Recent Advances in THz Integrated Electronic Systems

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TERA FLAG

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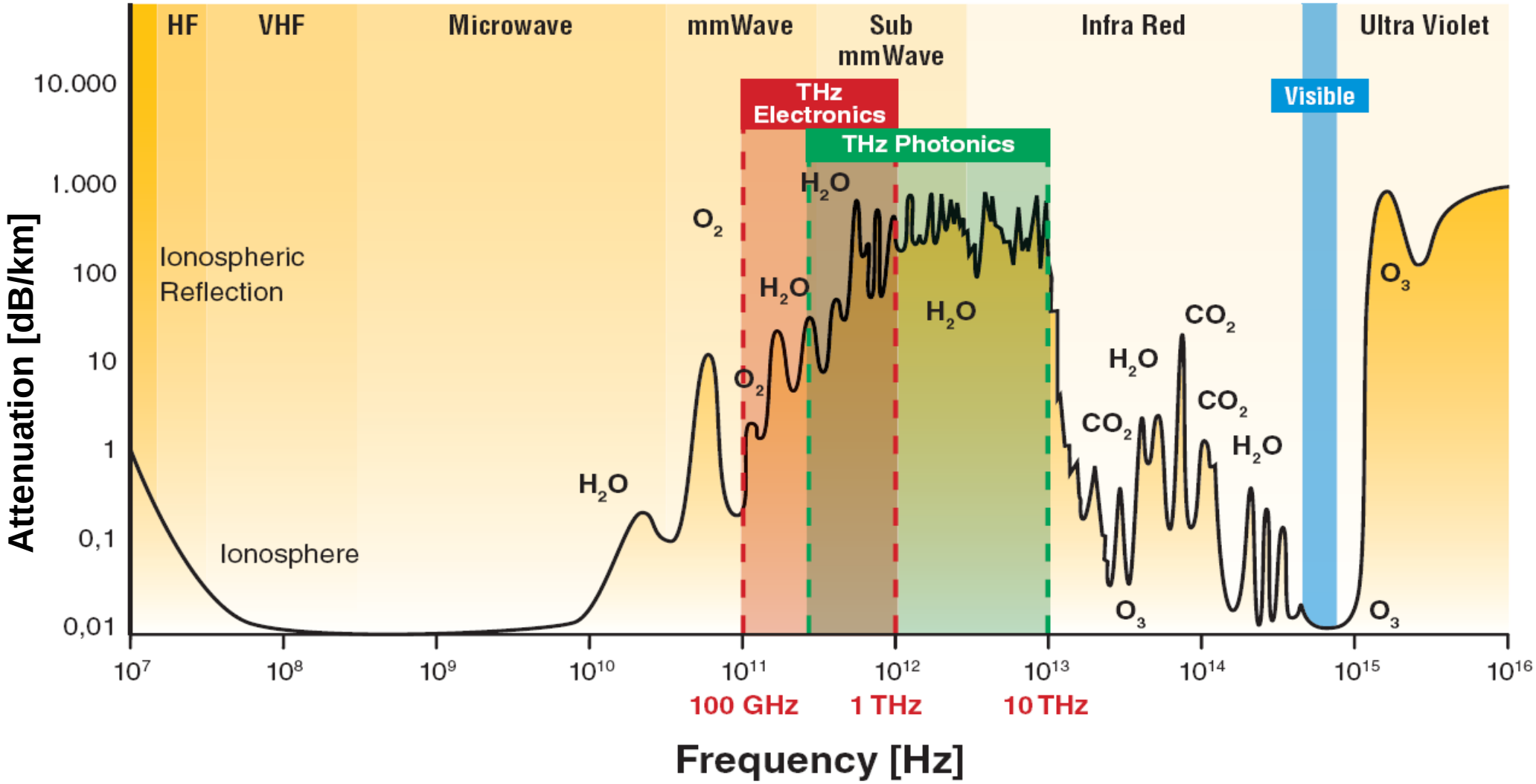
Institute for High-Frequency & Communication Technology

IHCT

Where could we use THz electronics?



