Advanced SiGe BiCMOS Process Technologies for mm-Wave Applications

IEEE Phoenix Waves and Devices Chapter
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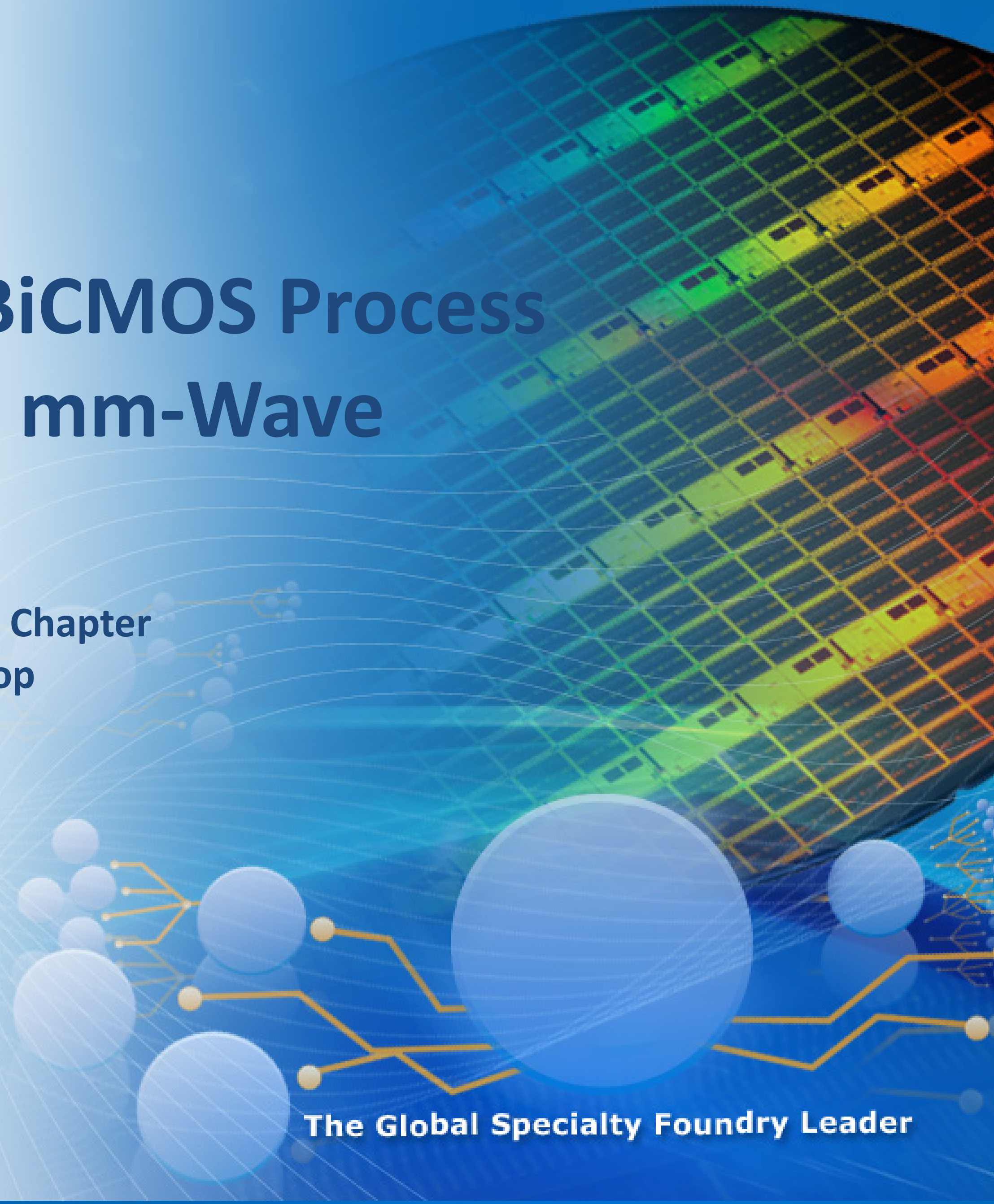
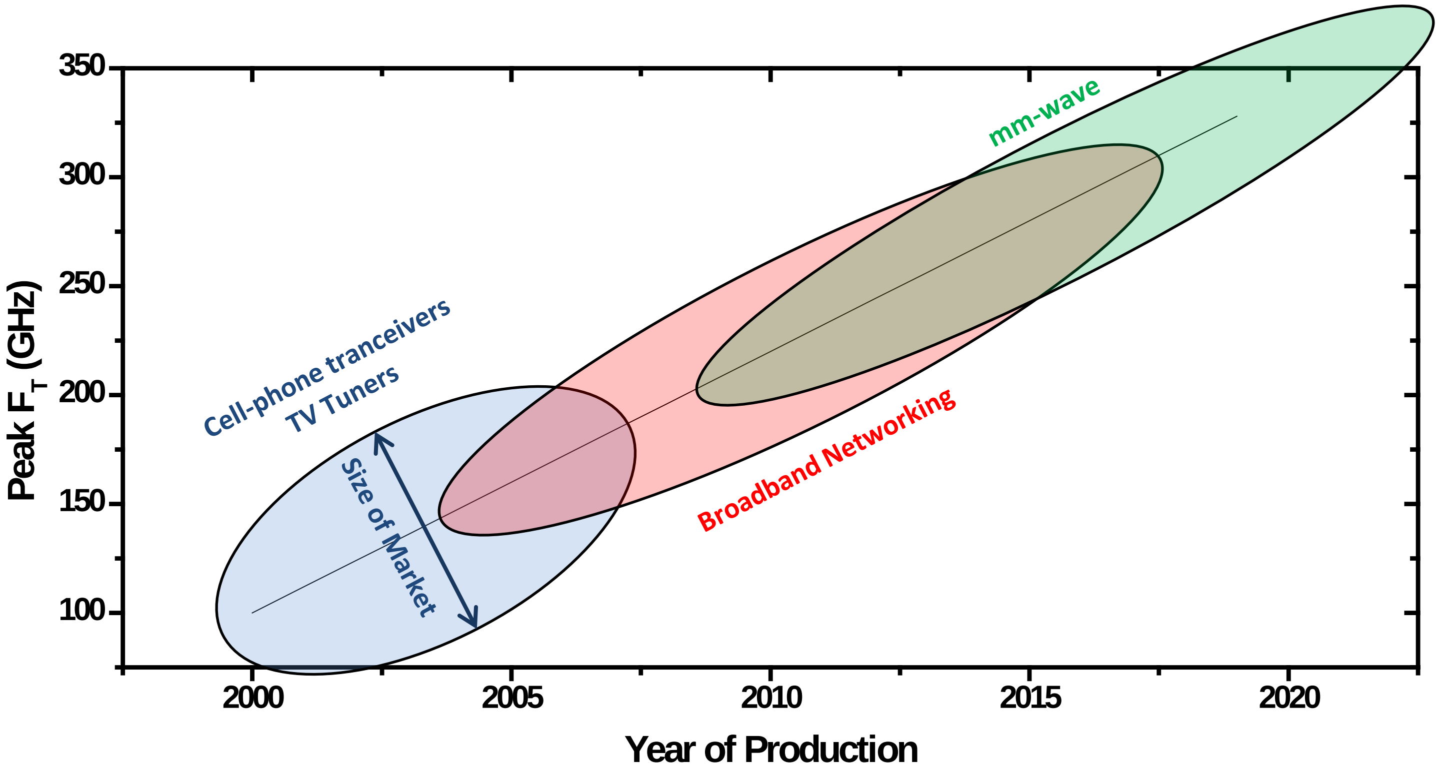


