SiGe Heterojunction Bipolar Technology and Applications

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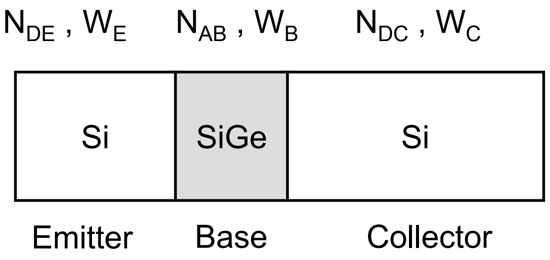
Outline

- Introduction
- SiGe device physics
- SiGe material properties
- Integration of SiGe base
- Device Performance
- Circuit Applications
- Conclusion

Device Physics behind the SiGe HBT



N_{DE} , W_E N_{AB} , W_B N_{DC} , W_C

Si	SiGe	Si
Emitter	Base	Collector

$N_{DE} > N_{AB}$ for a Si bipolar

$$\beta_{SiGe} = \overbrace{\frac{N_{DE}\, W_E\, D_{nb}}{N_{AB}\, W_B\, D_{pe}}}^{\beta_{Si}} \exp\left(\Delta Eg / kT\right)$$

We can trade current gain β and increase base doping N_{AB}

We can decrease emitter doping N_{DE} to get lower C_{je} ($N_{DE} < N_{AB}$)

$$V_A = \frac{q\, N_{AB}\, W_B^{\,2}}{\varepsilon_o \varepsilon_s}$$

Early Voltage is increased with base doping N_{AB}

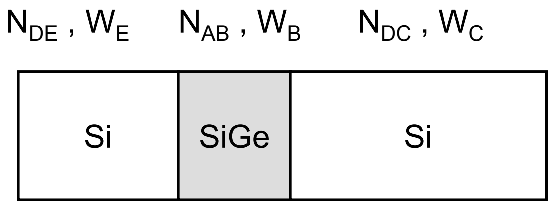
$$f_{max} = \sqrt{\frac{f_T}{8\pi R_b C_{jc}}}$$

f_{max} improved by lower Rb due to increased N_{AB}

$$BV_{CEO} = \frac{BV_{CBO}}{\sqrt[n]{\beta}}$$

n = 4 for NPN

Device Physics behind the SiGe HBT

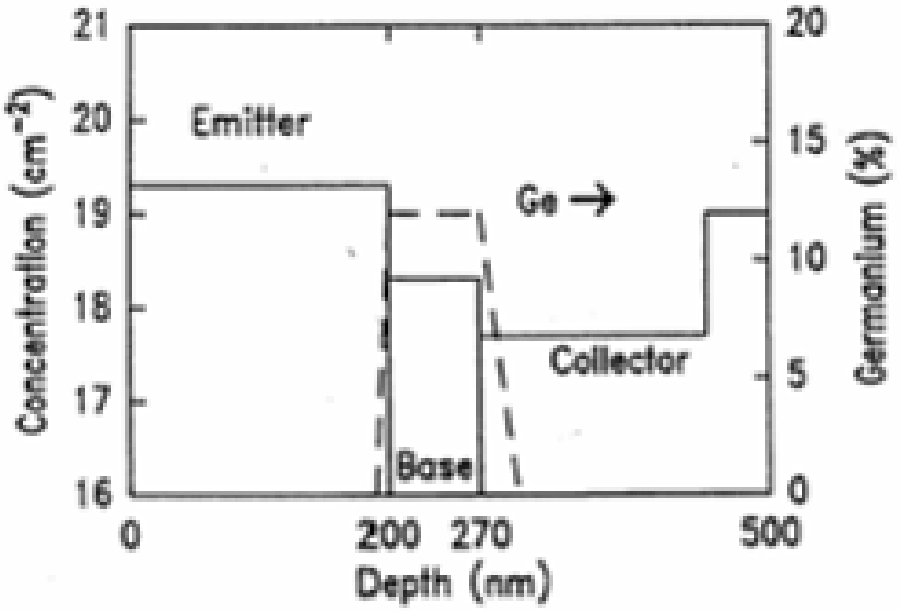


$$\tau_t = \frac{1}{2\pi f_T} = \tau_F + (r_e + R_e + R_c)\, C_{jc} + r_e\, C_{je} \qquad r_e = \frac{V_T}{I_C}$$

$$\tau_F = \overset{\tau_e}{\frac{W_E^2\, G_{nb}}{2\, D_{pe}\, G_{ne}} \exp(-\Delta Eg / kT)} + \overset{\tau_b}{\frac{W_B^2}{2\, D_{nb}}} + \overset{\tau_c}{\frac{W_C}{2V_{sat}}}$$

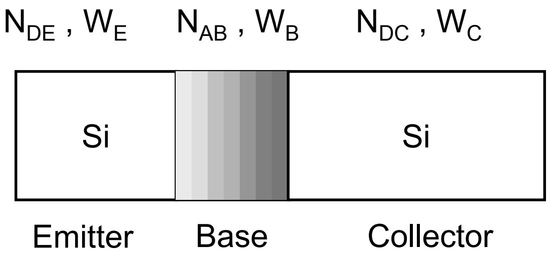
$$\frac{qW_B^2}{2\mu\Delta E_{gG}}$$ (For Graded SiGe base)

Results from Box base SiGe Transistor



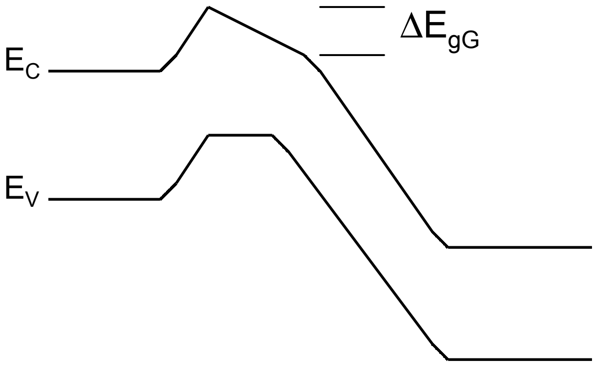
	ρ_{BI} kΩ/□	J_C mA/μm^2	β	τ_B ps	τ_E ps	τ_C ps	f_T GHz
Si	7.3	0.5	12	3.7	5.8	0.4	15
SiGe	7.0	0.7	1500	3.7	0.3	0.4	36

Device Physics behind the graded SiGe base HBT



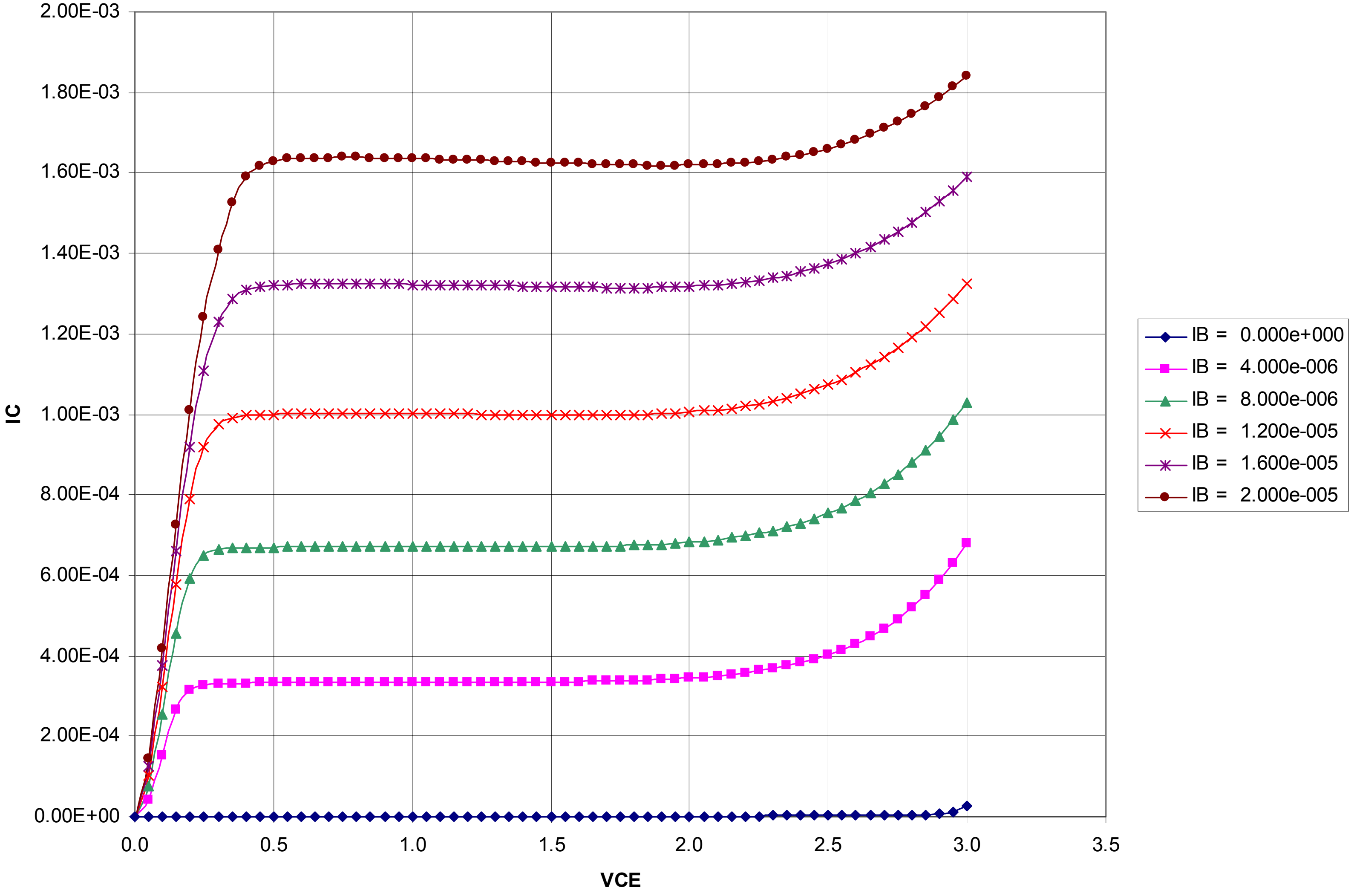
$N_{DE} > N_{AB}$ for graded SiGe base

$$\beta_{SiGe} = \overbrace{\frac{N_{DE}\, W_E\, D_{nb}}{N_{AB}\, W_B\, D_{pe}}}^{\beta_{Si}} \; (\Delta E_{gG} / kT)$$