RF/mmWave/THz Application Scenarios

High-speed Communication

- 60GHz, E-band, 5G, 6G, …
- IEEE 802.15.3d-2017 252.72-321.84GHz
- Towards 100GBit/s
- Interconnects
- Data servers
- Networking and protocols

Radar Applications

- 77GHz, 120GHz, 240GHz
- Automotive
- Remote control
- Gesture recognition
- Process control
- 3-D Imaging
- Patient monitoring

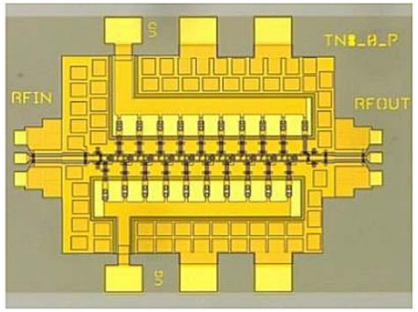
mmWave, THz Imaging and Sensing

- Non-destructive testing
- Security
- Bio-medical
- Space
- Material characterization
- Spectroscopy
- Super-Resolution Imaging

TeraFlag closing the THz “Applications Gap”

Electronic Device Technology Options

- **III/V substrates**
  - 25nm InP HEMT, fmax=1.5THz, 9dB >1THz amp
  - GaN, Fmax=0.58 THz
  - InP-GaAsSb DHBT, Fmax=1.18 THz
- **Silicon substrates**
  - CMOS bulk/SOI/FinFETs, fmax≈300-350 GHz
  - SiGe BiCMOS/SiGe HBT, fmax=700GHz [2]
- **Heterogeneous integration**
  - InP + SiGe
- **Electronic-Photonic integration**
  - Modulators, WG, Ge photo-diodes + Silicon