The Global Specialty Foundry Leader

Overview

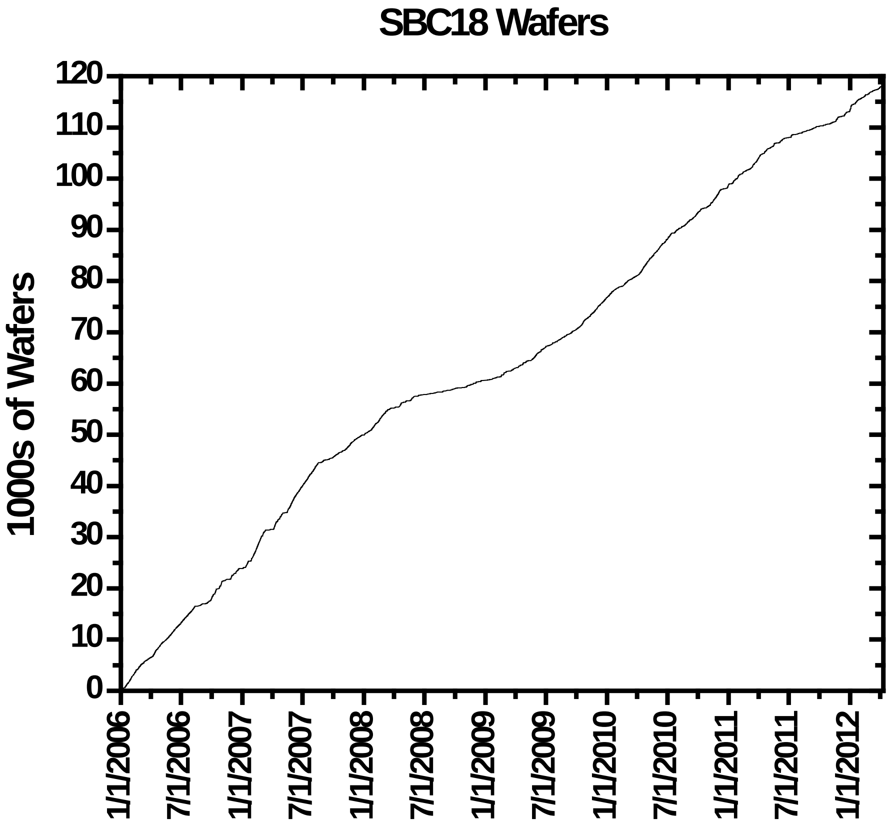
- SiGe Production History
- Comparison of SiGe BiCMOS to other competing technologies
- Summary of key mm-Wave components
- Circuit Examples

Historical View of SiGe BiCMOS RF Applications



- **mm-Wave applications are expected to make up a good portion of the market for SiGe BiCMOS technologies over the next decade**

Historical Volume of Wafer Production

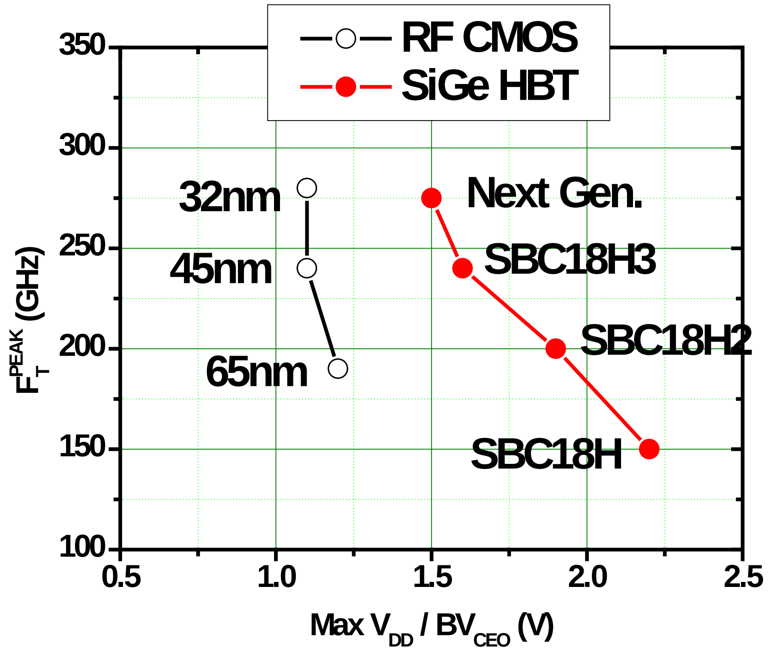


- **Last 6 years of production history for the SBC18 family of processes**

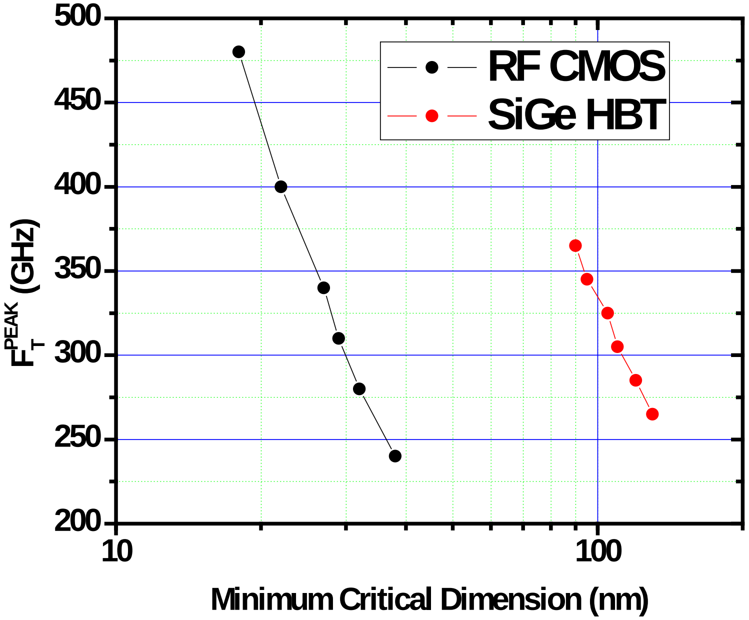
- **Roughly 20K Wfr/Yr Run Rate**

- **Almost none of this is mm-Wave but it shows the experience with producing wafers on a technology capable for mm-Wave applications**

Comparisons with RFCMOS



ITRS Roadmap Data

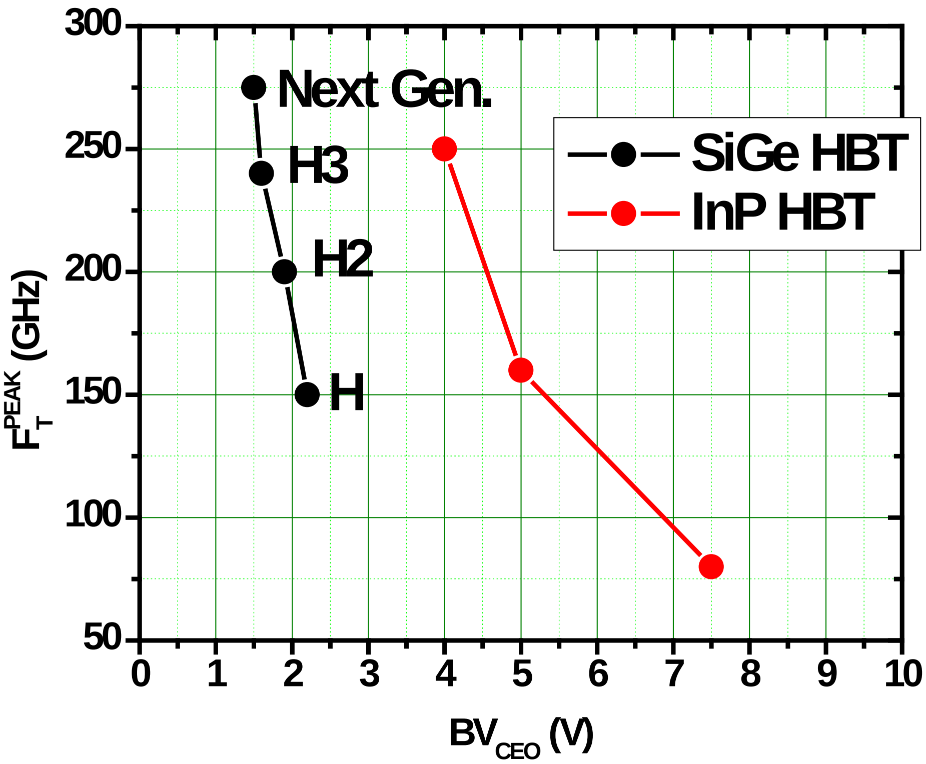


- SiGe HBTs have at least a 0.5V advantage in usable supply voltage but usually it’s quite a bit more since devices are often operated past BV_{CEO}

- At the device level, RF CMOS can achieve similar RF performance to SiGe HBTs, but at much more advanced nodes
- For the moment, SiGe BiCMOS has a distinct cost advantage over the equivalent RF CMOS node

Comparisons with InP

InP Data from Northrop Grumman Foundry Services Website



- InP-based devices can achieve similar RF performance to SiGe HBTs with much higher breakdown voltage but at several times the cost per die

- InP technologies also offer a much lower level of integration

Overall mm-Wave Technology Comparison Table

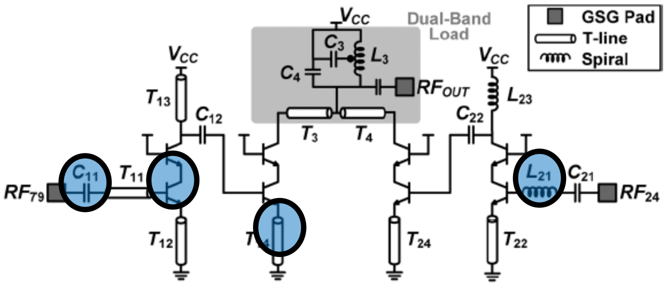
For technologies currently in production

