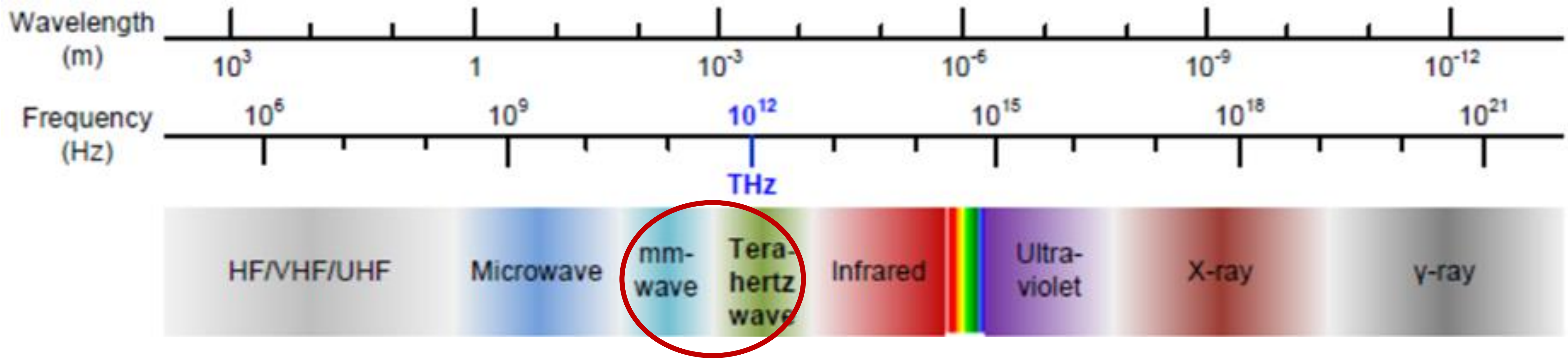
Millimeter-wave Electronics

XU, Dong

Compound Semiconductor Division, SITRI, Shanghai

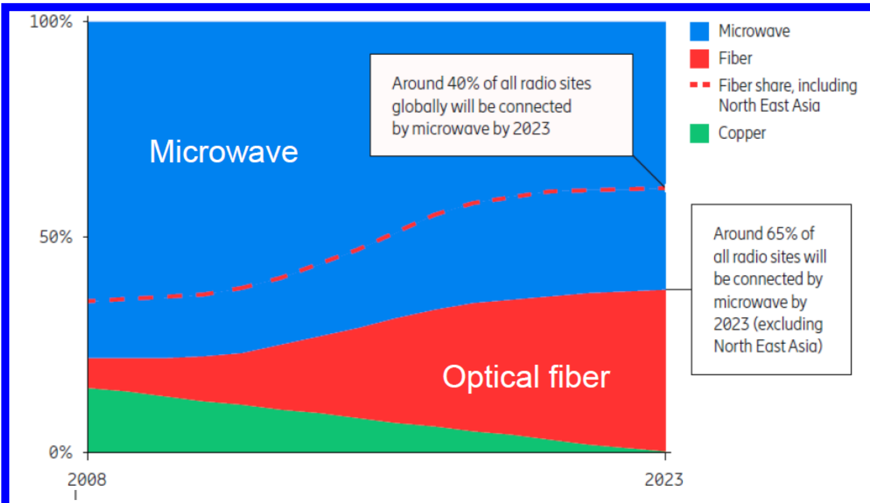
November 12, 2019

MMW, Sub-MMW and Tera Hertz

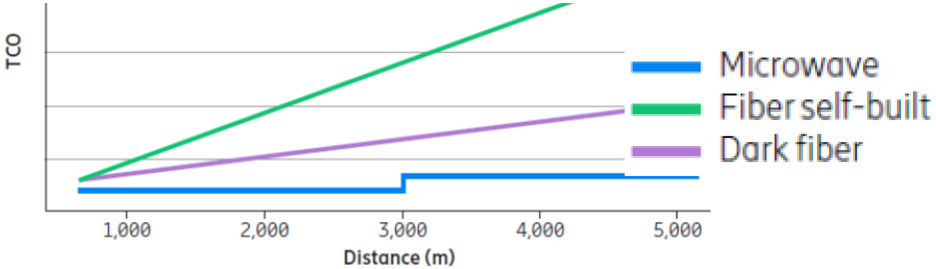


- High frequency: Wide bandwidth for high-speed RF data link and wireless communication
- Short wavelength: High precision Radar/imaging, and compact antenna-integrated RF module
- Low photon energy: Non-destructive and safe to human body, security/biomedical imaging
- THz frequencies: Corresponding to vibrational/rotational transition energies of bio-molecules
- "THz Gap": Hard-to-reach and, therefore, remains unexploited so far:
  - Electronics: Operation speed of FET and HBT limited by line widths and layer thickness
  - Optical devices: Energy gaps corresponding to such long wavelengths too small

