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RFSOI : How did we get here and where are we headed?

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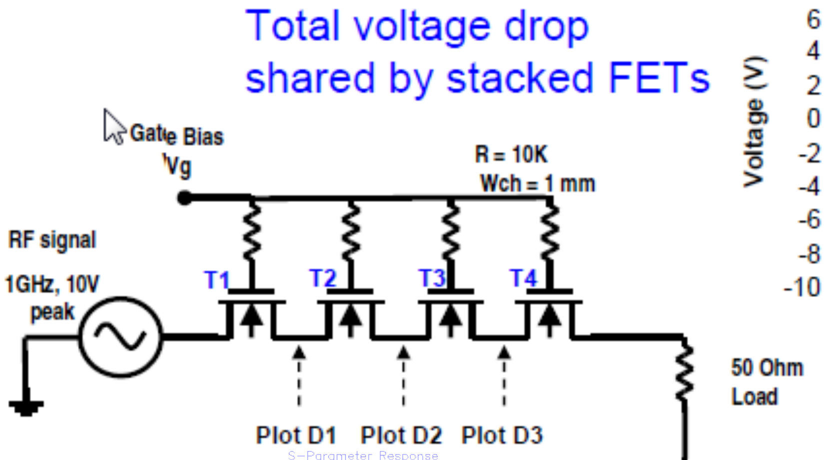
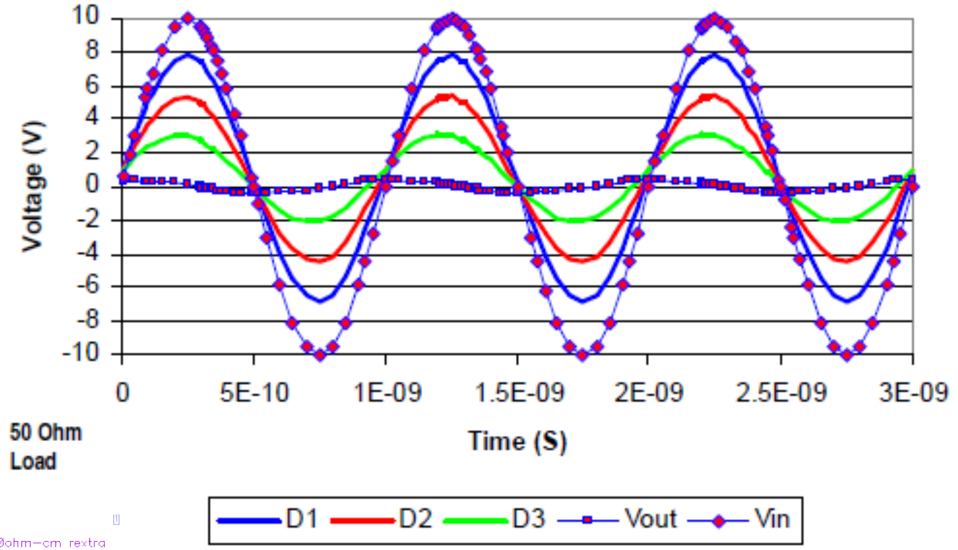
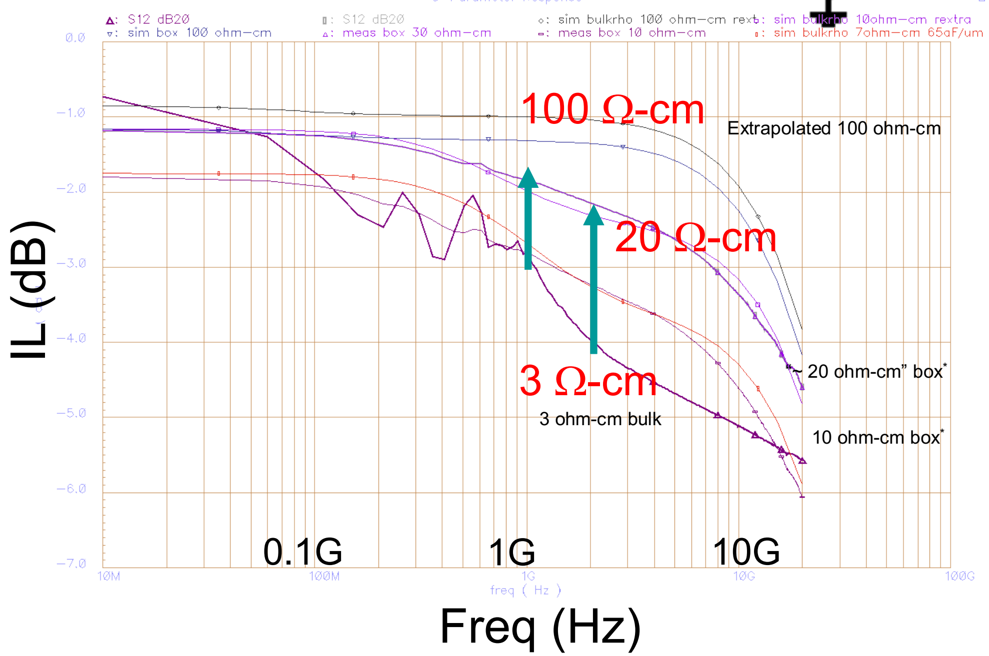
4/15/2024

RFSOI Transistor Stacking Concept

- The need for high resistivity silicon substrates was realized very early. Without HiRES silicon substrates at low cost, RFSOI would never have succeeded!





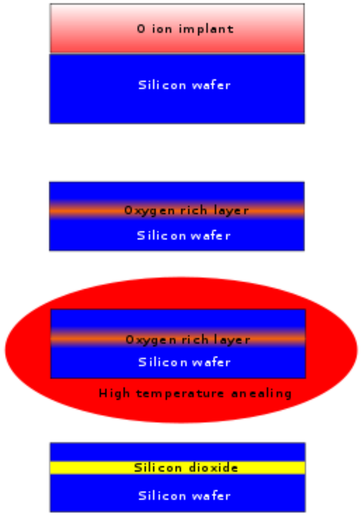


* Combination of substrate resistivity and proper Resistor network yields correct voltage division in the frequency range of operation in OFF state and optimum insertion loss in the ON state

Chronology of RFSOI Technology Development

- Critical technology breakthroughs allowed RFSOI to be omnipresent in today's handsets

