ABCS, Antimonide Based Compound Semiconductors

- *High speed, low power, electronics, terahertz sources*

Christie Marrian

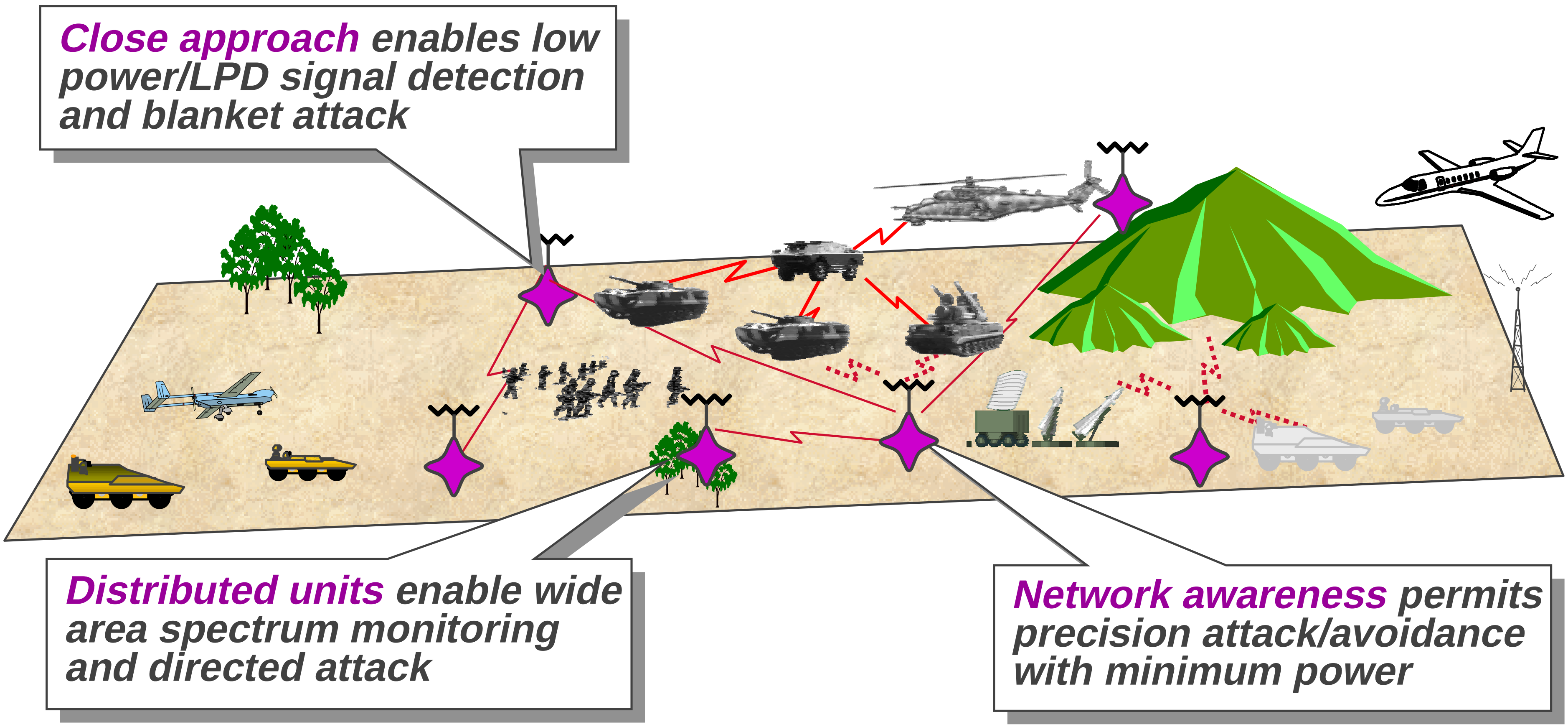
Microsystems Technology Office

Key Personnel

- Contracting Officer's Representatives
  - Colin Wood, ONR
  - Cindy Hanson, SPAWAR
    - Don Mullin, SPAWAR
  - Gernot Pomrenke, AFOSR
- DARPA Team
  - Julia Edwards, BAH
  - Courtney Brown, BAH
- Contractor PIs
  - ……..
  - Barry Gilbert, Erik Daniel, Mayo
  - Suzanne Mohney, PSU
- DARPA PMs


WolfPack Phase II/III
Dr. Paul Kolodzy
WolfPack PM

WolfPack : Operational Concept



WolfPack Technology responds to advanced LPD/LPI, Packet Network Radios

DARPA

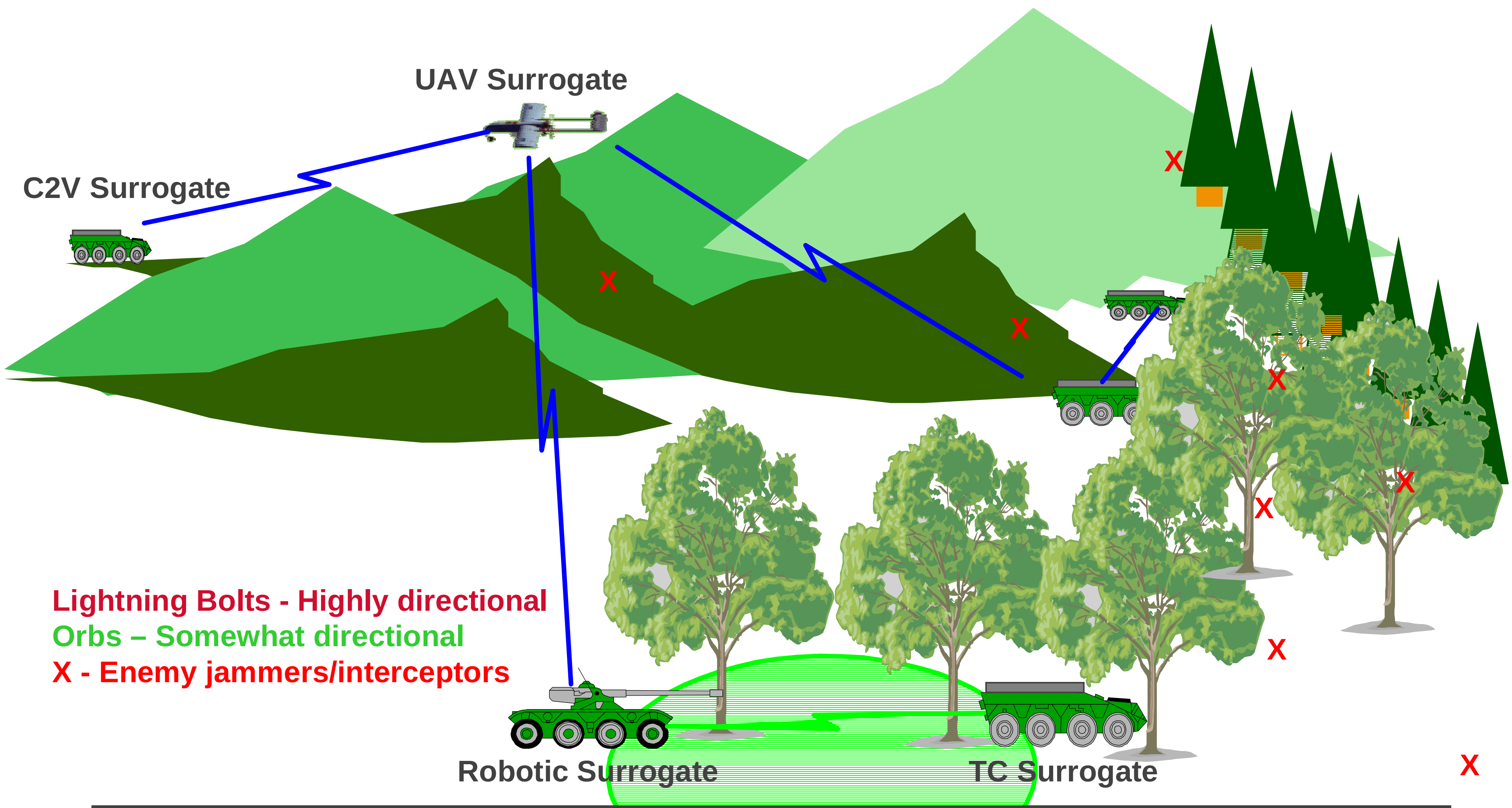
Future Combat Systems

Communications

25 June 2001

Dr. James A. Freebersyser
Program Manager, DARPA/ATO
jfree@darpa.mil
703 696 2296

DARPA FCS-C: Demo



Demonstrate Notional FCS Cell at TRL-5 for PDR by 15 Apr 03

Show Scaling Across Multiple FCS Cells in Simulation by 15 Aug 03

FCS Communications Limiters

<u>Poor Assumption</u>

- There Will Be Sufficient Always On Bandwidth to Support All Users
  - Intel, SA, C2, sensors, robotics, etc.

<u>Three Factors That Will Limit Network-Centric Operations</u>

- Electronic Attack
  - The bad guy will NOT sit idly by; the bad guy will attack the network
  - Detection, interception, jamming, denial of service, etc.
- LOS and Foliage Constraints for Dispersed Operations
  - For disbursed operations, multiple UAVs may be required per FCS cell
- Available Spectrum Is Being Reduced as Demand Increases
  - Exploit higher frequencies (eventually including optical)

Potentially, Each Factor Reduces Bandwidth Available by 10x (1000x Total)

ABCS, Antimonide Based Compound Semiconductors

- *High speed, low power, electronics, terahertz sources*

Christie Marrian

Microsystems Technology Office

DARPA Organization

Director
Tony Tether
Associate Director
Jane Alexander

Advanced Technology
Tom Meyer
William Jeffrey

- Early Entry, Rapid Reaction Forces, Special Forces
- Communications
- Maritime

Defense Sciences
Michael Goldblatt
Steven Wax

- Bio Warfare Defense Technologies
- Biology
- Materials & Devices
- Mathematics

Information Systems
Kathy MacDonald

- Information Assurance & Security
- Command & Control
- Planning & Logistics
- Asymmetric Threat

Information Technology

- Networking
- Embedded and Autonomous Computing
- User Interfaces & Translation
- Software Composition

MicrosystemsTechnology
Robert Leheny
Dave Honey

- Electronics
- Optoelectronics
- MEMS
- Combined Microsystems

Special Projects
James Carlini
Amy Alving

- Biological Warfare Defense Systems
- Surface/Underground Target Engagement
- Sensor/Navigation Sys

Tactical Technology
Allen Adler

- Air, Space, & Land Platforms
- Laser Systems
- Future Combat Systems
- Space-Based Sensors for Surveillance & Targeting