Technology	F_T (GHz)	F_{MAX} (GHz)	Supply Voltage (V)	Level of Integration	Quality of Passives	Cost
45nm RFCMOS[1]	240	280	1.1	High	Low	Medium
SiGe BiCMOS[2]	240	280	>1.6	Medium	Medium	Low
InP HBT[3]	250	300	>4	Low	High	High

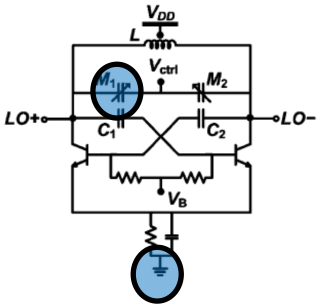
1. ITRS Tables
2. TowerJazz SBC18H3
3. Northrop Grumman 0.6um InP HBT Technology

- **SiGe BiCMOS offers a kind of “sweet-spot” for mm-wave applications due to its combination of RF performance with low cost and adequate levels of integration and quality of passives.**

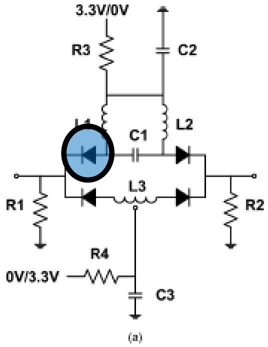
Key mm-Wave Components



24/79GHz Dual-Band LNA
Jain et al., IEEE JSSC 2009 p. 3469



24 GHz VCO
Jain et al., IEEE JSSC 2009 p. 2100

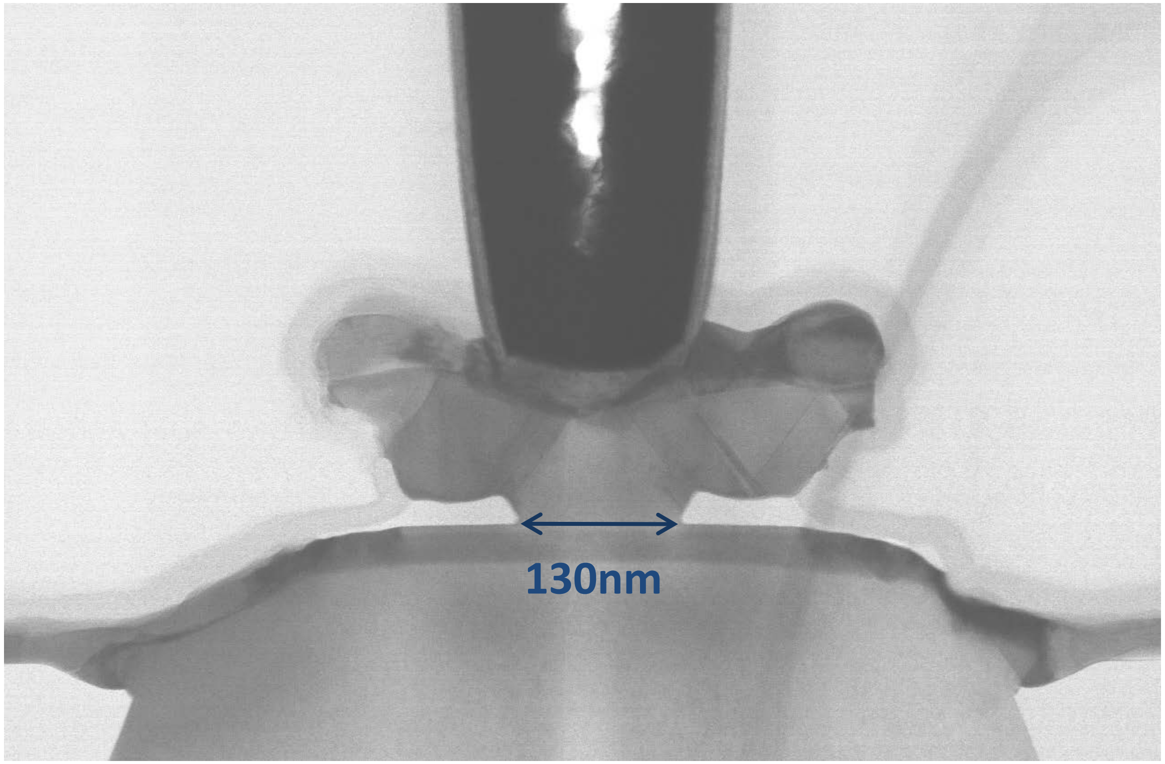


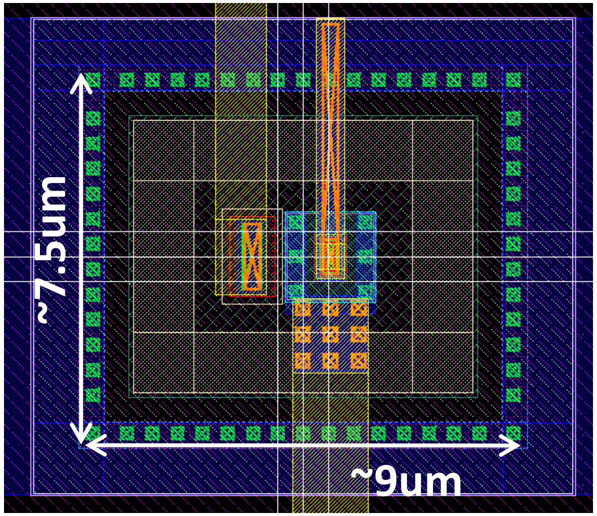
KU-Band Phase Shifter
Wang et al., IEEE µwave & Wireless Comp. Lett. 2010 p.37

SiGe HBT | Capacitors | Transmission Lines | Inductors | Varactors | p-i-n Diodes | RF Ground

- All of these components need to be stable and well-characterized out to very high freq.
- Ideally all of these components could be integrated onto a single chip

SiGe HBT Device: SBC18H3





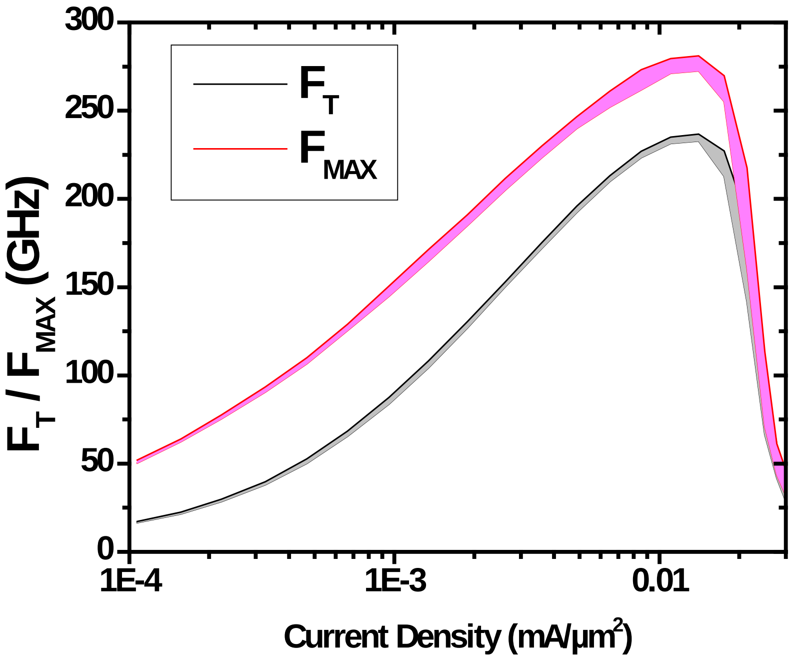
Minimum footprint device

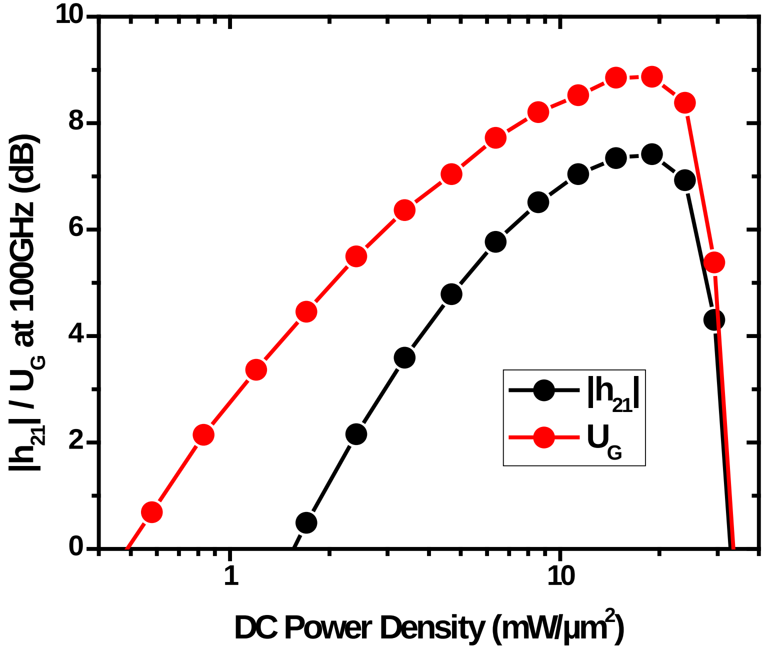
- TowerJazz' 3rd generation fully self-aligned 0.18um SiGe BiCMOS process technology
- CMOS and back end are exact replicas of mature SBC18 technology family (>1 decade, >150,000 wafers)

Advanced SiGe HBTs: What matters to mm-Wave Designers?

