超高速半导体器件与集成电路发展与展望

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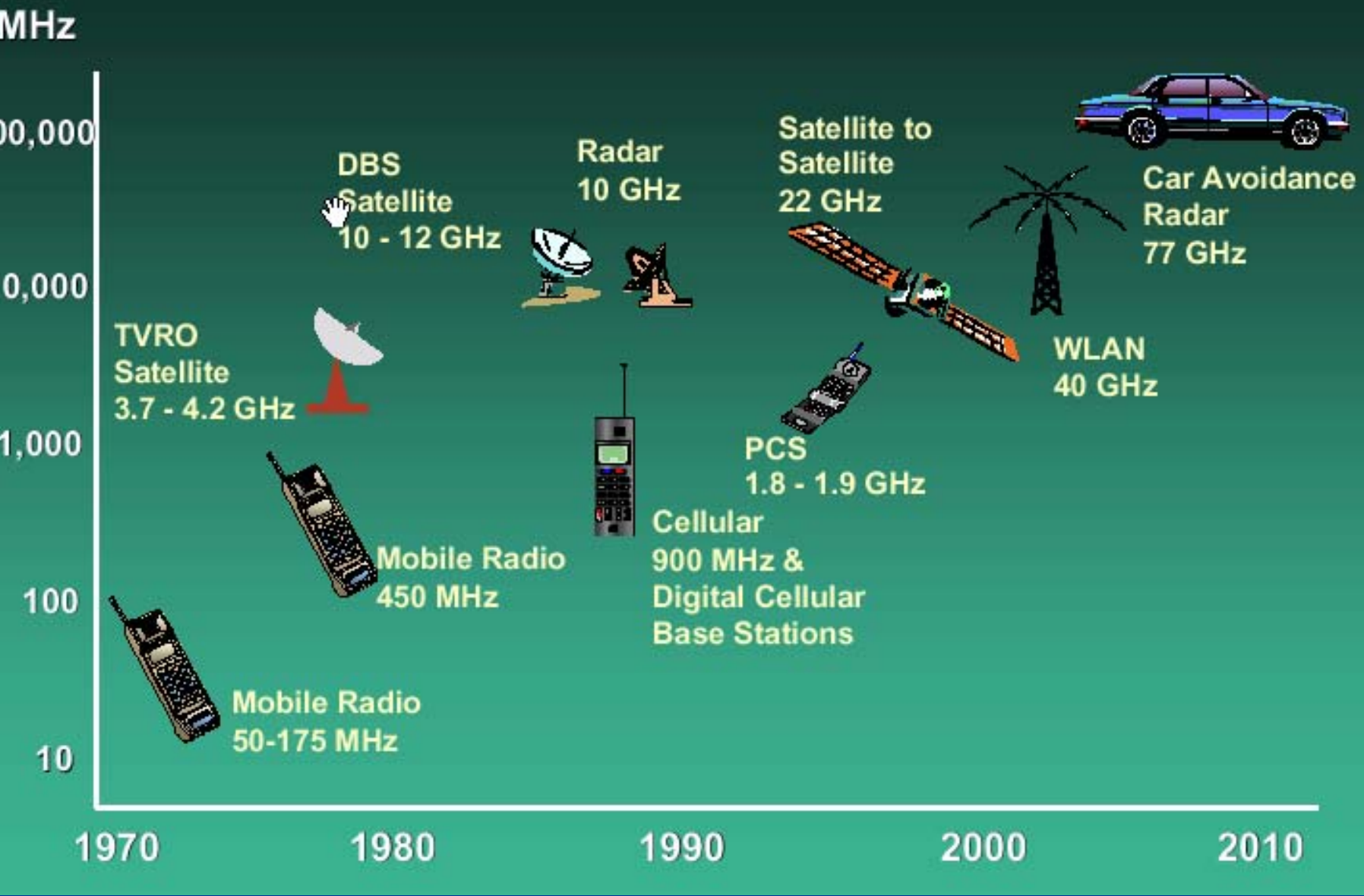
宽禁带半导体材料与器件重点实验室

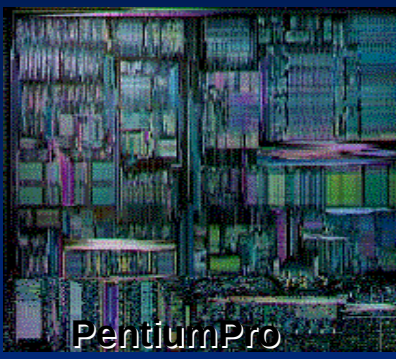
2007年10月11日

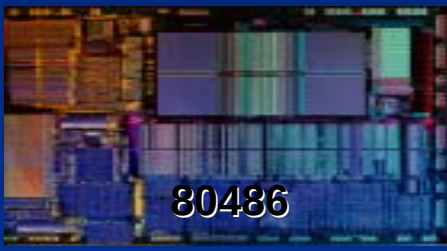
时代
无线通信构建
卫星导航
Broadband · Single · Dual · T
信基站
Anycall
CHINA MOBILE
蓝牙耳机
个人通信


MHz
00,000
0,000
1,000
100
10
1970
1980
1990
2000
2010
DBS
Satellite
10 - 12 GHz
Radar
10 GHz
Satellite to
Satellite
22 GHz
Car Avoidance
Radar
77 GHz
TVRO
Satellite
3.7 - 4.2 GHz
WLAN
40 GHz
PCS
1.8 - 1.9 GHz
Mobile Radio
450 MHz
Cellular
900 MHz &
Digital Cellular
Base Stations
Mobile Radio
50-175 MHz

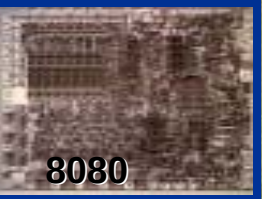
半导体器件与集成电路发展追求的目标

- Â 高速度
- Â 高密度
- Â 高可靠
- Â 低功耗

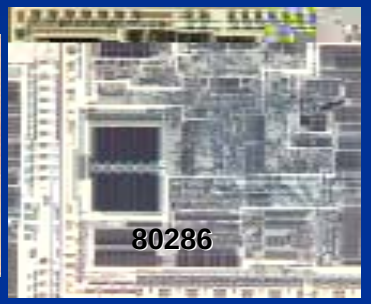




1200 k trans

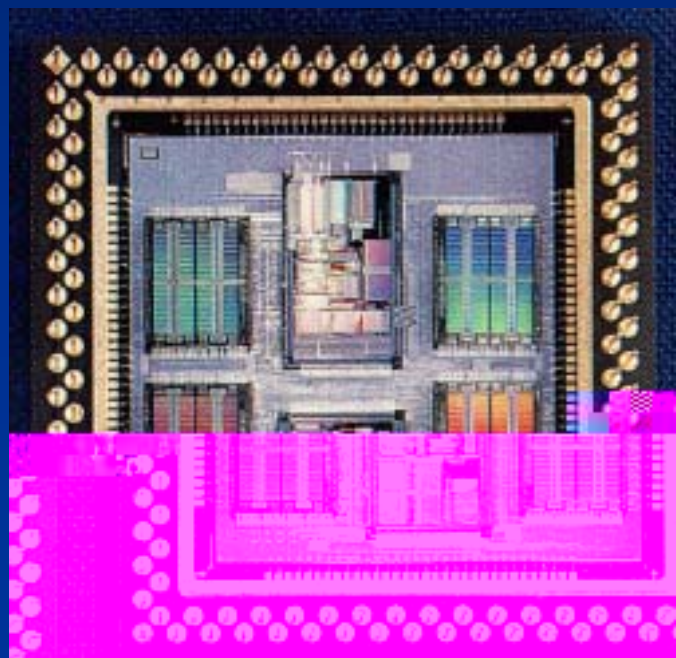


29 k trans



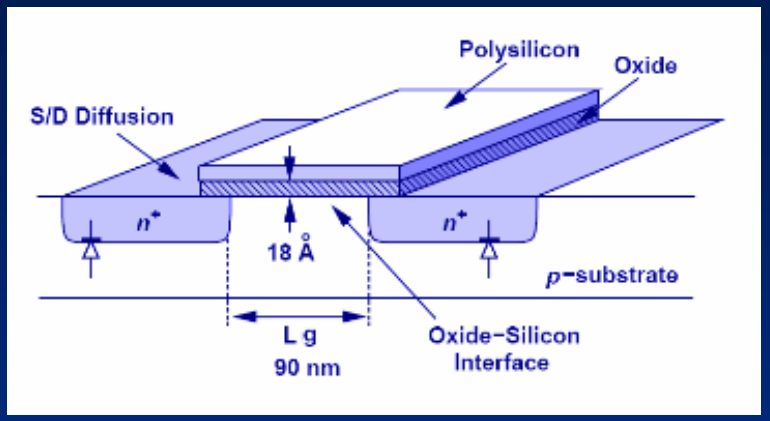
超高速器件和电路实现途径和方法

- 依靠特征尺寸的缩小
- 依靠设计技术的发展
- 依靠器件结构的变革
- 以靠新型材料的进步



(一) 依靠特征尺寸的缩小
提高器件和电路的速度

MOSFET的工作速度



- 在半导体器件中,电子在电场作用下的运动速度 v_d :

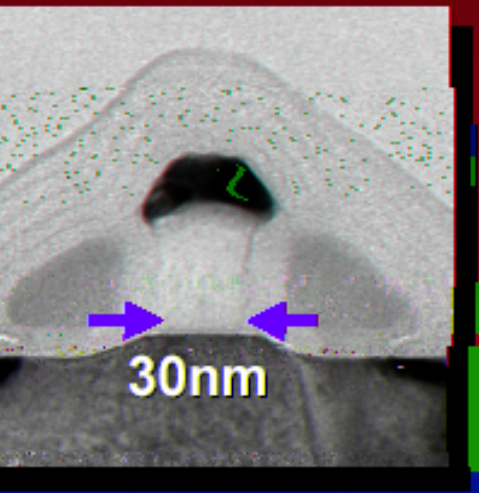
$$v_d = \mu_n E = \frac{\mu_n V_{ds}}{L_G}$$

- MOS器件的特征频率f_T:

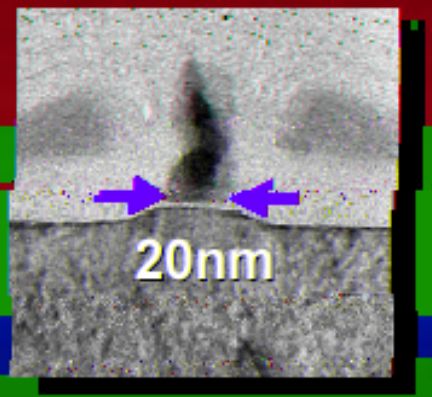
$$f_T \approx \frac{v_d}{2\pi L_G} = \frac{\mu_n V_{ds}}{2\pi L_G^2}$$

Intel's Transistor Research in Deep Nanotechnology Space

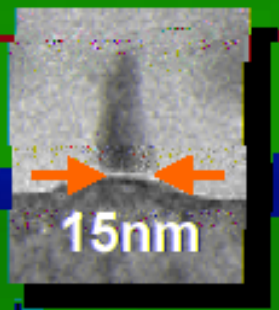
Experimental transistors for future process generations



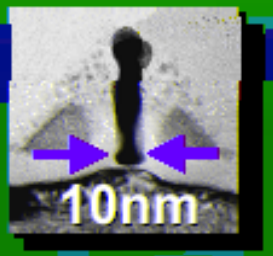
65nm process
2005 production



45nm process
2007 production



32nm process
2009 production

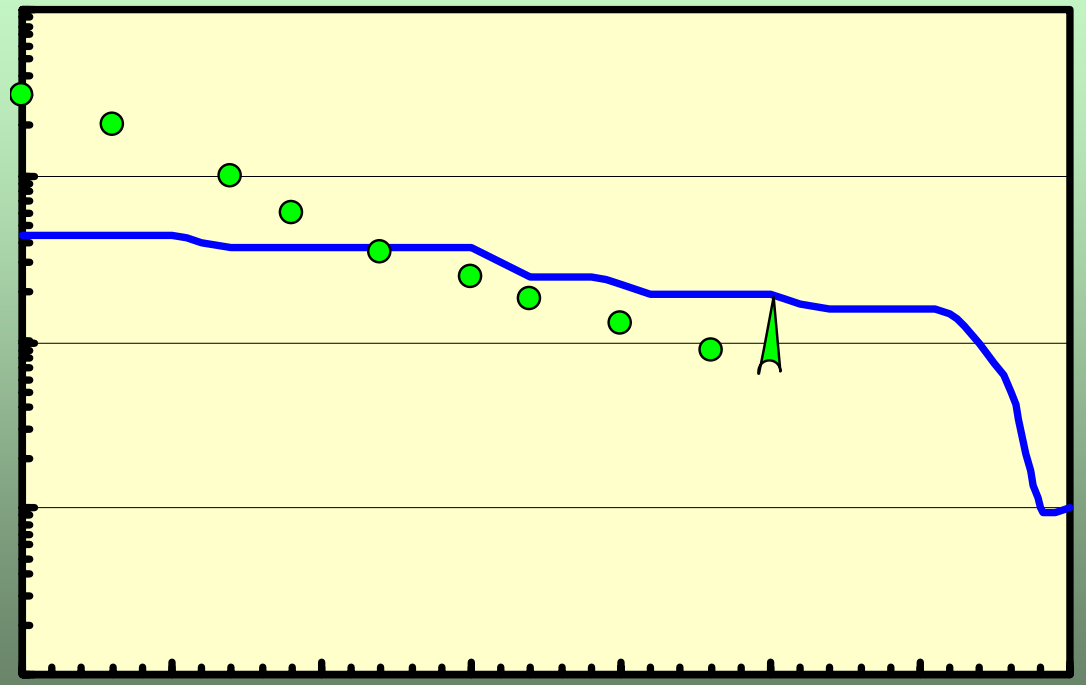


2011 production

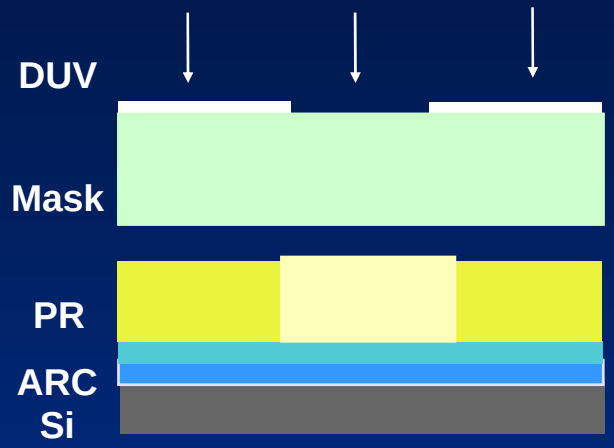
Transistors will be improved for production

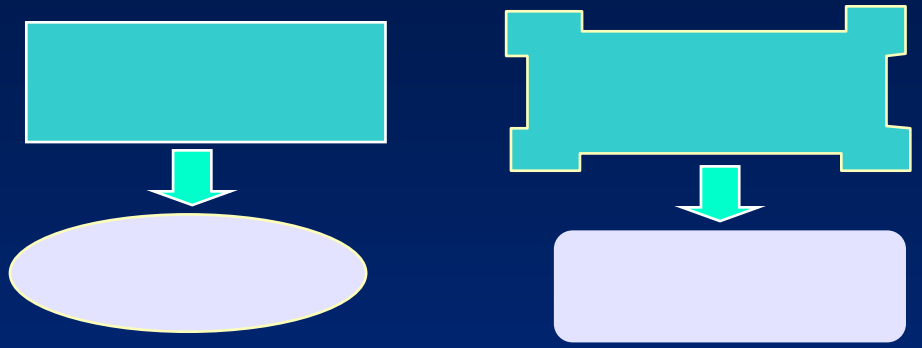
© Michael Garner Sept 16, 2003

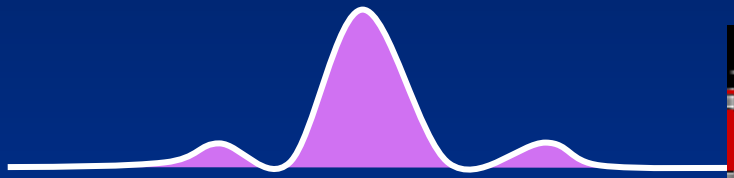
The Lithography light source wave length and Print image feature dimension



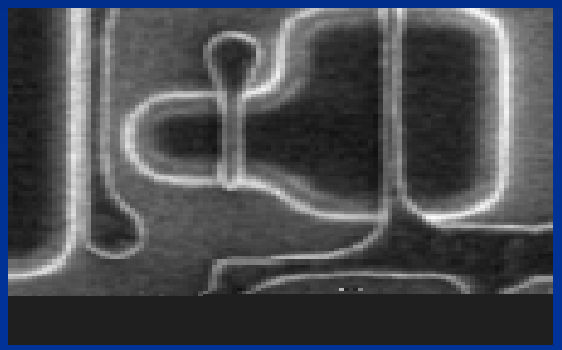
Lithography: phase shift, OPC







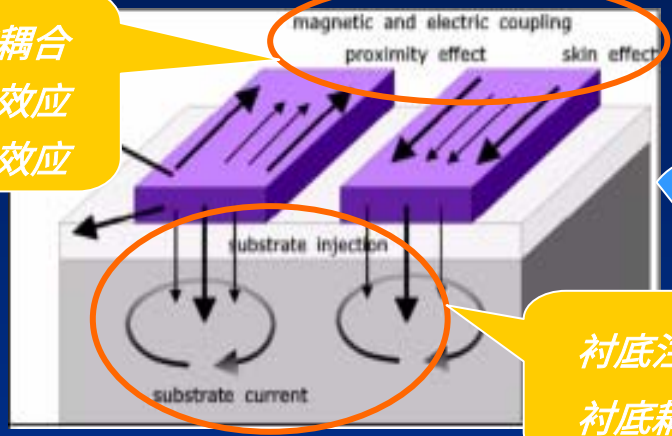
Optical proximity correction (OPC),
Rule based and model based



互连问题严重

在射频下，片上互电磁效应显著。

No single tool is able to solve all.



