Project: IEEE P802.15 Working Group for Wireless Speciality Networks (WSNs)

Submission Title: Semiconductor technologies for THz Communications
Date Submitted: 7 May 2018
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Re: n/a

Abstract: The implementation of circuits at frequencies above 100GHz poses significant challenges. Many circuits have been proposed using either heterogenous bipolar transistors (HBT) or high electron mobility transistors (HEMT) in III-V compound material. However, when price is an issue and large digital circuits are needed, CMOS technologies are preferred but they perform poorly at frequencies well above 100GHz. This presentation describes the capabilities of these technologies and discusses several approaches to reach high power at RF together with large digital circuits.

Purpose: Information for the IG THz

Semiconductor technologies for THz Communications

Date: 2018-05-07

Authors:

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Abstract

The implementation of circuits at frequencies above 100GHz poses significant challenges. Many circuits have been proposed using either heterogenous bipolar transistors (HBT) or high electron mobility transistors (HEMT) in III-V compound material. These are performant but specialty expensive implementations.

When price is an issue and large digital circuits are needed, CMOS technologies are preferred. They, however, perform poorly at frequencies well above 100GHz.

This presentation describes the capabilities of these technologies and discusses several approaches to reach high power at RF together with large digital circuits.

Outline

Application needs

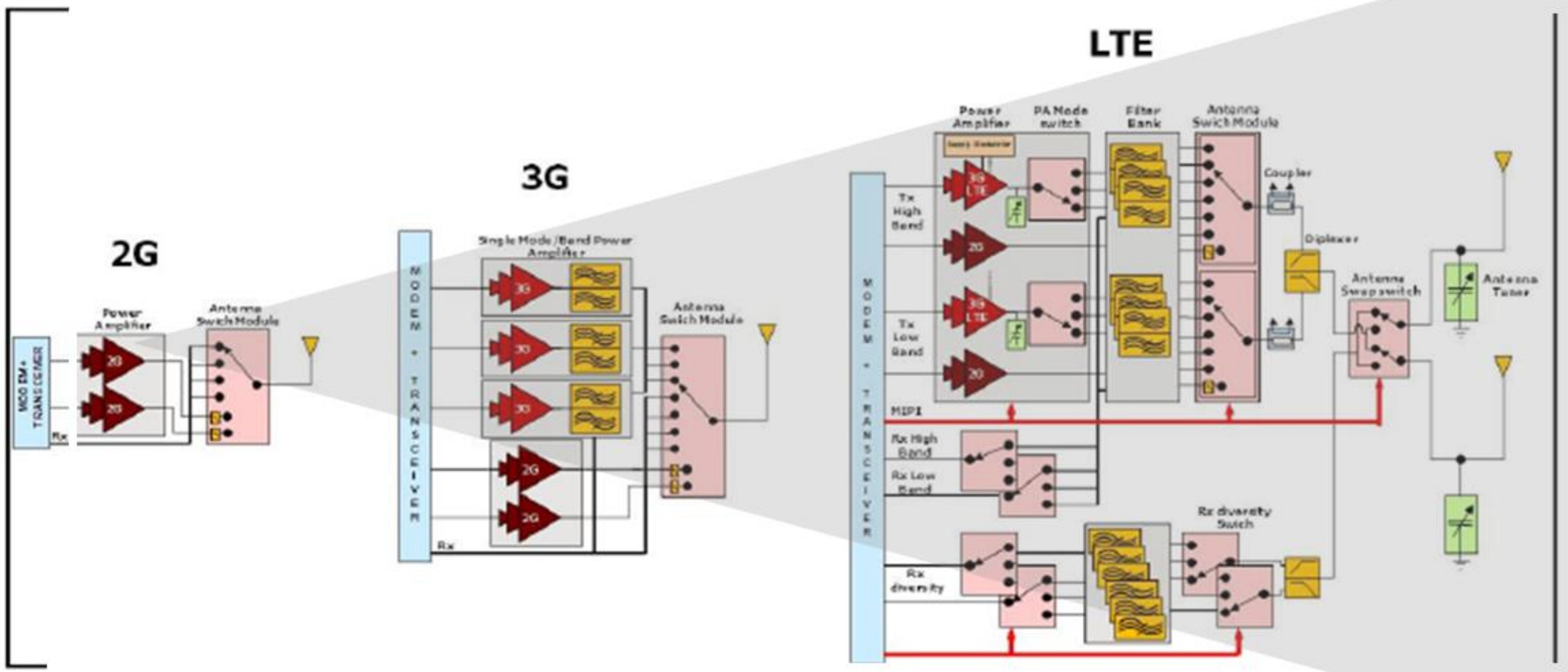
The active device scene

Circuits >100GHz implemented in bulk CMOS

Conclusions

Application needs

5G: increasing complexity for the RF front-end
Going to mm-wave



5G

Even more complex

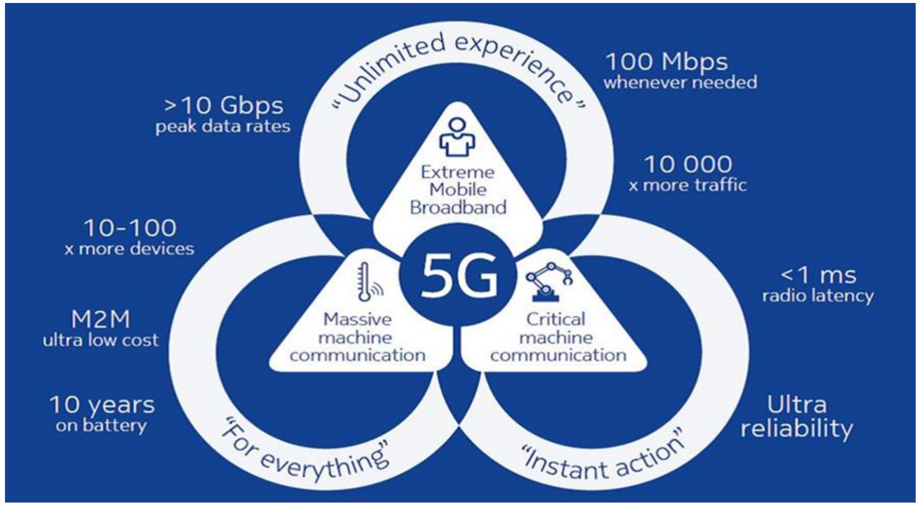
- Lots of carriers
- Carrier aggregation
- MIMO
- mm-wave