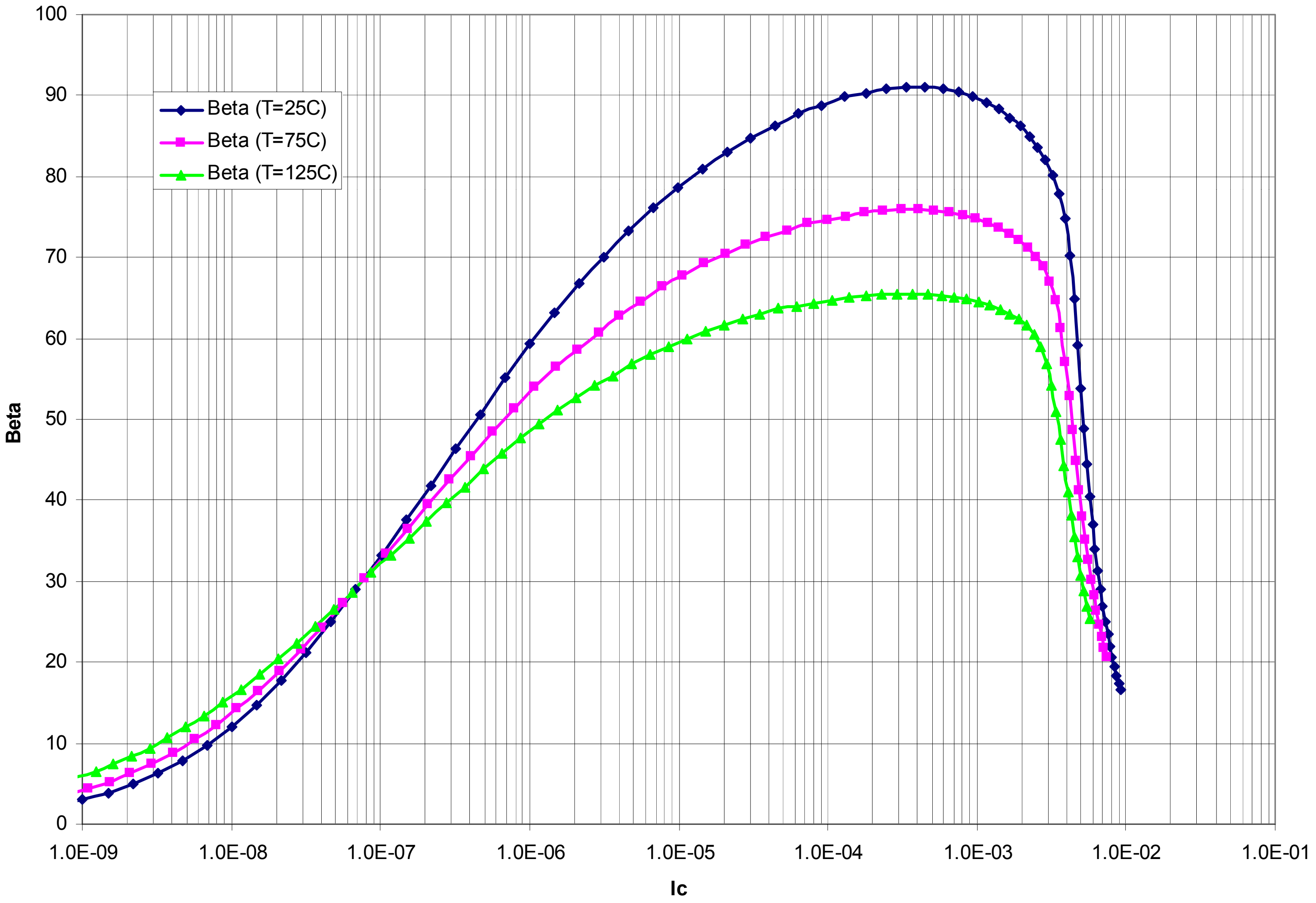


$$V_A = \frac{q\, N_{AB}\, W_B^{\,2}}{\varepsilon_o \varepsilon_s} \; \exp (\Delta E_{gG} / kT)$$

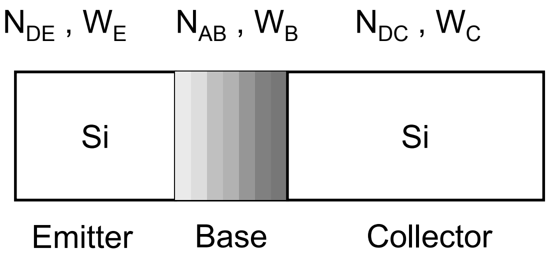
I-V Curves for a typical SiGe Transistor



Beta vs Ic for a typical SiGe Transistor



Device Physics behind the graded SiGe base HBT



$N_{DE} > N_{AB}$ for graded SiGe base

$$\tau_t = \frac{1}{2\pi f_T} = \tau_F + (r_e + R_e + R_c)\, C_{jc} + r_e\, C_{je}$$

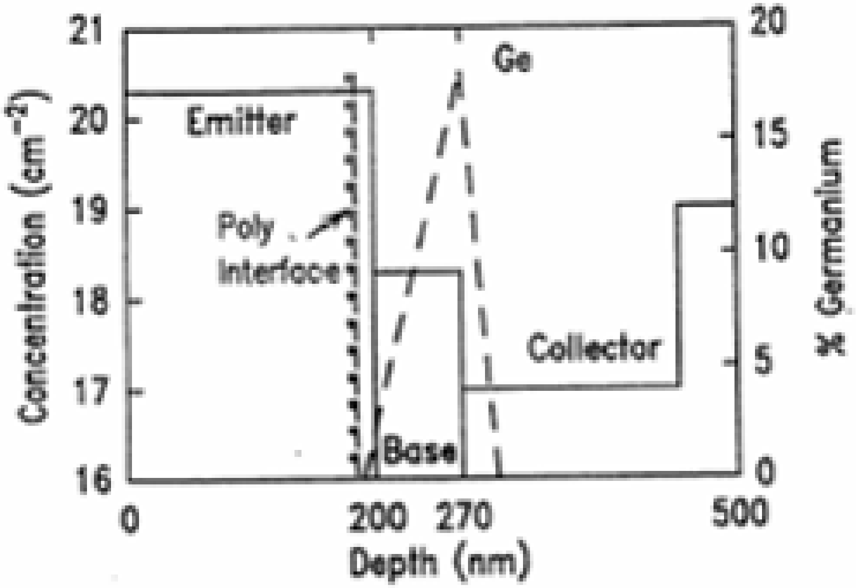
$$r_e = \frac{V_T}{I_C}$$

$$\tau_F = \tau e + \tau b + \tau c$$

$$\frac{\tau e\ (\mathrm{SiGe})}{\tau e\ (\mathrm{Si})} = \frac{\mathrm{Rbi\ (Si)}}{\mathrm{Rbi\ (SiGe)}}\ \frac{kT}{\Delta E_{gG}}$$

$$\frac{\tau b\ (\mathrm{SiGe})}{\tau b\ (\mathrm{Si})} = \frac{2kT}{\Delta E_{gG}} \left(1 - \frac{kT}{\Delta E_{gG}} \right)$$

Results from Triangular base SiGe Transistor

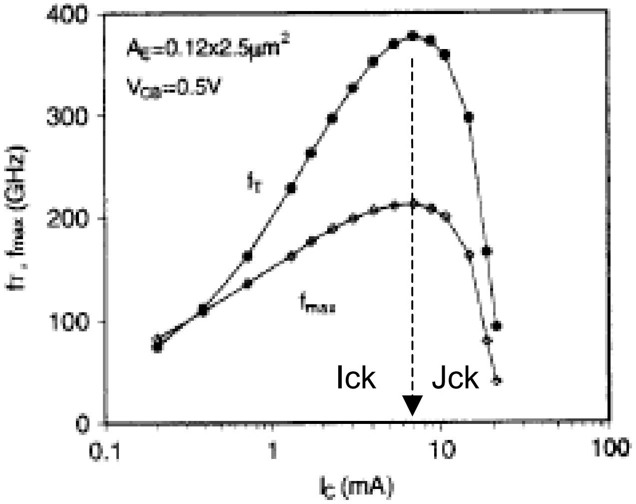


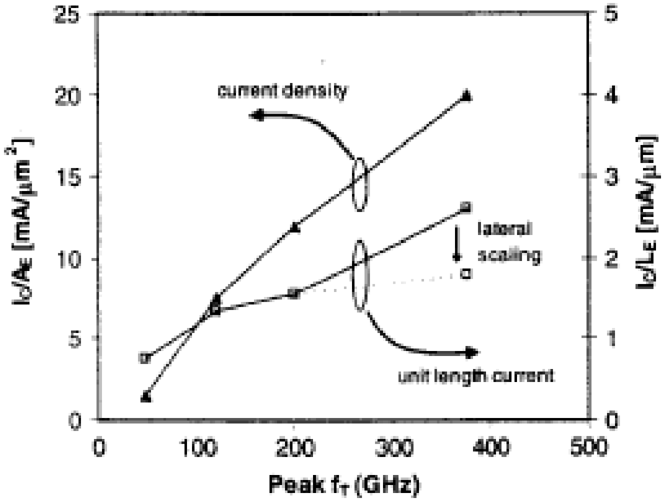
	ρ_{BI} kΩ/□	J_C mA/µm²	β	τ_B ps	τ_E ps	τ_C ps	f_T GHz
Si	6.6	0.33	30	4.0	0.7	1.0	26
SiGe	6.6	0.39	320	1.5	0.1	1.0	52

Comparing Box and Triangular Profiles

Box Ge Profile	Triangular Ge Profile
Double Heterojunction - difficult to grow	Single Heterojunction - simpler growth
beta ~ exp (ΔE_g /kT)	beta ~ (ΔE_{gG}/kT)
V_A improved only by base doping	V_A improved by exp (ΔE_{gG}/kT)
Low base resistance	High base resistance
No significant improvement in f_T	f_T improved by base transit time
Significant improvement in f_{max}	f_{max} improved thru f_T
$N_{DE} < N_{AB}$	$N_{DE} > N_{AB}$
High Ge content, Lo thermal budget	Lo Ge content, more tolerant
Lightly doped emitter has to be grown	Emitter need not be grown
Integration difficult due to grown emitter	Easily integrates in a poly emitter process