电磁耦合
邻近效应
趋肤效应

衬底注入
衬底耦合

2 & 3-D Field Solvers

Transmission Lines

RLC

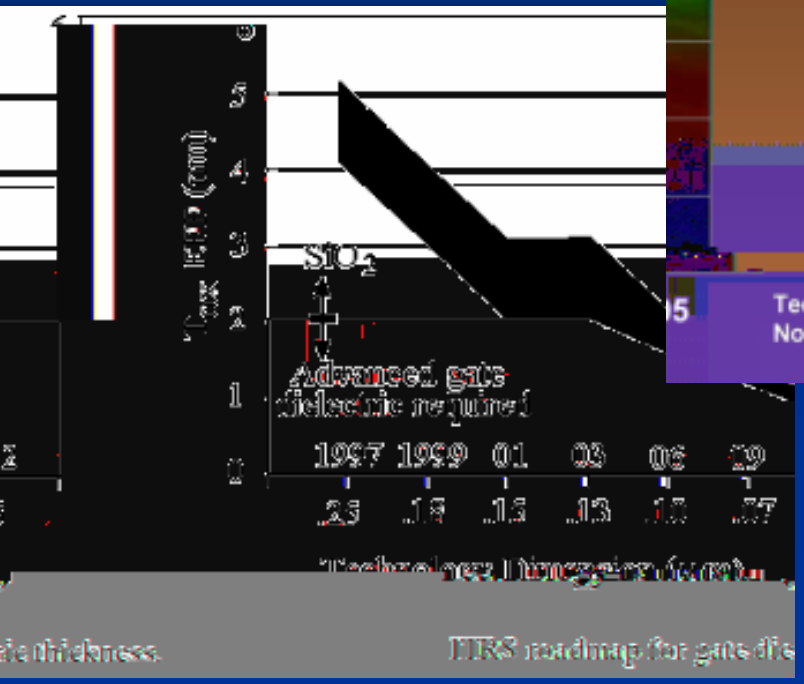
Solution Complexity

Speed-down

Accuracy

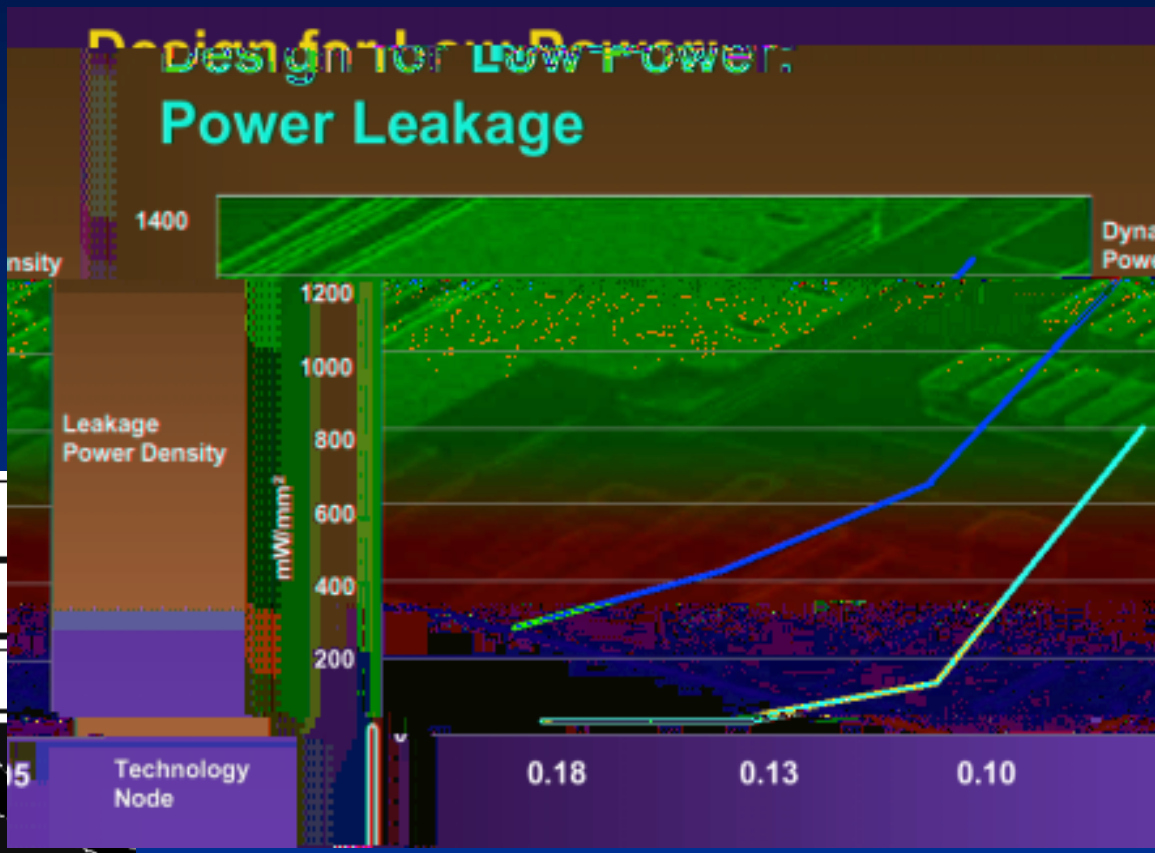
DC 10.0 40.0 100 200 GHz

栅氧厚度和静态漏电问题

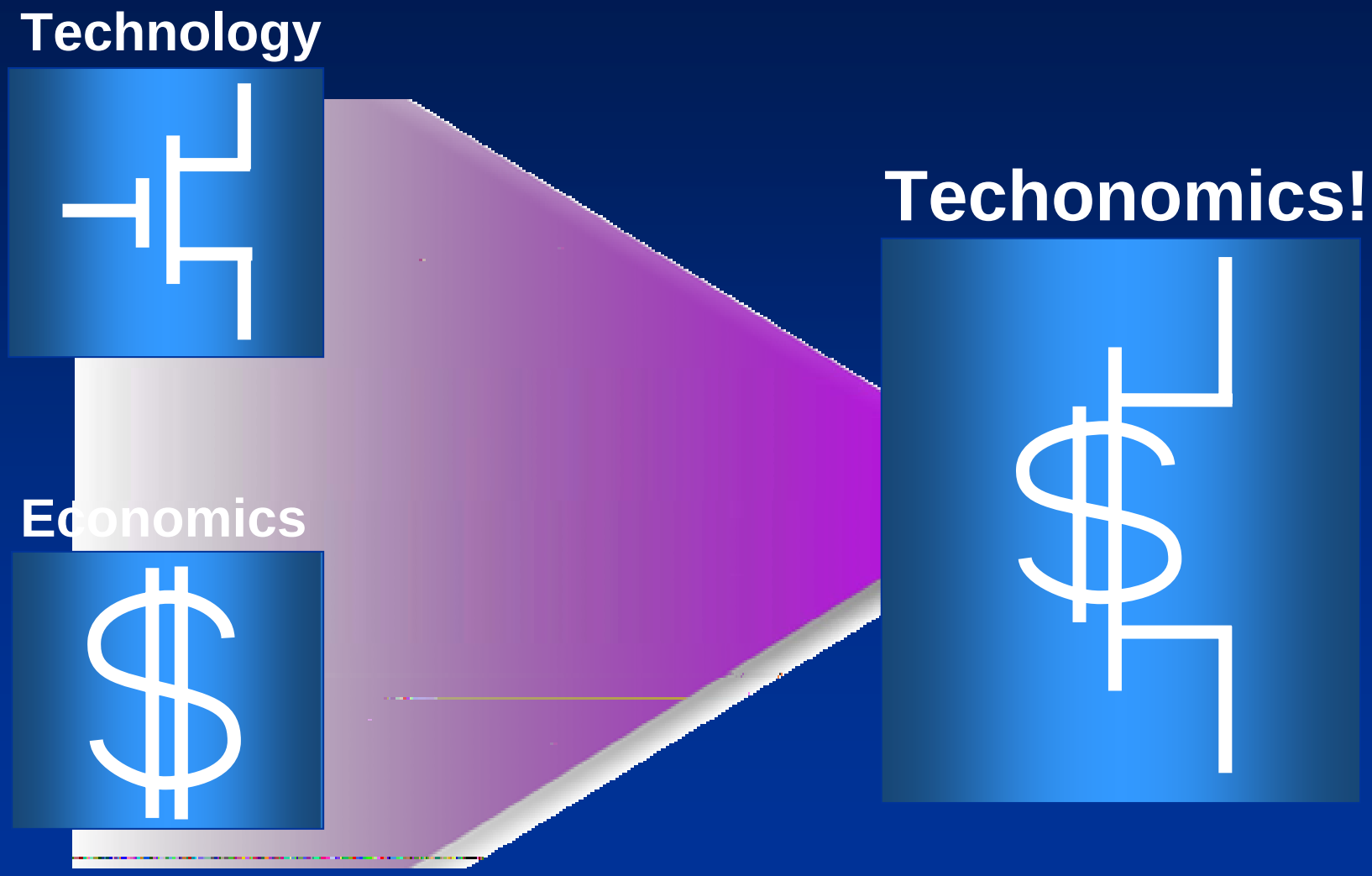


ic thickness

ITRS roadmap for gate die



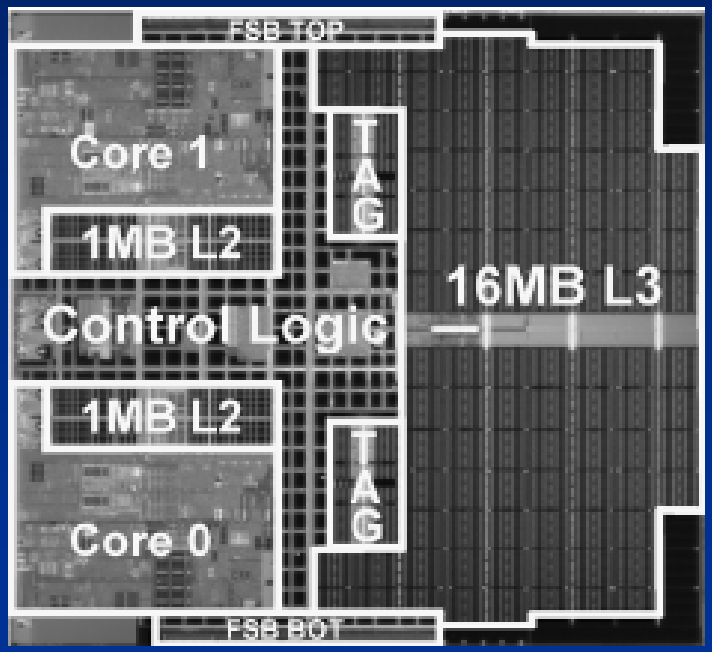
The Great Techonomics Shake-up



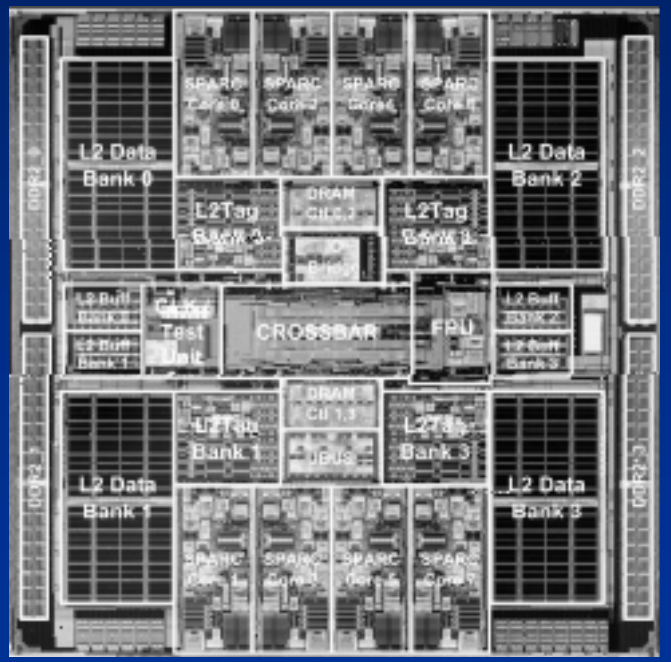
(二) 依靠设计技术的发展提高集成电路的速度

超高速IC技术发展趋势（1）

1、共享存储器的多核结构



Intel公司Xeron 2核共享存储器



Sun公司SPARC 8核CPU版图

网络处理器芯片发展

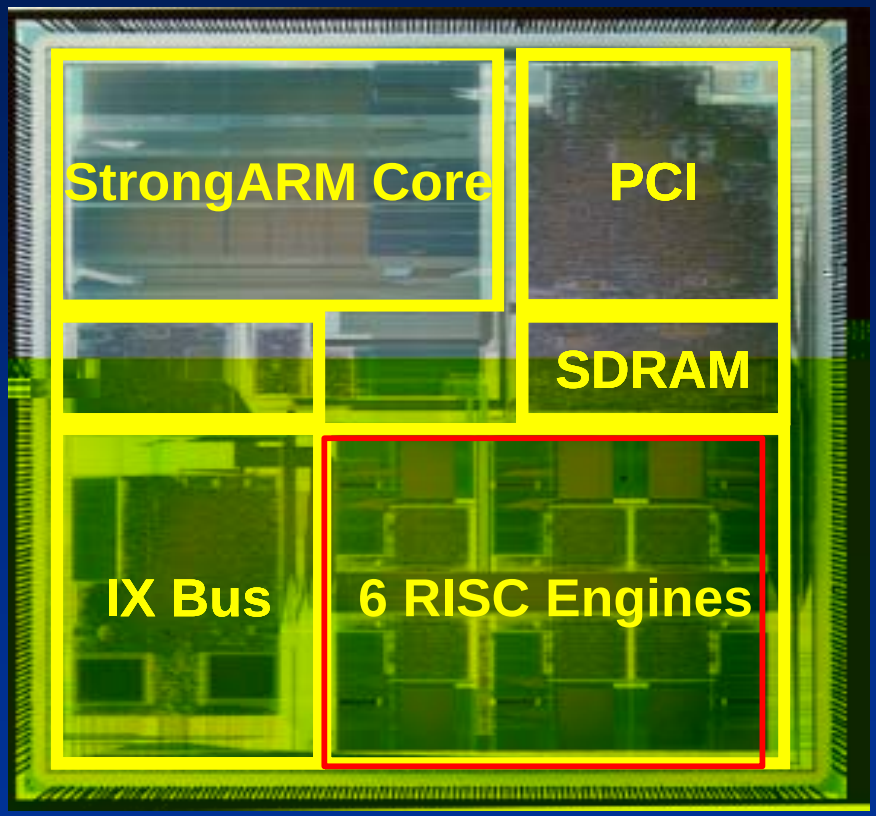
Access/
Edge

NP技术发展

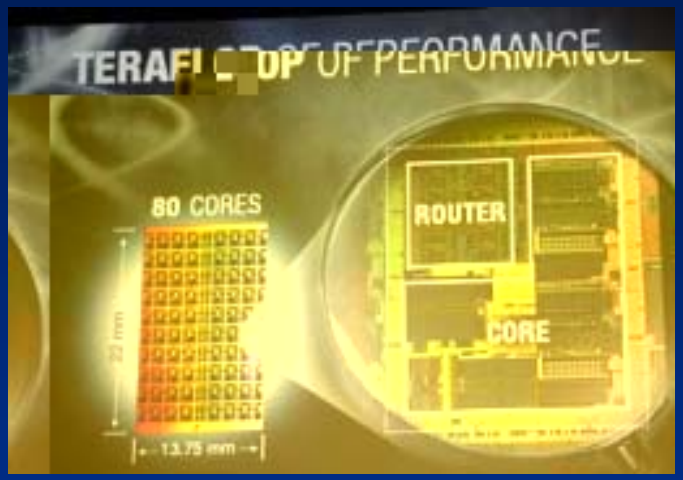
XDNP多核处理器结构

(1) 处理器是一种典型的同构多核处理器结构；

(2) 增加交换内核数量是提高NP交换能力的一种重要途径，



2、分享存储器的多核结构



Intel公司Tera-Scale 80核处理器

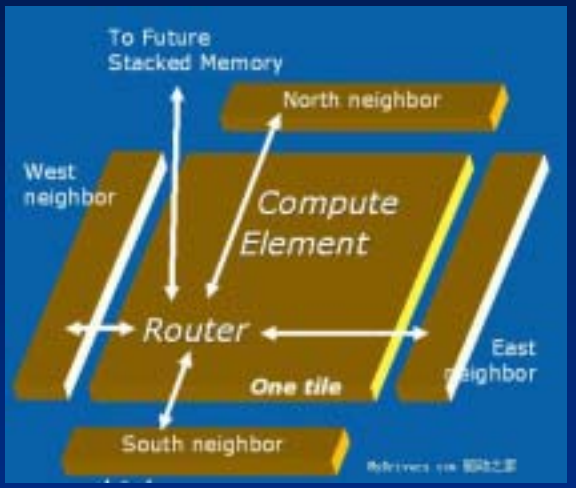
- 65nm SOI 工艺，275平方毫米
- 主频3.16GHz，电压0.95V
- 功耗62W
- 32位非X86结构
- 浮点运算能力1.01TFloFs（每秒万亿次）
- 相当于1万颗Pentium Pro 运算能力

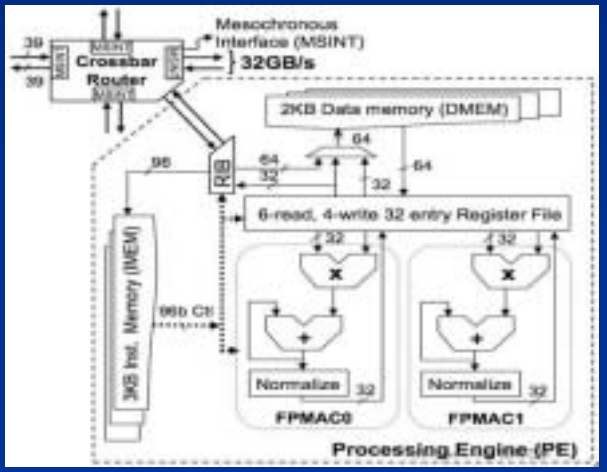
超高速IC技术发展趋势（2）

多核处理器单核结构的发展

特点：
(1)增加了用于数据交换的网络通信接口；