"All RF Data Link": Ericsson

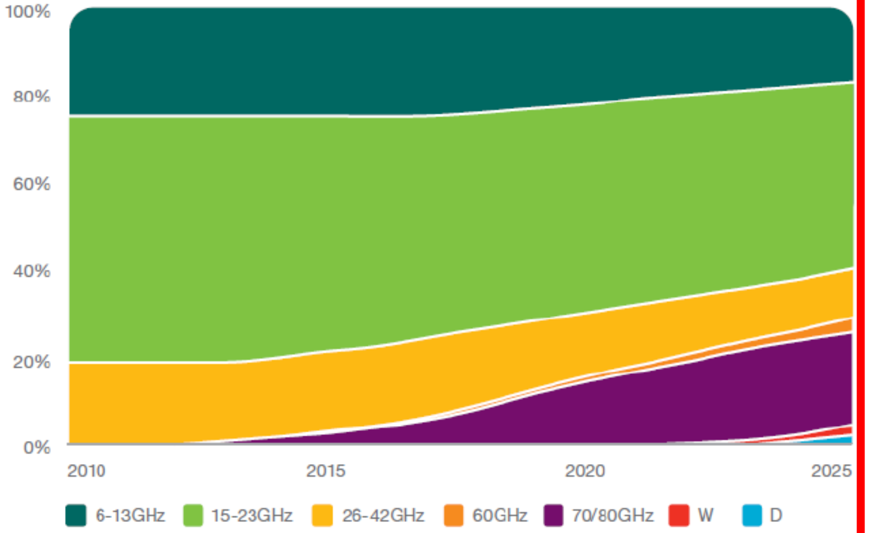


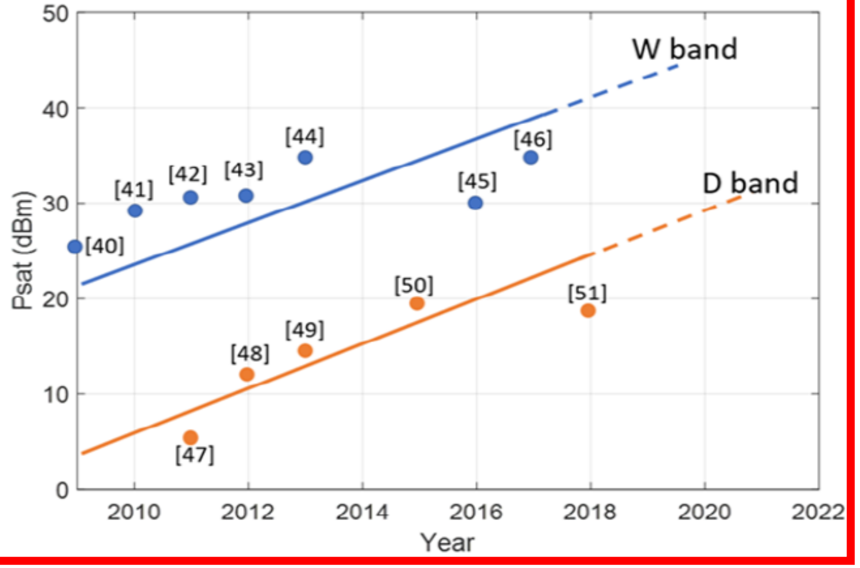
Cost of 10Gb/s link in Germnay



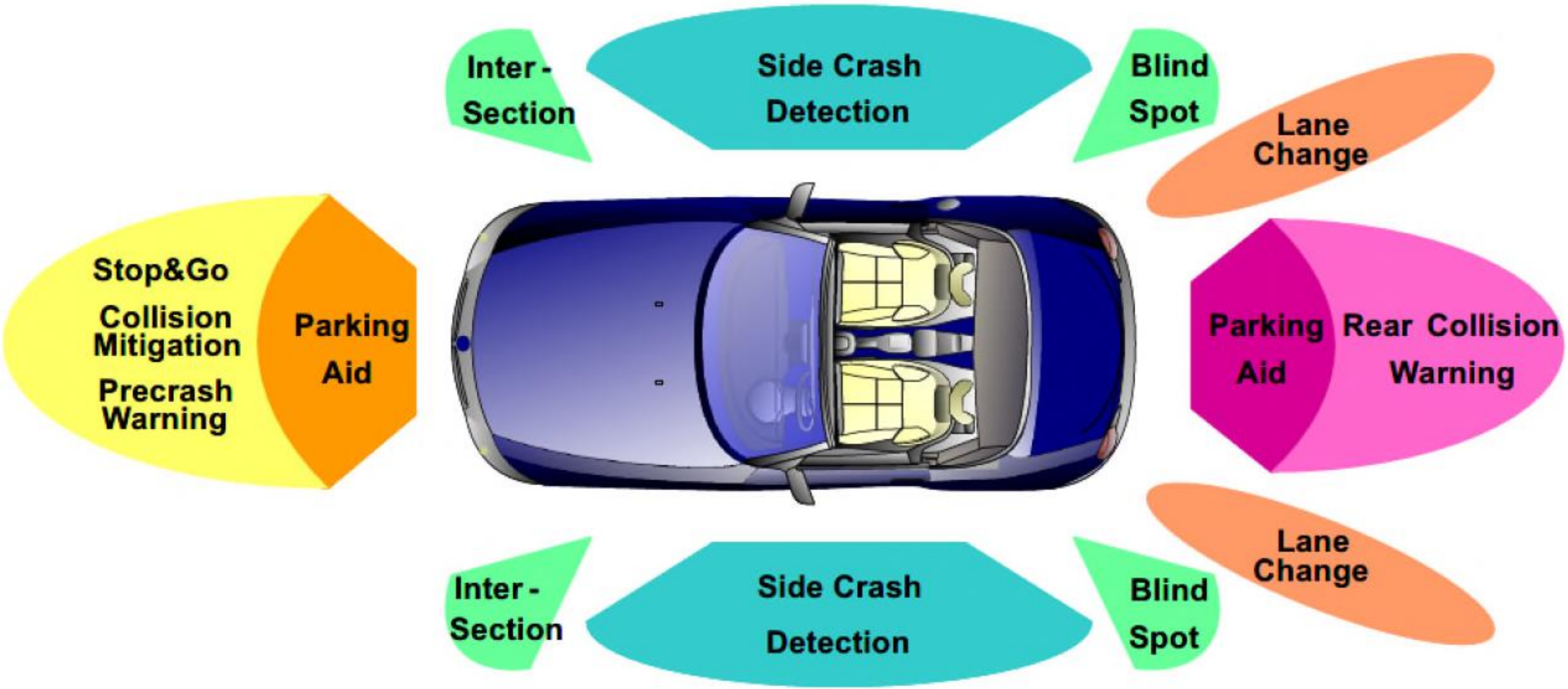
Ericsson: E-Band 139Gb/s Link, May 2019

VDI: D-Band is E-band of Tomorrow





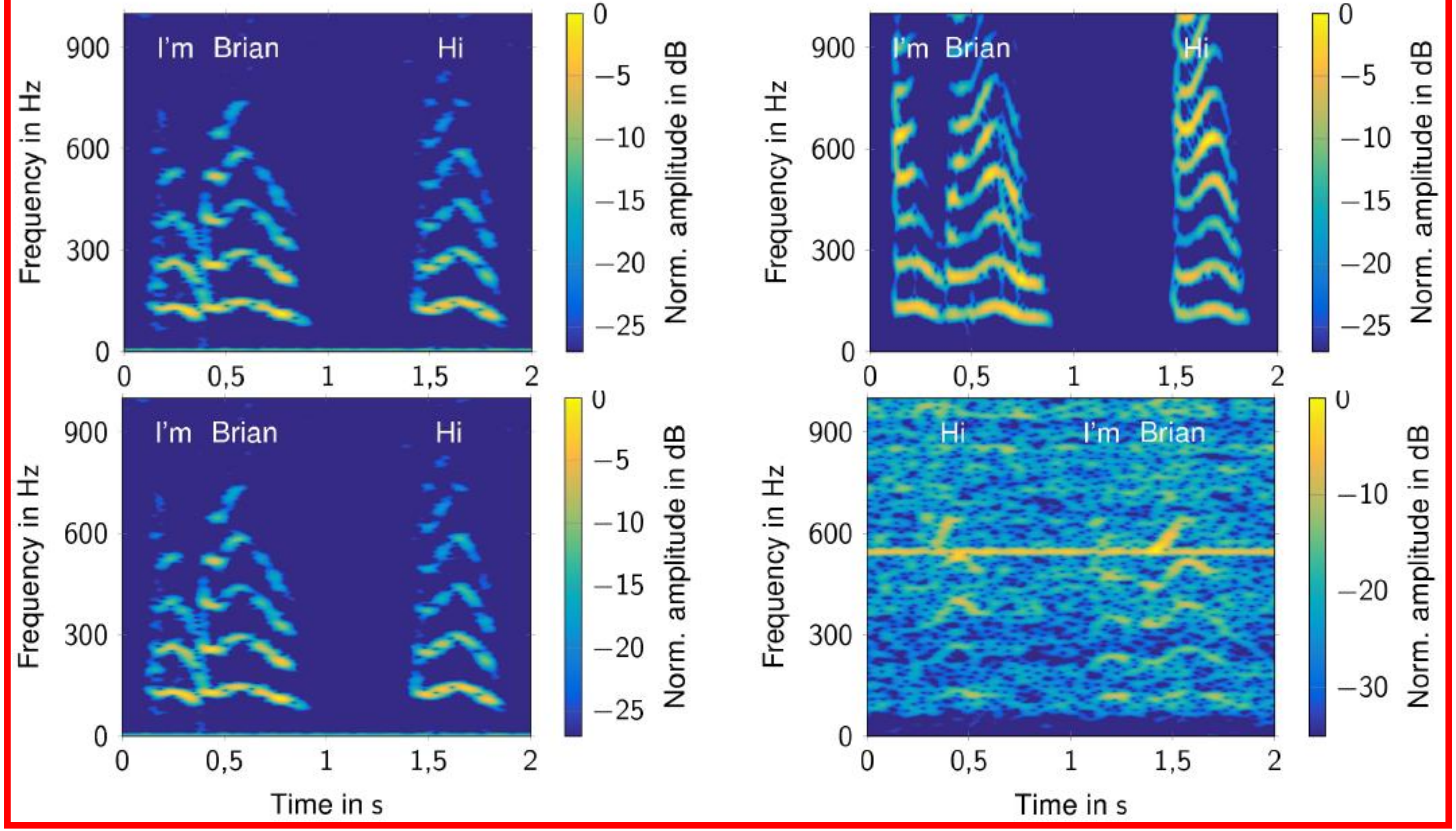
Automobile Radar Sensors



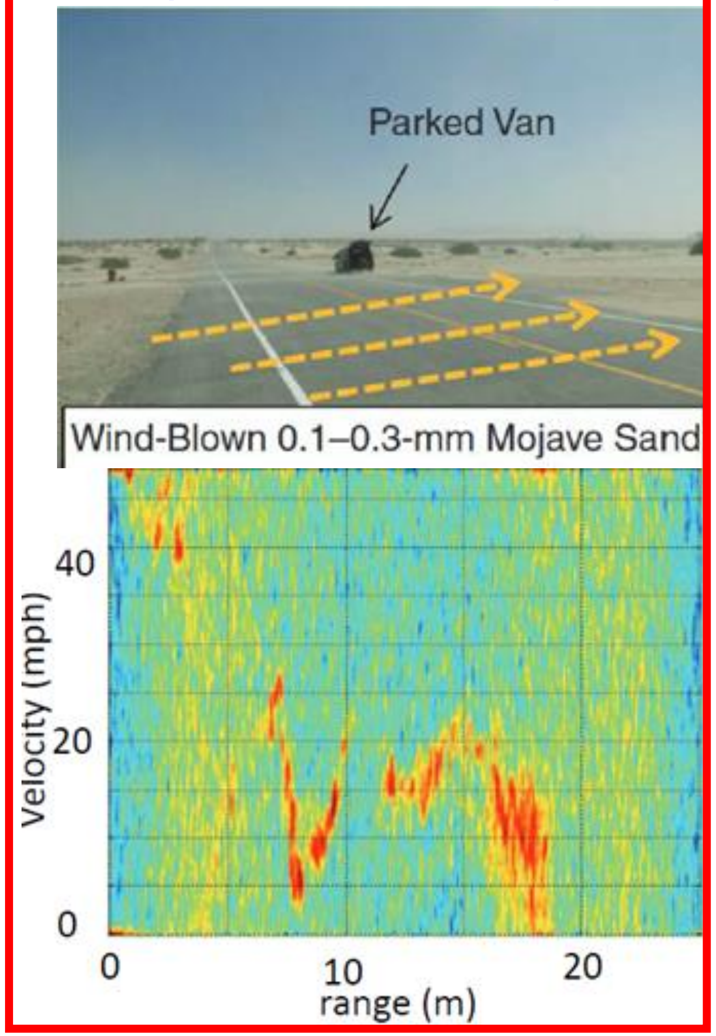
Exotic Applications

160-GHz Radar Microphone

Reference Microphone

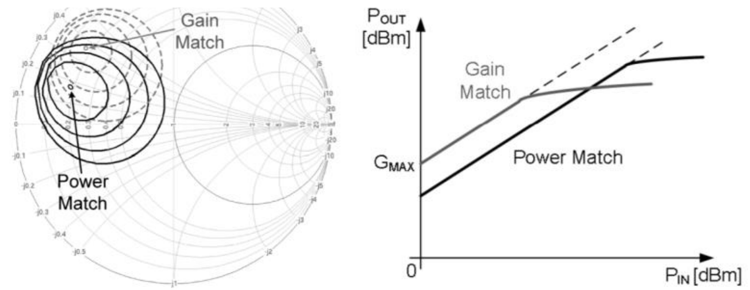


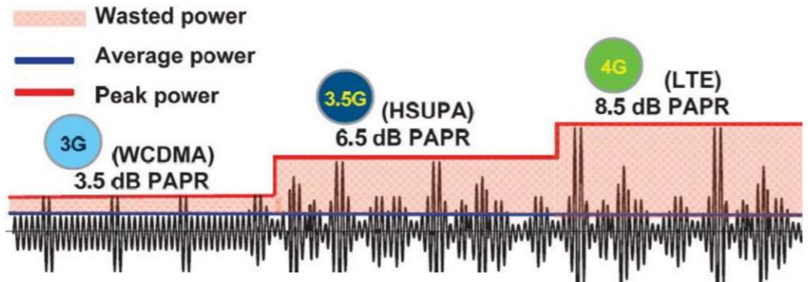
670 GHz Radar Wind-meter (0.2 m/s resolution)



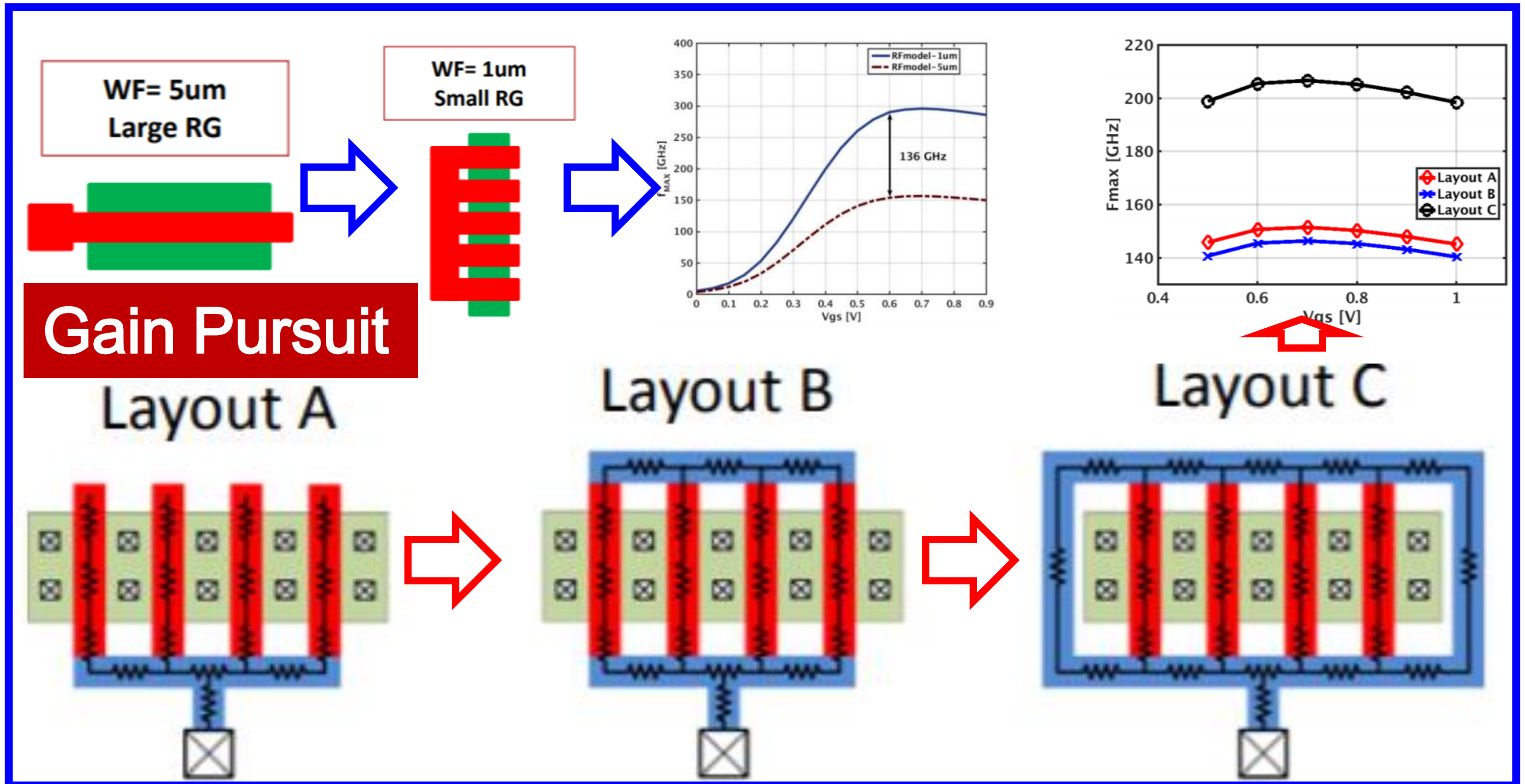
CMOS: MMW Challenges and Accomplishments