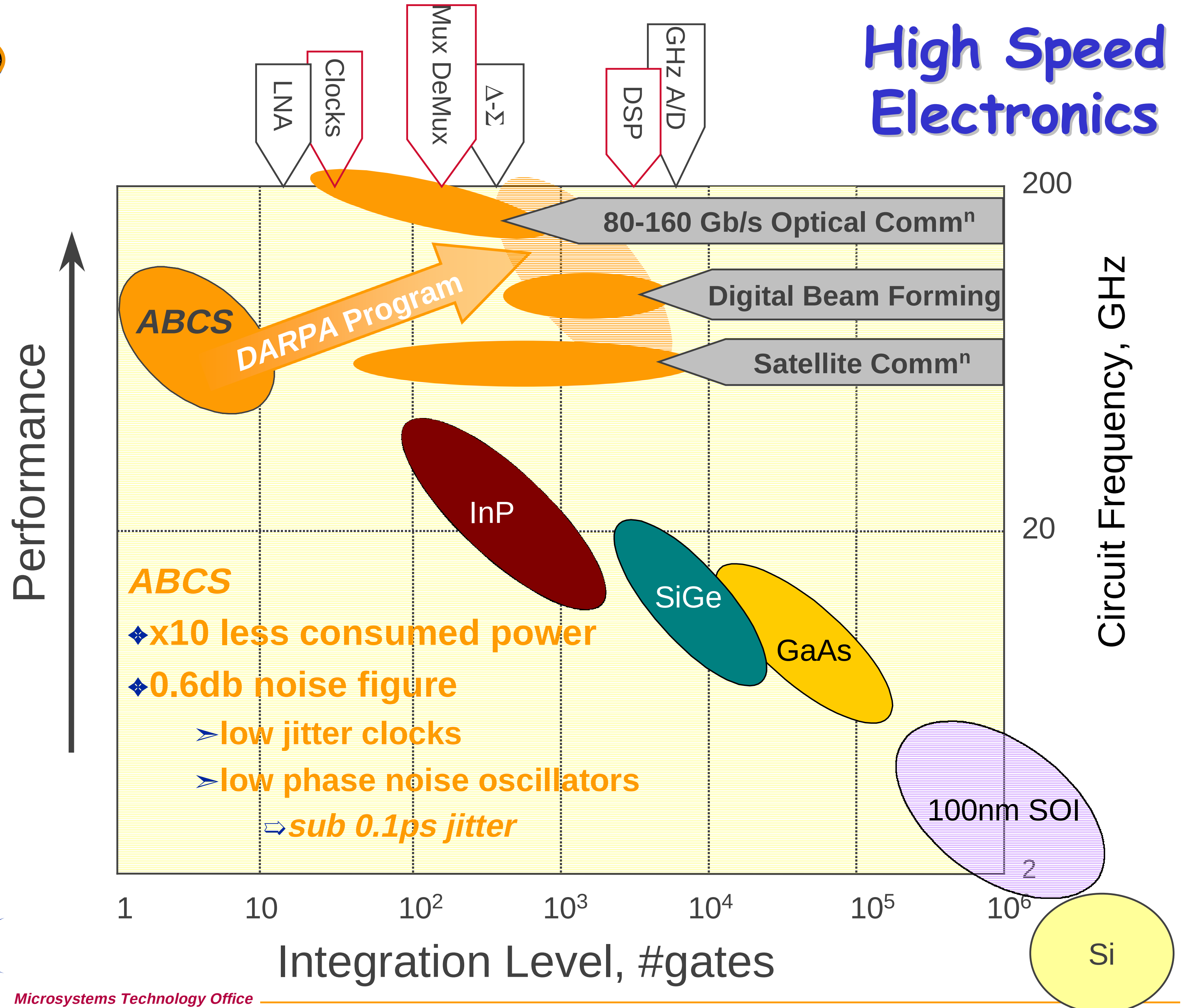
Military Assistant
Col R. Kurjanowicz, USAF

Operational Liaisons
Col R. Kurjanowicz, USAF; LTC G. Sauer, USA

MTO & Microelectronics

- Scaling Si Microelectronics
  - How ‘Nano’ can we go?
  - Mixed signal Si based Microsystems
    - TEAM
  - Heterogeneous integration
    - IRFFE
- Alternative Material Systems
  - Molecular Electronics
    - Devices, Assembly and Architecture
  - ***ABCS* family of Compound Semiconductors**
    - **High speed, Low consumed power**
  - ……

High Speed Electronics



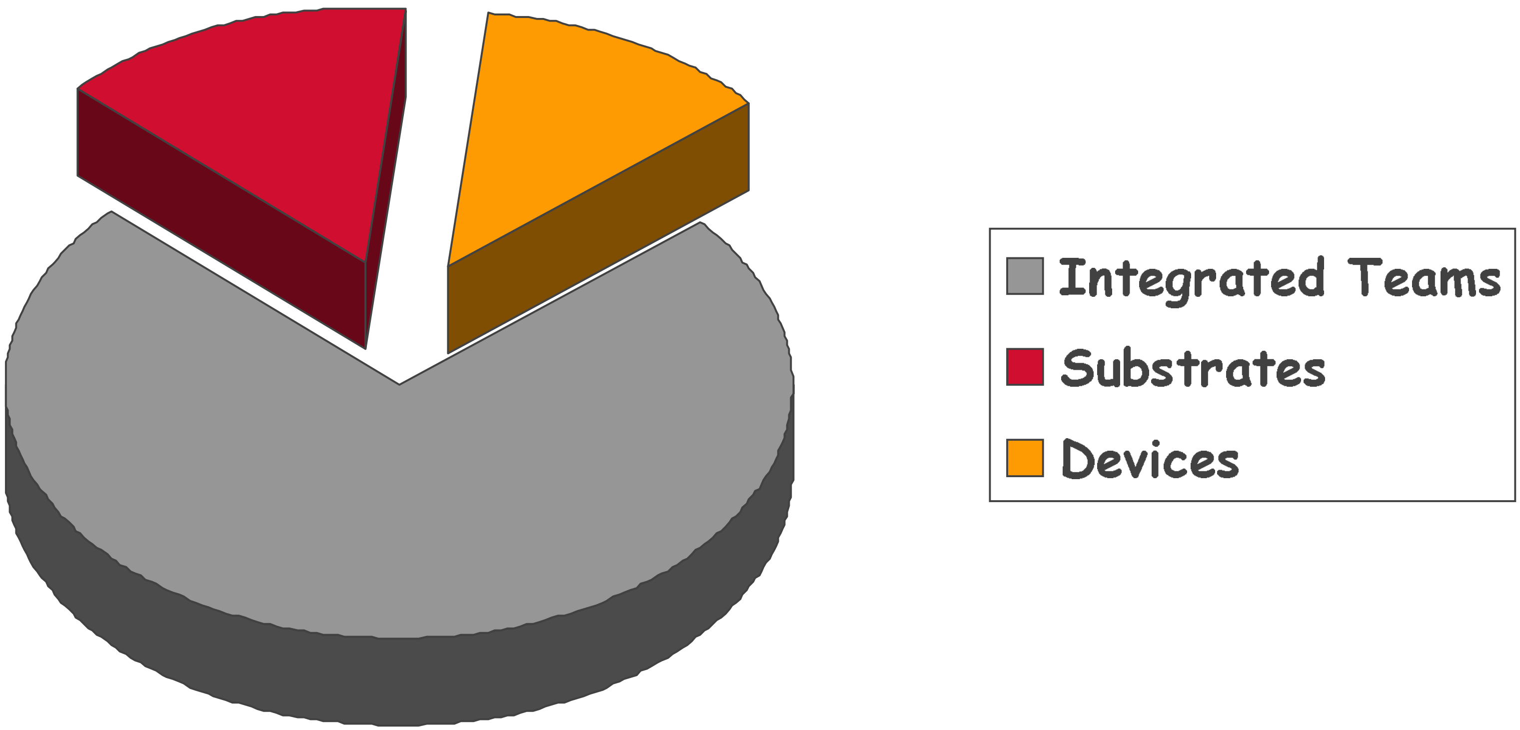
ABCS Program Goals

- Low consumed power, high frequency electronics circuits based on the 6.1 Angstrom family of compound semiconductors (ABCS).
  - *Substrate Technology*. ABCS substrates with $<<10^8$ defects/cm^2 with essentially any desired thermal and/or electronic property
  - ***Electronics Integration*. >5x10^3 devices/circuit through demonstrations of analog, digital or mixed signal circuits which have beyond state-of-the-art performance in terms of frequency of operation and low power consumption**
  - *THz to IR Devices:* Innovative devices that operate in the THz to the IR region of the electromagnetic spectrum

Programmatic Challenges

Task	Challenge	Program Approach
Substrates	Low defect, <$10^8/cm^2$, semi-insulating substrates Availability	◆Lateral overgrowth and bond & etch back ◆Contract substrate deliverables
Low Power, High Speed Electronics	Expanding beyond single transistors Design for 100GHz & low consumed power	◆Develop process technology to integrate 1000's devices ◆Teaming: model-design-layout-fab-evaluate
Exit Strategy	Defining *ABCS* program goals	◆Milestones driven by projected system needs ◆'Customers' involved in evaluation of milestones

Resource Allocation



ABCS Contractors

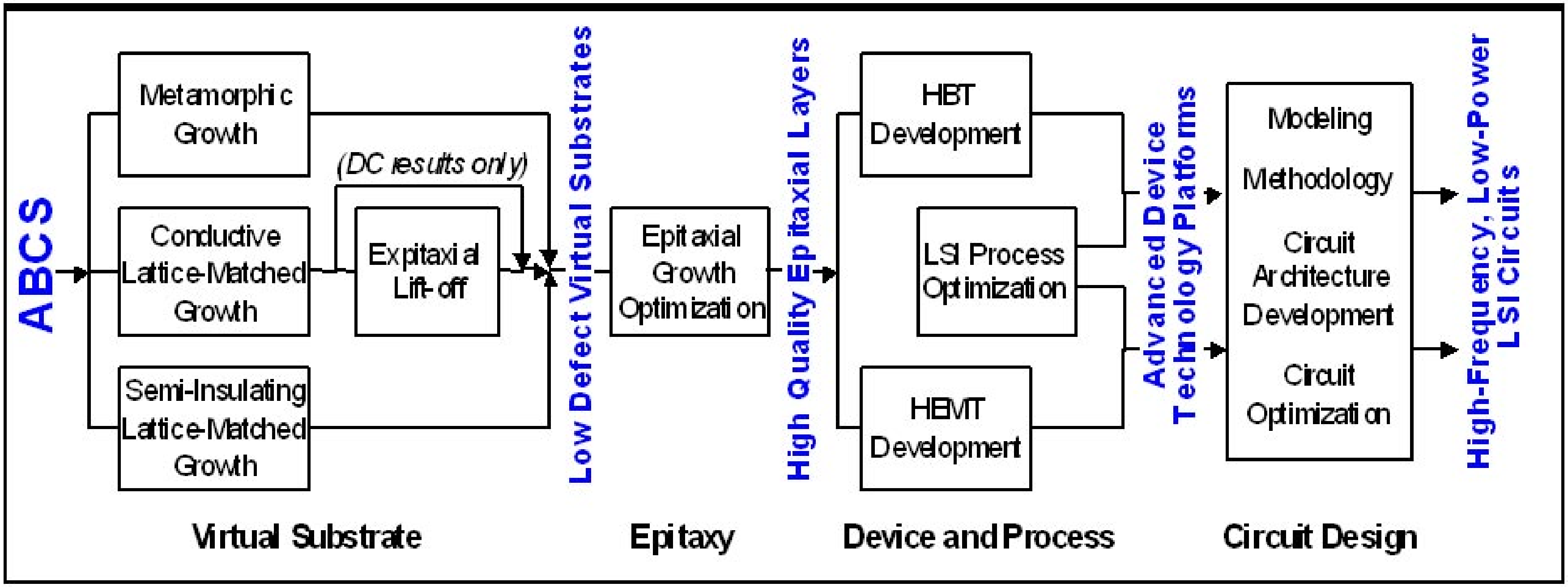
Organization	Project Title
HRL	Antimonide-Based Compound Semiconductor (ABCS)
TRW/NRL	Antimonide-Based Compound Semiconductors (ABCS)
Rockwell/USCB	Antimonide-Based Compound Semiconductor Transferred-Substrate Transistors and Circuits
Lowell/AFRL	Low Defect Density Substrates and High Quality Epi-Substrate Interfaces for ABCS
Columbia	InAs HVT for Extremely Low Power and High Speed Applications
PSU	Contacts to Antimonide-Based Compound Semiconductors
Rice	Antimonide-Based Semiconductor Quantum Wells for Coherent Terahertz Wave Generation
NRL	ABCS IR Sources
Mayo	Mayo SPPDG Collaborative Role in the ABCS Program