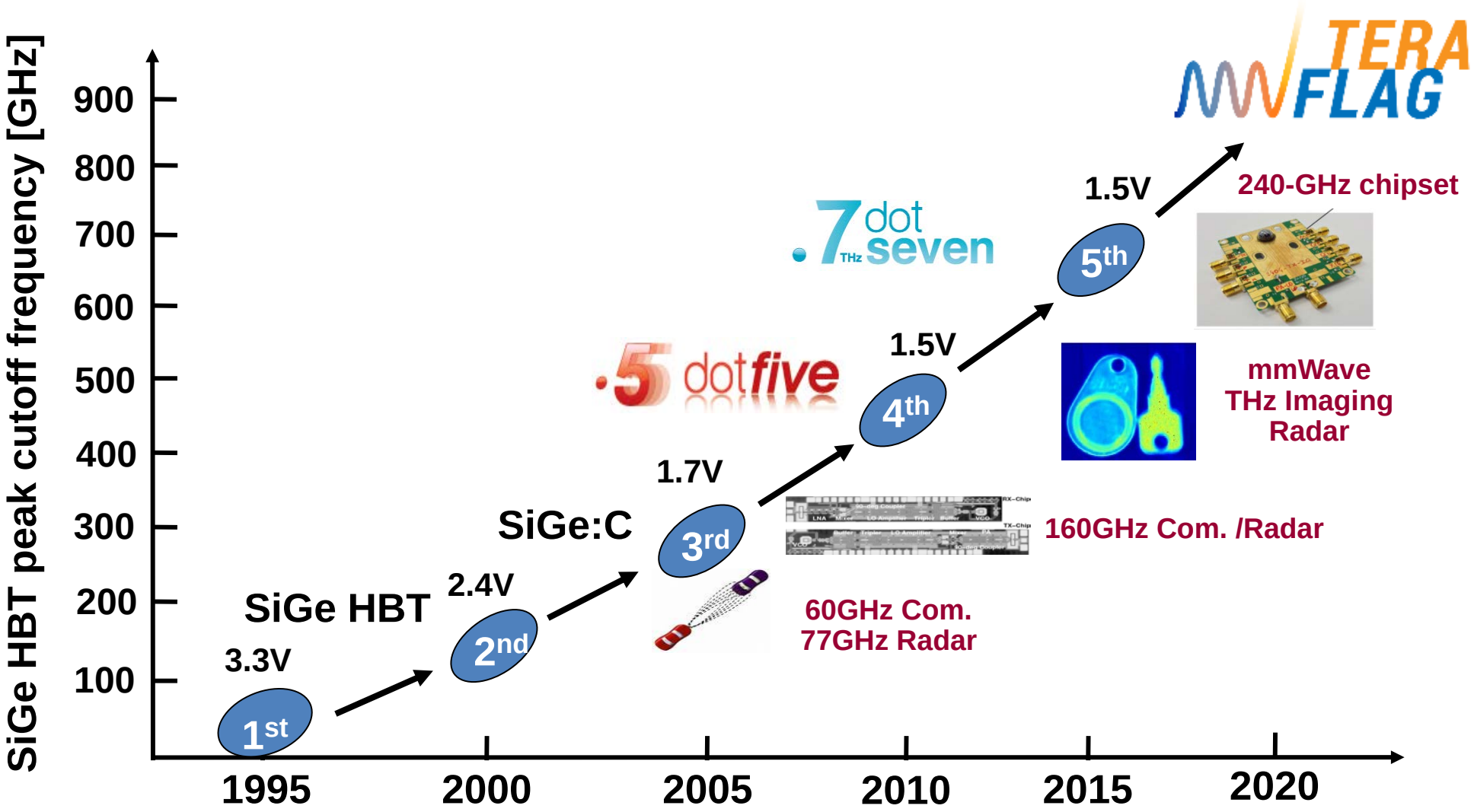


[1] X. Mei et al., "First Demonstration of Amplification at 1 THz Using 25-nm InP High Electron Mobility Transistor Process," in IEEE Electron Device Letters, vol. 36, no. 4, pp. 327-329, April 2015.

Next: Leverage economies of scale!

- **High yield & high performance**
- **Integrated electronic THz systems**
- **Monolithic & hybrid integrated**
- **Low cost**
- **Lots of devices!**

Silicon (SiGe) HBT Technology Evolution



How do faster devices help us in electronics?

- **Fundamental circuits:**
  - Higher carrier frequencies
  - More gain per stage (e.g. fewer gain stages)
  - Larger bandwidth
  - Lower DC power consumption
  - Higher efficiency (PAE)
  - Larger output power
  - Lower noise figure
- **Sub-harmonic circuits:**
  - Lower harmonic number
  - Higher output power
  - Lower noise figure

1. **Improve existing components**
2. **Go to higher frequencies**

What else?

Future Trends in Academia (Electronics-Side)

Integrated Electronic Systems Research

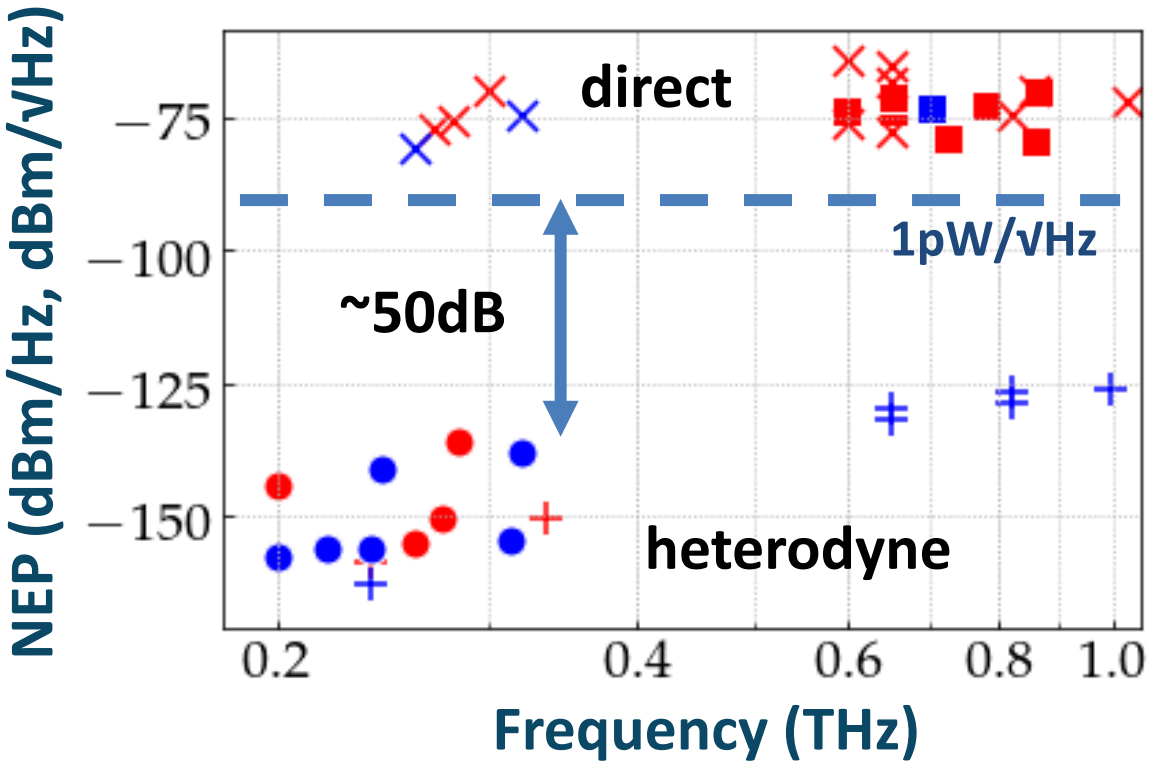
1. **Improve performance in existing applications**
   - Low power, high efficiency, larger band-width etc.
   - New ways for THz generation and detection
2. **Novel systems, algorithms, and applications**
   - Programmability, re-configurability, scalability, new functionality
   - Beam steering/forming
   - Chip-scale integration and packaging
   - Mass-production
   - Sensor fusion
   - Real-time
   - Low-cost

