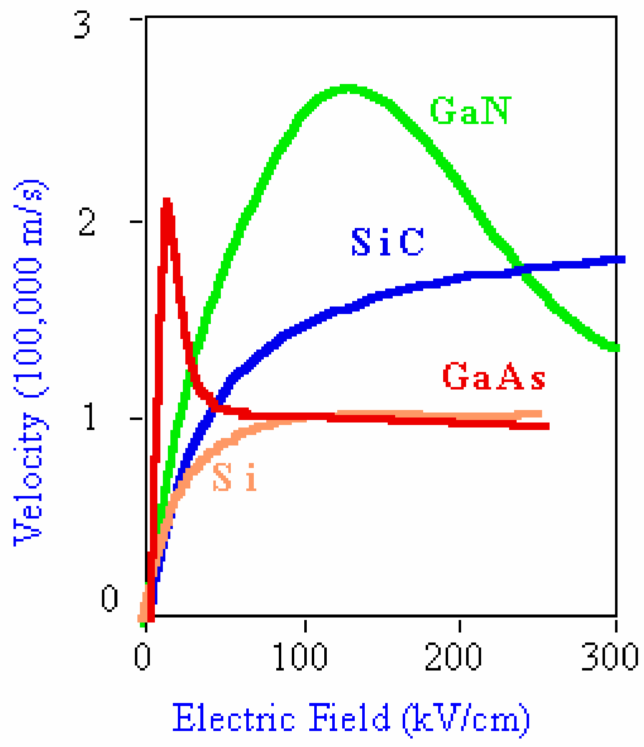
화합물 반도체 (I-2)
Introduction & Material Properties

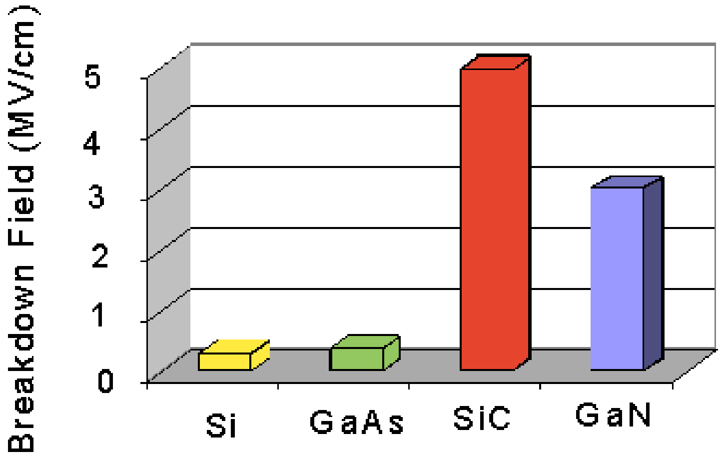
2007 / 가을 학기

Wide Bandgap Materials for High Power RF Devices

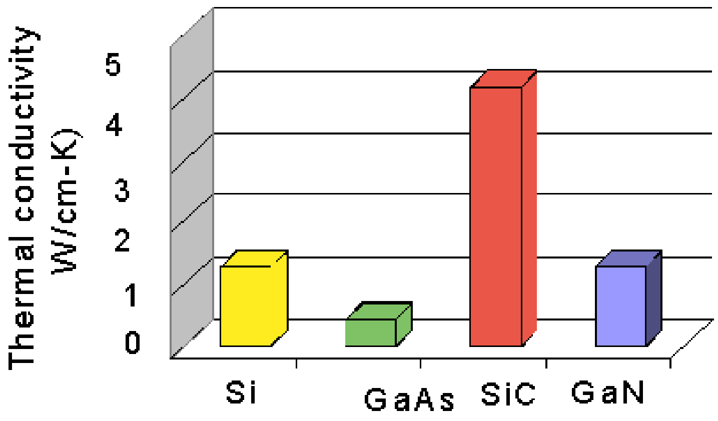
High Drift Velocity



High Breakdown Field

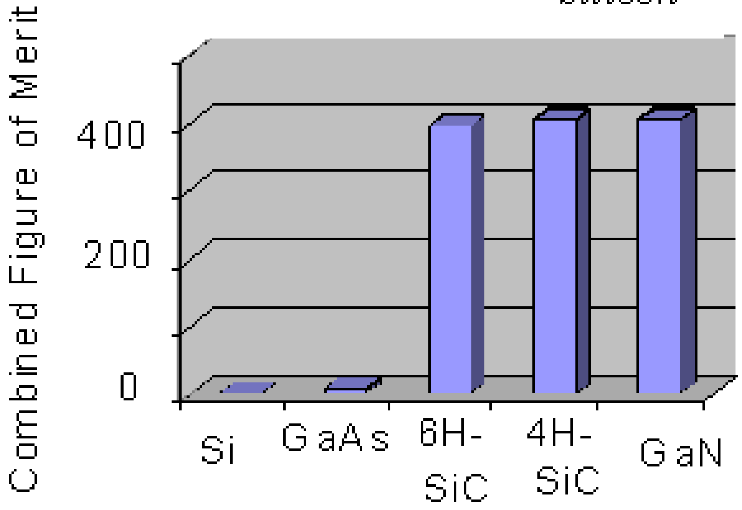


Thermal Conductivity



Combined Figure of Merit - high frequency/high power

$$CFOM = \frac{\chi \varepsilon_O \mu v_S E_B^2}{\left(\chi \varepsilon_O \mu v_S E_B^2\right)_{silicon}}$$



(* Huang : $\text{HMFOM} = E_c\sqrt{\mu}$)

Material	Combined Factor of Merit (CFOM)
Si	1
GaAs	7.36
6H-SiC (disregarding anisotropy of mobility)	393
4H-SiC	404
GaN	404
Diamond	30080

Various Figure-of-Merits for Power Devices (Ref.: A. Q. Huang, IEEE T-ED, 2004)

$$\text{BFOM} = \varepsilon \mu E_C^3$$

- conductive loss

$$\text{BHFFOM} = \frac{1}{(R_{\text{on,sp}} C_{\text{in,sp}})}$$

- including switching loss

$$\text{NHFFOM} = \frac{1}{(R_{\text{on,sp}} C_{\text{oss,sp}})}$$

- driving reactive load

USA's GaN Electronic Device Program (I)

Table 1. DARPA's three-track attack

Track/module type	*Prime contractor*	*Funding (Phase II)*	*Required module output power*	*Companies also on team*
1: X-band transmit/receive module	Raytheon	$26.9 million (up to $59.4 million)	60 W continuous wave	Cree
2: Q-band high-power amplifier module (more than 40 GHz)	Northrop Grumman Space Technologies	$16.5 million (up to $53.4 million)	20 W continuous wave	Monolithics, Emcore, Boeing, Sirenza Micro Devices
3: Wideband high-power amplifier module (2–20 GHz)	TriQuint Semiconductor	$15.8 million (up to $31.7 million)	100 W continuous wave	BAE Systems, Lockheed-Martin, II-VI, Nitronex, Emcore

Taken from DARPA's broad agency announcement

- launched from 2005
- supported by DARPA
(from Compound Semiconductor(CS) magazine, May 2005)
http://compoundsemiconductor.net/articles/magazine

USA's GaN Electronic Device Program (II)

Table 2. DARPA's 18 and 30 month "go/no-go" targets

Target	*Track 1*	*Track 2*	*Track 3*
18 months	8–12 GHz transistor with a 1.25 mm gate periphery operating at 40 V with 39 dBm continuous-wave output power, 12 dB gain, a PAE of 60%, a wafer yield of 50% and 10^5 hours' projected performance	Q-band transistor with a 0.5 mm gate periphery operating at 25 V with 39 dBm continuous-wave output power, 8 dB gain, a PAE of 35%, a wafer yield of 50% 10^5 hours' projected performance	As for Track 1
30 months	8–12 GHz power-amplifier MMIC operating at 48 V with 15 W continuous-wave output power, 16 dB gain, a PAE of 55% and a wafer yield of 50%	Q-band MMIC operating at 28 V with 4 W continuous-wave output power, 7.5 dB gain, a PAE of 37% and a wafer yield of 50%	2–20 GHz power-amplifier MMIC operating across a decade of bandwidth at 48 V with 15 W continuous-wave output power, 16 dB gain, a PAE of 30%, and a wafer yield of 50% (at least 12 three-inch wafers)

Taken from DARPA's broad agency announcement – actual program goals have been modified slightly

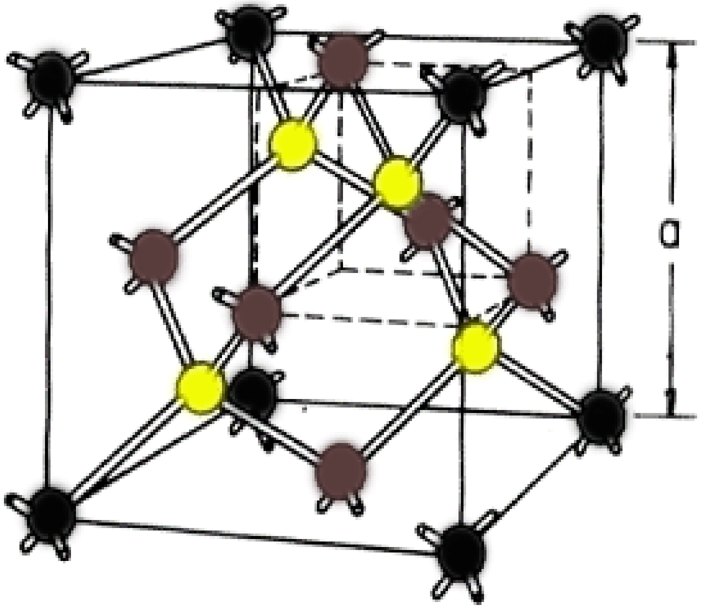
(from Compound Semiconductor(CS) magazine, May 2005)

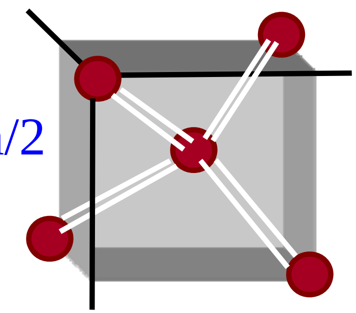
http://compoundsemiconductor.net/articles/magazine

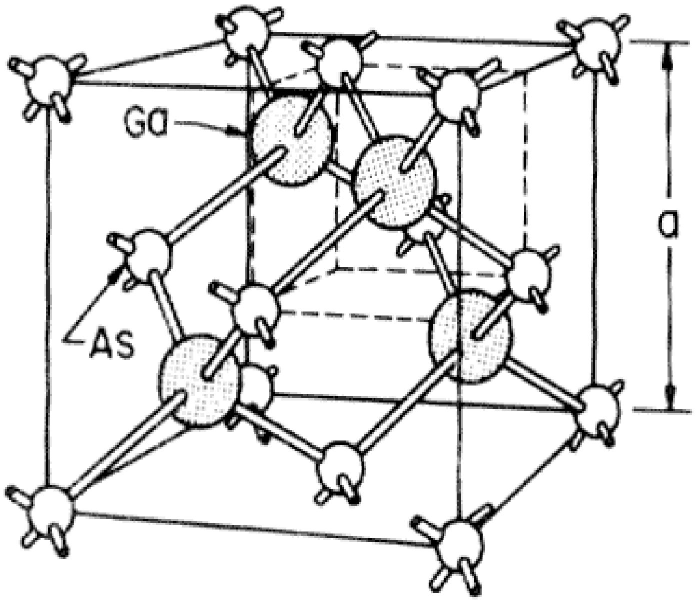
Lattice Structure of Basic Semiconductors (I)

2 FCC (Face Centered Cubic) cells – separation (a/4, a/4, a/4)

- Diamond Structure; Si - 1Si FCC cell + 1Si FCC cell
- Zincblende Structure; GaAs - 1 Ga FCC cell + 1As FCC cell