- Noise (RF and 1/f)
- F_T vs. F_{MAX}
- Gain at low current (low V_{BE})
- Gain in saturation (low V_{CE})
- Transconductance (G_M / Y_{21})
- Short-emitter devices
- Wide Emitter devices
- BV_{CER}
- Linearity
- ....

RF Performance

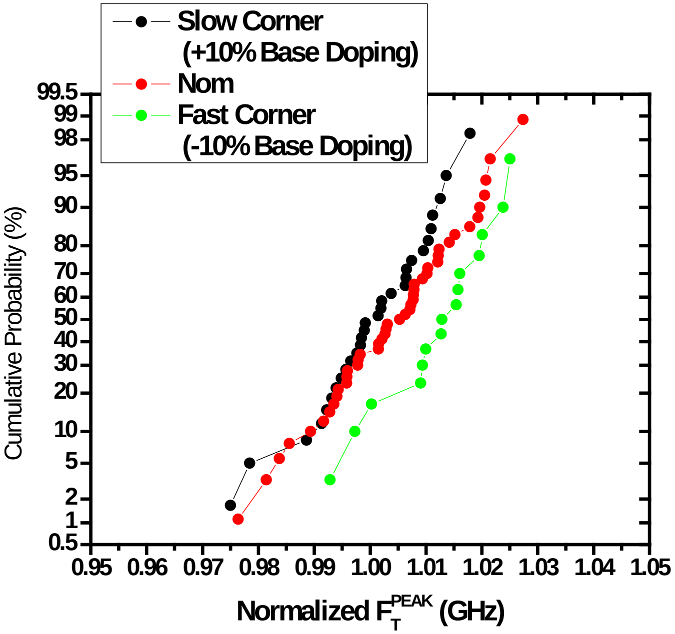


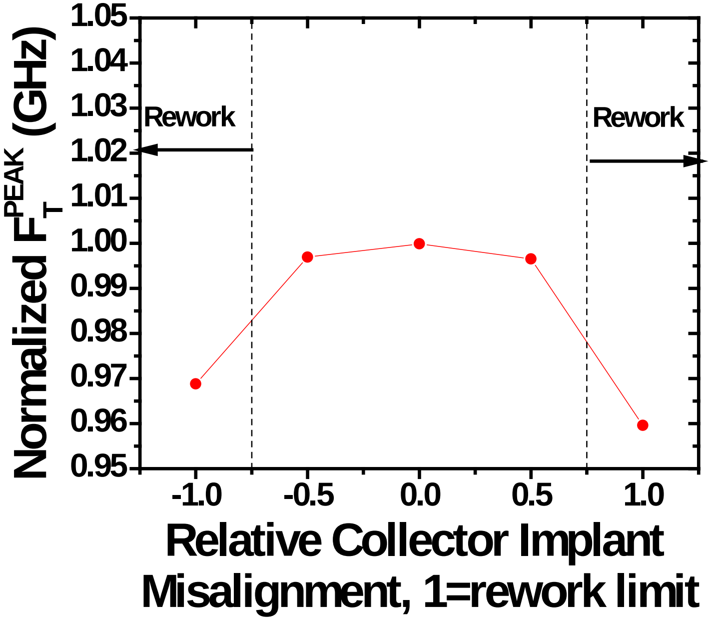


- Data is from 15 sites on a typical SBC18H3 wafer
- Shaded areas show 25-75 percentile data spread

- A different way of looking at the same data: power consumption for a given gain at 100GHz

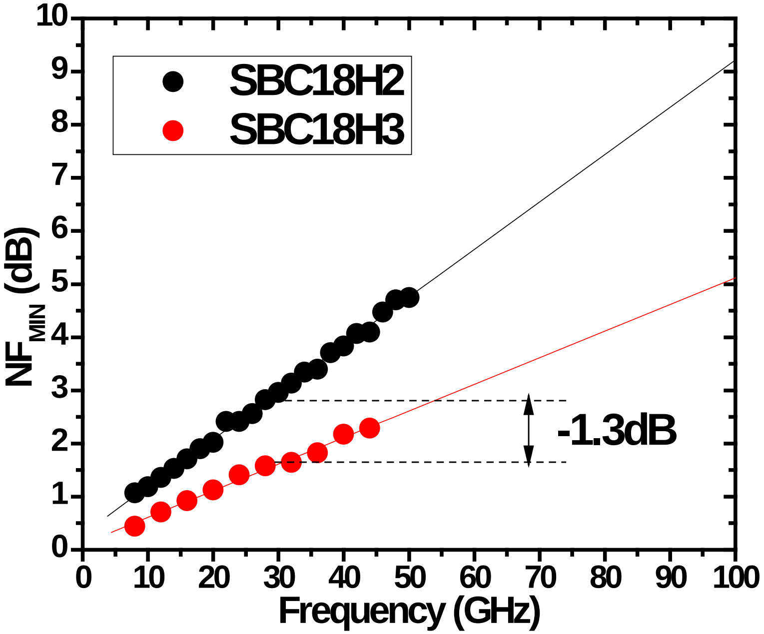
RF Performance with Process Variation



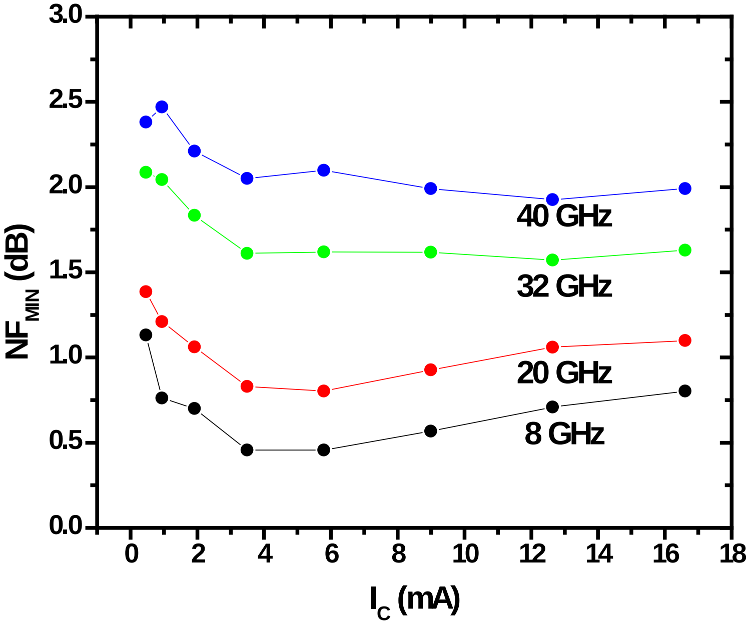


- SBC18H3 has been designed for process insensitivity
- +/- 5s variation in base doping only leads to about +/- 1% in FT
- Even beyond rework limits, most challenging mask alignments will lead to only +/- 3% in FT