→ front-end with many
- antennas
- filters
- switches
- LNA
- PA

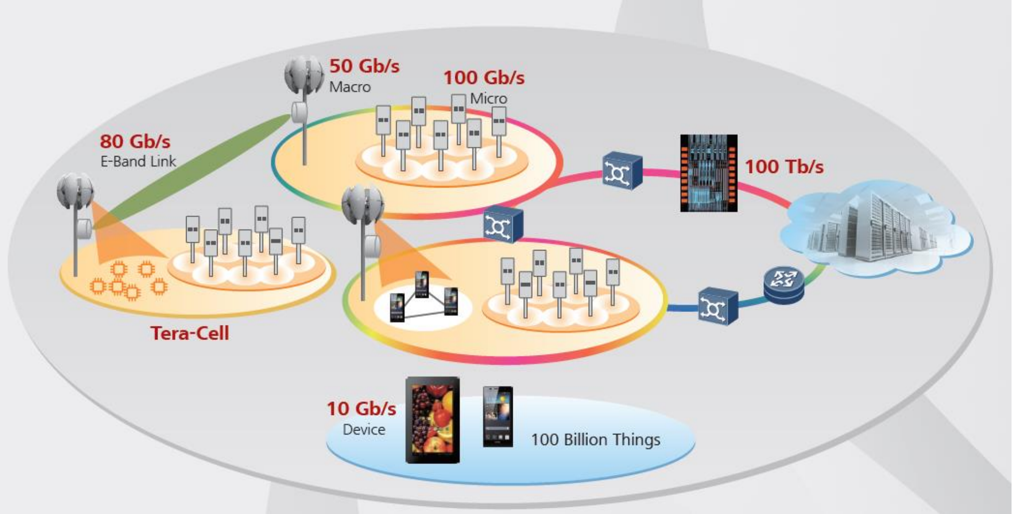
Increasing integration level reduces overall cost, form factor, power:
- combination of power amplifier with its controlling circuitry
- bringing as much as possible into one IC or module (3D integration)

Wireless communication: 5G and beyond

Source: Nokia

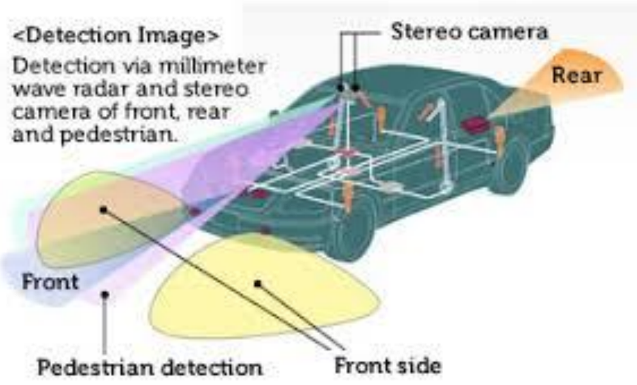


Source: Huawei, 5G: A Technology vision



- 5G will provide a total solution for a wide range of requirements
  - Contains existing sub-6 GHz bands of 4G and new bands at mm-wave up to 90GHz
  - Increased back- and fronthauling requirements towards 100s Gb/s
- 6G: wireless data rates > 100 Gb/s
  - Carrier frequencies > 100 GHz : optical & wireless communication will meet
  - See e.g.
    - European projects in ICT-09 cluster: operation > 90 GHz, up to 1Tb/s
    - IEEE802.15.3d

Sensing: mm-wave offers several advantages



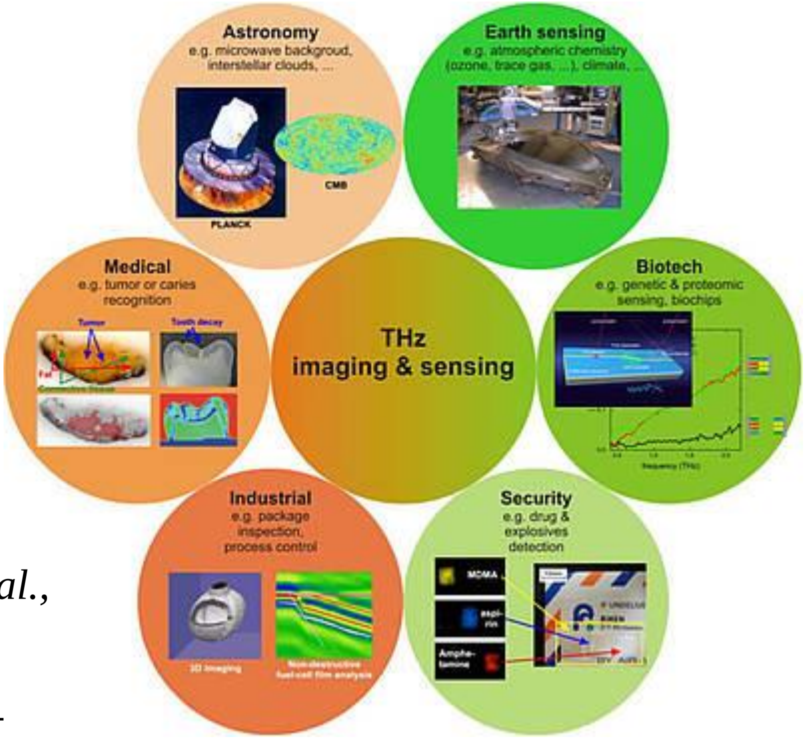
Radar:

- Range resolution = c/(2*bandwidth) → larger bandwidth easier to realize at higher frequencies
- Better resolution of velocity and angle with smaller wavelength
- Automotive radar 76-81 GHz: maturing market using Si technologies
  - BiCMOS and single-chip CMOS
  - Future >100 GHz ?
- Smart home/office/building/city, e-health, ... : numerous applications from sub-10 GHz to >100GHz, potentially large market, pressure on form factor, power consumption

Mm-wave imaging

Spectroscopy

...



Source: P. de Maagt et al.,

Key requirements for >100GHz implementations

Efficient circuits @ frequency > 100GHz:

- PA: high output power for link budget (range)
- VCO/PLL: low phase noise for good EVM (spectral efficiency)

Highly integrated solution including

- RF
- Digital (digital calibration, PHY processing)
- Memory

Relatively large volumes

Key requirements for >100GHz implementations

Efficient circuits @ frequency > 100GHz:

PA: high output power for link budget (range)

VCO/PLL: low phase noise for good EVM (spectral efficiency)

CMOS ?

Highly integrated solution including

RF

Digital (digital calibration, PHY processing)

Memory

CMOS ?