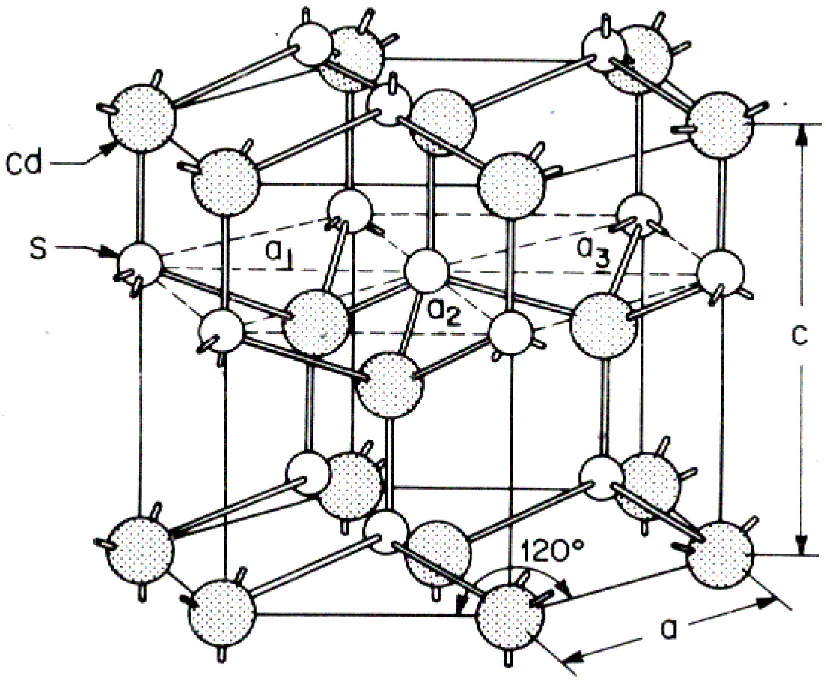




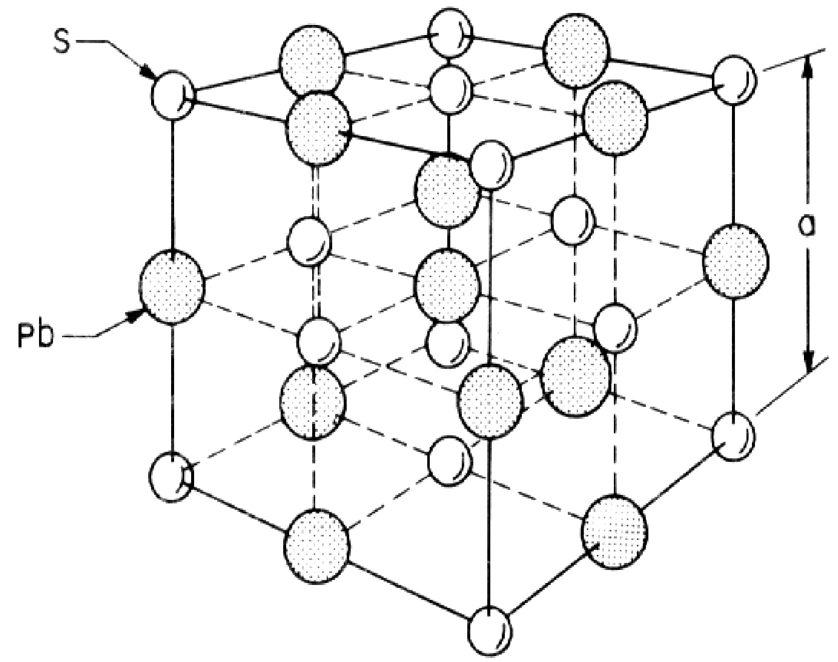
Diamond Structure
ex) Si, Ge, C …

Zincblende Structure
ex) GaAs, GaP …3-5

Lattice Structure of Basic Semiconductors (II)

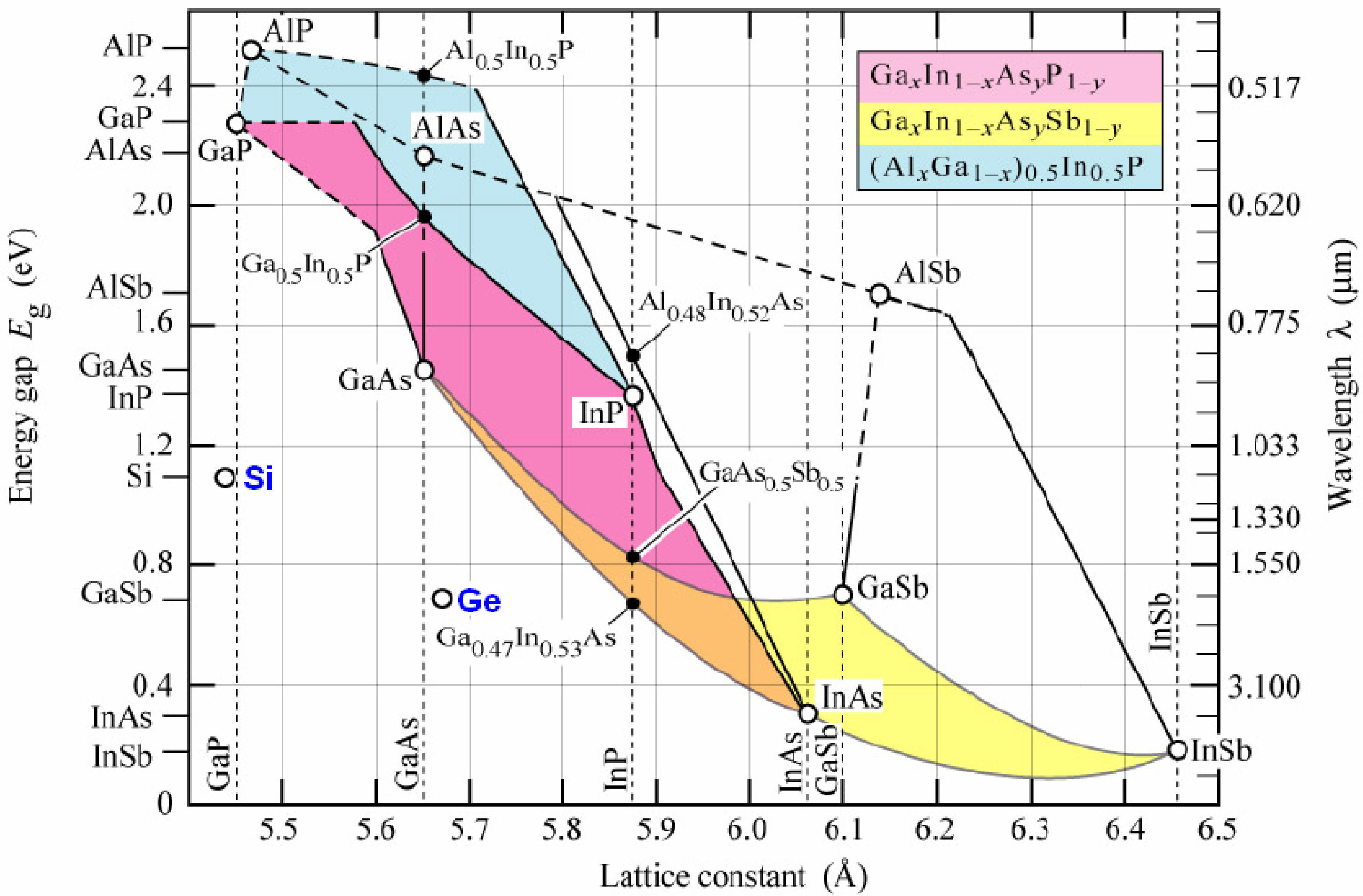


Wurtzite Structure
ex) CdS, ZnS …2-6



Rock-salt Structure
ex) PbS, PbTe …4-6

Various III-V Semiconductors

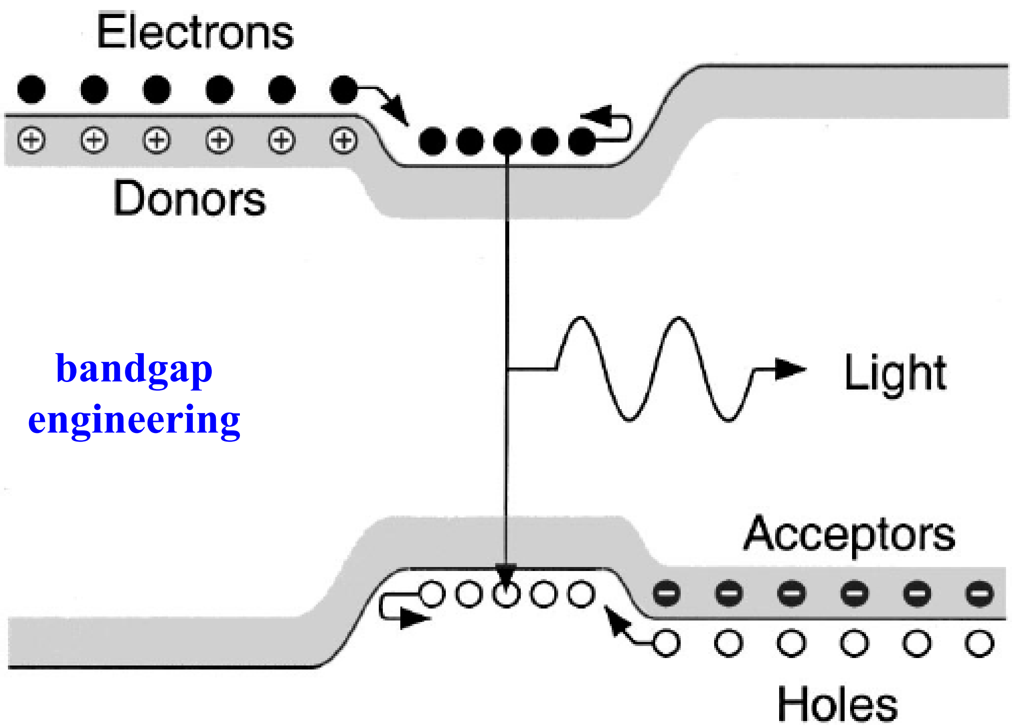


— direct bandgap
- - indirect bandgap

cubic
↓
diamond 구조
zinc-blende 구조

* 같은 lattice constant를 갖는 반도체 - GaAs/AlAs or InAs/GaSb/AlSb : GaAs substrate
$InP/In_{0.53}GaAs/In_{0.48}AlAs$: InP substrate

Double Heterostructure LED & Laser Diode



bandgap engineering

Potential Well (Quantum Well)을 활용한 발광

- 효율적인 전자와 hole의 재결합
- 전하와 빛의 confinement
- 발광 효율 개선

2000 Nobel Prize in Physics
- H. Kroemer
- Z. Alferov

(with J. Kilby for IC Invention)

Nobel Lectures (Reviews of Modern Physics, Volume 73, July 2001)

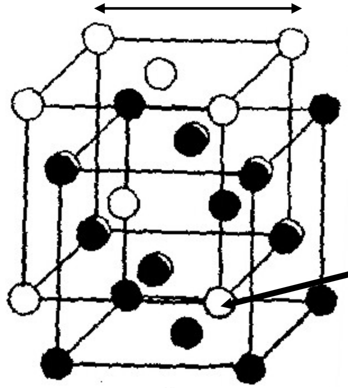
- **H. Kroemer, "Quasielectric fields and band offsets: teaching electrons new tricks"**
- **Z. I. Alferov, "The double heterostructure concept and its applications in physics, electronics, and technology"**

III-V Compound의 crystal 구조

*** Crystal structure**

$$\psi(\mathbf{r}) = e^{i\mathbf{k}\cdot\mathbf{r}} u_{n\mathbf{k}}(\mathbf{r})$$

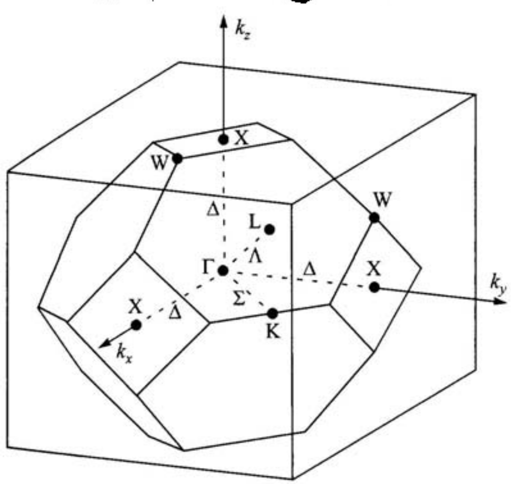
a: lattice constant



Real Space

<Zinc-Blende 구조>

(-1/4,1/4,1/4)