Collector Design: Effect of Collector doping on f_T

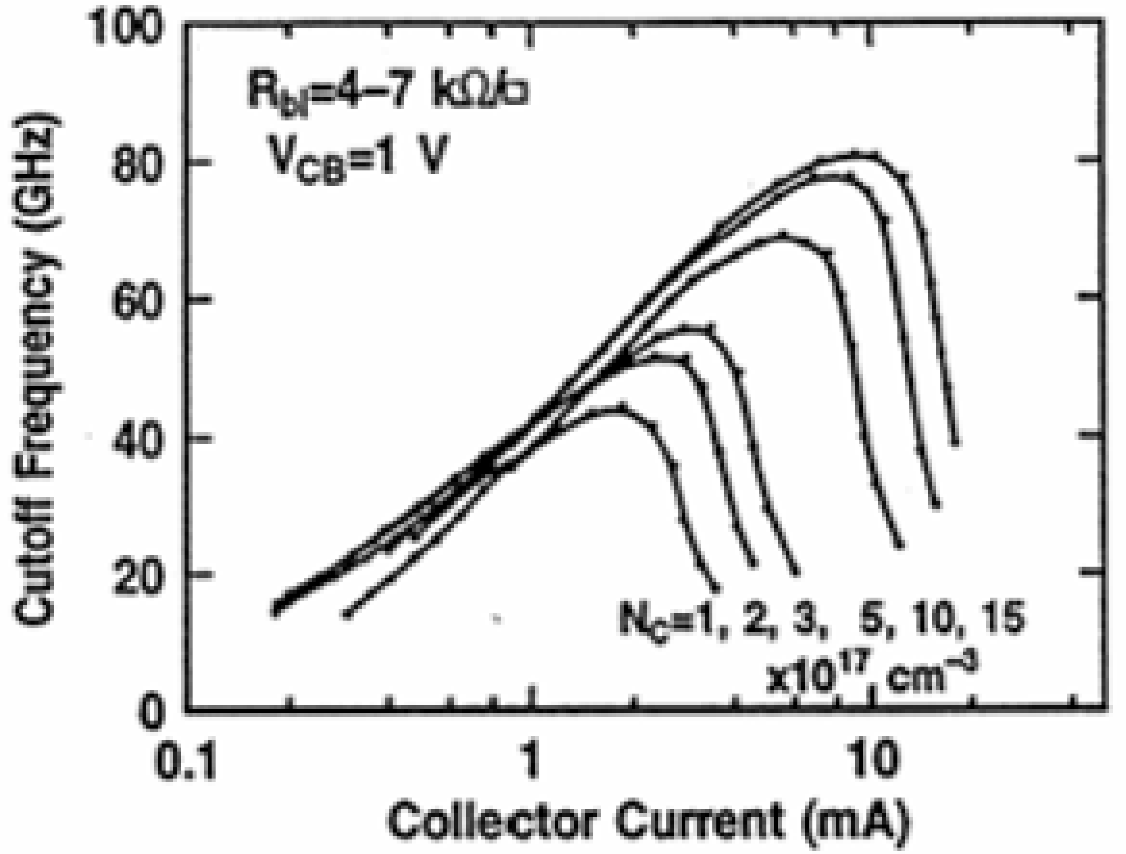




The current density Jck at which Ft peaks
is directly related to collector doping

$$\mathbf{Jck = q\, N_{DC}\, v_{sat}}$$

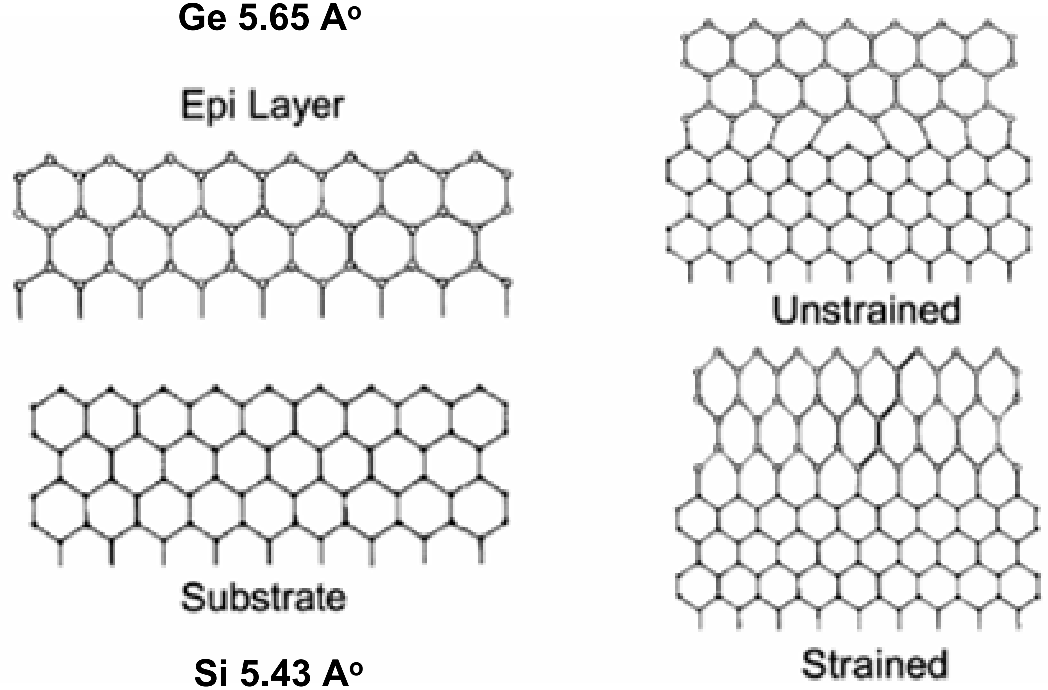
Collector Design: Effect of Collector doping on f_T



Important Properties of Semiconductors

Property	Ge	Si	GaAs	Units
Band gap	0.66	1.12	1.42	eV
Lattice Constant	5.65	5.43	5.65	A
Intrinsic concentration	2.40E13	1.45E10	1.79E6	cm-3
Electron Mobility	3900	1500	8500	cm2/V.sec
Hole mobility	1900	450	400	cm2/V.sec
Thermal conductivity	0.6	1.5	0.46	W/cm.C
Melting Point	937	1415	1238	deg C
Coeff of Expansion	5.8E-6	2.6E-6	6.9E-6	/ deg C