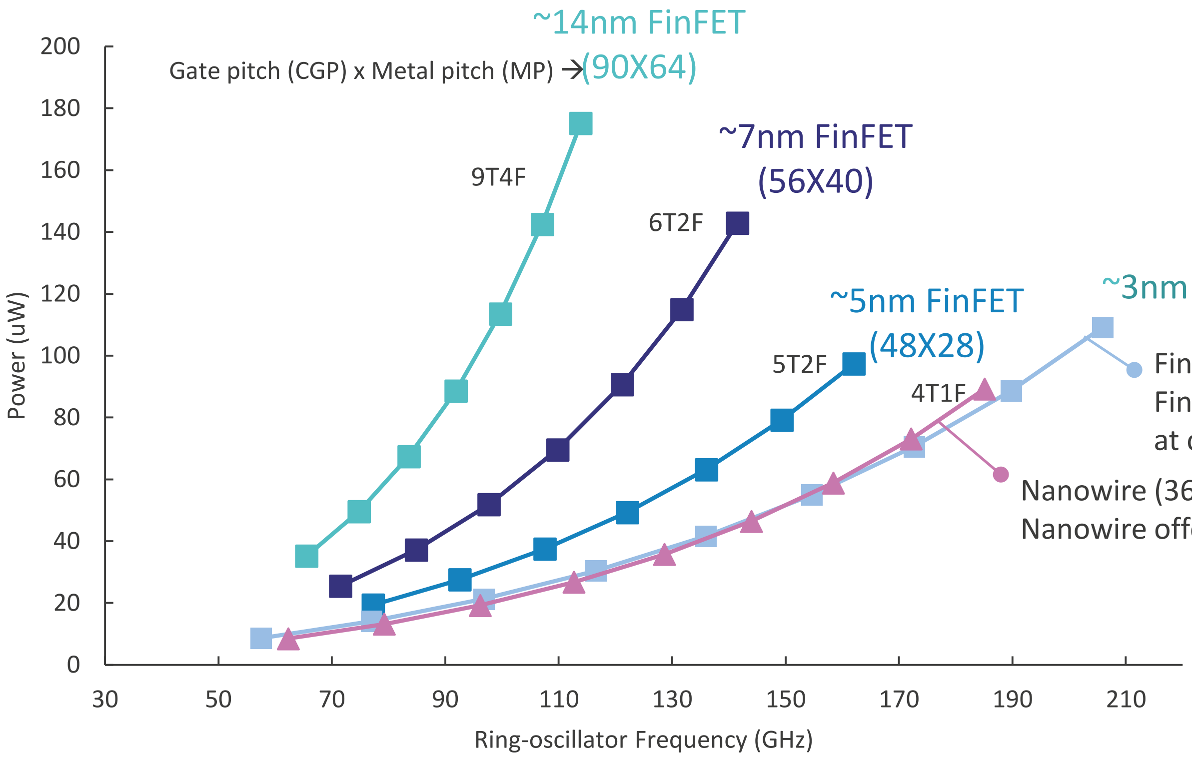
Relatively large volumes

CMOS ?

The active device scene

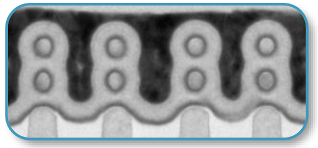
Evolution for logic
f_T of Si-based FETs will not increase (much) with further scaling

XTXF: #Tracks#Fins
CGP: Contact to Gate pitch
MP: Metal Pitch



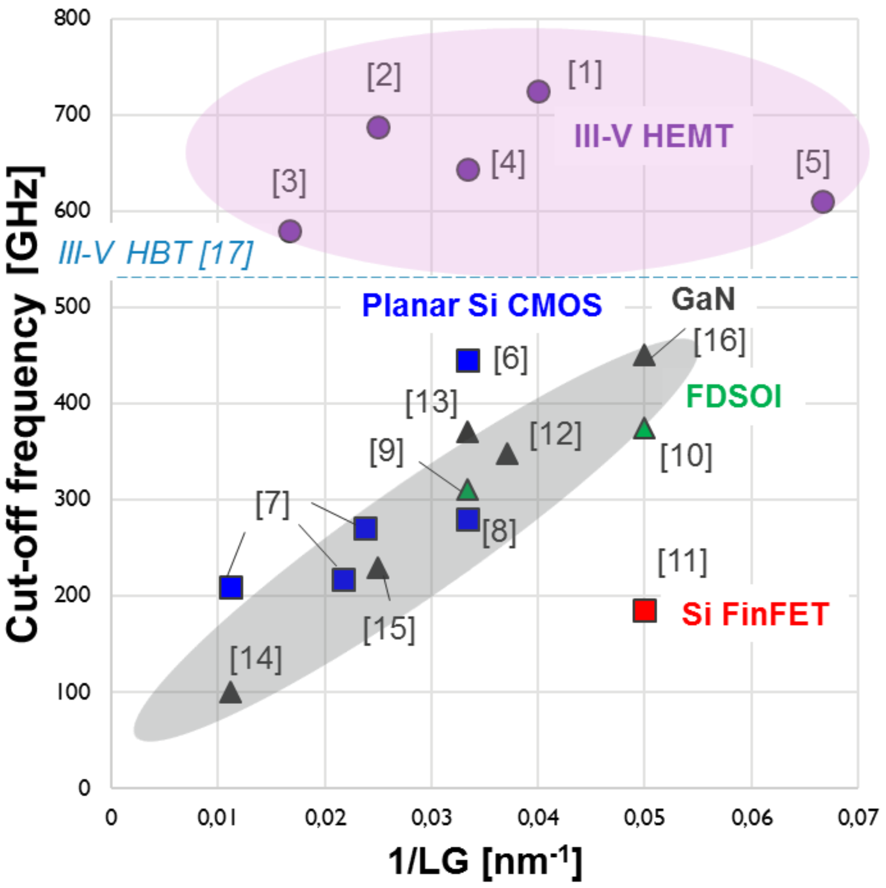
FinFET (42CGP x 24MP)
FinFET is highest performance option
at cost of larger area

Nanowire (36CGP x 24MP)
Nanowire offers better performance-area trade-off



Silicon based!

