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Millimeter-wave Research at NRL in the IoT Age

RWW2020: IoT Vertical and Topical Summit

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Some IoT Concerns:

- Privacy
- Security
- Attacks
- Volume of Data
  - Processing
  - Management

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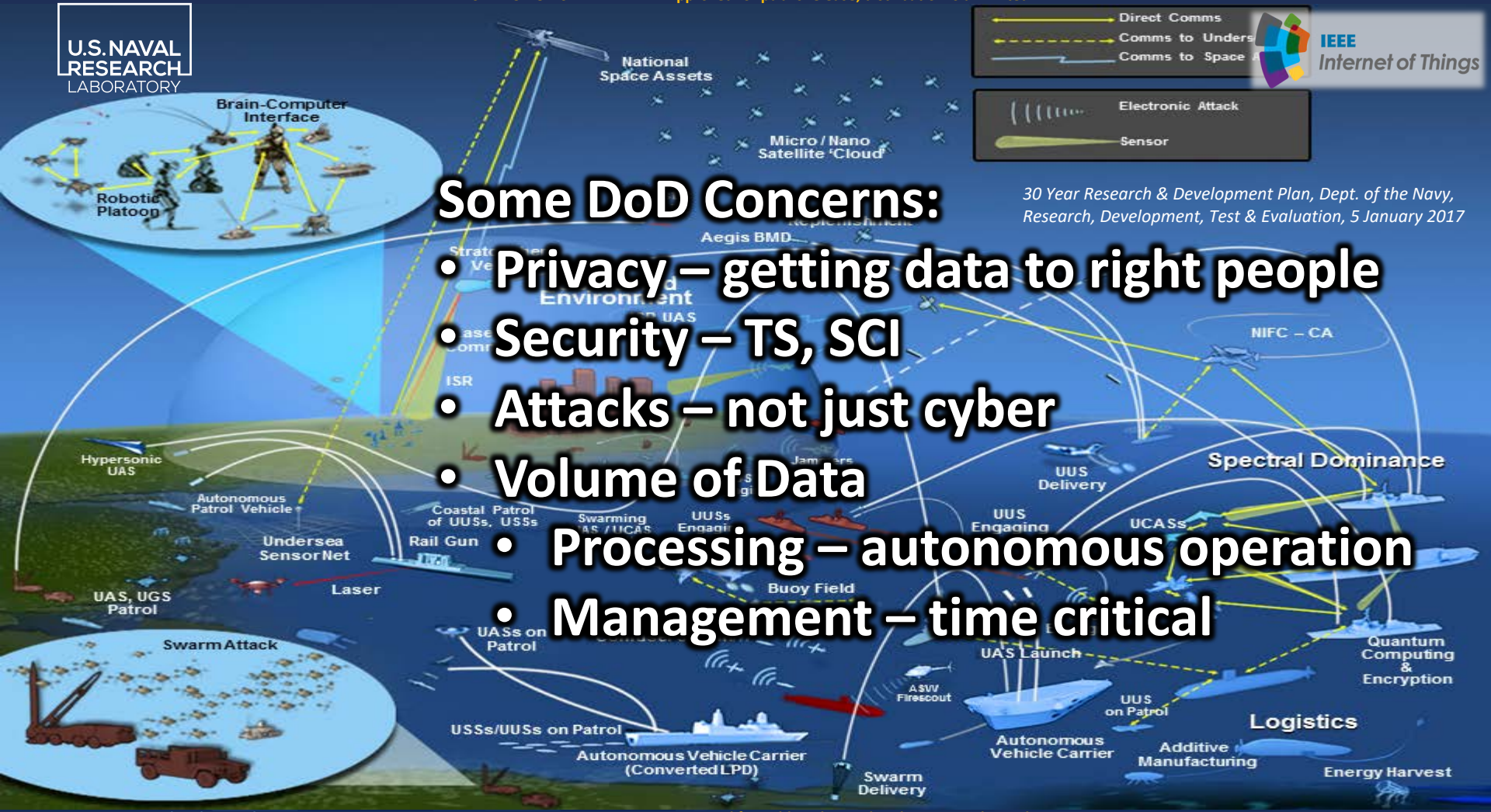

Some DoD Concerns:

- Privacy – getting data to right people
- Security – TS, SCI
- Attacks – not just cyber
- Volume of Data
- Processing – autonomous operation
- Management – time critical

30 Year Research & Development Plan, Dept. of the Navy, Research, Development, Test & Evaluation, 5 January 2017

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Millimeter-wave Benefits and Challenges

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Application	Benefits	Challenges
Communications	Large channel capacity (data throughput), high directionality, low probability of detection and intercept, spectrum availability	Efficiency, control components, passives, atmospheric losses (upper mm-wave)
Radar (Active Imaging)	High resolution, high directionality, “see” through dust, smoke, etc.	Atmospheric losses (upper mm-wave), power, efficiency
Electronic Warfare	Counter to emerging threats (exploiting 5G and other commercial technologies)	High bandwidth, control components, passives, power, efficiency
Passive Imaging	High resolution, high directionality, “see” through dust, smoke, etc.	Atmospheric losses (upper mm-wave)
Power Transmission	Narrow beamwidth, high directionality	Efficiency
Directed Energy Weapon	Narrow beamwidth, high directionality, more difficult to harden against	Power, efficiency, electric field breakdown, power supply, control components, passives, frequency agility

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Channel Capacity Advantage at mm-waves

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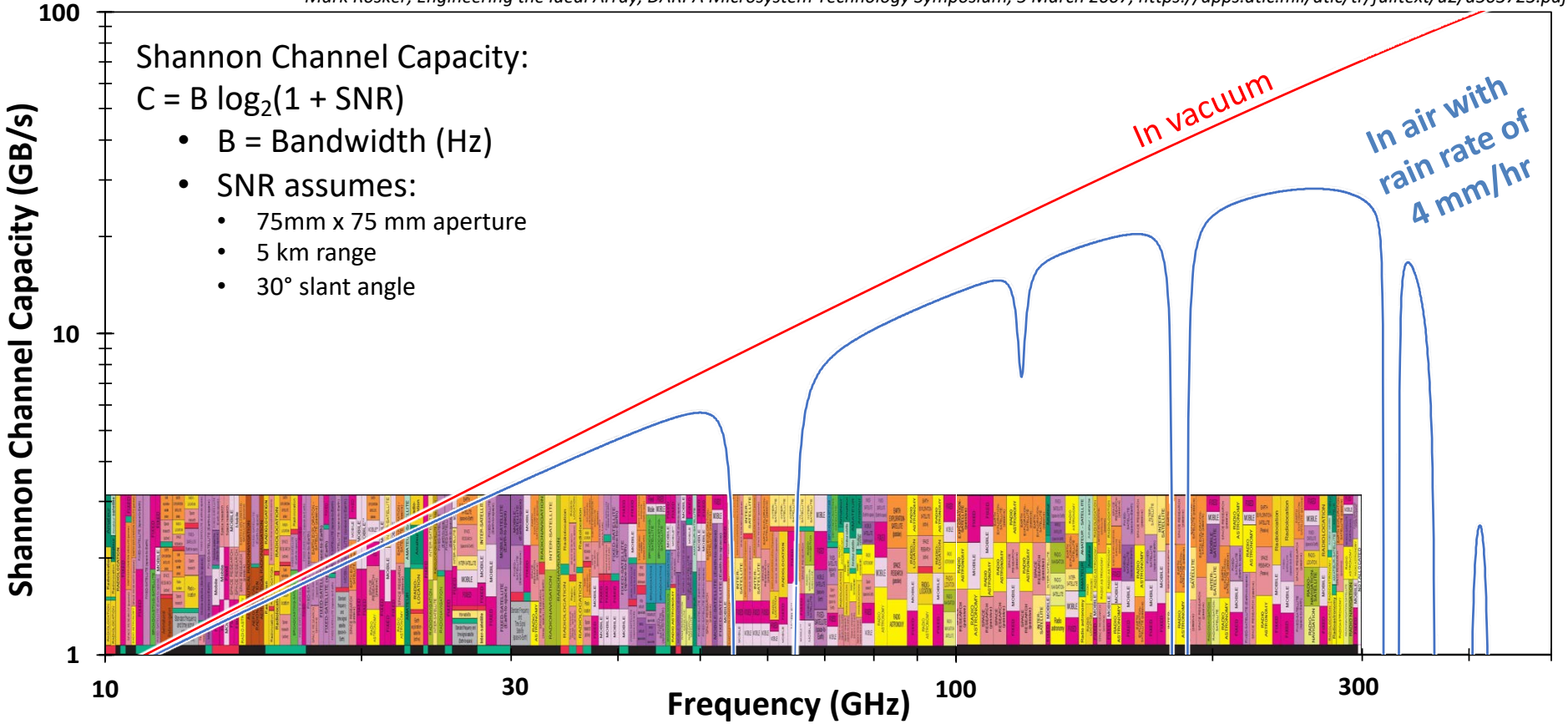
Mark Rosker, Engineering the Ideal Array, DARPA Microsystem Technology Symposium, 5 March 2007, https://apps.dtic.mil/dtic/tr/fulltext/u2/a503723.pdf



