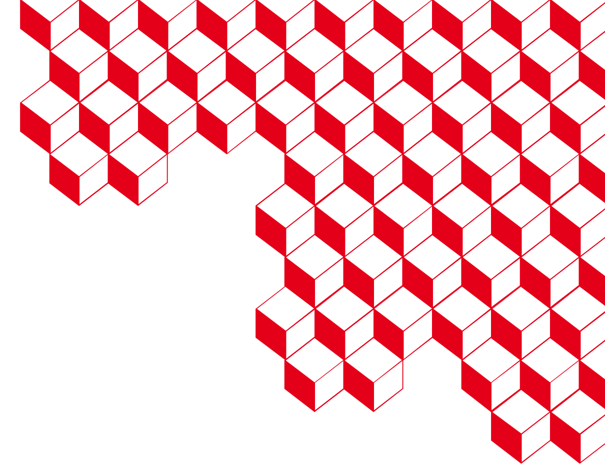

Innovation From Substrate to Device for RF Applications

Olivier Faynot

Silicon Component Division General Manager

INSTITUT CARNOT CEA LETI

OUTLINE

- Introduction
- Filters: Interest of Li-based substrates for 5G and beyond
- Actives devices: How materials and devices will help for 6G
- Summary and Take away

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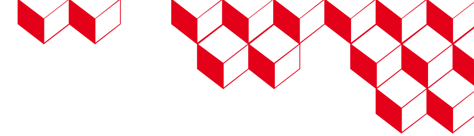
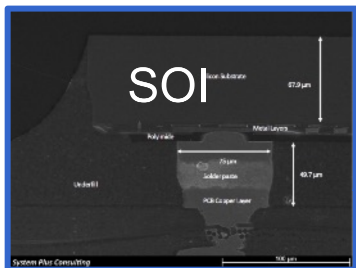


RF FEM module example

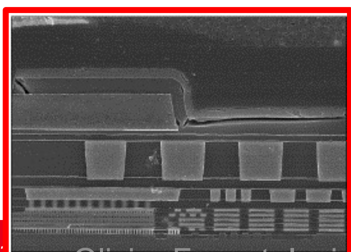
ACTIVES

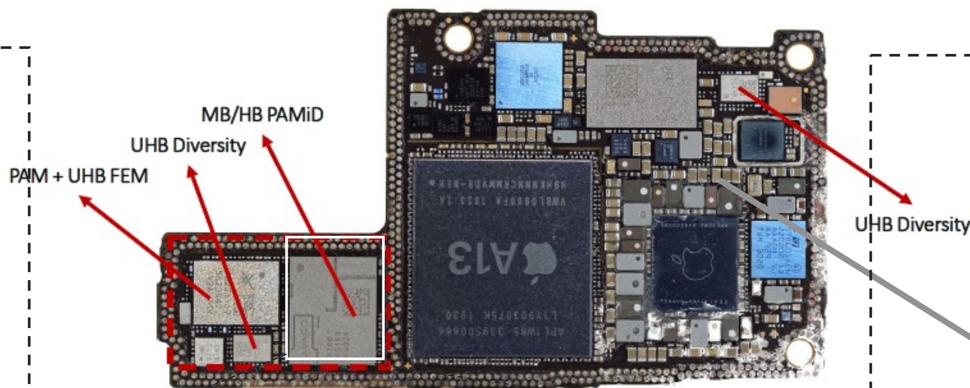
RF Switch RF SOI

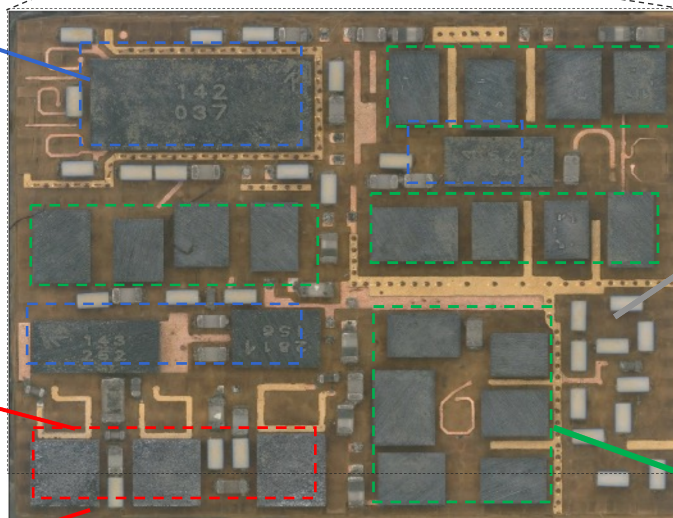


AsGa PA

LNA



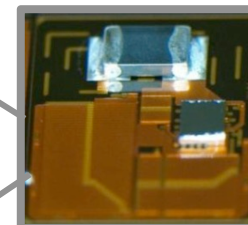




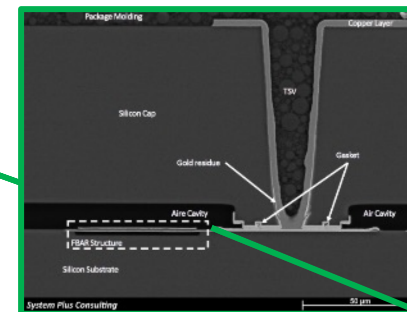
Adapted YOLE report, RF Front end report 2021