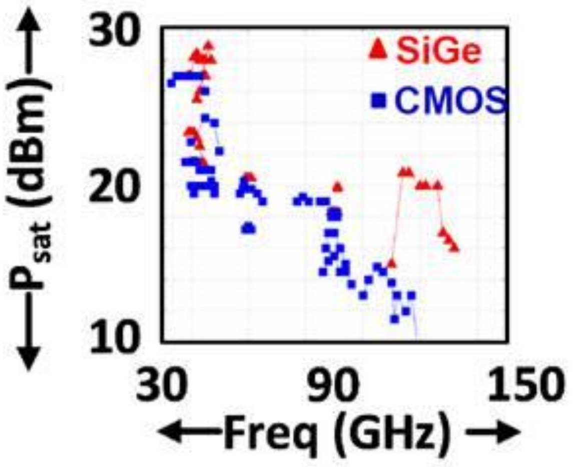
High-speed applications need fast device with good power handling capabilities ... which can be combined with CMOS



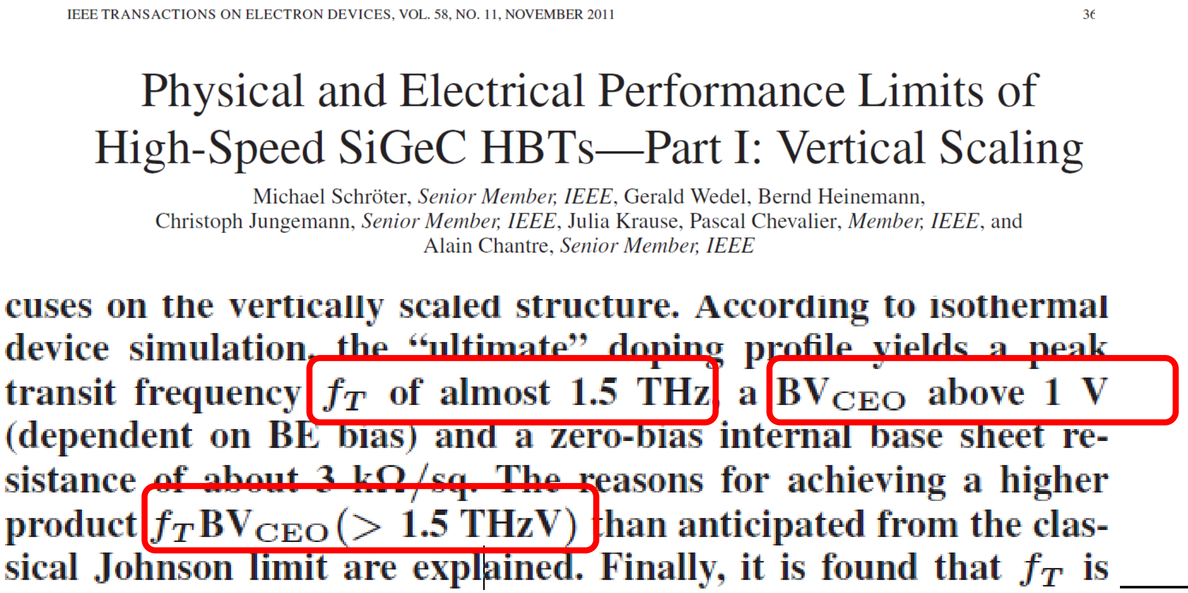
- CMOS cannot do it alone anymore
- f_T of Si-based FETs will not increase (much) with further scaling
- FinFET delivers intrinsically lower speed than planar
- III-V HEMT offers >500GHz f_T at relaxed gate length
- GaN similar to planar bulk but stronger driving capabilities

SiGe HBT beating CMOS in speed/power handling

1. Superiority evidenced by published designs



2. Long-term predictions for SiGe



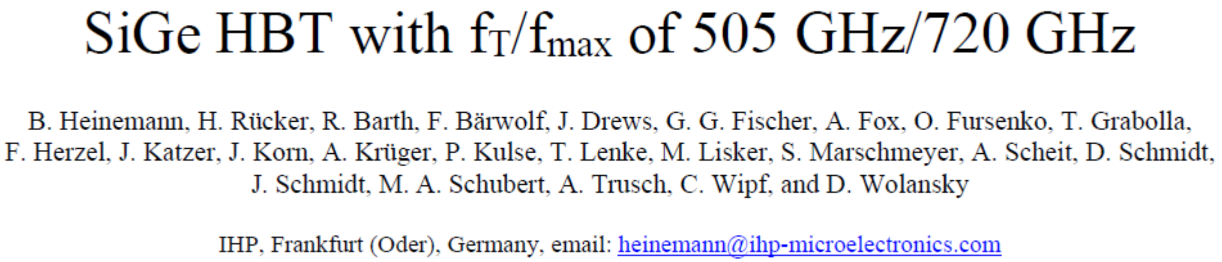
IEEE TRANSACTIONS ON ELECTRON DEVICES, VOL. 58, NO. 11, NOVEMBER 2011 3

Physical and Electrical Performance Limits of High-Speed SiGeC HBTs—Part I: Vertical Scaling

Michael Schröter, *Senior Member, IEEE*, Gerald Wedel, Bernd Heinemann,
Christoph Jungemann, *Senior Member, IEEE*, Julia Krause, Pascal Chevalier, *Member, IEEE*, and
Alain Chantre, *Senior Member, IEEE*

cuses on the vertically scaled structure. According to isothermal device simulation, the "ultimate" doping profile yields a peak transit frequency f_T of almost 1.5 THz, a BV_{CEO} above 1 V (dependent on BE bias) and a zero-bias internal base sheet resistance of about 3 kΩ/sq. The reasons for achieving a higher product $f_T BV_{CEO} (> 1.5\ \text{THzV})$ than anticipated from the classical Johnson limit are explained. Finally, it is found that f_T is

3. SiGe technology developments



SiGe HBT with f_T/f_{max} of 505 GHz/720 GHz

B. Heinemann, H. Rücker, R. Barth, F. Bärwolf, J. Drews, G. G. Fischer, A. Fox, O. Fursenko, T. Grabolla,
F. Herzel, J. Katzer, J. Korn, A. Krüger, P. Kulse, T. Lenke, M. Lisker, S. Marschmeyer, A. Scheit, D. Schmidt,
J. Schmidt, M. A. Schubert, A. Trusch, C. Wipf, and D. Wolansky