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Meeting the Challenges

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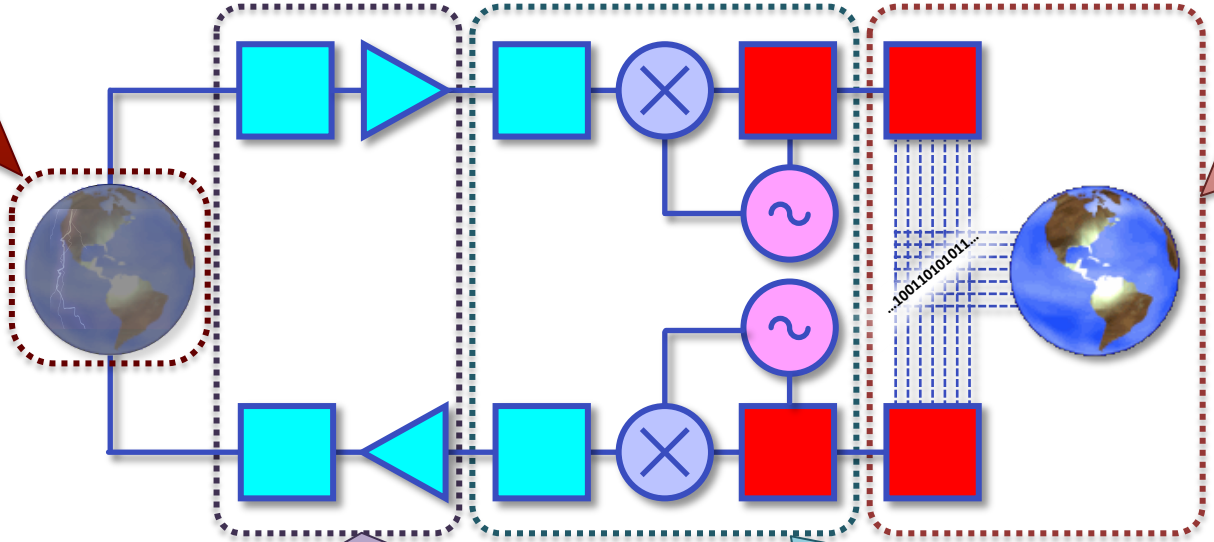
Canonical System

Dynamic, Interference, Jamming, Noise, Wideband



Affordability, Autonomy, Computational horsepower, Efficiency, Machine learning, Networkability, Non-von-Neumann architectures

Affordability, Dynamic range, Efficiency, High power, Linearity, Low noise, Sensitivity, Shared aperture

Affordability, Agility, Adaptability, Linearity, Low Loss, Reconfigurability, Wideband

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Vacuum Electron Device Components

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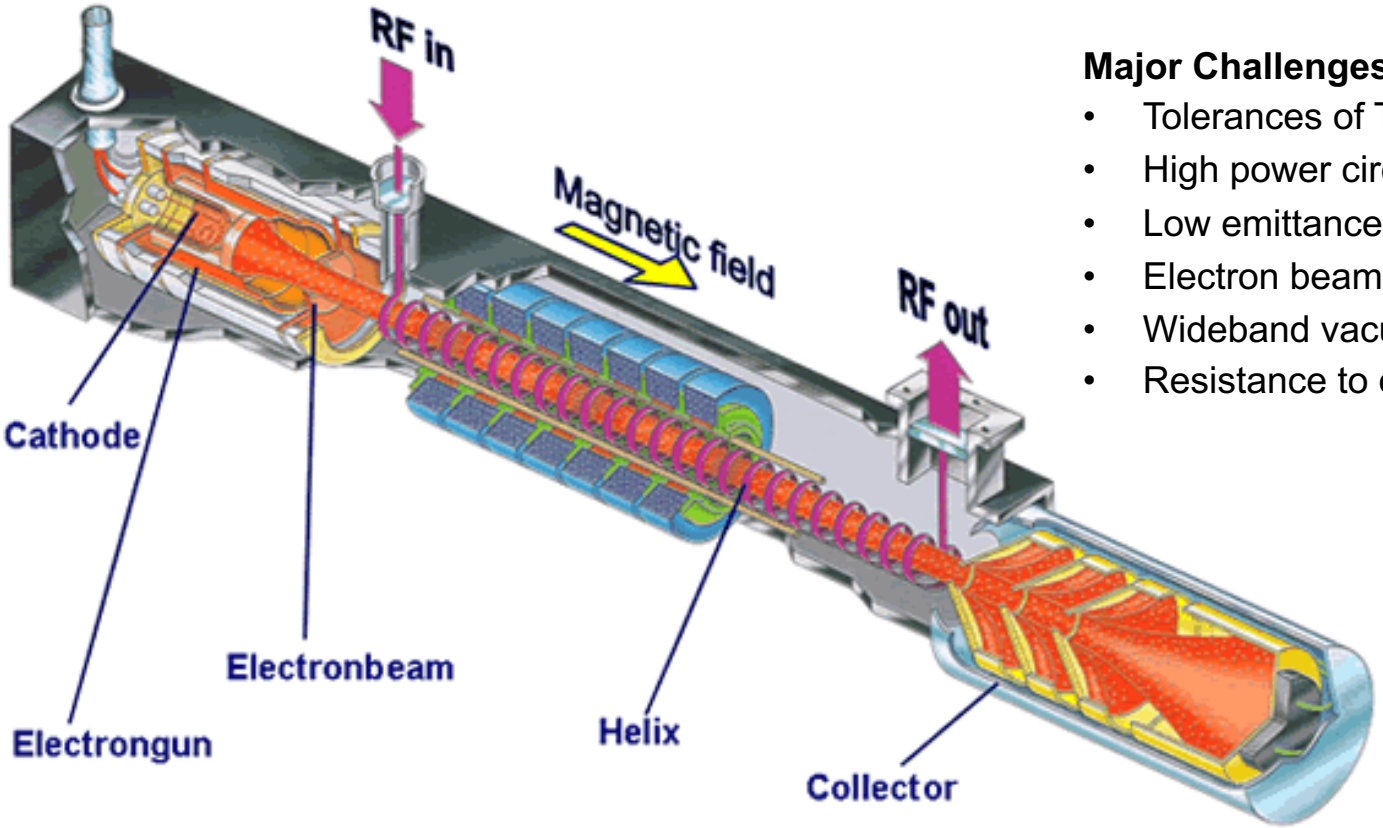

Major Challenges:

- Tolerances of TWT circuits
- High power circuit microfabrication
- Low emittance electron beam generation
- Electron beam transport
- Wideband vacuum windows
- Resistance to oscillation at high gain

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TWT Circuit Additive Manufacturing Approaches