1990

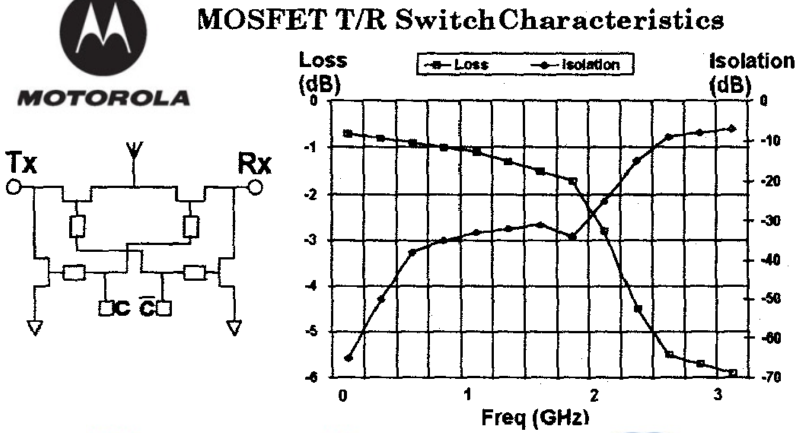


NTT ibis

- SIMOX substrates introduced
- 50% speed/power improvement over bulk
- RD -> production

1995

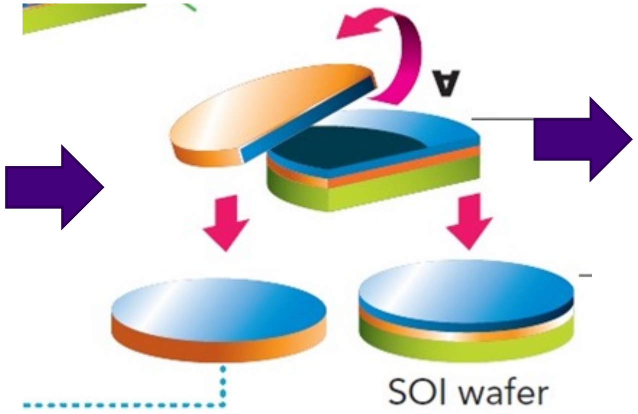
MOTOROLA



Honeywell NEC NTT

- Demonstration of fully integrated switches / RFIC / controllers
- Performance limited by lack of low-cost High Res silicon substrate
- SIMOX yields problematic for large volume product

Early 2000's



Soitec

- SmartCut process dramatically improves yield and drives digital volume
- Low Cost 1000 Ohm-cm silicon substrates introduced
- RFSOI foundry development starts

Chronology of RFSOI Technology Development

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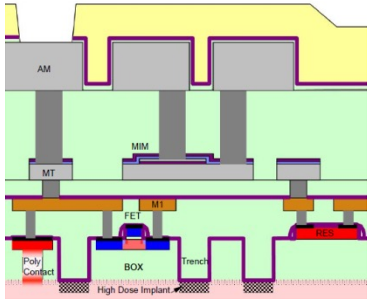
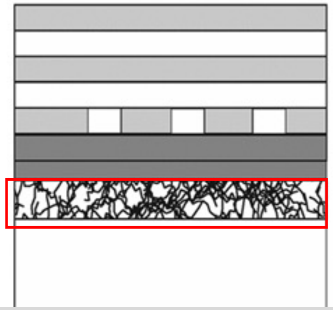
Mid 2000's

Late 2000's





>2024

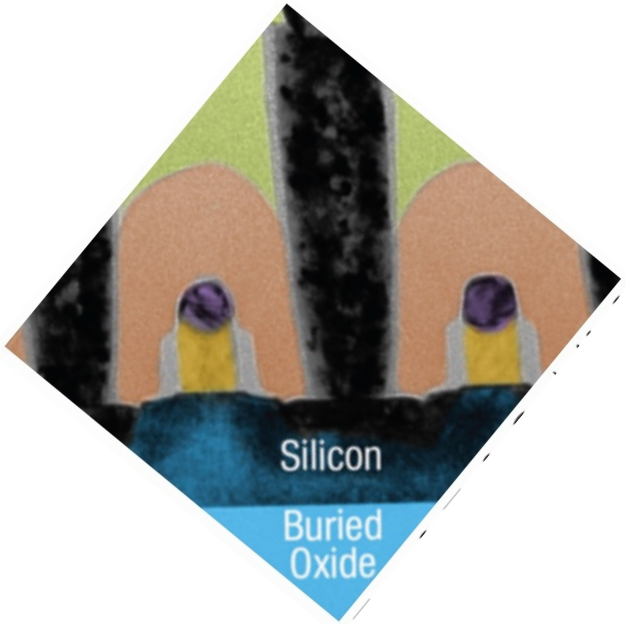
- Silicon foundries offer RFSOI technologies
- Rapid proliferation of design groups worldwide
- Linearity still limited by silicon substrate surface interface effects

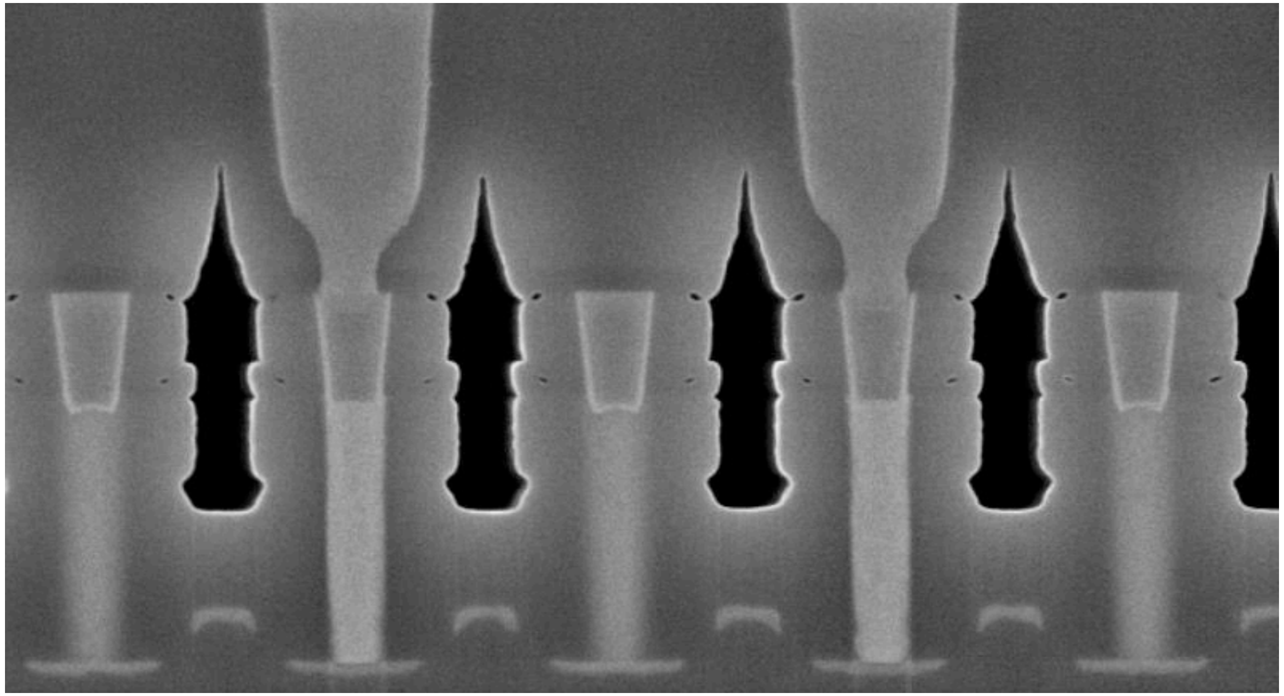
- Two distinct surface treatment approaches nearly eliminate substrate surface effects:
  - Handle Wafer Treatments
  - Trap Rich Interface Layer