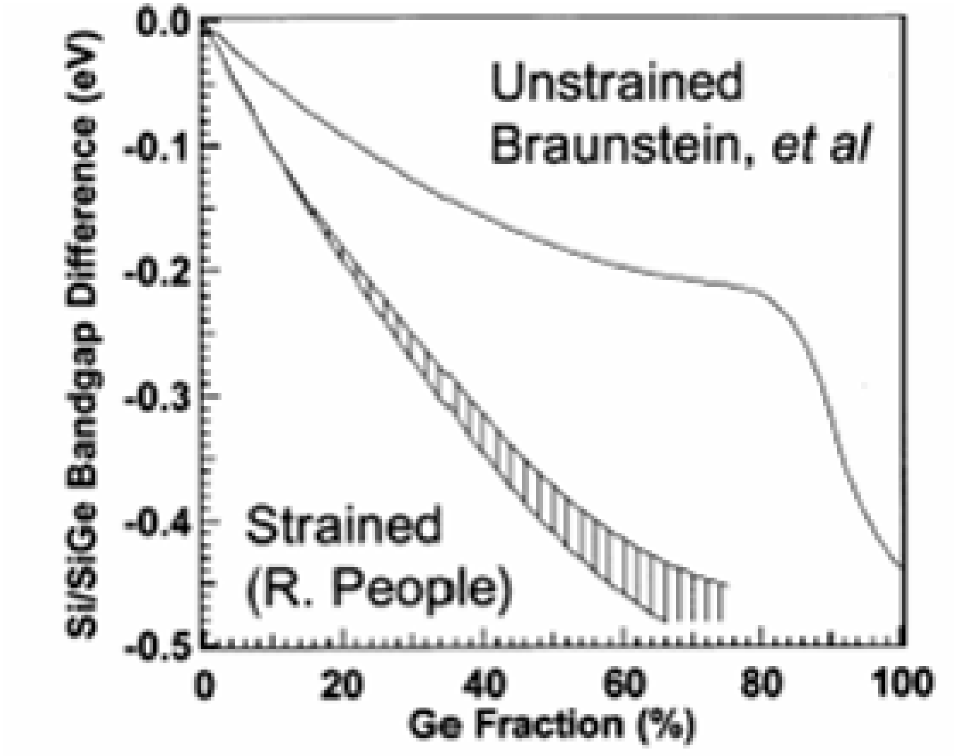
Strained Layer SiGe Epitaxy



Ge 5.65 A^o

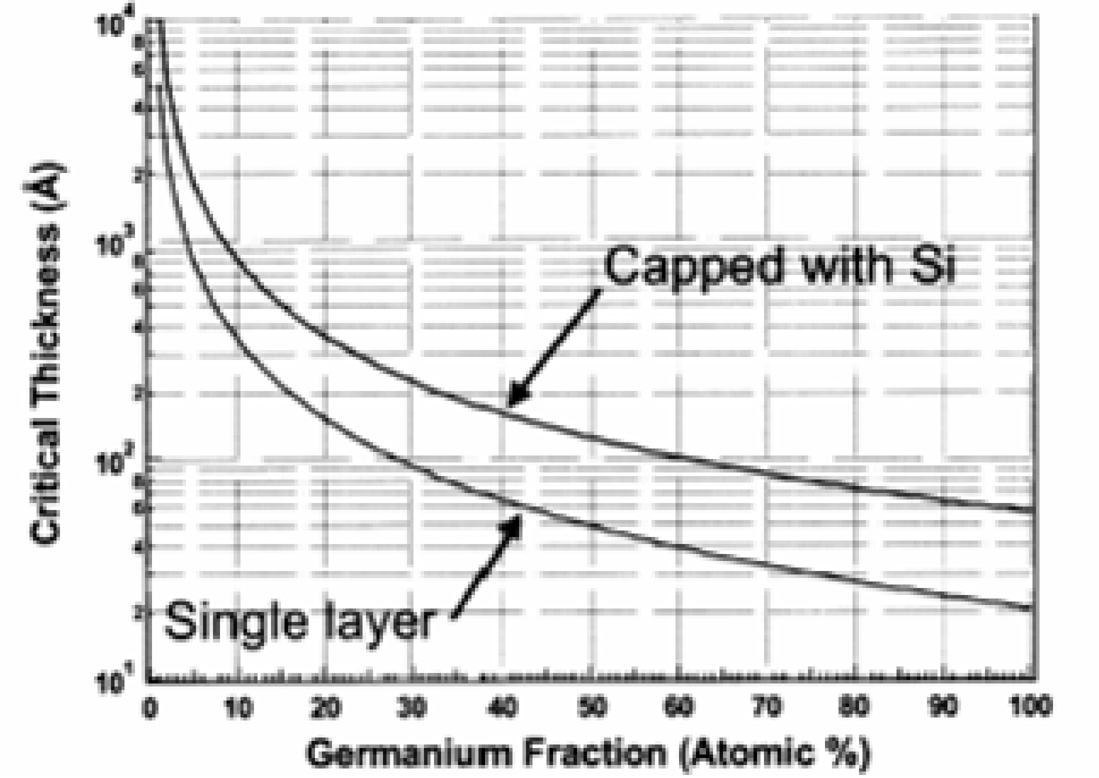
Si 5.43 A^o

Bandgap reduction as a function of Ge fraction



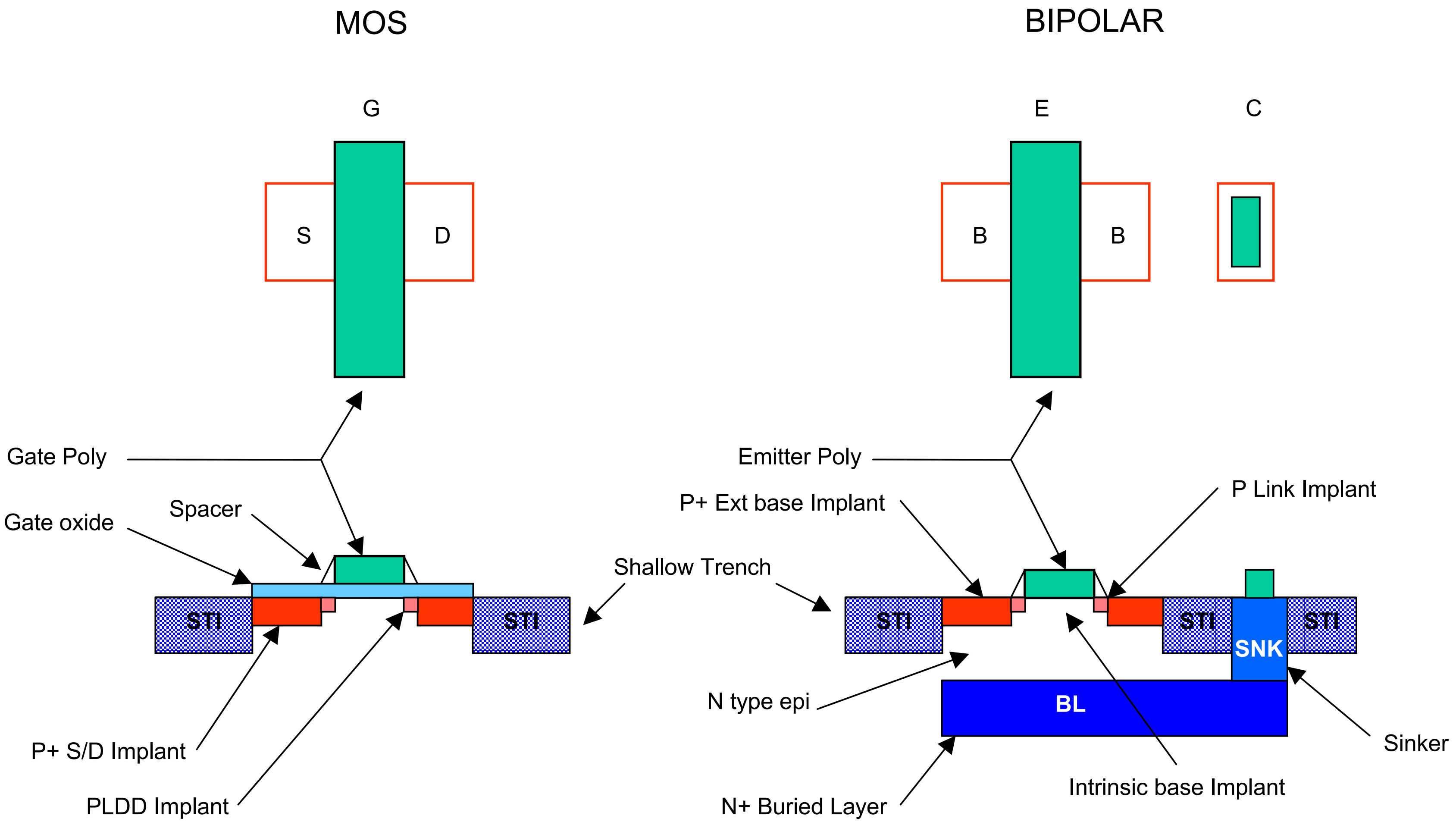
- Bandgap drops rapidly for strained SiGe
- Unstrained SiGe bandgap changes slowly with Ge fraction

Critical Layer thickness as a function of Ge fraction

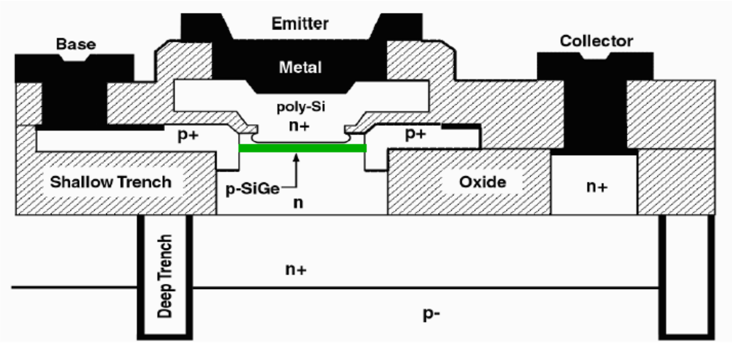


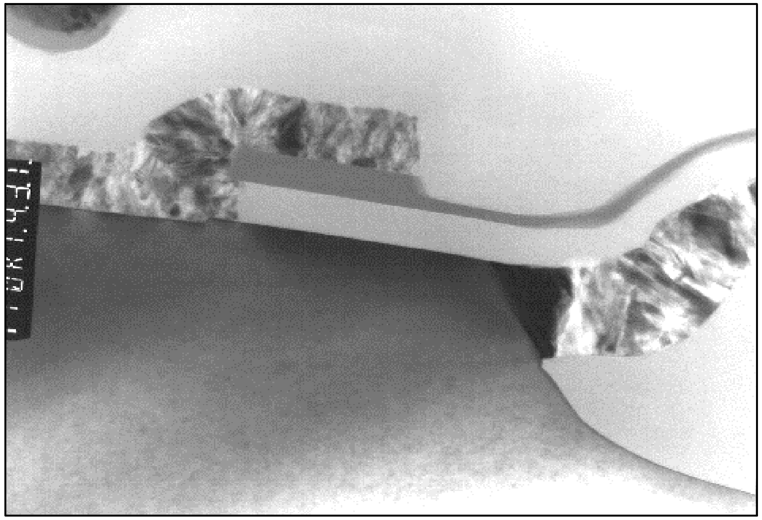
Adding a Si cap layer improves the stability of the SiGe film

Comparing MOS and Single Poly Bipolar



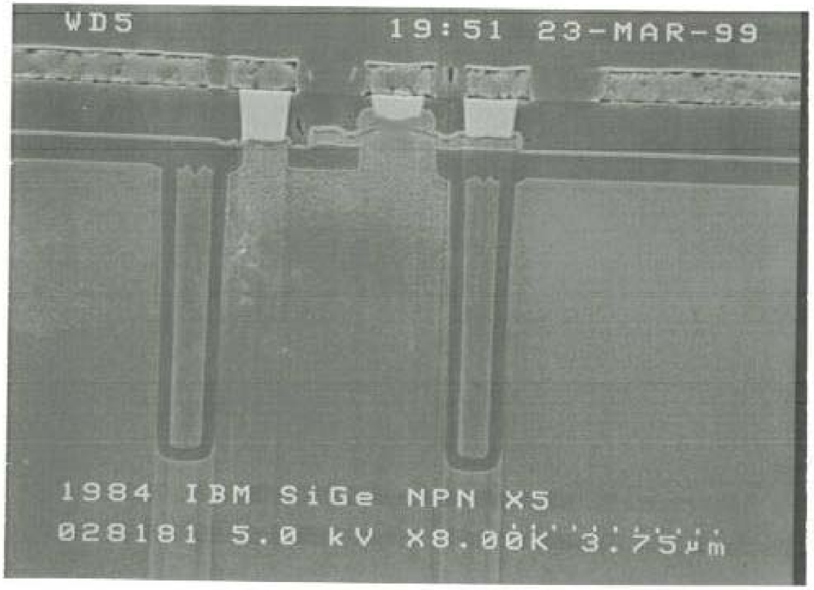
Non-selective SiGe base Transistor

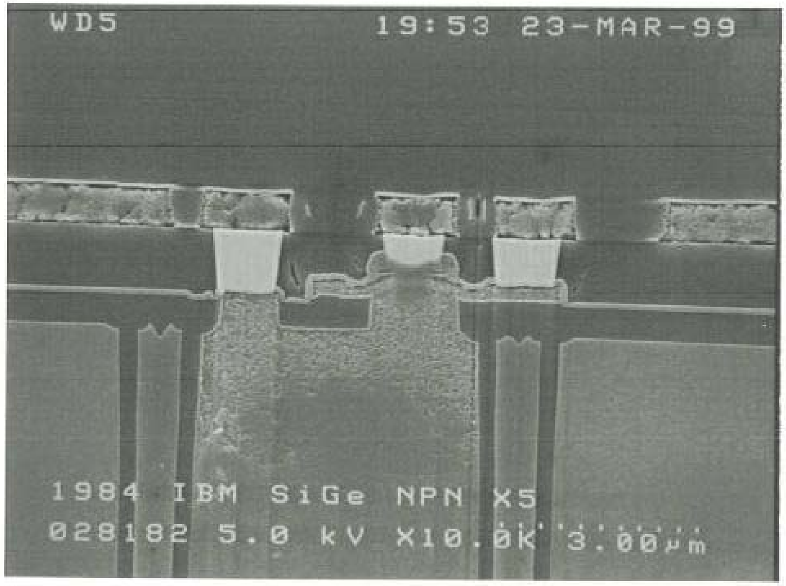




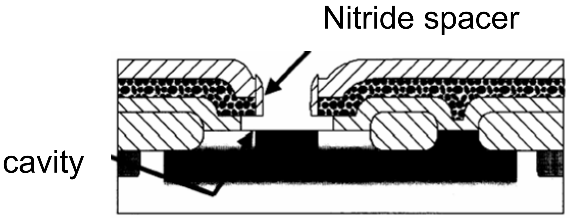
- SiGe film is deposited all over the wafer
- Needs ~100A seed layer to start on oxide
- Single crystal on silicon
- Poly on oxide
- Poly on oxide naturally contacts the base
- Poly can also be used as a resistor
- Needs Silane and Germane
- Simple process to run
- Dummy emitter needed for self-aligned devices

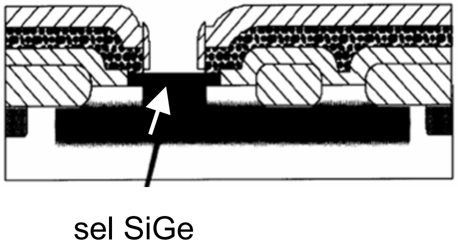
SEM Cross section of a SiGe Bipolar Transistor