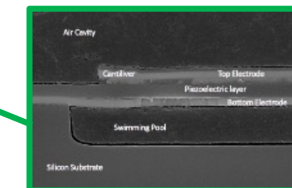
PASSIVES

Capacitors: MLCC or high-K on Silicon

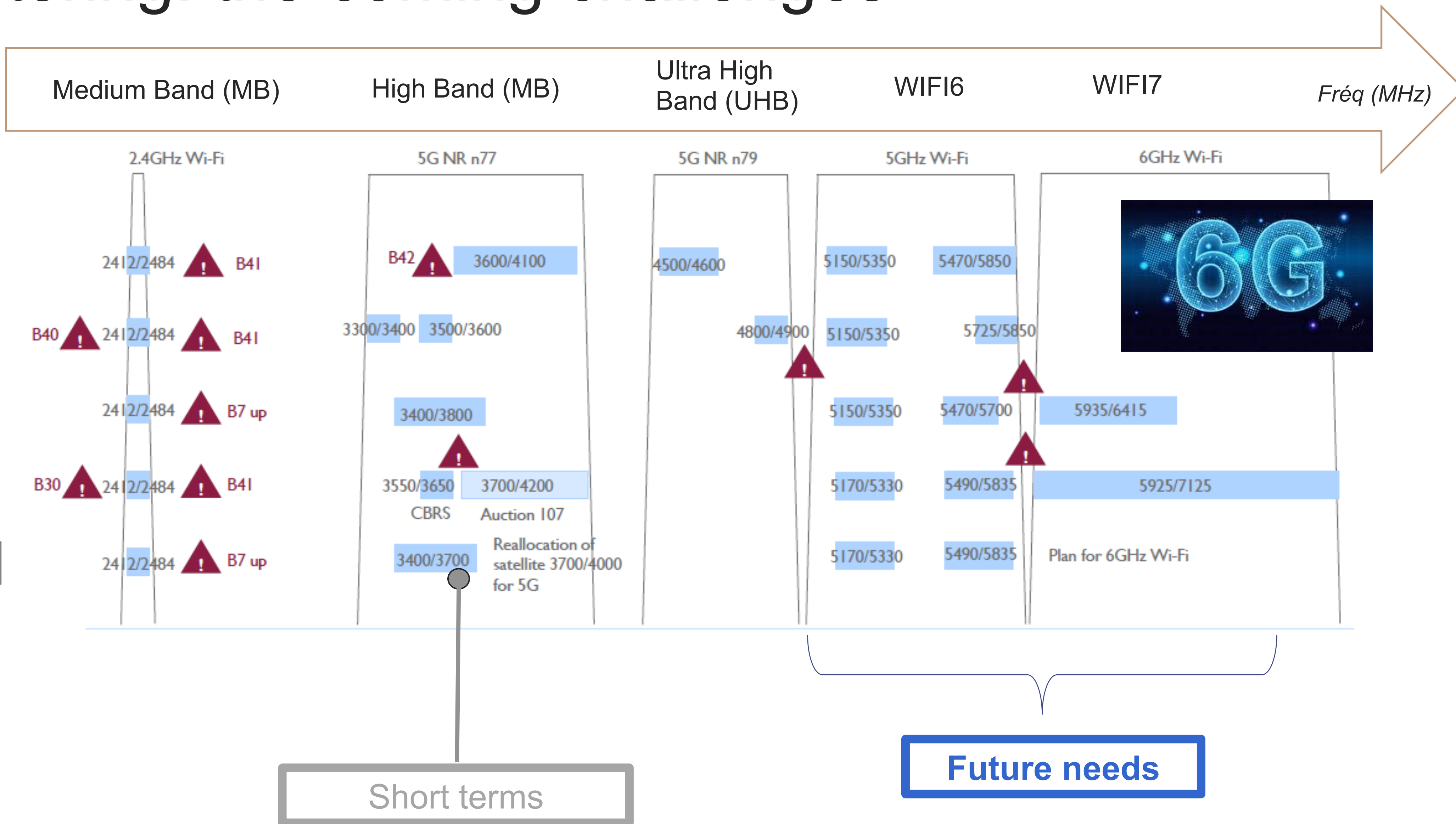


AIN acoustic RF filters on Silicon

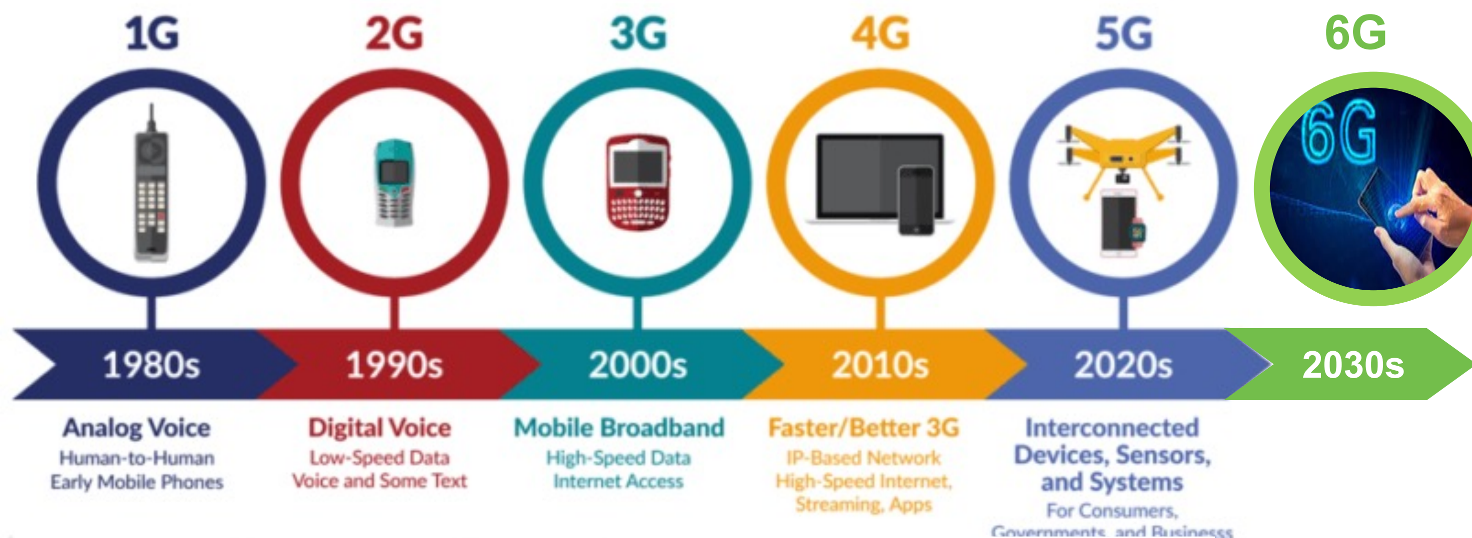




RF Filtering: the coming challenges



IC components enabled by materials



1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba	57-71 lanthanoids	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra	89-103 actinoids	Rf	Db	Sg	Bh	Hs	Mt	Ds	Rg							

La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr

Used in/before the 1980s

Added in the 1990s

Added in the 2000s

Added in the 2010s

Added in the 2020s

Adapted from lamresearch.com/happy-150th-birthday-to-the-periodic-table/ and Huawei forum, 2022

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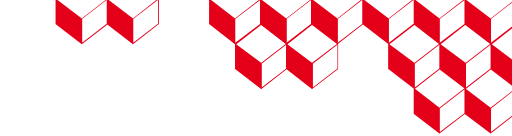