Enhanced PAPR for Spectrum efficient coding schemes like QAM and OFDM

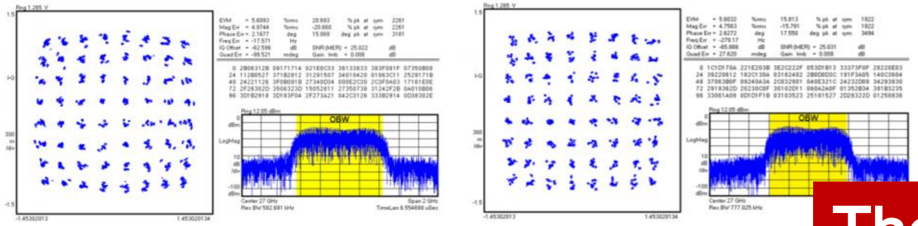




PAPR: Peak Average Power Ratio



KU Leuven: 40nm 28GHz CMOS PA

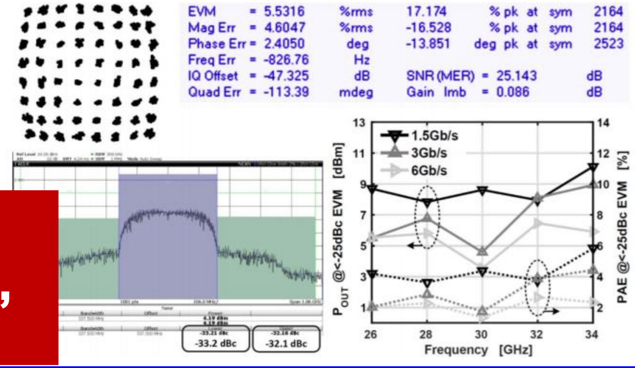


4Gbps at 27GHz
EVM = -25dB
Pout = 8.8dBm
PAE =9.6%

6Gbps at 27GHz
EVM = -25dB
Pout = 8.4dBm
PAE = 8.8%

The "State-of-the-ART"

KU Leuven: 28nm 29-57GHz CMOS PA

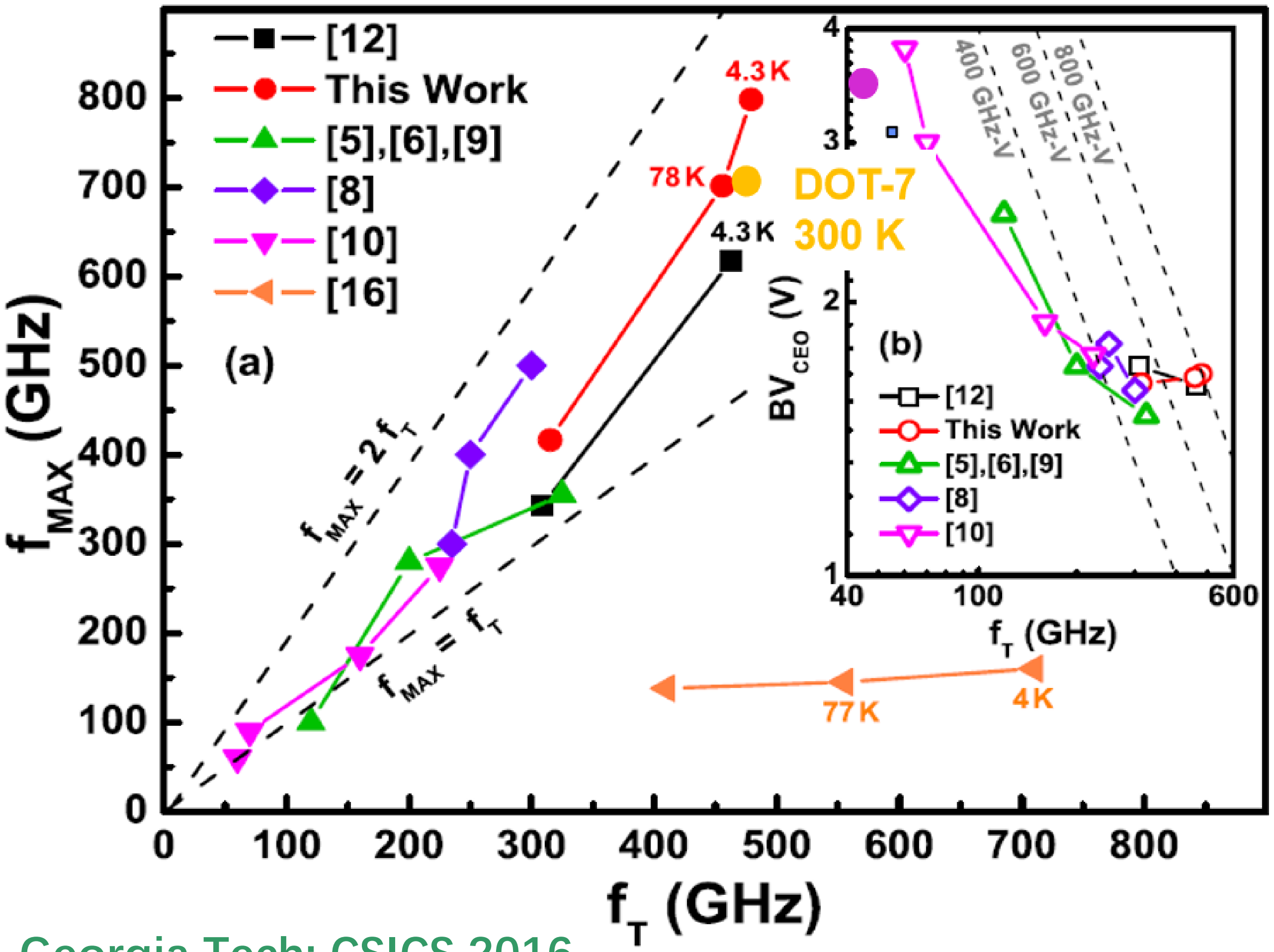


64-QAM, 8.3dB PAPR,
no predistortion

P_{OUT} = 10.1dBm
V_{DD} = 0.9V
F = 34GHz
DR = 1.5Gb/s

More MMW Powerful SiGe BiCMOS

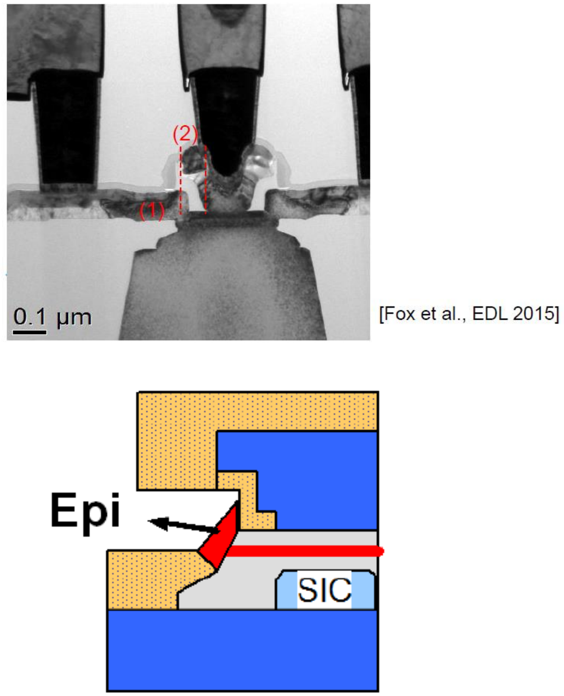
- $f_T + f_{max}$ > 1 THz in SiGe Is Clearly Possible (at very modest lith)
- The Prediction : 1000 GHz f_{max} at 300K @ BV_{CEO} > 1.5 V



709 GHz @ 300K
800 GHz @ 4.3K
both @ 130 nm

Georgia Tech: CSICS 2016

Cross Section of EBL HBT



Epitaxial base link

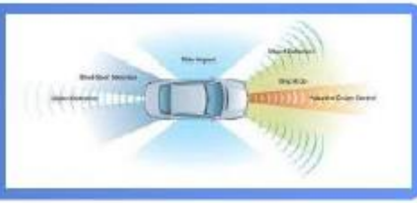
- in-situ doped epitaxial external base
- SiGe base & base link formation decoupled
- No link anneal

BiCMOS: To Enable More Low-Cost MMW Applications

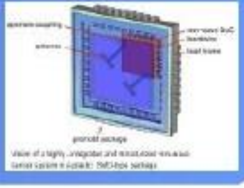
- Optical networking & Instrumentation
  Long haul, // optics, FFTH,… & ADC/DAC,… → **100 Gb/s**

- Wireless HDMI, C2C & P2P links
  HDTV, STB, PCs, Smart Phones,… → **60 GHz**

- Automotive radars
  Cruise speed control & Pre-crash → **77* GHz**



- Industrial & Automotive sensors
  Velocity & position sensors → **120 GHz**



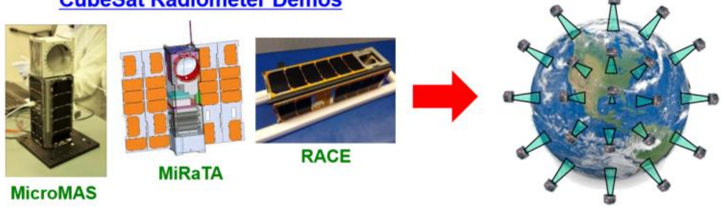
- Medical & Security
  Imaging (active & passive) → **≥160 GHz**

SiGe for Radiometers

- **Spaceborne Passive Sensors for Profiling the Earth's Atmosphere**
  - temperature (60 GHz, 118 GHz, …)
  - precipitation and humidity (183 GHz, 325 GHz, …)
- **Advantages of SiGe for CubeSat Radiometers:**
  - Much better 1/f noise than III-V HEMTs → critical for radiometers!
  - Inherent total-dose radiation tolerance as fabricated
  - Integration and economy of scale

CubeSat Radiometer Demos

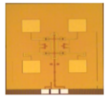
Goal: Large Constellations



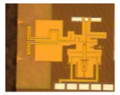
Other Interesting SiGe Circuits …

IHP G2

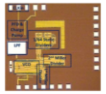
- **316 GHz 2x2 Transmitter Array**
  - **Novel Locking Mechanism**



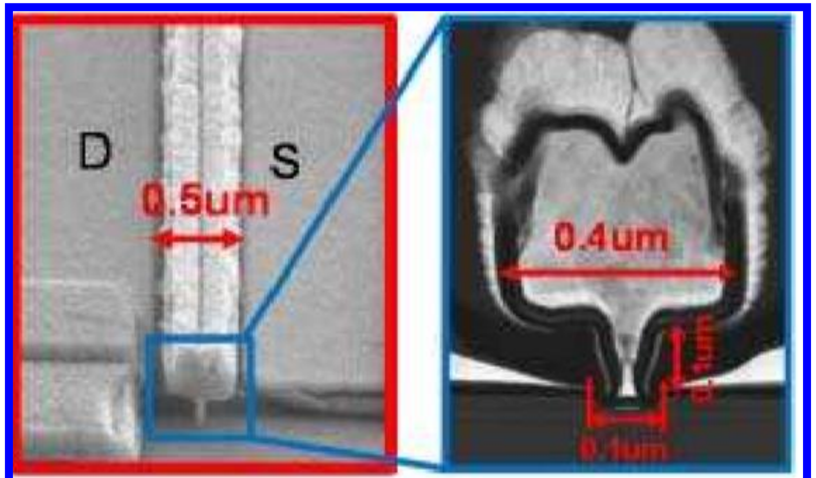
- **314 GHz Transmitter/Receiver**
  - **Low Noise Figure (19.5 dB)**