IHP, Frankfurt (Oder), Germany, email: heinemann@ihp-microelectronics.com

4. Maturing results in EU project

TARANTO

Project ID: 737454
Funded under: H2020-EU.2.1.1.7. - ECSEL

TowARds Advanced bicmos NanoTechnology platforms for rf and thz applicatiOns

From 2017-04-01 **to** 2020-03-31, ongoing project

Project details

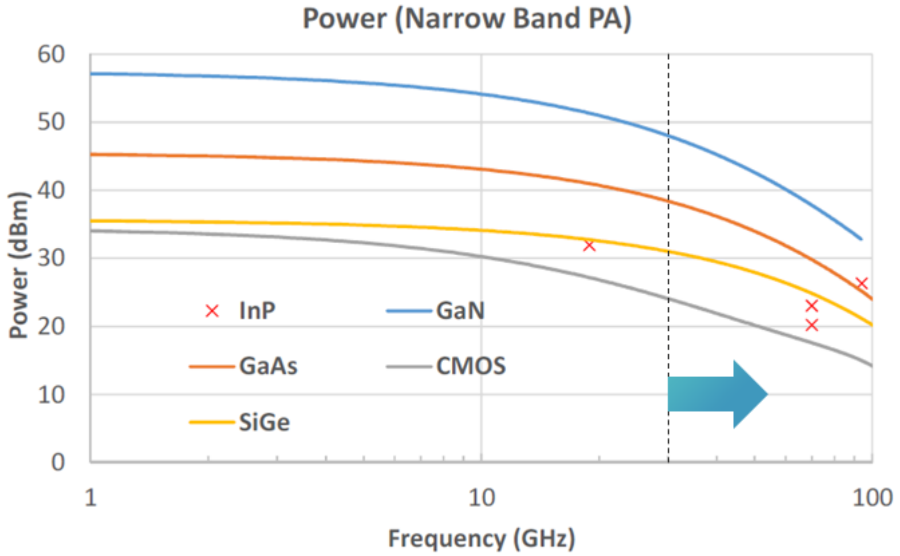
Total cost: EUR 43 025 971,22	**Topic(s):** ECSEL-2016-1 - ECSEL Key Applications and Essential technologies (RIA)
EU contribution: EUR 12 081 281,89	**Call for proposal:** H2020-ECSEL-2016-1-RIA-two-stage See other projects for this call
Coordinated in: France	**Funding scheme:** ECSEL-RIA - ECSEL Research and Innovation Action

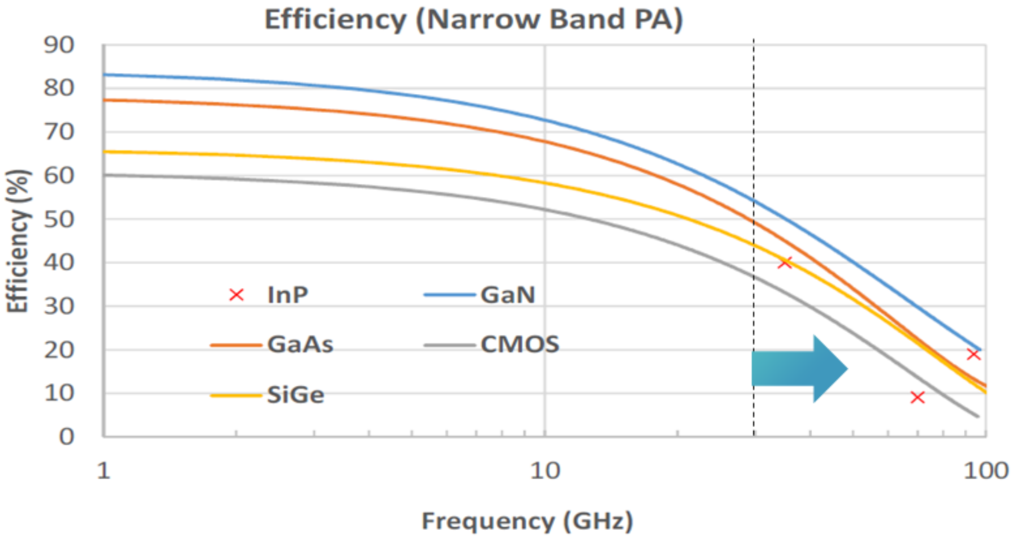
Objective

The TARANTO project targets to break the technological barriers to the development of the next BiCMOS technology platforms, allowing the improvement of the performance of the HBT (Heterojunction Bipolar Transistors) with a much higher level of integration. This new generation of transistors HBT will be a key factor to meet the needs of high-speed communications systems and high data rate required for the integration of heterogeneous intelligent systems as well as for intell...

GaN and GaAs devices yield high output power and efficiency at high frequencies
The trend continues @ >100GHz

[Mikovic et al., IEDM 2016.]





	Bandgap (eV)	Breakdown field (MV/cm)	Thermal conductivity (W/cm-K)	Johnson FOM Ebr x vsat/2π (10^{12} V/s)	Saturation velocity (10^7 cm/s)
Si	1.1	0.6	1.5	0.5	1
GaAs	1.4	0.5	0.5	1	1.5
GaN	3.4	3.5	1.5	8	2.7

All-silicon versus III-V co-integration

FinFET → lateral nanowires
Best for complex logic
Speed limited by 3D parasitics
Poor driving capabilities

BiCMOS
Logic usually lags few generations behind
Compatible with FD-SOI
[ST Microelectronics, BJT + 28nm FD-SOI, BCTM 2016]
Stronger driving capabilities than FinFET
Highest f_T of silicon devices
f_T > 1 THz possible at BV_{CEO} > 1V

RF-SOI
Higher f_T than FinFET
Body bias is extra feature
Allows for device stacking in PAs
Switches with very low Ron*Coff

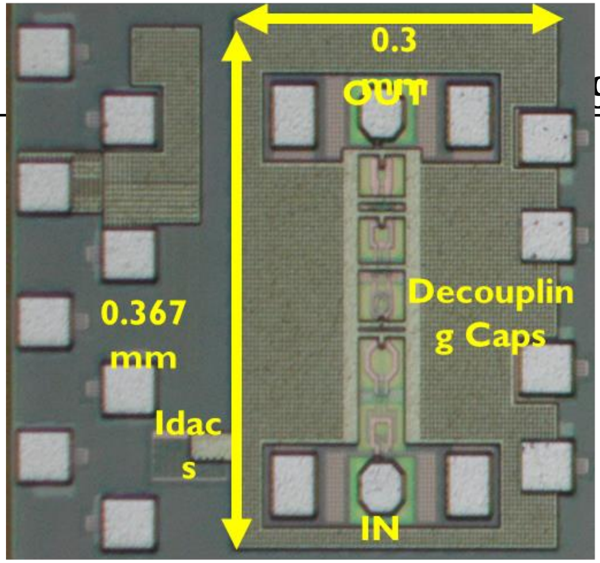
III-V
Higher f_T than Si possible
Better power handling
Growth on 300mm Si complex but feasible

