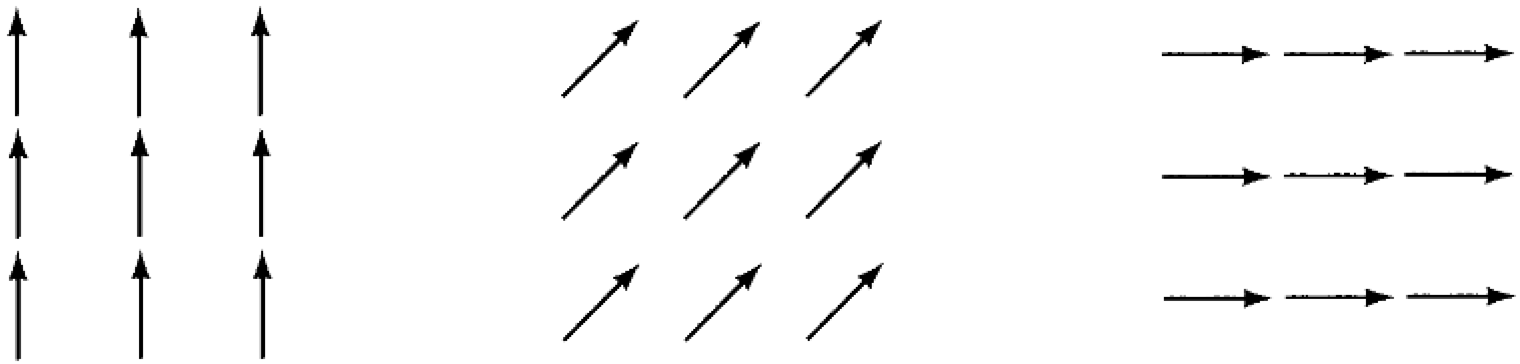
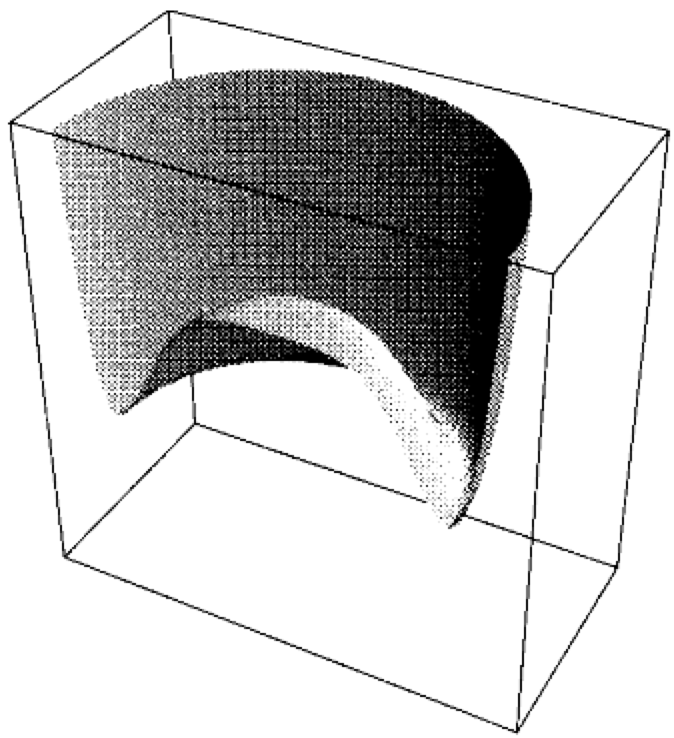
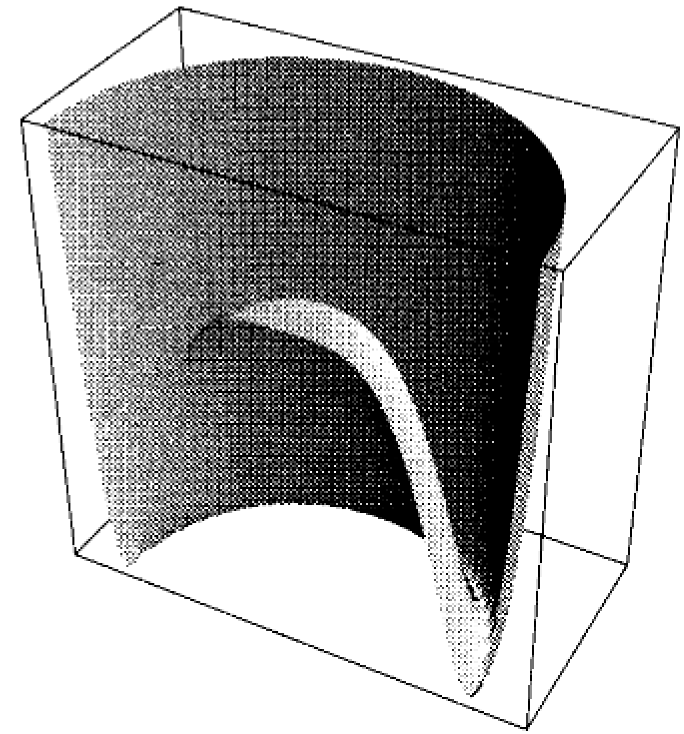