- >2B US$ RFSOI market
- Wafer Capacity > 1Million WPY
- High performance switches and Tuners
- Participation in 100% of 4G /5G handsets and devices

The modern RFSOI Switch Transistor

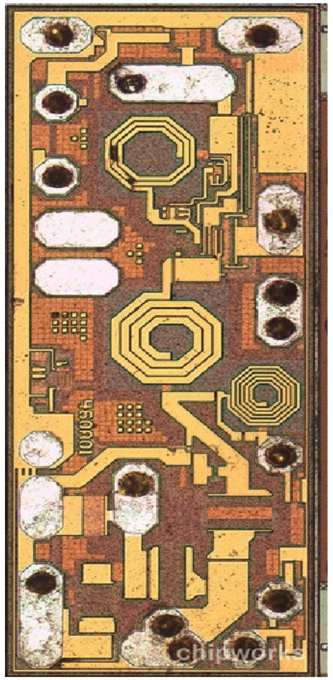
- PDSOI (Partially Depleted SOI) channels for optimal body control at high VRMS voltages
- Gate lengths Lg < 120nm
- Epi thickness < 1000A
- Air Gap technology to reduce COFF
- Combination of lithography layers to optimize performance and cost.



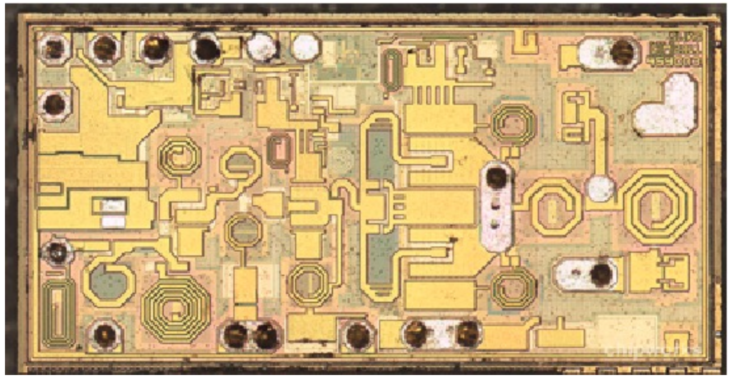


Integration of Passive Devices

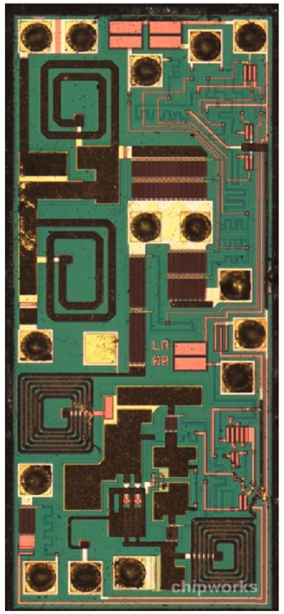
- RF integration of passives is essential for reduced overall system cost
- Precision Passive devices account for more than 60% area and cost
- Inductors/transformer metrics are critical → Limit the overall circuit performance



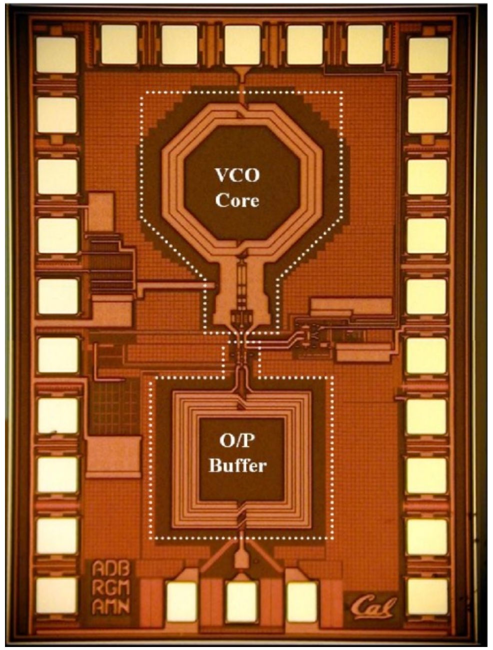
5 GHz LNA[1]



5 GHz PA[1]



2.4 GHz BPF[1]



1.8 GHz VCO[2]

1- http://www.chipworks.com/about-chipworks/overview/blog/apple-iphone-5-the-rf/

2 - https://buffy.eecs.berkeley.edu/PHP/resabs/resabs.php?f_year=2004&f_submit=one&f_absid=100326

9SW Technology: GF RFSOI Evolution

- **Over 1 million RFSOI wafers shipped**

Continuous enhancements in ***performance***, ***integration***, ***area*** *and* ***cost***.

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IBM

2008
7RF SOI

2011
7RF SOI
12 μm Cu BEOL

2012
7RF SOI
5 V CMOS
DGnFET LNA
50 V Vncap

2013
7RF SOI
"LowD" Low-IMD switch
NoBTQ

2014
7SW SOI
- ✓ 30% improvement in Ron-Coff*
- ✓ Up to 30% smaller die*
- ✓ Trap Rich SOI Substrates

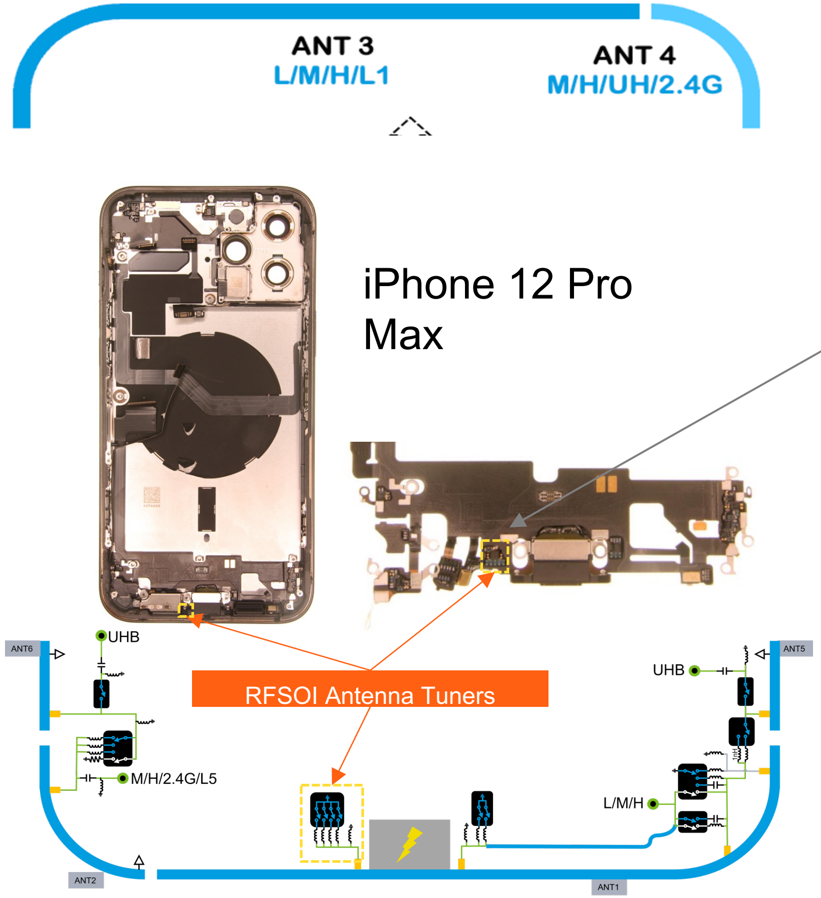
2018
8SW SOI
- ✓ 300mm technology
- ✓ Airgap to lower Coff
- ✓ Ron-Coff* < 100fs
- ✓ 130nm CMOS
- ✓ State-of-the-art LNA