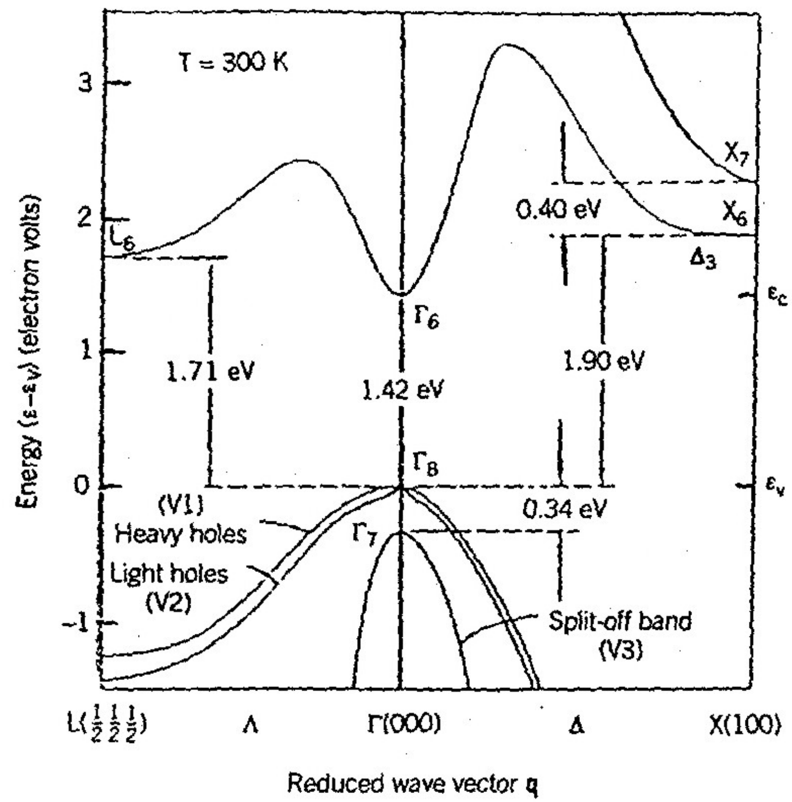


k Space

<Reciprocal Lattice>

(Ref.) Sze, 1.2.2

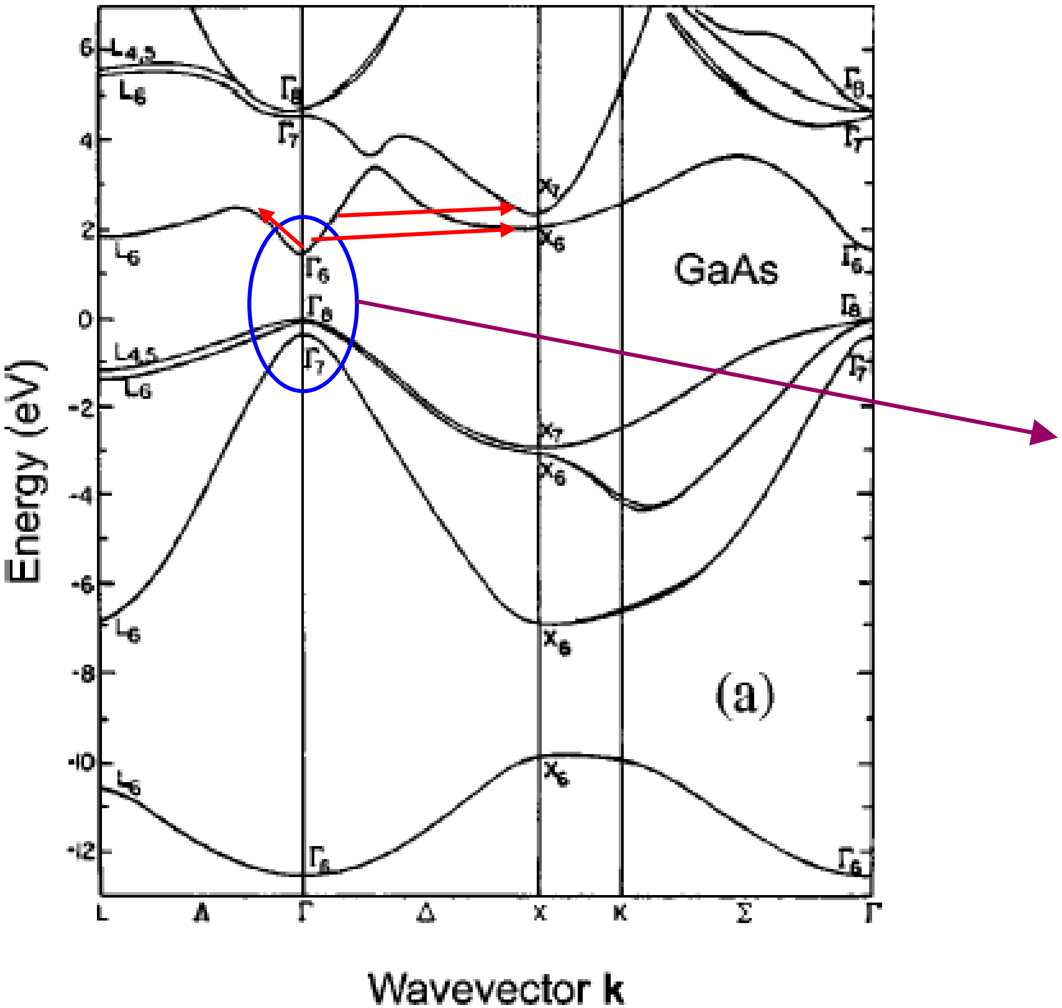
*** Energy Band-gap diagram**



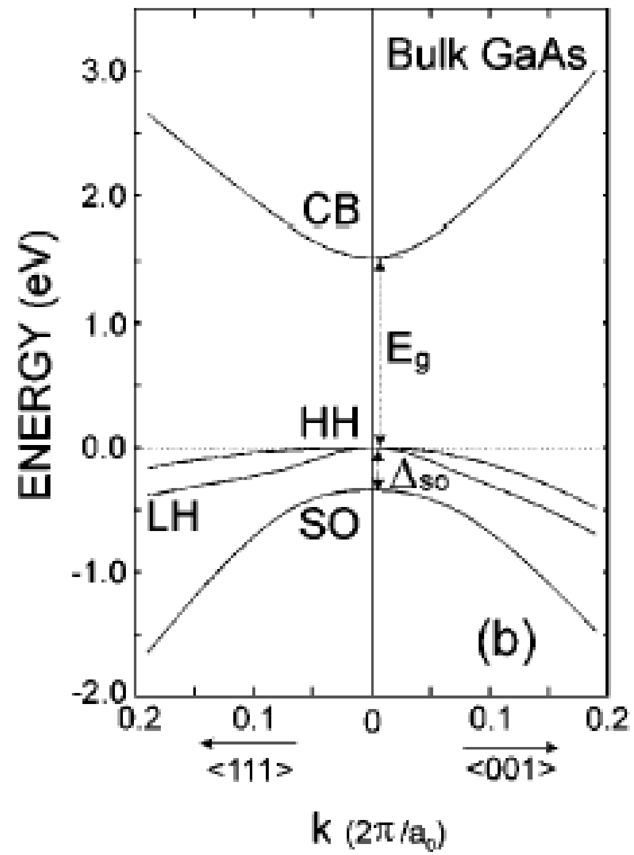
*** Energy gap ∝ (Lattice constant)** $^{-1}$

*** conduction band -** Γ_6**,** L_6**,** X_6 **valley**

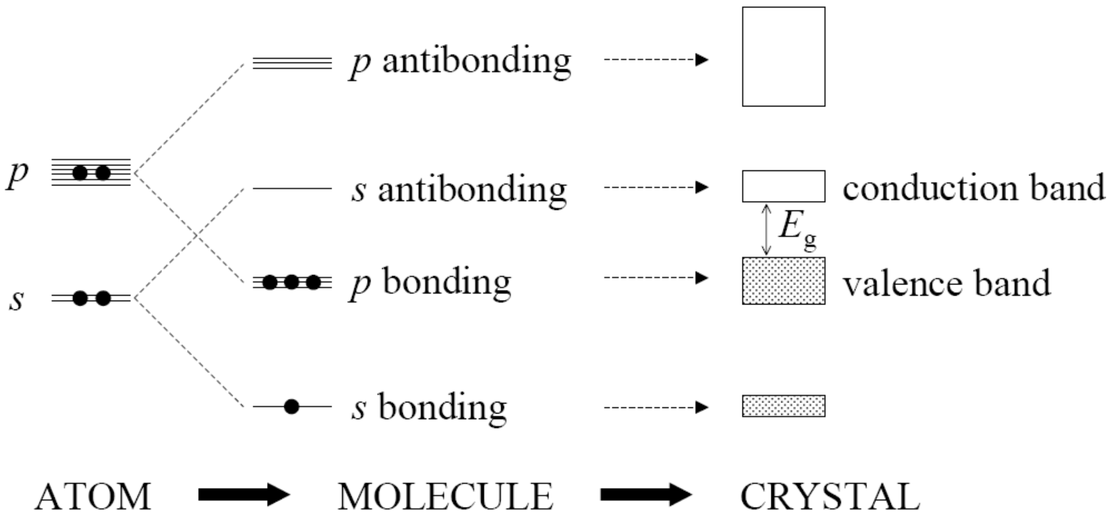
GaAs의 Energy Band 구조



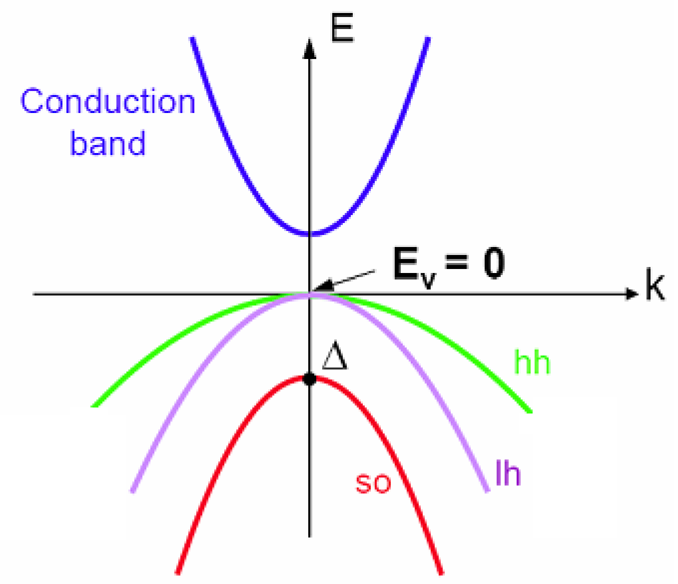
- Intra-valley Scattering
- Inter-valley Scattering
- Inter-band Scattering



Atomic Physics of Semiconductors

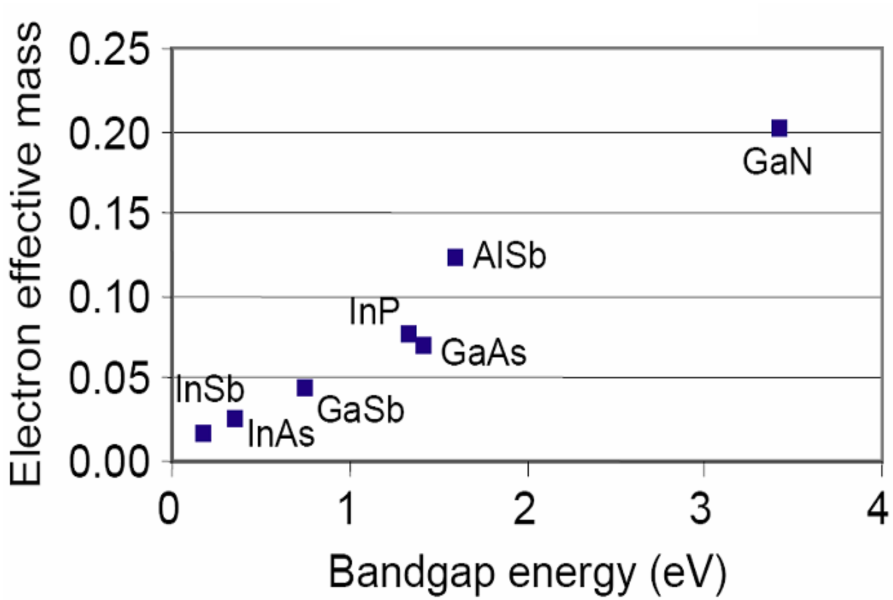


Four band model (direct bandgap)



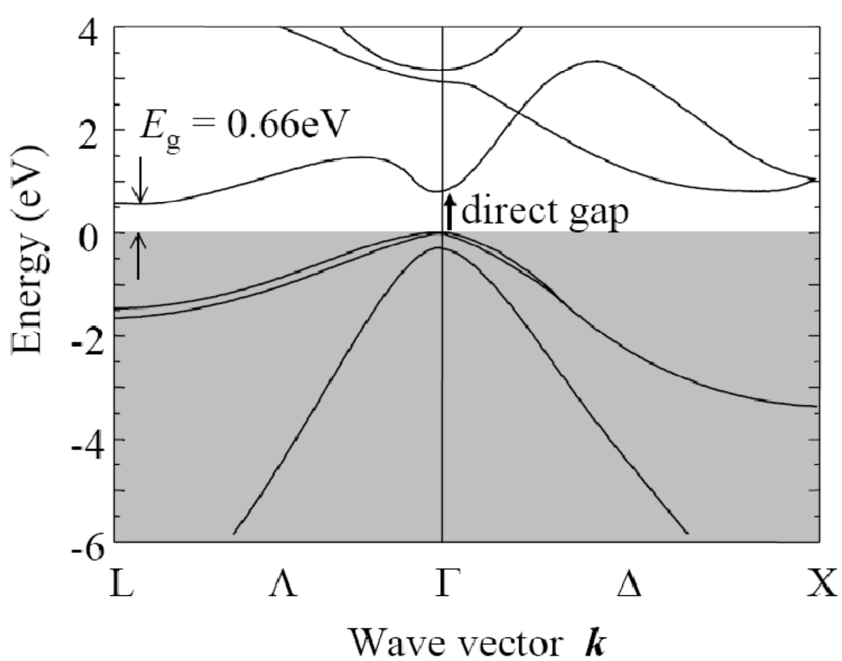
$$\frac{1}{m^*} = \frac{1}{\hbar^2}\frac{\partial^2 E}{\partial k^2}$$