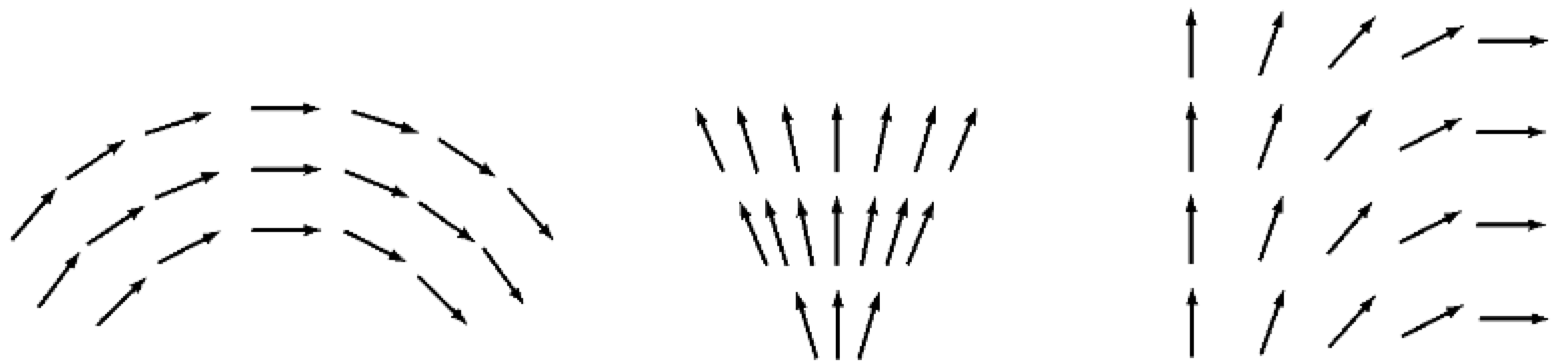
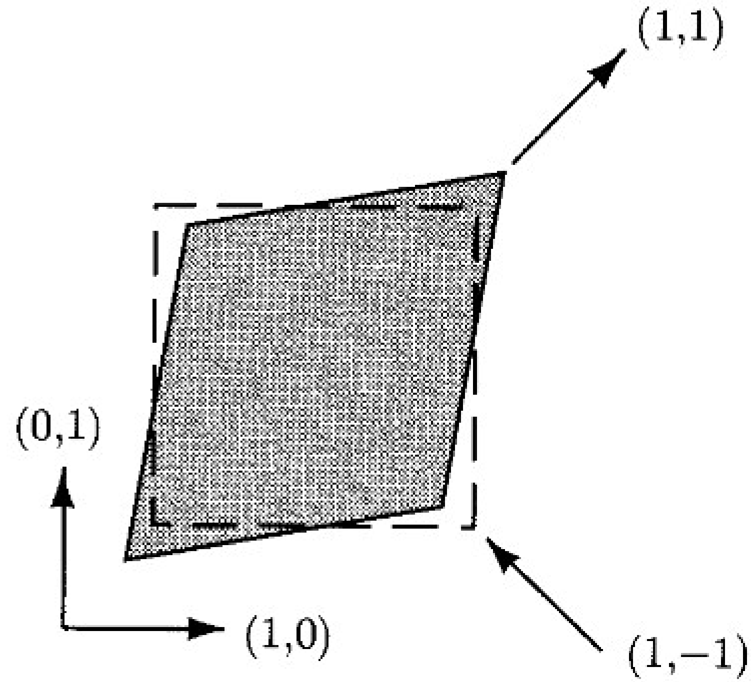