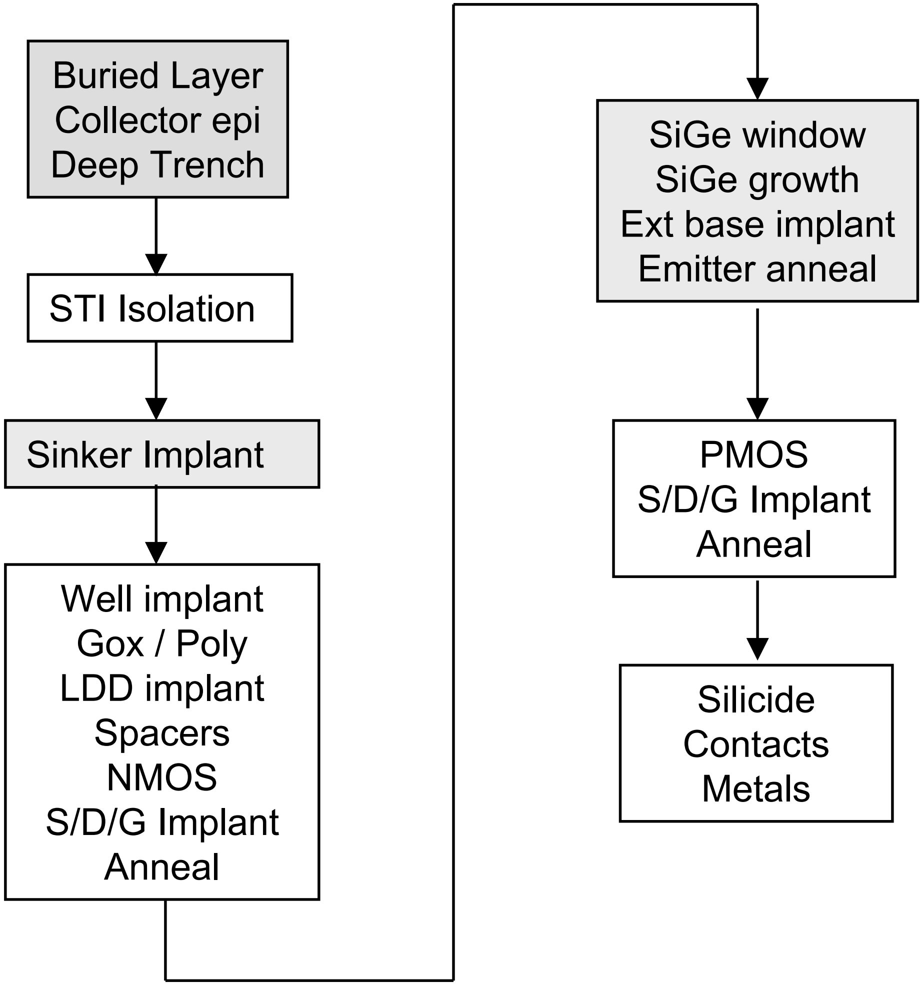
Selective SiGe base Transistor





- SiGe grows on exposed regions of the Si wafer
- Oxide is used as a mask
- No need for a seed layer
- Needs DCS, HCl and Germane
- Sensitive to exposed pattern density
- Low throughput
- Additional poly is needed to contact the base
- Integrates into an existing double poly process

SiGe BiCMOS Integration



Buried Layer
Collector epi
Deep Trench

STI Isolation

Sinker Implant

Well implant
Gox / Poly
LDD implant
Spacers
NMOS
S/D/G Implant
Anneal

SiGe window
SiGe growth
Ext base implant
Emitter anneal

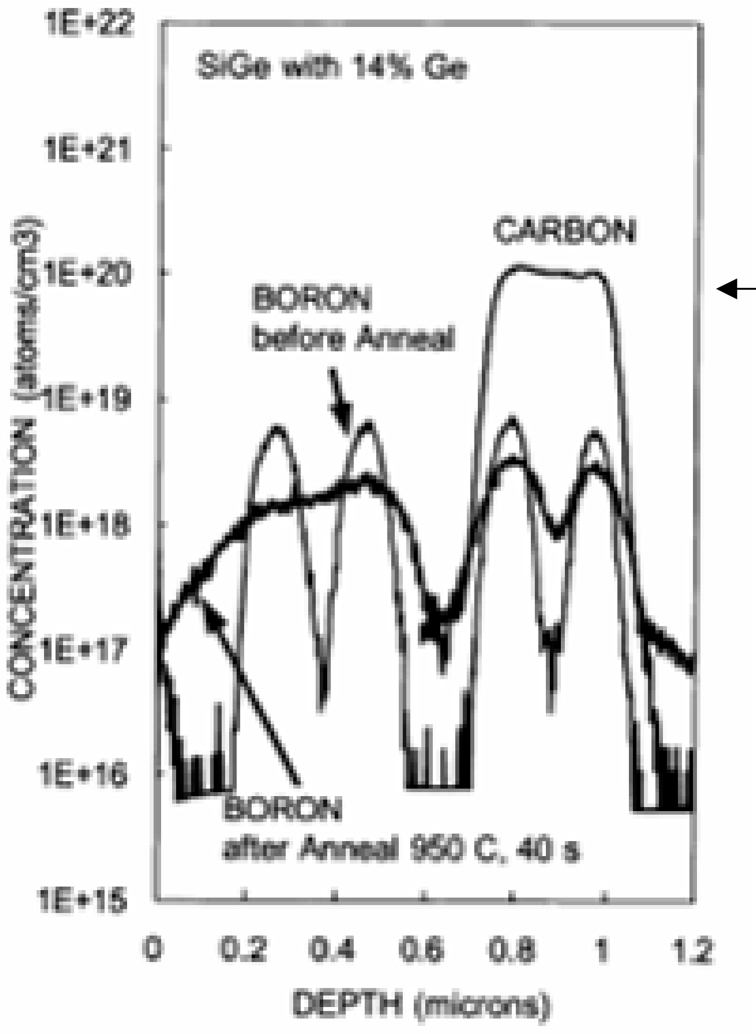
PMOS
S/D/G Implant
Anneal

Silicide
Contacts
Metals

Why add Carbon to SiGe base?

- The thin boron doped base diffuses during thermal processing widening the base and degrading the f_T
- B diffuses with an interstitial Si atom generated by unoptimized epi, oxidation, implantation etc.
- C can take on the interstitial Si sites suppressing B diffusion
- C being a smaller atom, the strain due to Ge can be reduced
- Less strain means less dislocations and less diffusion
- C has to be substitutional instead of interstitial
- Solubility of C in Si is low, some go into interstitial sites
- Substitutional C can be evaluated by XRD.

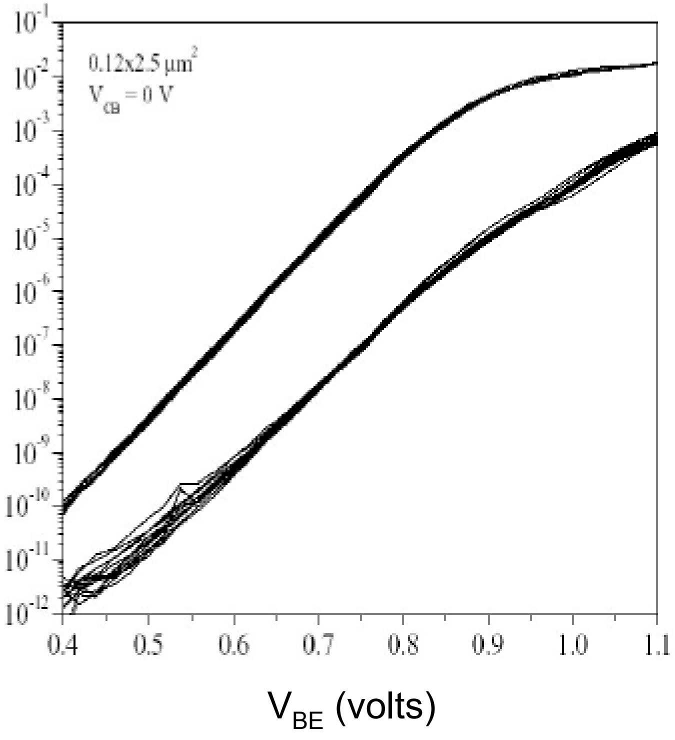
Effect of Carbon on Boron Diffusion



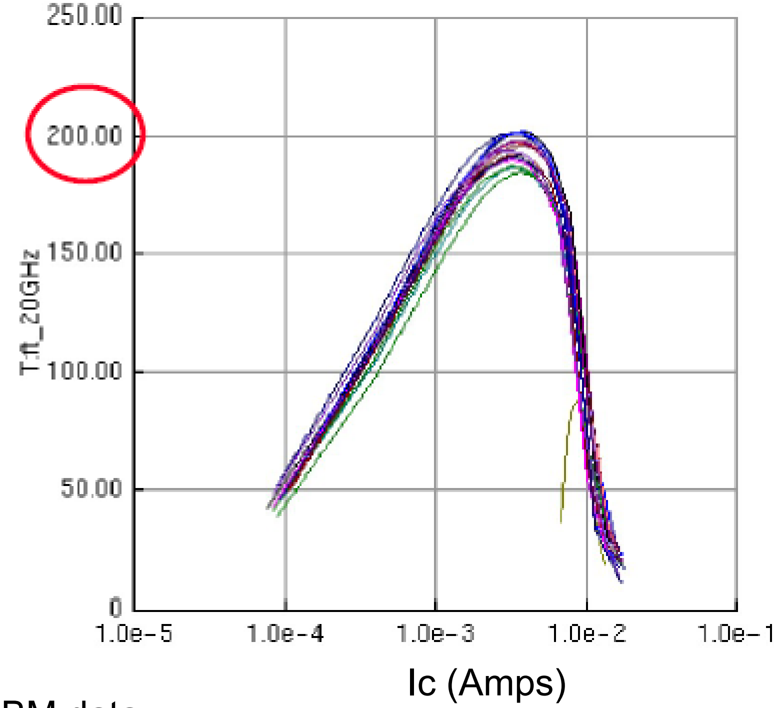
← 0.2% C

Uniformity of Device Results

Gummel (20 sites)



Cutoff Frequency (20 sites)