(2)采用共享存储器技术减小单核专用存储器面积；
(3)网络通信用于内核之间的互连。

优势：
(1)通用内核的使用缩短芯片开发周期
(2)灵活的设计，研发人员少
(3)分布式运算，极大提高系统运算能力





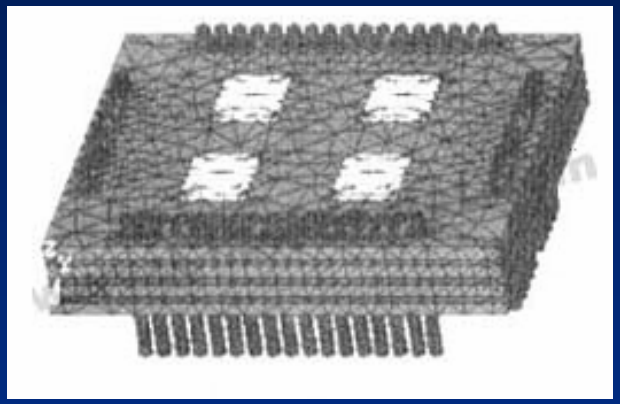
典型多核芯片的单核电路结构

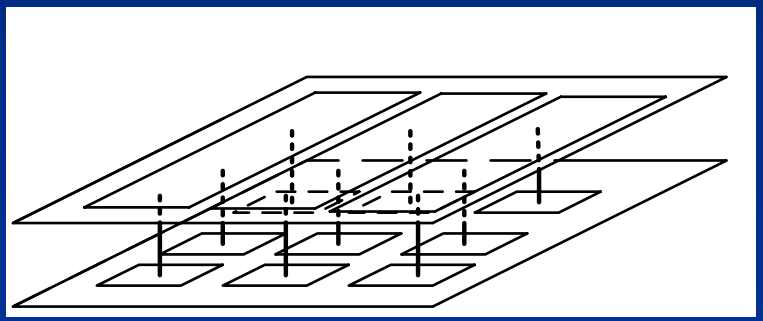
超高速IC技术发展趋势（3)

新型存储器结构

存储器已经成为SoC芯片的主要单元，在NP和通用CPU中，存储器占用面积已经超过50%。随着芯片和内核数量的增加，存储器占用比例还会继续增加。

新一代存储器正向三维存储器结构和共享存储器结构发展。



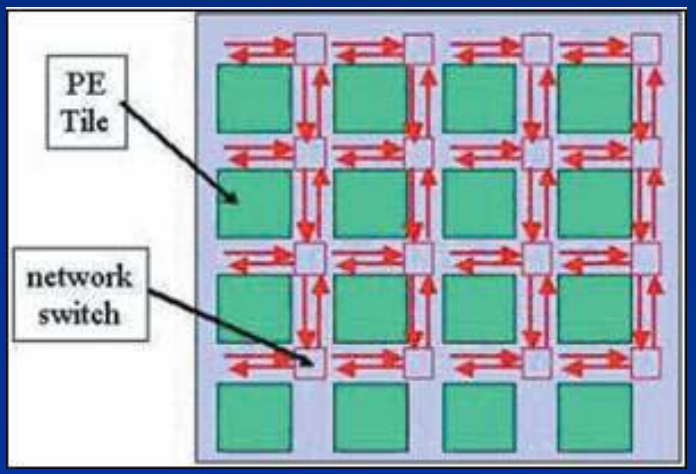


三维存储器结构

高速IC技术发展趋势（4）

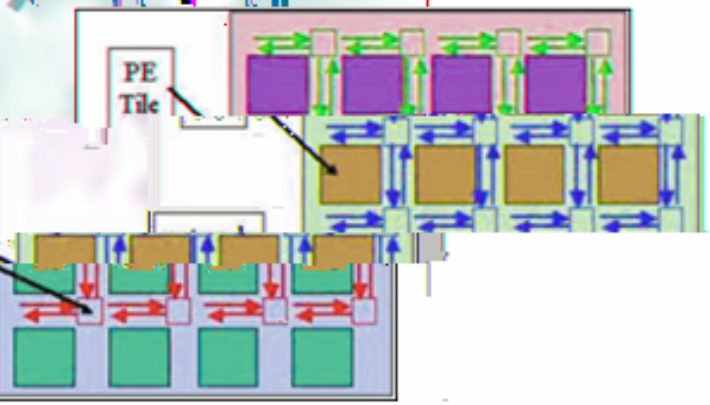
新型总线互连技术NoC

SoC芯片面积的增加，使得芯片全局一致性降低，无法满足超大规模集成电路芯片高频率工作要求。在新一代的处理器中，开始采用基于路由和交换技术的网络互连技术(NoC)，作为芯片内核互连解决方案。



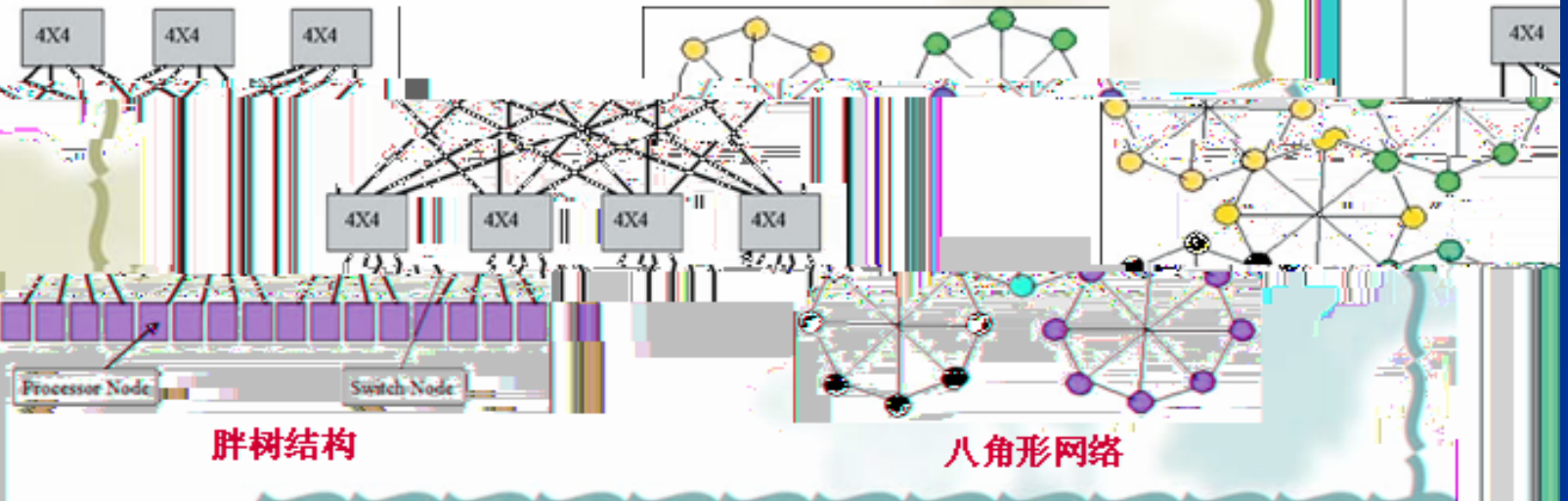
NOC拓扑结构

NOC拓扑结构



2维网状结构

蜂窝状结构



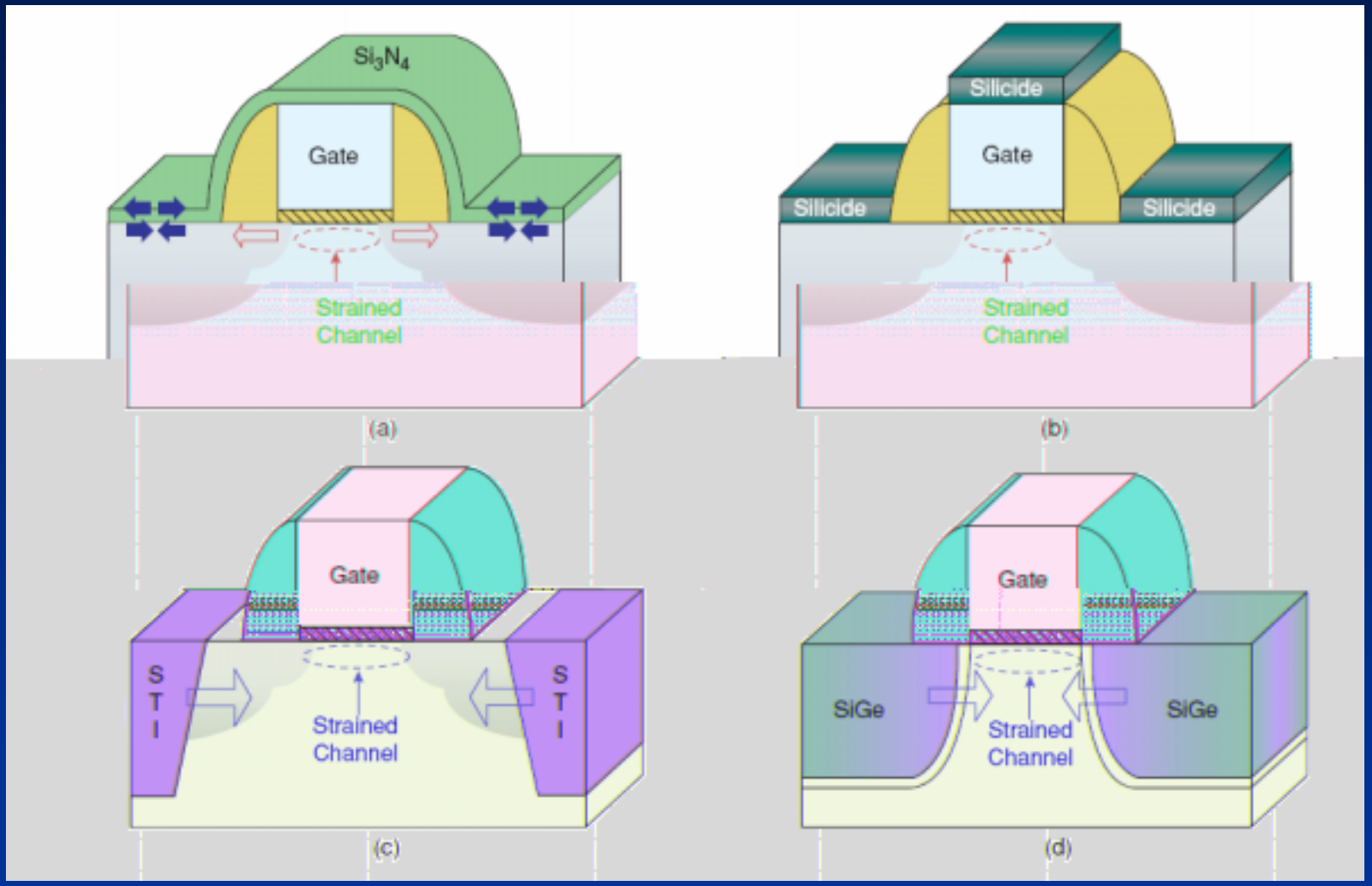
胖树结构

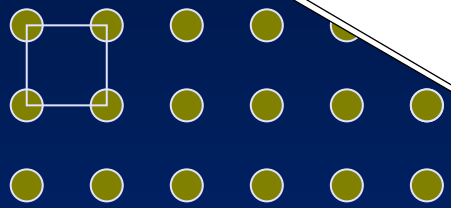
八角形网络

蚁群算法

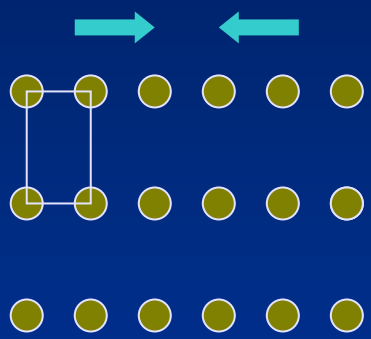
(三) 依靠器件结构的变革
提高器件和电路的速度

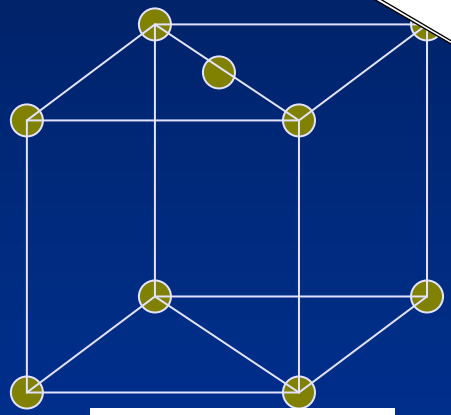
（一） 应变硅技术


Si_3N_4
Gate
Strained
Channel
(a)
Silicide
Gate
Silicide
Silicide
Strained
Channel
(b)
Gate
STI
STI
Strained
Channel
(c)
Gate
SiGe
SiGe
Strained
Channel
(d)