(a) (b) (c)


(1,1)
(0,1)
(1,0)
(1,−1)

NUMBER OF INDEPENDENT ELASTIC CONSTANTS

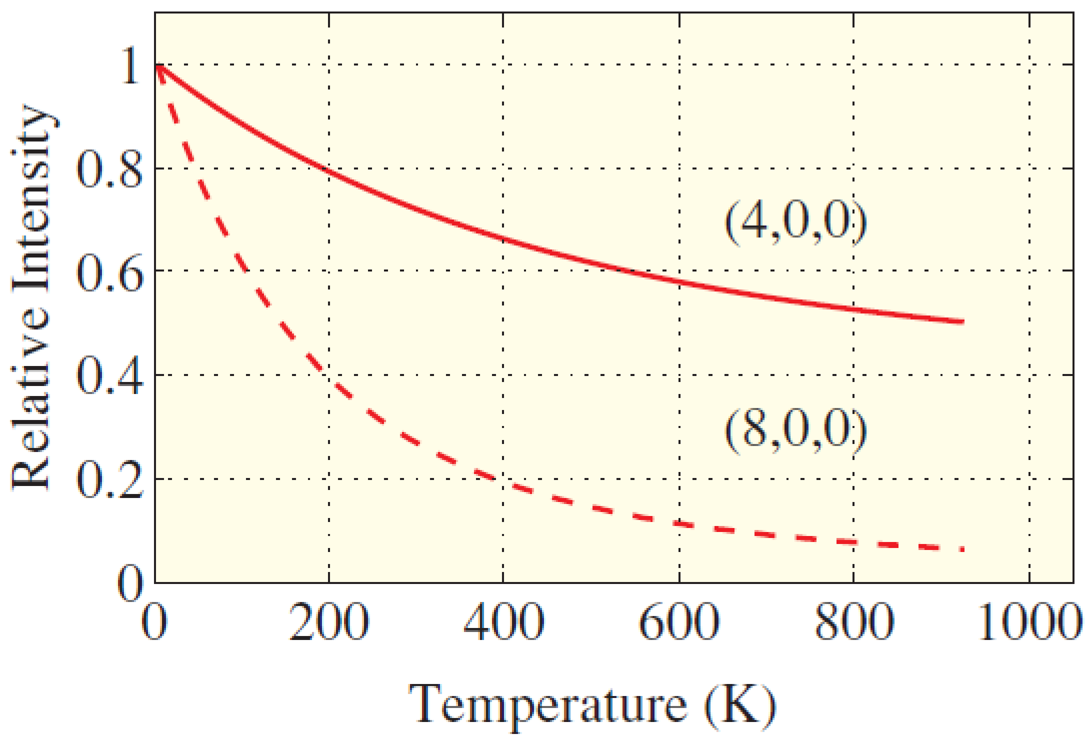
CRYSTAL SYSTEM	POINT GROUPS	ELASTIC CONSTANTS
Triclinic	all	21
Monoclinic	all	13
Orthorhombic	all	9
Tetragonal	C_4, C_{4h}, S_4	7
	C_{4v}, D_4, D_{4h}, D_{2d}	6
Rhombohedral	C_3, S_6	7
	C_{3v}, D_3, D_{3d}	6
Hexagonal	all	5
Cubic	all	3

ELASTIC CONSTANTS FOR SOME CUBIC CRYSTALS[a]

SUBSTANCE	C_{11}	C_{12}	C_{44}
Li (78 K)	0.148	0.125	0.108
Na	0.070	0.061	0.045
Cu	1.68	1.21	0.75
Ag	1.24	0.93	0.46
Au	1.86	1.57	0.42
Al	1.07	0.61	0.28
Pb	0.46	0.39	0.144
Ge	1.29	0.48	0.67
Si	1.66	0.64	0.80
V	2.29	1.19	0.43
Ta	2.67	1.61	0.82
Nb	2.47	1.35	0.287
Fe	2.34	1.36	1.18
Ni	2.45	1.40	1.25
LiCl	0.494	0.228	0.246
NaCl	0.487	0.124	0.126
KF	0.656	0.146	0.125
RbCl	0.361	0.062	0.047