Electron Effective Mass



$$\frac{1}{m_e^*} \approx \frac{1}{m_e}\left(1+\frac{20eV}{E_g}\right)$$

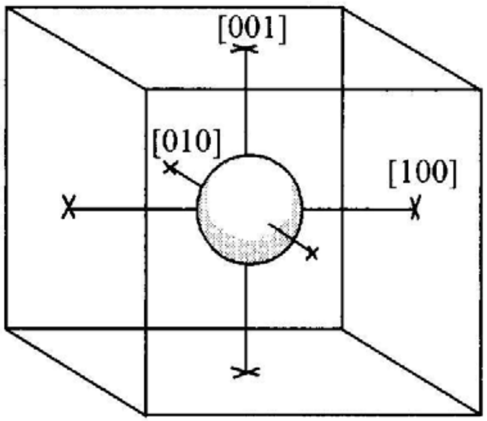
Germanium Band Structure



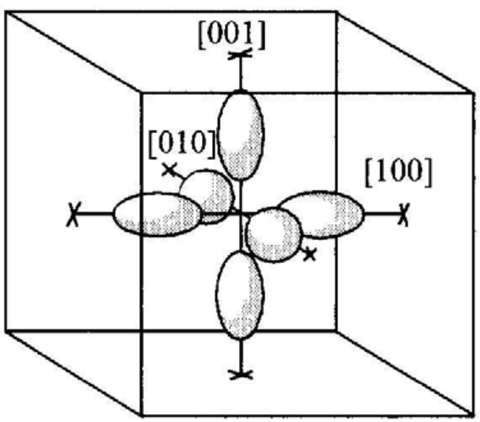
- **Indirect gap at 0.66 eV**
- **Direct gap at 0.80 eV**

Constant Energy Surfaces

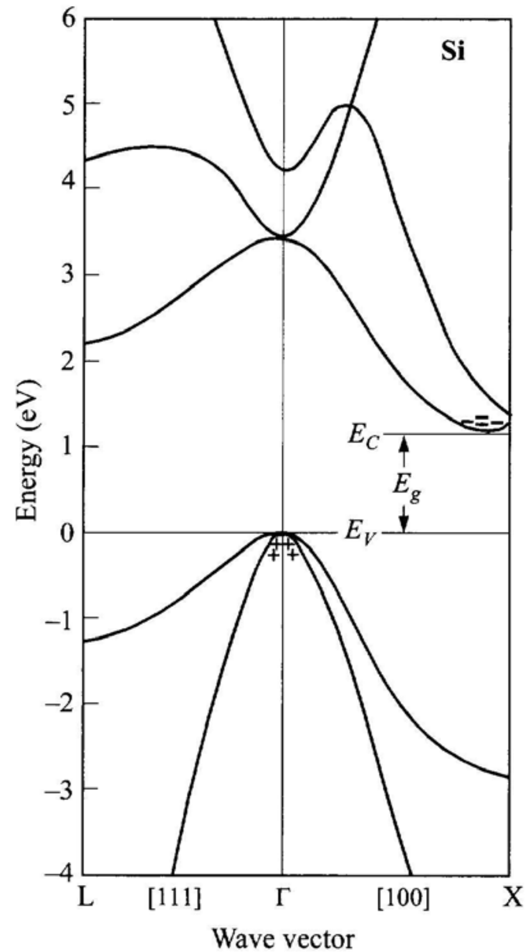
Electrons in Conduction Band



GaAs

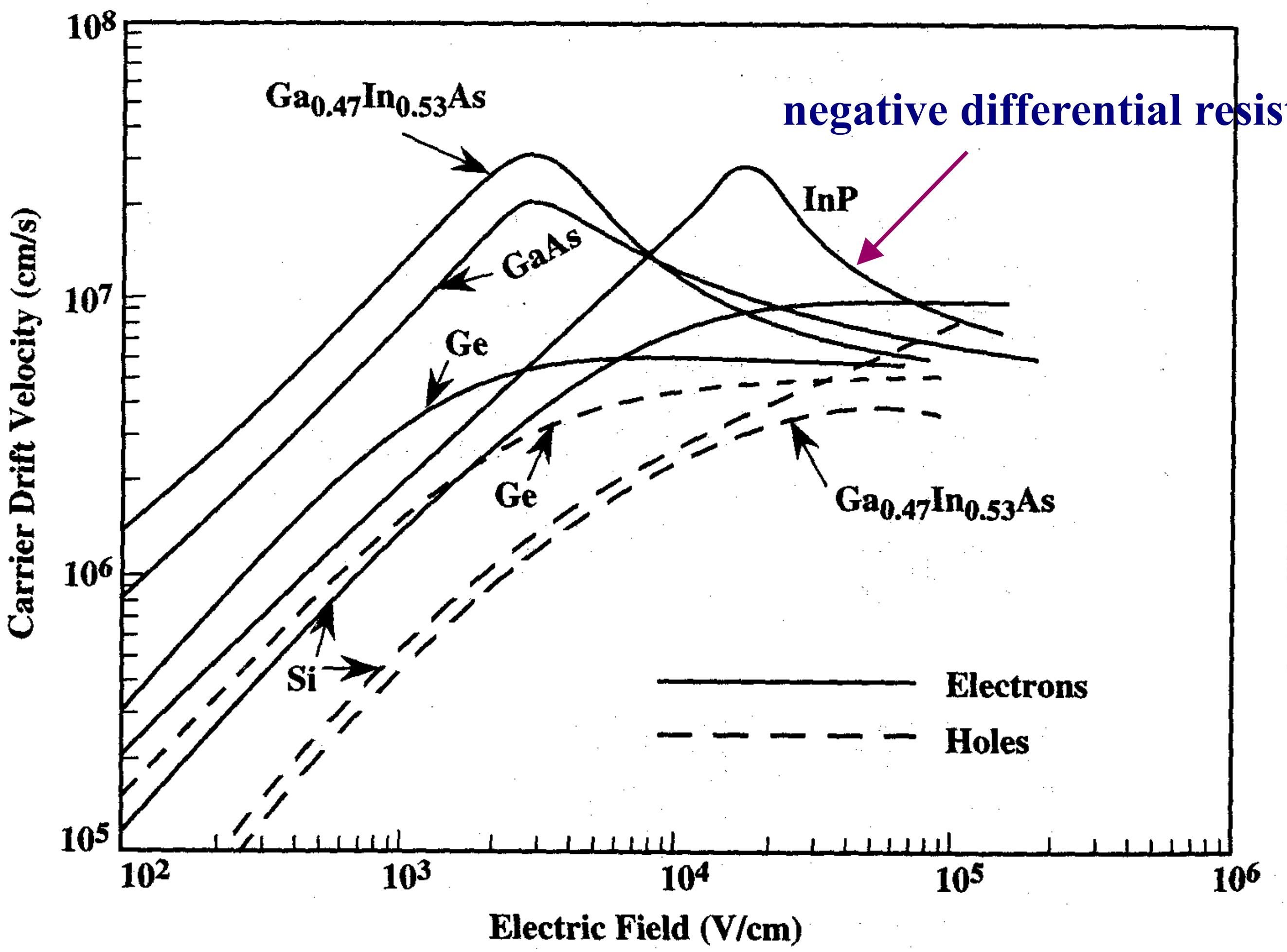


Si



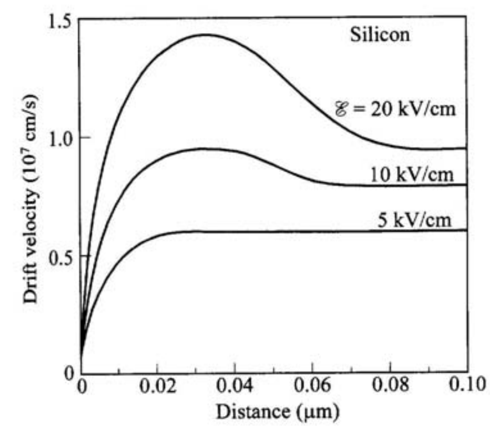
(Ref.) Sze, 1.3

Compound Semiconductor의 전기적 특성



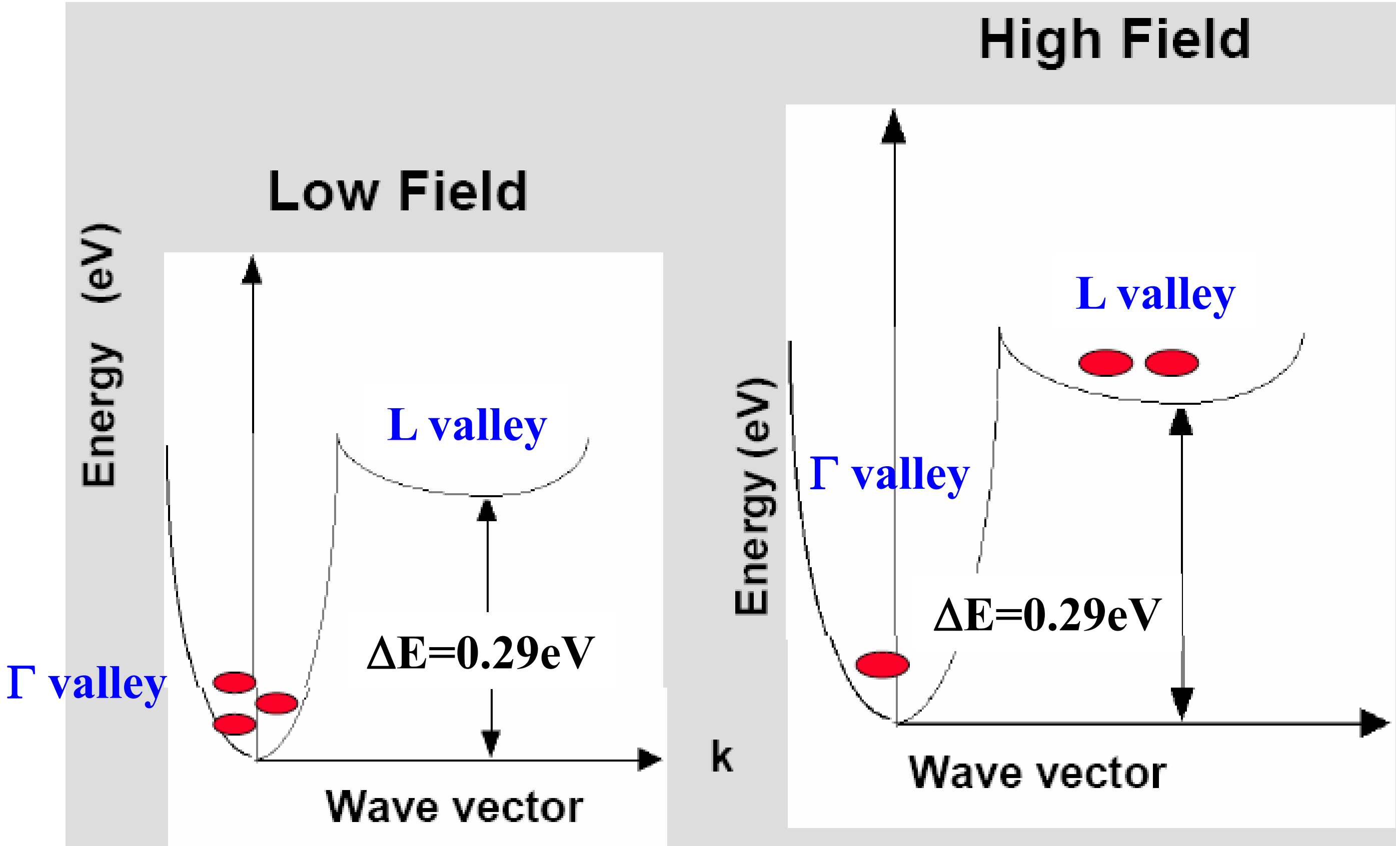
- Ballistic Transport
- Velocity Overshoot

(Ref. : Sze, 1.5.3)