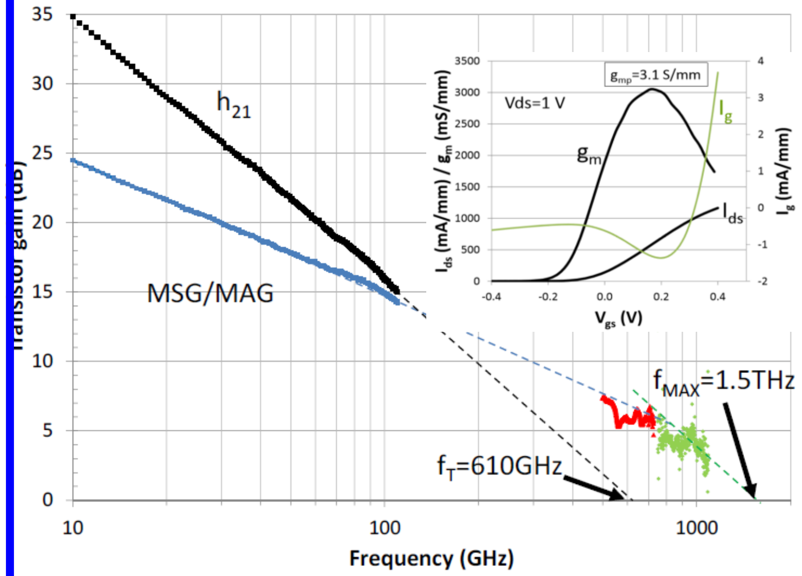


- **107-123 GHz Synthesizer**
  - **High Output Power (15 dBm)**
  - **Low Phase Noise (-95 dBc/Hz at 1 MHz)**

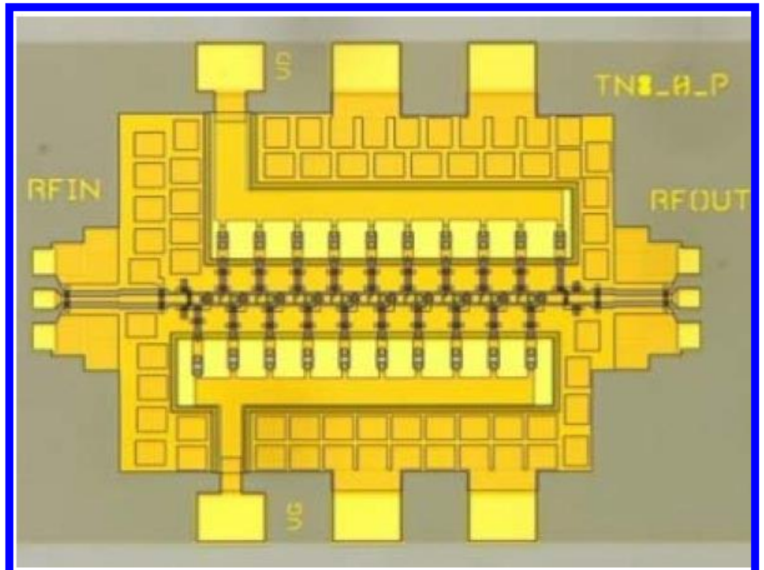


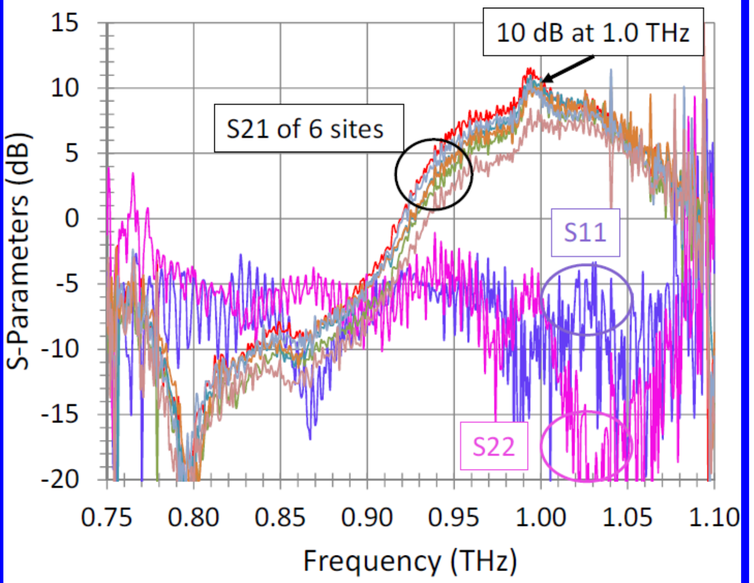
InP HEMT: 25nm Device for THz Operation



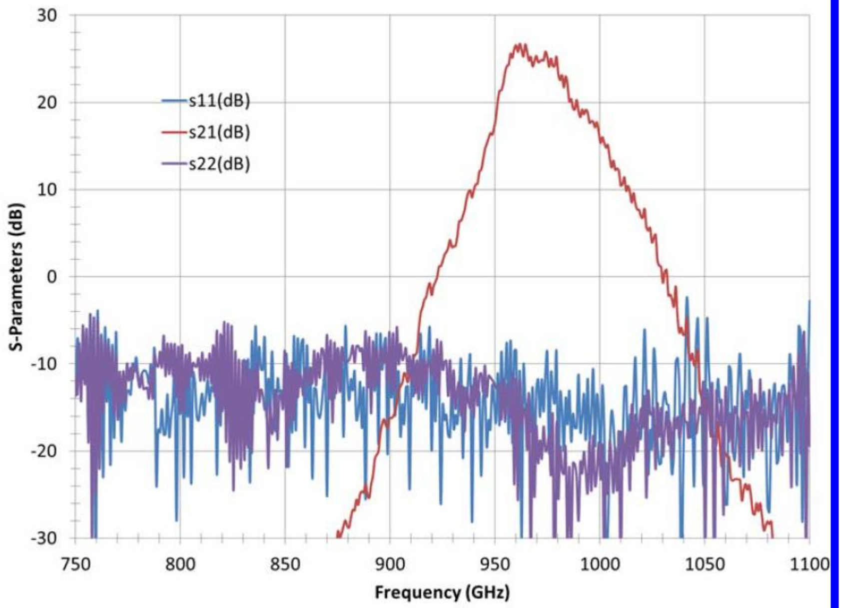


Tera-FET: 95A InAs channel, L_g=25 nm
~20 um substrate, 4um back via,
Gm=3 S/mm, f_T/f_{max}=0.61/1.5 THz





10-stage TMIC:10dB@1THz

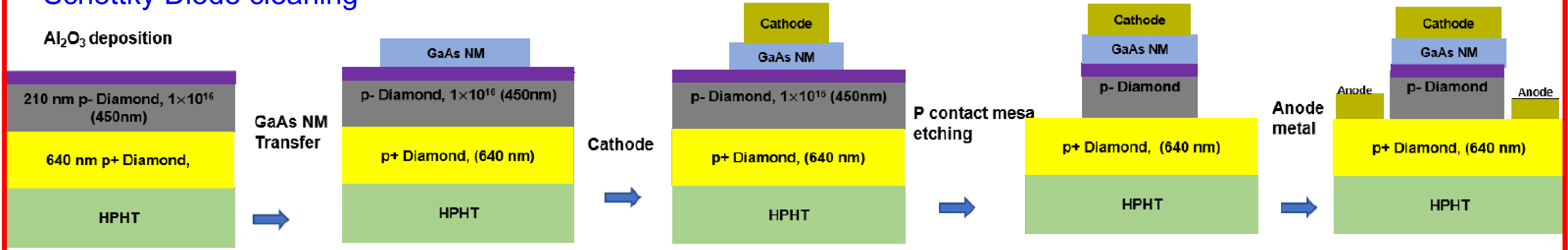


4 cascaded amplifiers:16dB@1THz

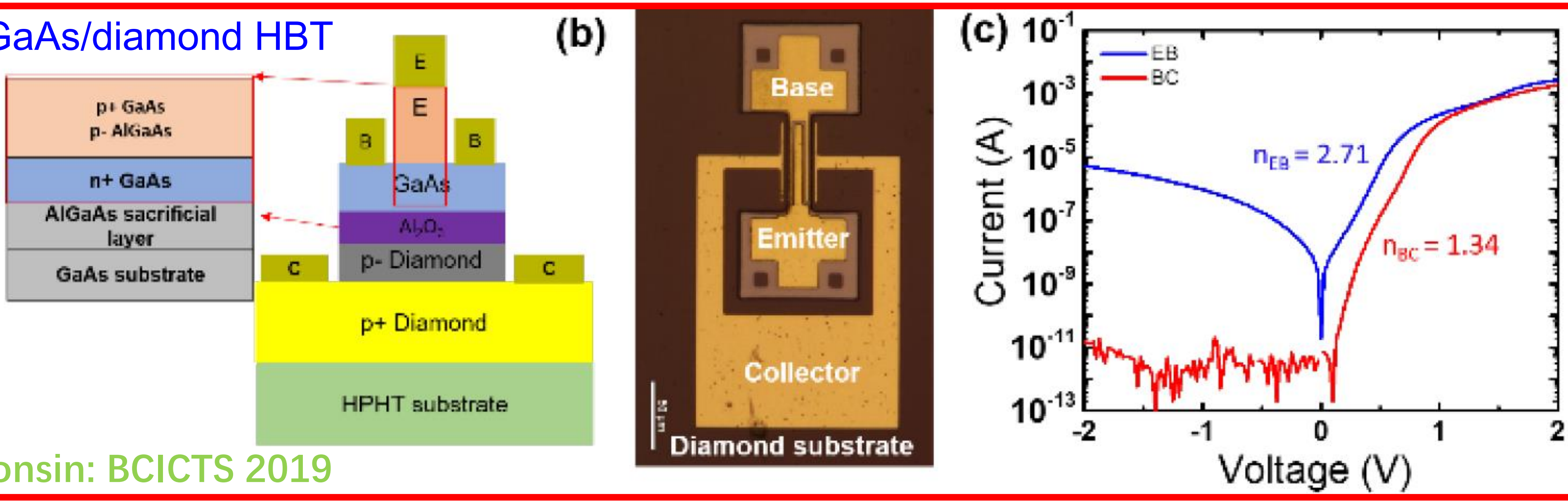
AlGaAs/GaAs HBT with Diamond Collector

GaAs P+/P- diamond Schottky Diode cleaning

Univ. of Wisconsin: BCICTS 2019



pnp AlGaAs/GaAs/diamond HBT



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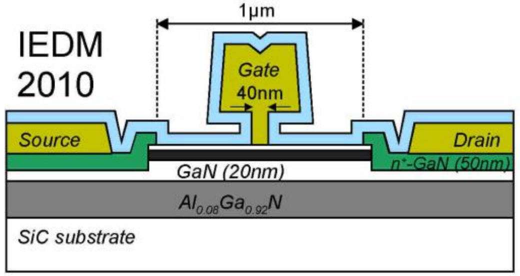
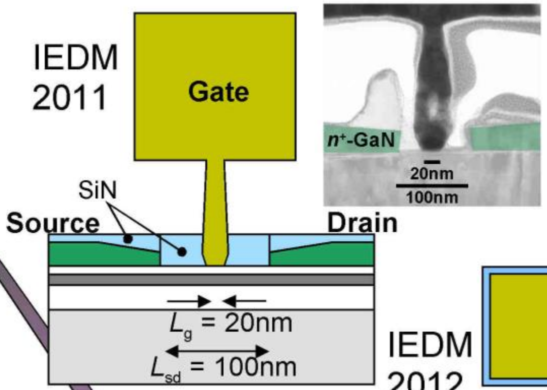
GaN/SiC HEMT: Review of "The-State-of-the-Art"