Compressive





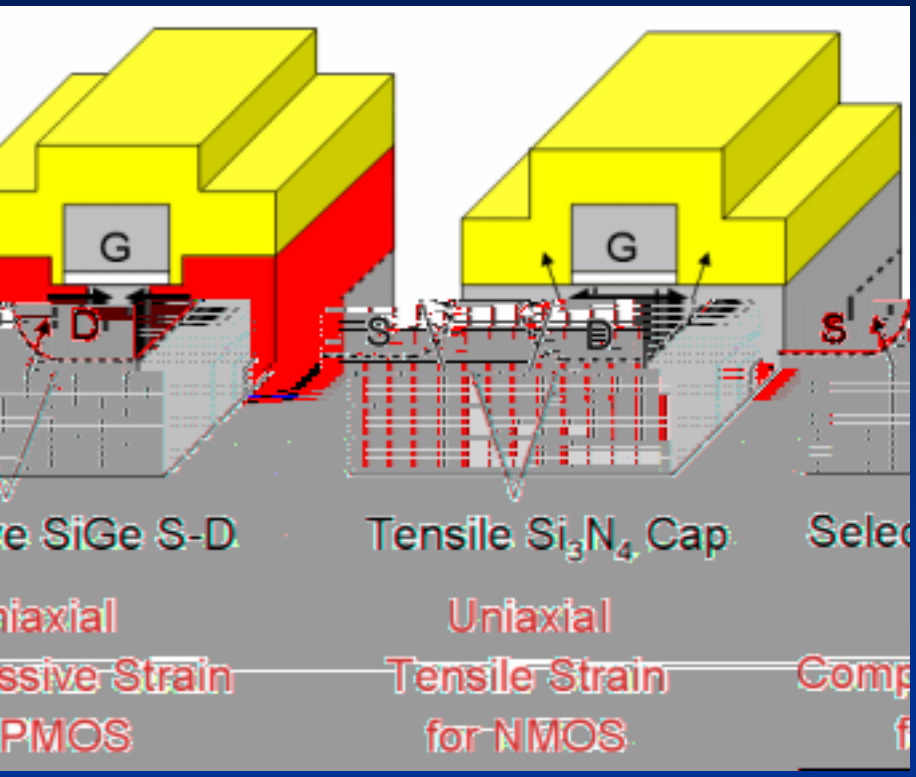
$$E_k = \frac{\hbar^2 k^2}{2m^*}$$

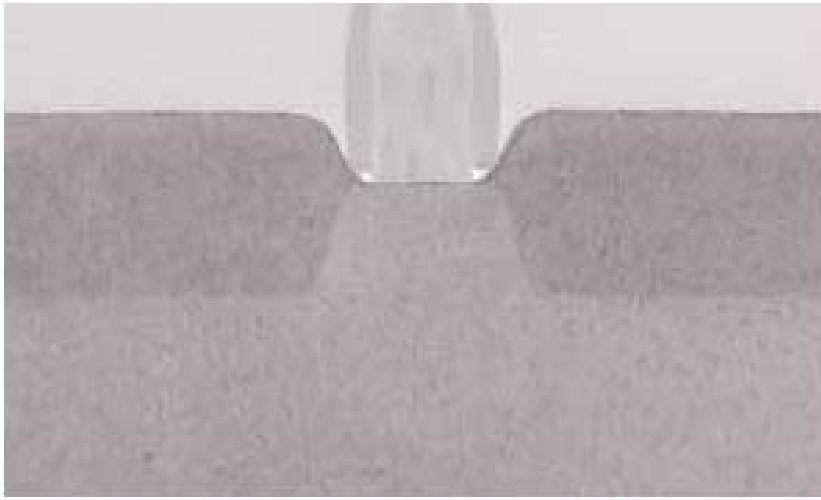
The symmetric of crystal

- ► **The band structure**
- ► **The effective carrier mass**
- ► **The carrier mobility**

The transistor is facing to more and more stress jus

不同的应变引入方法

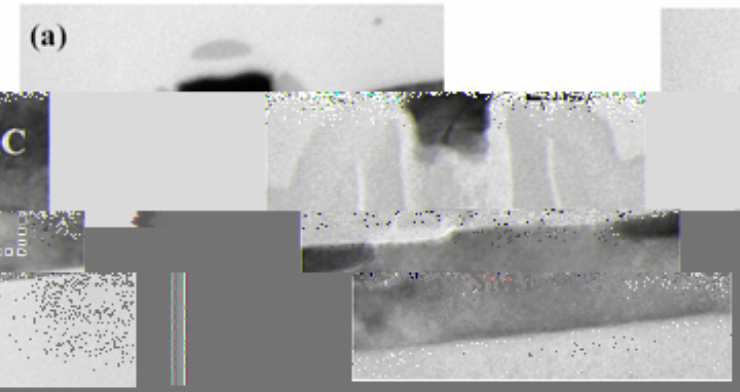




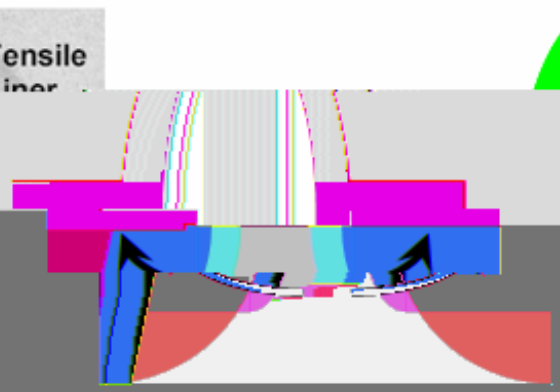
在nMOS晶体管的S/D区域内选择生长高质量、无缺陷的SiC（含1.6%的碳）外延薄膜。使用循环淀积和刻蚀（cyclic-deposition and etch，CDE）工艺可以获得高的碳含量和高选择性。（来源：ASM）

NMOS Stressors

Uniaxial



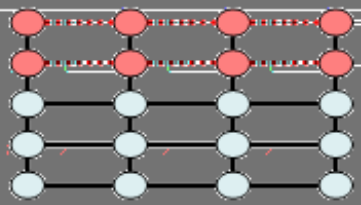
Stress Memory Technique
Horstmann, el al, IEDM 2005