- ◆ 전자의 effective mass $\propto 1/E_g$
- ◆ Breakdown Field $\propto E_g$

Inter-valley Transfer in GaAs Conduction Band



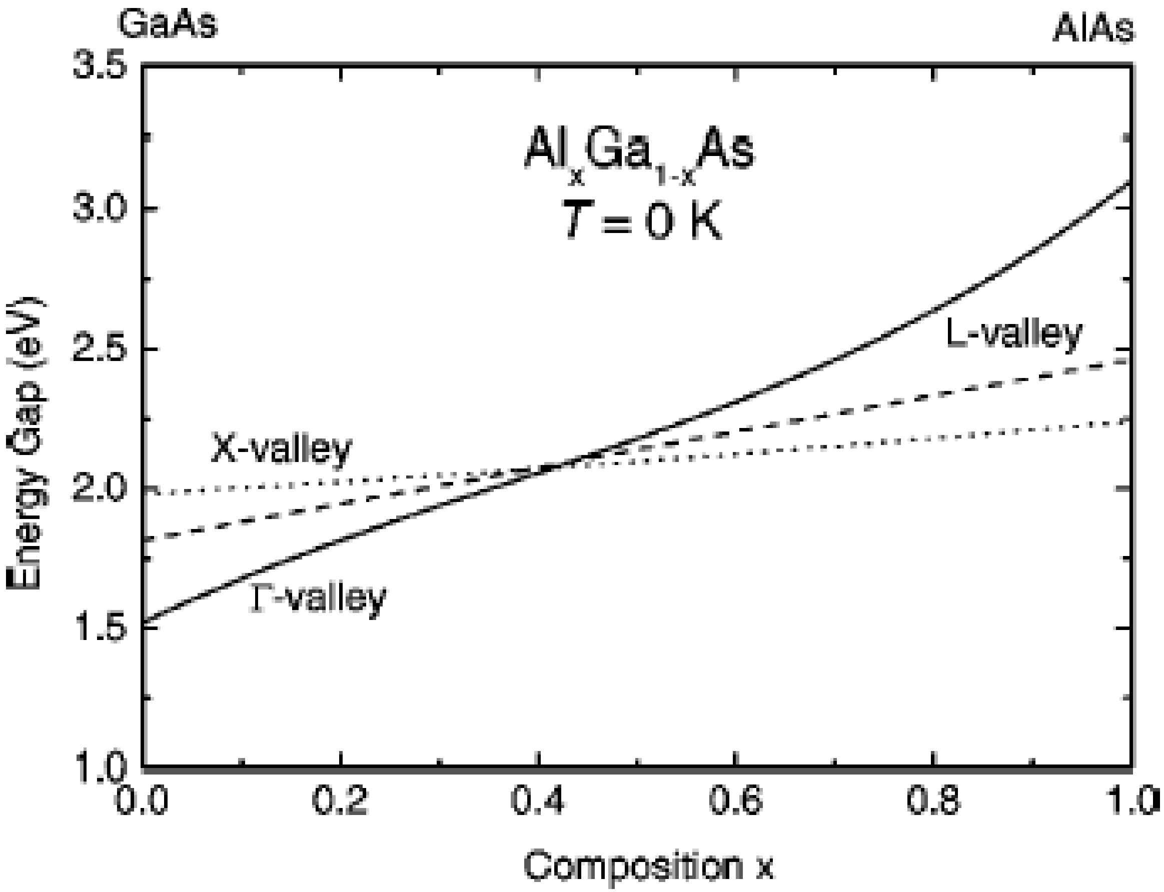
$$v_g = \frac{\partial \omega_n(\mathbf{k})}{\partial k} = \frac{1}{\hbar}\frac{\partial E_n(\mathbf{k})}{\partial k}$$

$$\frac{1}{m^*} = \frac{1}{\hbar^2}\frac{\partial^2 E_n}{\partial k^2}$$

$$n = n_\Gamma + n_L + n_X$$

$$\mathbf{v} = \left(n_\Gamma \mathbf{v}_\Gamma + n_L \mathbf{v}_L + n_X \mathbf{v}_X\right)/\, n$$