IEDM 2010



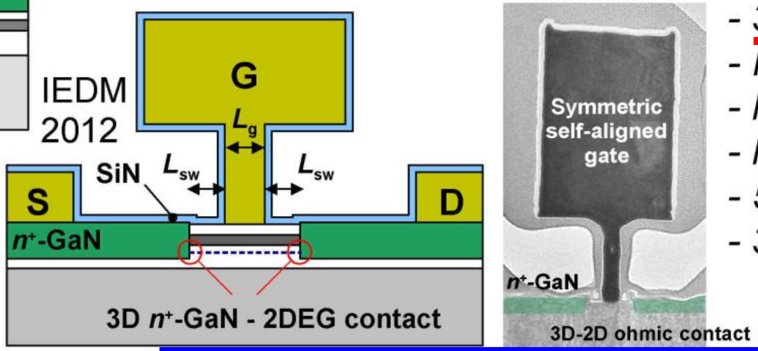
- *Vertical epi scaling*
- *n+GaN ohmic regrowth*
- *40-nm T-gate (Lsd = 1μm)*
- *Ft/Fmax = 220/400 GHz, JFoM = 9.2 THz-V (D-mode)*
- *First G-band GaN-MMIC (>4.5 dB gain at 180-200 GHz)*

IEDM 2011



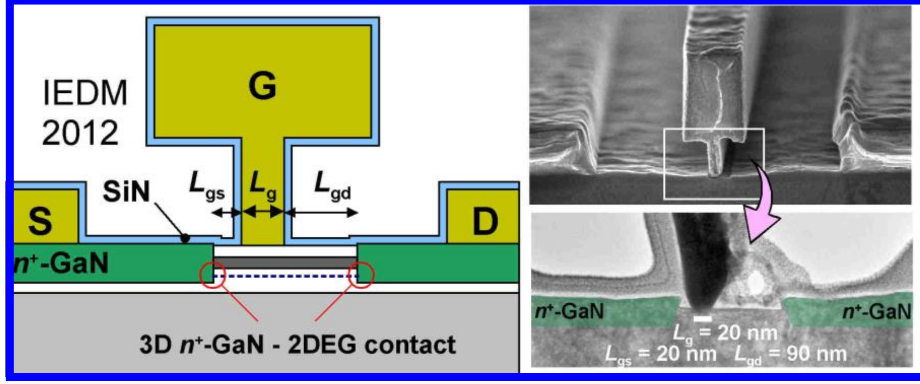
- *Self-alined-gate (Lg=20nm, Lsd=100nm)*
- *Velocity enhancement by lateral scaling*
- *Ft/Fmax = 310/364 GHz, JFoM = 2.8 THz-V (D)*
- *Ft/Fmax = 343/236 GHz, JFoM = 4.0THz-V (E)*
- *9-stage ring oscillator*

IEDM 2012



- *3D n+GaN ohmic contact to 2DEG*
- *Impact of Lsw on DC/RF performance*
- *Ft/Fmax = 454/444 GHz, JFoM = 4.5 THz-V (D)*
- *Ft/Fmax = 342/518 GHz, JFoM = 4.8 THz-V (E)*
- *51, 501-stage ring oscillator*
- *3-level BCB interconnect*

IEDM 2012

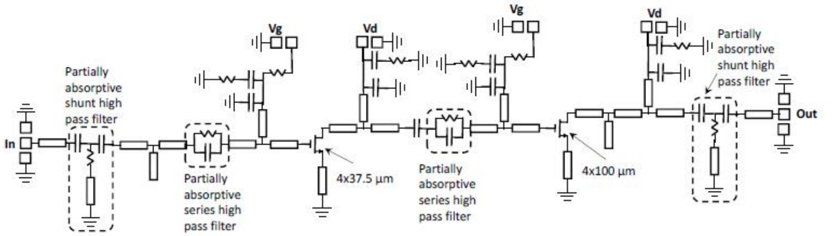


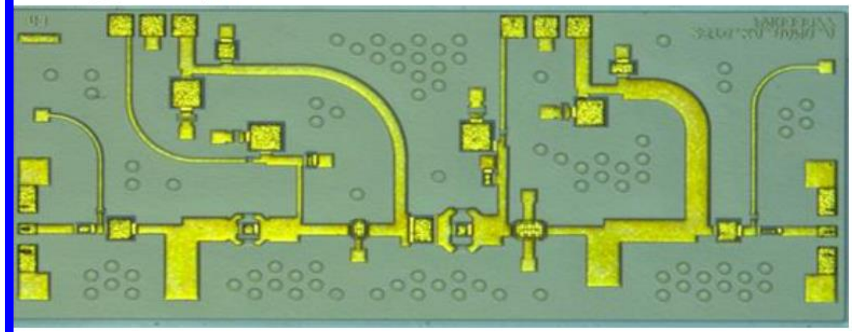
- *Asymmetric self-aligned-gate*
- *Ft/Fmax = 329/582 GHz, JFoM = 5.6 THz-V (MBE, D)*
- *Ft/Fmax = 200GHz at Vds=0.2V*
- *NFmin = 0.8 dB (50GHz, 20mW)*
  = 1.0 dN (50GHz, 6mW)

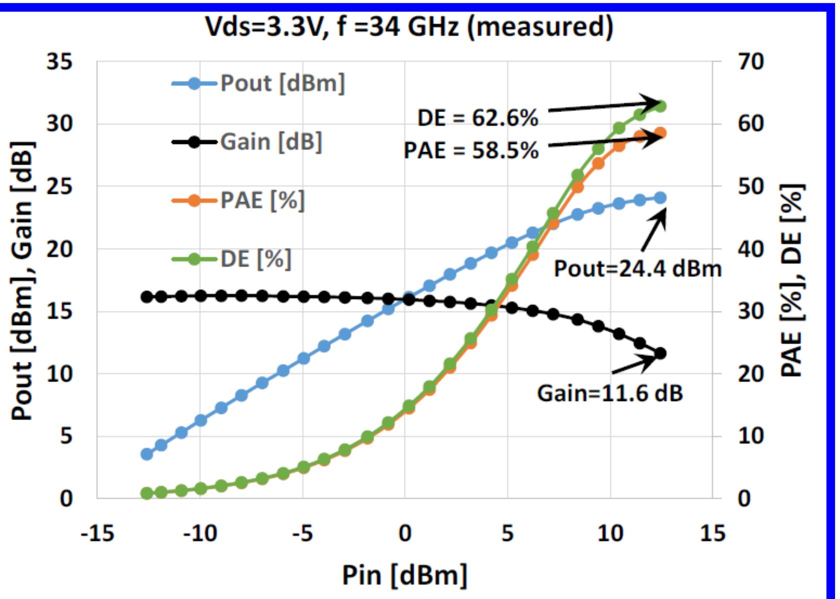
HRL: IEDM 2010 - 2012

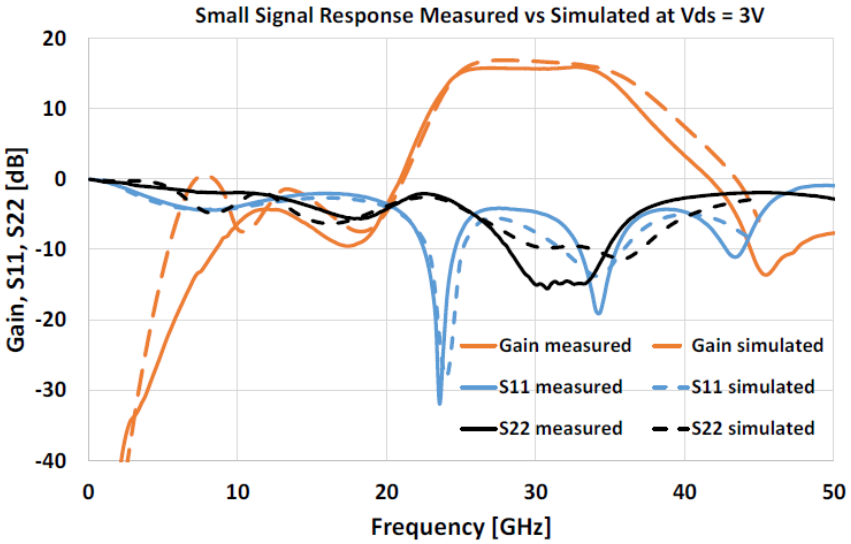
Ka-Band GaN/SiC PA with 58.5% PAE

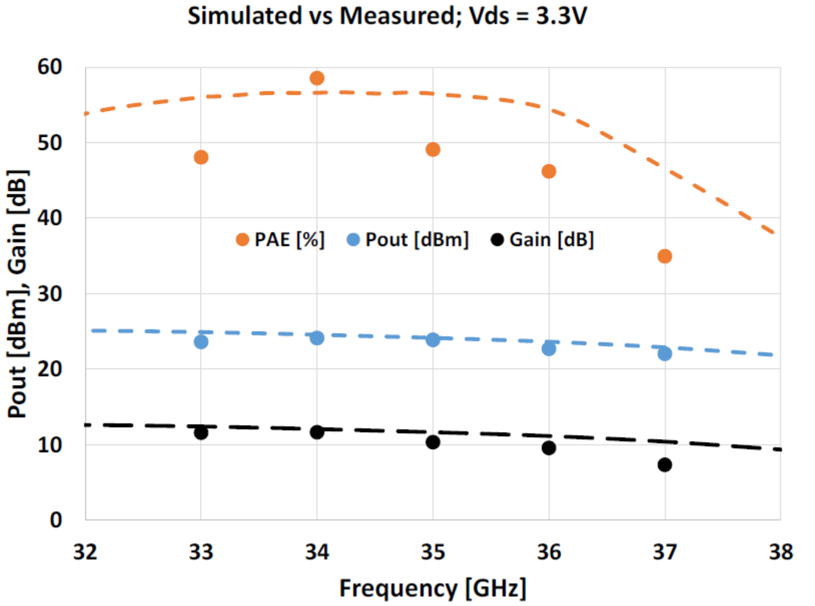
- HRL's 40 nm T4A GaN process: f*t*>300 GHz, f*max*>500 GHz, and BV > 15V
- 2 stage MMIC PA: 1st stage: 4x37.5 µm, 2nd stage: a 4x100 µm
- Highest attainable PAE using a scalable non-linear Angelov HEMT model extracted from prior wafers
- Designed in MWO environment
- PAE of 58.5% with associated gain of 11.9 dB and associated Pout of 24.4 dBm at 34 GHz under CW