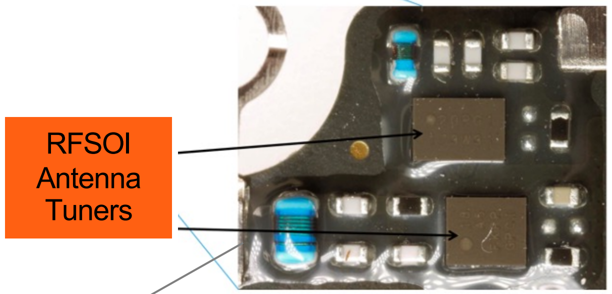
2023
9SW SOI

9SW SOI
- ✓ 300mm technology
- ✓ Ron-Coff* < 80fs
- ✓ Improved 90nm digital density/performance
- ✓ Dual Airgap module

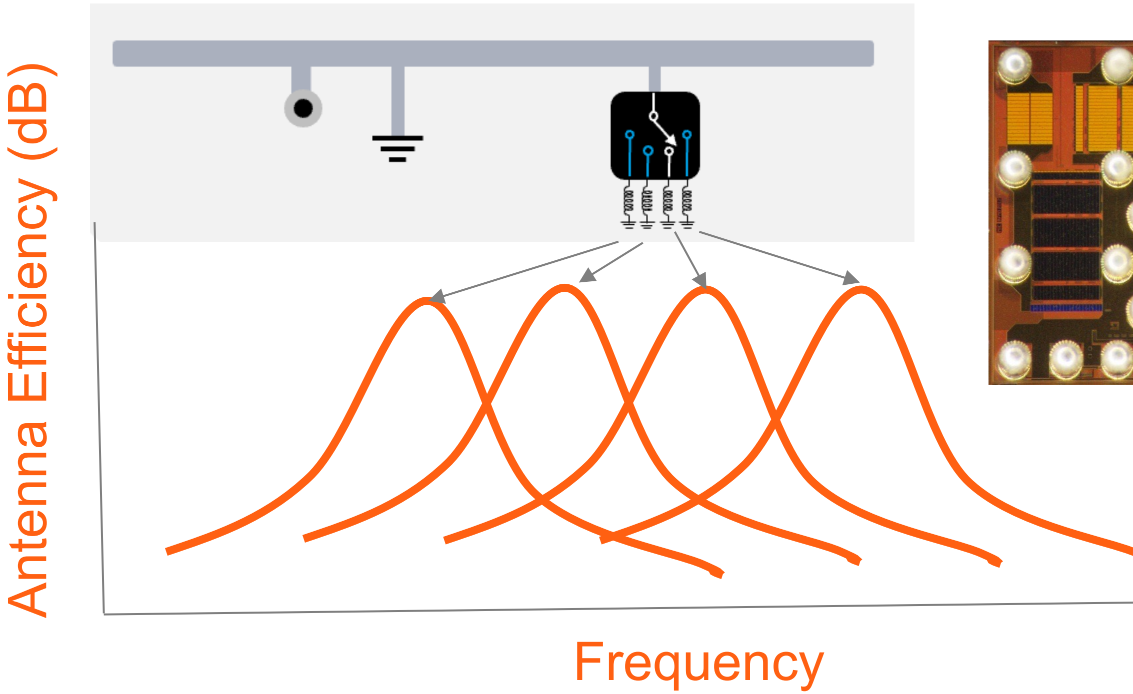
RFSOI Antenna Tuners

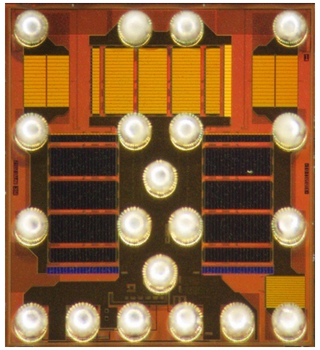
- Improve Antenna Efficiency for the plethora of bands in mobile handset = battery usage efficiency!





There are 13 antenna RFSOI antenna tuners
in the Iphone 14 !
(20mm2 of RFSOI area)