DARPA ABCS

TRW Team's Technical Plan

TRW

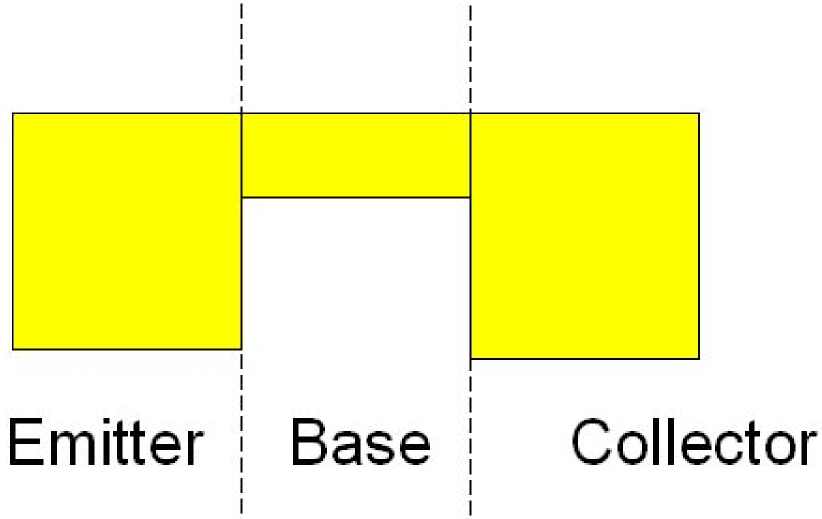
TRW team's technology development flow efficiently addresses the technical issues of 6.1 Å development



ABCS

Ideal HBT

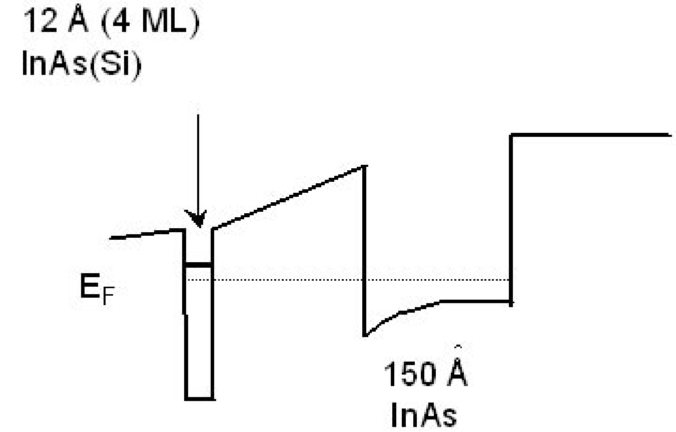
TRW



- The beauty of 6.1A system is the wide variety of materials to design "ideal" semiconductor devices.

High Sheet Charge Density by Modulation Doping using Thin InAs(Si) Layers

InAs 20 Å
AlSb 100 Å
InAs 3 Å
InAs(Si) 9 Å
AlSb 125 Å
InAs 150 Å
AlSb 2.4 μm
GaAs 0.3 μm
SI GaAs substrate

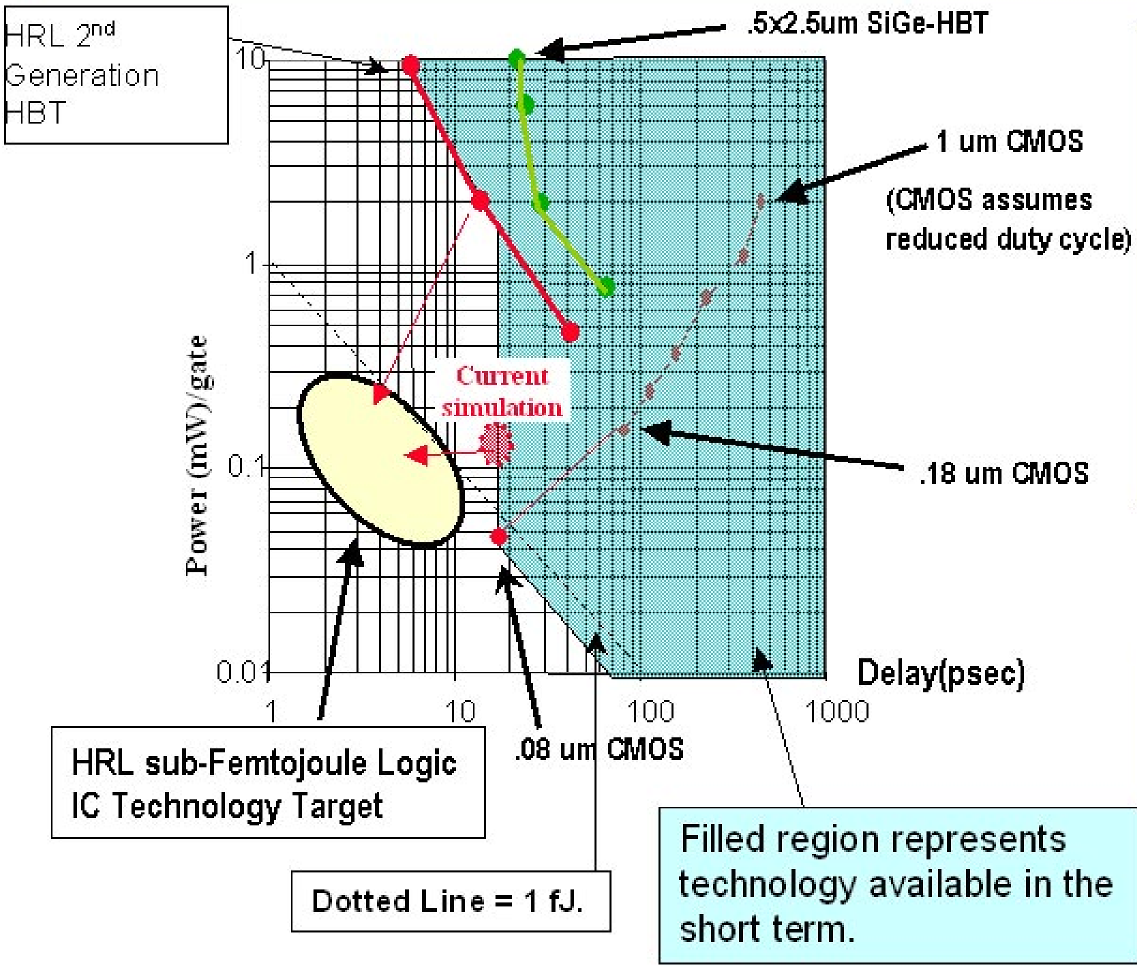


$n_s = 2.5 \times 10^{12}$ cm^{-2} , $\mu = 17{,}000$ cm^2/Vsec

- Used Si doping in a thin (12 Å) InAs donor layer located above the InAs quantum well to achieve high sheet carrier density.
- The large confinement energy of the thin quantum well allows the electrons to transfer into the 150 Å InAs channel.
- Sheet densities as high as 3.2×10^{12} cm^{-2} and 5.6×10^{12} cm^{-2} have been achieved by single- and double-sided modulation doping, respectively.

Ref: *Electron. Lett.*, vol. 34, no. 14, Feb. 1998

Moving towards Higher-Speed and Lower-Power ICs.



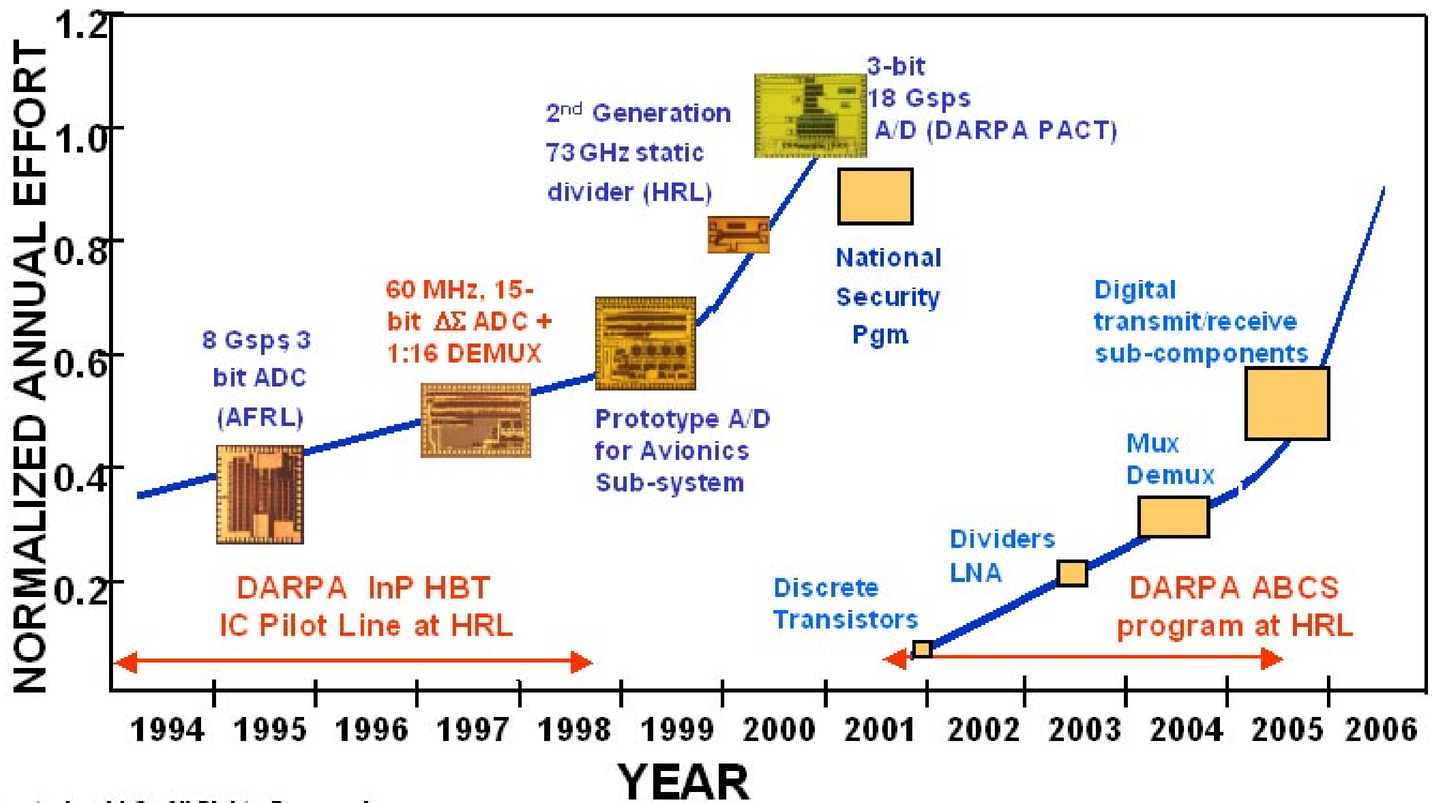
Systems are becoming:

- More mobile (i.e. battery powered).
- More complex (digitally beam-steered phased arrays).
- More demanding (higher bandwidth, mmW frequencies, all digital).