AlGaAs Lattice-Matched to GaAs Substrate



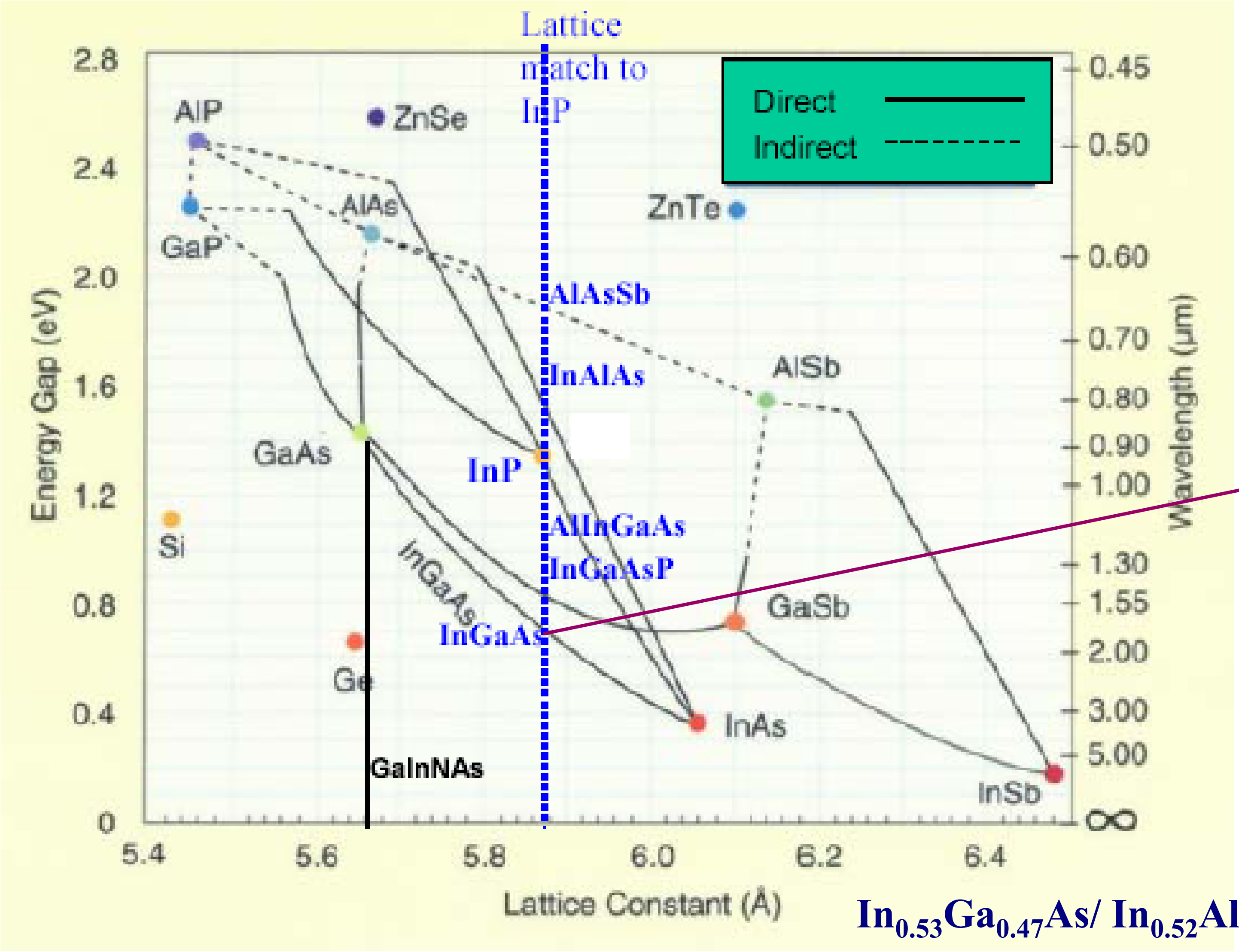
Industry Standard

- **6 inch GaAs wafer**
- **4 inch InP wafer**

$$E_g(A_{1-x}B_x) = (1-x)E_g(A) + xE_g(B) - x(1-x)C$$

bowing parameter C

InP-based Material System

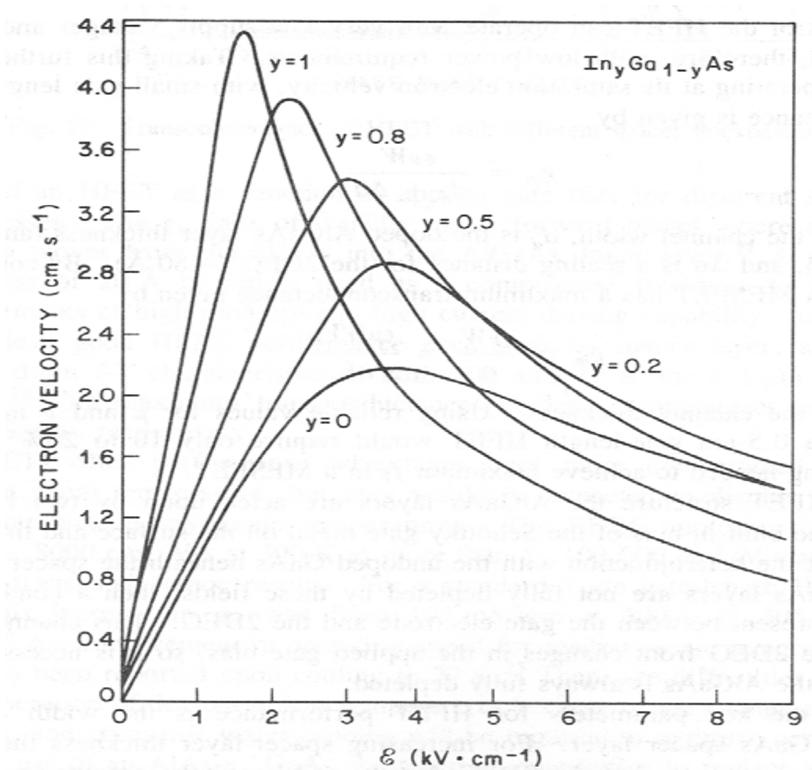


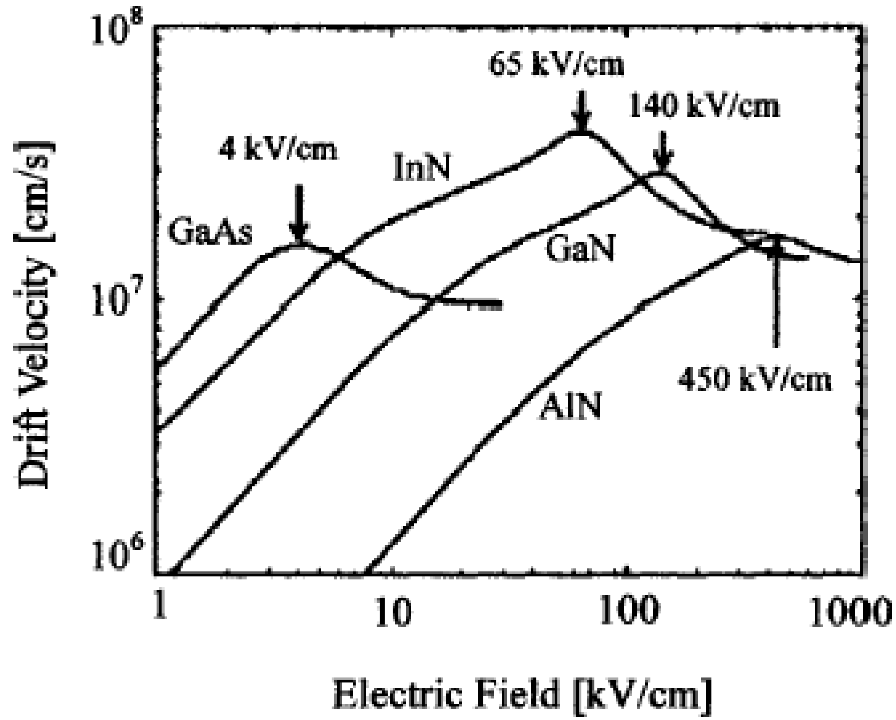
$In_{0.53}Ga_{0.47}As$

- **1.55 μm 광통신**
- **초고속 시스템**

$In_{0.53}Ga_{0.47}As$/ $In_{0.52}Al_{0.48}As$/InP System

v-E Characteristics of InGaAs & Nitride Semiconductors

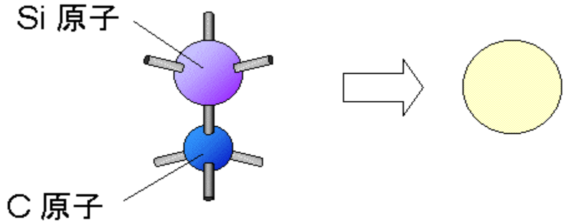


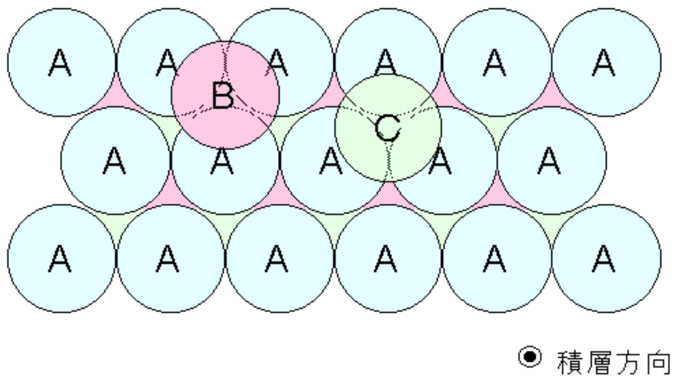


- Monte Carlo Calculation (Hess)
: Unstrained InGaAs

material	υ_{peak} (10^7 cm/s)
InN	4.2
GaN	2.9
AlN	1.7
GaAs	1.6

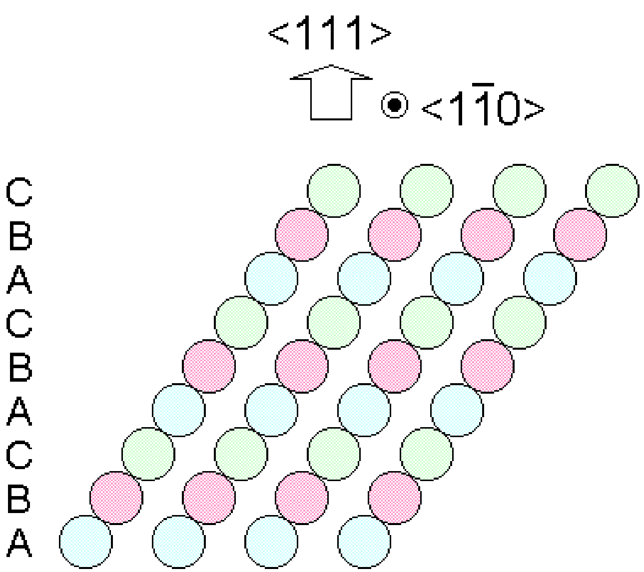
SiC Crystal Structures



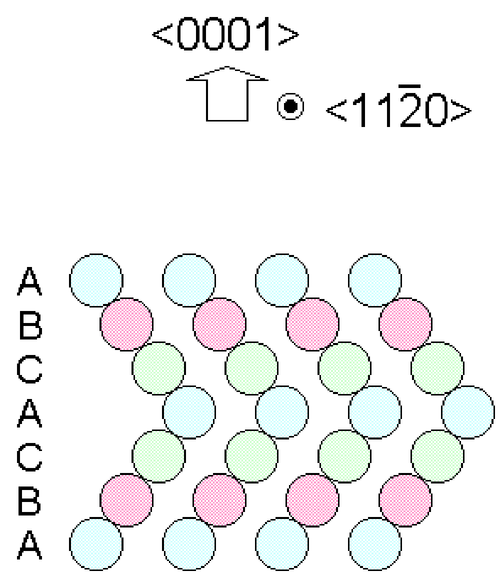


Closely-Packed Crystal Structures

Stacking Order of 3C-SiC



Stacking Order of 6H-SiC

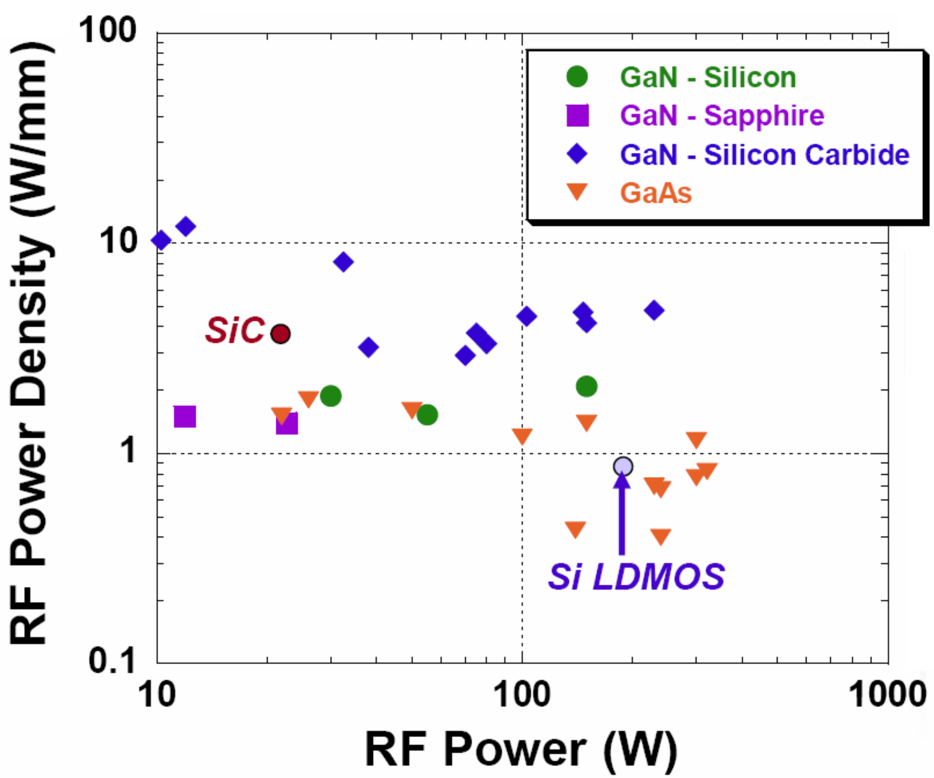


Properties of typical SiC polytypes and Si, GaAs, GaN

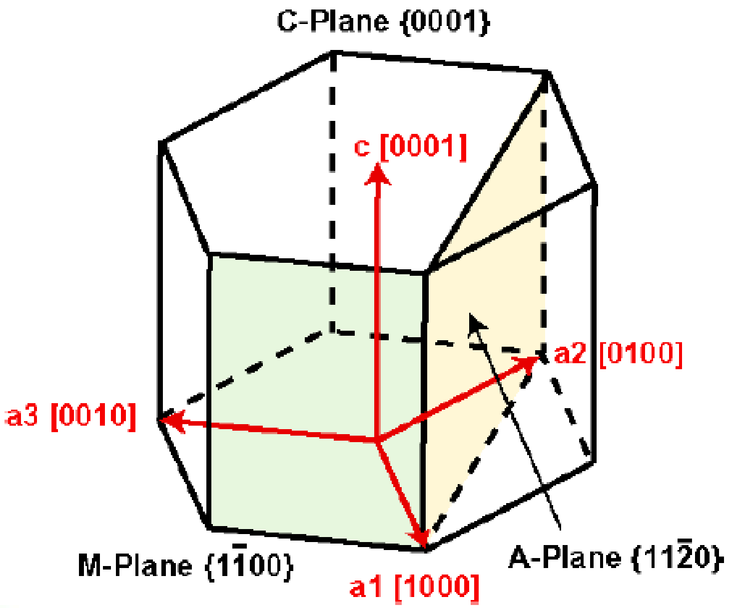
	SiC			Si	GaAs	GaN
Crystal Form	**3C** (ZB)	**6H**	**4H**	**dia.**	**ZB**	**W**
Band Structure	indirect				direct	
Bandgap [eV]	2.3	3.0	3.3	1.11	1.43	3.5
Electron Mobility [cm²/V s]	1000	450	900	1500	8500	900
Hole Mobility [cm²/V s]	50	50	100	600	400	30?
Breakdown Field [MV/cm]	2	3	3	0.3	0.4	3
Thermal Conductivity [W/cm K]	4.9	4.9	4.9	1.5	0.5	1.3
Electron Saturation Velocity [10^7cm/s]	2.7	2	2.7	1	2*	2.5
Dielectric Constant ε	9.7	9.7	9.7	11.8	12.8	9.5

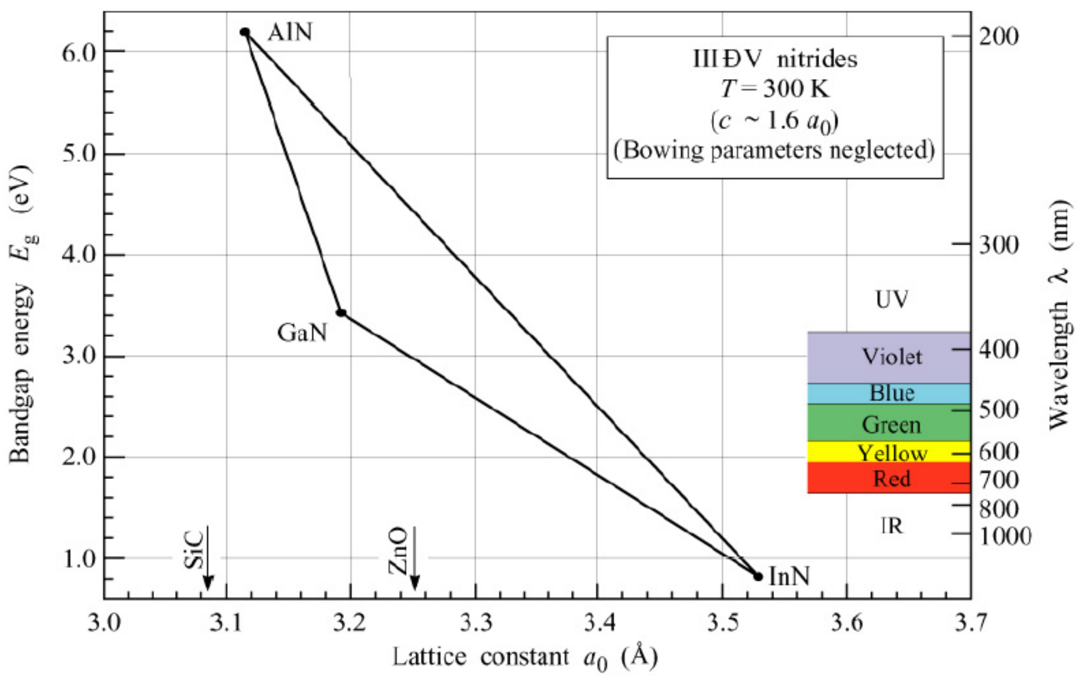
Various Substrate for GaN Power Amplifiers

	Sapphire	n-type SiC	s.i. SiC	GaN bulk	Si
Lattice mismatch (%)	13	3.1	3.1	0	17
Availability / Price (2“, $)	100	500	3000	not available	100
Thermal Conductivity (W/cmK)	0.3	4	4	1.3	1.48



Wurtzite GaN, InN, and AlN

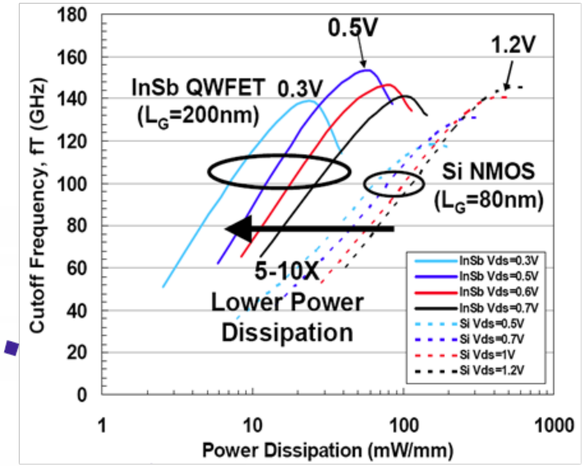




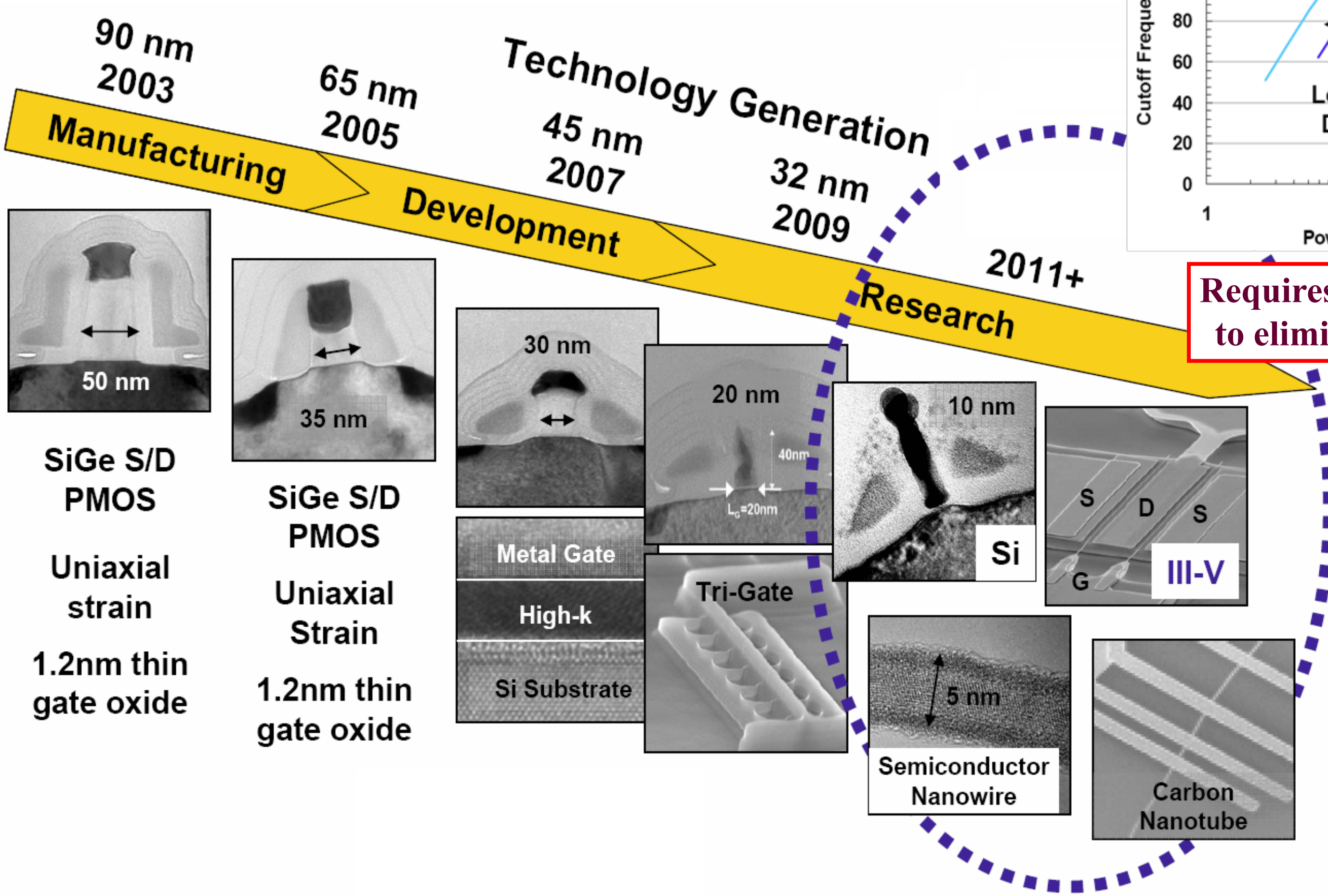
*** substrate for GaN/InN/AlN - Al_2O_3 (lattice mismatched)**
SiC (lattice mismatched)
GaN (lattice matched) : difficult to grow