RF Noise



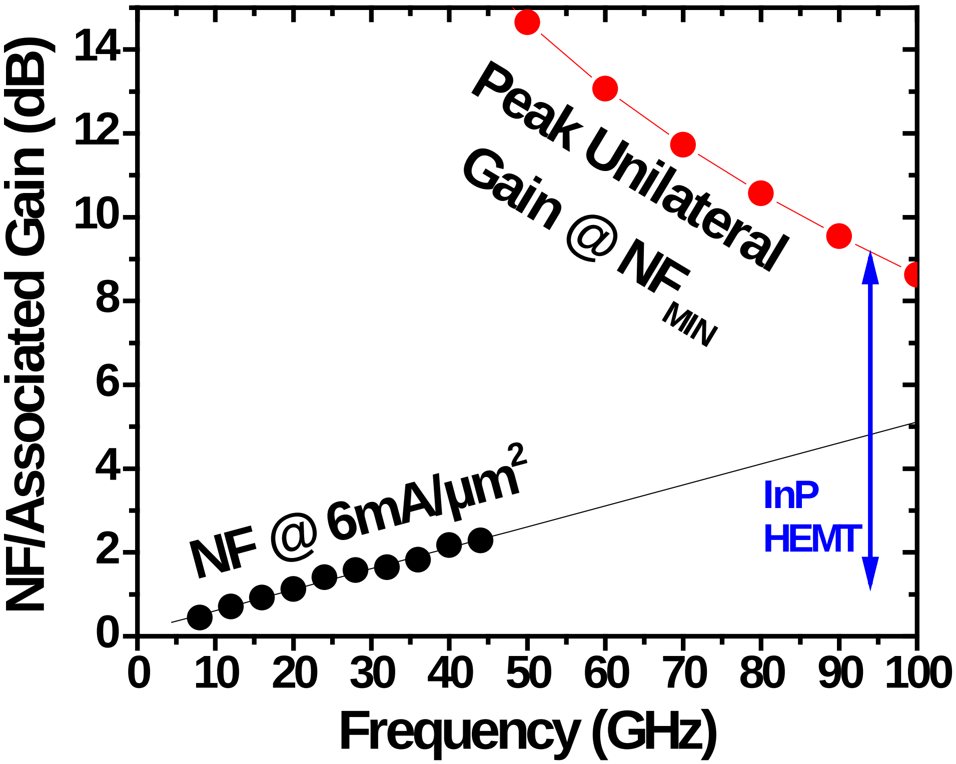
0.13x20 µm Single Emitter, Dual Base, Dual Collector



- Minimum noise figure is substantially improved with each succeeding process generation along with F_T / F_{MAX}

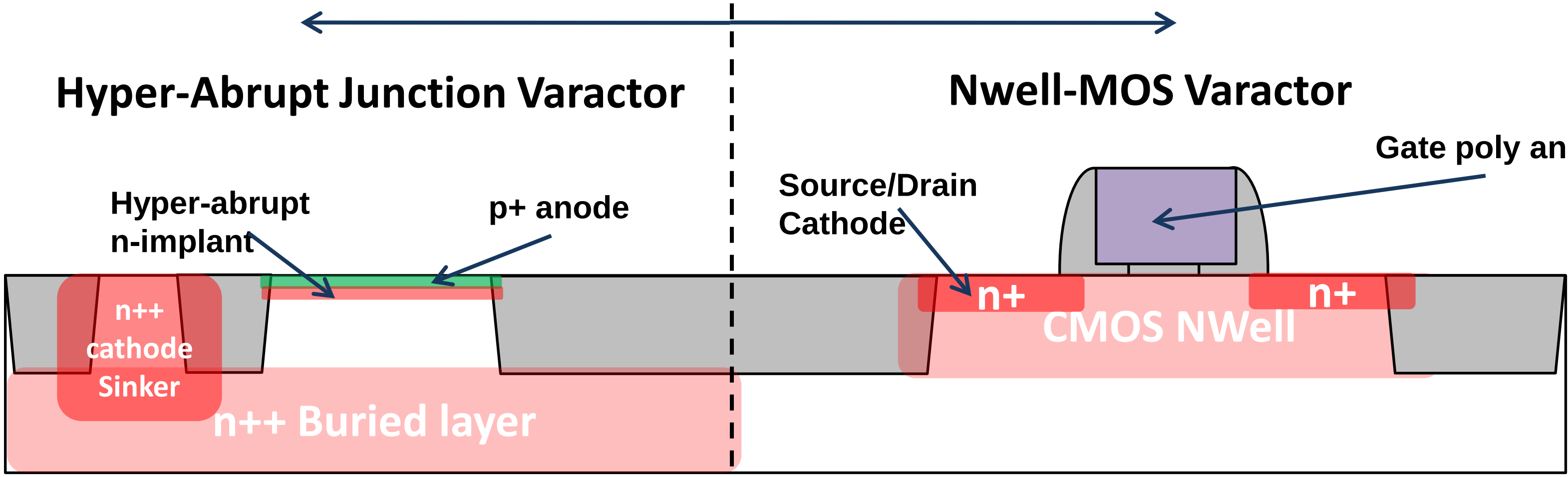
- Ideally the NF is very flat across bias since the NF_{MIN} never coincides with the peak gain condition

Gain vs. Noise

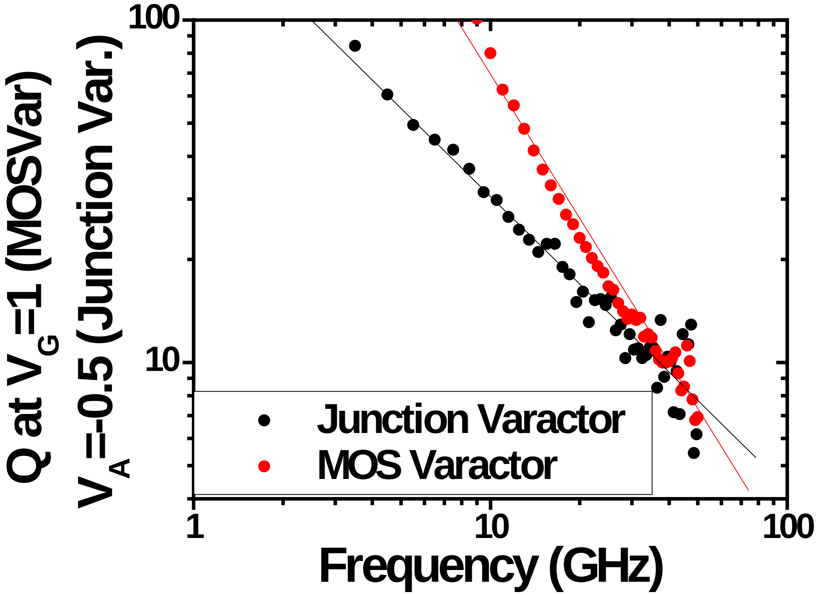


- If we benchmark against an InP HEMT (from ITRS tables) the gain at mm-Wave is comparable
- Noise floor is still inferior to III-V technologies but the gap is closing.

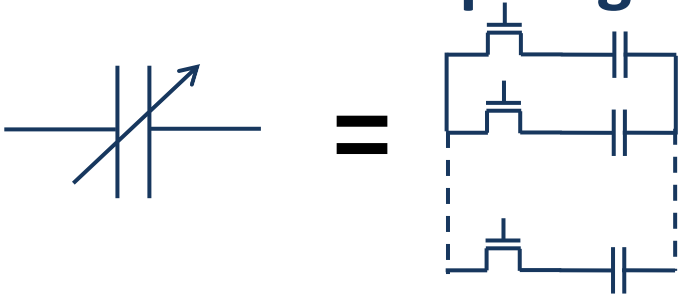
Varactors



- BiCMOS technologies offer two types:
  - Hyper-abrupt p-n junctions for linearity
  - MOS for high Q
- Varactor Q is often the limiting factor in the loss of the VCO circuit.
- At mm-wave frequencies the Q of both devices starts to look similar
- Frequency synthesis at ~100GHz usually uses harmonic generation so Q at 50 or even 33 GHz might be most important