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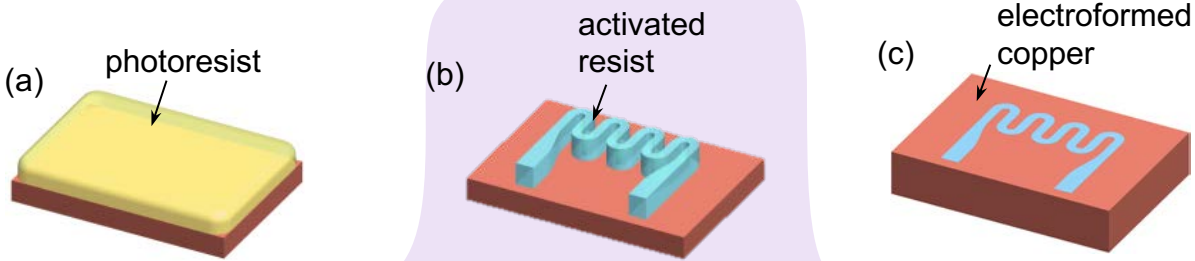
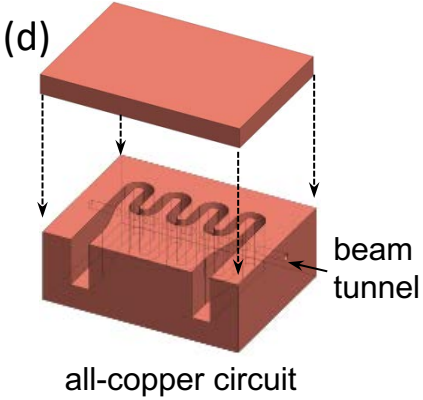
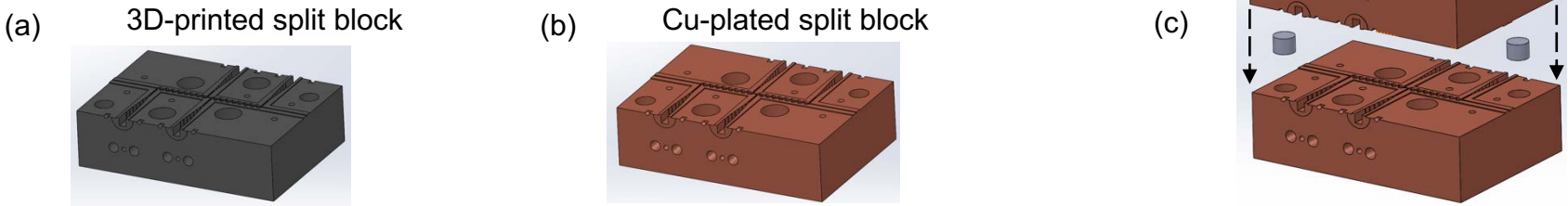
1. UV lithography and copper electroforming (UV-LIGA):





2. 3D-printed mold electroforming (3D-PriME)
   - Build circuit form using 3D printer rather than UV lithography

3. Direct 3D printing, with surface electroplating:



Alan Cook, et.al., IEEE Access Vol. 7, p. 72561-72566 (2019)

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TWT Circuit Additive Manufacturing

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W-band serpentine waveguide traveling-wave circuit fabricated by 3D printer, after Cu electroplating:

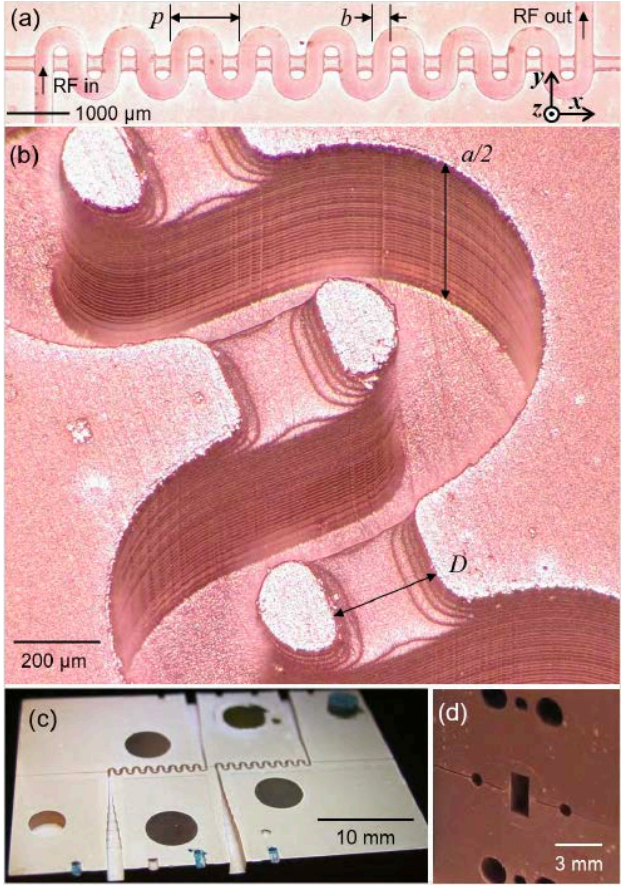
(a) Half of split-block circuit, top view.

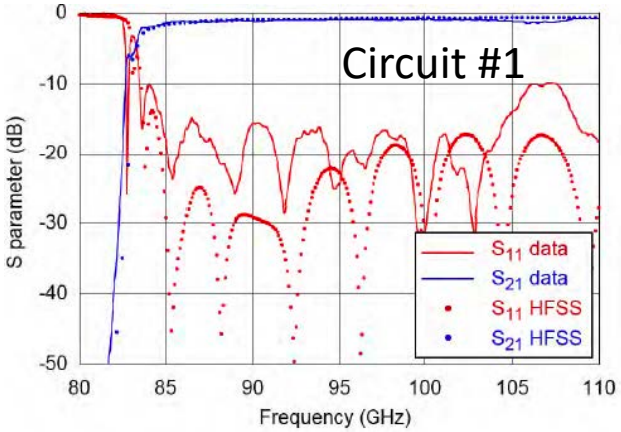
(b) Detail view of circuit; fine corrugations in waveguide wall due to 3D-printed layers are visible.

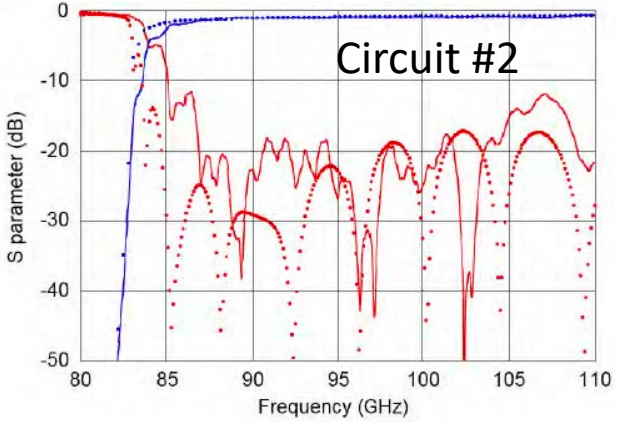
(c) Bottom half of split block, containing two circuits, integrated waveguide transitions, and alignment holes.

(d) WR10 waveguide opening when split block is assembled.