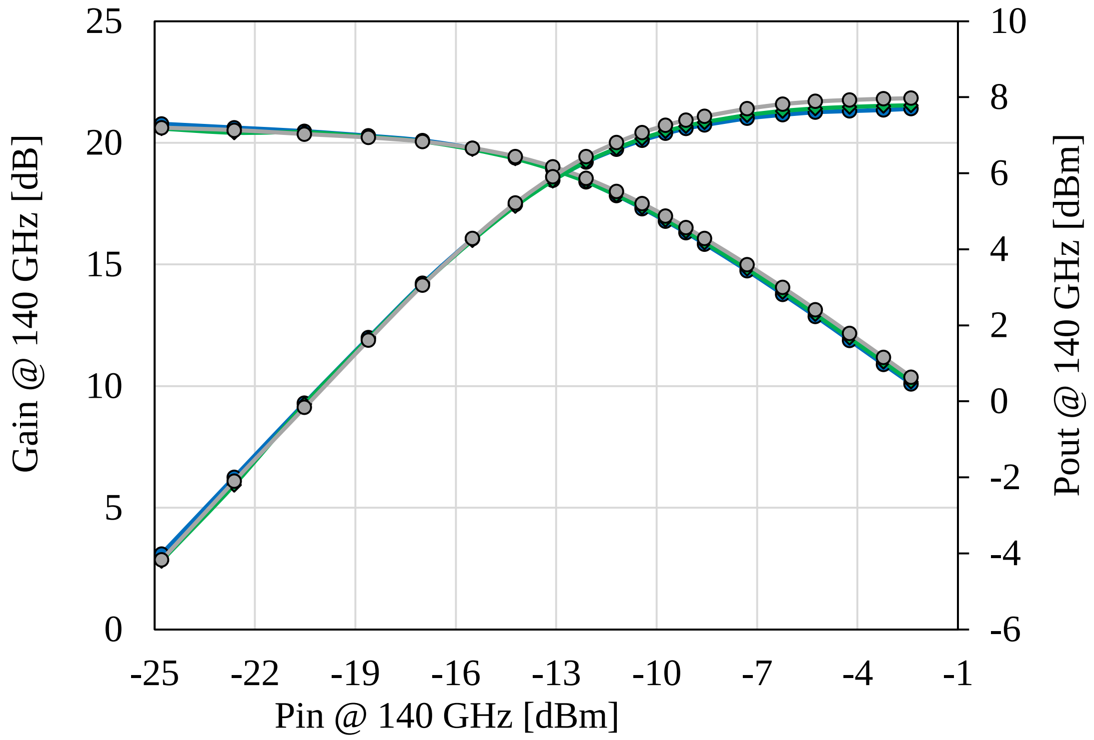
several research groups in the world are considering co-integration of III-V materials on silicon

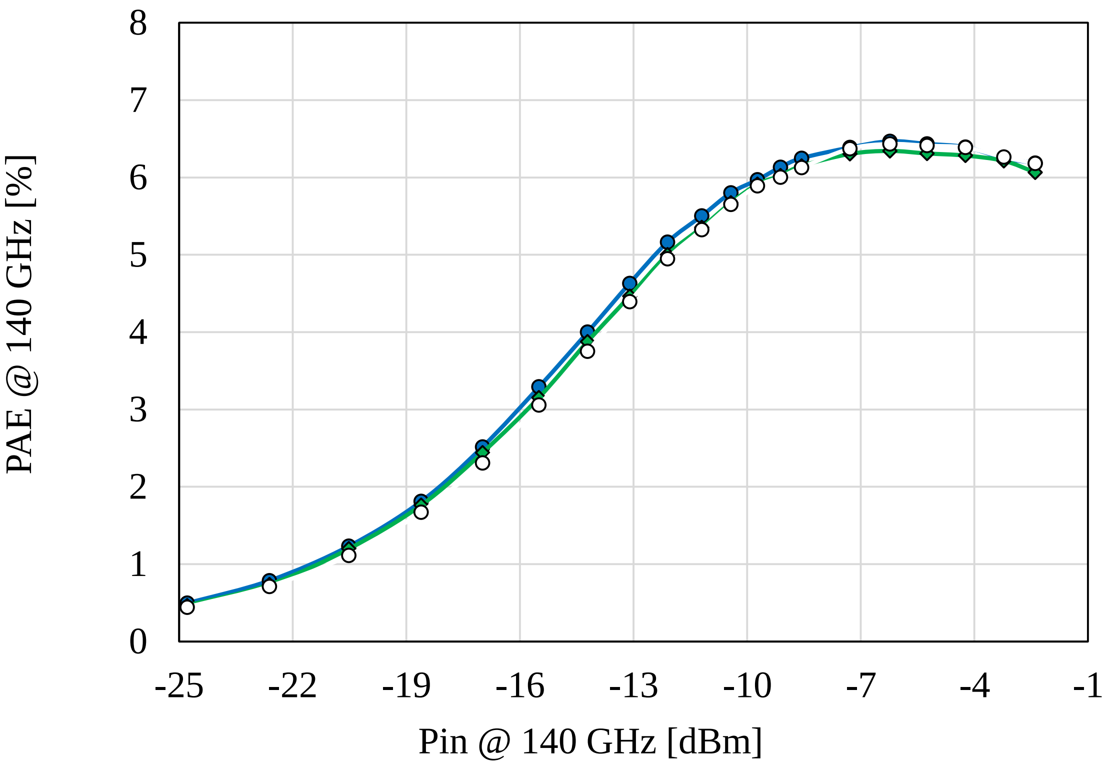
Circuits >100GHz implemented in bulk CMOS

140GHz PA in bulk CMOS

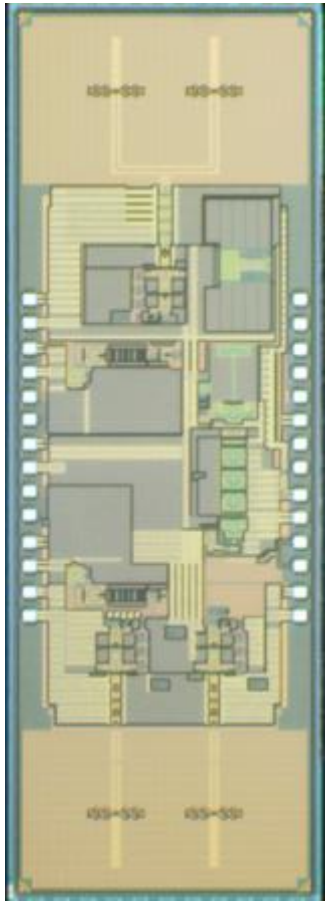
- 28 nm HPM
- V_{DD} = 0.9 V
- PA area = 0.11 mm^2
- PA Pdc = 81 mW