From 5G to 6G : still new components need

Peak Data Rate (Gbps)
1000
100
20

User Experienced Data Rate (Gbps)
1
0.1

Energy Efficiency
2x
1x

Spectral Efficiency
2x
1x

Air Latency (ms)
1
0.1

Connection Density (devices/km²)
10^7
10^6

Reliability
10^{-7}
10^{-6}
10^{-5}

Positioning outdoor/indoor (m)
1/0.1
10/1

6G
5G

Only 2x improvements

Better energy storage components

overcoming passives limitations with new materials

Large portfolio of Li-based materials

Unique physical and electrical properties

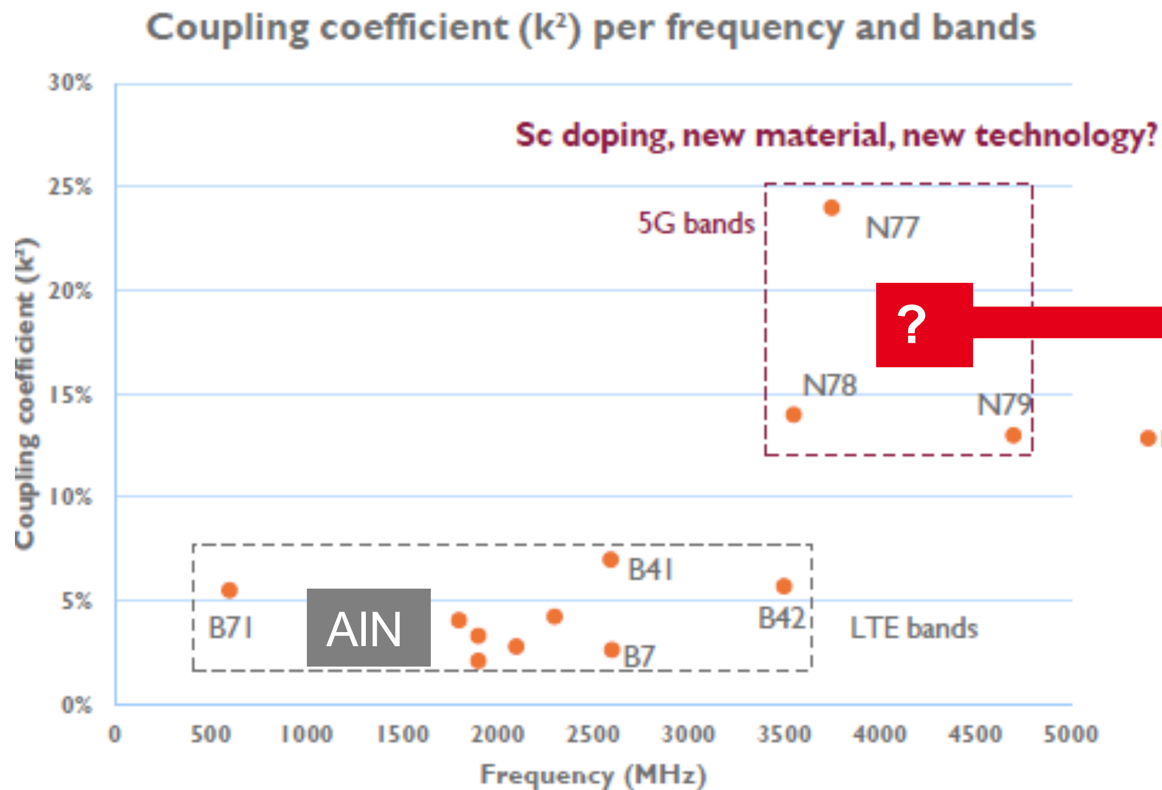
3 Li Lithium 6.941

Better use of frequency = better RF filtering

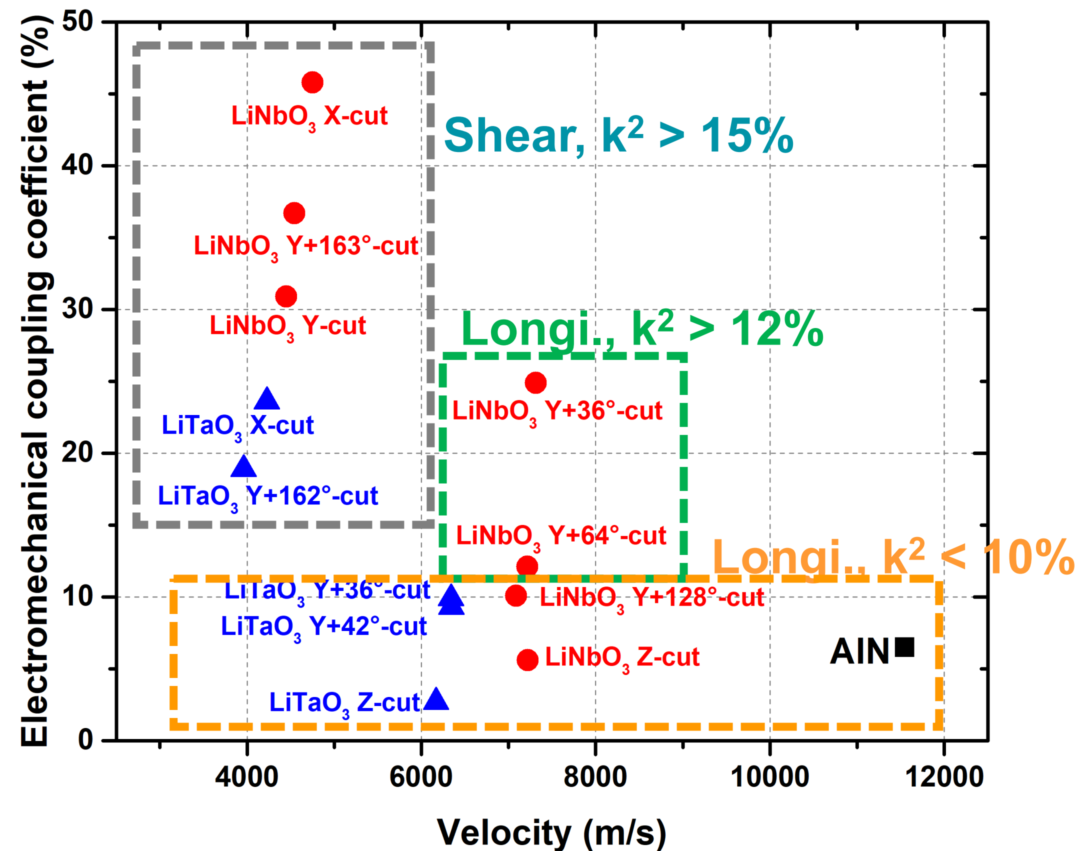
Source: Samsung research, 2021

Game changer: lithium based RF filters

Bandwidth: a strong and unmet demand yet!



from YOLE report, RF Front end report 2021

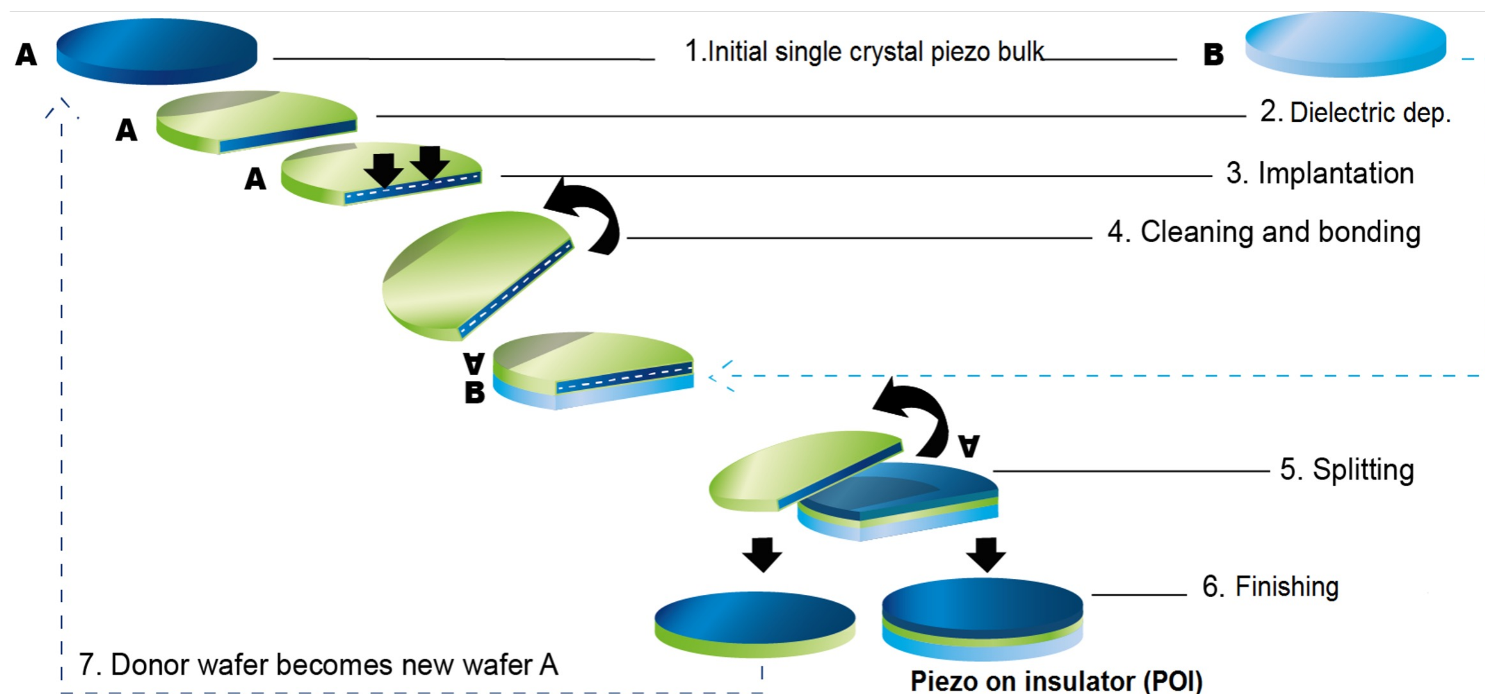


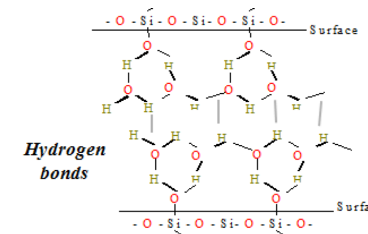
From M. Bousquet et al. Eumw 2020

Cristalline Lithium material on silicon…

Layer transfer: Smart Cut™ technology

- Molecular bonding
- Ion implantation based film layer transfer <1um
- Perfect crystal / nanometer scale layer uniformity





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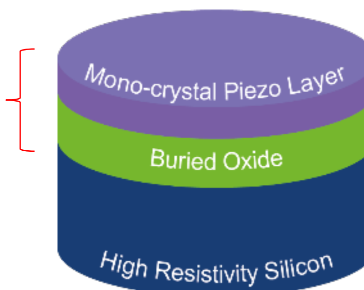


Piezo-on-Insulator (POI)

E. Butaud and al. Single Smart Cut POI Substrate Design for UHF, L and S Band Filters, EumW 2020

RF filters landscape for 5G and Beyond

Performances

TC-SAW
$LiNbO_3$ & $LiTaO_3$
(4 & 6 inches)

IHPSAW, POI
$LiNbO_3$ & $LiTaO_3$
(4 & 6 inches)

BAW poly & epi
AlN & AlScN
(6 & 8 inches)