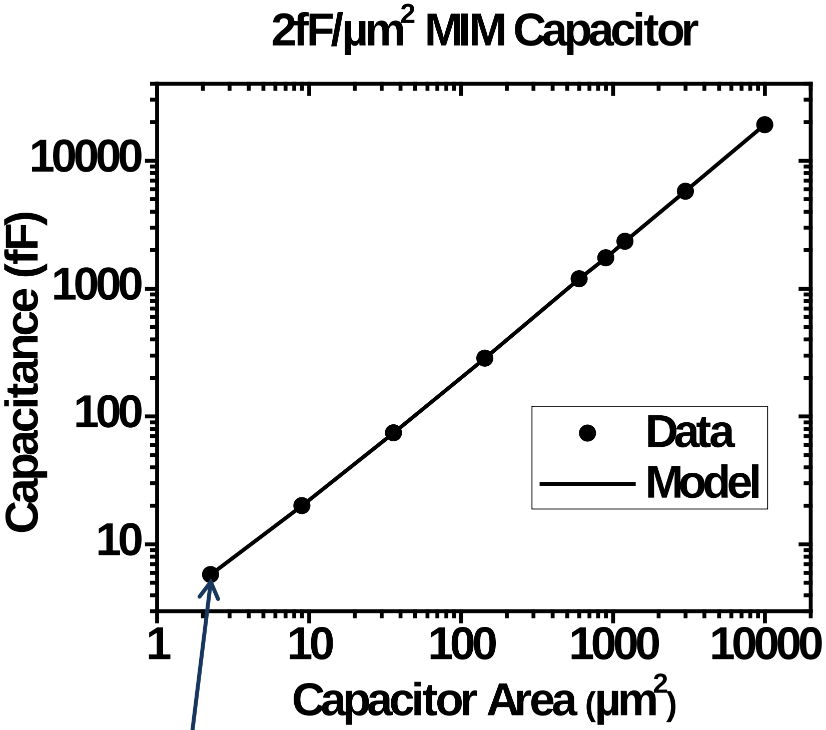
Other VCO Topologies

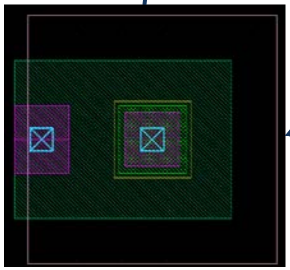


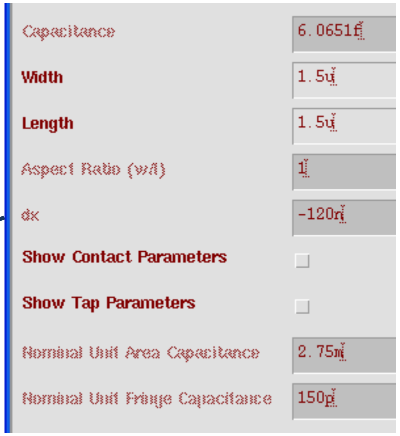
- "Digital" varactors have become common in high frequency VCOs

- MOSFETs are used to switch MIM capacitors in or out of the circuit. These are often used in parallel with a traditional varactor for ultra-linear fine-tuning

- A key enabling feature for these devices is accurate modeling of ultra-small MIM capacitors

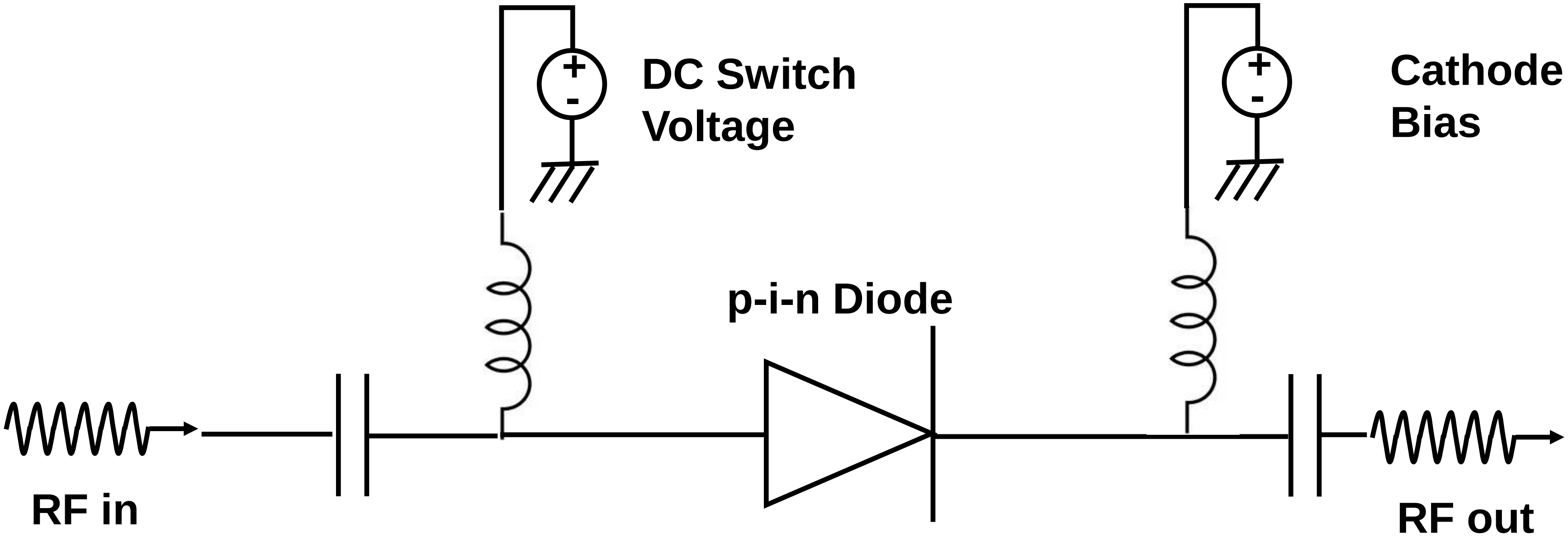




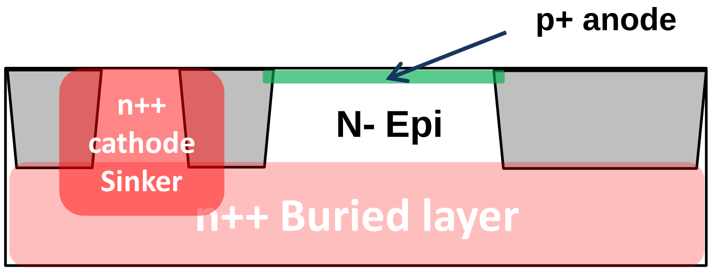


Capacitance	6.0651f
Width	1.5u
Length	1.5u
Aspect Ratio (w/l)	1
dx	-120n
Show Contact Parameters	☐
Show Tap Parameters	☐
Nominal Unit Area Capacitance	2.75m
Nominal Unit Fringe Capacitance	150p

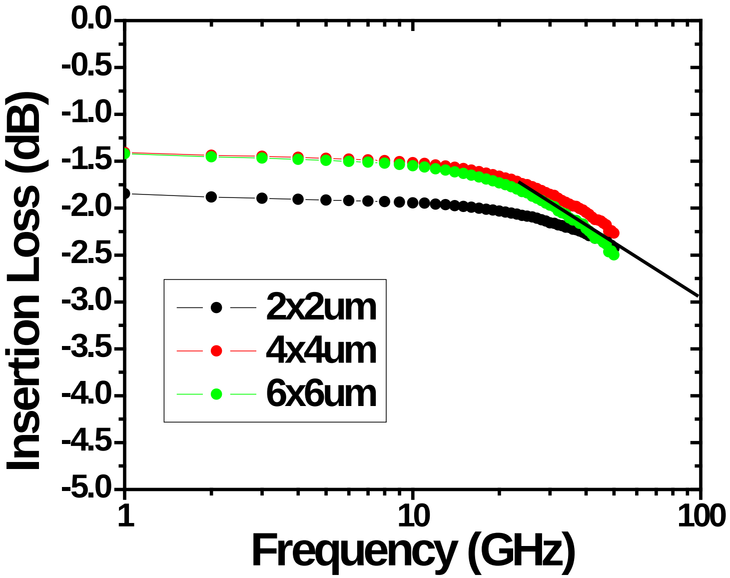
p-i-n Diodes

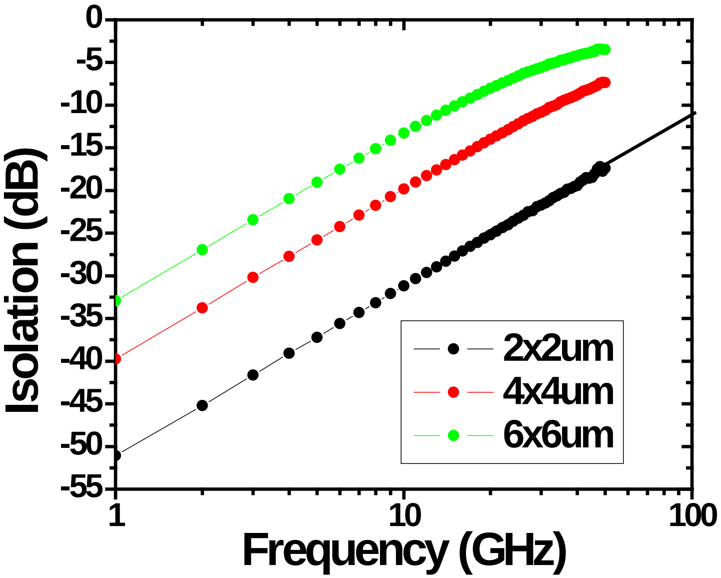


- p-i-n diodes can be used as RF switches when surrounded by a bias tee
- Off-State capacitance is very low due to low-doped n- intrinsic region inherent in BiCMOS technologies