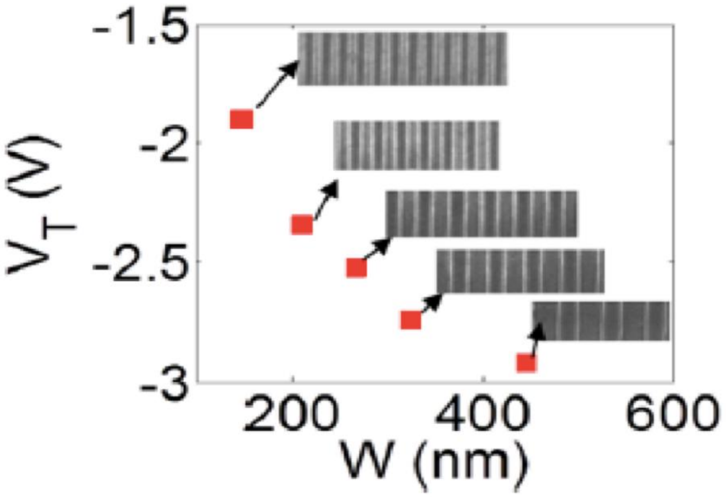


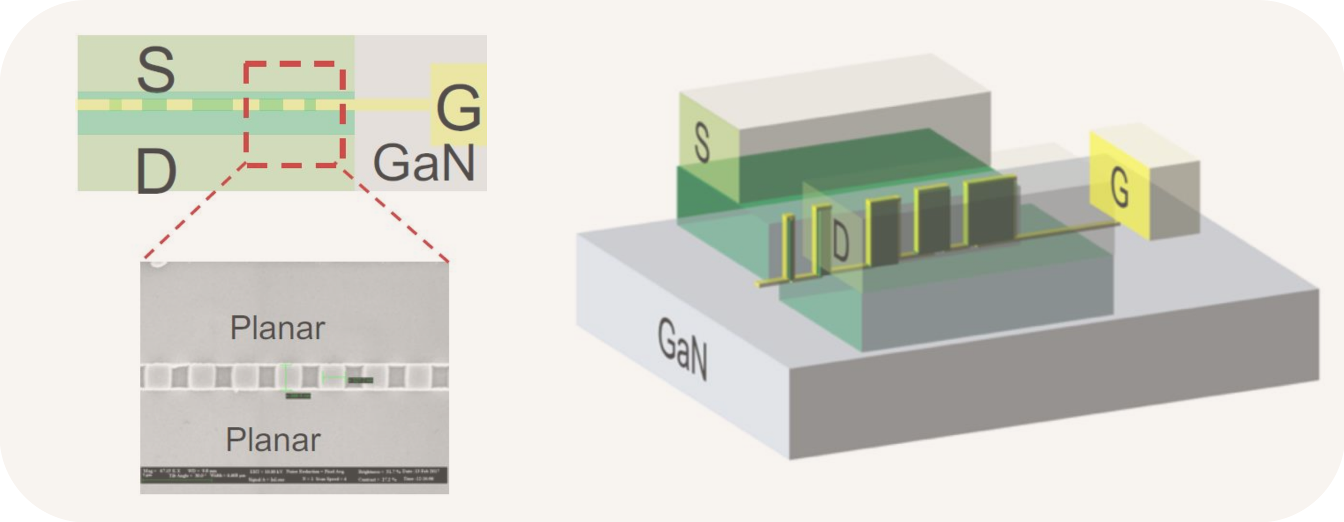


HRL: BCICTS 2019

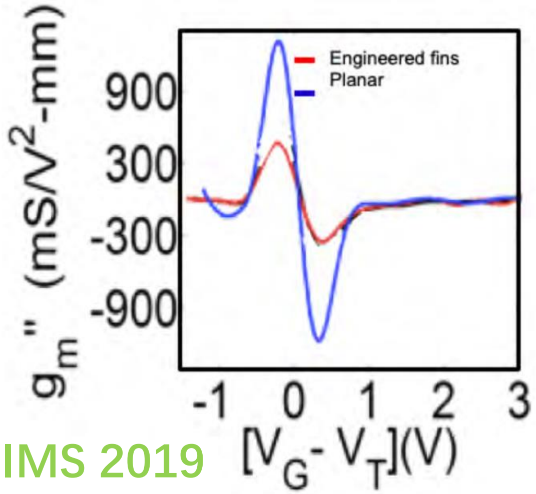
GaN/SiC HEMT: High-Linearity FINFET

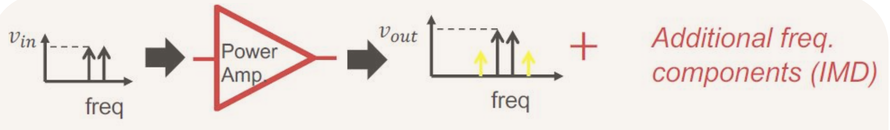
FINFET with different widths corresponds different Vp



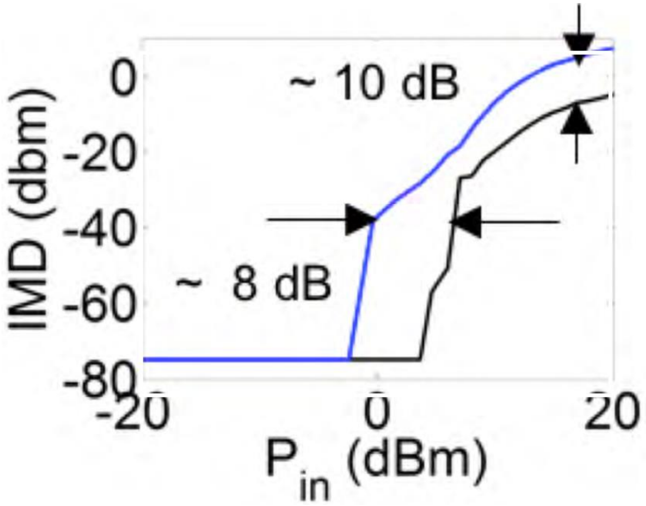


Superimposition of properly designed FETs leads to reduced gm" and improved IMD



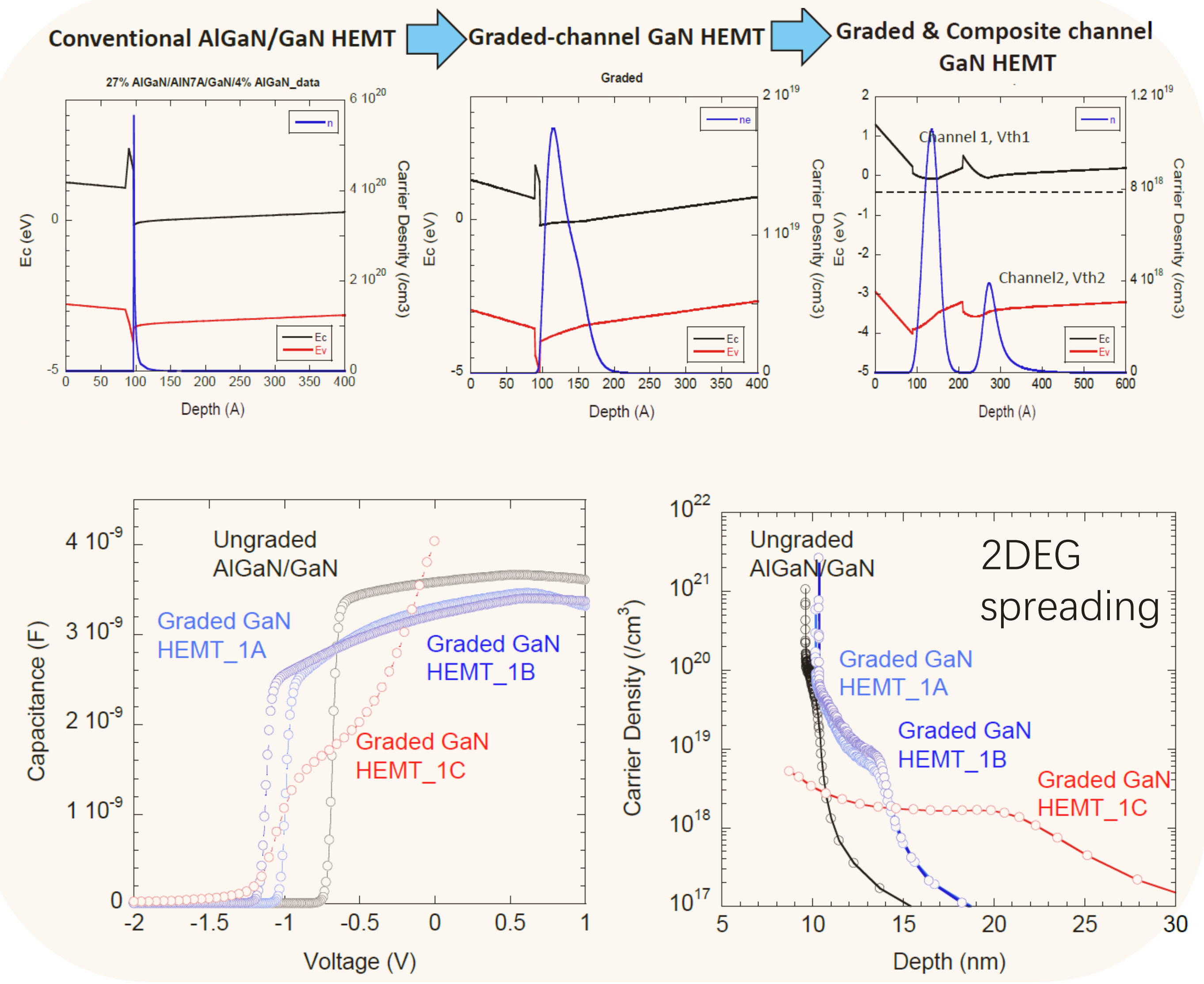


$$IMD \propto \frac{g_m'' A^3 (3\cos((2\omega_1 - \omega_2)t) + 3\cos((2\omega_2 - \omega_1)t))}{4}$$