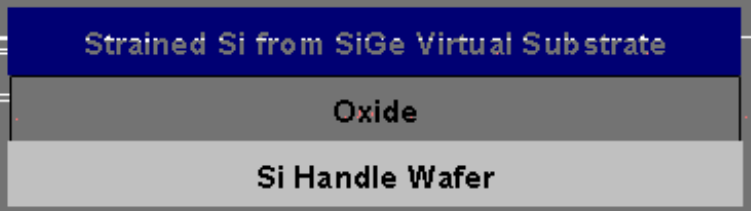
t-ESL
Grudowski, et al, VSLI 2006

Ang, et al,

Biaxial

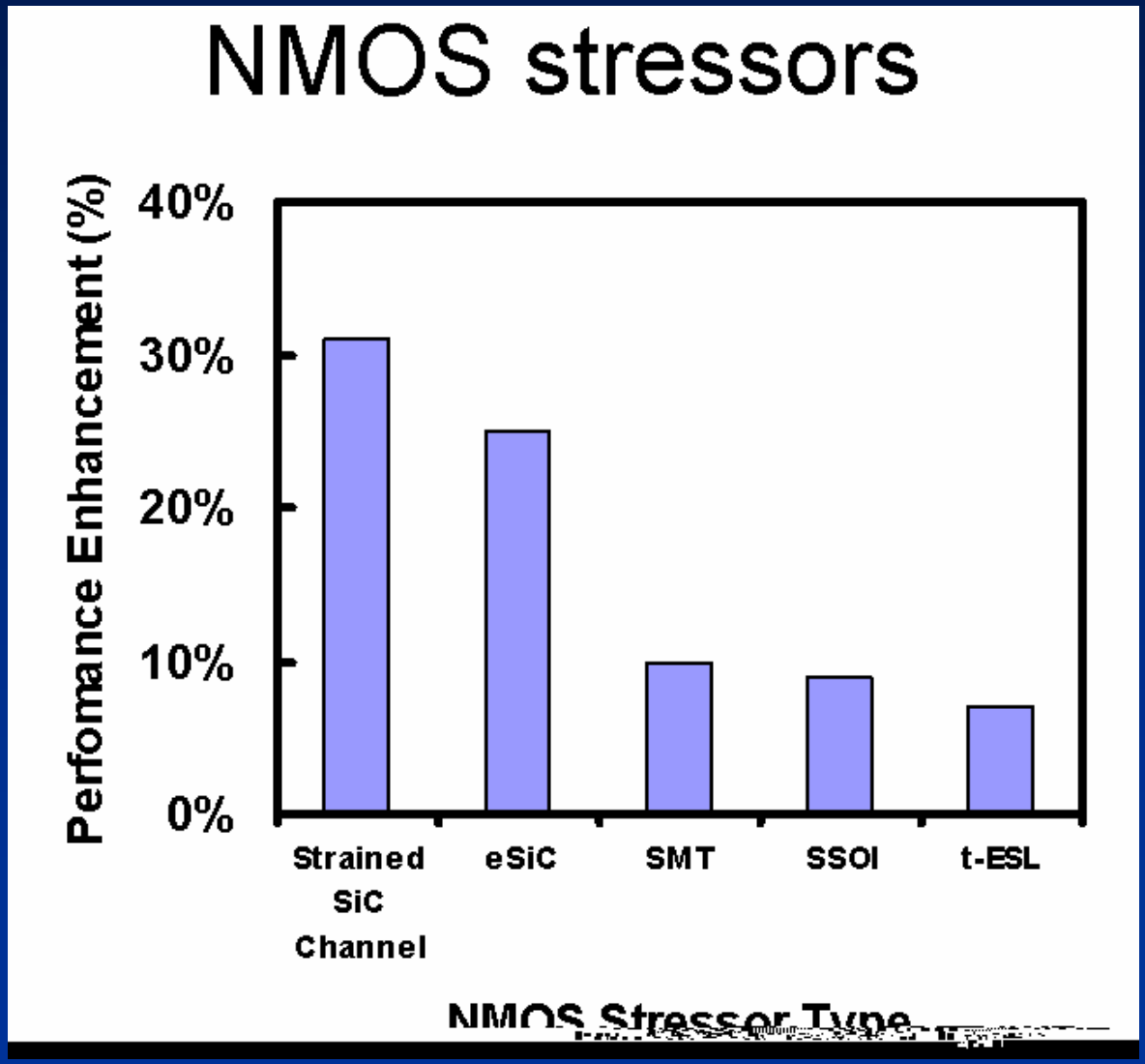


rained SiC Channel
nst, et al, VLSI 2003



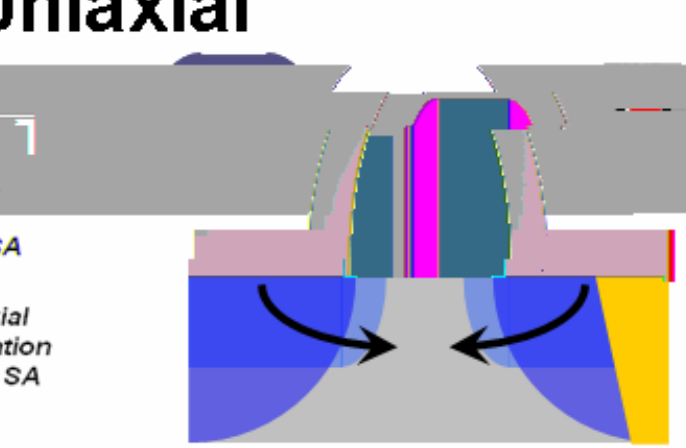
SSOI
Thean, et al, VSLI 2005

Strain Engineering



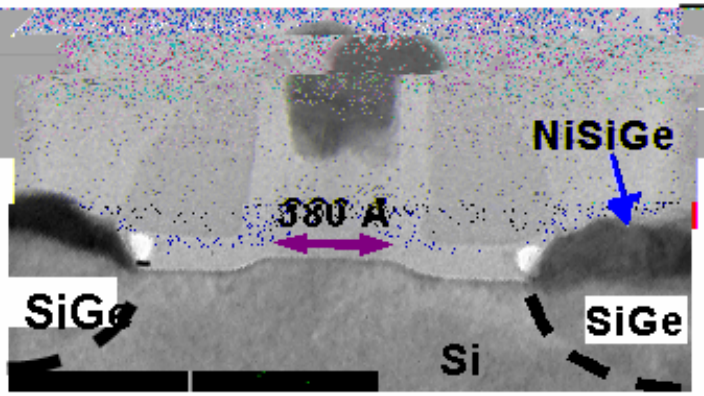
PMOS stressors

Uniaxial



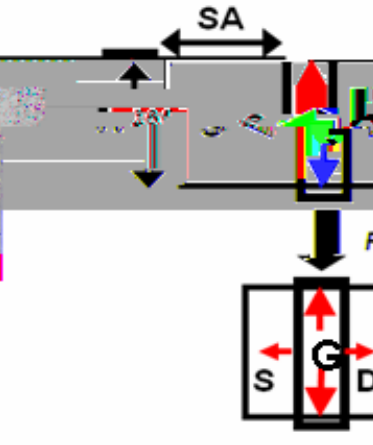
c-ESL

2005 Grudowski, et al, VSLI 2006



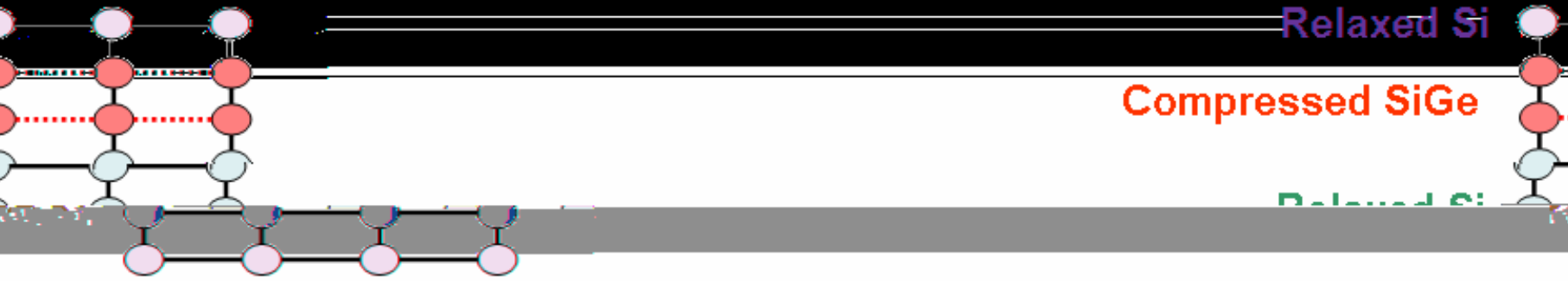
eSiGe

Zhang, et al, VLSI 2005



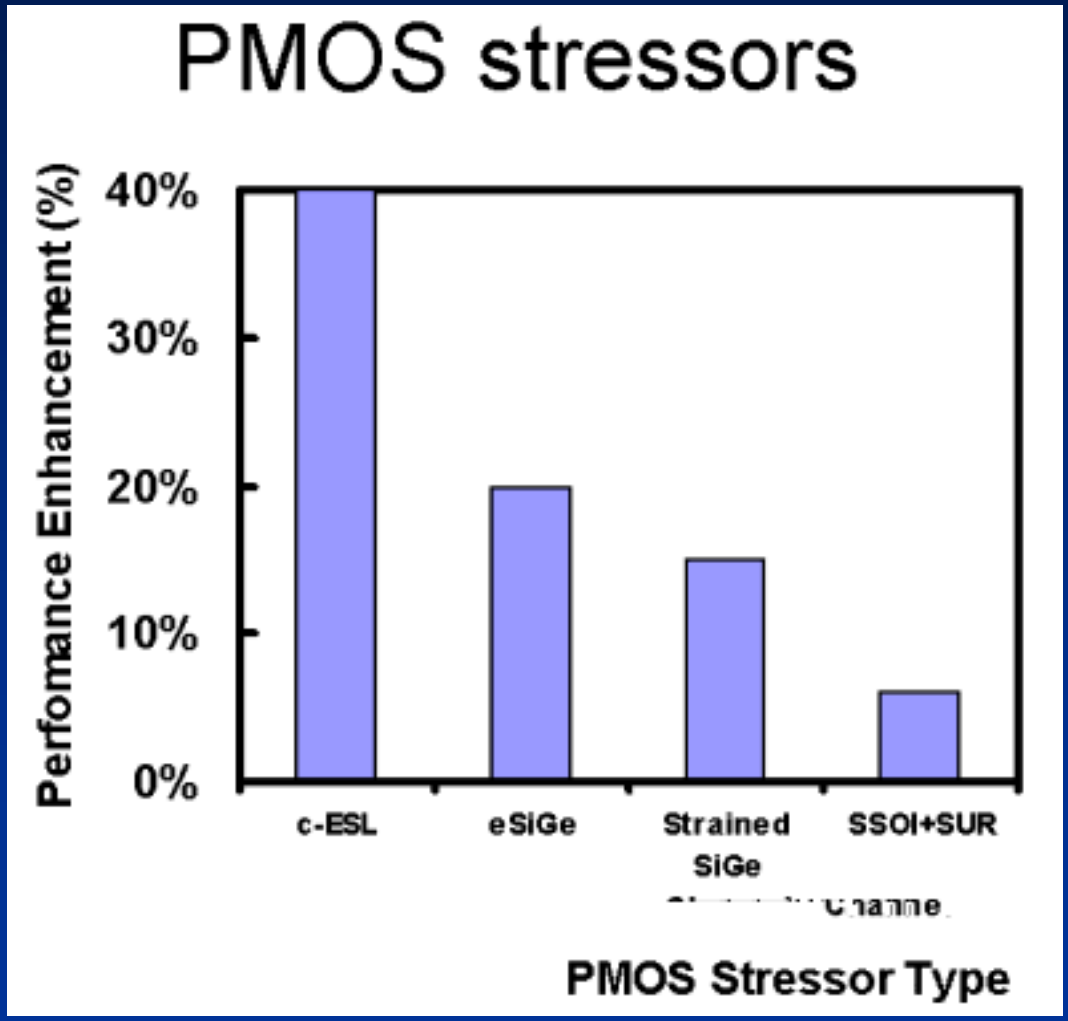
SSOI+S

Thean, et al, I

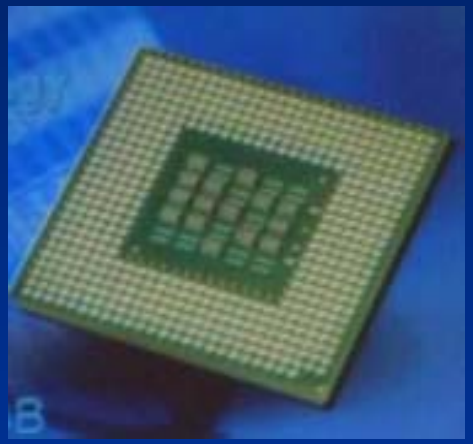


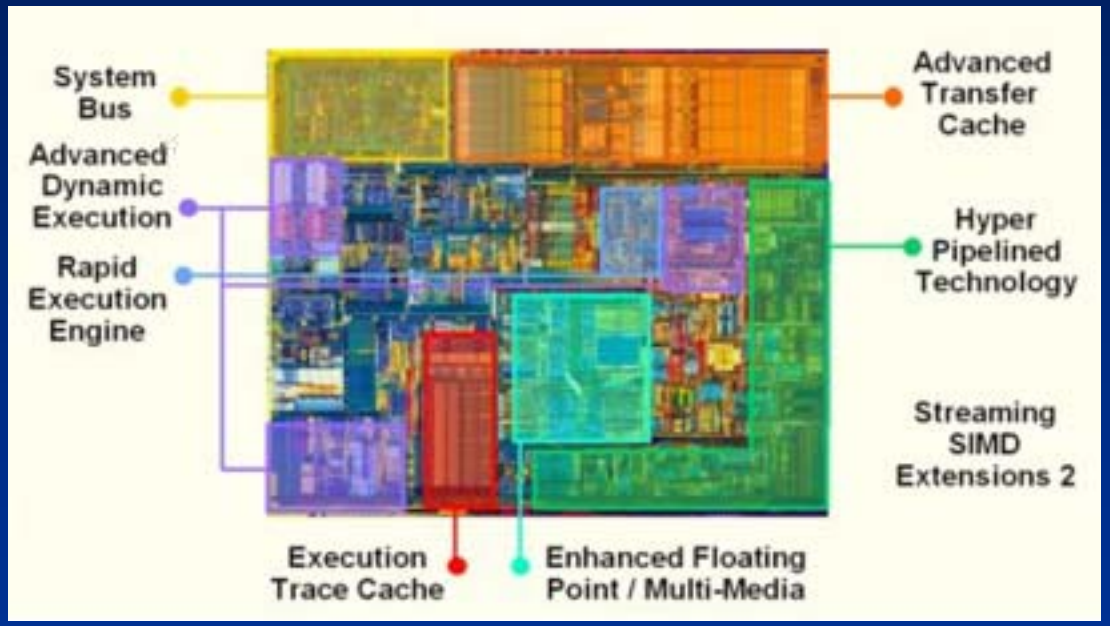
Colleart, et al, ESSDERC 2002

Strain Engineering

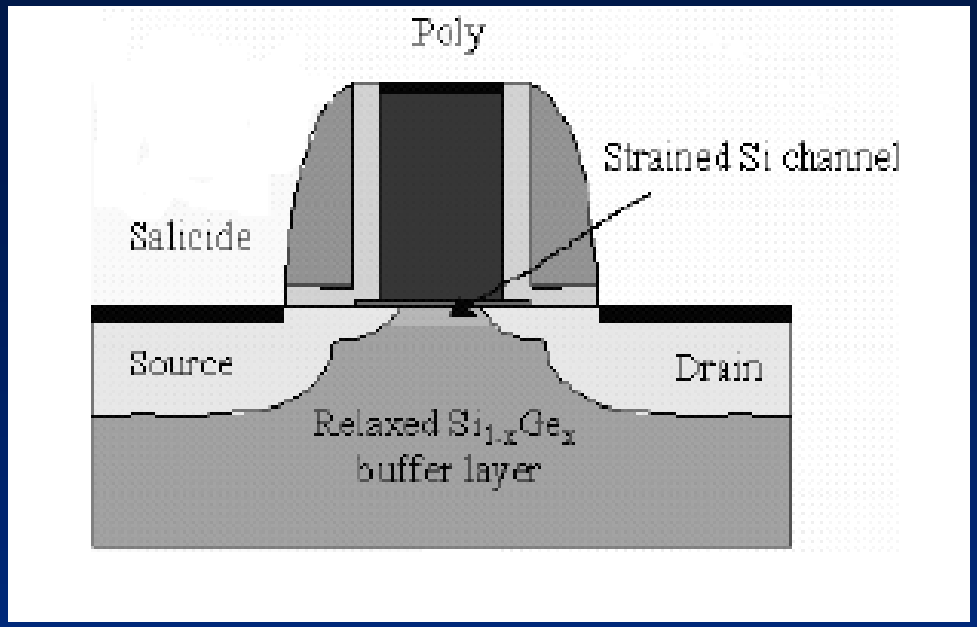


Intel于2002年8月发布了将应变Si技术应用在90nm CMOS技术上，正式宣告应变Si技术将进入量产，引起了IC业界极大关注。2005年完成90nm 的Prescott Pentium 4 处理器,主频3.4GHz





Intel的Prescott Pentium 4 处理器

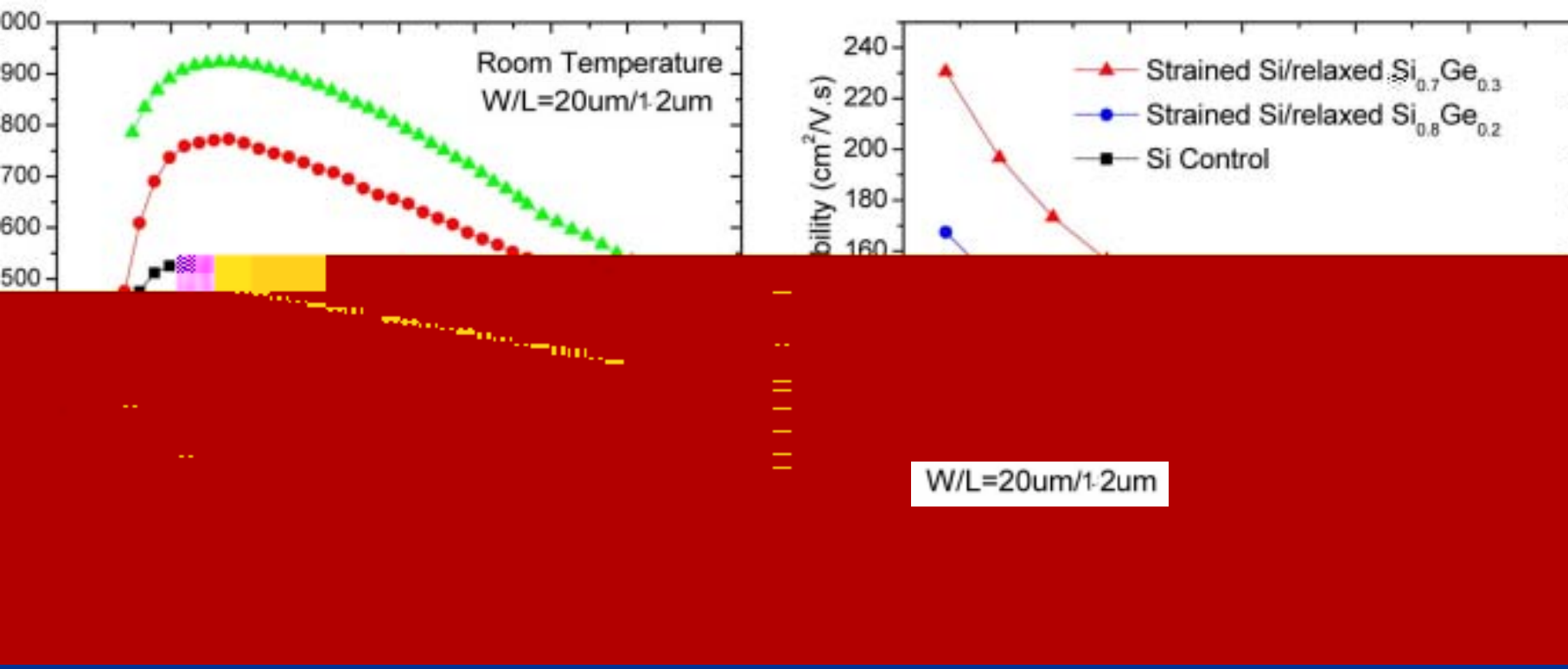


全局应变结构

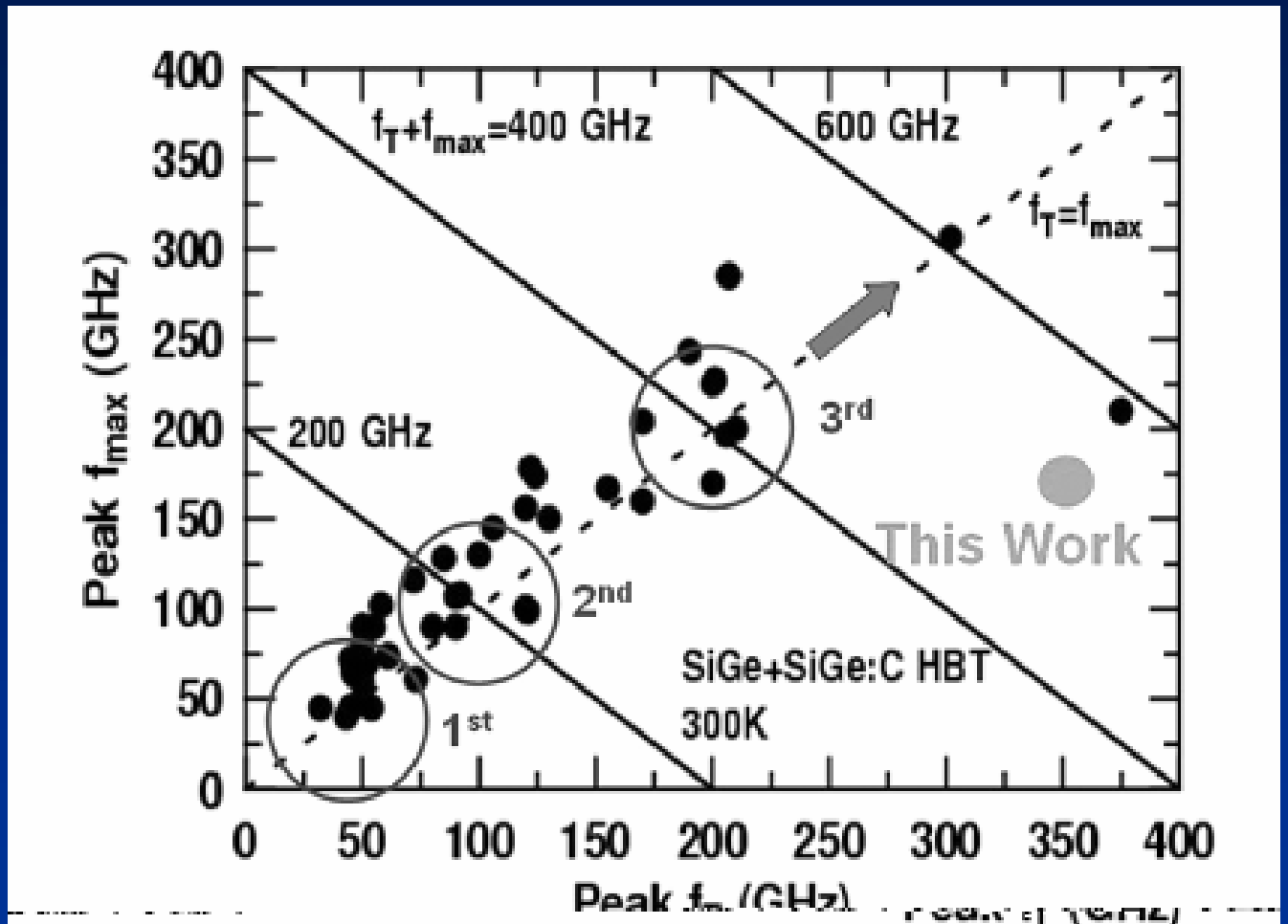
在SiGe上生长的Si层就会受到一个双轴张应力的作用，生长的SiGe高Ge组分层就会受到一个双轴压应力的作用。前者制造NMOS，后者制造PMOS。产生的应变改变了Si的能带结构，进而提高了载流子迁移率。

图示是一个在$Si_{1-x}Ge_x$缓冲层上生长Si导电沟道的NMOS器件示意图。

国内最新研究进展


Room Temperature
W/L=20um/1.2um
Strained Si/relaxed $Si_{0.7}Ge_{0.3}$
Strained Si/relaxed $Si_{0.8}Ge_{0.2}$
Si Control
W/L=20um/1.2um