Take the next step!
from materials, devices/components to systems!

closing the THz “Industry-Gap”

1. Improve performance (Devices to Components)

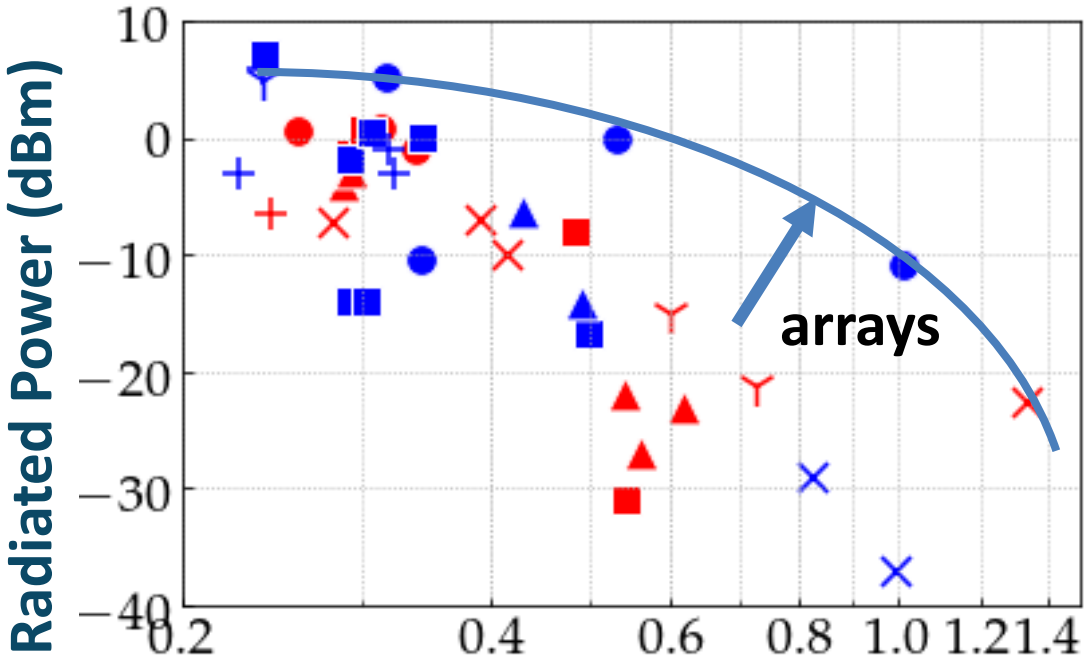
Detectors (CMOS/SiGe)



■	CMOS Direct	■	SiGe Direct
×	CMOS Direct (int. amp.)	×	SiGe Direct (int. amp)
●	CMOS Heter.(on-chip)	●	SiGe Heter.(on-chip)
+	CMOS Heter.(free-space)	+	SiGe Heter.(free-space)