Future systems will need more speed with a large reduction in power-delay.

HRL Model for ABCS Application Insertion Based on InP Experience

- ABCS insertions expected to follow a similar model to InP, but with a shorter development and insertion cycle.
- Uses include integrated sub-components for digital transmit/receive at Ka, Q and possibly V-bands.
- Applications include digital beam-forming for phased arrays.



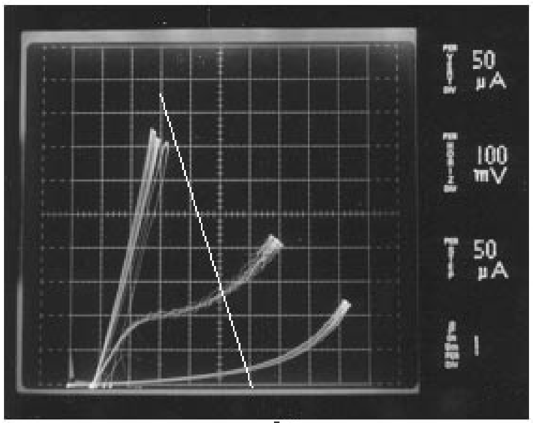
HRL LABORATORIES

HRL Antimonide-Based Compound Semiconductor(ABCS) Program

Antimonide Based Compound Semiconductors ABCS DARPA

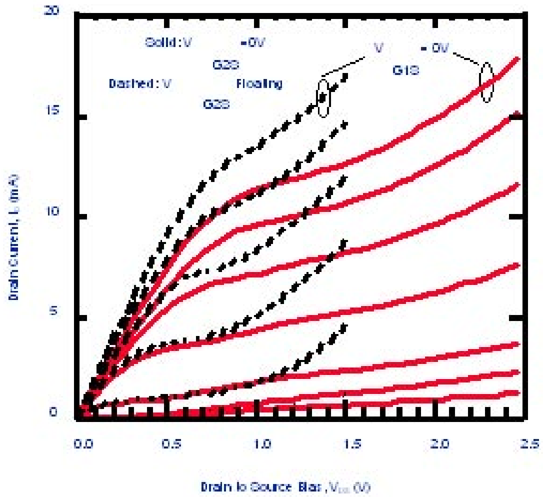
- **Program Tasks**
  - Development of viable alternative substrate technology.
  - Development of advanced ABCS nanometer-scale HEMT IC. Technology.
  - Development of low Vbe ABCS HBT IC Technology.
  - Design and fabrication of mixed-signal/integrated circuits with unprecedented unloaded propagation delay (<4 pS) and power-delay product (<1 fJ).
  - Incorporation into a manufacturable IC process.
  - Development of complex prototypes for possible systems applications.

InAs-based HBT

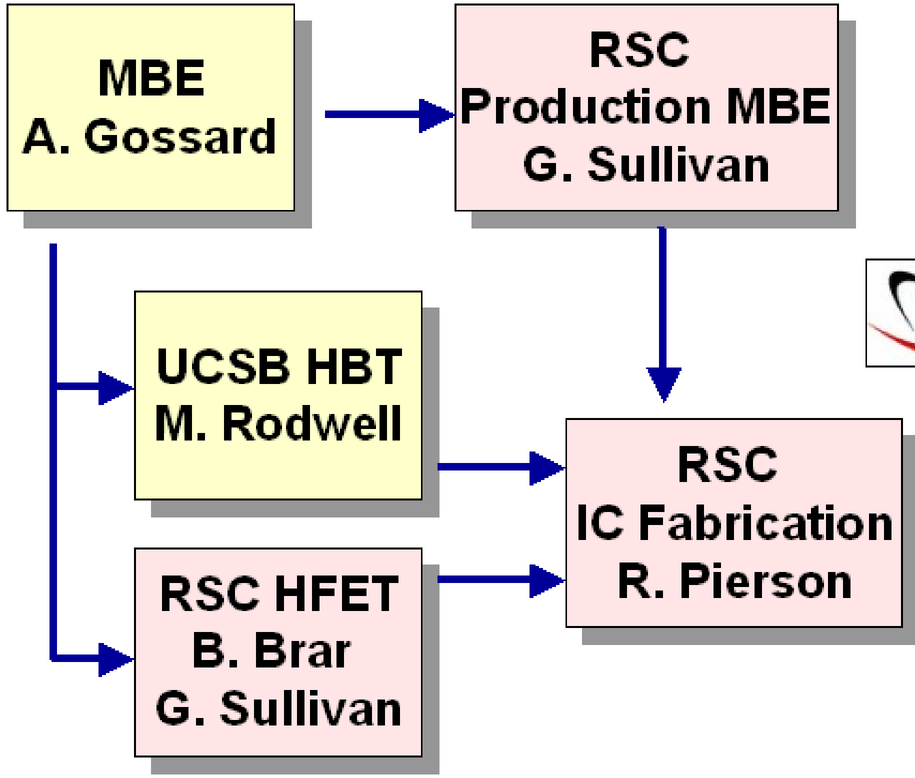


Load Line for 2 levels of logic.

InAs-based HEMT

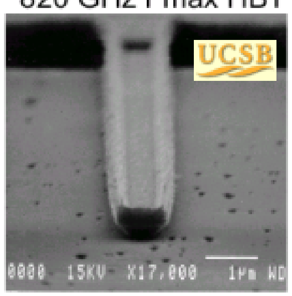


RSC & UCSB ABCS Team

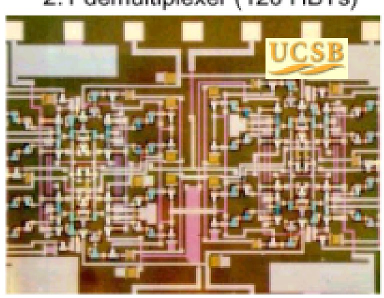


New RSC MBE

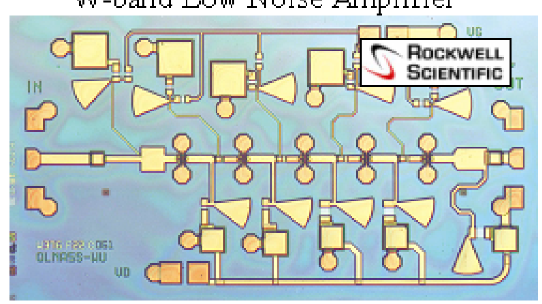
820 GHz Fmax HBT



2:1 demultiplexer (120 HBTs)



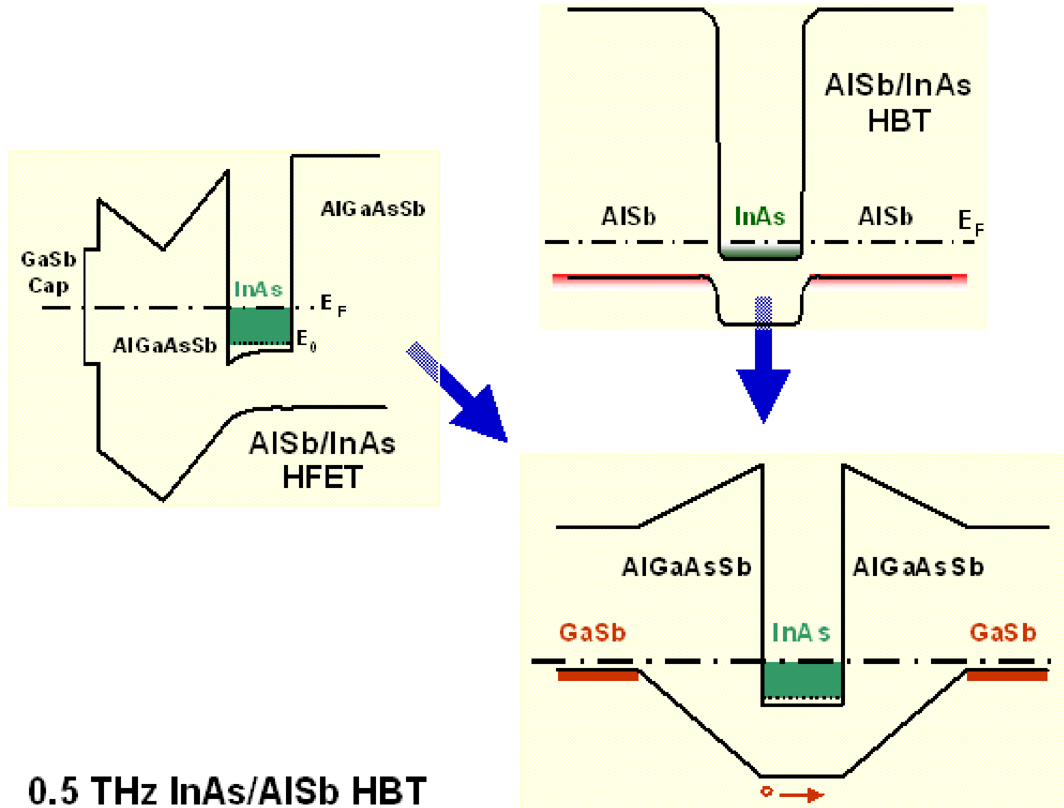
W-band Low Noise Amplifier



Transferred-Substrate Antimonide-Based Devices

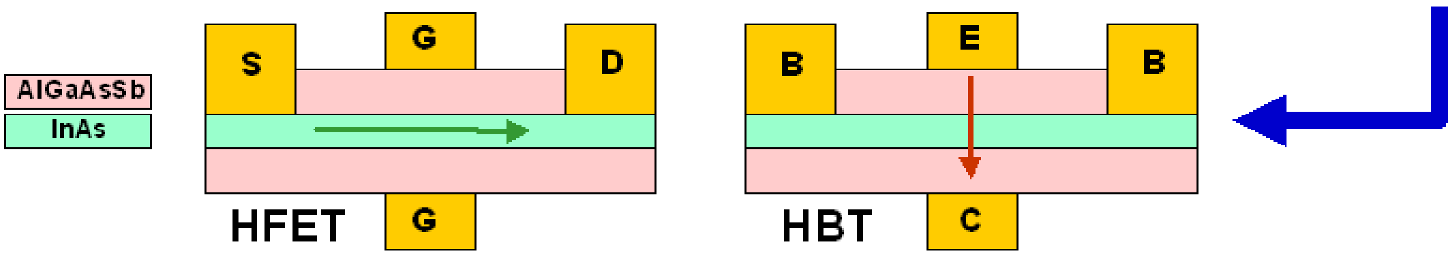
HFETs & HBTs for high-speed low-power circuits