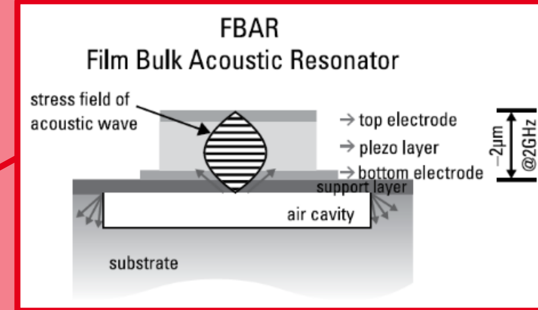
XBAR®
$LiNbO_3$
(4 inches)

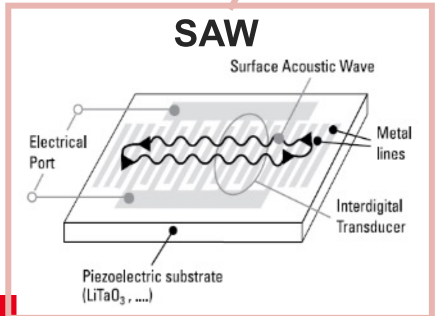
SAW
$LiNbO_3$ & $LiTaO_3$
(4 & 6 inches)

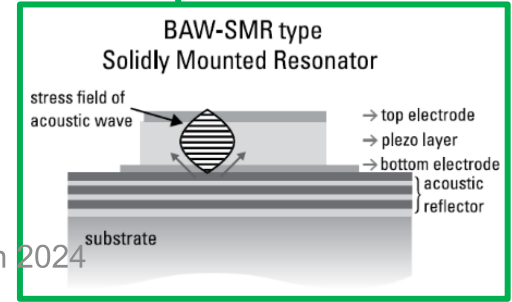
BAW
$LiNbO_3$ & $LiTaO_3$
(6 & 8 inches)

1 2 3 4 5 6

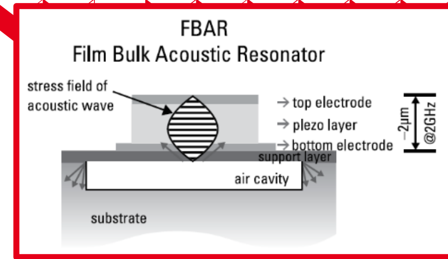
Frequency (GHz)



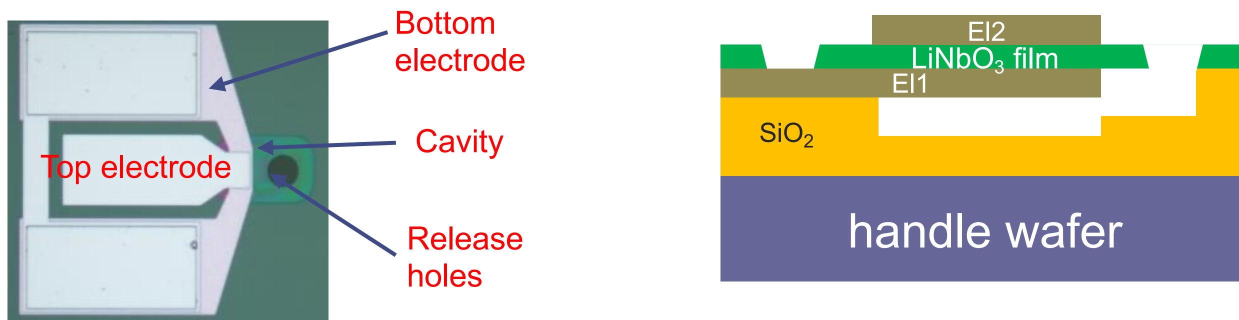


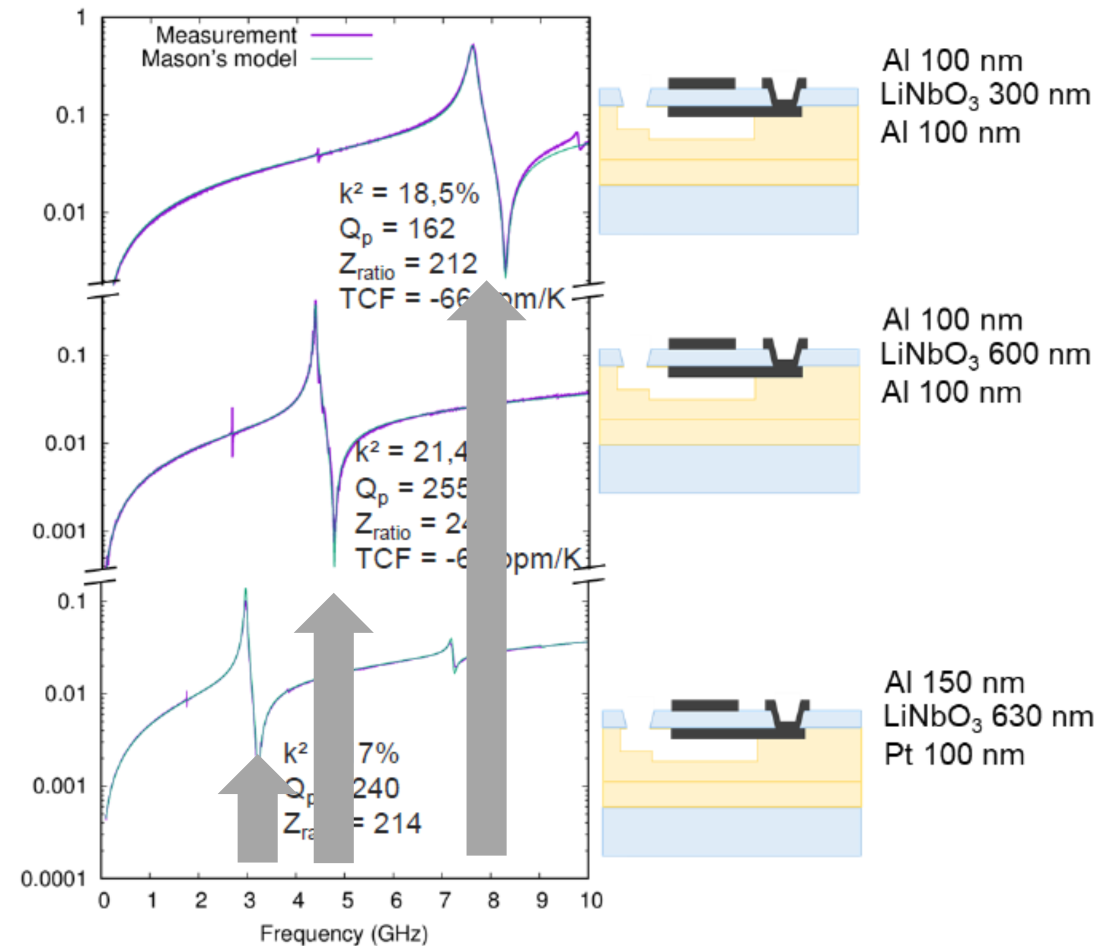


FBAR LNO Filters for 7GHz and beyond



- LiNbO3 Y+36-cut (Smart-Cut™), patterned electrodes (AlSi) & sacrificial layer cavity





- Resonance frequency increases up to 7 GHz while reducing LNO thickness
- Kt^2 remain at high level > 17% even at small frequency
- Strong potential for 5G+/6G