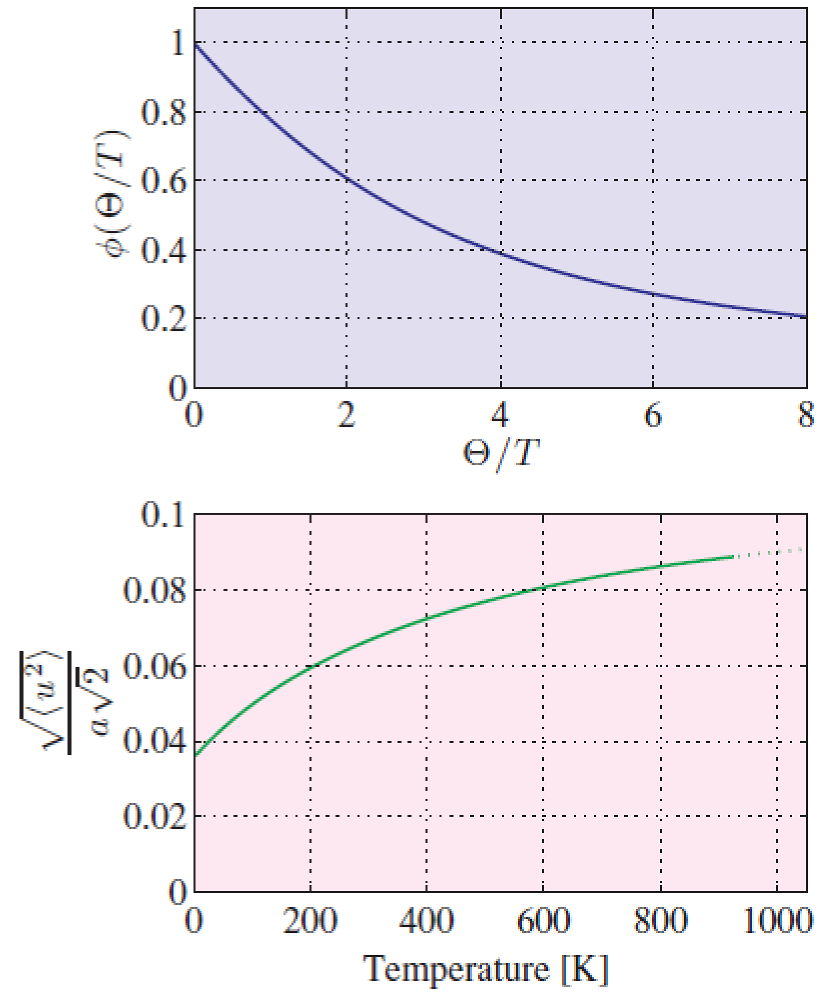
[a] Elastic constants in 10^{12} dynes-cm^{-2} at 300 K.