- 0.6dB NF, 12dB gain, 2.4mW W-band LNAs
- 8-channel, 400mW, 80 Gbps MUX/DEMUX
- No Substrate Limitations
- Ultimate Scaling
- Possible HBT/HFET Circuits



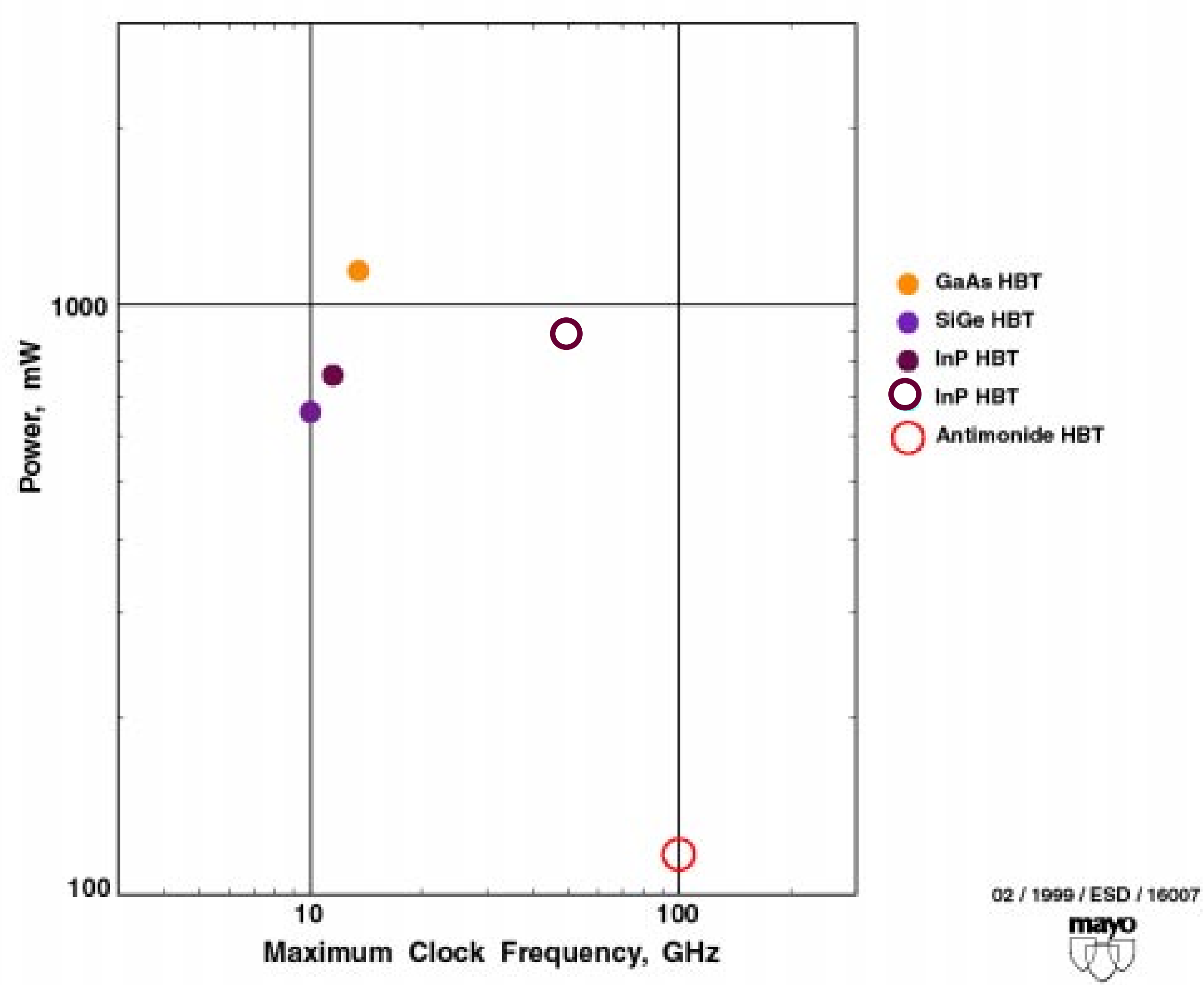
1 THz InAs/AlSb HFET

0.5 THz InAs/AlSb HBT



ROCKWELL SCIENTIFIC

Circuit Design: Improvement with Antimonide HBT



2:1 Mux/Demux HSPICE CML logic circuit simulation

SYSTEM ENABLING CAPABILITIES OF ANTIMONIDE DEVICES: ANTIMONIDES OPEN UP ENTIRELY NEW OPERATING REGIMES IN SPEED/POWER PERFORMANCES

(Numerical Values Based on HSPICE Simulations Conducted at Mayo Foundation Using Representative Analog and Digital Circuits)

APPLICATION	EXISTING TECHNOLOGY		UTILIZATION OF ANTIMONIDES	
DIGITAL RADAR RECEIVER WITH DELTA-SIGMA ADC	LNA: InP E-HEMT 1 dB NF, 8 dB Gain	24 m W	LNA: InAs E-HEMT 0.6 dB NF, 12 dB Gain	3.6 mW
	6 Bit 8 Gsps ADC/DAC: INP HBT	12.0 W	6 Bit 16 Gsps ADC/DAC: Ant. HBT	2.4 W
	14 Bit Delta-Sigma Loop Filter (250 MHz Bandwidth)	10.0 W	14 Bit Delta-Sigma Loop Filter (500 MHz Bandwidth)	10.0 W
	DEMUX: InP HBT 6:48	15.0 W	DEMUX: Ant. HBT 6:96	1.3 W
	Digital: CMOS	2.5 W	Digital: CMOS	5.0 W
	Total:	42.0 W	*Twice the Bandwidth, Less Than 1/2 the Power — Total:	19.2 W
HIGH SPEED OPTICAL TRANSCEIVER LINK	Data Rate: 40 Gb/s Analog Components (TIA, PLL, AGC): InP HBT	4.0 W	Data Rate: 80 Gb/s Analog Components (TIA, PLL, AGC): Antimonide HBT	2.7 W
	Laser Diode (InGaAs):	0.5 W	Laser Diode (InGaAs):	0.5 W
	1st MUX/DEMUX: InP HBT 1:4	1.8 W	1st MUX/DEMUX: Ant. HBT 1:8	0.4 W
	2nd MUX/DEMUX: SiGe HBT 4:32	3.6 W	2nd MUX/DEMUX: SiGe HBT 8:64	7.2 W
	Total:	9.9 W	*Twice the Speed, Same Power — Total:	10.8 W

*2-4x Improvements Are Extremely Important in Many Systems

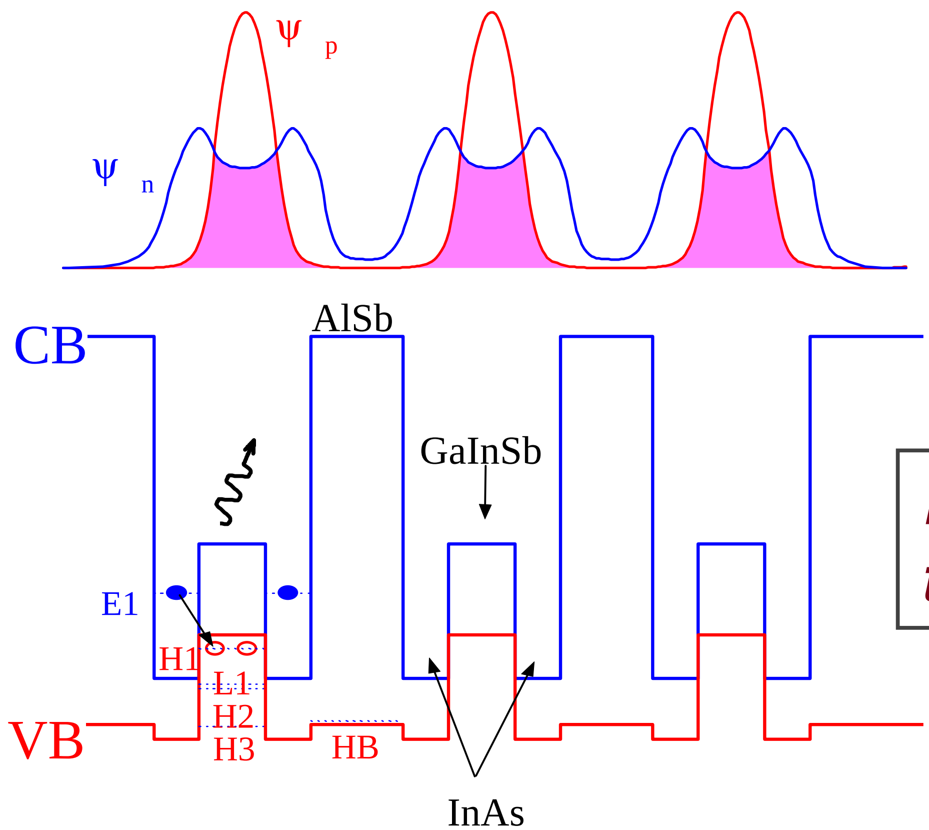
03 / 1999 / ESD / 16131

mayo

ABCS: IR Sources

Raising the Temperature: W Laser

- Reduction of loss mechanisms
  - *10x demonstrated improvement*
- Wavefunction overlap with electrical confinement
  - e^- and h^+ in separate layers

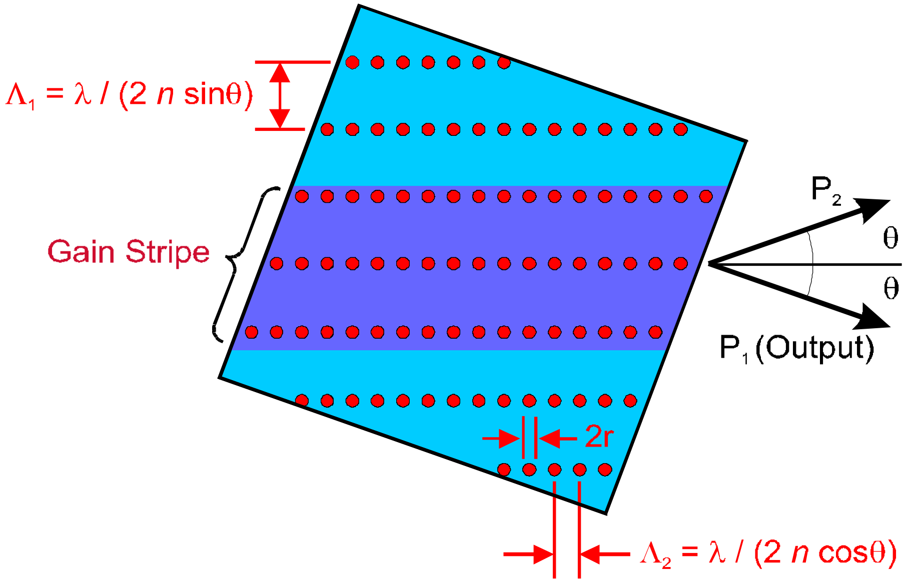


Type-II or Interband Cascade Active Region

Higher temperature operation through bandgap engineering

Meyer et al. APL 67,757 (1995)