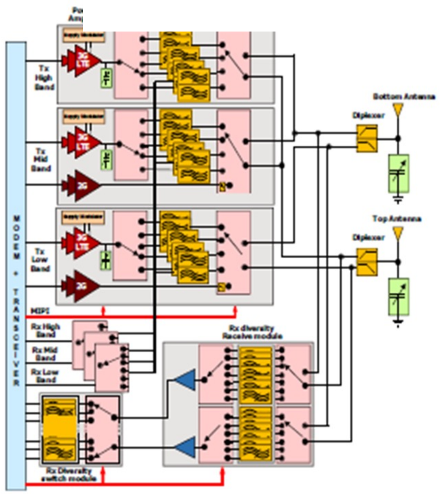


Cellular RF Front End architecture evolution

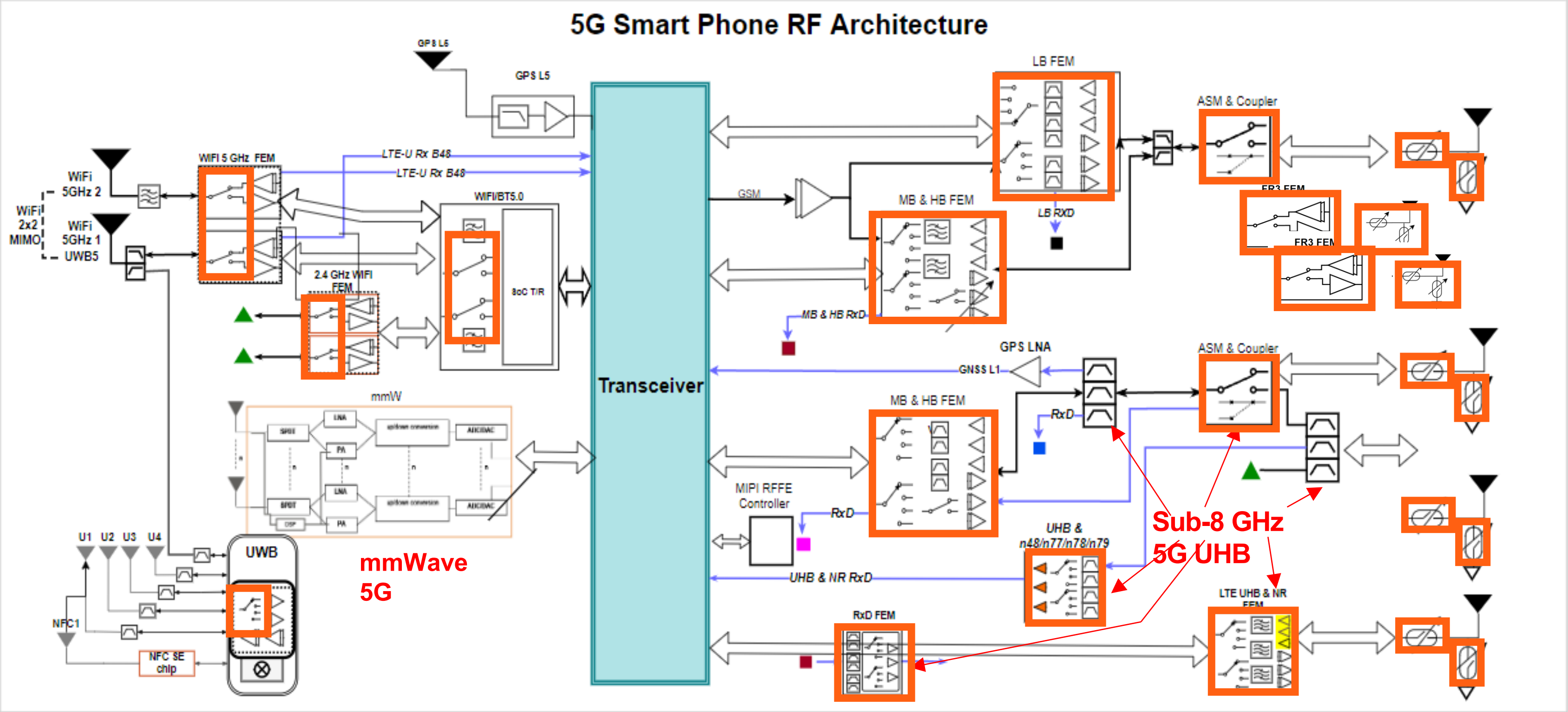
- **Increased RFSOI content due to the complexity of 5G mobile handsets**

RFSOI included

4G



Source: Soitec



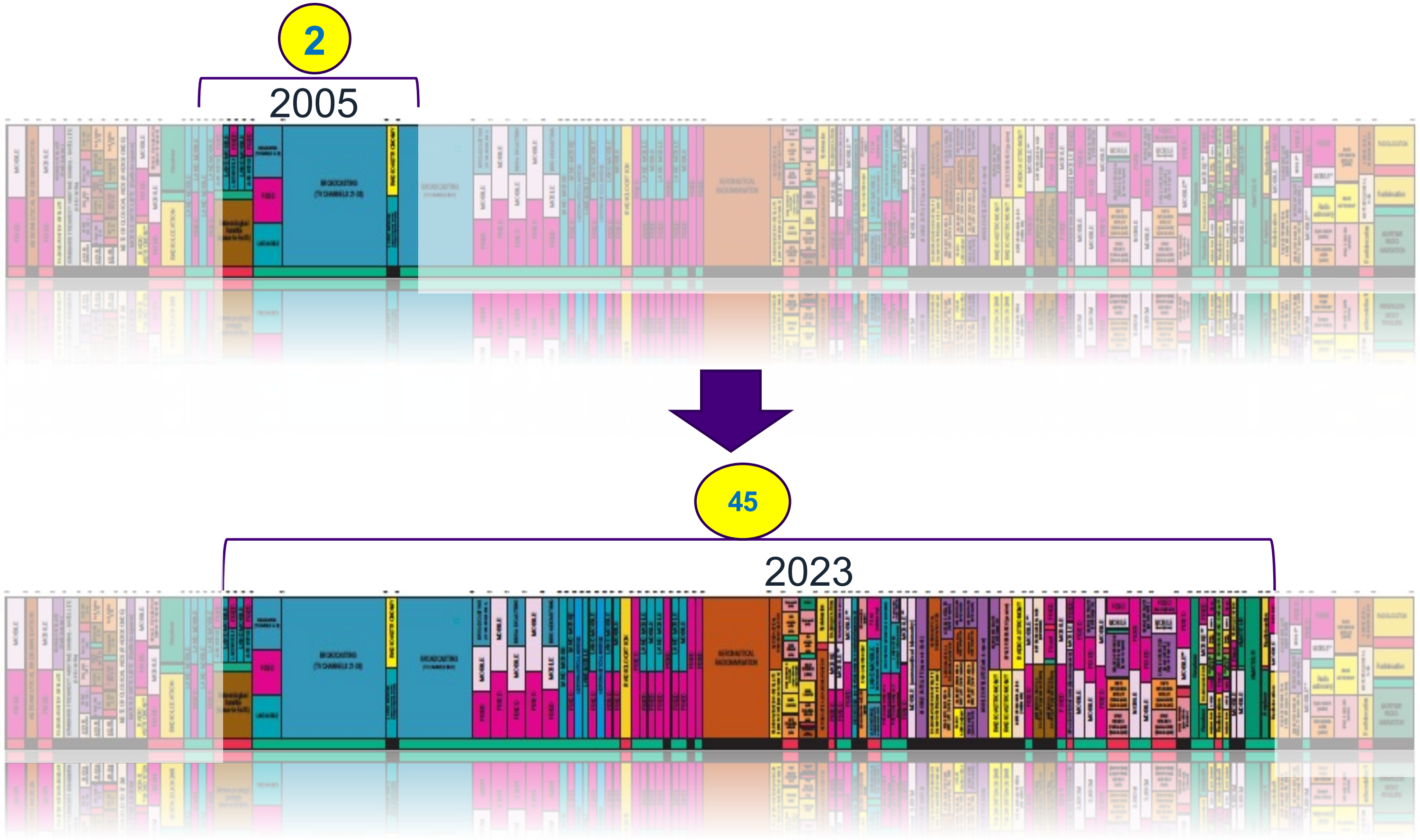
- Max #bands: 25
- Max #antenna: 4
- Carrier aggregation & 4x4 MIMO
- RFFE Si Area: 30-40 mm^2