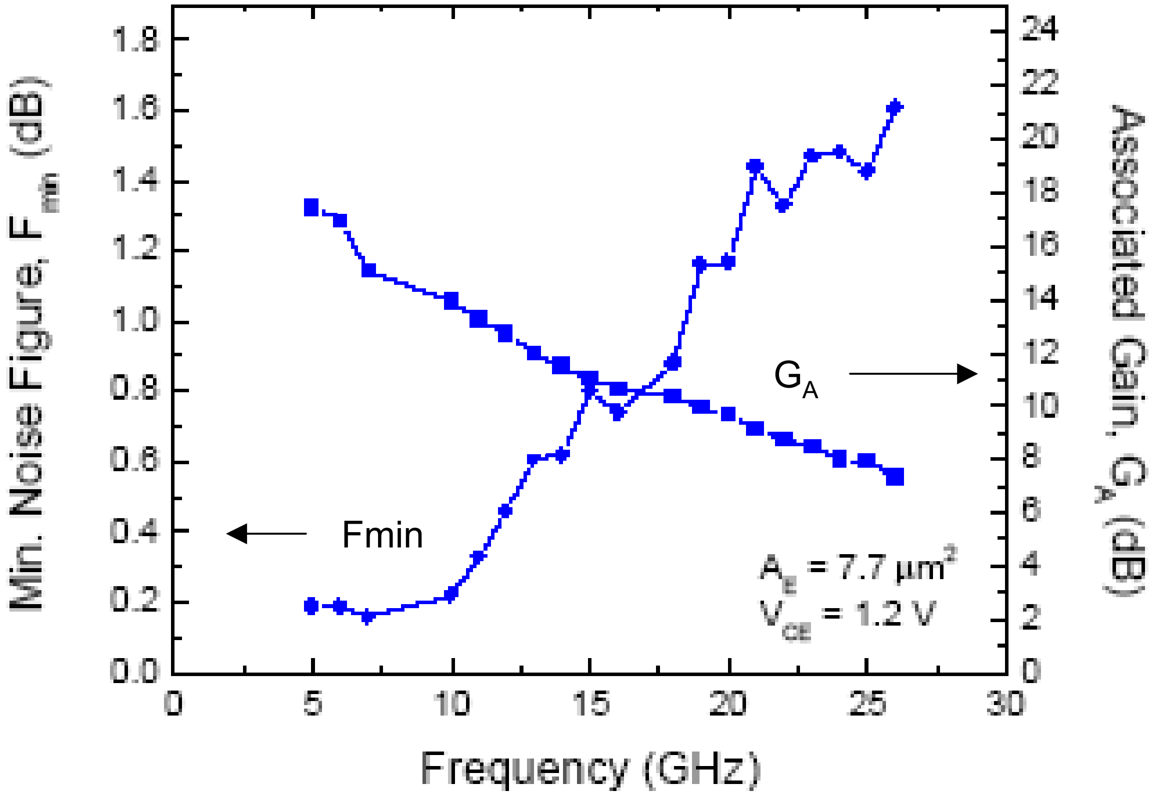
IBM data

Latest HBT device results

Material	Affiliation	f_T (GHz)	fmax (GHz)	t_{pd} (ps)	Reference
InP/InGaAs	Vitesse	325	325	1.95	EDL, p 520, Aug 2004
InP/InGaAs	HRL	406	423		IEDM, p 553, Dec 2004
InP/InGaAs	UIUC	550	255		IEDM, p 549, Dec 2004
InP/InGaAs	POSTECH, Korea	215	687		IEDM, p 557, Dec 2004
InP/InGaAs	UC, Santa Barbara	183#	165#		EDL, p 360, June 2004
InAlAs/InGaAs	UC, Santa Barbara	300	235		EDL, p 56, Feb 2001
InAlAs/InGaAs	UC, Santa Barbara	162*	820*		EDL, p 396, Aug 1999
InGaP/GaAs	Hitachi	156	255		TED, p 2625, Nov 2001
AlGaAs/GaAs	Rockwell	60	350		TED, p 2655, Nov 1992
Si/SiGe	Infineon	225	300	3.3	IEDM, p 255, Dec 2004
Si/SiGe	IHP, Germany	300	250	3.2	IEDM, p 251, Dec 2004
Si/SiGe	IBM	300	350	3.3	IEDM, p 247, Dec 2004
Si/SiGe	IBM	350	170	4.2	IEDM, p 771, Dec 2002

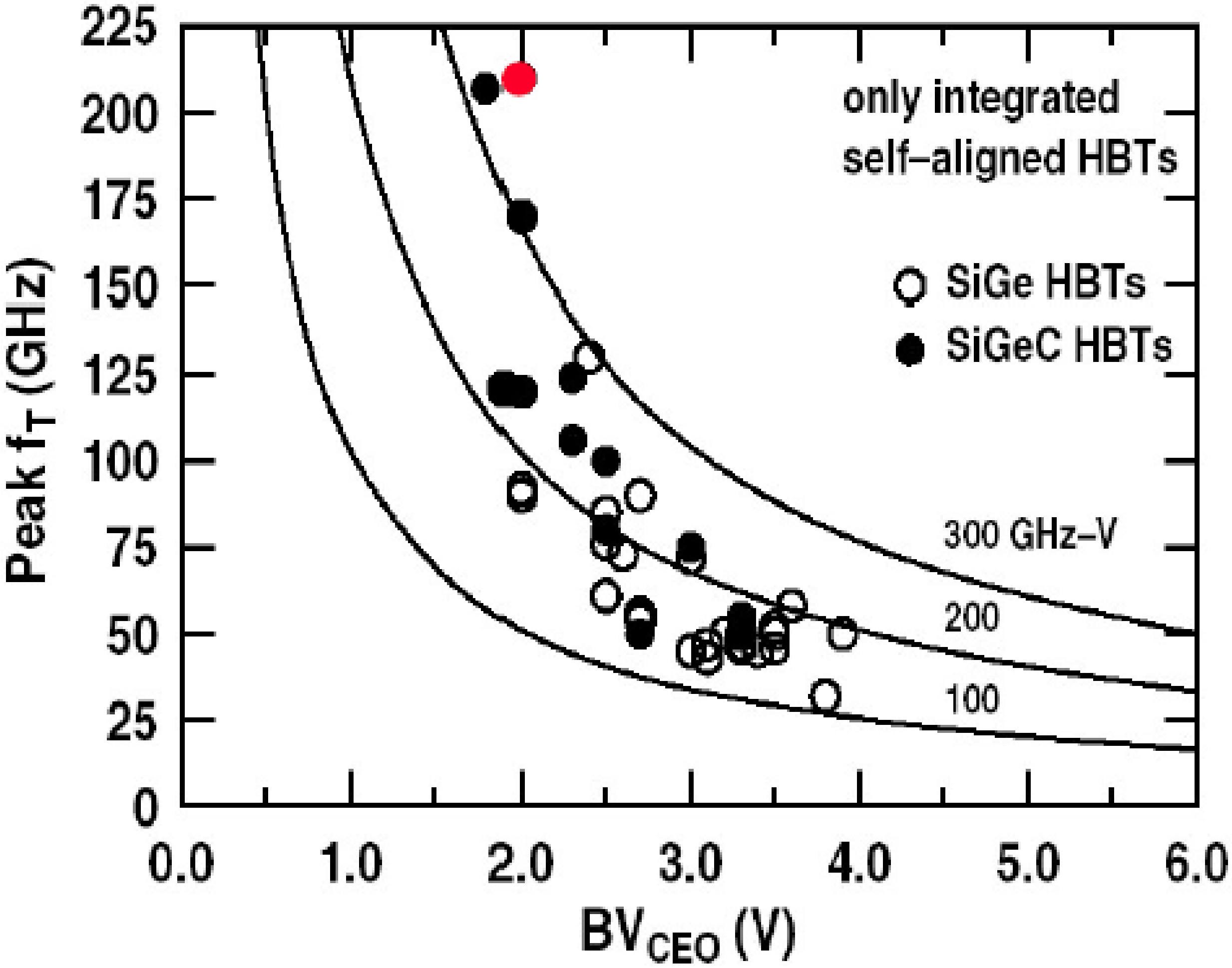
Re-grown emitter * transferred- substrate technology

SiGe HBT Noise Figure Data from IBM



Ft = 200GHz, Ae=0.12x64μ^2 Greenberg et al., IEDM 2002, pp. 787-790.

BVCEO – f_T Curve – Johnson Limit

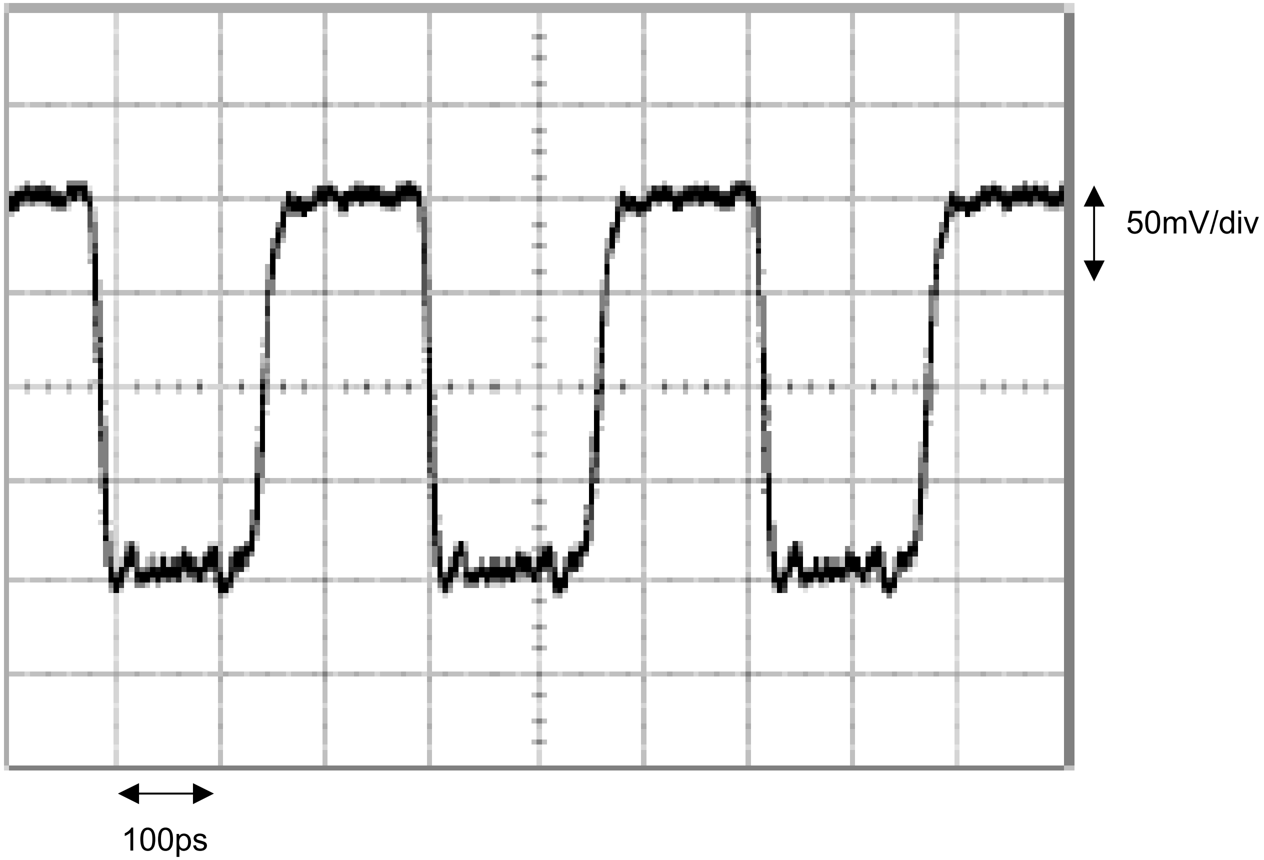


510GHzV
BV$_{CEO}$. Ft
product

High Speed HBT Frequency Dividers

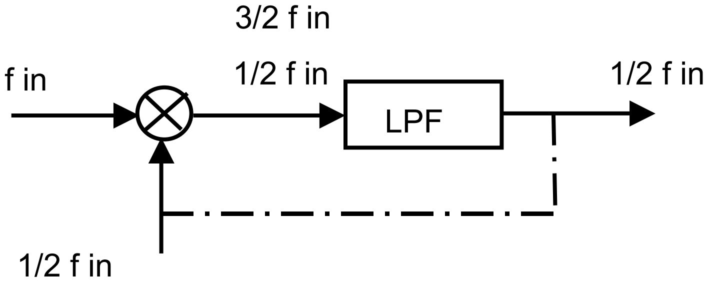
Material	Affiliation	f (GHz)	Type	Reference
InP/InGaAs	NTT	150	Dynamic	Tsunashima, p 284, GaAs IC, 2003
InP/InGaAs	Vitesse	152	Static	Gang He, p 520, EDL, Aug 2004
InP/InGaAs	Hughes	>100	Static	Mokhtari, p 1540, JSSC, Sep 2003
AlInAs/InGaAs	Hughes	72.8	Static	Sokolich, JSSC, pp 1328, Sep 2001
InGaP/GaAs	Hitachi	39.5	Static	Oka, p 2625, TED, Nov 2001
InGaP/GaAs	Tektronix	12.5	Static	Prasad, p 320, Elec Letters, Feb 1993
AlGaAs/GaAs	NTT	34.8	Static	Yamauchi, p 121, GaAs IC Symp, 1989
SiGe	Infineon	110.0	Dynamic	Meister, p 103, BCTM 2003
SiGe	Infineon	99.0	Dynamic	Bock, p 763, IEDM 2002
SiGe	Infineon	102.0	Static	Bock, p 255, IEDM 2004
SiGe	IBM	96.0	Static	Rylyakov, p 288, GaAs IC Symp, 2003
SiGe	Infineon	86.0	Static	Meister, p 103, BCTM 2003
SiGe	Hitachi	81.0	Static	Washio, p 767, IEDM 2002
CMOS 0.18μ	UCLA	40.0	Dynamic	Lee, p 594, JSSC, April 2004