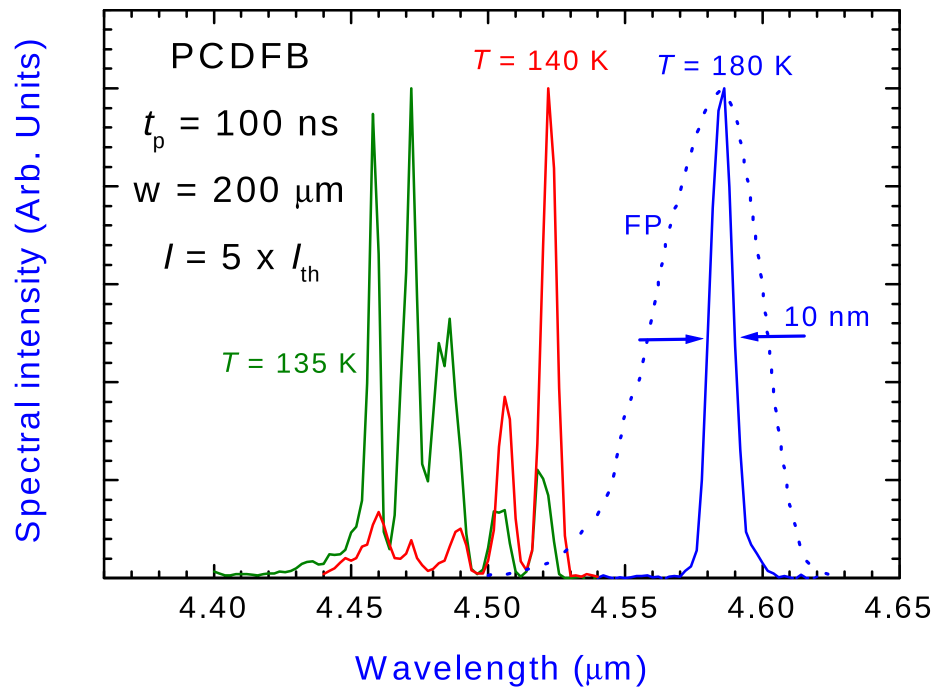
ABCS Photonic Crystal Distributed Feedback Laser (PCDFB)



Distinct from "photonic bandgap" lasers

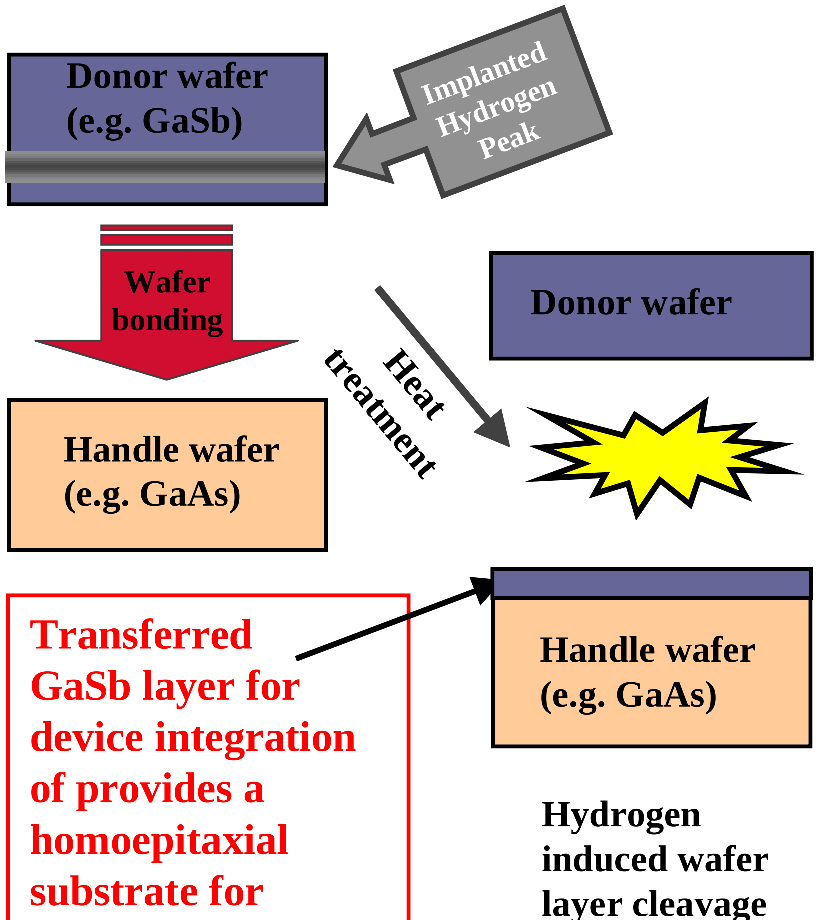
Vurgaftman et al., APL 78, 1466 (2001);
See also: S. Kalluri et al., ASLA, AWA6 (1999)

•2D photonic crystal provides diffraction along two axes
– Combines & enhances best features of DFB (spectral purity) & α-DFB (narrow divergence)



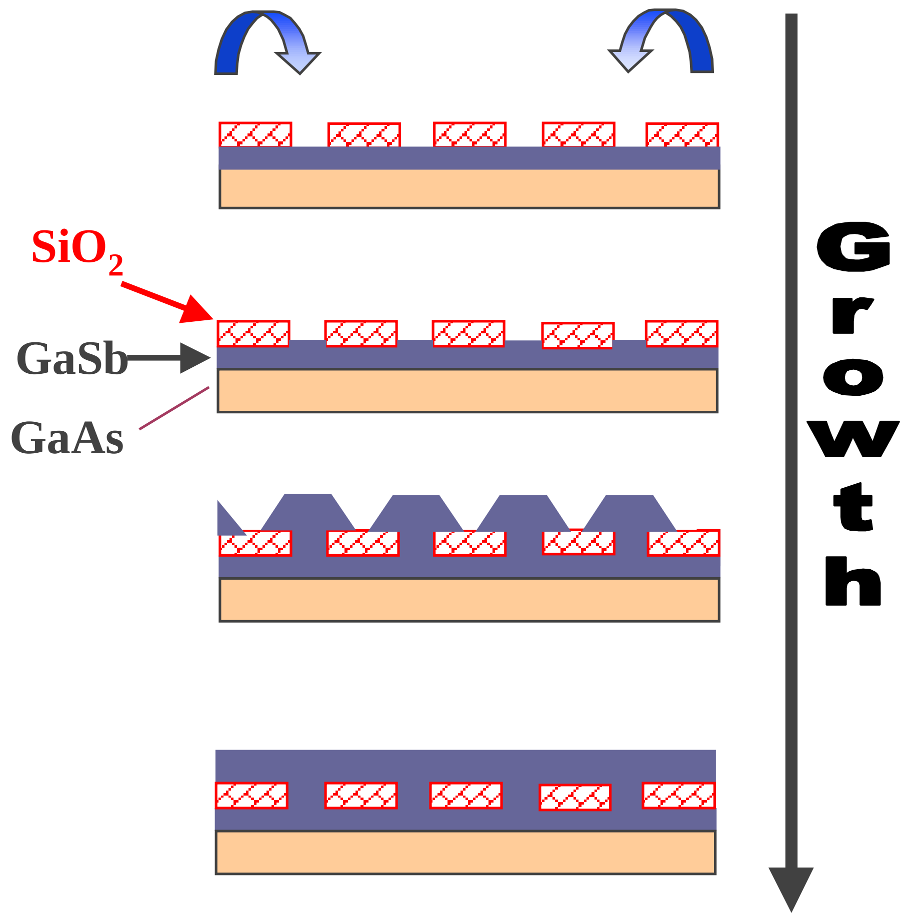
Key Challenge: Substrates

Ion-cut: Substrate formation for device integration



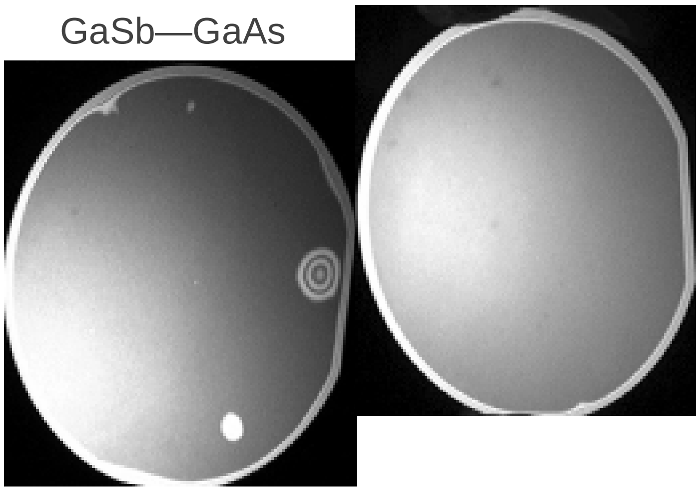
Transferred GaSb layer for device integration of provides a homoepitaxial substrate for device fabrication