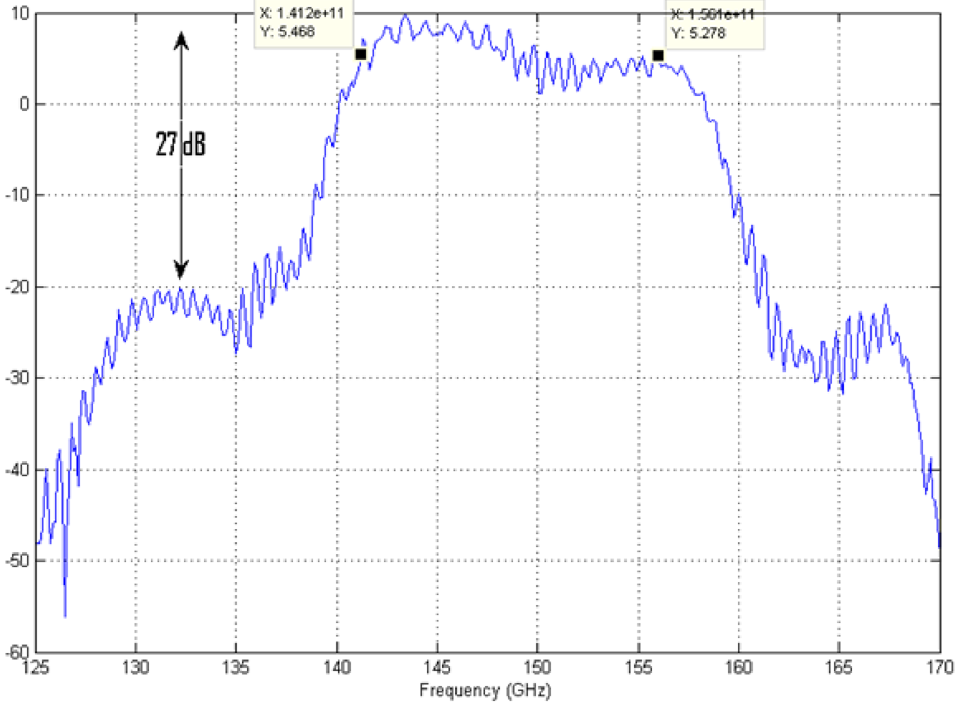


140GHz FMCW radar in bulk CMOS with on-chip antennas



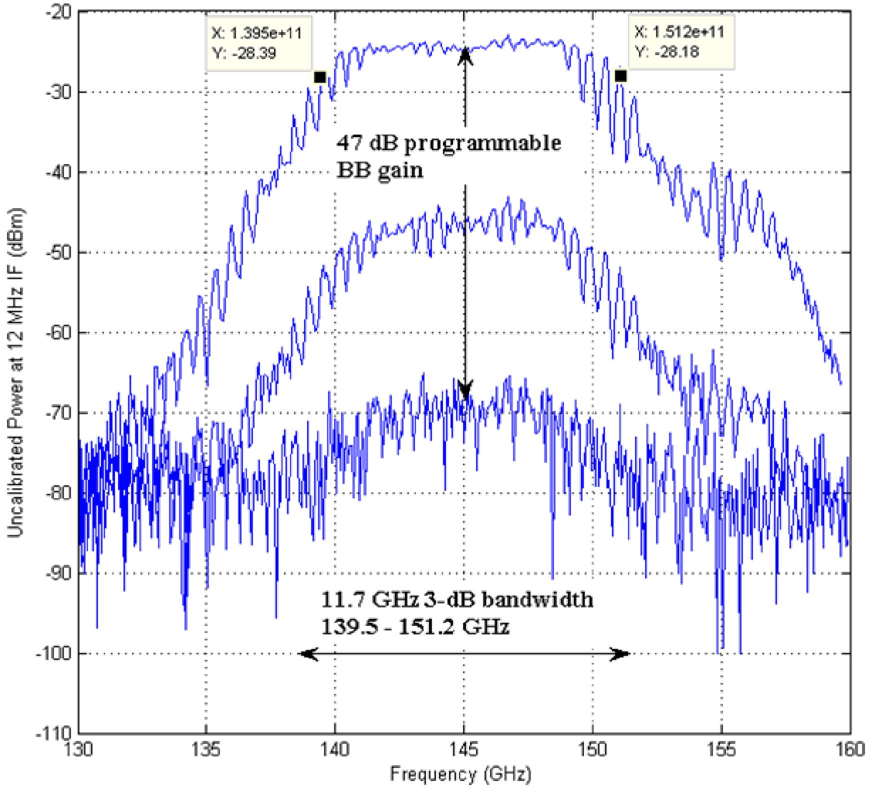
TX

- EIRP with 2 PA's active: 9 dBm
- 3 dB Bandwidth: 141 GHz – 156 GHz



RX

- 47 dB programmable Baseband gain
- 3 dB RF Bandwidth:
  139.5 GHz – 151.2 GHz
- 3 dB baseband Bandwidth:
  750 kHz – 18 MHz



Conclusions

Conclusions

- **Need for high(er) speed and high power at a small factor**

  Higher degree of integration, packaging challenges
- **Scaling roadmap slowing down, CMOS not going faster anymore**
- **Will market embrace other devices co-integrated with CMOS?**
  - Or will design tricks in CMOS and digital compensation techniques rule out non-CMOS?
  - Which device will win? SiGe HBT, III-V HBT, HEMT, MOSFET, ...?
  - 300 mm wafers are a must
  - Affordable?

References for slide 13

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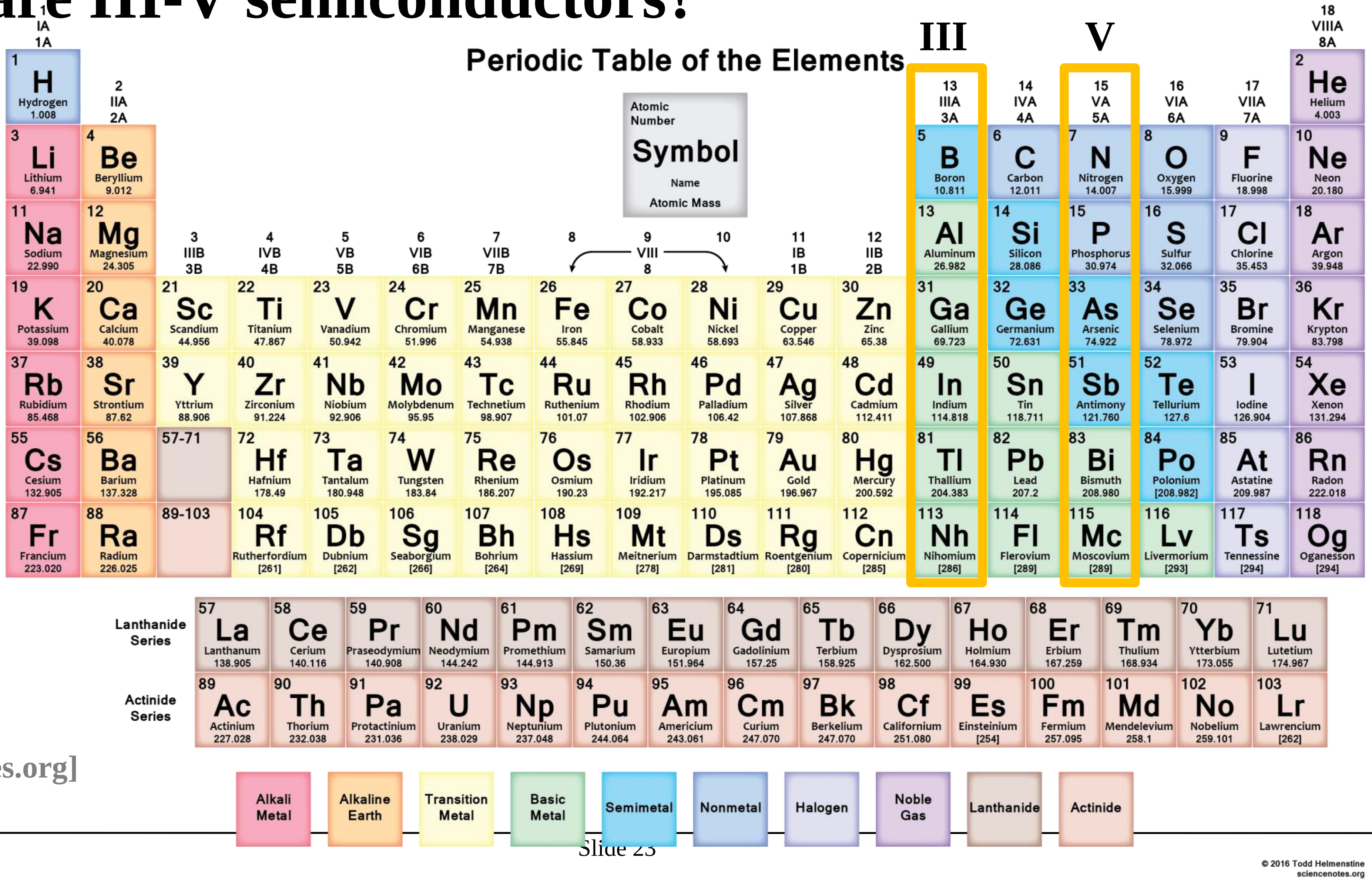
What are III-V semiconductors?