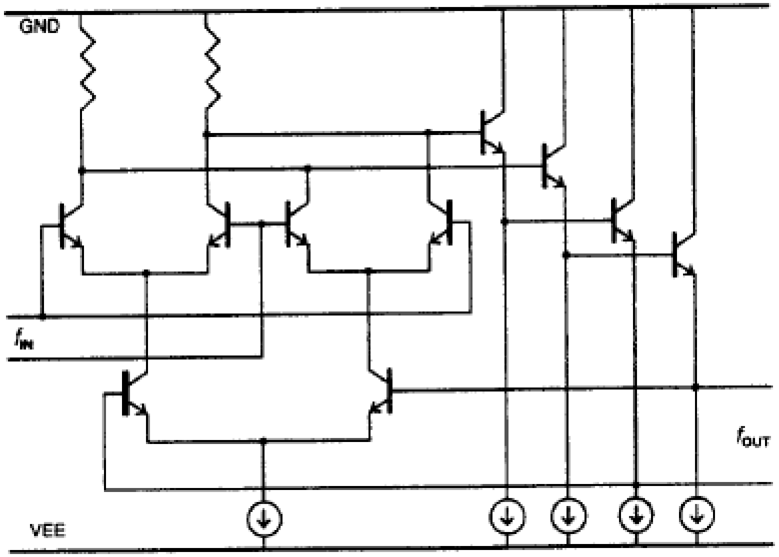
Infineon SiGe 1:32 Static Divider running at 102 GHz



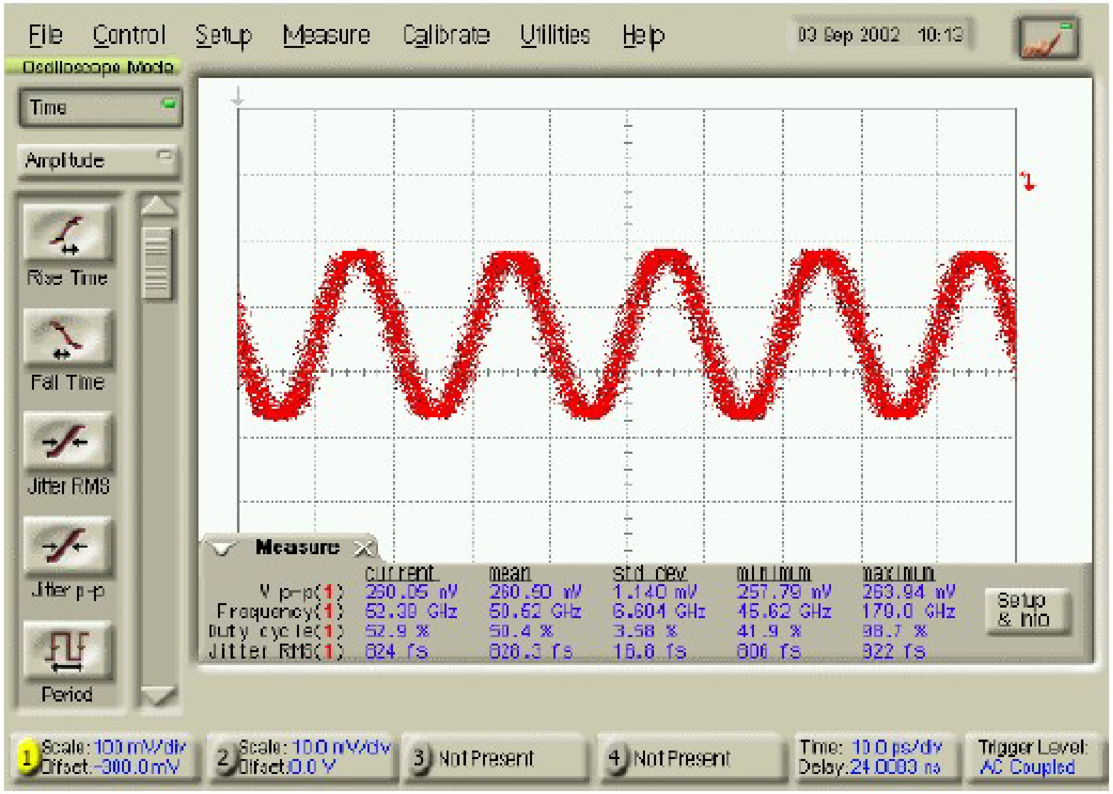
J. Bock et al., Infineon, 3.3ps SiGe technology, IEDM 2004. pp 255-258.

Principle of Dynamic Frequency Dividers





100GHz SiGe Dynamic Frequency Divider from IBM



	current	mean	std dev	minimum	maximum
V p-p(1)	260.05 mV	260.50 mV	1.140 mV	257.79 mV	263.94 mV
Frequency(1)	52.39 GHz	50.62 GHz	6.604 GHz	45.62 GHz	170.0 GHz
Duty cycle(1)	52.9 %	50.4 %	3.58 %	41.9 %	98.7 %
Jitter RMS(1)	824 fs	828.3 fs	16.8 fs	806 fs	922 fs

1 Scale: 100 mV/div Offset: -300.0 mV
2 Scale: 10.0 mV/div Offset: 0.0 V
3 Not Present
4 Not Present
Time: 10.0 ps/div Delay: 24.0083 ns
Trigger Level: AC Coupled

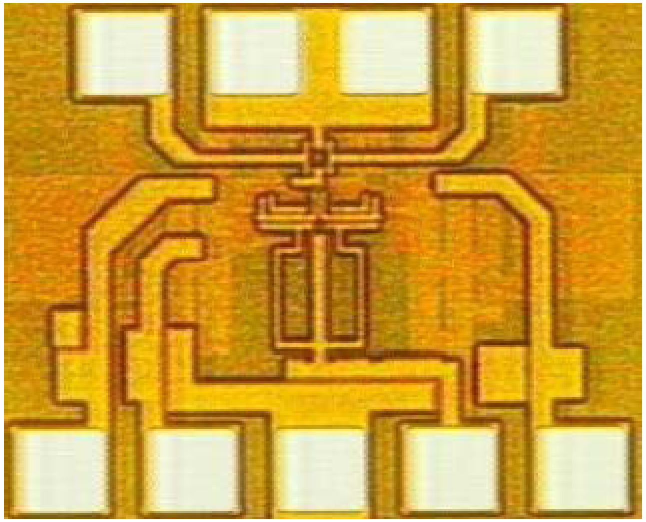
50GHz output. Vert: 100mV/div Hor: 10ps/div (200 HBTs) T-MTT Oct 2004, pp 2390-2408

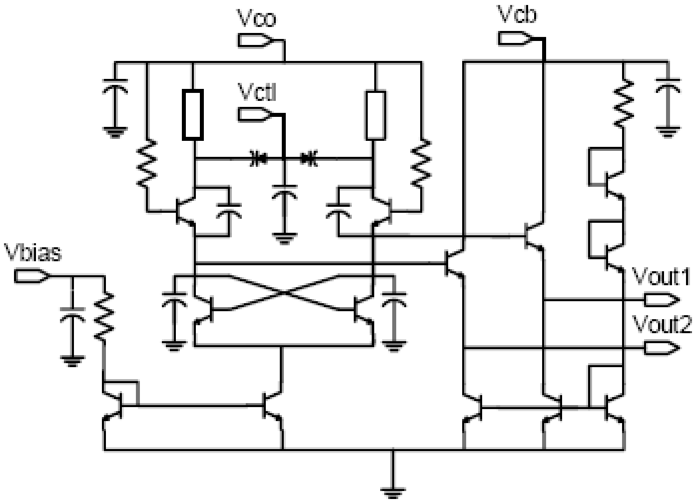
HBT Oscillators and VCOs

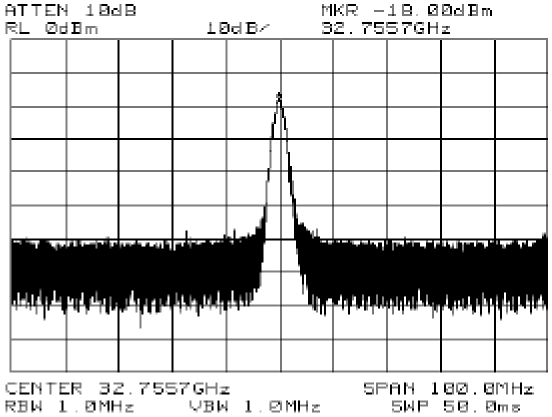
Material	Type	Affiliation	f (GHz)	L(f) dBc/Hz	f offset (MHz)	Reference
InGaP/InGaAs	Osc	Teratec	134	72	1	Uchida, p 237, GaAs IC 1999
InGaP/GaAs	VCO	FBIH	34.2	108	1	Hilsenbeck, p 223, GaAs IC 2003
InGaP/GaAs	VCO	KAIST	22.3	108	1	Kim, p 478, MWCLett. Nov 2003
InGaP/GaAs	YIG osc	Tektronix	7.8	135	1	Prasad, p 87, MTT-S, May 1994
InP/InGaAs	VCO	TRW	62.4	104	1	Wang, p 388, MGWLett., 1995.
SiGe	VCO	Infineon	98.0	97	1	Perndl, p 67, BCTM 2003
SiGe	VCO	IHP	76.0	-	-	Winkler, p 454, ISSCC 2003
SiGe	VCO	RUB	46.9	108.5	1	Li, p.184, JSSC, Feb 2003
CMOS 0.12μ	VCO	Infineon	51.0	85	1	Tiebout, p 372, ISSCC, 2002

33GHz SiGe Voltage Controlled Oscillator

Ka-Band VCO







IBM SiGe 8T Technology (200 GHz)

33 GHz center frequency

3.7 mW power dissipation

-100 dBc phase noise (1 MHz)