Lateral Epitaxial Overgrowth: Low defect density in overgrowth regions



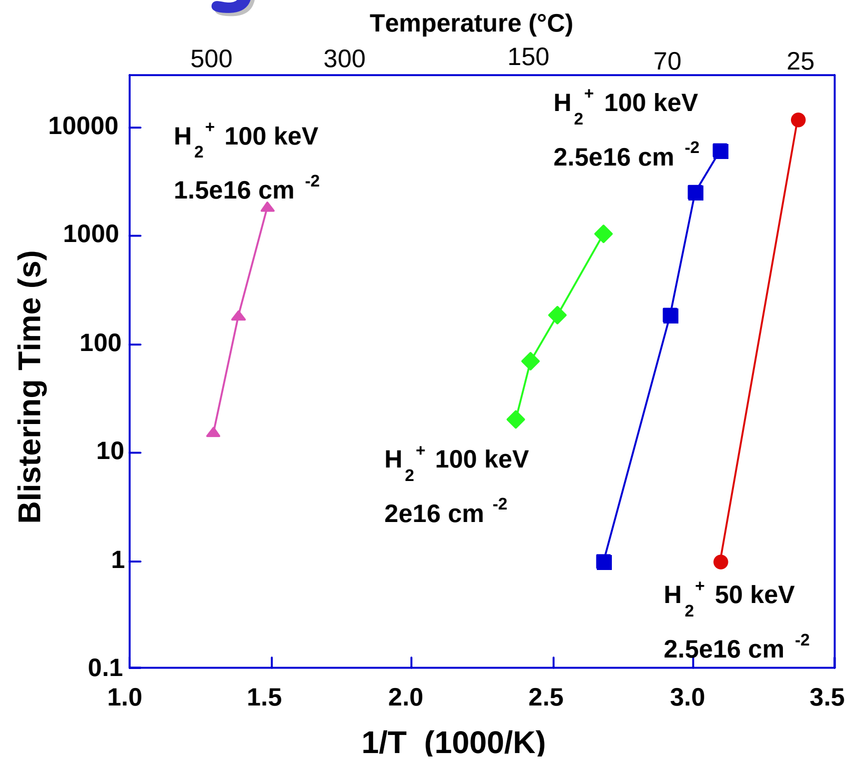
Wafer Bonding

Reflection IR Images



"As bonded" Images of 50 mm wafers

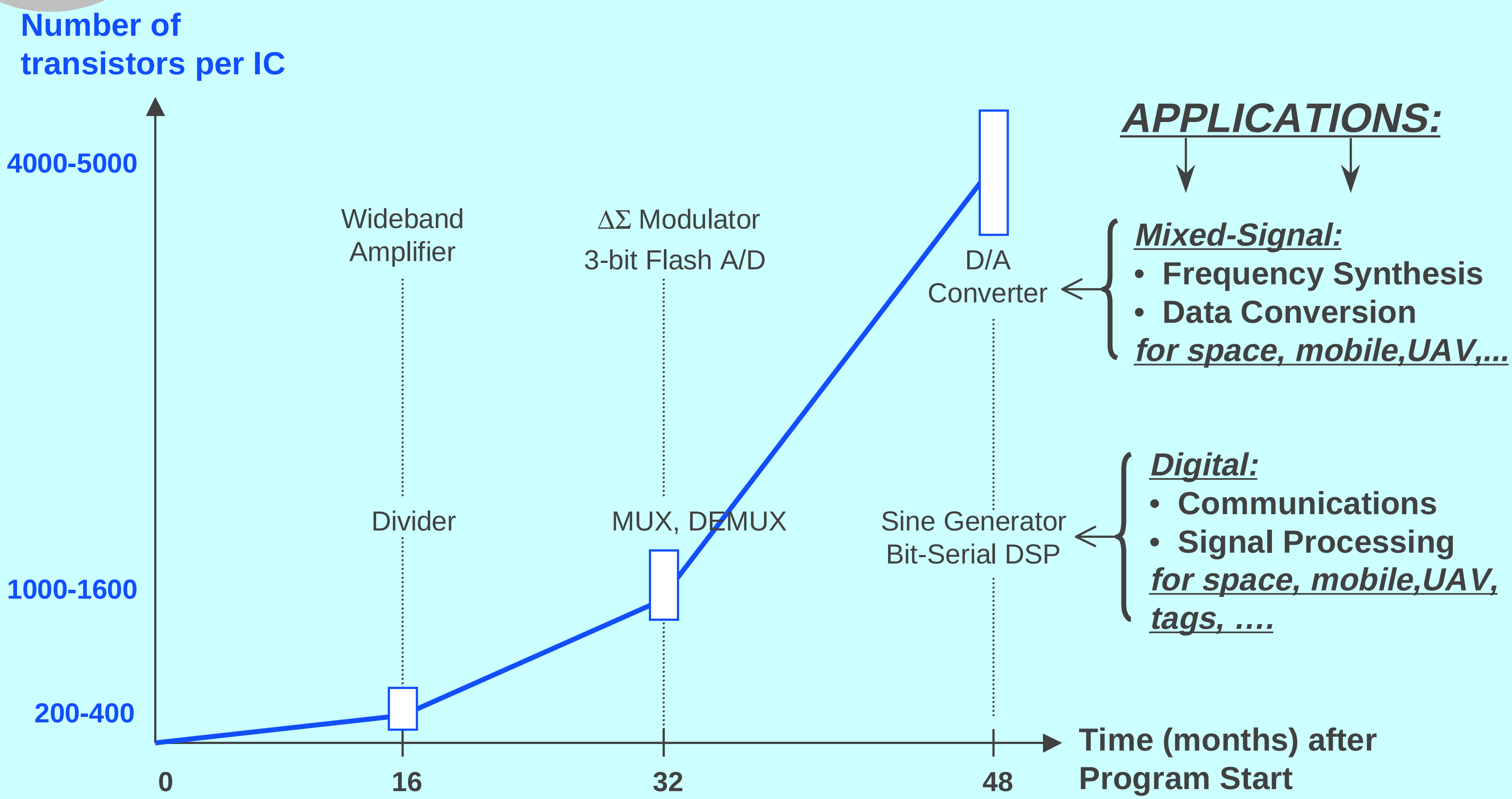
GaSb Splitting Temperature



- GaSb and InAs have poor thermal conductivity, high carrier concentration and low mechanical strength
  - InAs and GaSb ~ 0.01 Ω cm compared to >10^7 Ω cm for SI GaAs
  - Diamond, poly-SiC or poly-AlN for µwave and IR lasers
- Use wafer bonding for high performance substrates for 6.1Å devices
  - SI GaAs substrates (~8% lattice mismatch → 10^8 cm^{-2} dislocations)

ABCS Integration Roadmap

??



Micro Air Vehicles (MAV)

- Goal: Develop and demonstrate MAV less than 15 cm (in any dimension)
- Savings in power consumption important in the lighter MAVs
- High speed increases functionality in all cases (now using off-the-shelf Si-CMOS or SiGe products)
- Processing bottleneck: 1Mbps transmission pipeline and 1MIPS processors (only 2 frames/sec)

MAV Requirements

Specifications	***Lutronix***	***Aerovironment***
Configuration	Rotary	Fixed wing
Dimensions	<15cm	<15cm
Mass	0.30kg	0.06kg
Power Consumption (mW)		
RF Communications	2,500	650
Processing	3,000	25
Sensors	100	<50
GPS	2,000	<400
Propulsion	72,400	5,000
Total Power	**80W**	**6.2W**

ABCS electronics will result in less power consumption and more functionality (high speed)

ABCS Technical Issues

- Low voltage operation & noise margins
  - Innovative device design with bandgap engineering
  - III-V MOSFET
- Semi-insulating Substrates
  - Delaminating and rebonding
  - Metamorphic epitaxial growth
  - ‘Novel’ lattice matched substrates
- Circuit design
  - Third party assistance through MAYO
  - NEOCAD circuit demonstrations

Technical Challenges

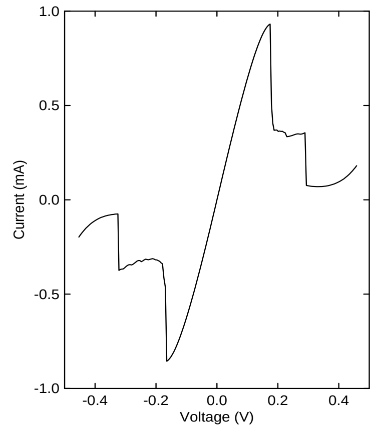
- Substrates
  - semi-insulating for high frequency circuits
  - lower defect levels
    - minority carrier devices
- Integration
  - unique material and processing requirements to achieve combined functionality
    - 1000's of devices
    - HBT, HEMT + RTD for high frequency and low power
- Circuit design
  - overcome device-circuit technology gap
    - circuits can lag device performance by several generations
  - ensure viable noise margins for 0.5 V operation

Material Comparison

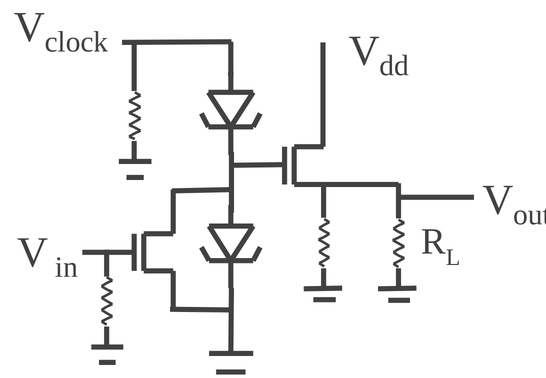
	InAs	$In_{0.53}Ga_{0.47}As$	GaAs	InP
Electron Effective Mass (m^*_Γ / m_0)	0.023	0.041	0.067	0.077
Electron Mobility (cm^2/V-sec @ 300K, $N_D=10^{17} cm^{-3}$)	16000	7800	4600	2800
Γ- L Valley Separation (eV)	0.9	0.55	0.31	0.53
Electron Peak Velocity (10^7cm/sec)	4.0	2.7	2.2	2.5
Energy Bandgap (eV @ 300K)	0.36	0.72	1.42	1.35