Transistor Nanotechnology

(source) R. Chau, Intel

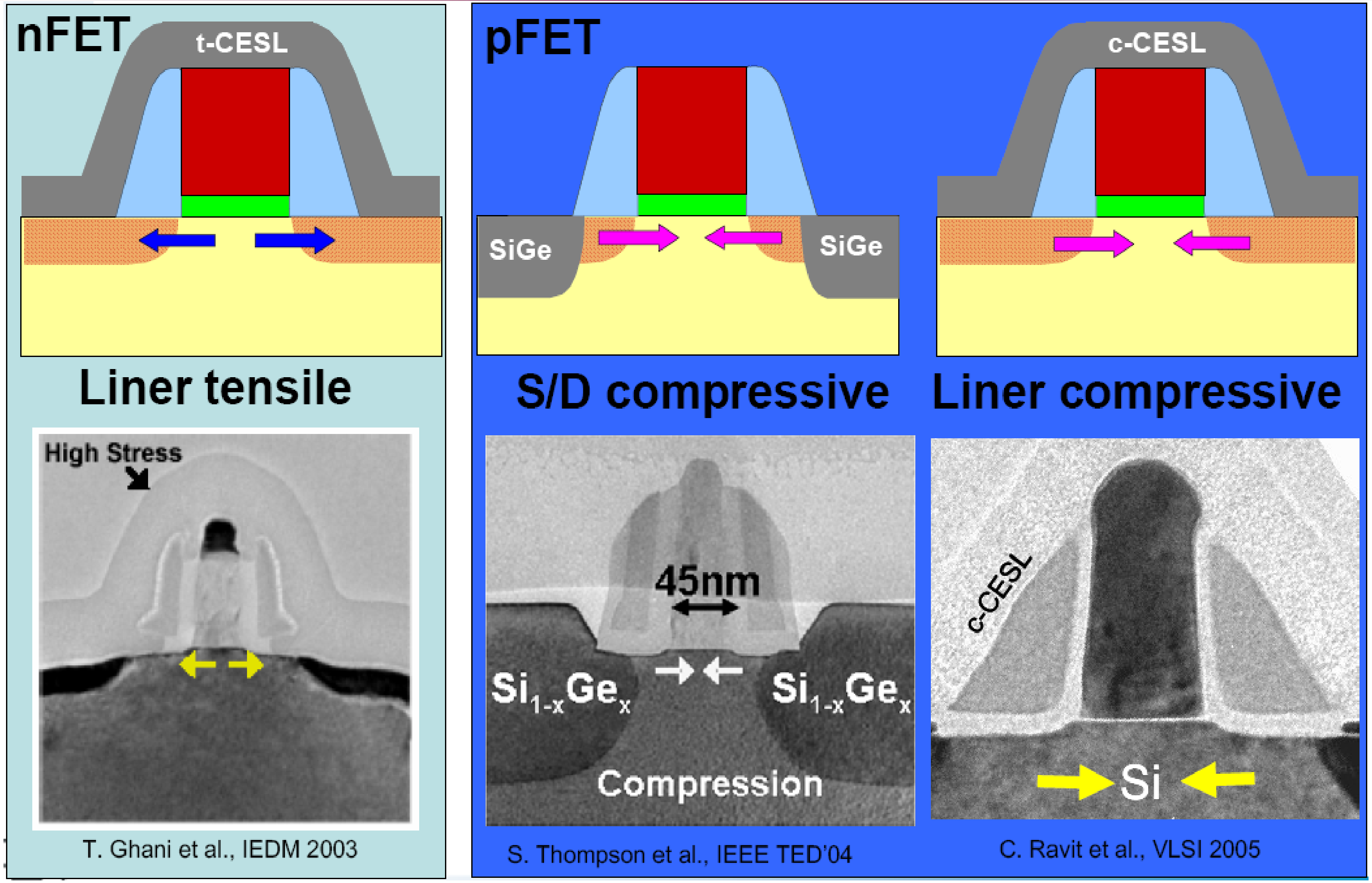


Requires a high-k/metal-gate to eliminate Schottky I_{GATE}



Emerging Nanoelectronic Devices

Strained Si MOSFET - 45nm node

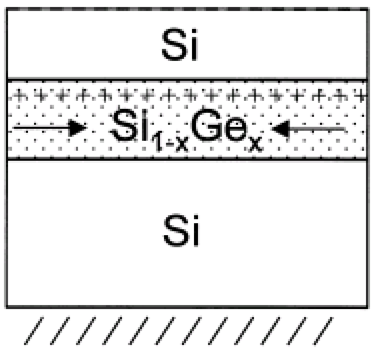


INTEL, 45nm Node

(Ref.) T. Ernst, 2006

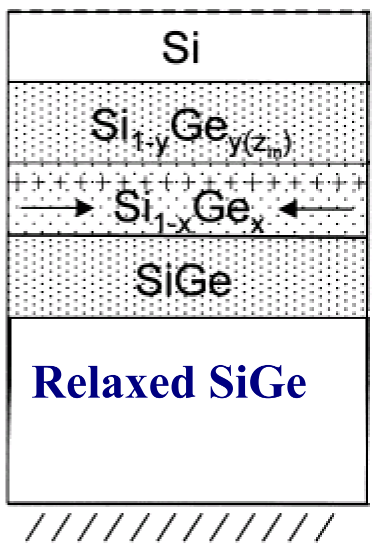
Valence Band of SiGe in Compressive Strain

*** Pseudomorphic**



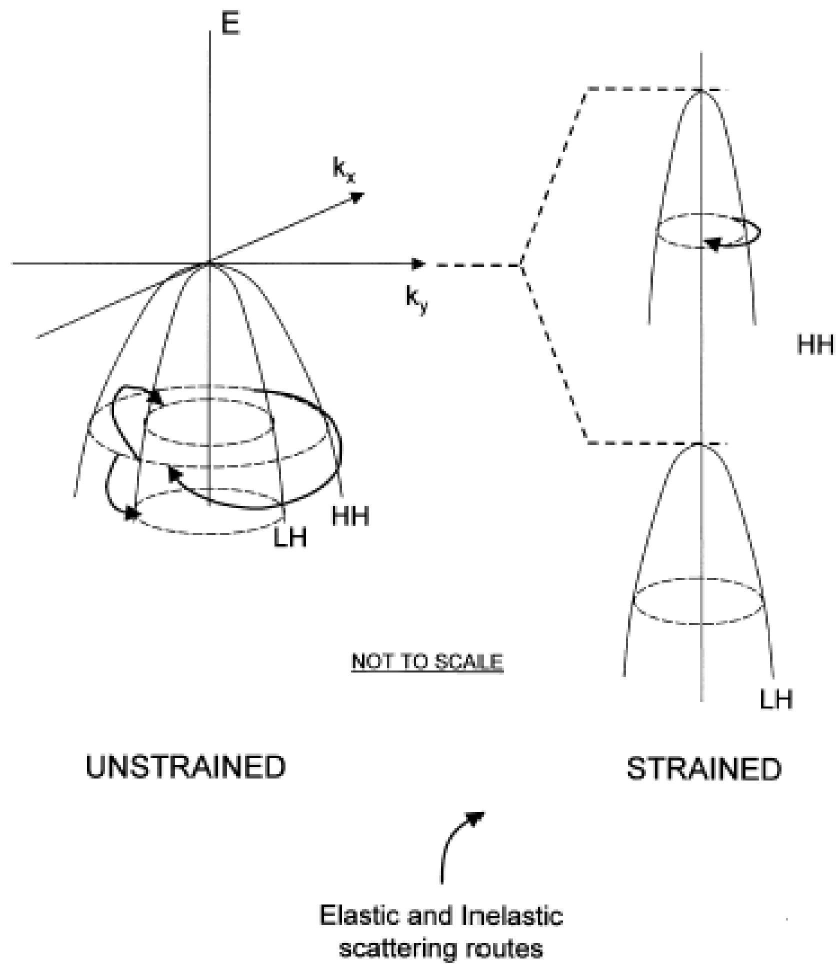
$x \leq 0.5$

*** Virtual Substrate - Metamorphic**

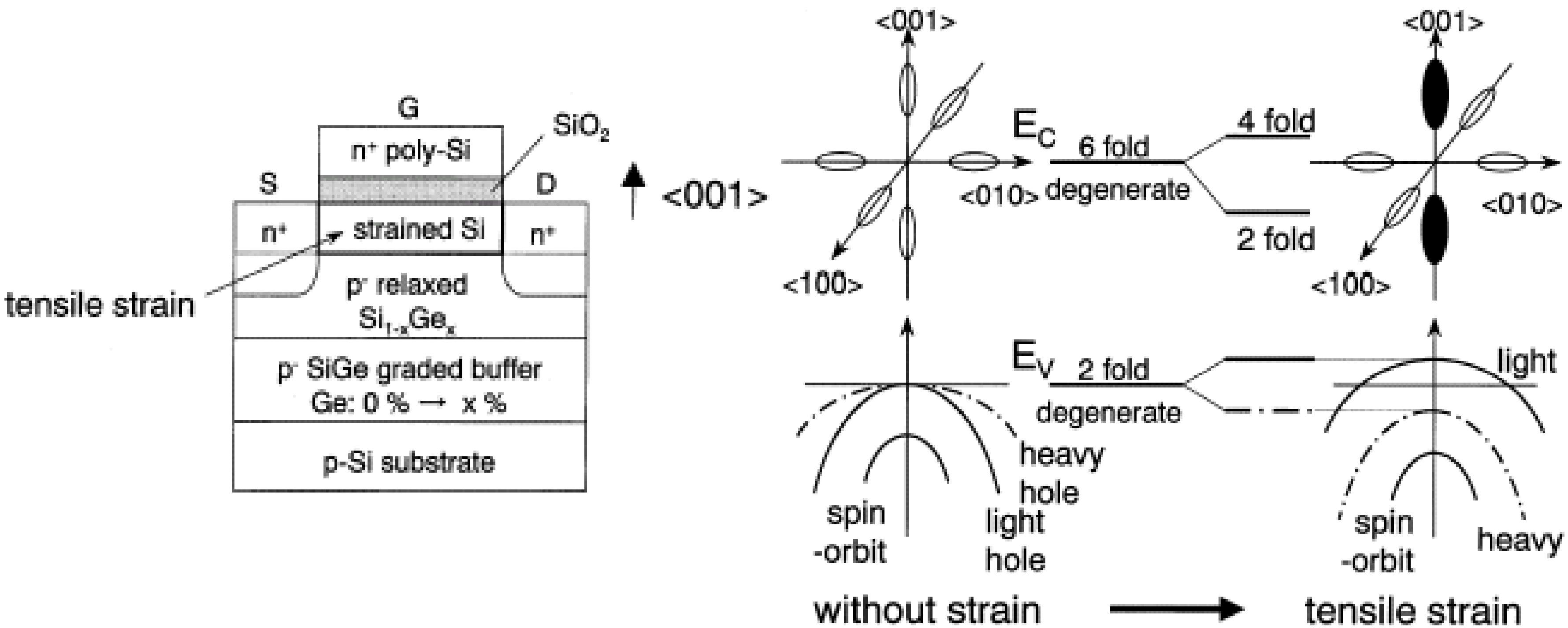


$x \approx 0.7\text{–}1.0$

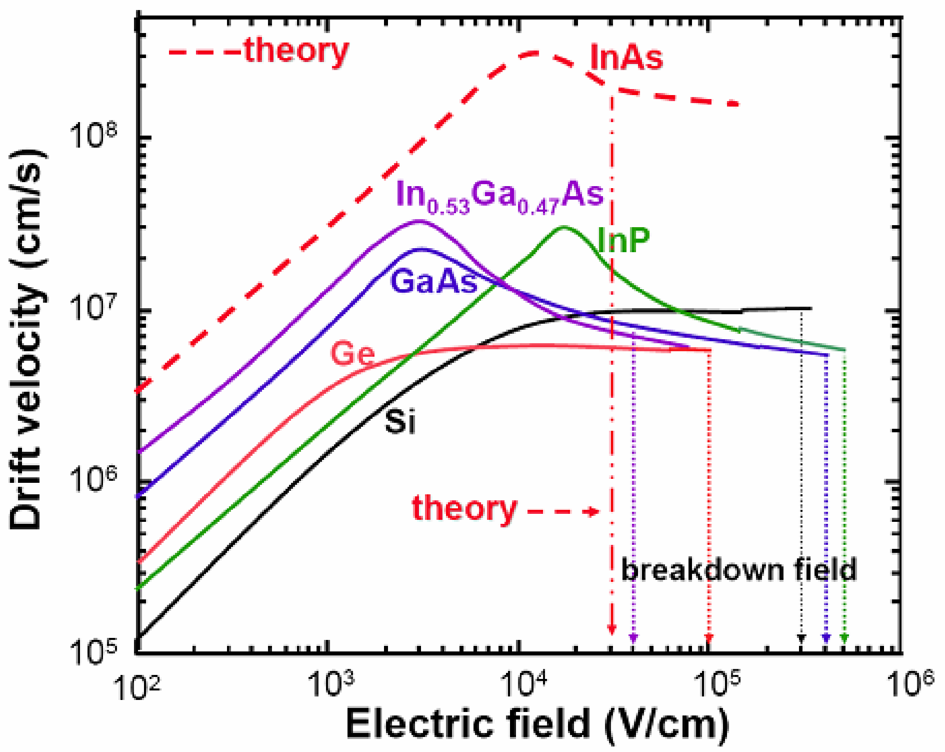
*** Valence Band of SiGe in Compressive Strain**