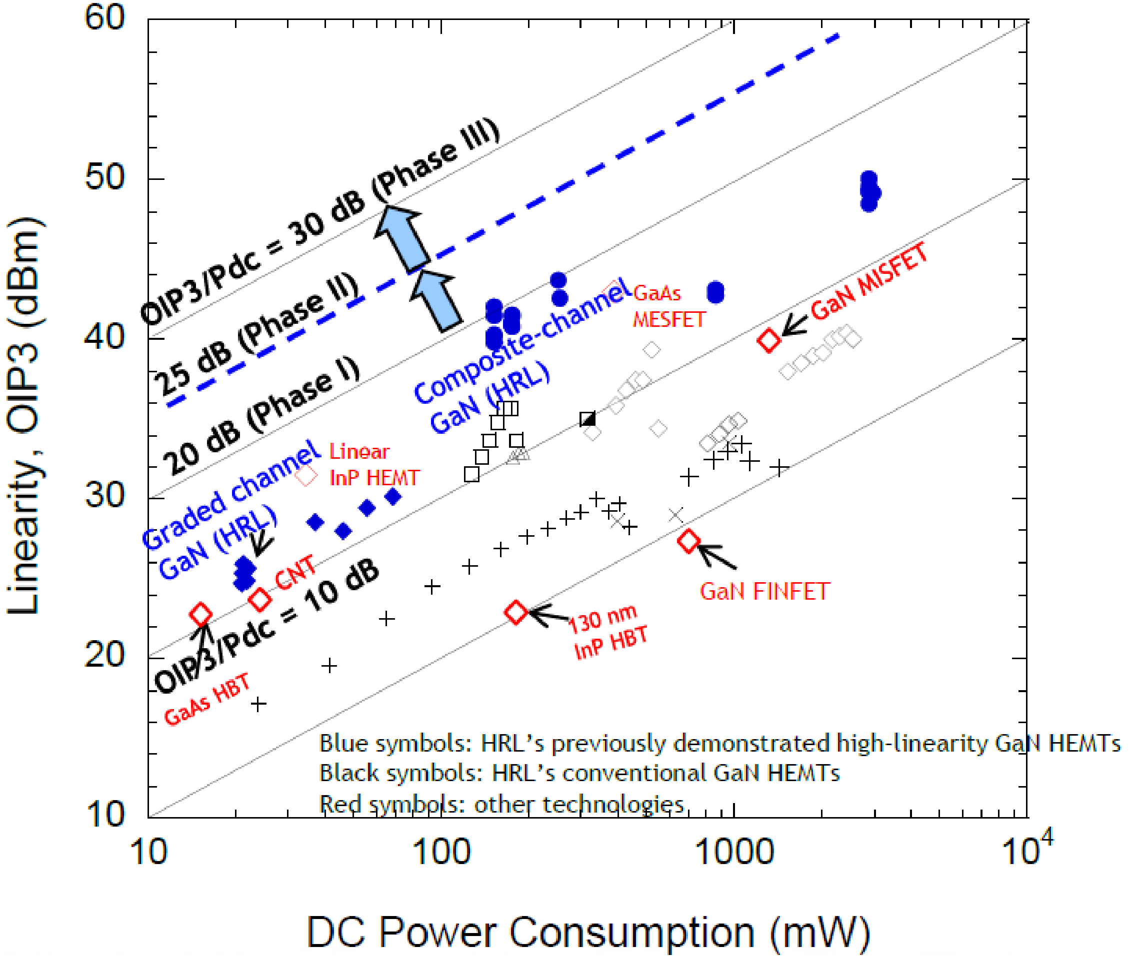


MIT: IMS 2019

GaN/SiC HEMT: High-Linearity with Graded Channel

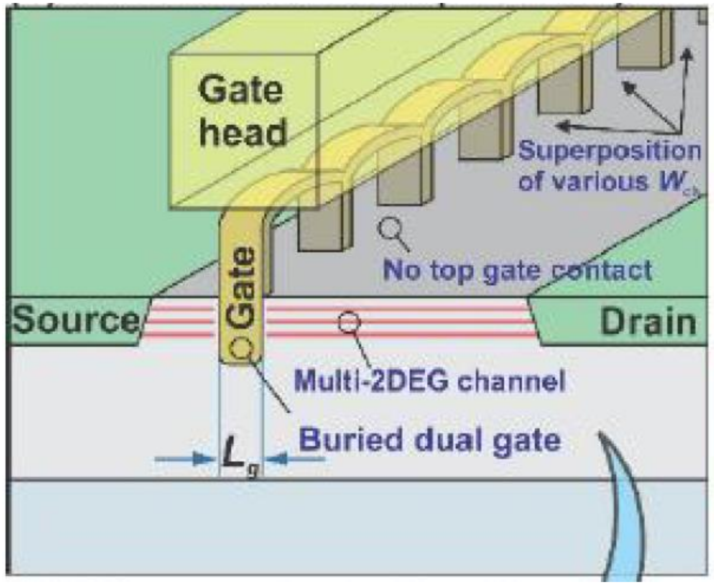


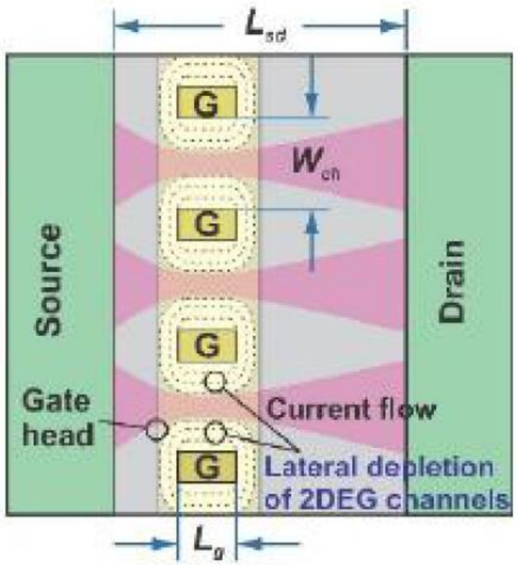
DARPA DREAM: Ultra linear mmw GaN HEMT with OIP_3/P_{DC}> 30dB at 30GHz

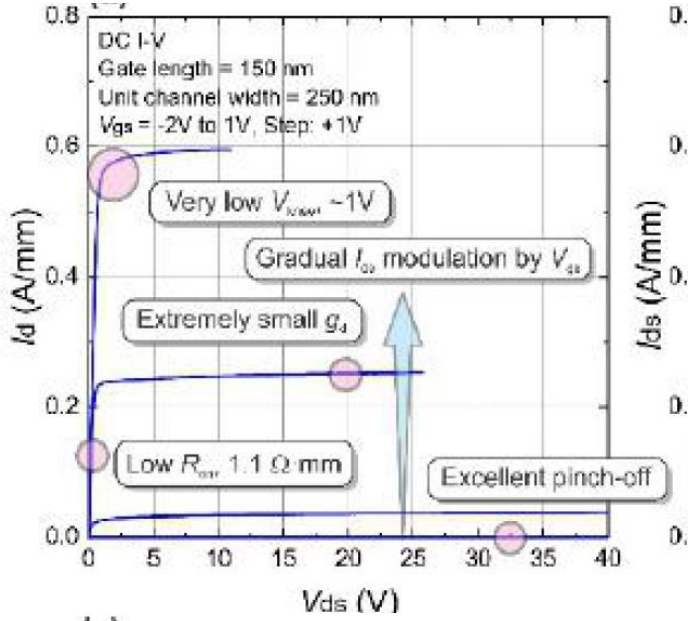


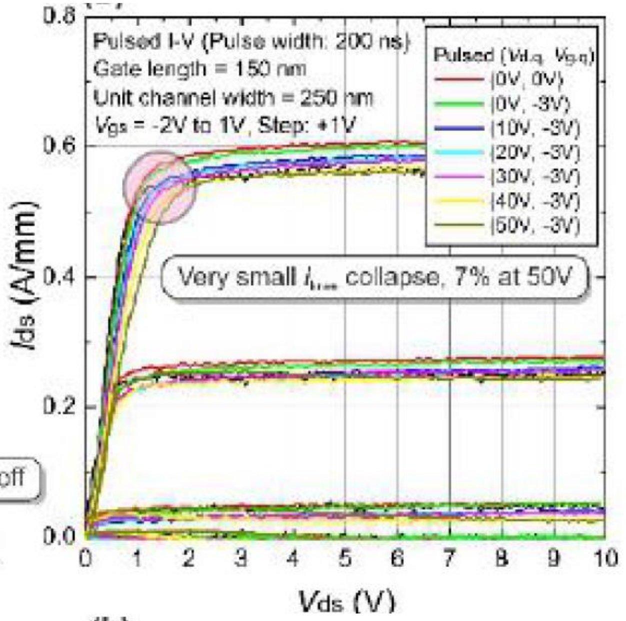
HRL: IMS 2019

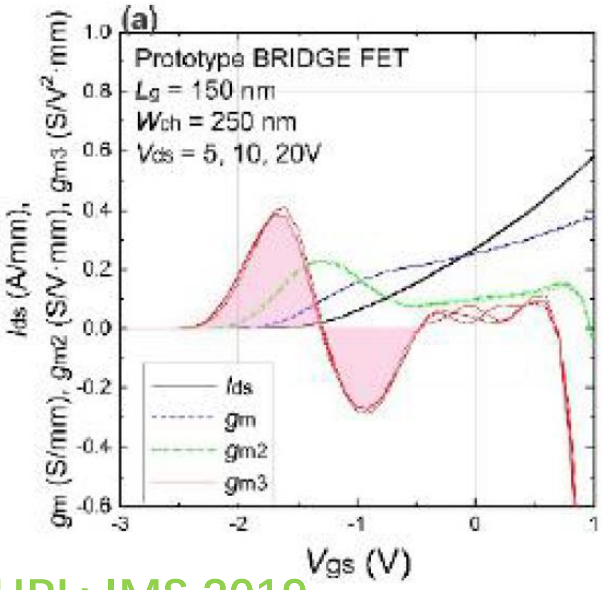
Buried Gate GaN/SiC HEMT with High Linearity