p-i-n Diodes

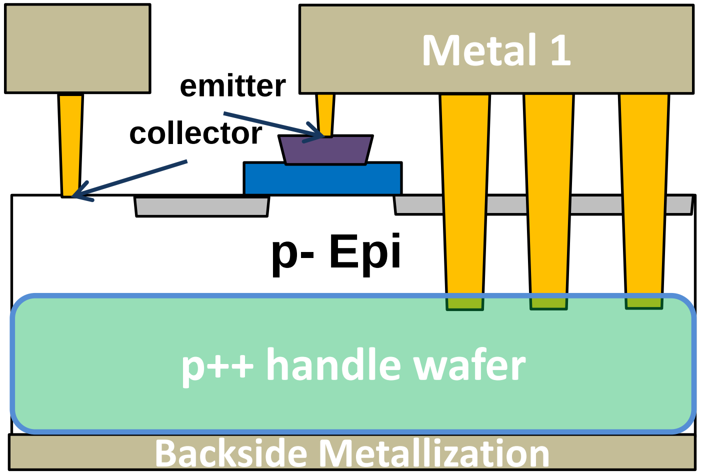




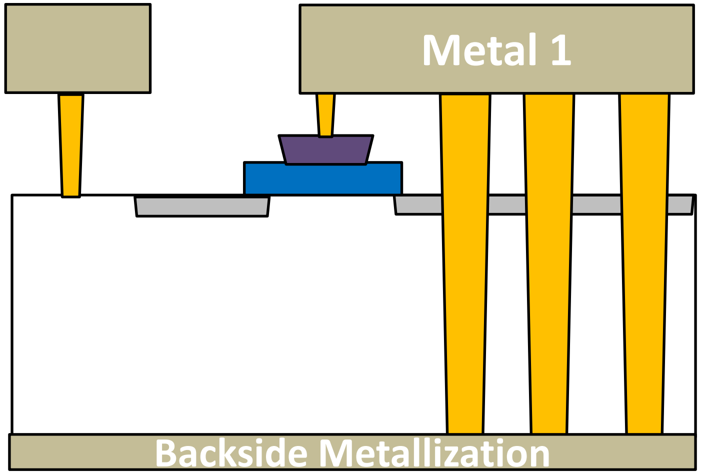
- Smaller devices exhibit lowest best isolation due to lower total capacitance but suffer somewhat in insertion loss due to higher series resistance.
- At high frequencies it seems as if RS is no longer the limiting factor for IL.
- 2x2um devices project to at least -10dB of isolation with better than -3dB of IL at 100GHz

RF Ground Solutions

- Deep Silicon Vias



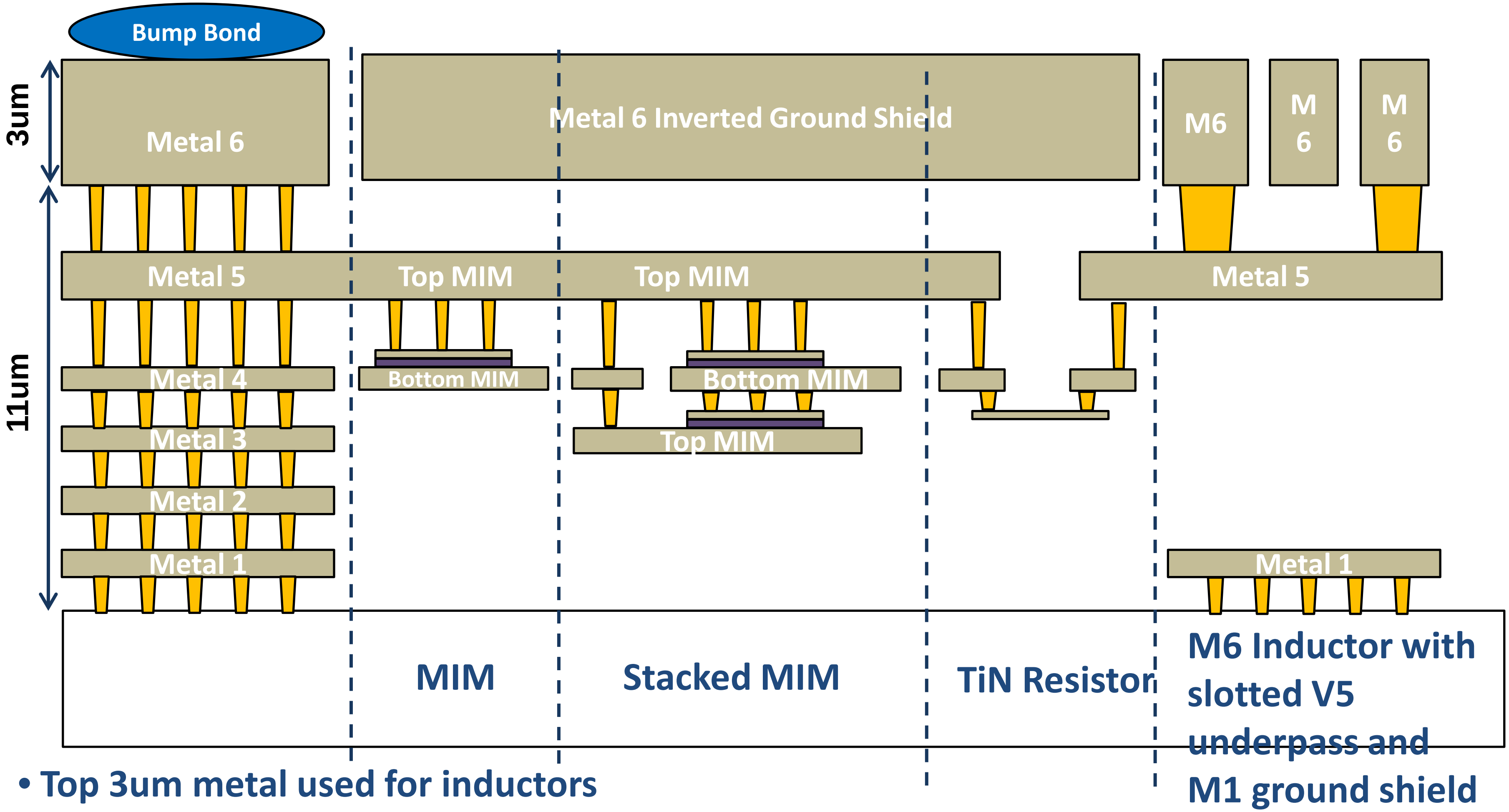
- Through-Silicon Vias



- Extremely “localized” grounding. DSVs can be placed within several µms of active devices.
- <5pH/via. < 50 W/via
- In production now

- Through-Silicon Vias for low inductance / low resistance emitter ground leads
- 1000 µm2 Pad can produce 22pH inductance to ground with less than 1W/via
- In prototype now

RF Back End



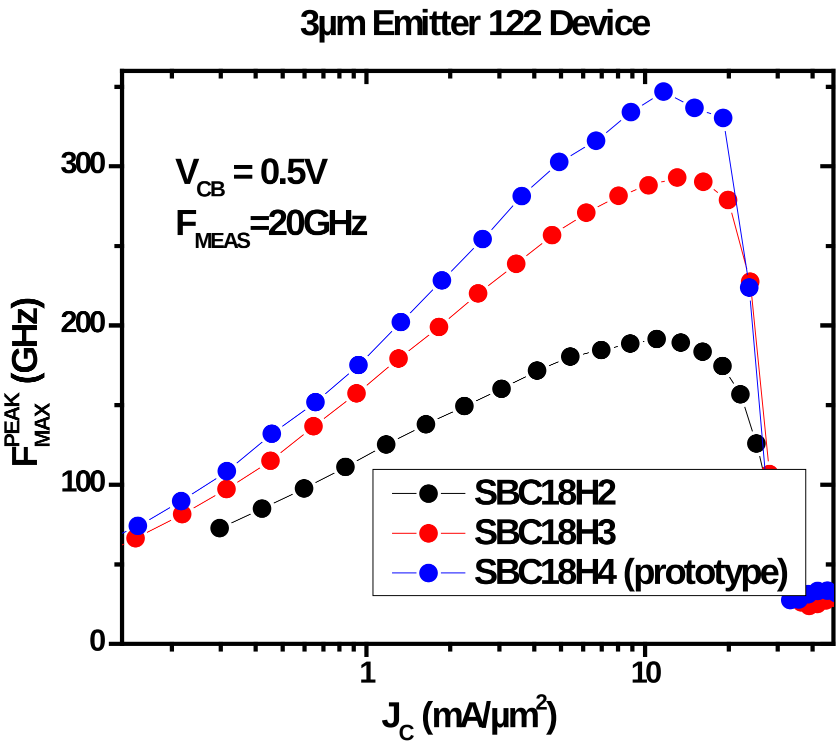
- Top 3um metal used for inductors
- 11um separation between M6 and silicon
- Slotted vias available for inductor underpasses
- Can use M6 ground shield combined w/Bump bonding for uninterrupted ground plane