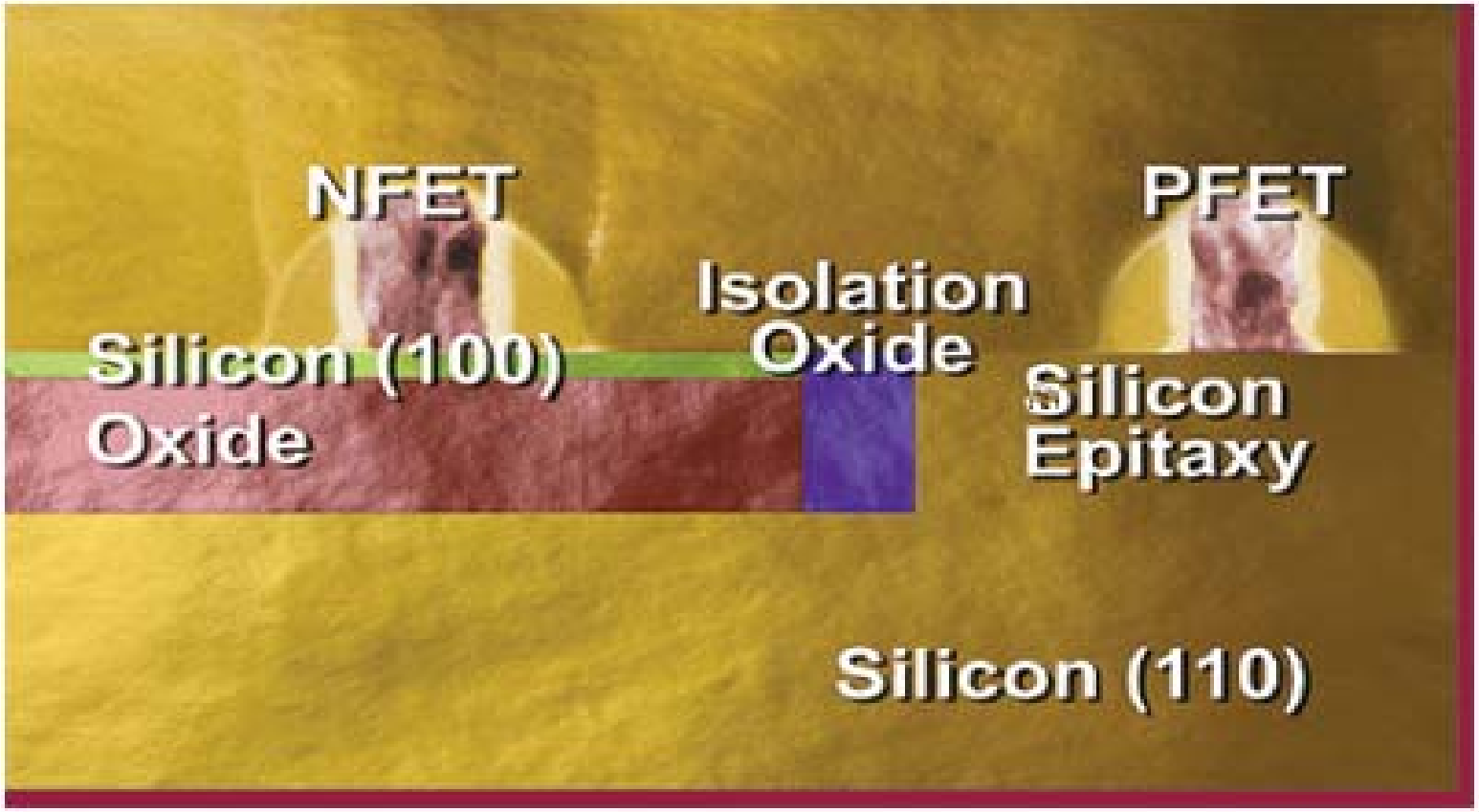
Strain Si + SiGe HBT BiCMOS



e f_T-f_{max} space.

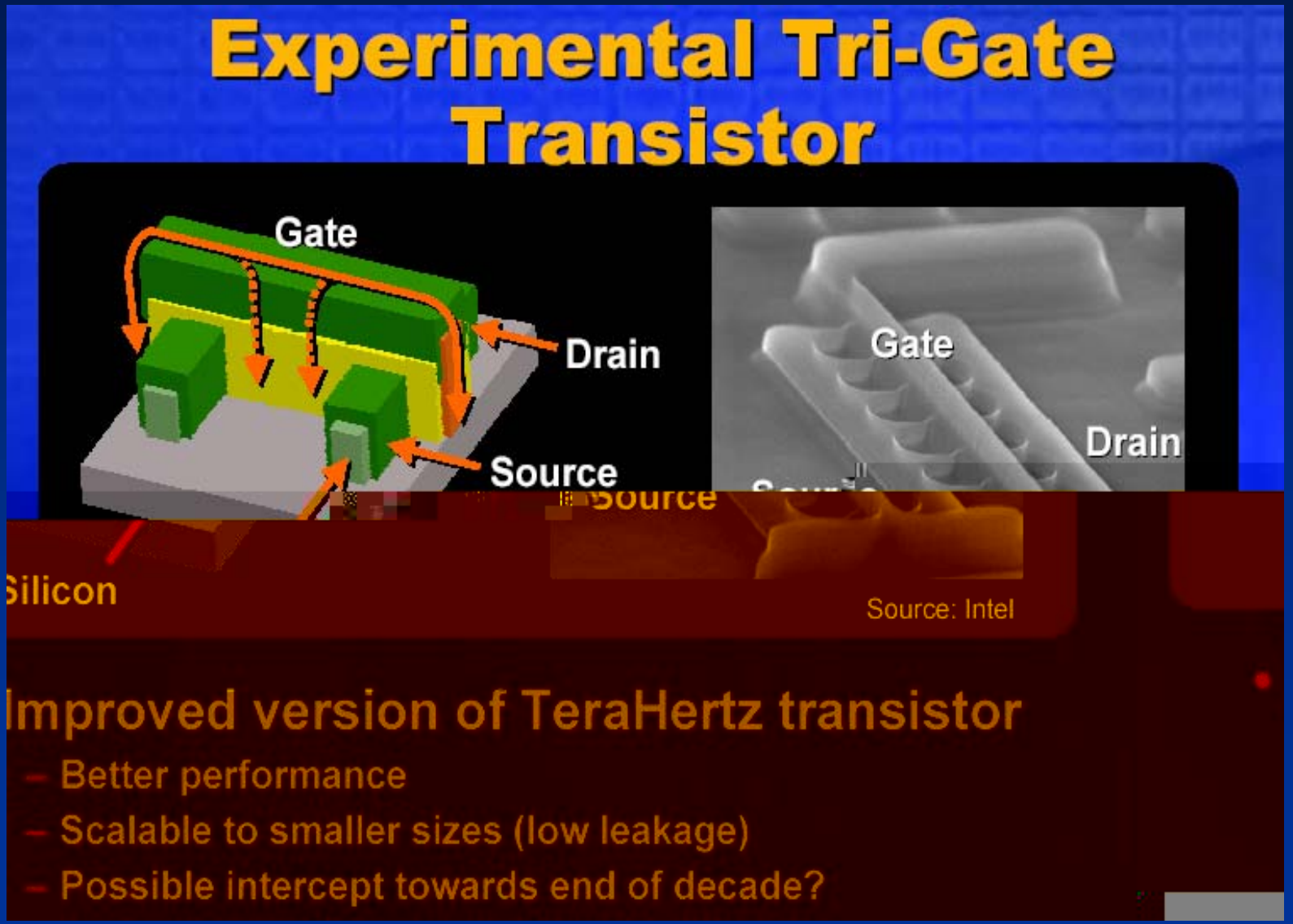
Comparison of SiGe HBT technology nodes in th

（二） 杂合晶向技术



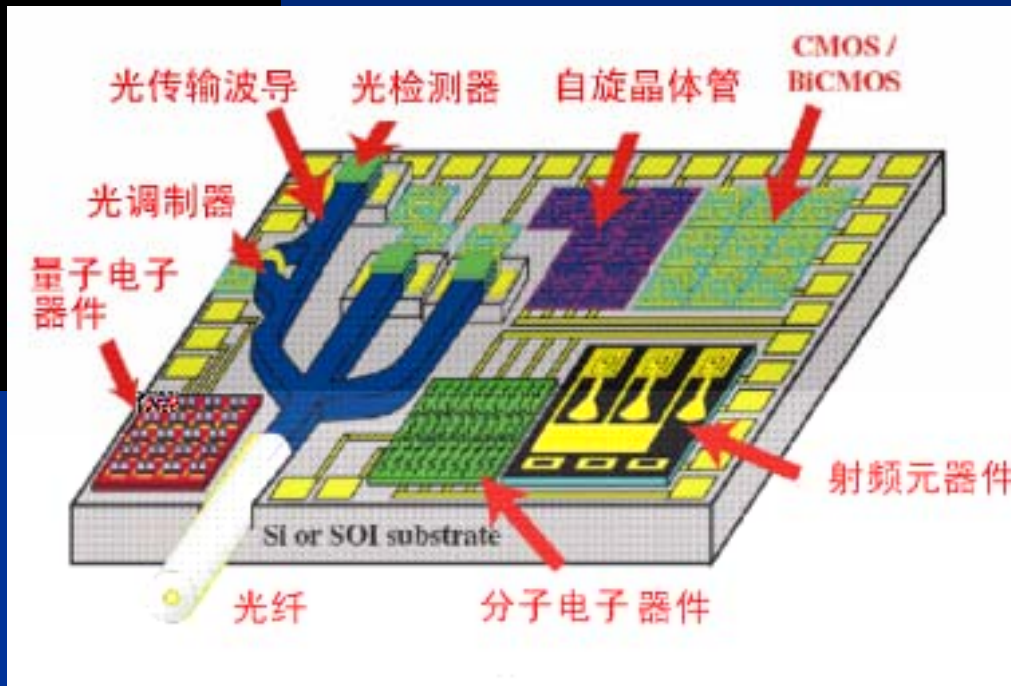
杂合晶向技术能够在（110）晶向晶圆上制造出pFETs，使得其运行速度提高了一倍。（来源：IBM）

Terahertz Electronics



光电集成技术

Integration Phases
Discrete Components
Hybrid Integration (Optics)
Hybrid Integration (Optics and Electronics)
Optoelectronic Integration (Optics and Electronics)

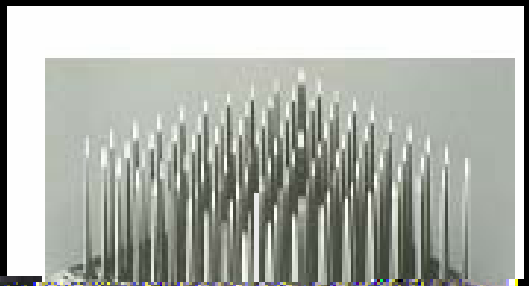

光传输波导
光检测器
自旋晶体管
CMOS / BiCMOS
光调制器
量子电子器件
射频元器件
Si or SOI substrate
光纤
分子电子器件

(四) 依靠新型材料的进步
提高器件和电路的速度

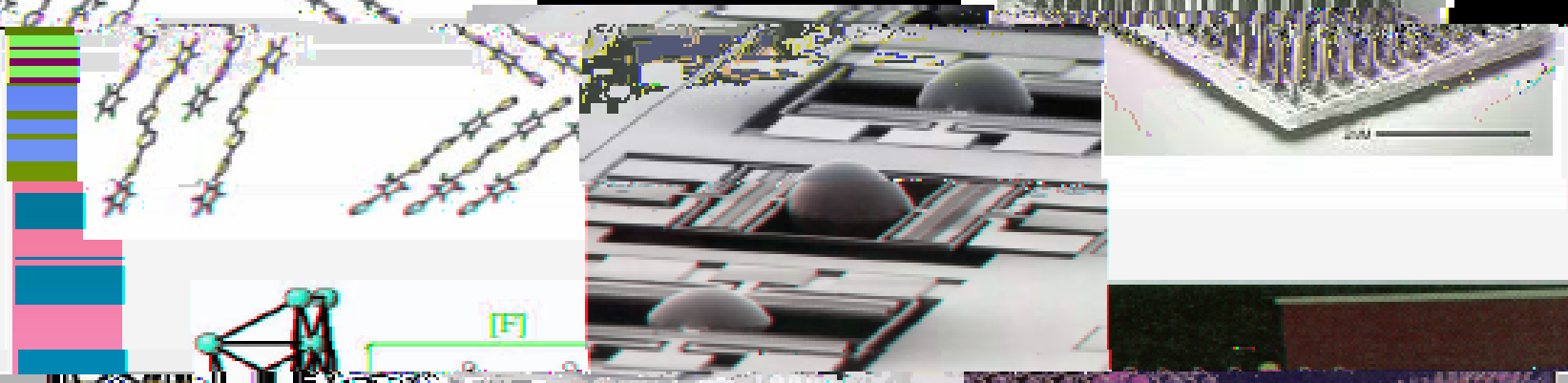
Transitioning to the Post-Silicon Age

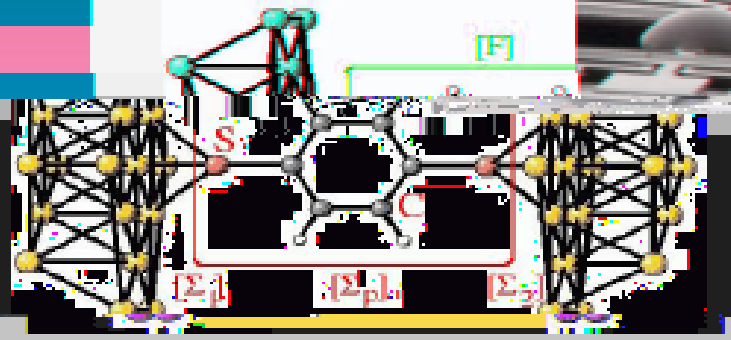
Organic

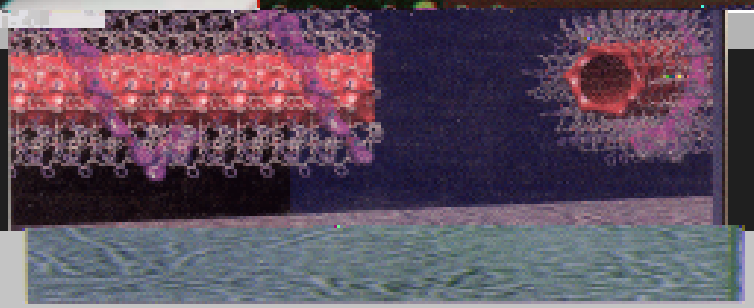
Nanotube



NanoOptics





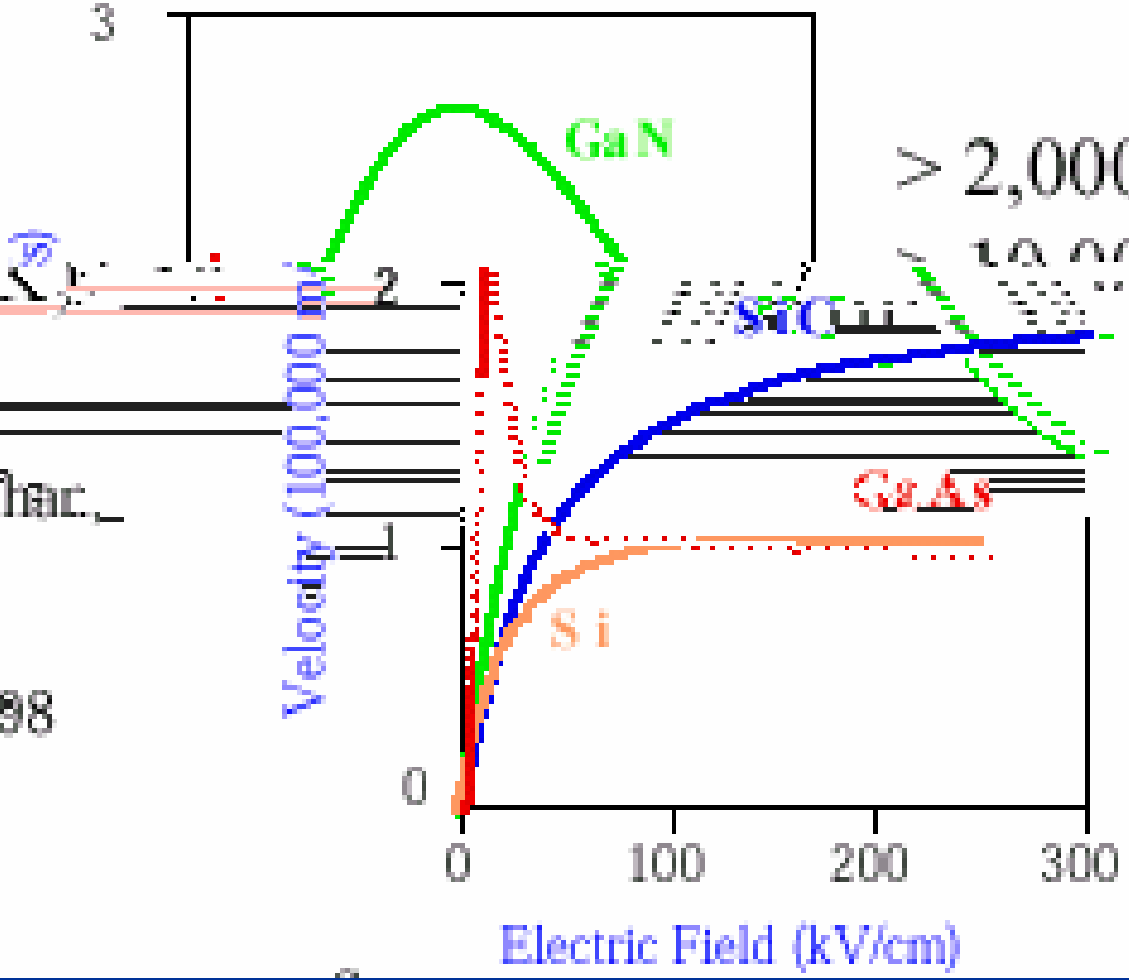


Molecular

Implementation platforms that work under very low SNR, are non-deterministic, unpredictable and unreliable