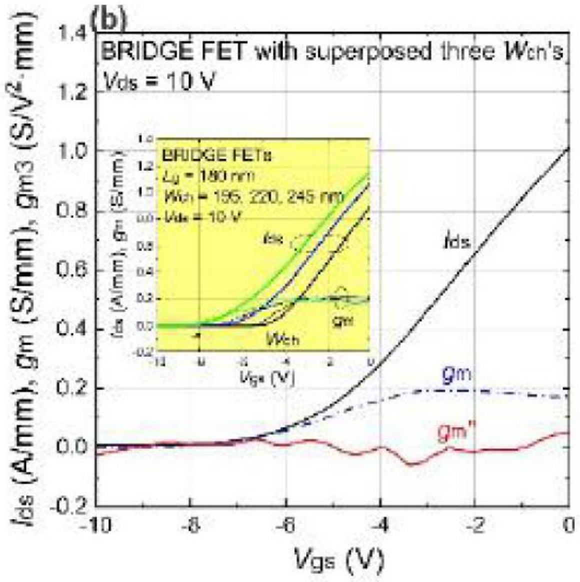


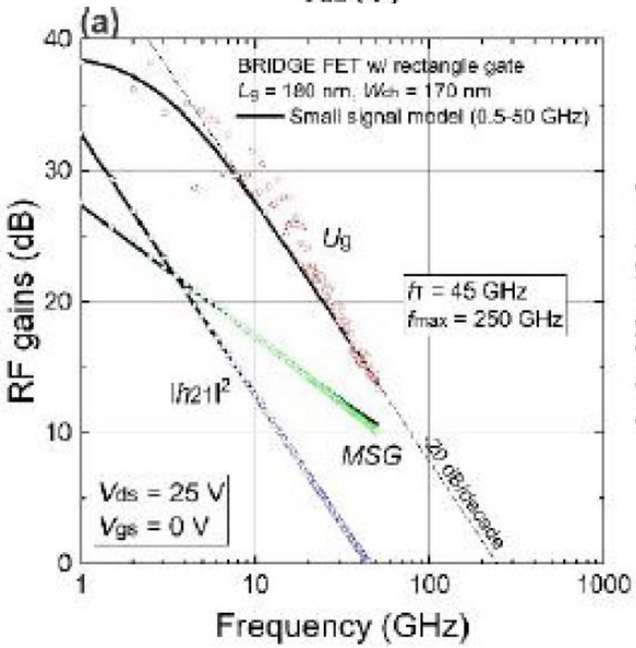


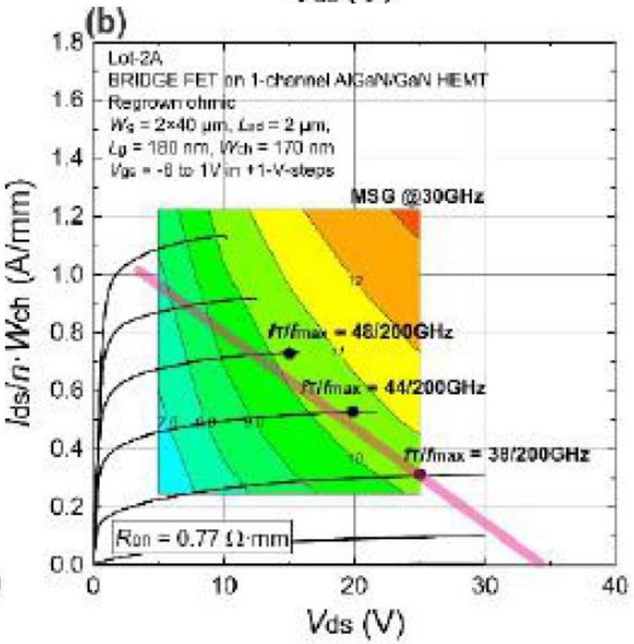






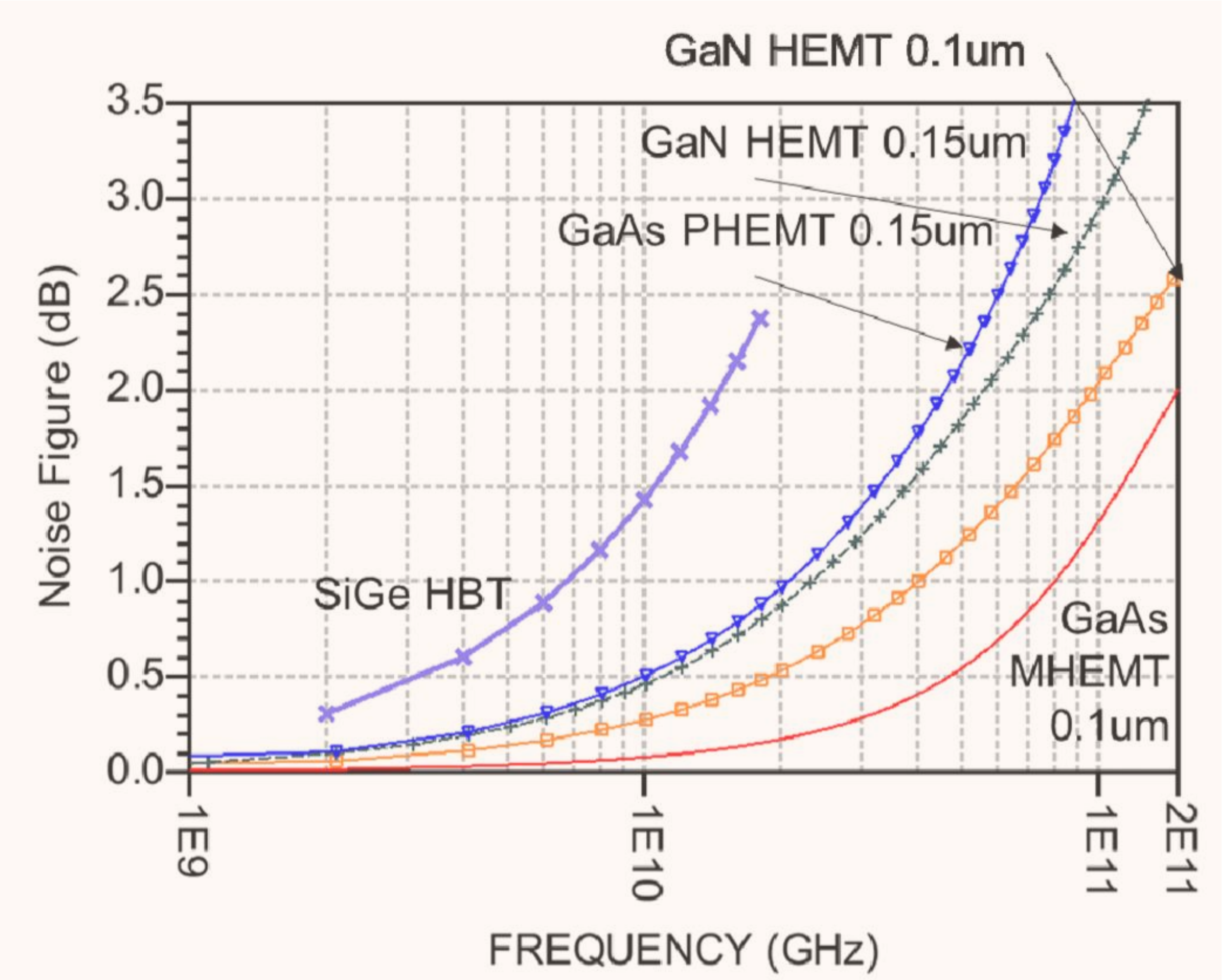






HRL: IMS 2019

GaN/SiC HEMT for LNA Applications (up to W Band)

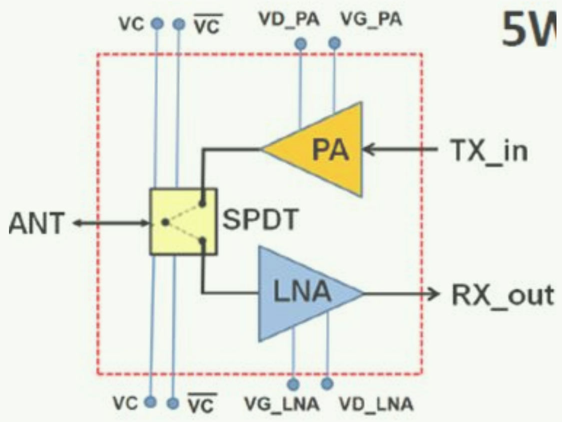


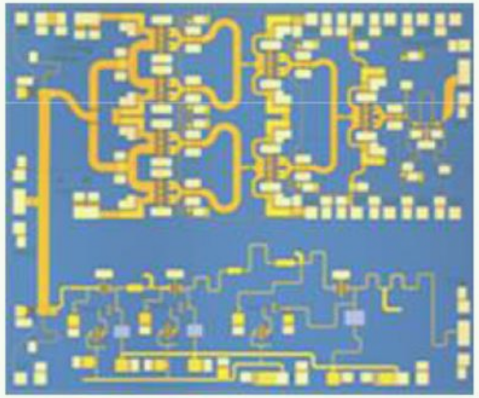
- 0.15µm GaN HEMT: Surprisingly low F_{min} typically ~3dB @W band
- Competitive versus (even better than) InGaAs based PHEMT, but with >5x ruggedness to incoming power to avoid adopting limiter design
- Another ~0.8dB F_{min} improvement achieved when using 0.1µm GaN HEMT
- GaN HEMT F_{min} next only to InP MHEMTwith similar gate lengths

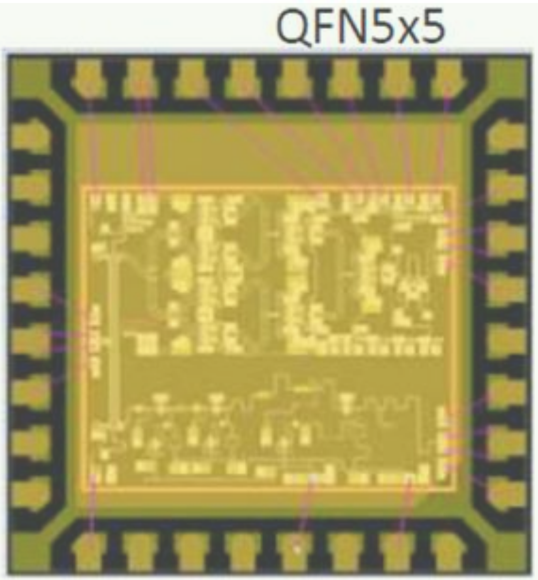
OMMIC: CSICS 2017

GaN/Si HEMT Lower Cost

100nm GaN/Si Based TR for Ka Band

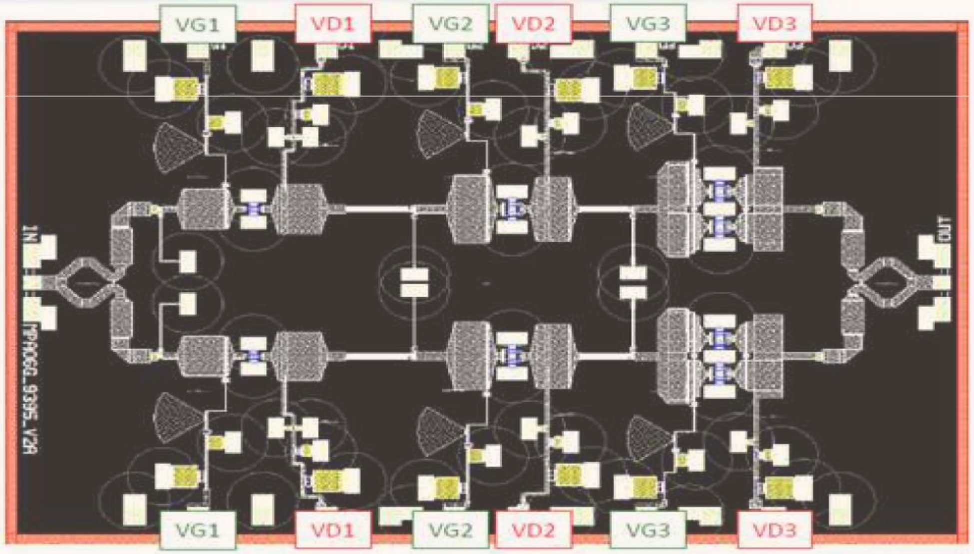




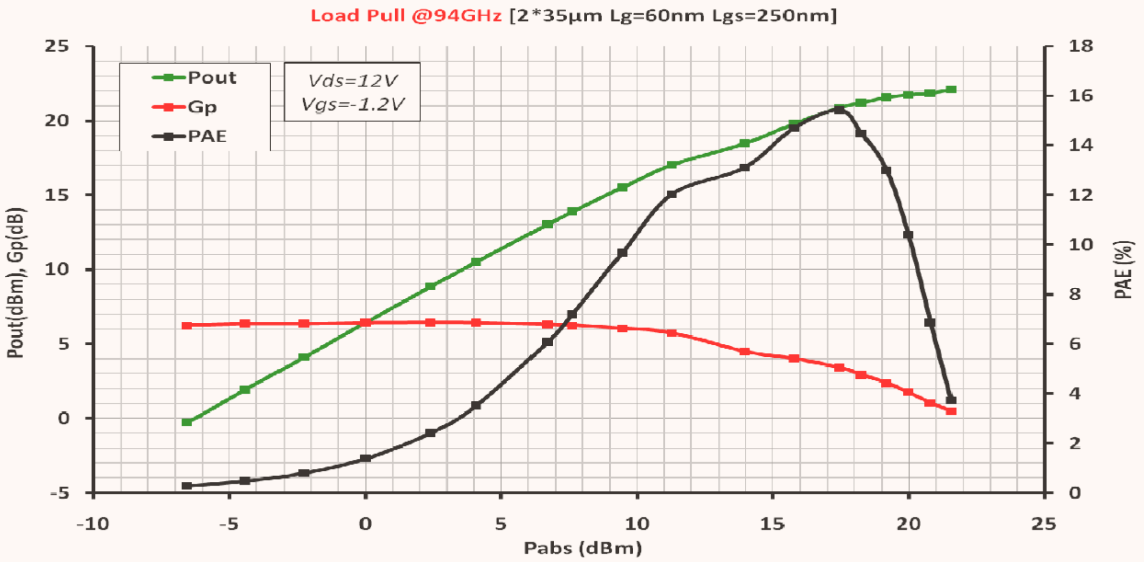


OMMIC: EMWW 2018

60nm GaN/Si Based PA for W Band



600mW, 12dB gain , 10%PAE @ 94GHz, 12V



THANK YOU

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