From A. Reinhardt et. Al. IFCS 2023

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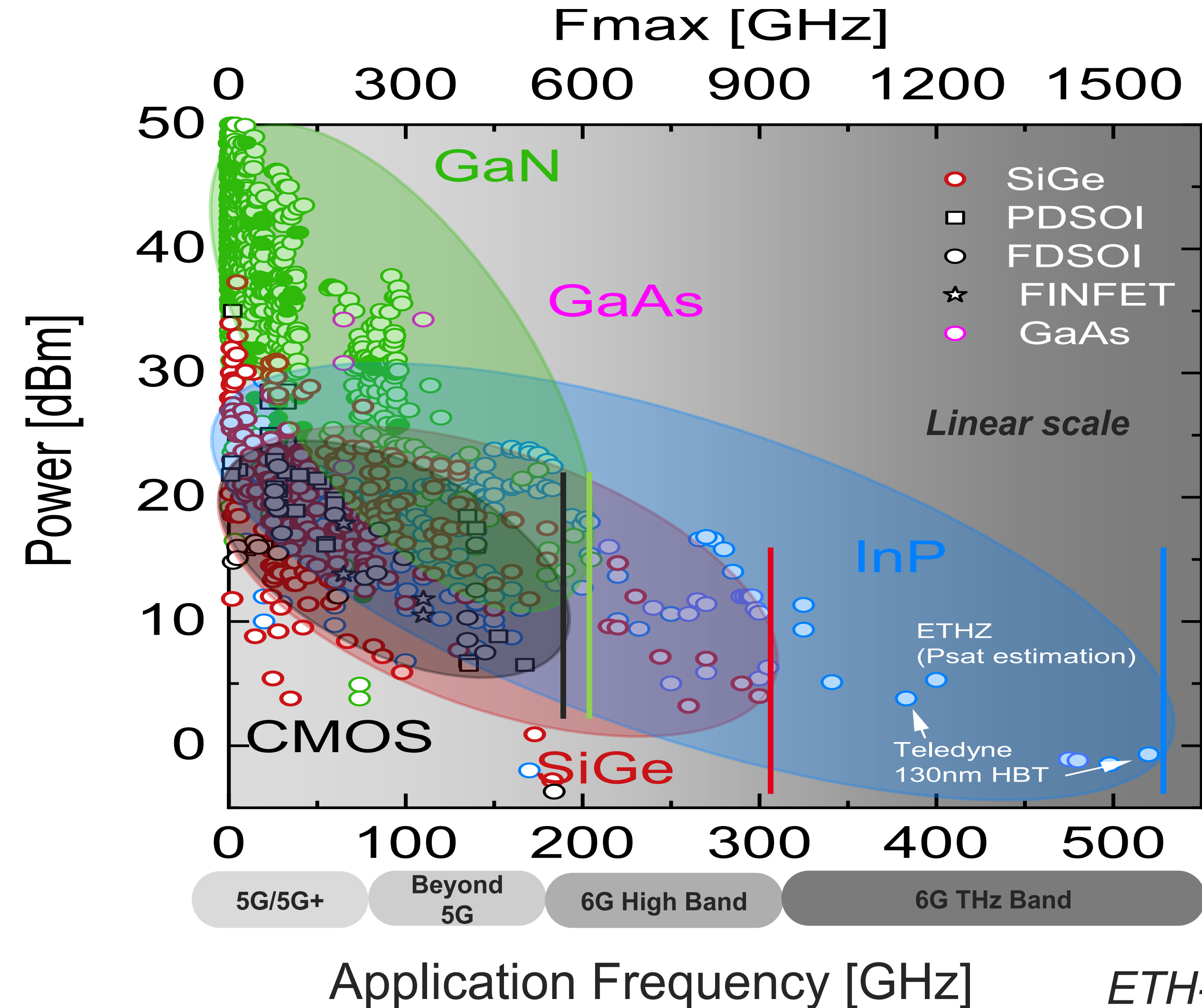
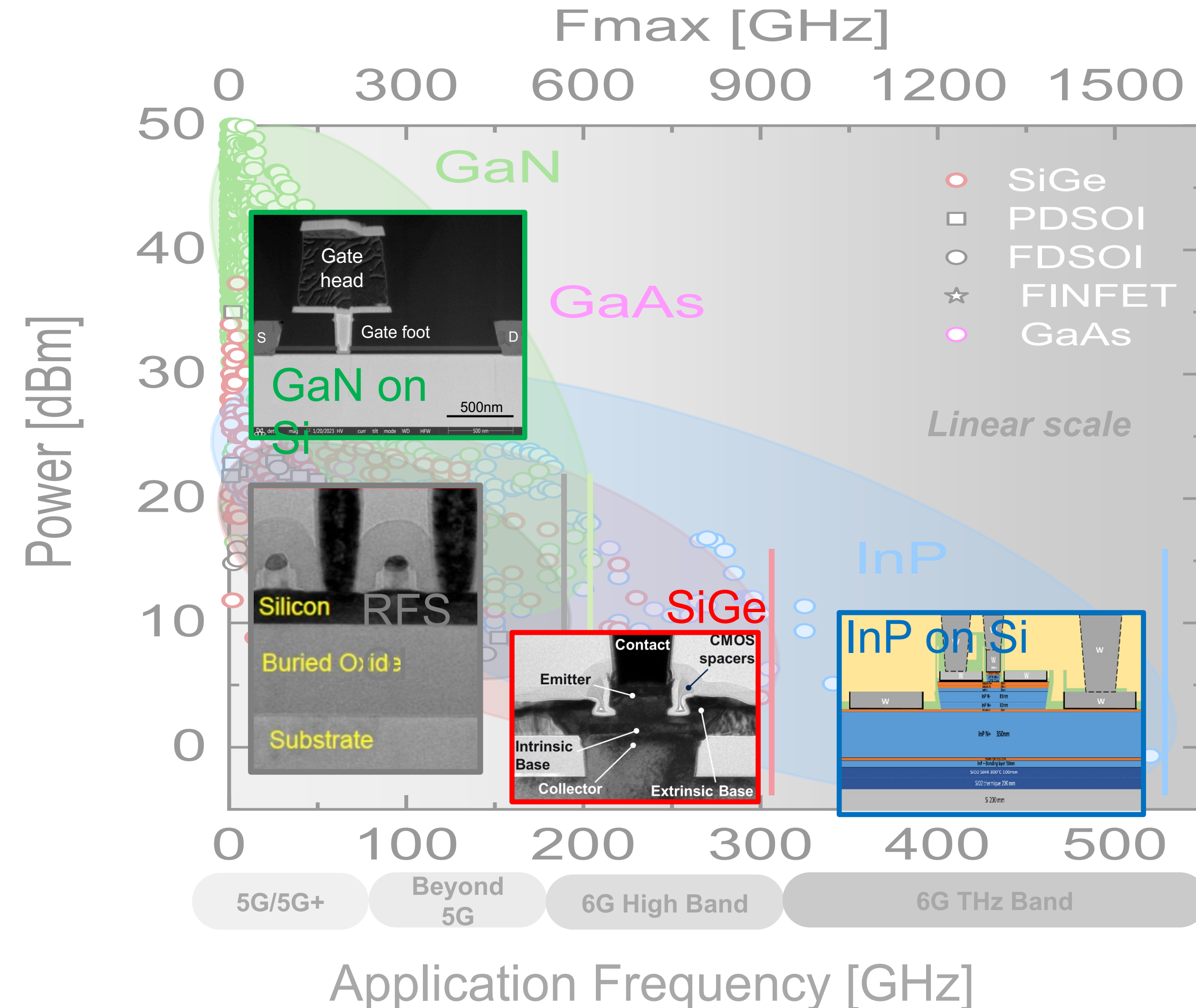
Technologies for PA vs Frequency & Power



ETH-Zurich survey

- **SiGe bipolar** transistor faster than MOS device
- **GaN RF** not the fastest, best in power density at lower frequencies (F_{max}<600GHz)
- **InP devices** beats all silicon devices in speed

Technologies for PA vs Frequency & Power



- **RFSOI:** industry[1]
- **SiGe bipolar:** industry[2]
- **GaN-on-Si RF:** R&D @ CEA-Leti[3]
- **InP-on-Si RF:** R&D @ CEA-Leti[4]

[1] ‘Optimizing RFSOI Performance through a T-shape Gate and Nano-Second Laser Annealing Technique’, L. Lucci et al. RFIC’23