Alan Cook, et al., IEEE Access Vol. 7, p. 72561-72566 (2019)







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WBG and Ultra-WBG mm-Waves Materials

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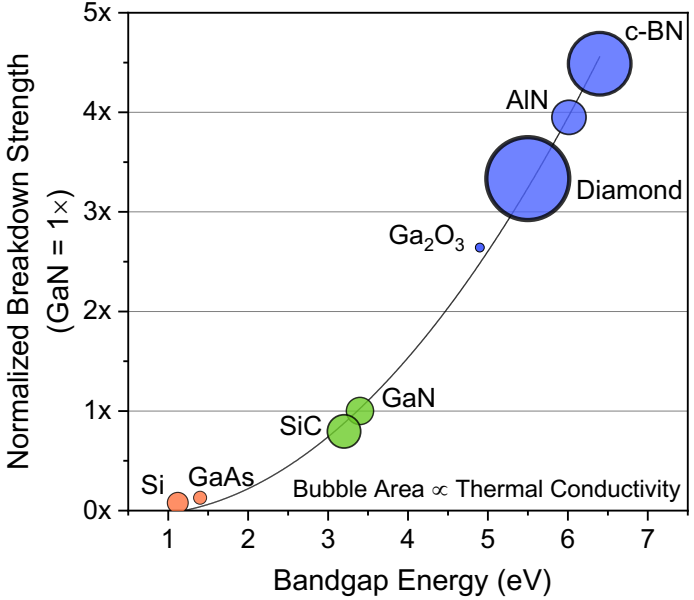
Now that GaN is replacing GaAs, what are the candidate technologies for the next generation?

	Material	Bandgap (eV)	N-type Doping	P-type Doping	Alternatives?
WBGS	SiC (4H)	3.2	✓	✓	?
	GaN	3.4	✓	Limited	Polarization Doping
	β-Ga_2O_3	4.9	✓	X	?
	ε-Ga_2O_3	4.9	?	?	Polarization Doping
UWBGS	Diamond	5.5	X	✓	Transfer Doping
	AlN	6.2	Limited	X	Polarization Doping
	c-BN	6.4	Si: 0.24 eV	Be: 0.2 eV	?



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WBG and Ultra-WBG mm-Waves Materials

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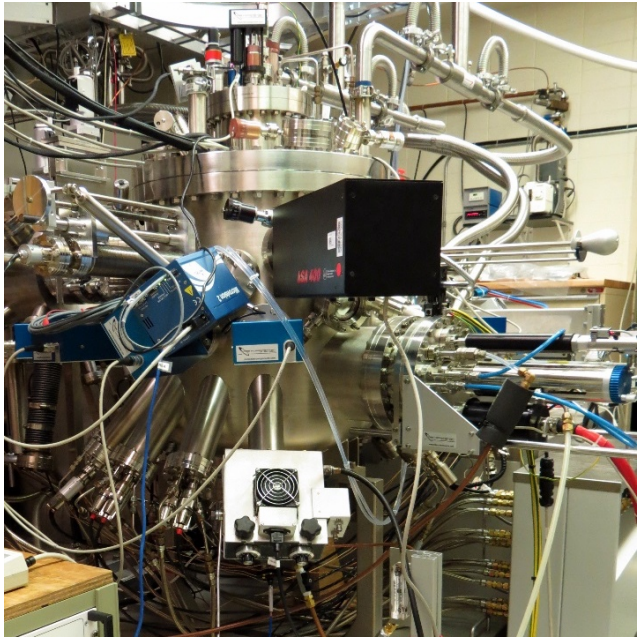
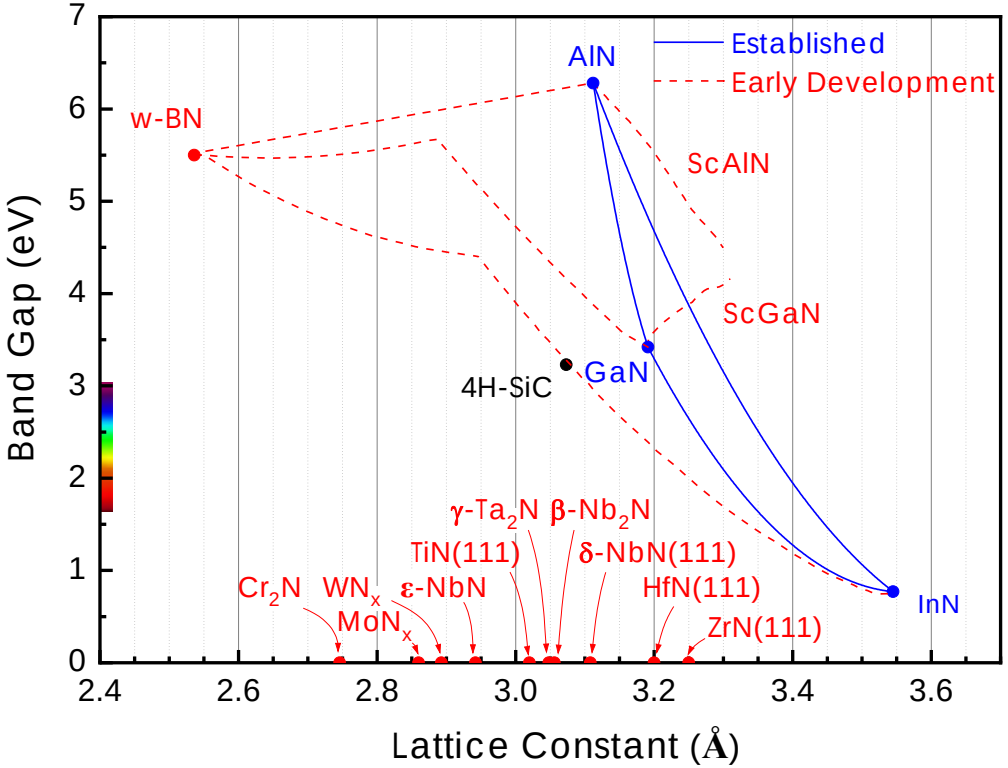
Plasma-assisted nitride molecular beam epitaxy:



3” Nitride MBE



M. Hardy, et al., IEEE MTT-S International Microwave Workshop Series on Advanced Materials and Processes for RF and THz Applications (IMWS-AMP 2018), July 16-18, 2018, Ann Arbor, MI, USA

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Development of ScAlN for mm-Wave Transistors

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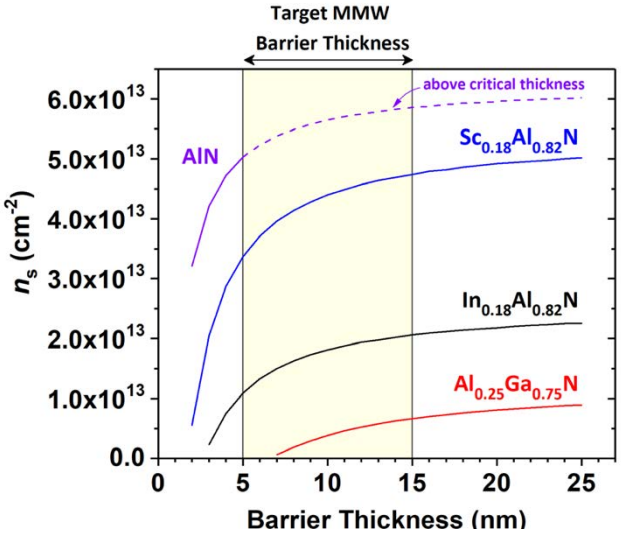
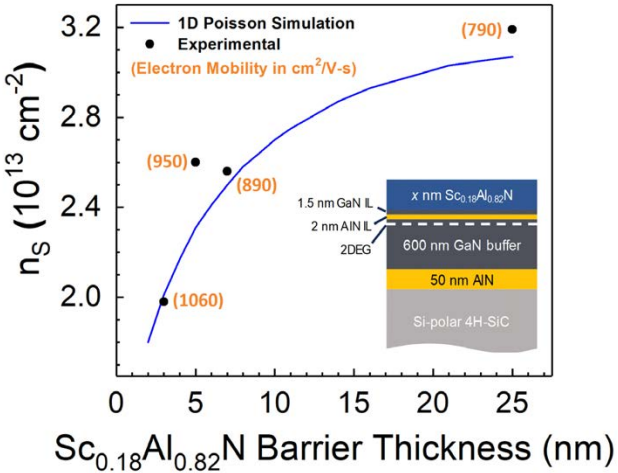
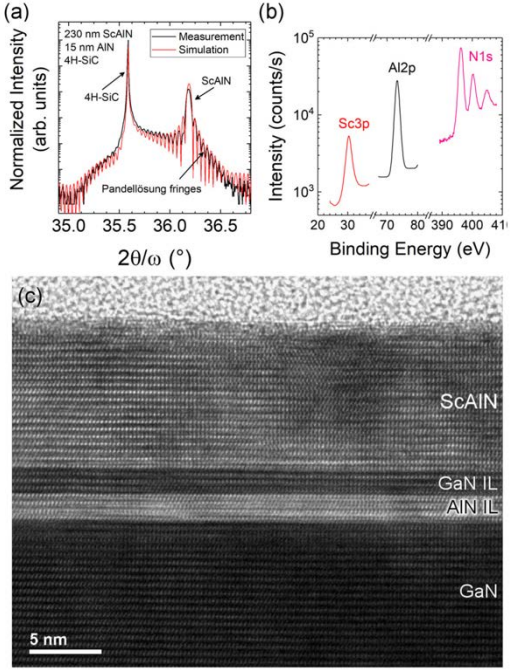


Sheet charge density (*ns*) for HEMTs with various barrier layer materials as a function of barrier thickness. The simulated structure includes the barrier layer and GaN channel.