- Max #bands: >40
- Max # Antenna: >8
- 4G-5G coexistence and higher frequency bands : Stringent SW loss, isolation, linearity, LNA performance
- RFFE Si area: >80 mm^2

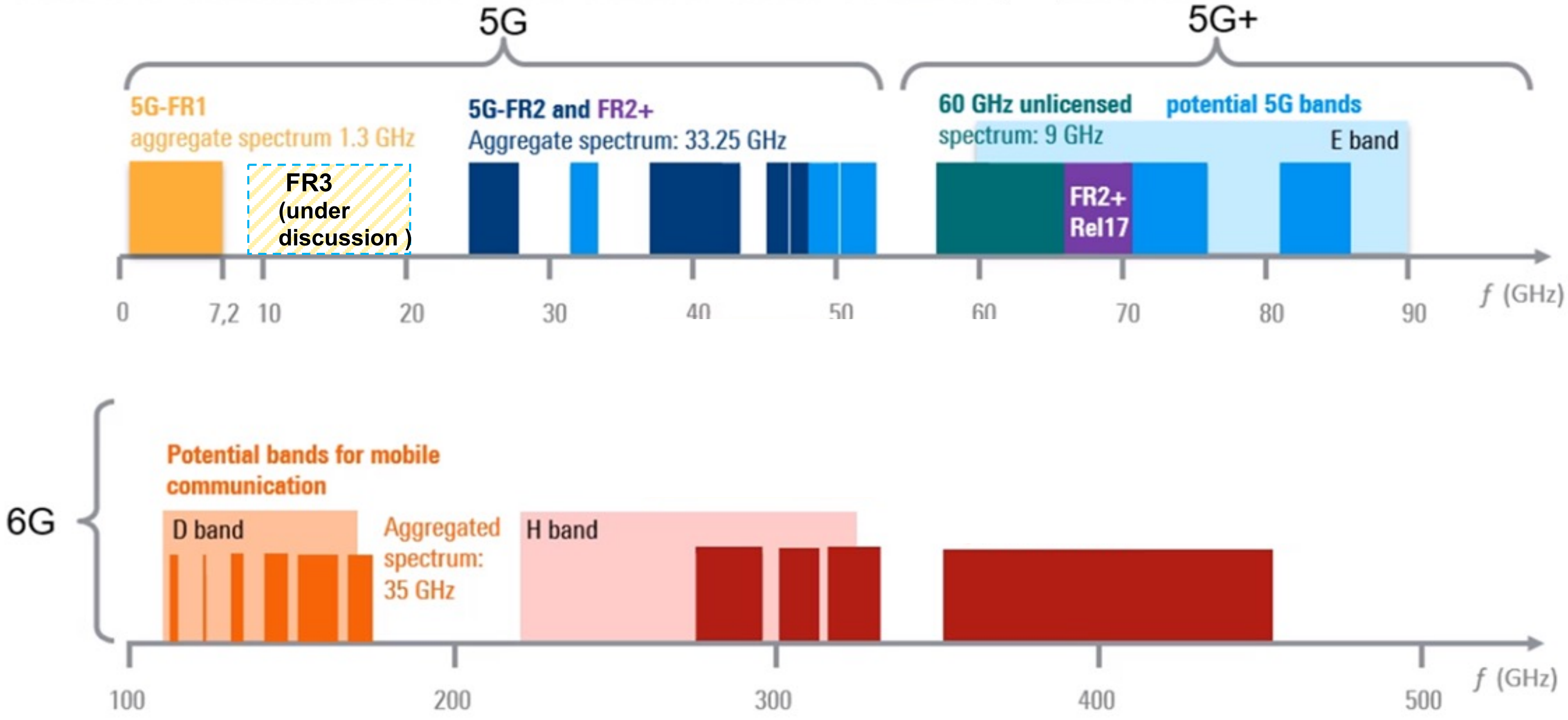
6G will have more #bands, higher carrier frequencies – need for technology differentiation for performance and battery power

How many cellular bands need to be supported in a premier tier 5G phone today (2023)?