[3] Current Status of Terahertz Integrated Circuits - from Components to Systems, U. Pfeiffer, BCICTS, Plenary 2019

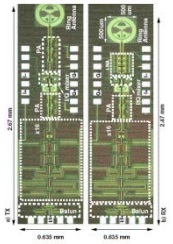
Sources (CMOS/SiGe)



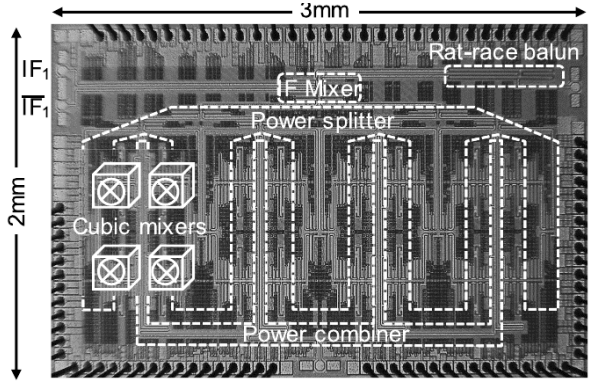
■	CMOS Osc.(on-chip)	■	SiGe Osc.(on-chip)
▲	CMOS Osc.(radiating)	▲	SiGe Osc.(radiating)
●	CMOS Osc.(rad. array)	●	SiGe Osc.(rad. array)
+	CMOS Mul.(on-chip)	+	SiGe Mul.(on-chip)
Y	CMOS Mul.(radiating)	Y	SiGe Mul.(radiating)
×	CMOS Mul.(rad. array)	×	SiGe Mul.(rad. array)

2. Novel systems, algorithms, and applications

Communication



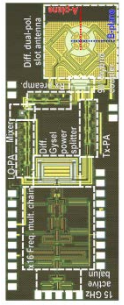
x6



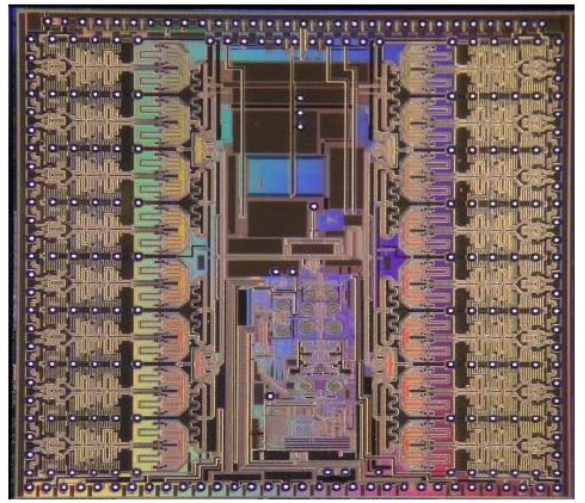
240GHz IHCT [4]

300GHz Tokyo [5]

Radar



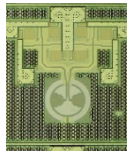
x16
x32



240GHz IHCT [6]

60GHz, 94GHz IBM [7,8]

Imaging



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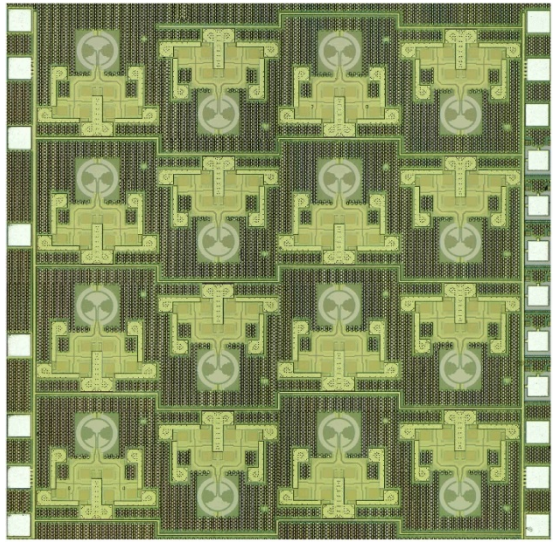
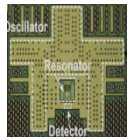
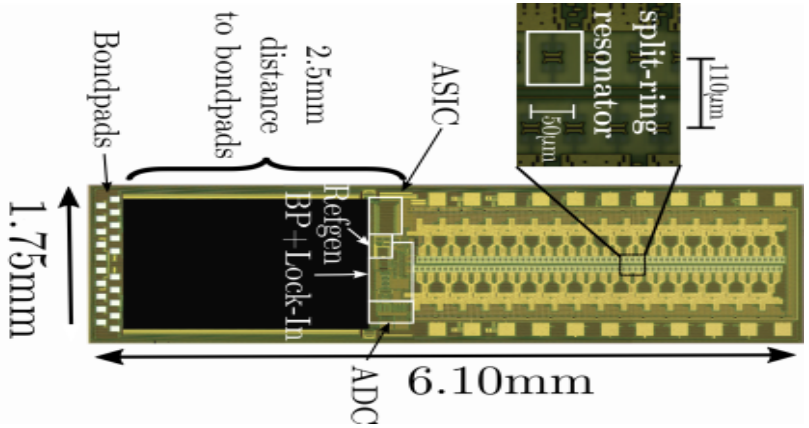