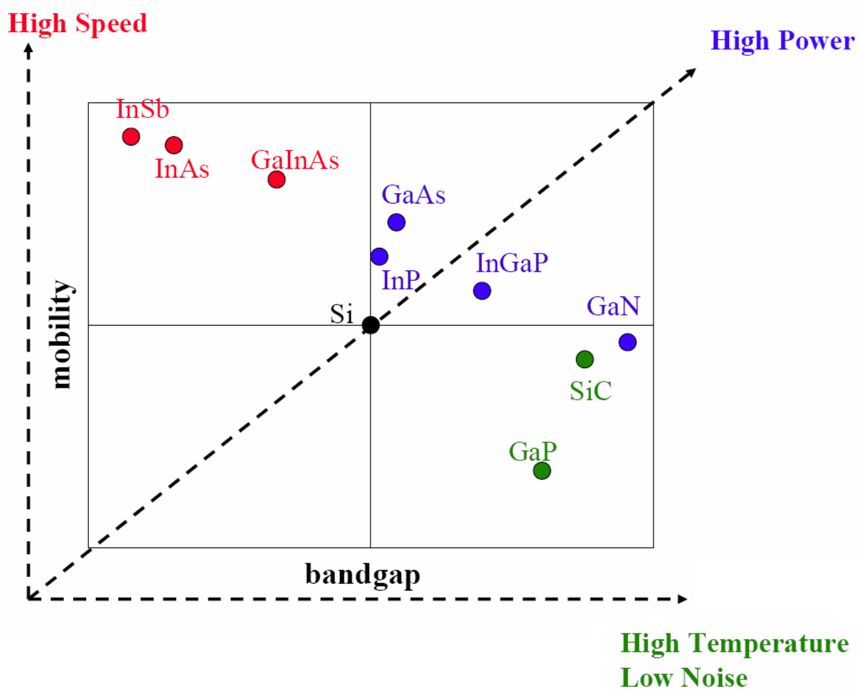
Conduction/Valence Band of Si in Tensile Strain



Right Material for n-Channel (I)

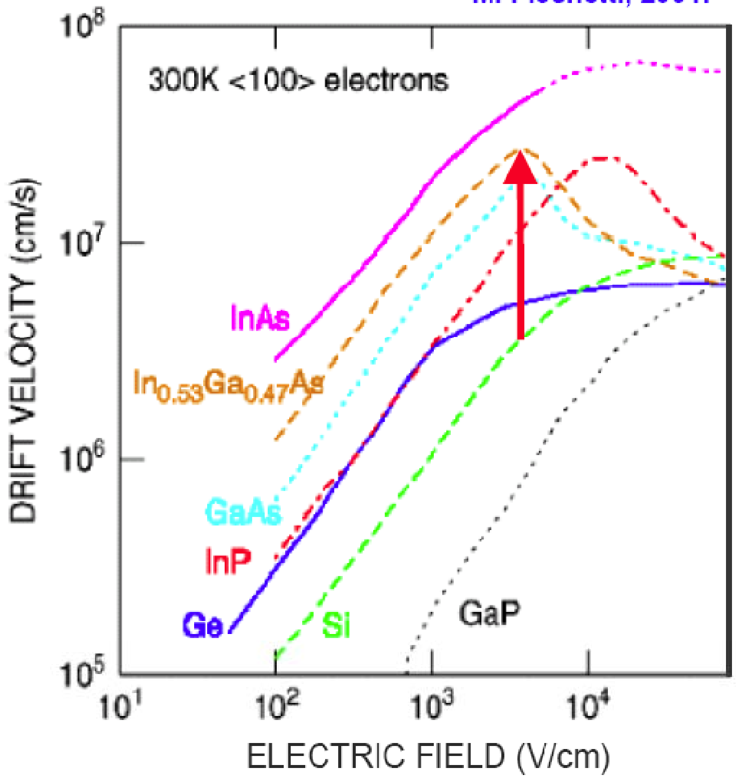


(From Jerry Woodall)



(Source) T. P. Ma, Sematech Workshop, 2005

M. Fischetti, 2001.



(Source) D. K. Sadana, Sematech Workshop, 2005

Higher mobility leads to higher speed at a given bias.

S. Laux, P. Solomon, M. Fischetti, 2003.

DD	Si 10nm	Si 20nm	InGaAs 20nm	InGaAs vs Si 10nm	InGaAs vs Si 20nm
(V)	(ps)	(ps)	(ps)	(%)	(%)
0.25	4.9	5.9	2.8	76	110
0.6	2.8	3.8	1.9	45	98

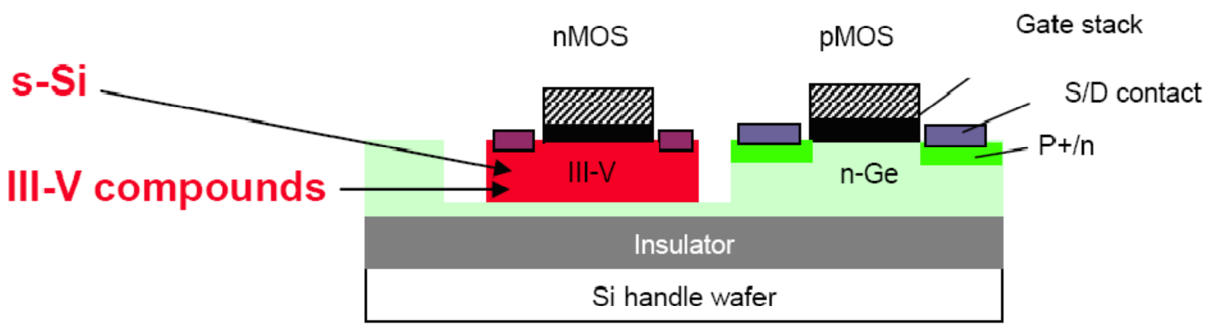
Performance benefits continue down to L_g= 20 nm.

Mobility continues to be important in scaled devices

High-mobility dual-channel CMOS for (sub)-22 nm

(Target of DUALLOGIC) - 36month project of EU

Monolithic co-integration of Ge pMOS with III-V nMOS on the same engineered substrate using a 65 nm/200 mm platform



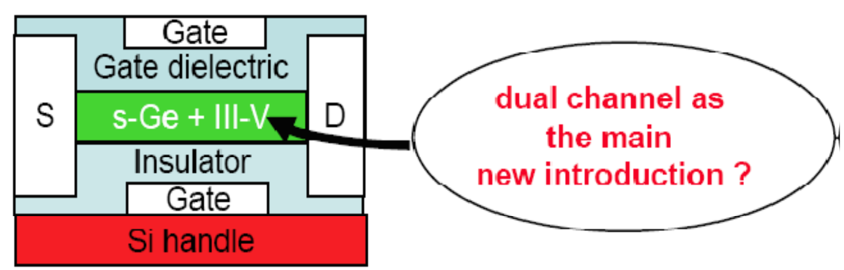
Material	μ_e (cm^2/Vs)	μ_h (cm^2/Vs)
Diamond	2200	1800
Si	1350	480
Ge	3900	1900
InP	5400	200
GaAs	8500	400
InGaAs(53%)	12000	300
InAs	40000	500
GaSb	3000	1000
InSb	77000	850

Main project components

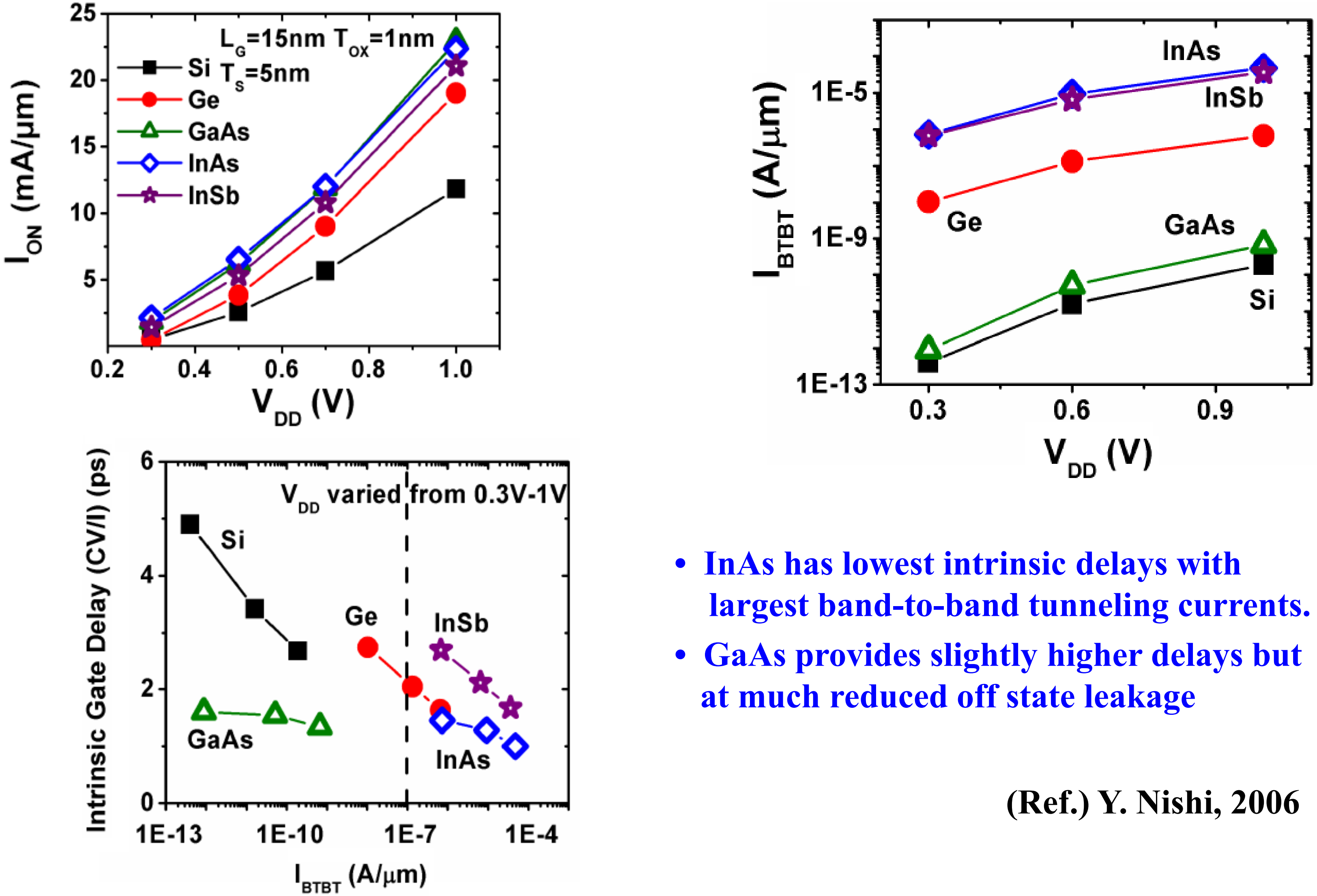
- Local GeOI substrates and evaluation
- III-V Selective epitaxy process and tool development
- Front end modules development and co-integration
- Device modeling and generic circuit design

(LETI, ST-Crolles, AIXTRON, IMEC, IBM-Zurich, NCSR, UoG, KUL, NXP, UoG)

Sub-22 nm node



High Mobility Channel Materials



- InAs has lowest intrinsic delays with largest band-to-band tunneling currents.
- GaAs provides slightly higher delays but at much reduced off state leakage

(Ref.) Y. Nishi, 2006