[2] ‘SiGe Speaks to the Sky’ P. Chevalier IMS’23

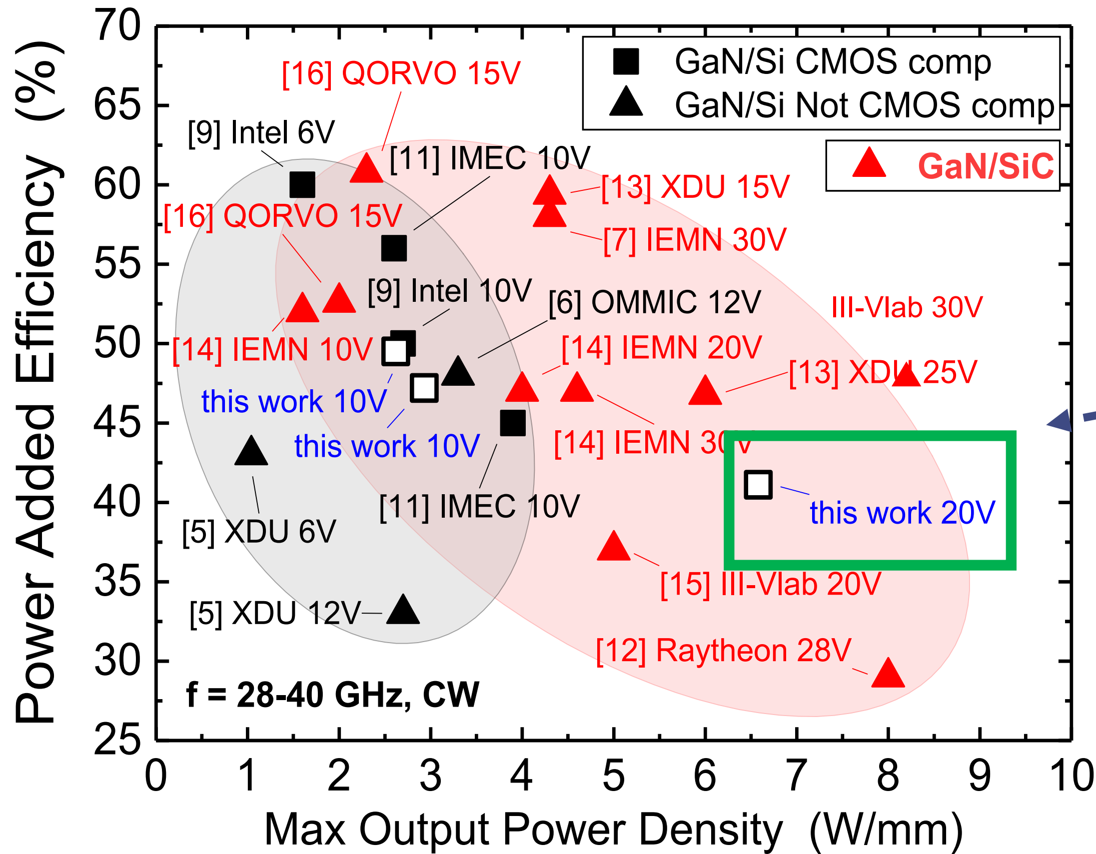
[3] ‘6.6W/mm 200mm CMOS compatible AlN/GaN/Si MIS-HEMT with in-situ SiN gate dielectric and low temperature ohmic contacts’, E. Morvan et al. IEDM’23

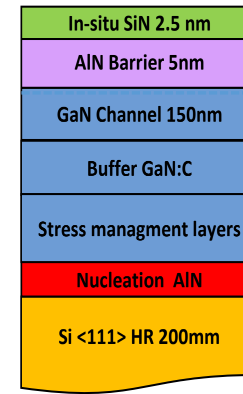
[4] ‘Advanced semiconductors for Sub-THz communications: InP on silicon pathfinding’, H. Boutry et al. Leti-Days’23

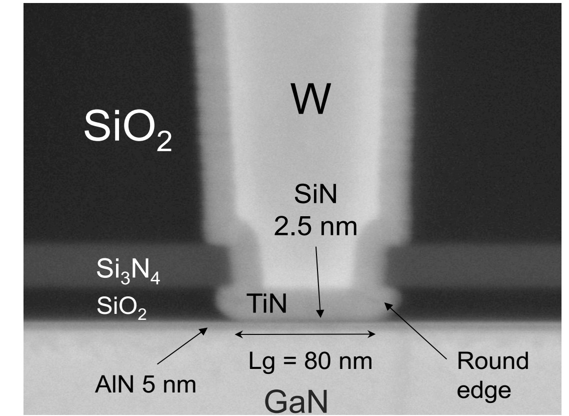
ETH-Zurich survey

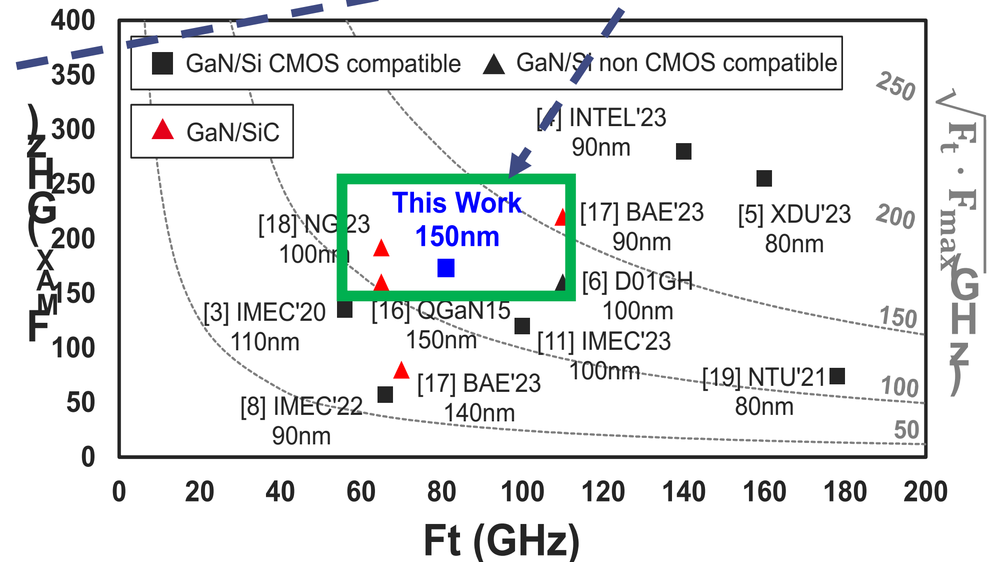
Competitive RF GaN/Si HEMT

SiN/AlN MIS-HEMT









- Close to **GaN/Si** SoA
- Enters **GaN/SiC** domain

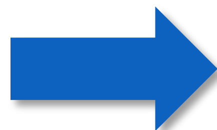
- Competitive Ft/Fmax with Longer Lg

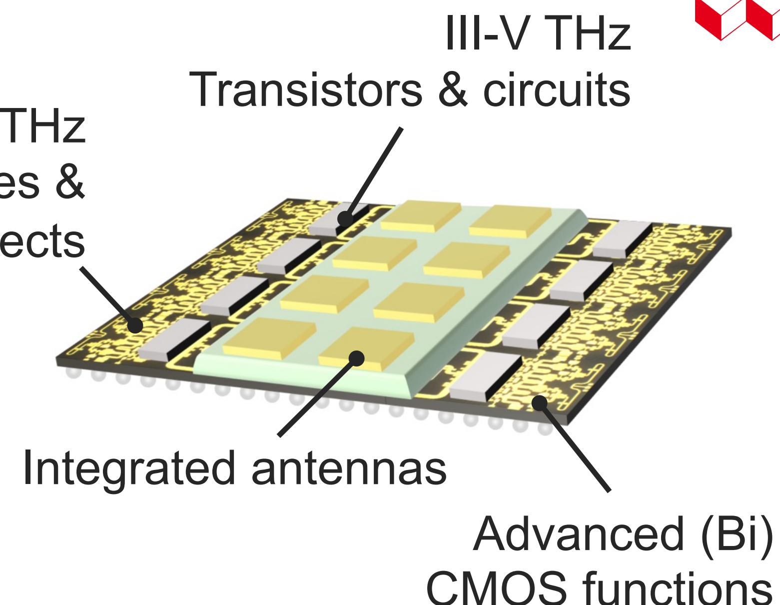
E. Morvan, et. al, IEDM 2023
A. Divay, et. Al, VLSI 2024