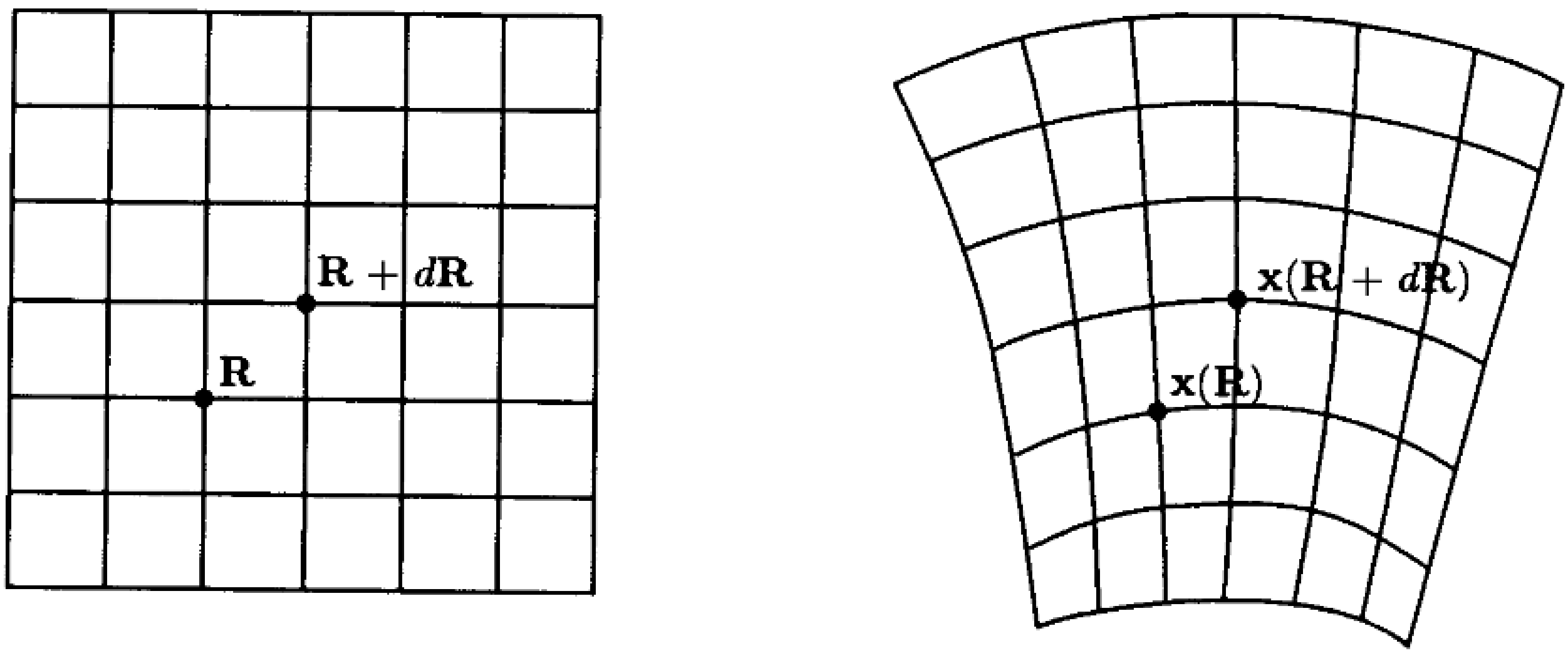
Material	Shear modulus	Bulk modulus
Tungsten carbide	2.2×10^{12}	3.2×10^{12}
Steel	0.83×10^{12}	1.5×10^{12}
Gold	0.28×10^{12}	1.7×10^{12}
Pyrex	0.25×10^{12}	0.4×10^{12}
Nylon	0.12×10^{12}	0.59×10^{12}
Rubber	$\sim 10^7$	0.03×10^{12}
Jello	$\sim 10^4$	0.02×10^{12}
Polystyrene foam	1.3×10^8	2×10^8
Shaving foam	$\sim 10^3$	$\sim 10^6$
Ice	0.025×10^{12}	0.073×10^{12}
Water	0	0.02×10^{12}
Air	0	10^6 (1 atm)