- A. 10
- B. 20
- C. 30
- D. 45



Congested licensed bands below 6GHz – motivation for higher carrier frequencies

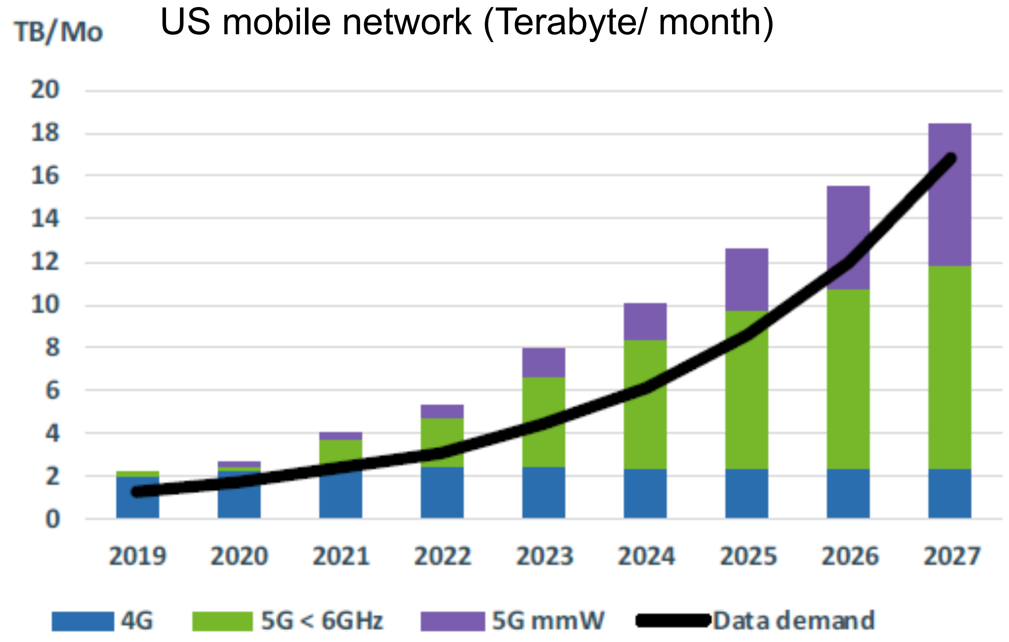


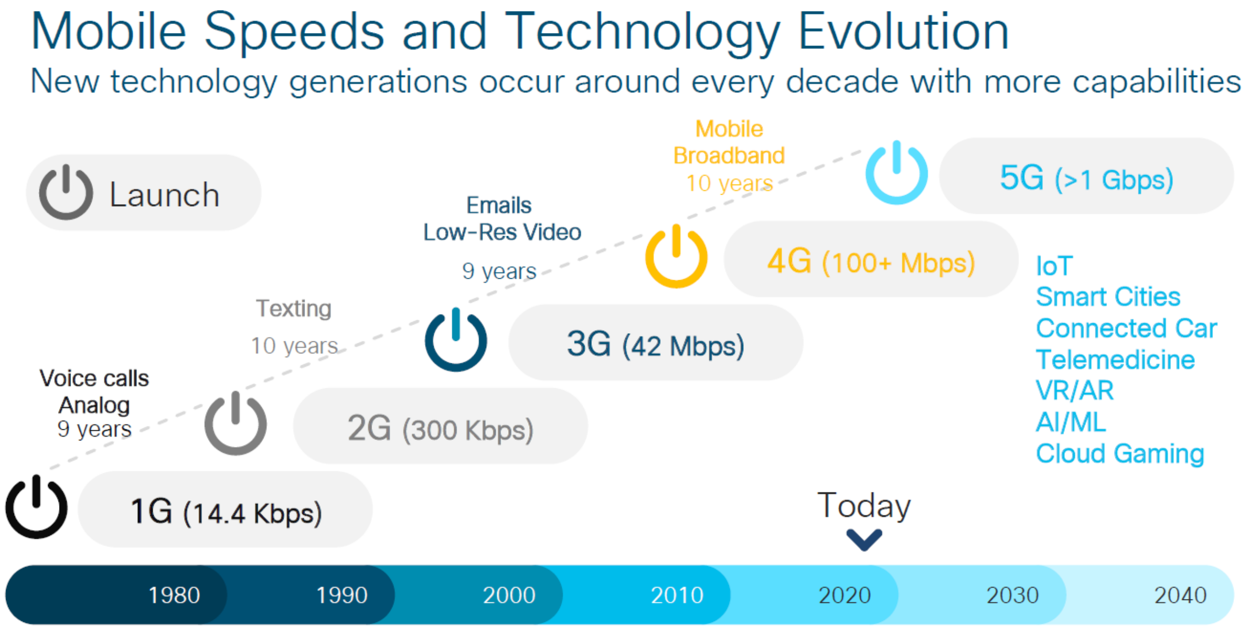
Higher Frequency band --> Higher contiguous spectrum bandwidth --> Higher data rate

Source: Taro Eichler, Millimeterwave and THz Technology for 5G and Beyond, Rohde & Schwarz

Revolution of mobile communication technology

- Mobile data volume and speed to increase >10X in 10 years.

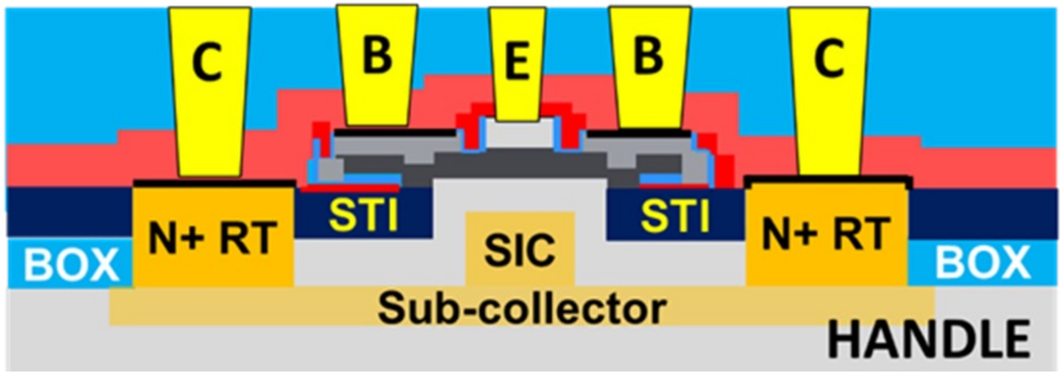




Source: https://www.eetimes.eu/rf-soi-engineered-substrates-at-the-heart-of-modern-rf-mmwave-front-ends

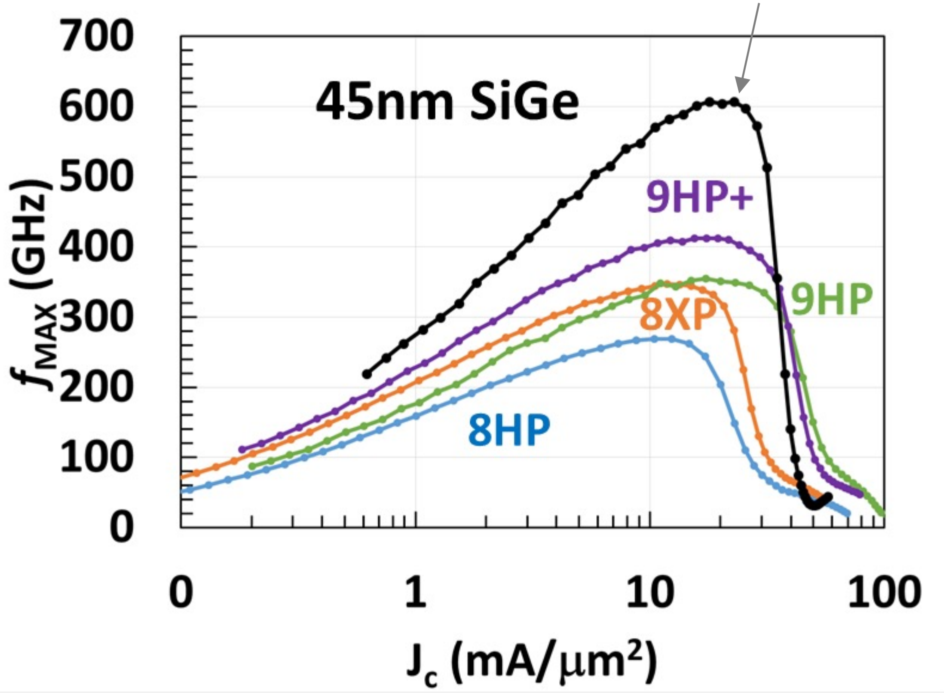
Source: Cisco Annual Internet Report, 2018–2023

45nm RF-SOI SiGe BiCMOS Development



- First RFSOI-based BiCMOS demonstration with SiGe NPN HBTs having fT/fMAX 388/600 GHz.
- 45nm SOI CMOS digital & RF FET baseline process
- High resistivity SOI substrate and high-Q passives
- Combines best of SOI and HBT for >100GHz phased arrays
  - SOI NFET for superior LNA, switch, phase shifters, passive mixer
  - SiGe HBT for higher PA Pout & PAE and lower phase noise VCO