GSR

High Drift Velocity and high mobility



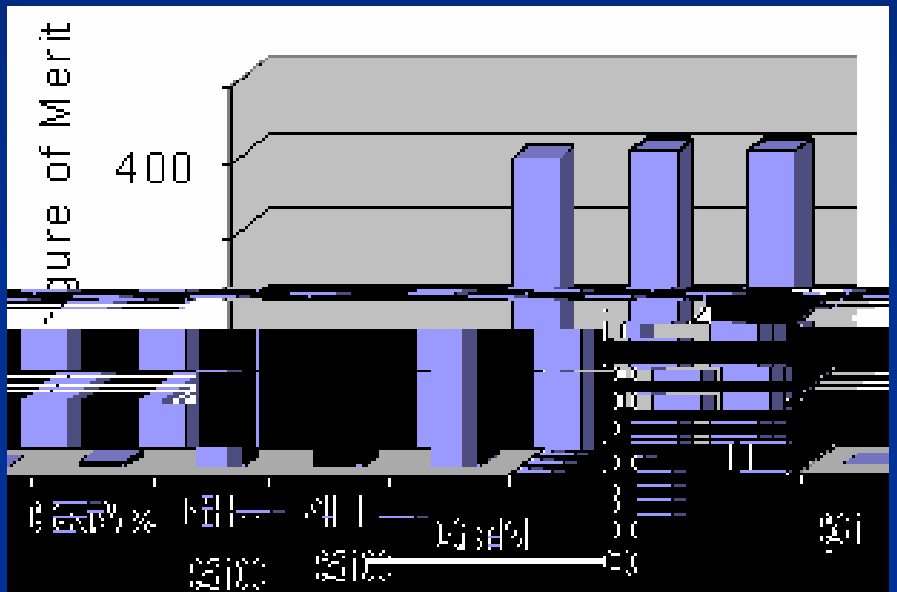
> 2,000 cm^2/V-s (300 K)

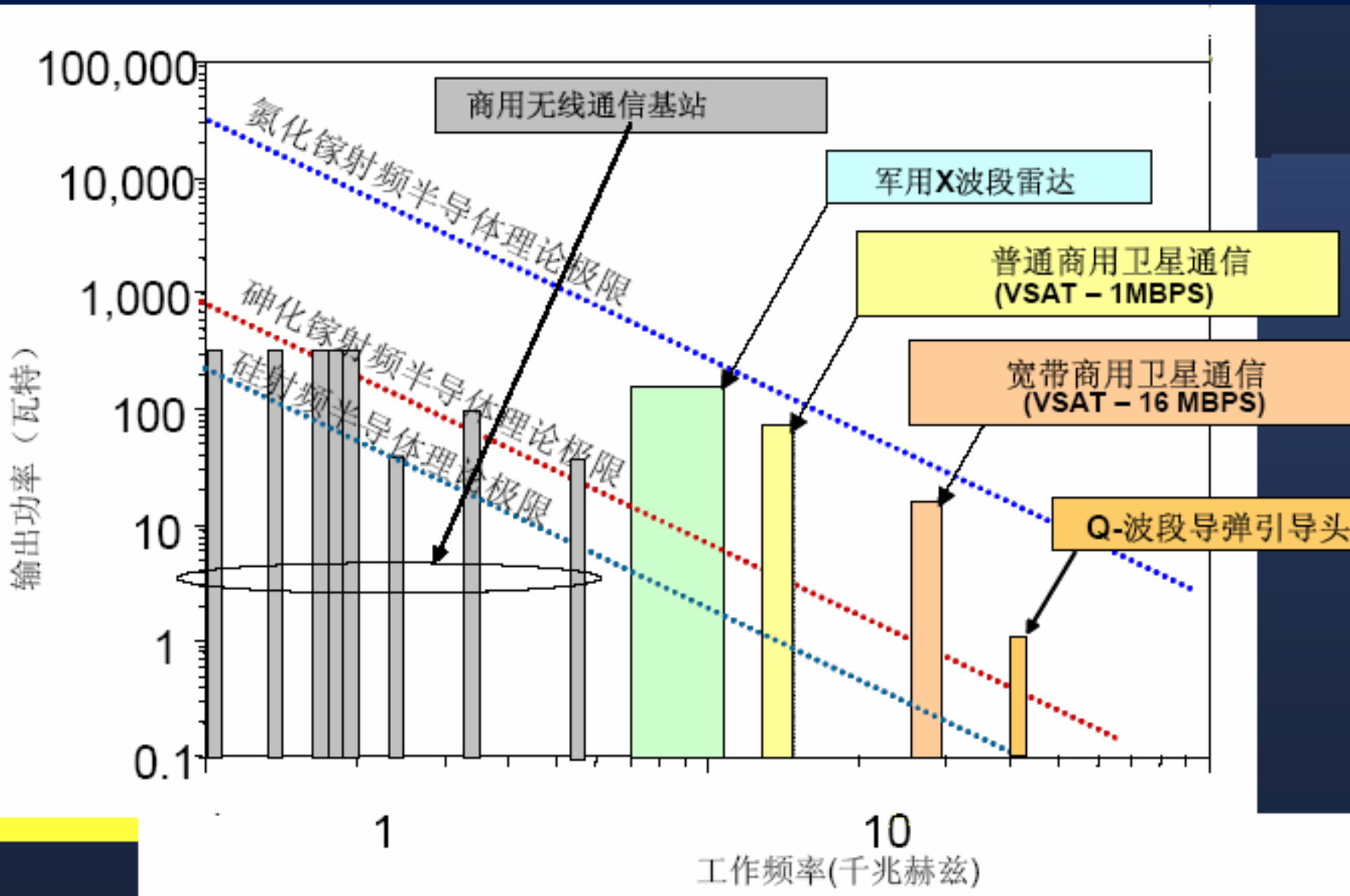
R. Gaska, J. W. Yang,
M. As
M. S. Shur, Appl. Phys. Le
77, No. 6, pp. 707-709, Feb

超高速应用的综合品质因素

$$CFOM = \frac{\chi \varepsilon_0 \mu v_s E_B^2}{\left(\chi \varepsilon_0 \mu v_s E_B^2\right)_{Si}}$$

其中，χ为热导率，ε_0为介电常数，μ为迁移率，v_s为电子饱和速度，E_B为击穿电场强度。




100,000
10,000
1,000
100
10
1
0.1
输出功率（瓦特）
氮化镓射频半导体理论极限
砷化镓射频半导体理论极限
硅射频半导体理论极限
商用无线通信基站
军用X波段雷达
普通商用卫星通信
(VSAT – 1MBPS)
宽带商用卫星通信
(VSAT – 16 MBPS)
Q-波段导弹引导头
1
10
工作频率(千兆赫兹)

不同材料特性比较

	Si	GaAs	SiC(4H)	GaN
禁带宽度(eV)	1.11	1.43	3.2	3.4
临界击穿电场（MV/cm)	0.3	0.4	2	3.3
2DEG薄层电子密度（/ cm^2 ）	NA	$4x10^{12}$	NA	$20x10^{12}$
电子饱和速度(cm/s)	$1x10^7$	$2x10^7$	$2x10^7$	$2.5x10^7$
电子迁移率(cm^2/Vs)	1500	6000	800	1600

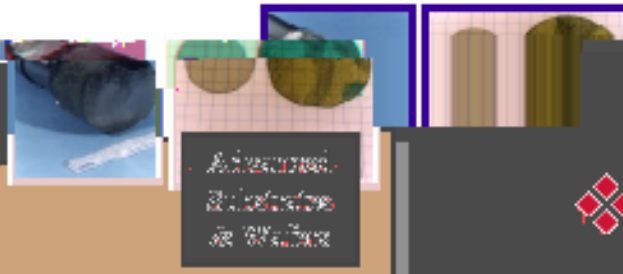
WBG Compound Semiconductors

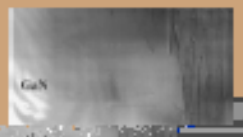
Focus Areas

aterial Technology
Bulk Crystal
Enitaxial Materials

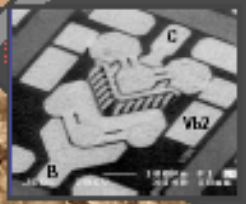
vice Technology

rmal Control &
ckages





Epitaxial Materials



Electron Devices

Integrated Circuits

GaN在超高速器件方面的发展

- **UCSB (USA)**
  f_T=153GHz, f_{max}=230GHz (L_G=0.10μm)
- **Rockwell (USA)**
  f_T=123GHz, f_{max}=174GHz (L_G=0.10μm)
- **Fraunhofer Institute (Germany)**
  f_T=65GHz, f_{max}=140GHz (L_G=0.18μm)
- **National Institute of Information and Communication Technology (Japan)**
  f_T=163GHz, f_{max}=192GHz (L_G=0.18μm)

GaN/SiC材料生长设备

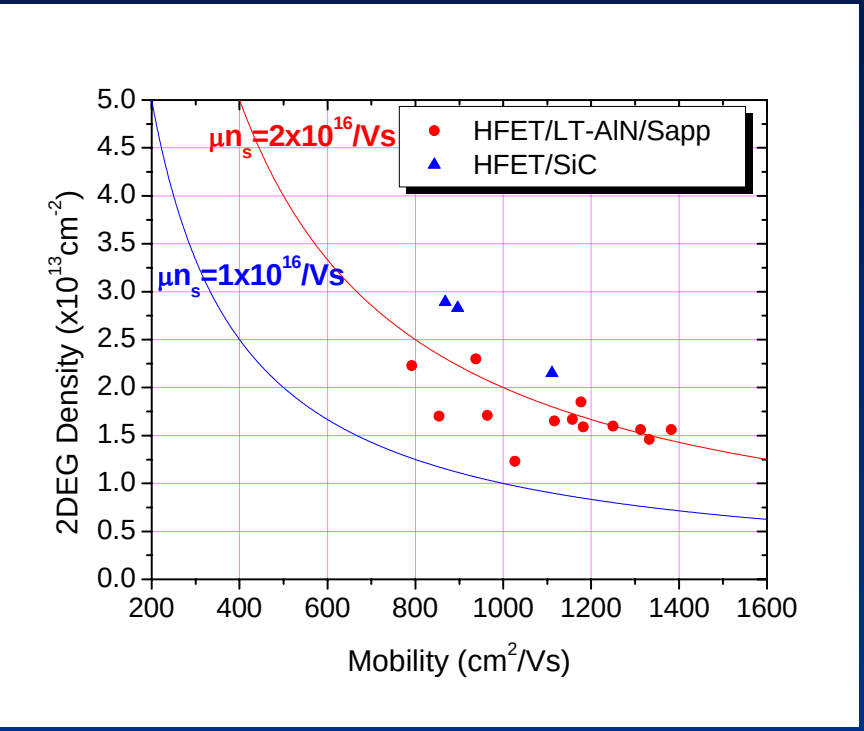
GaN材料外延设备：自主知识产权、运行良好的GaN 材料生长用MOCVD-120 和MOCVD-320 系统；

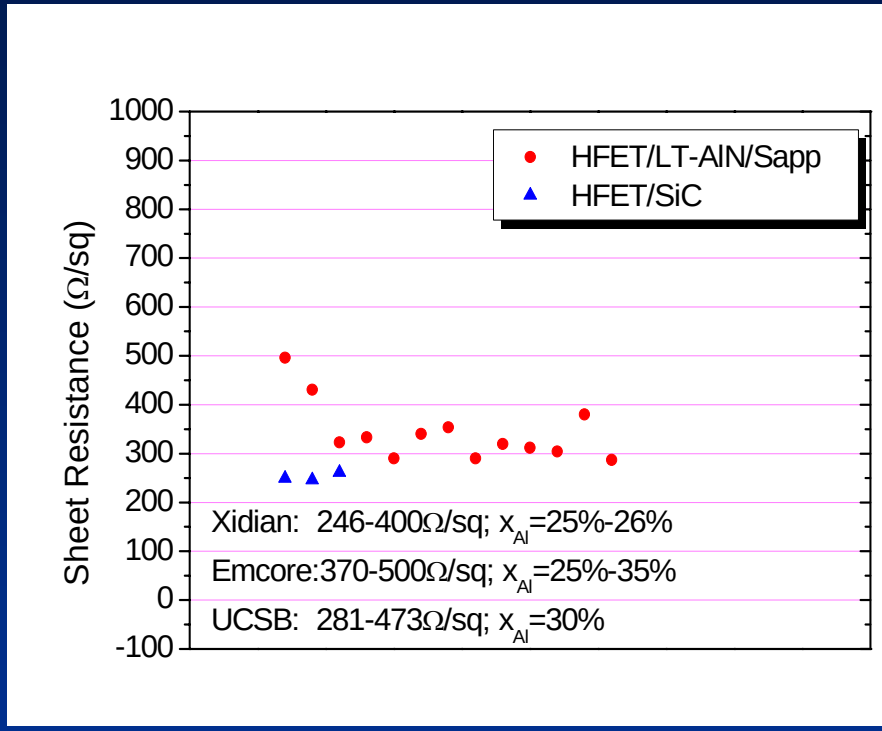
衬底制备： SiC CVD 设备（瑞典Epigress VP508GFR），可同时生长六片2 英寸SiC；

Layer structures of AlGaN/GaN Heterostructure

西电GaN HEMTs研究

GaN异质结材料电特性（用于微波器件）





GaN异质结材料生长部分结果(2005-2006年)

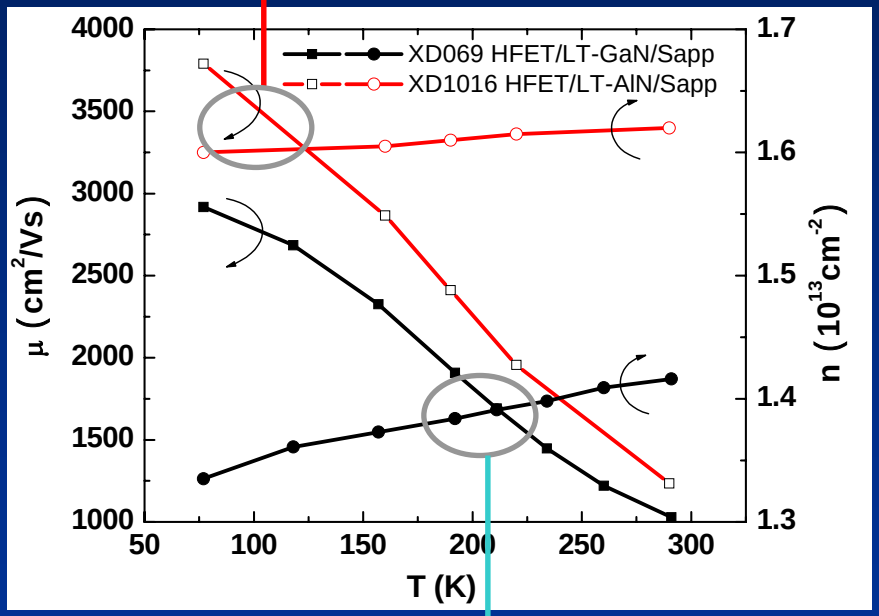
- GaN异质结材料2DEG迁移率和面密度乘积高于$2x10^{16}$/Vs；
- 方块电阻均在246~400Ω/□之间。

