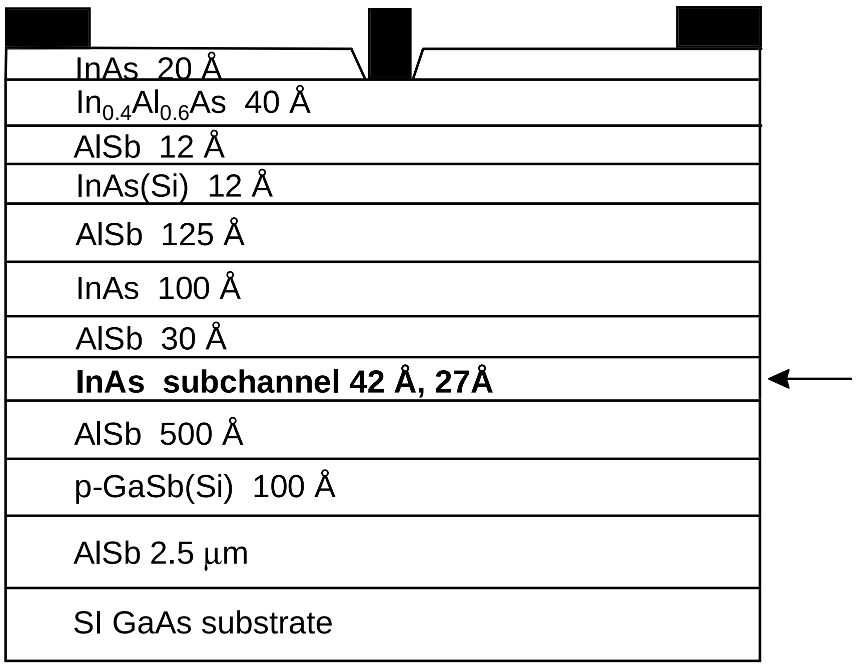
f_T = 250 GHz (after removal of bond pad capacitance)

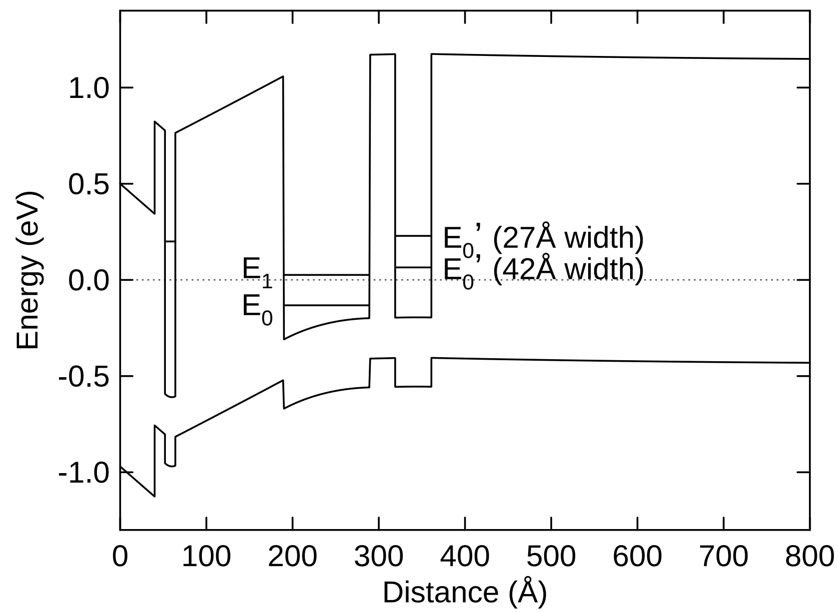
Ref: *Electronics Letters*, vol. 34, no. 15, July 1998

Intrinsic f_T versus Gate Length



InAs Subchannel Width Comparison





42 Å InAs subchannel: μ = 20,000 cm^2/V-s, n_s = 1.9 x 10^{12} cm^{-2}
(E_0 = 311 meV, effective bandgap = 671 meV)

27 Å InAs subchannel: μ = 15,000 cm^2/V-s, n_s = 1.9 x 10^{12} cm^{-2}
(E_0 = 475 meV, effective bandgap = 835 meV)

InAs Subchannel Width Comparison

	42 Å InAs subchannel	27 Å InAs subchannel
Transconductance	800 mS/mm	780 mS/mm
Output Conductance	200 mS/mm	240 mS/mm
Voltage Gain (g_m/g_d)	4.0	3.2
Drain Current (V_{GS} = - 0.4 V)	22 mA	27 mA
Gate-Source Capacitance	64 fF	80 fF
Gate-Drain Capacitance	18 fF	17 fF
Intrinsic Current Gain Cutoff Frequency (f_T)	220 GHz	170 GHz
Inductive Shift in S_{22}	Small	Larger

(L_G = 0.12 μm, V_{DS} = 0.6 V, W = 100 μm)

Summary

- **Demonstrated 0.1 μm HEMTs with InAlAs/AlSb barrier and p^+ GaSb layer within buffer.**
  - f_T = 120 GHz, $f_{T,\ int.}$ = 160 GHz.
  - Composite barrier enables recessed gates.
  - Negligible kink effect.
  - Gate leakage current reduced by order of magnitude.
- **First AlSb/InAs HEMT microwave noise measurements.**
  - 1.0 dB noise figure with 14 dB associated gain at V_{DS}=0.4 V and 4 GHz.
  - Noise modeling predicts 0.3 dB noise figure at 4 GHz with expected technological improvements.
- **Demonstrated 0.5 μm HEMTs with intrinsic $f_T L_g$ product of 50 GHz-μm.**
  - Highest reported for any FET in this gate-length region.
- **Demonstrated 60 nm HEMTs with f_T of 90 GHz at 100 mV.**
  - Highest reported for any FET at this drain bias.
- **Demonstrated 0.1 μm HEMTs with InAs subchannel.**
  - Improved charge control and reduced impact ionization effects.
  - f_T = 180 GHz, $f_{T,\ int.}$ = 250 GHz at V_{DS}=0.6 V.