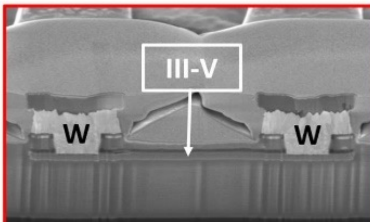
InP HBT on Si substrate for 6G

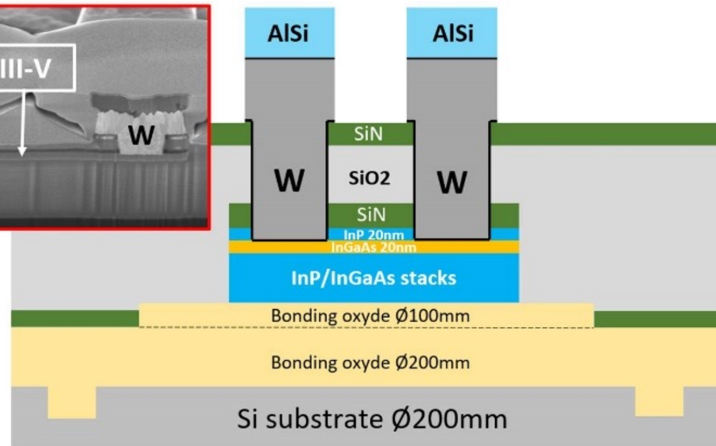
STCO analysis towards 6G:

- CMOS compatible III-V THz HBT on Si substrate
- 3D integration: µbump, direct hybrid bonding

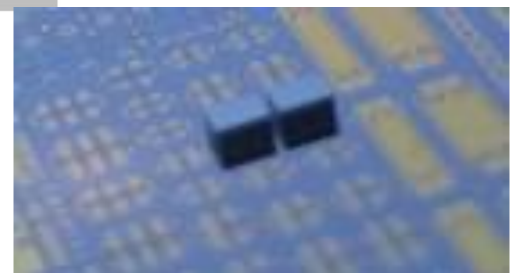


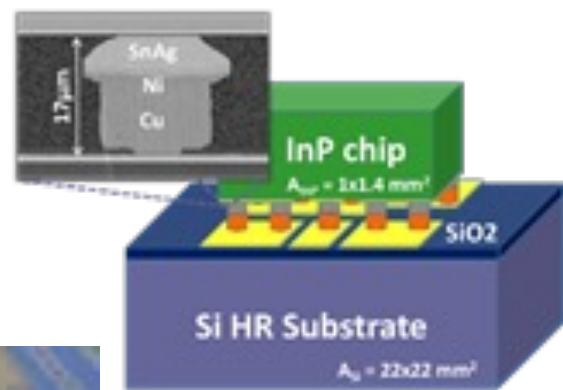


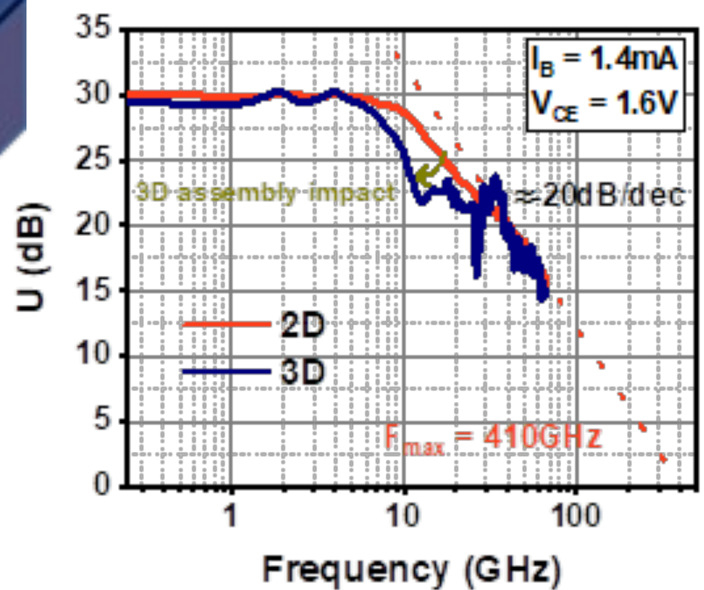




IEMN



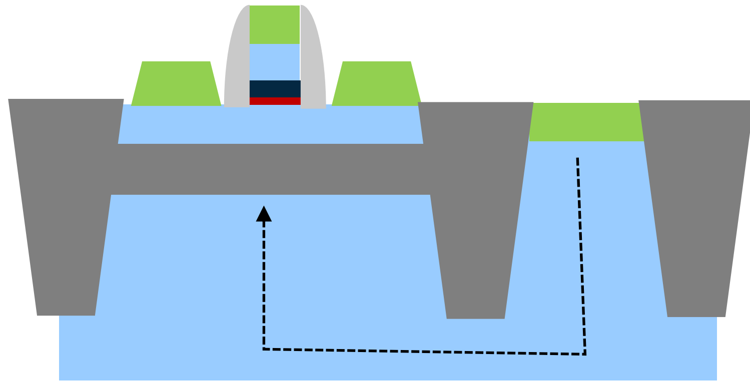




A. Lombrez, et.al, MAM 2024
A. Lombrez, et. Al EuroSOI 2024 (submitted)

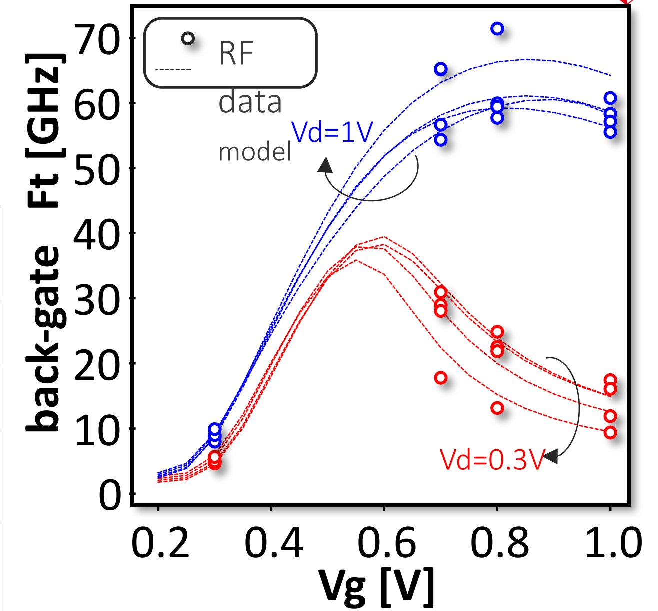
A. Oliveira, et. Al, EuMW 2024 (submitted)

Is it the end of RF CMOS?



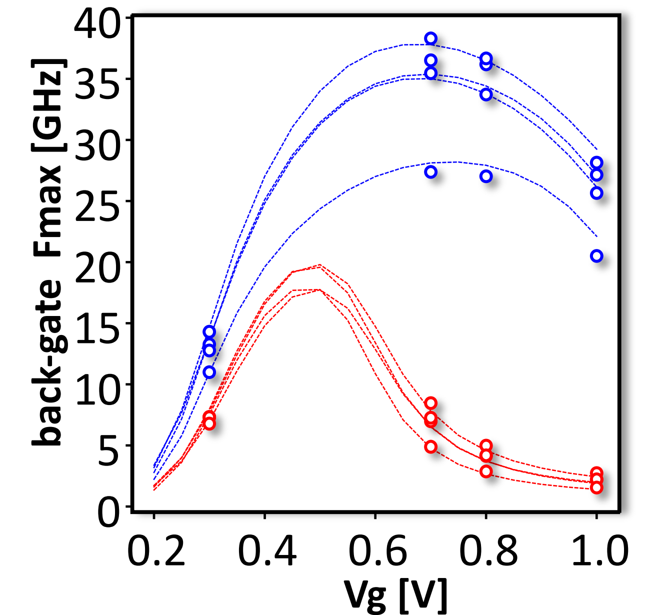
	22FDX	14nm FInFET	28nm Bulk	45nm PDSOI
f_T n-FET [GHz]	347	314	310	296
f_{max} n-FET [GHz]	371	180	161	342
f_T p-FET [GHz]	242 275 (mmWave)	285	185	-
f_{max} p-FET [GHz]	288 299 (mmWave)	140	104	-