Complete SBC18H3 Device Roster

Family	Device	Characteristics
CMOS	1.8V CMOS	Model-exact copy of all other TJ 0.18um CMOS
	3.3V CMOS	
Bipolar	HS NPN	240 GHz F_T / 280 GHz F_{MAX}
	STD NPN	55GHz F_T / 3.2V BV_{CEO}
	LPNP	β=35
Resistors	Poly	235 Ω/sq and 1000 Ω/sq
	Metal	25 Ω/sq TiN on M3
Capacitors	Single MIM	2 or 2.8 fF/μm^2
	Stacked MIM	4 or 5.6 fF/μm^2
Varactors	1.8V MOS	Q @ 20GHz = 20
	Hyper-abrupt junction	Q @ 20GHz =15, Tuning Ratio = 21%
RF Diodes	p-i-n	Isolation <-15dB, Insertion loss > -3.5dB at 50GHz
	Schottky	F_C > 800 GHz

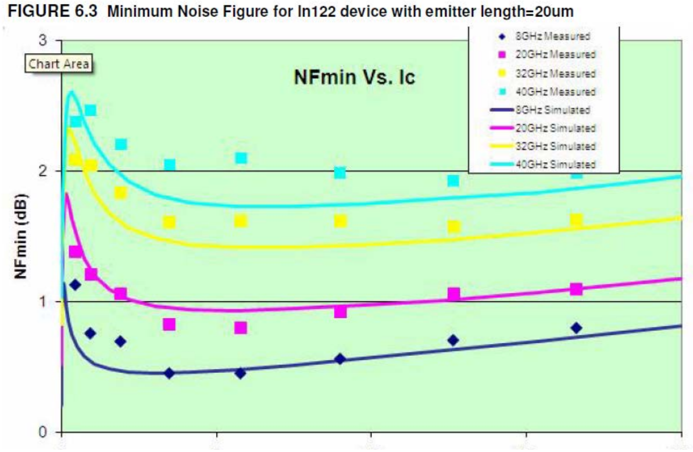
Roadmap

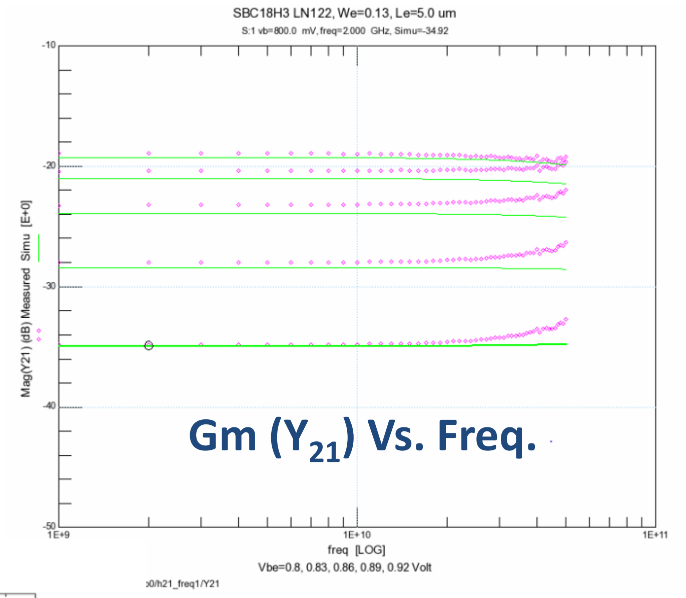
- Prototype devices for SBC18H4 have been built but require some special processing steps that are not ready for manufacturing yet.
- Rev. 0 model available now (otherwise compatible with H3 kit)
- Tentative date for PDK and first allowed tape in is July 2012
- Advantages of SBC18H4 will be along the same lines as H3 over H2 (higher F_{MAX}, lower NF_{MIN})



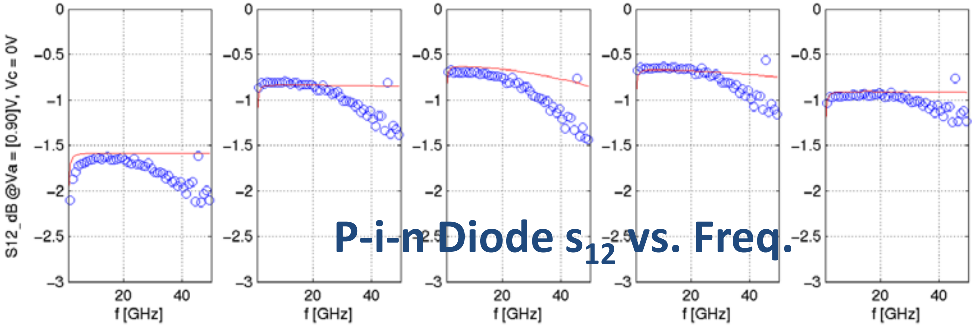
RF Modeling

NF at 40GHz





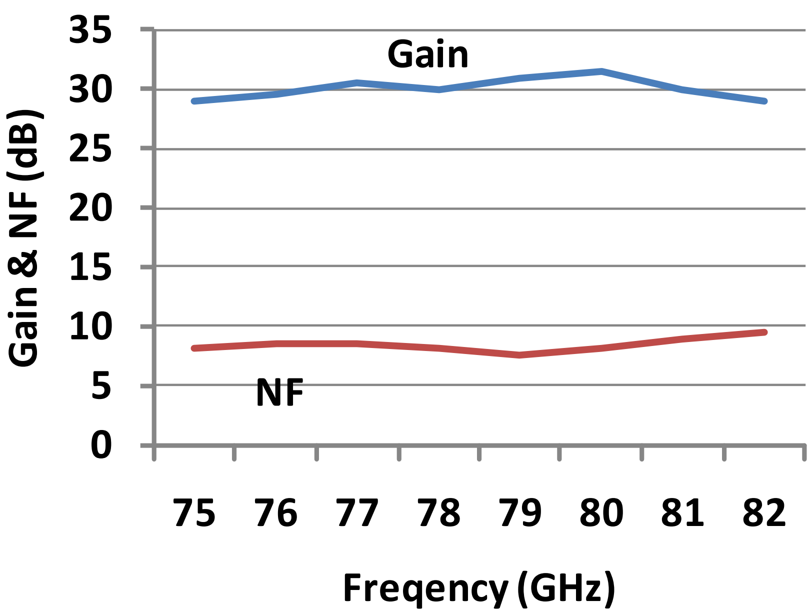
Gm (Y_{21}) Vs. Freq.



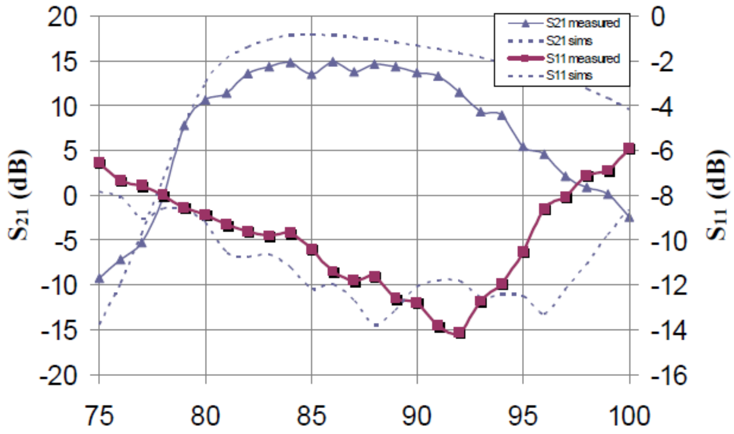
P-i-n Diode s_{12} vs. Freq.

- Accurate RF models are almost more critical than the process they are trying to model!
- Challenges with calibration and de-embedding at mm-Wave frequencies make RF modeling a complex science.

Circuit examples from past technology generations


80GHz RX+SX Test Results

- 80GHz LNA built in SBC18H2 Technology (Courtesy Sabertek Inc.)



- W-band 5-Stage LNA built in SBC18H2 Technology (UCI)

- Simulated data shows accuracy of models out to mm-wave frequencies
- Even past generation devices seem adequate to create reasonable circuits out to 90GHz
- New generations push past 100GHz and lower power consumption for circuits at lower frequencies

Conclusion

- SiGe BiCMOS technologies capable of producing practical circuits operating up to at least 100GHz are currently available
- These technologies are based on a background of nearly a decade of high-volume processing
- Newer generations increase design margin and reduce power consumption at mm-Wave frequencies, making them more suitable for commercial manufacturing