½ THz IHCT [9]

Sensing



x128



½ THz IHCT [10]

½ THz IHCT [11]

Community Skills

- **Interdisciplinary character**
  - Connect: physics, photonics, electronics, and applications with engineering skills
- **Education**
  - New set of required skills
  - Co-design challenge: THz applications, EM propagation, antennas, RF circuit design, mixed-signal design, and packaging
  - Value chain: materials, processes, components, to applications
  - Strong academia industry collaborations required

Conclusions

- **Existing applications**
  - RF to THz: sensors, radar, communication, spectroscopy, imaging
- **New THz systems and integration concepts**
  - massively parallel systems,
  - Multi-channel communication, phased array radars, cameras, diffuse illumination, super-resolution sensors
- **Technology options**
  - Substrates: III/V, Silicon, heterogeneous integration, electronic-photonic integration
- **Source arrays**
  - Power, low noise, oscillators …
- **Detector arrays**
  - Heterodyne
  - CMOS cameras feasible
- **Antennas**
  - On-chip integrated
- **THz Systems on chip**
  - From digital mixed-signal to THz-ICs
- **Packaging and assembly**
  - Integrated antennas

… closing the THz “Industry-Gap”

References

- [1] Xiaobing Mei, et. al., “First Demonstration of Amplification at 1 THz Using 25-nm InP High Electron Mobility Transistor Process”, EDL 2015
- [2] Silicon-Germanium Heterojunction Bipolar Transistors for mm-Wave Systems: Technology, Modeling and Circuit Applications, River Publishers Series, Ed. N. Rinaldi, M. Schröter
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- [4] N. Sarmah, et. al., “A fully integrated 240-GHz direct-conversion quadrature transmitter and receiver chipset in SiGe technology”. 64.2 (Feb. 2016), pp. 562–574. (55 cit.)
- [5] K. Katayama, “A 300 GHz CMOS Transmitter With 32-QAM 17.5 Gb/s/ch Capability Over Six Channels”, JSSC 2016
- [6] J. Grzyb, et. al., “A 210-270 GHz circularly polarized FMCW radar with a single-lens-coupled sige HBT chip,” TSAT 2016.
- [7] Jean-Olivier Plouchart, et al., “A Fully-Integrated 94-GHz 32-Element Phased-Array Receiver in SiGe BiCMOS”, RFIC 2017
- [8] A. Natarajan, et. al., “Phased-array radar and multistatic array imaging with 16-element 60GHz SiGe Tx and Rx”, Government Microcircuit Applications and Critical Technology Conference, March 2012.
- [9] U. Pfeiffer, *et al.*, “A 0.53 THz reconfigurable source module with up to 1 mW radiated powerfor diffuse illumination in terahertz imaging applications”, JSSC 2014
- [10] J. Grzyb, et. al. “A 0.55 THz near-field sensor with µm-range lateral resolution fully integrated in 130 nm SiGe BiCMOS,” JSSC 2016.
- [11] P. Hillger et. al., “A 128-pixel 0.56 THz sensing array for real-time near-field imaging in 0.13 µm SiGe BiCMOS”, JSSC 2018