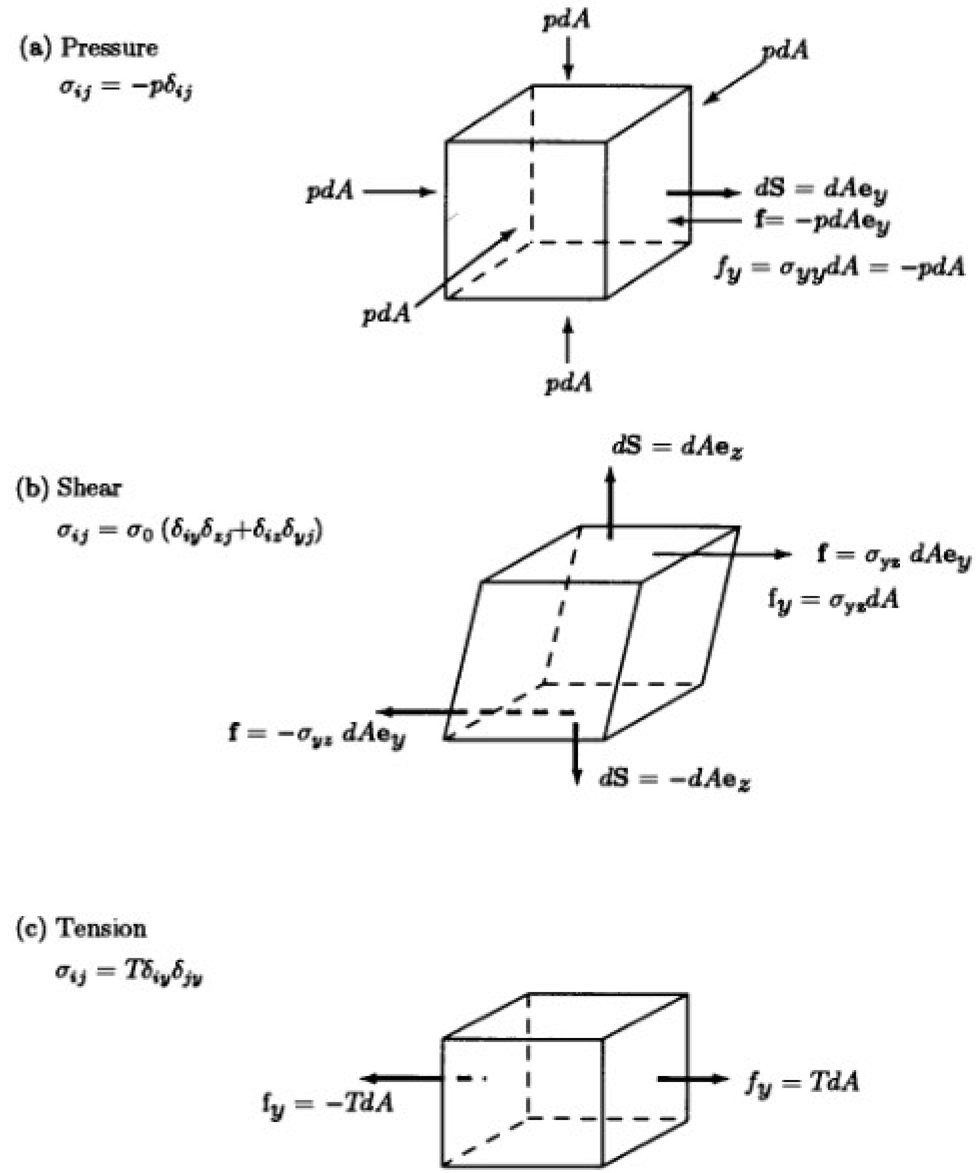
Relative Intensity
1
0.8
0.6
0.4
0.2
0
(4,0,0)
(8,0,0)
0
200
400
600
800
1000
Temperature (K)

	A	Θ (K)	$B_{4.2}$ (Å^2)	B_{77}	B_{293}
Diamond	12	2230	0.11	0.11	0.12
Al	27	428	0.25	0.30	0.72
Si	28.1	645	0.17	0.18	0.33
Cu	63.5	343	0.13	0.17	0.47
Ge	72.6	374	0.11	0.13	0.35
Mo	96	450	0.06	0.08	0.18





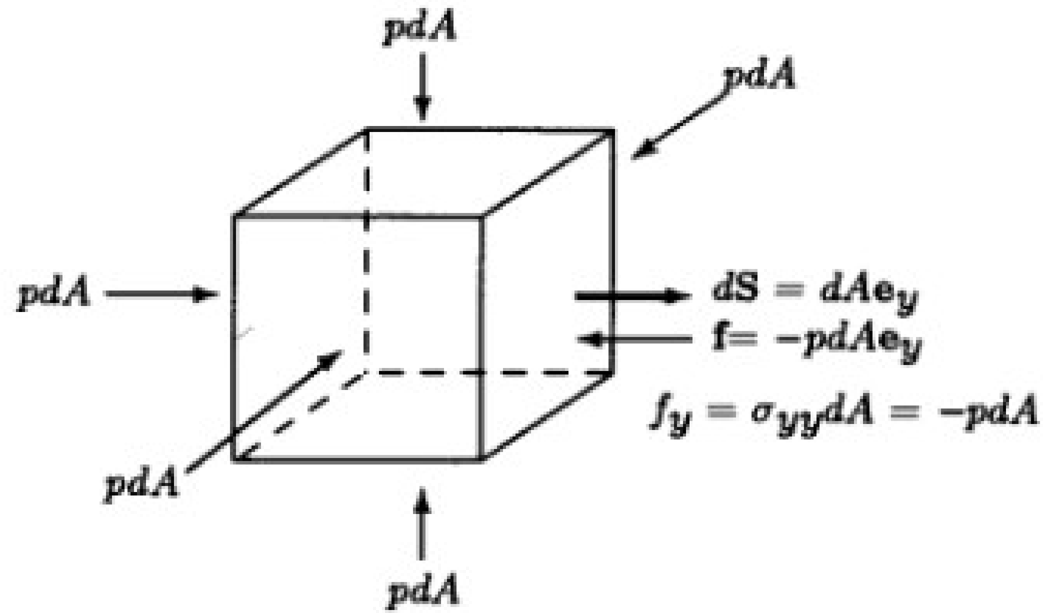
R + dR
R
x(R + dR)
x(R)