Sb-Based RITD/HEMT Logic Circuits

RITD

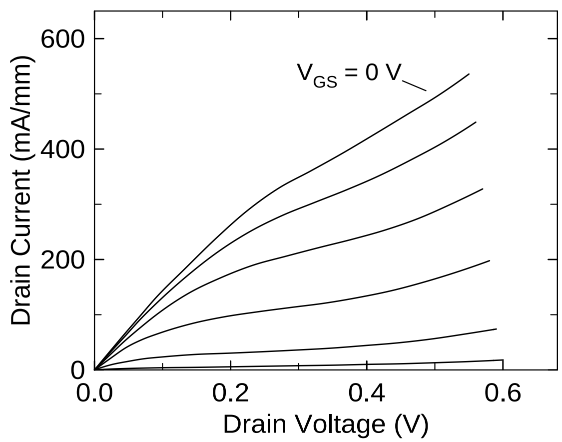


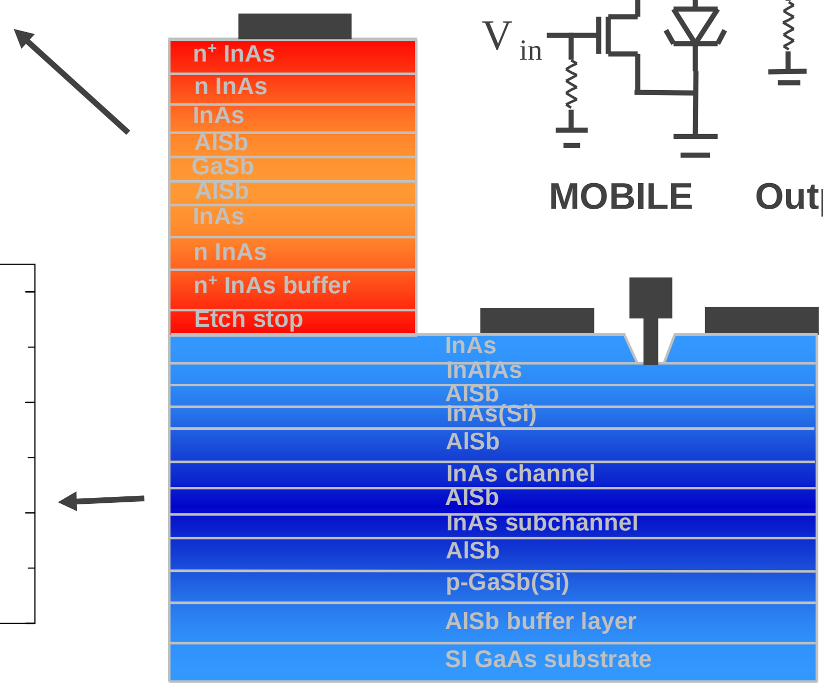
MOBILE-based flip-flop



MOBILE Output buffer

0.1 µm HEMT

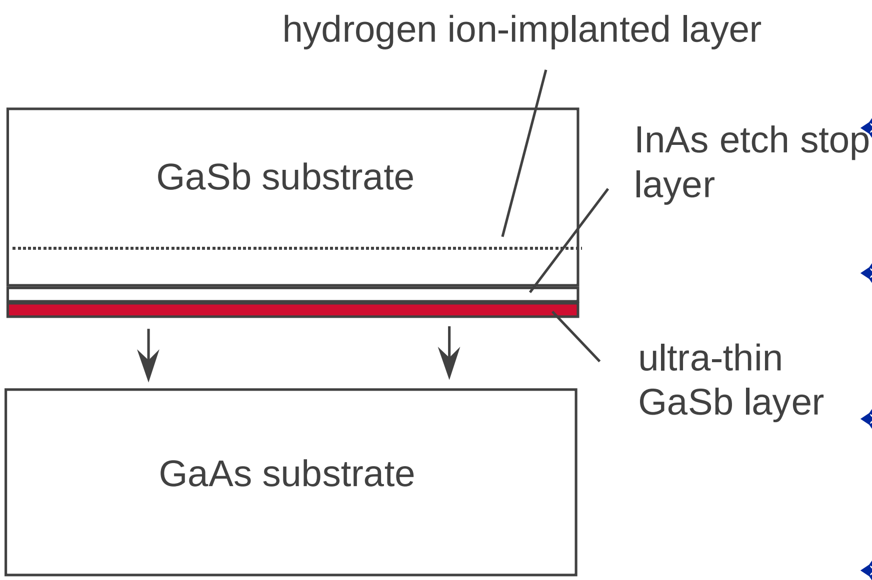




- Demonstrated material growth and fabrication technology required for integration
- HEMT and RTD performance is comparable to that obtained on discrete devices

Making Ultra-Thin GaSb Layers on GaAs Substrate

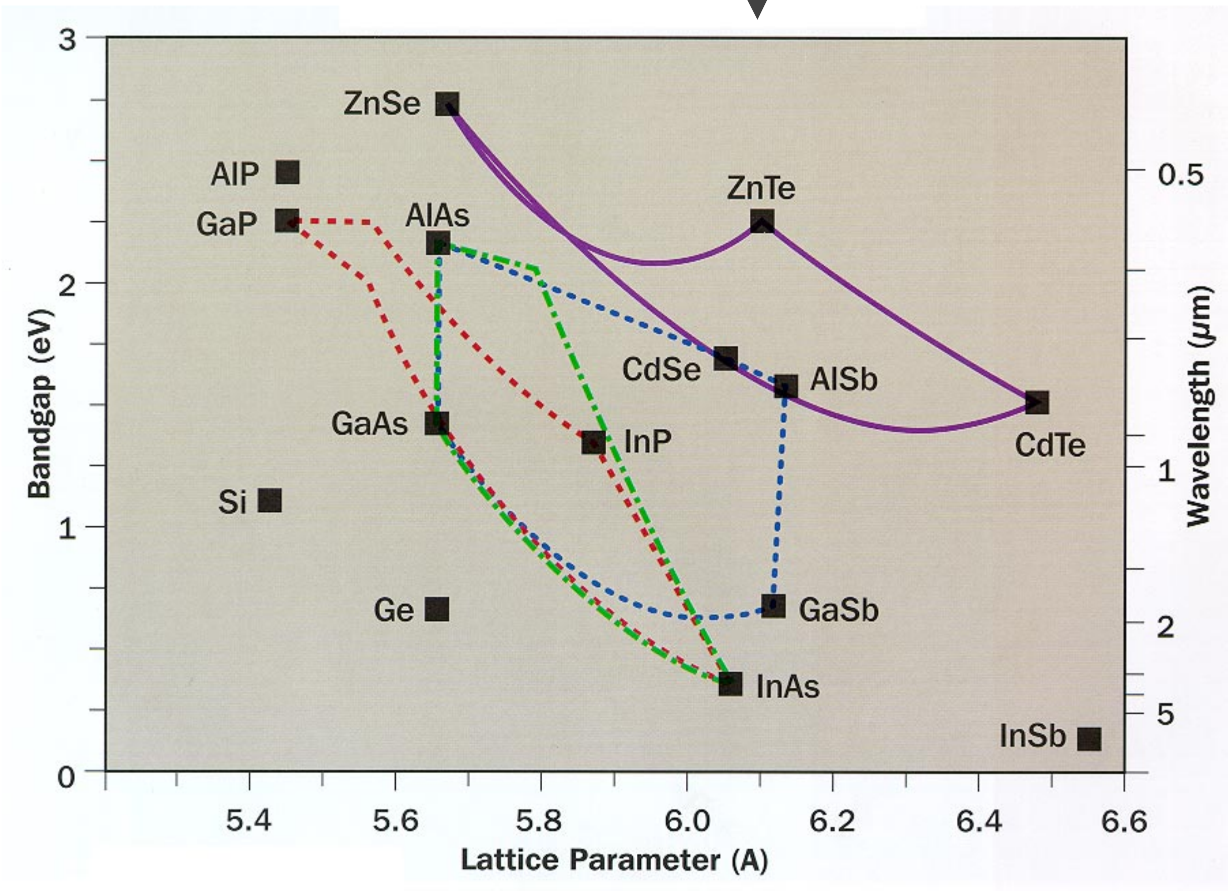
"Ultra-Cut" Process



- Grow 25 nm InAs/GaSb layers on GaSb substrate.
- Implant hydrogen into GaSb substrate (peak is 100 nm below surface).
- Direct bond the GaSb surface to GaAs substrate.
- Heat wafer-bonded pair to split off GaSb substrate (Smart-Cut).
- Etch 100 nm of GaSb and stop at InAs layer.
- Etch InAs layer and stop at GaSb layer.
- Grow dislocation-free HEMT layers.

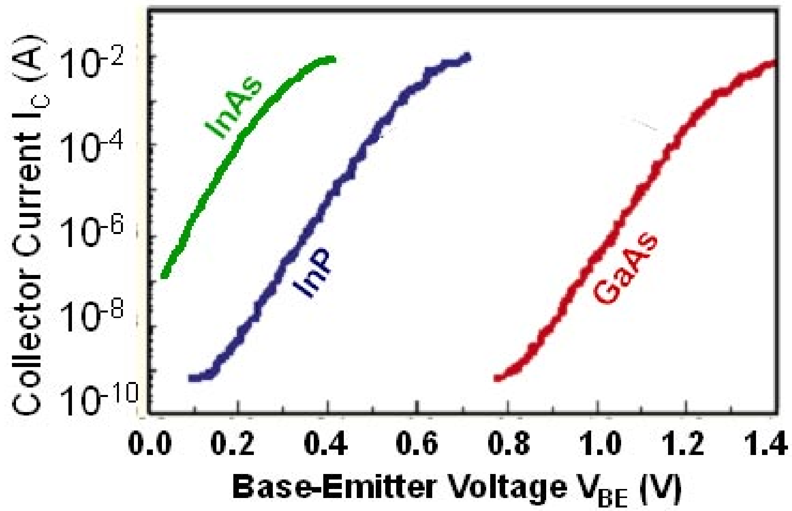
AlSb/InAs/GaSb Material System

“6.1 Å” III-V Materials



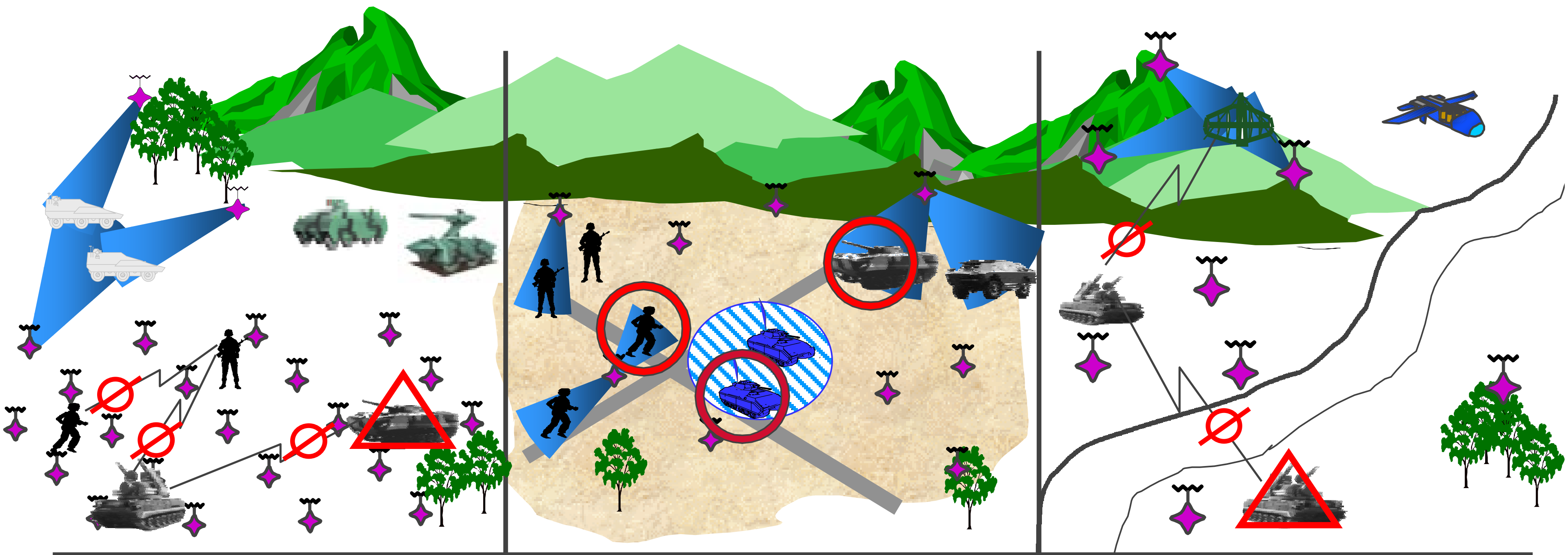
InAs HBT Technology

- A key use of InAs technology is for low power, high speed digital.
- Narrow bandgap materials have lower HBT Vbe turn-on voltage.
- Digital circuit designs have several Vbe stacks to the bias supply.
- The low InAs Vbe allows for either reduced power supply or increased gate functionality.



WolfPack : Operational Missions

Electronic Attack	Electronic Protect	Distributed Suppression of Enemy Air Defenses



- **Extend RF Situation Awareness / Response**
  - Selectively deny communications
  - Precision target info
  - Provide tactical deception

- **Provide Safe Zone for Allied Operations**
  - Precision 3D location
    - Red / Blue
  - Deny adversary comms
  - Raise noise floor for cloaking of allied signals

- **Enhance SEAD Lethal / Non-lethal Response**
  - Precision emplacement
  - Suppress IADS
    - Communications
    - Radars
  - Precision target Info

Movies: Can be effective……

WolfPack: Concept……………….