Measured sheet carrier density (n_s) for HEMT structures with varying $Sc_{0.18}Al_{0.82}N$ barrier thickness. The simulated carrier density for is shown as a solid line. Mobility for each sample is shown next to the corresponding n_s data point.



(a) XRD 0002 2θ/ω linescan and simulation.
(b) XPS spectra showing the Sc3p, Al2p and N1s peaks.
(c) Cross-sectional STEM of a ScAlN-barrier HEMT structure having an ~ 8-nm-thick barrier.

M. Hardy, et al., IEEE MTT-S International Microwave Workshop Series on Advanced Materials and Processes for RF and THz Applications (IMWS-AMP 2018), July 16-18, 2018, Ann Arbor, MI, USA

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Simultaneous Transmit and Receive

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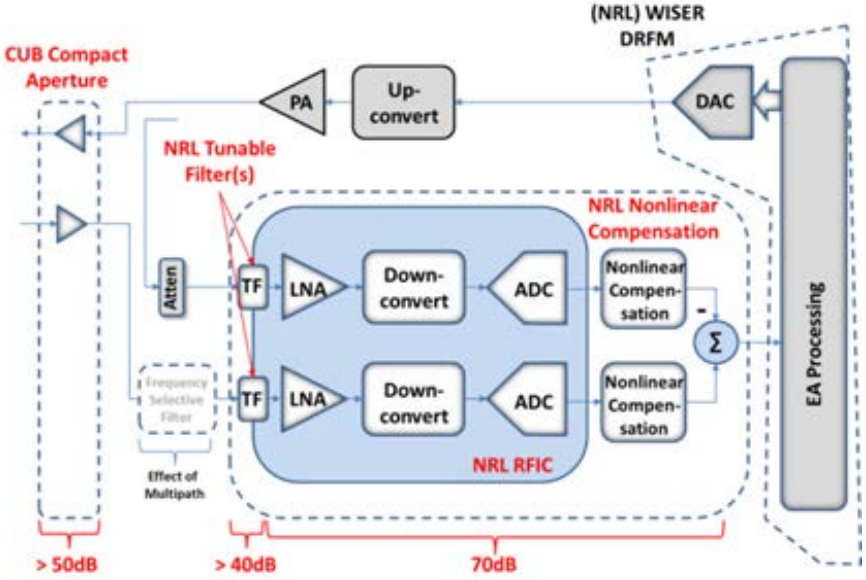
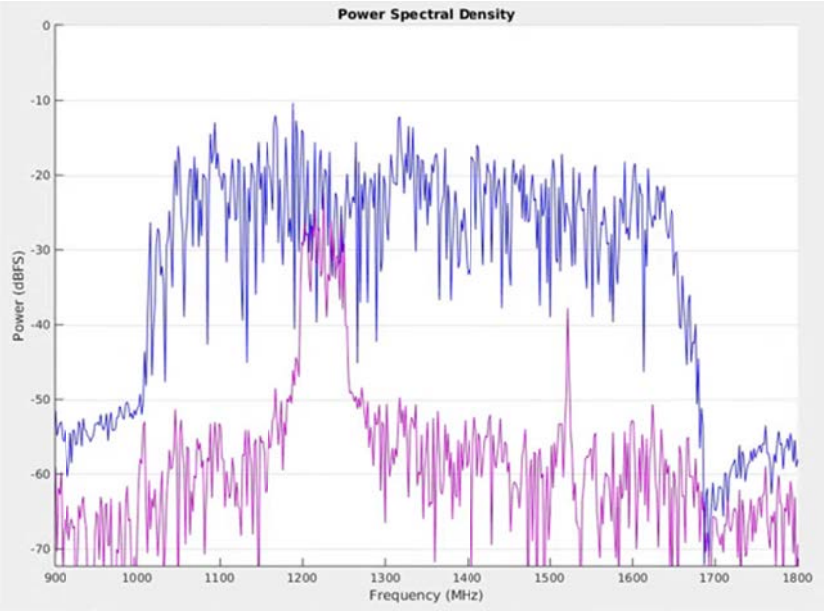
Signal Processing Electronic Attack RFIC (SPEAR)



The Signal Processing Electronic Attack RFIC (SPEAR) system:

- High performance antennas
- RFIC system on a chip
- Digital signal processing

Time snapshot results with adaptive cancellation: a communications signal and a chirp signal (purple) are clearly detected despite the simultaneous transmission (blue) over a 700 MHz bandwidth



L. Boglione, STAR Performance with SPEAR (Signal Processing Electronic Attack RFIC) https://apps.dtic.mil/dtic/tr/fulltext/u2/1042246.pdf

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Phase Change Material Based Switches

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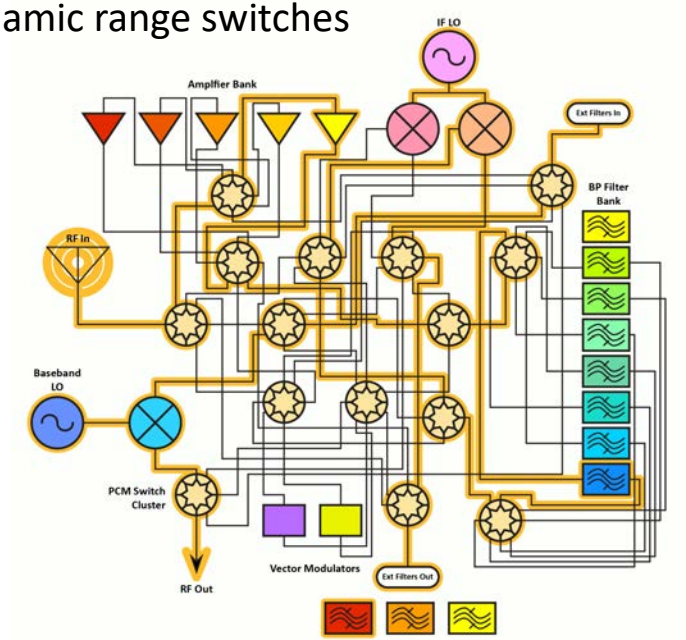
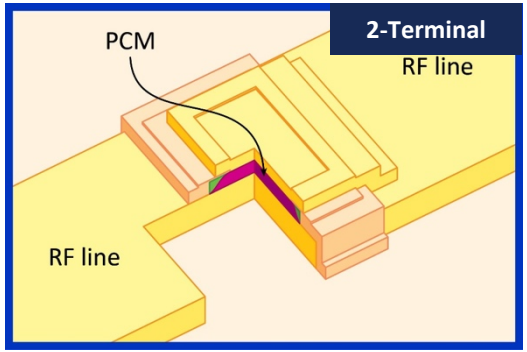
Navy systems require:

- reconfigurability
- adaptability, and
- ability to perform many functions,

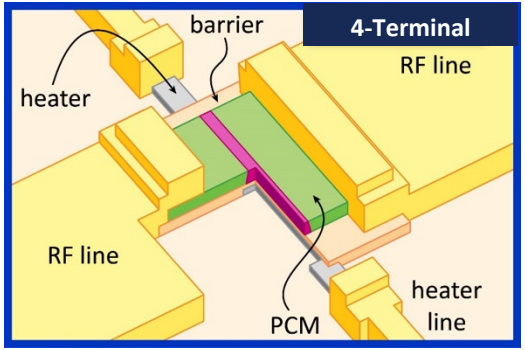
creating demand for broadband, low-loss, high dynamic range switches





- Phase transition occurs due to **direct** Joule heating
- Simpler design and fabrication
- More complex circuit/system implementation
- Very low length (thickness) to area ratio leading to very low ON state loss but **poor OFF state isolation**

- Phase transition occurs due to **indirect** Joule heating
- More complex design & fabrication
- Simpler circuit/system implementation
- Higher length to area ratio leading to **high OFF state isolation**, sufficiently low ON state loss achievable



J. Champlain, IEEE MTT-S International Microwave Workshop Series on Advanced Materials and Processes (IMWS-AMP 2017), 20-22 September 2017, Pavia, Italy
El-Hinnawy et al., CS MANTECH Conf (2014), Denver, CO USA

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Phase Change Material Based Switches

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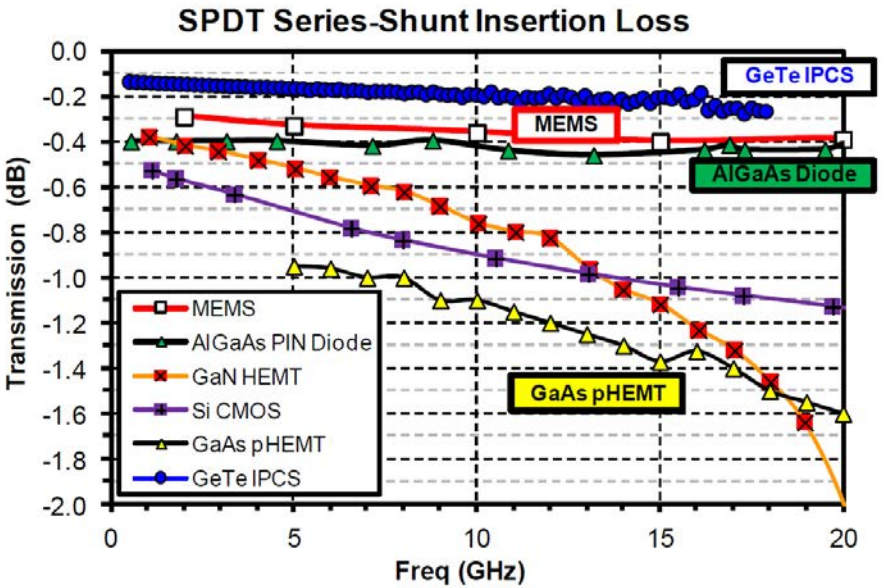
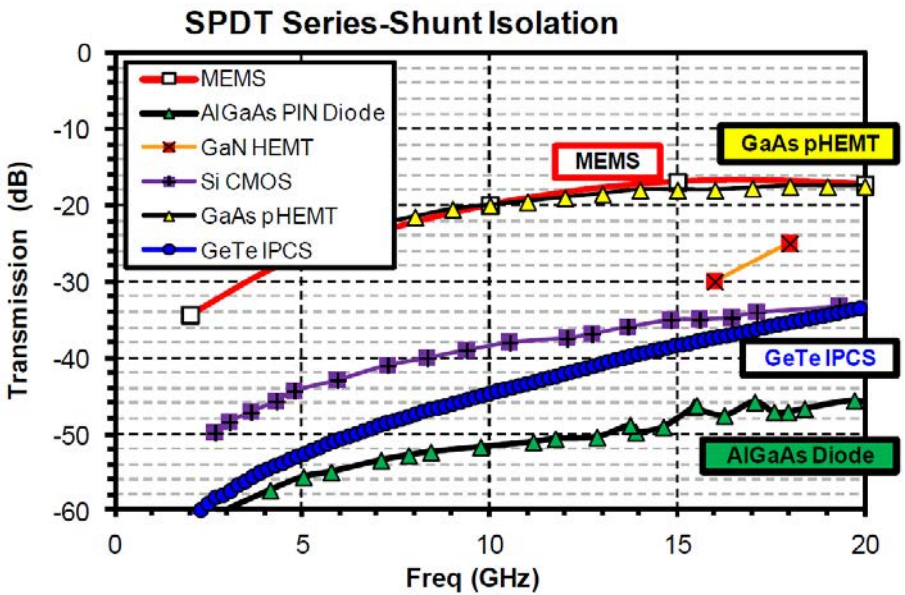
GeTe RF Switch (NGES/NRL collaboration)

- Zero standby power consumption
- Exceptionally broadband: f_{RC} > 10 THz
- Linear: TOI > 65 dBm
- Extremely low insertion loss: < 0.1 dB @ 10 GHz, < 0.3 dB @ 40 GHz
- IC compatible: back-end-of-line process compatible with various semiconductor technologies





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Heterogeneous Integration at the Device Level

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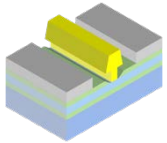
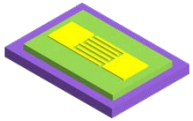
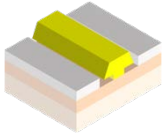
Enable rapid prototyping and superior hybrid performance of RF ICs via heterogeneous integration of *pre-fabricated devices* using microassembly techniques → Use best material for right function (performance), quickly (time) and affordably



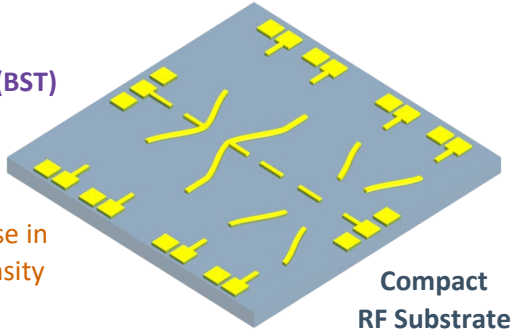
Antimonide-based compound semiconductors (ABCS) – III-V with 10X reduction in power consumption



Barium strontium titanate (BST) – 50X increase in dielectric constant and 3:1 tunability



GaN – 10X increase in output power density



Compact RF Substrate

D. J. Meyer, et. al., 236th ECS Meeting, October 13-17, 2019, Atlanta, GA

Time

Lack of rapid prototyping: Slow development time of new technologies and designs for RFICs and MMICs

Example: DoD-funded program, where contractor spent:
5 months for design
+
10 months for validation lot
=
1.25 year design cycle
and performance not met due to lot-to-lot variation!