III

V

Periodic Table of the Elements

Atomic Number
Symbol
Name
Atomic Mass

1 IA 1A	2 IIA 2A	3 IIIB 3B	4 IVB 4B	5 VB 5B	6 VIB 6B	7 VIIB 7B	8	9 VIII 8	10	11 IB 1B	12 IIB 2B	13 IIIA 3A	14 IVA 4A	15 VA 5A	16 VIA 6A	17 VIIA 7A	18 VIIIA 8A
1 H Hydrogen 1.008																	2 He Helium 4.003
3 Li Lithium 6.941	4 Be Beryllium 9.012											5 B Boron 10.811	6 C Carbon 12.011	7 N Nitrogen 14.007	8 O Oxygen 15.999	9 F Fluorine 18.998	10 Ne Neon 20.180
11 Na Sodium 22.990	12 Mg Magnesium 24.305											13 Al Aluminum 26.982	14 Si Silicon 28.086	15 P Phosphorus 30.974	16 S Sulfur 32.066	17 Cl Chlorine 35.453	18 Ar Argon 39.948
19 K Potassium 39.098	20 Ca Calcium 40.078	21 Sc Scandium 44.956	22 Ti Titanium 47.867	23 V Vanadium 50.942	24 Cr Chromium 51.996	25 Mn Manganese 54.938	26 Fe Iron 55.845	27 Co Cobalt 58.933	28 Ni Nickel 58.693	29 Cu Copper 63.546	30 Zn Zinc 65.38	31 Ga Gallium 69.723	32 Ge Germanium 72.631	33 As Arsenic 74.922	34 Se Selenium 78.972	35 Br Bromine 79.904	36 Kr Krypton 83.798
37 Rb Rubidium 85.468	38 Sr Strontium 87.62	39 Y Yttrium 88.906	40 Zr Zirconium 91.224	41 Nb Niobium 92.906	42 Mo Molybdenum 95.95	43 Tc Technetium 98.907	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.906	46 Pd Palladium 106.42	47 Ag Silver 107.868	48 Cd Cadmium 112.411	49 In Indium 114.818	50 Sn Tin 118.711	51 Sb Antimony 121.760	52 Te Tellurium 127.6	53 I Iodine 126.904	54 Xe Xenon 131.294
55 Cs Cesium 132.905	56 Ba Barium 137.328	57-71	72 Hf Hafnium 178.49	73 Ta Tantalum 180.948	74 W Tungsten 183.84	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.217	78 Pt Platinum 195.085	79 Au Gold 196.967	80 Hg Mercury 200.592	81 Tl Thallium 204.383	82 Pb Lead 207.2	83 Bi Bismuth 208.980	84 Po Polonium [208.982]	85 At Astatine 209.987	86 Rn Radon 222.018
87 Fr Francium 223.020	88 Ra Radium 226.025	89-103	104 Rf Rutherfordium [261]	105 Db Dubnium [262]	106 Sg Seaborgium [266]	107 Bh Bohrium [264]	108 Hs Hassium [269]	109 Mt Meitnerium [278]	110 Ds Darmstadtium [281]	111 Rg Roentgenium [280]	112 Cn Copernicium [285]	113 Nh Nihonium [286]	114 Fl Flerovium [289]	115 Mc Moscovium [289]	116 Lv Livermorium [293]	117 Ts Tennessine [294]	118 Og Oganesson [294]

Lanthanide Series	57 La Lanthanum 138.905	58 Ce Cerium 140.116	59 Pr Praseodymium 140.908	60 Nd Neodymium 144.242	61 Pm Promethium 144.913	62 Sm Samarium 150.36	63 Eu Europium 151.964	64 Gd Gadolinium 157.25	65 Tb Terbium 158.925	66 Dy Dysprosium 162.500	67 Ho Holmium 164.930	68 Er Erbium 167.259	69 Tm Thulium 168.934	70 Yb Ytterbium 173.055	71 Lu Lutetium 174.967
Actinide Series	89 Ac Actinium 227.028	90 Th Thorium 232.038	91 Pa Protactinium 231.036	92 U Uranium 238.029	93 Np Neptunium 237.048	94 Pu Plutonium 244.064	95 Am Americium 243.061	96 Cm Curium 247.070	97 Bk Berkelium 247.070	98 Cf Californium 251.080	99 Es Einsteinium [254]	100 Fm Fermium 257.095	101 Md Mendelevium 258.1	102 No Nobelium 259.101	103 Lr Lawrencium [262]

Alkali Metal | Alkaline Earth | Transition Metal | Basic Metal | Semimetal | Nonmetal | Halogen | Noble Gas | Lanthanide | Actinide

Typical III-V compounds:

Ga-As
Al-Ga-As
Ga-N
Al-Ga-N
In-P

[Source: sciencenotes.org]