西电GaN HEMT研究

高性能AlGaN/GaN异质结材料

μ_{300K}=1234cm²/Vs； μ_{77K}= 3791cm²/Vs

n_{300K}=1.62E13cm^{-2}；n_{77K}= 1.6E13cm^{-2}

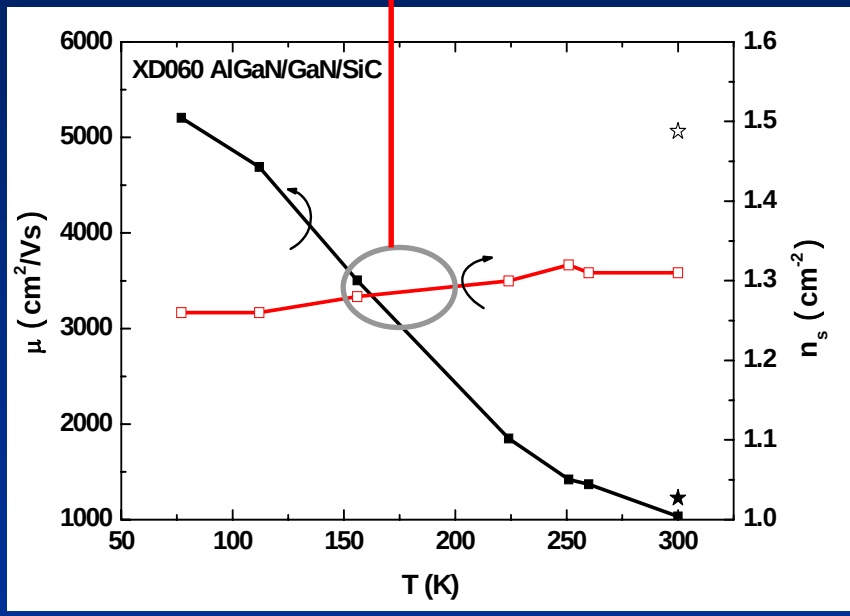


μ_{300K}=1029cm²/Vs； μ_{77K}= 2918cm²/Vs

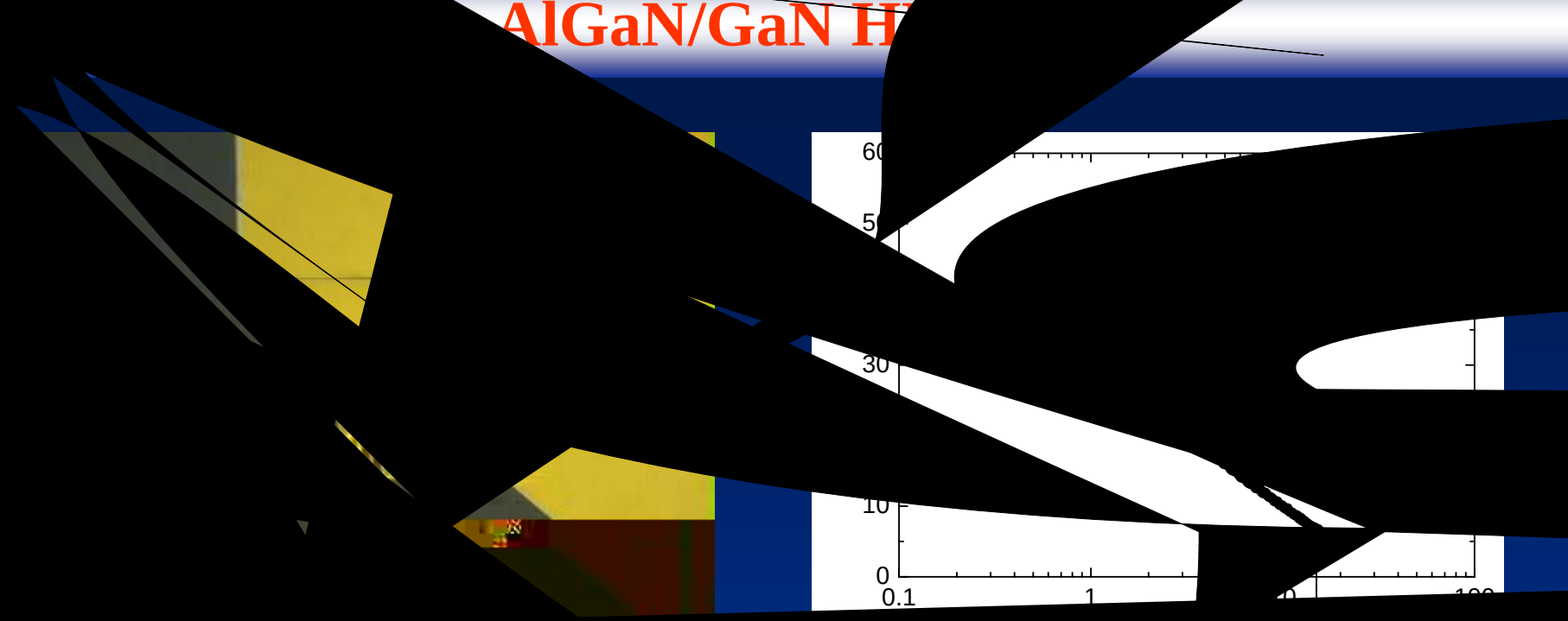
n_{300K}=1.42E13cm^{-2}；n_{77K}= 1.34E13cm^{-2}

μ_{300K}=1031cm²/Vs； μ_{77K}= 5207cm²/Vs

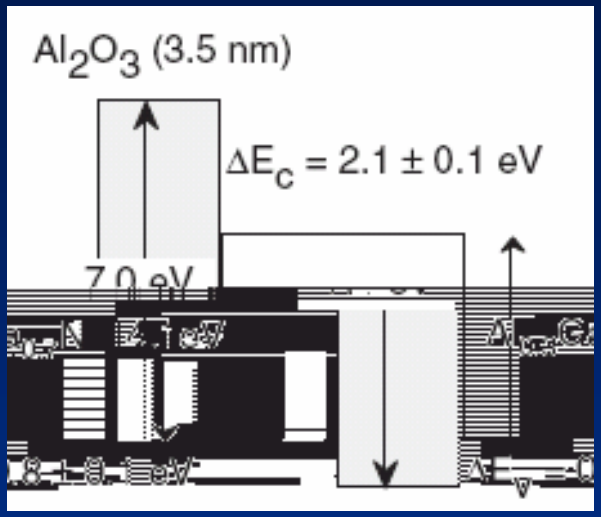
n_{300K}=1.31E13cm^{-2}；n_{77K}= 1.26E13cm^{-2}

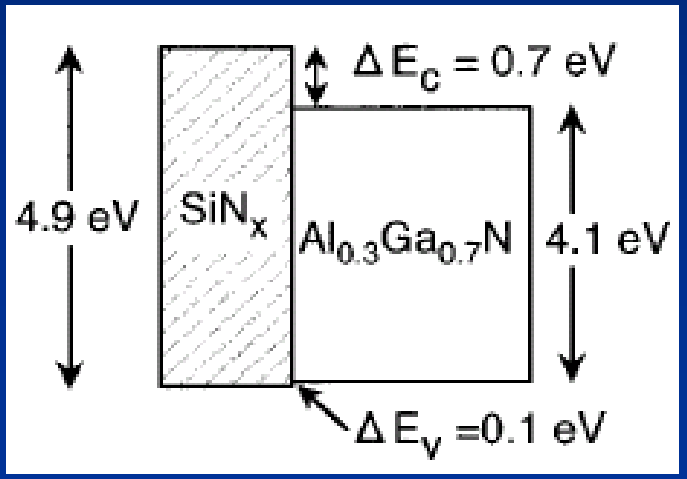


AlGaN/GaN H



原子层淀积Al_2O_3 /AlGaN高质量界面





	禁带宽度（eV）	介电常数	击穿电压 (MV/cm)
$Al_{0.3}Ga_{0.7}N$	4.1	9-9.5	>5
PECVD SiO_2	9	3.9	10
PECVD SiN	5	7	10
ALD Al_2O_3	7-9	9-10	>10

原子层淀积Al_2O_3 SEM, AFM分析

Fig.1. SEM观测到的Al_2O_3(3.5 nm) / AlGaN表面，白色亮点为AlGaN中缺陷

Fig.2. SEM观测到的Al_2O_3/Si表面，几乎没有缺陷

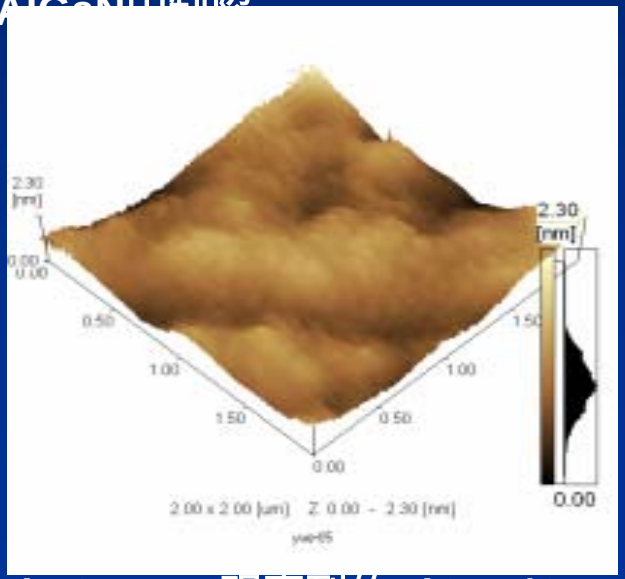


Fig.3. AFM观察到的AlGaN/GaN表面三维图形(Rms=0.278nm)

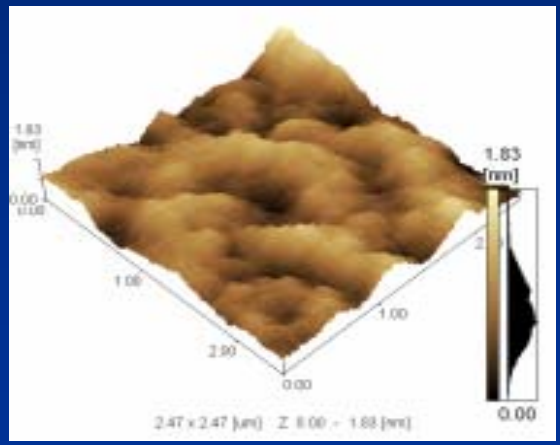
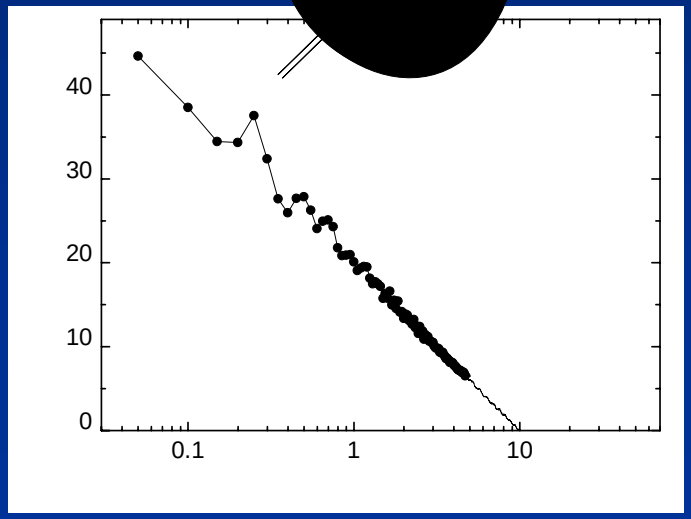
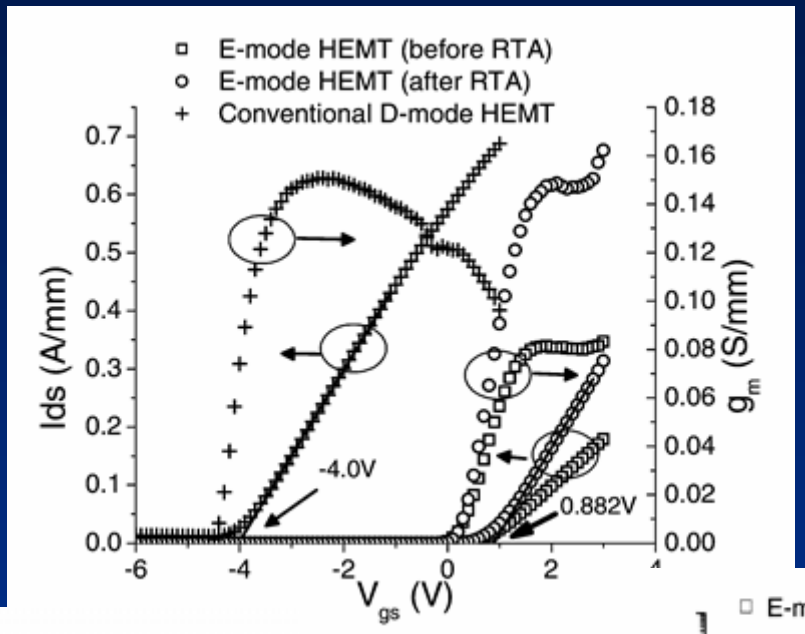


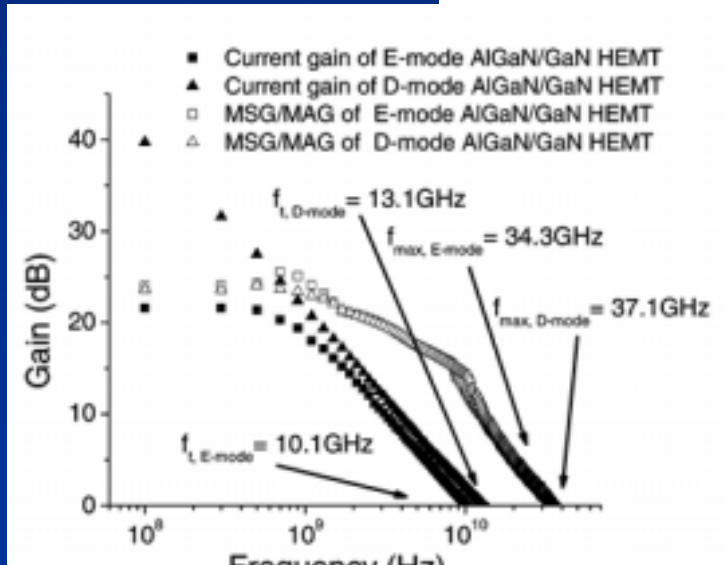
Fig.4. AFM观察到的Al_2O_3(3.5nm) /AlGaN 表面三维图形(Rms=0.268nm)

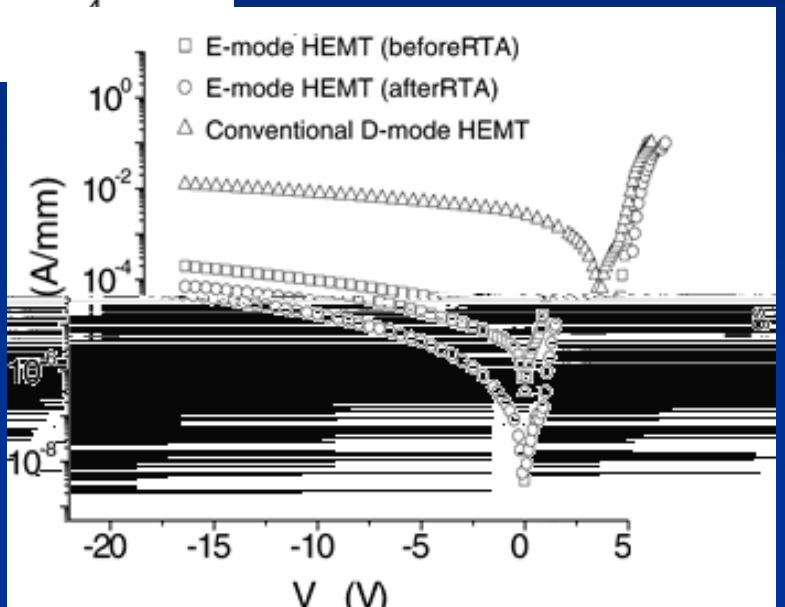
GaN HEMT新结构 MOS-HEMT



增强型（Enhancement Mode) HEMT







结 论

超高速是集成电路追究的主要目标，高速宽带的信息处理是主要的应用驱动。

- 依靠缩小线宽提高速度越来越困难，还在不断发展
- 设计技术是提高速度的有效方法，空间还很大
- 新型材料是增强速度的有效手段，潜力无限

实现基于材料和器件的设计技术

基于设计的器件和材料技术

谢 谢 !