Performance

Cannot intimately combine various DoD-developed RF device technologies or select substrate material (mixed signal)

Material	Digital Processing	Output Power	Noise and linearity
Si or SiGe	✓	✗	✗
GaN	✗	✓	✗
III-V's	✗	✗	✓

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Heterogeneous Integration at the Device Level

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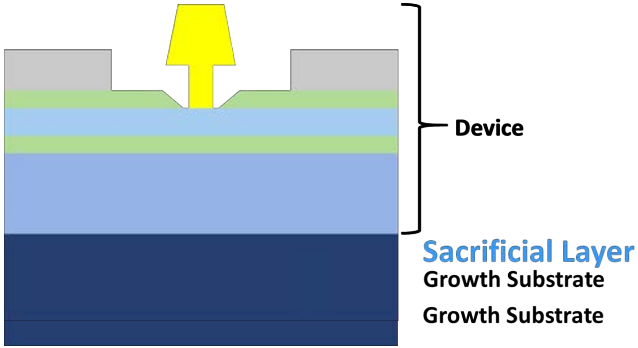
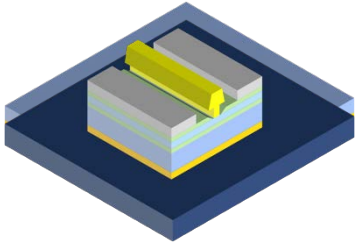
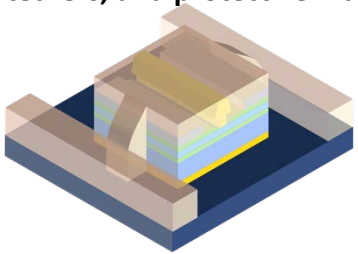
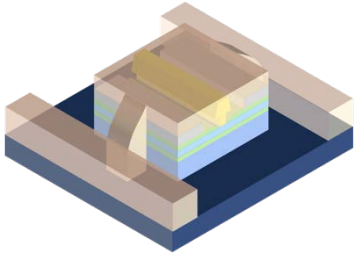


- Standard device processing
- Isolate device to substrate

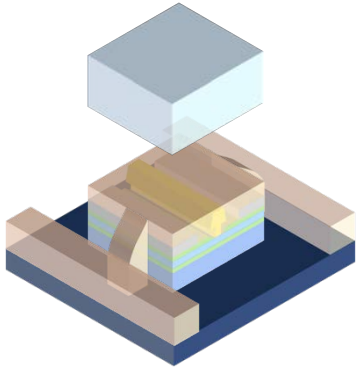


- Pattern photoresist anchors, tethers, and protective mask

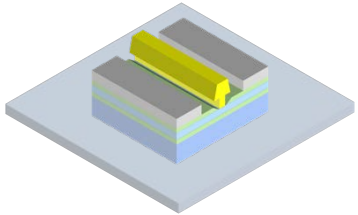




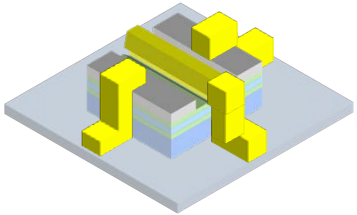
- Etch sacrificial layer



- Pick up device with polymer stamp



- Print (place) device
- Remove photoresist



- Pattern metal interconnects

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Heterogeneous Integration at the Device Level

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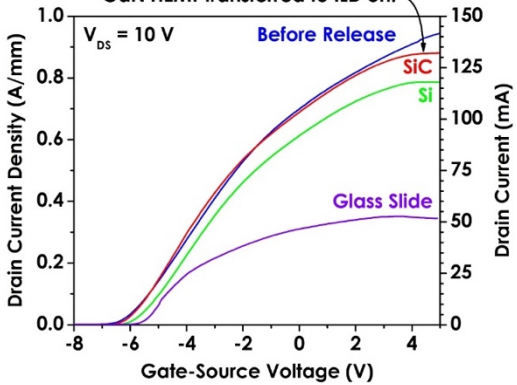
Initial results for MBE N-polar GaN HEMTs:

- Electrical performance similar before lift-off and after transfer to SiC (up to 8 W/mm of dissipated power)
- Insufficient bond strength between device and inter-layer dielectric (ILD) to overcome effect of curvature
- Several strategies for improving planarity including reducing alloyed contact area were successful

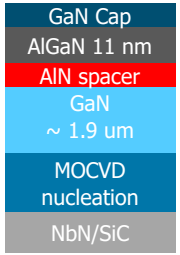
GaN HEMT on ILD/Si

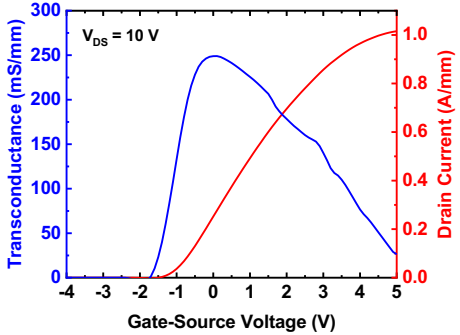
GaN HEMT transferred to ILD on:

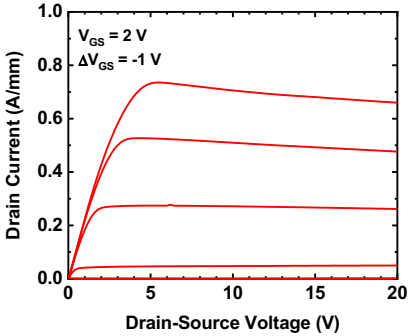


More recent results for MOCVD Ga-polar GaN HEMTs (collaboration with Qorvo)

- 99% release yield
- Improved ohmic alloy contact resistance of 0.5 Ohm-mm
- Maximum drain current > 1 A/mm
- Low gate leakage current after SiN_x passivation
- New mask set with devices optimized for lift-off







10×100 µm periphery FET

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Memristive Neuromorphic Computing Elements

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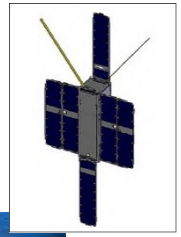
Fundamental Challenges Facing AI and other Next-Gen Computing:

- Great need and widespread applications for AI
- Limitations of CMOS-based AI (current SOA)
  - Von Neumann bottleneck
  - End of Moore's Law scaling
  - Massive amount of computation required for Deep Learning

→ Unsustainably large size, weight, and power (SWaP) expenditure for AI hardware

vs.

- Need for new HW devices for AI with low SWaP envelope
- DON and DoD currently operate systems that are:
  - mobile, unmanned, remote, and off-the-grid
  - with severe limits on payload (SWaP)



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Memristive Neuromorphic Computing Elements

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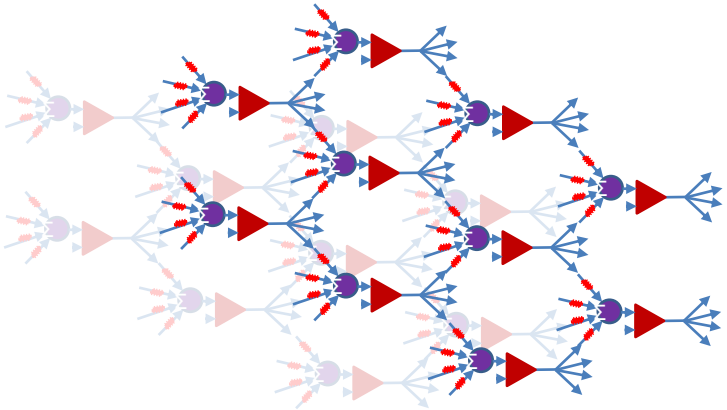
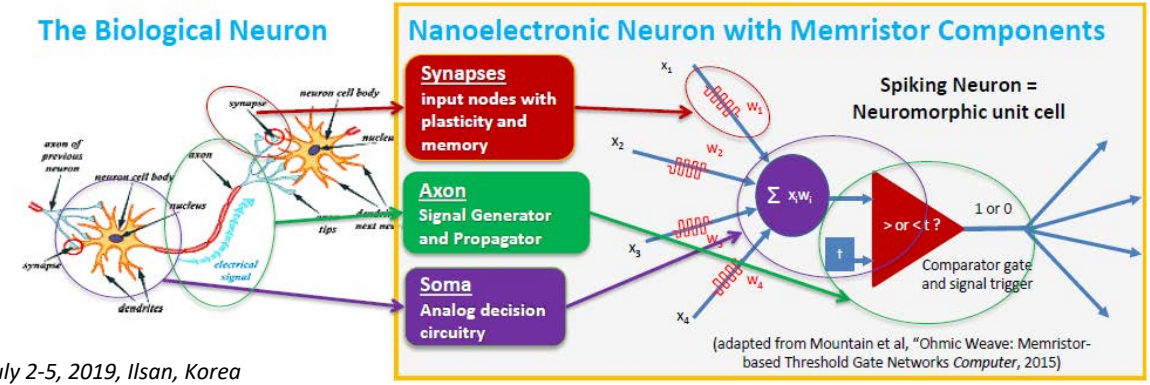
Nanoelectronic Spiking Neuron