Source GlobalFoundries



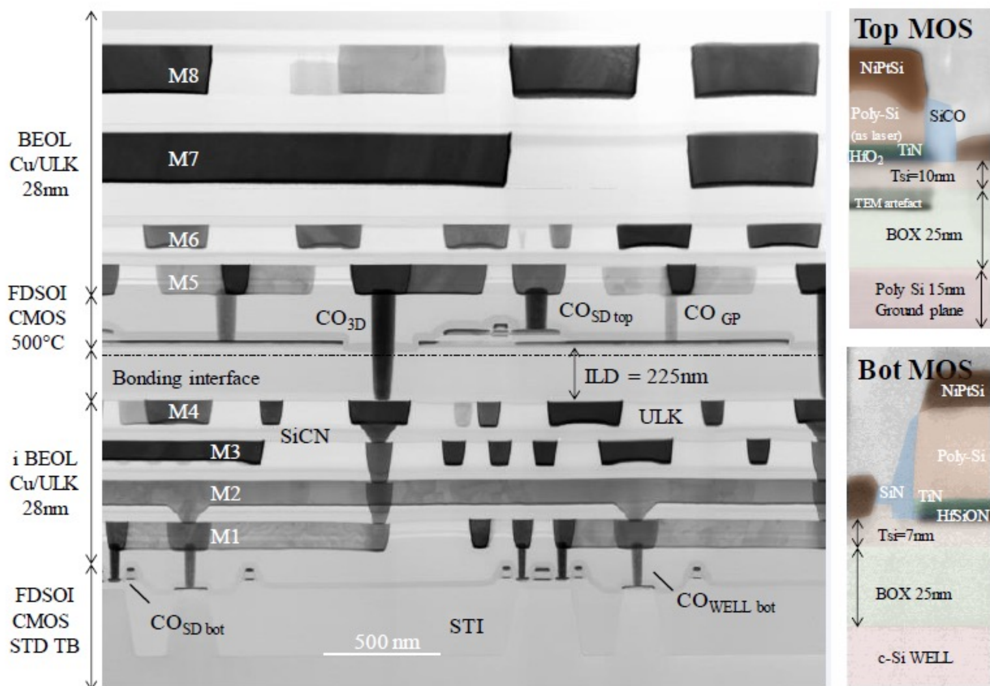
10 & 7nm FD-SOI enabled with substrate innovation:

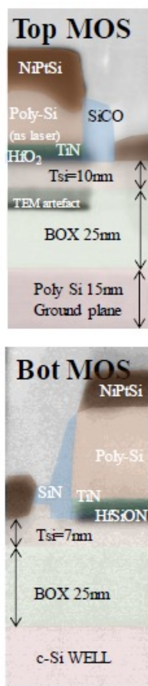
- BOX and Si scaling down
- Strain Silicon incorporation
- Possible combination with HR/Trap-Rich substrates

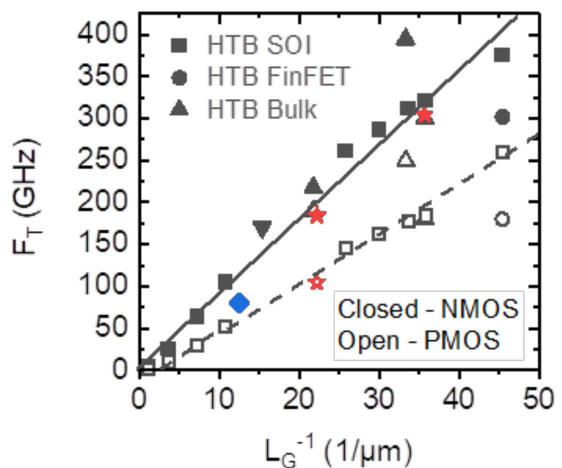


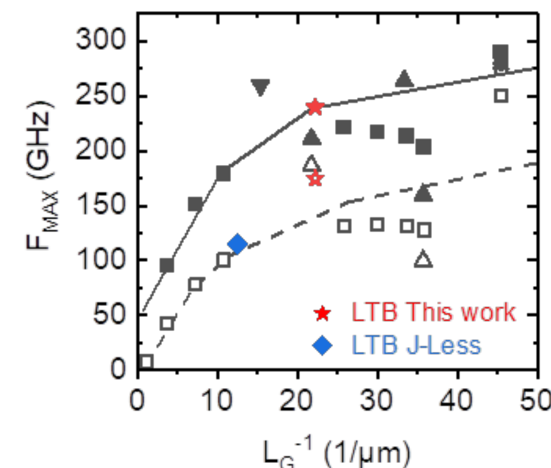
3D sequential integration, 28FDSOI platform

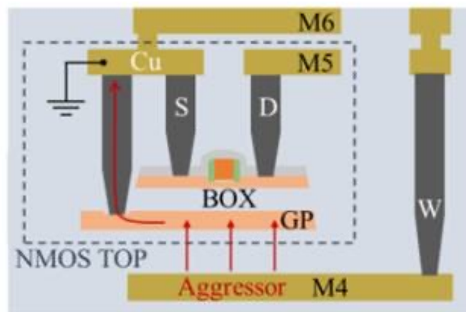
Cold process (~500°C) for top tier integration
➔ Bottom tier not impacted by thermal budget
➔ Device & system EM shielding between top & bottom tier

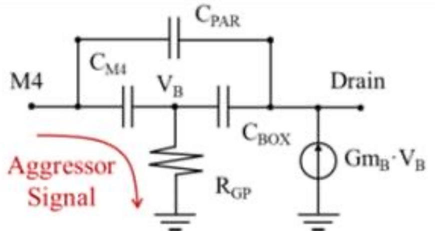


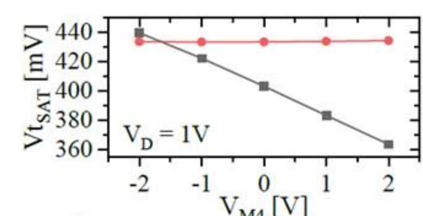


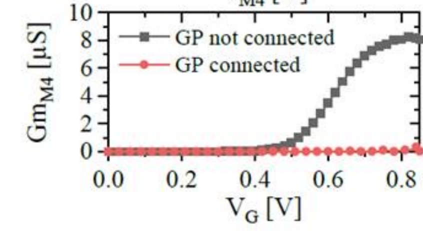


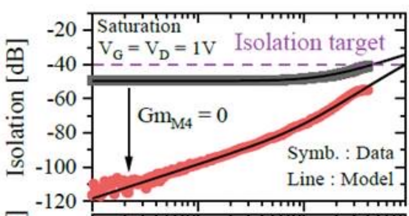


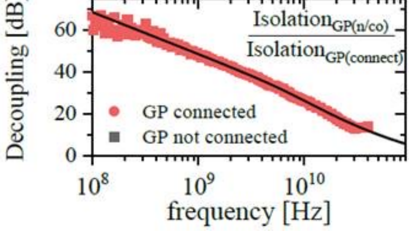












X. Garros et al., P. Sideris et al., IEDM 2019
T. M. Frutuoso et al., TED 2021
T. M. Frutuoso, et al., VLSI 2021
T. M. Frutuoso, et al, IEDM 2023
J. Lugo, et. Al, VLSI 2024

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Take Away

- New materials and associated substrates: a strong enabler for 5G and Beyond
- Li based substrates: key for high performance filters up to 7GHz demonstrated
- III-V on Silicon substrates: the solution for the best Power/Frequency trade-off
- 3D integration for RF Heterogenous integration
- Si CMOS technology not disqualified: FD-SOI and monolithic 3D as enabler to push it further

Many Thanks to all my colleagues from CEA-Leti from their inputs and support: Y. Lamy, B. Duriez, O. Valorge, O. Rozeau, L. Lucci, F. Gaillard, Y. Bogumilowicz, L. Perniola, T. Poiroux

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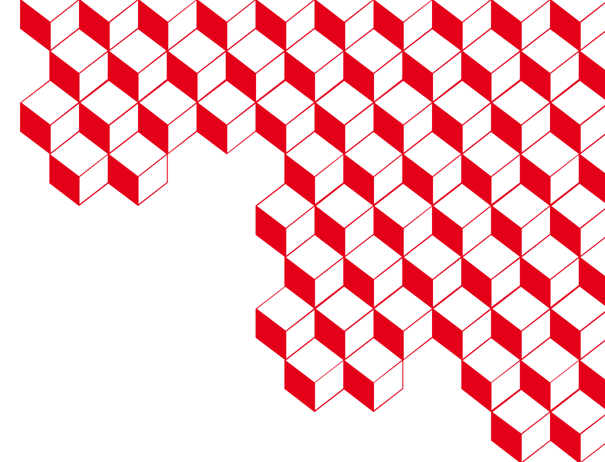
leti-innovation-days.com



Merci

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