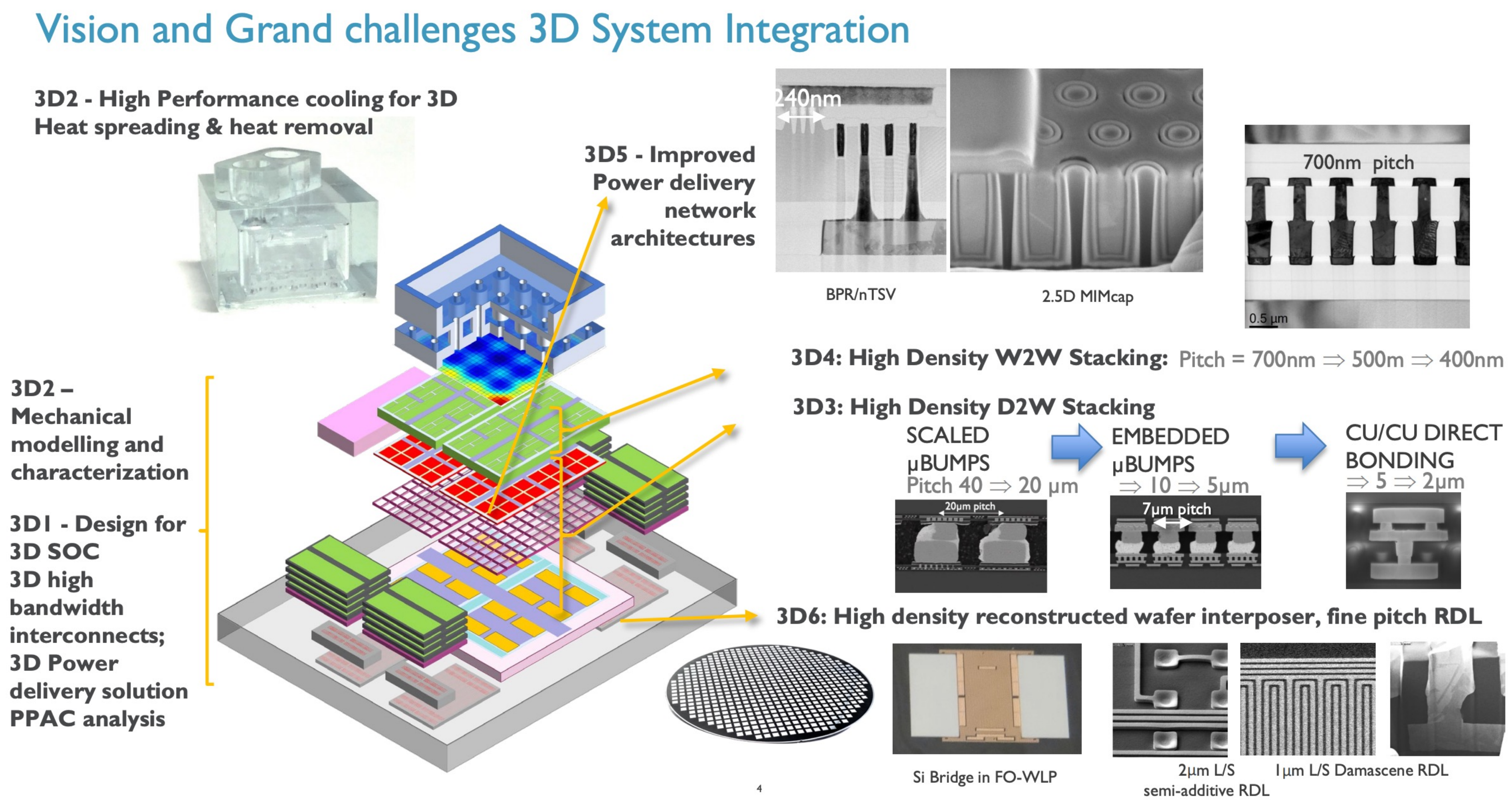
SiGe +SOI Integration!



Source: V. Jain et al., “415/610GHz fT/fMAX SiGe HBTs Integrated in a 45nm PDSOI BiCMOS process”, IEDM 2022

Where are we headed next in RFSOI?

- 3D System Integration will apply to RFICs for dramatic footprint reduction (IMEC's vision)
- RF components must however simultaneous manage: RF coupling / distortion / heat dissipation



imec

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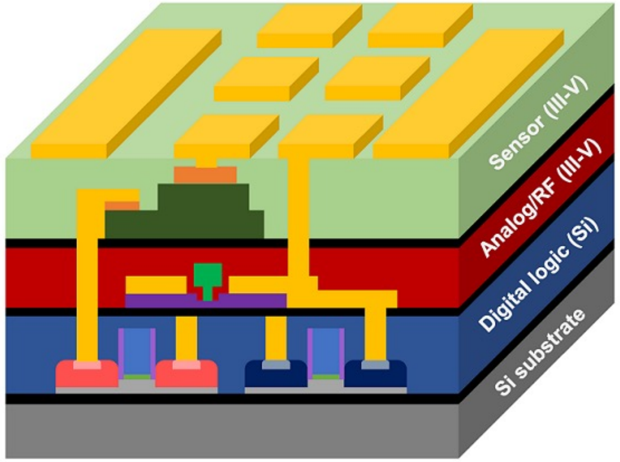
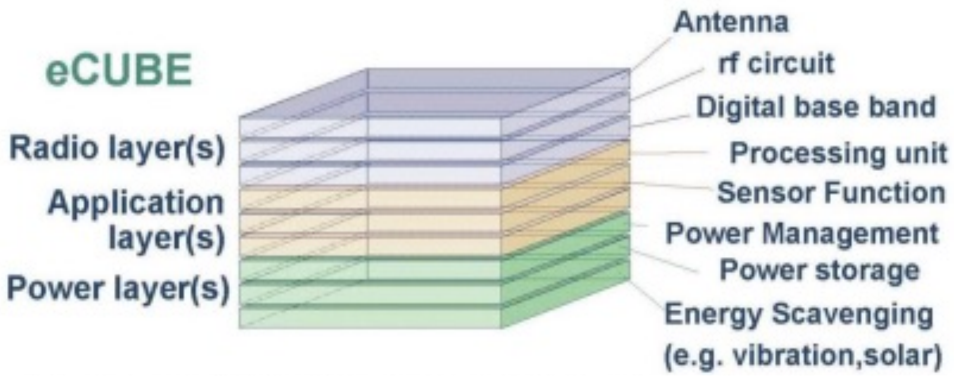


3D Heterogeneous Microsystems are multi-layered structures that integrate different materials and components in a compact and vertically stacked fashion



3D-system in package (SiP) concept for the realization of fully autonomous systems

Source: https://www.everythingrf.com/community/what-are-3d-heterogeneous-microsystems

Source: E. Beyne et al, “3D system integration technologies” ICICDT07

Conclusion

- Dramatic increase in mobile data traffic in next decade
- RFSOI-on-HRSI technology readily established in all major cellular 4G/5G platforms
- Substrate treatment technologies closed the gap in performance. Best tradeoff in cost/size/technology compared with other technologies.
- Rapid deployment of RFSOI multi-throw switches and capacitor arrays/tuner products for next generation wireless applications
- RF handset solutions will utilize a number of technologies to dramatically decrease component footprint