- a functional unit device *with*
- components based on memristors *(not CMOS)* *to*
- form the basis of neuromorphic computing hardware *with*
- far less size, weight, and power (SWaP) than is possible with conventional hardware



- **Solid-state neuron *components***
  1. ***Synapse*** **: memory and learning → memristor junctior**
  2. ***Axon*** **: spiking → neuristor**
  3. ***Soma*** **: decision circuit → multi-input crossbar latch**



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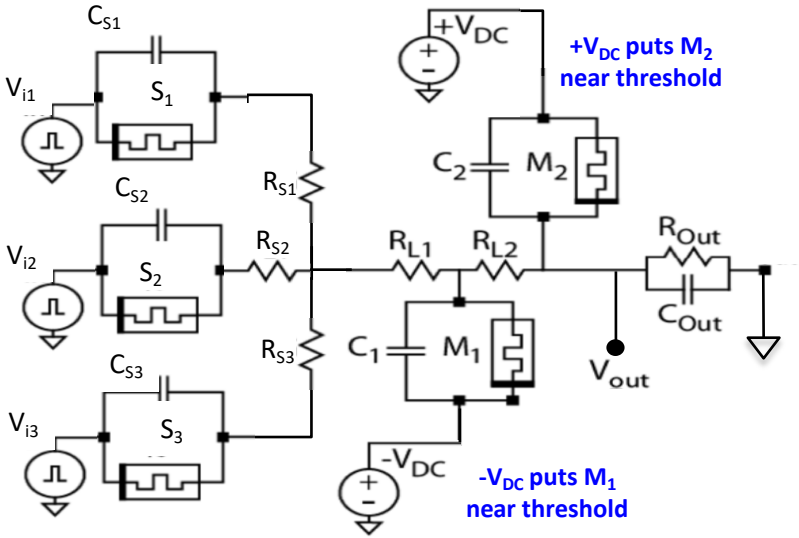
Simulation of Neuron Equivalent Circuit

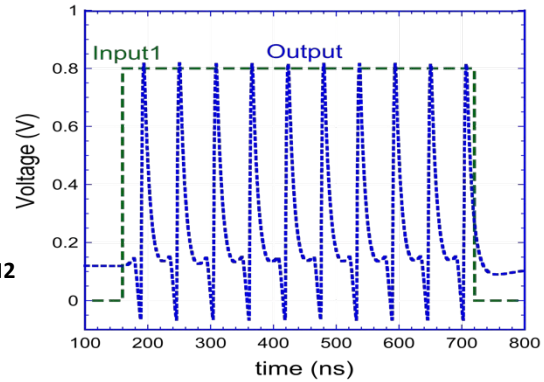
Pulse inputs (outputs of other neurons) sum and can fire spike train



Single Neuron With Single Input

1) Supply input voltage pulse (green) to synapse.
2) Record output (blue).

$V_{DC} = 1.75V$
$R_{L1} = 1.3k\Omega$
$R_{L2} = 15k\Omega$
$R_S = 15k\Omega$
$C_{M1} = 32pF = 4C_{M2}$
$C_S = 1.5pF$



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Conclusions

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- Total IoT spending in 2019 ~ $726B
- Total Navy Research, Development, Test & Evaluation budget (across all disciplines) ~ $20B
- Navy must:
  - Carefully invest in technologies that address specific Navy needs not addressed by commercial requirements
  - Leverage to maximum extent possible commercial developments
- NRL must:
  - Continue its role as the Navy's corporate laboratory
  - Pursue high-risk, high-payoff concepts that address warfighter needs in the IoT age
  - Engage and collaborate with commercial interests to rapidly transition technologies
  - Maintain a world-class workforce of scientists and engineers addressing critical military technology "gaps"

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Comparison TWT/MPM and GaN MMIC

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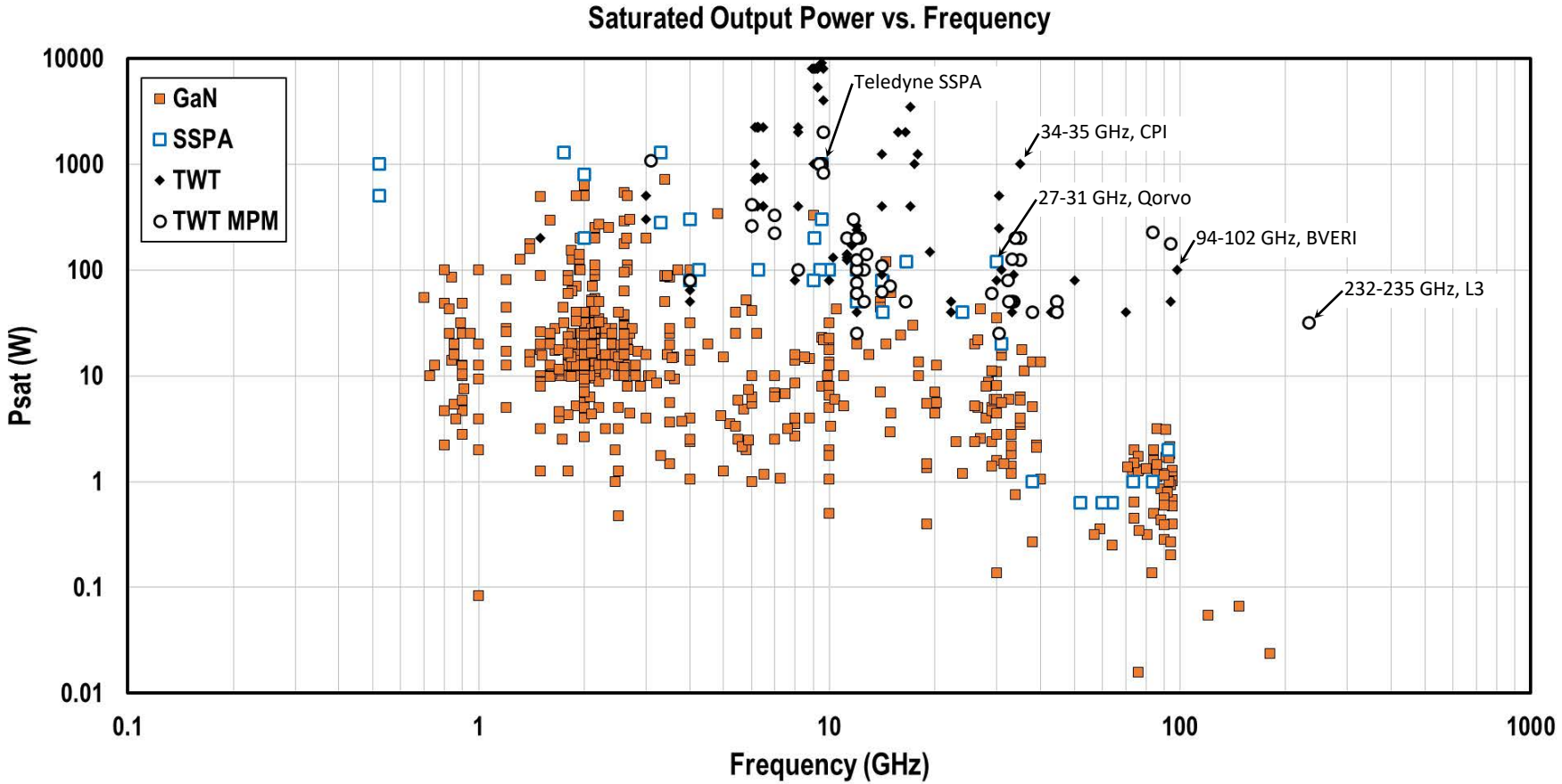

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Comparison TWT/MPM and GaN MMIC

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