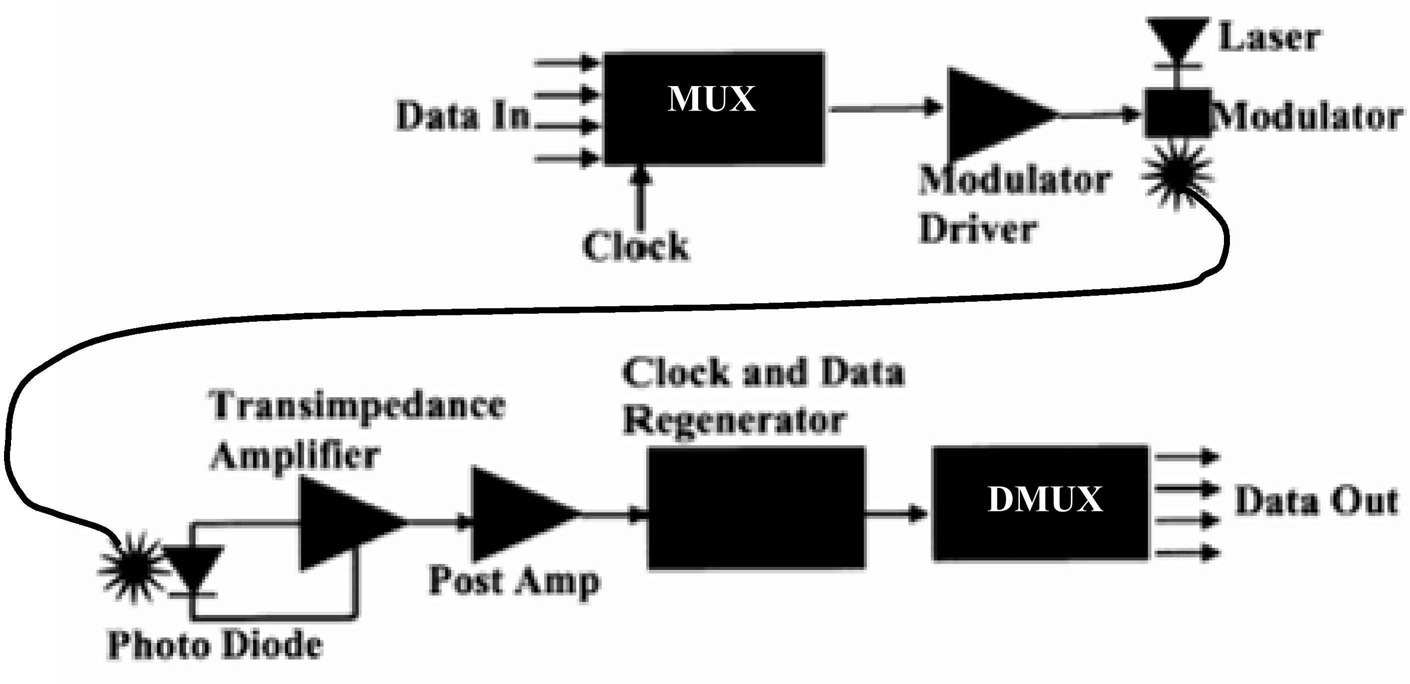
HBT Power Transistors and Amplifiers

Material	Type	Affiliation	f (GHz)	Pout (dBm)	Gain dB	PAE %	Reference
InGaP/GaAs	Power HBT	FBIH	2	41	14	71	Kurpas, p 561, IEDM 2004
InGaP/GaAs	Power HBT	TI	3	31.8	7	52	Liu, p.215, EDL, June 1994
InGaP/GaAs	Power Amp	Sharp	60	13.0	15	-	Handa, p.227, GaAs IC, 2003
InGaP/GaAs	WCDMA pa	KAIST	1.9	28	28	40	Kim, p 905, JSSC, June 2003
InGaP/GaAs	IS95B PA	Skyworks	0.837	28	27	40	Yang, p 1455, T- MTT, May 2004
AlGaAs/GaAs	Power HBT	Mitsubishi	12	30	6	72	Shimura, p 1890, TED, Nov 1995
SiGe	Power HBT	Northrop	2.8	53.6	6.9	46	Potyraj, p 2392, T-MTT, Nov 1996
SiGe (44GHz)	Power Amp	Skyworks	1.88	28	21.8	35	Nellis, p1751, JSSC, Oct 2004
InGaP 46GHz	Power Amp	Skyworks	1.88	28	27.1	39.3	Nellis, p1751, JSSC, Oct 2004
Si (27GHz)	Power Amp	Skyworks	1.88	28	22.1	33.1	Nellis, p1751, JSSC, Oct 2004
SiGe	PA	Infineon	7-18	17.5	14	11	Bakalski, p 61, BCTM 2003
SiGe 200GHz	PA Vcc=1.1	IBM	20	8	12	36	Pan, p 209, BCTM 2004

HBT Low Noise Amplifiers

Material	Type	Affiliation	f (GHz)	Gain dB	NF dB	Reference
InP/InGaAs	Wideband Amp	UCSB	140-220	8.5		Urteaga, p 1452, JSSC, Sep 2003
SiGe	VG LNA	ETH	16	14.5	3.8	Ellinger, p 702, Trans. MTT, Feb 2004
SiGe	LNA	STMicro	8.2	22	1.6	Gramegna, p 49, BCTM 2003
SiGe	DA LNA	UIUC	0.1-23	14.5	6	He, p 956, JSSC, June 2004
CMOS 0.18m	LNA	UCLA	24	12.9	5.6	K.Yu, p 106, MWCLett., March 2004

Block Diagram of a Fiber Optic Communication System



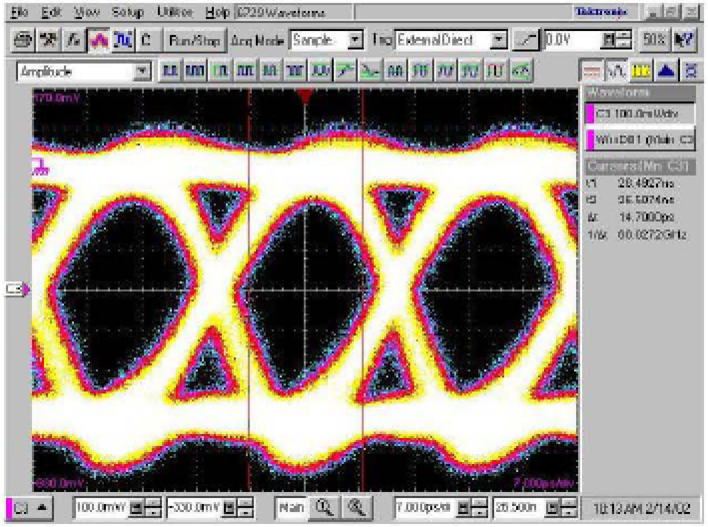
HBT Digital Communication Circuits

Material	Circuit	Affiliation	Speed (Gb/sec)	Reference
InP/InGaAs	4:1 MUX/DMUX	NTT	40.0	Ishii, MWCLett., p 2181, Nov 2003
InP/InGaAs	CDR/DMUX	Inphi	43.2	Nielsen, JSSC, p 2341, Dec 2003
InP/InGaAs	16:1 MUX	Vitesse	40.0	Hendarman, JSSC, p 1497, Sep 2003
InP/InGaAs	TIA	Vitesse	40.0	C.Wu, JSSC, p 1518, Sep 2003
SiGe	4:1MUX	IBM	70.0	Rieh, JSSC, p 2390, Oct 2004
SiGe	4:1 MUX/DMUX	IBM	50.0	Meghelli, JSSC, p 1790, Dec 2002
SiGe	CDR- Rx/Tx	IBM	43.0	Meghelli, JSSC, p 2147, Dec 2003
SiGe	TIA	Lucent	40.0	Weiner, JSSC, p 1512, Sep 2003
Si bipolar	2:I MUX	Siemens	50.0	Felder, JSSC, p 481, April 1996
CMOS 0.12μ	2:1 MUX/DMUX	Infineon	40.0	Kehrer, JSSC, p 1830, Nov 2003
CMOS 0.18μ	CDR/ 1:4 DMUX	UCLA	40.0	J. Lee, JSSC, p 2181, Dec 2003

OC768 40Gb/s 16:1 MUX and 1:16 DMUX

Packaged 16:1 MUX and 1:16 DeMux devices

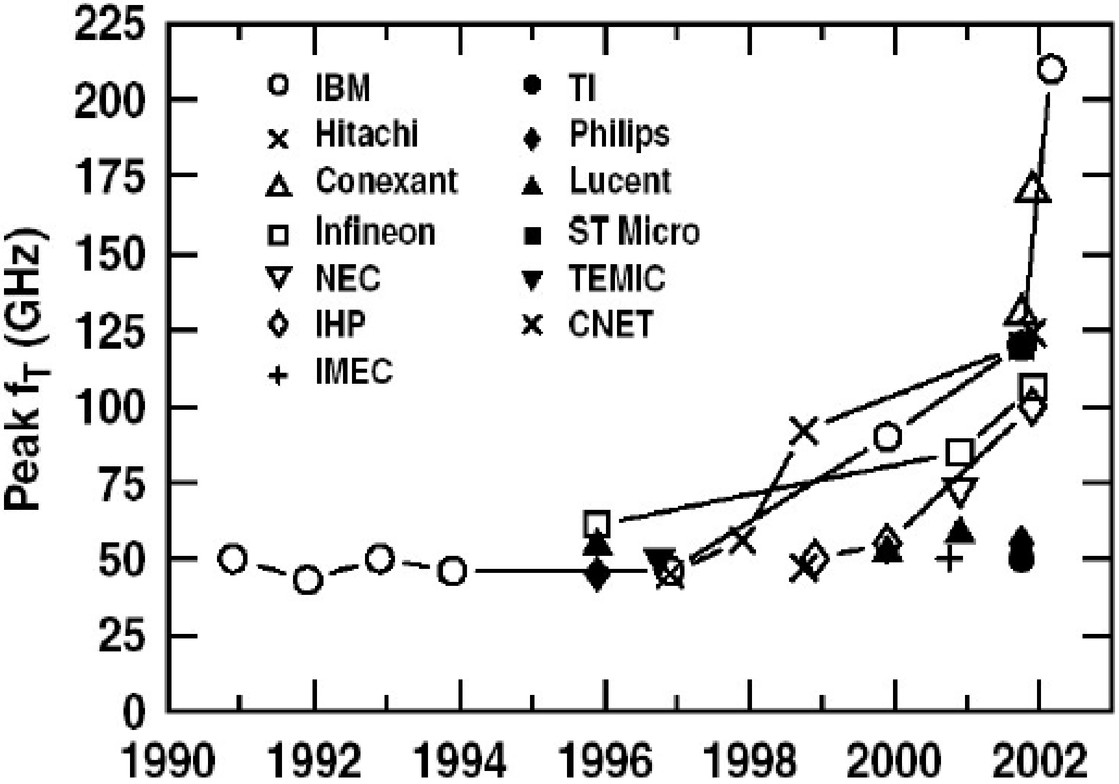
S76801CV 16:1 Mux output (43G PRBS 2^31)



Cursors (Mn C3)
t1 28.4927ns
t2 28.5074ns
Δt 14.7000ps
1/Δt 68.0272GHz

120 GHz SiGe HBTs

A sampling of some of the SiGe HBT players



Almost every company is working on SiGe!
For the fabless ones, foundry services are available from IBM, Jazz, TSMC etc.

Conclusion

- Presented the SiGe device physics
- Discussed SiGe material properties
- Integration of SiGe into bipolar/BiCMOS
- Showed device results
- Talked about circuit applications
- Demonstrated the future potential of SiGe