(a) Pressure
$\sigma_{ij} = -p\delta_{ij}$
pdA
pdA
pdA
$d\mathbf{S} = dA\mathbf{e}_y$
$\mathbf{f} = -pdA\mathbf{e}_y$
$f_y = \sigma_{yy}dA = -pdA$
pdA
pdA
$d\mathbf{S} = dA\mathbf{e}_z$
(b) Shear
$\sigma_{ij} = \sigma_0\,(\delta_{iy}\delta_{zj} + \delta_{iz}\delta_{yj})$
$\mathbf{f} = \sigma_{yz}\, dA\mathbf{e}_y$
$f_y = \sigma_{yz}dA$
$\mathbf{f} = -\sigma_{yz}\, dA\mathbf{e}_y$
$d\mathbf{S} = -dA\mathbf{e}_z$
(c) Tension
$\sigma_{ij} = T\delta_{iy}\delta_{jy}$
$f_y = -TdA$
$f_y = TdA$

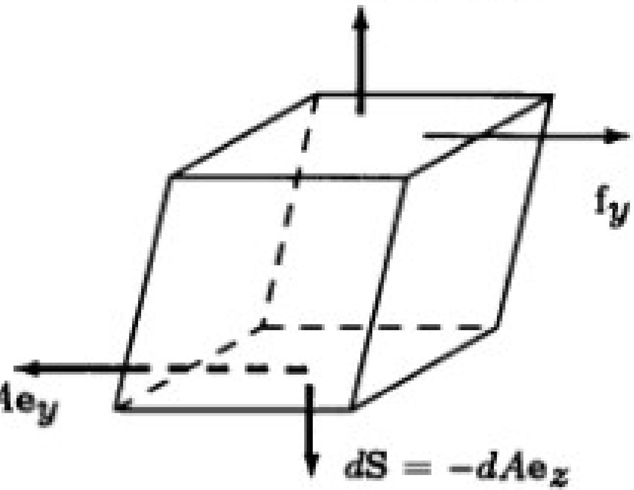
(a) Pressure

$\sigma_{ij} = -p\delta_{ij}$



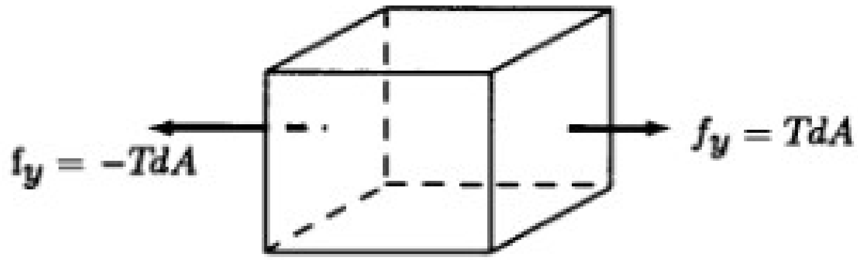
(b) Shear

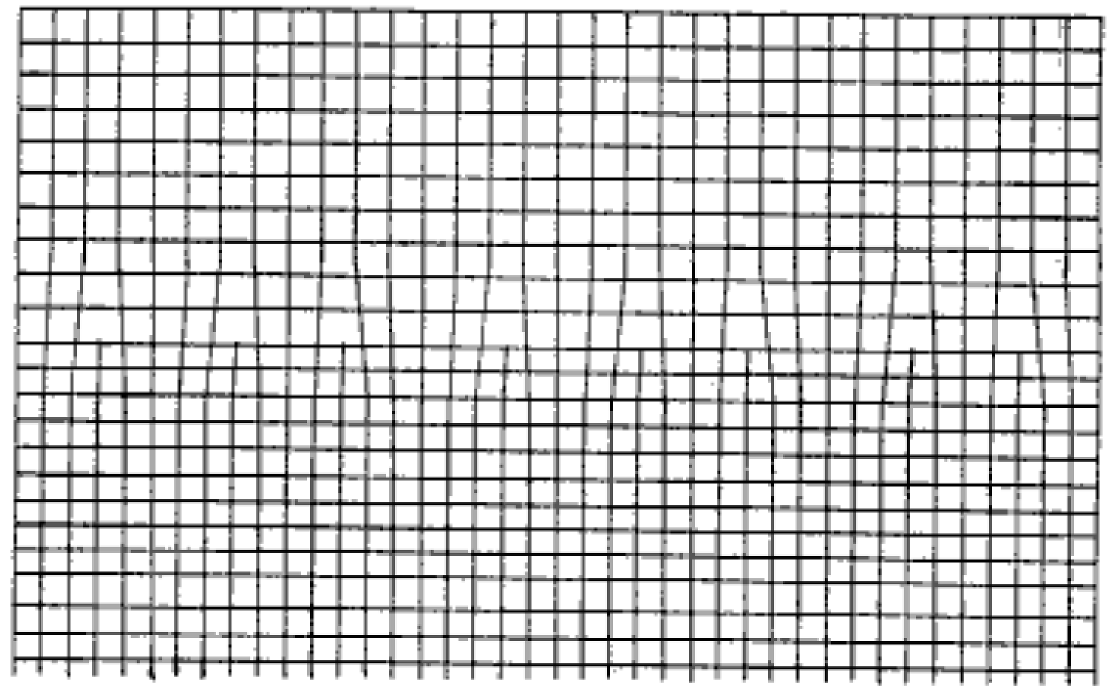
$$\sigma_{ij} = \sigma_0 \left(\delta_{iy}\delta_{zj} + \delta_{iz}\delta_{yj}\right)$$

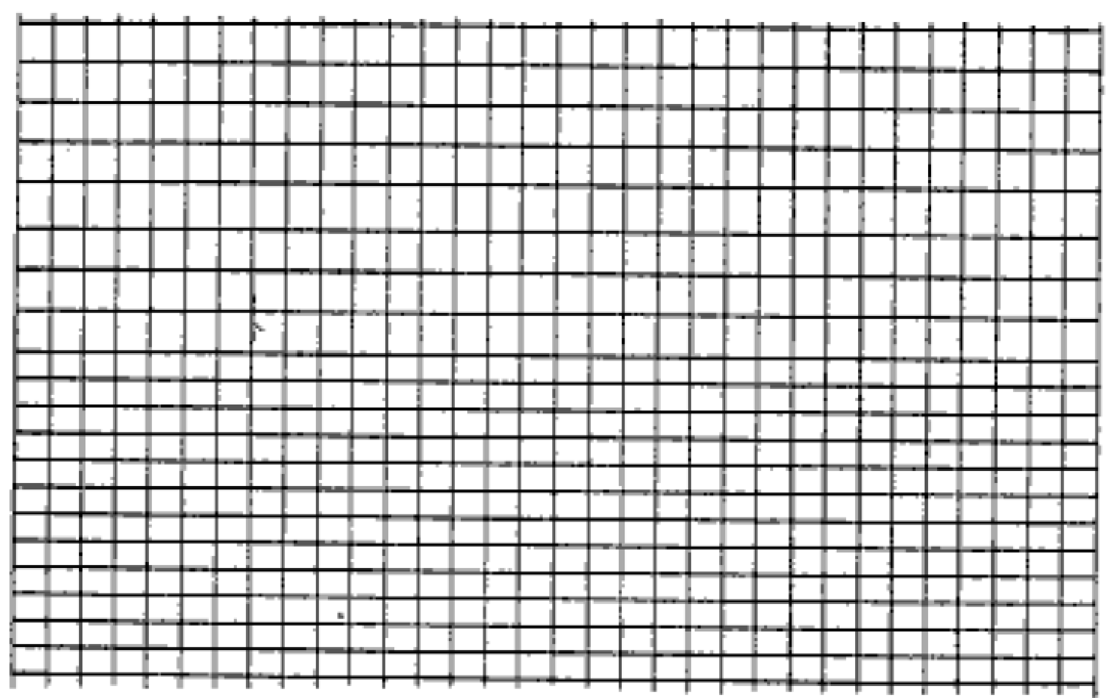


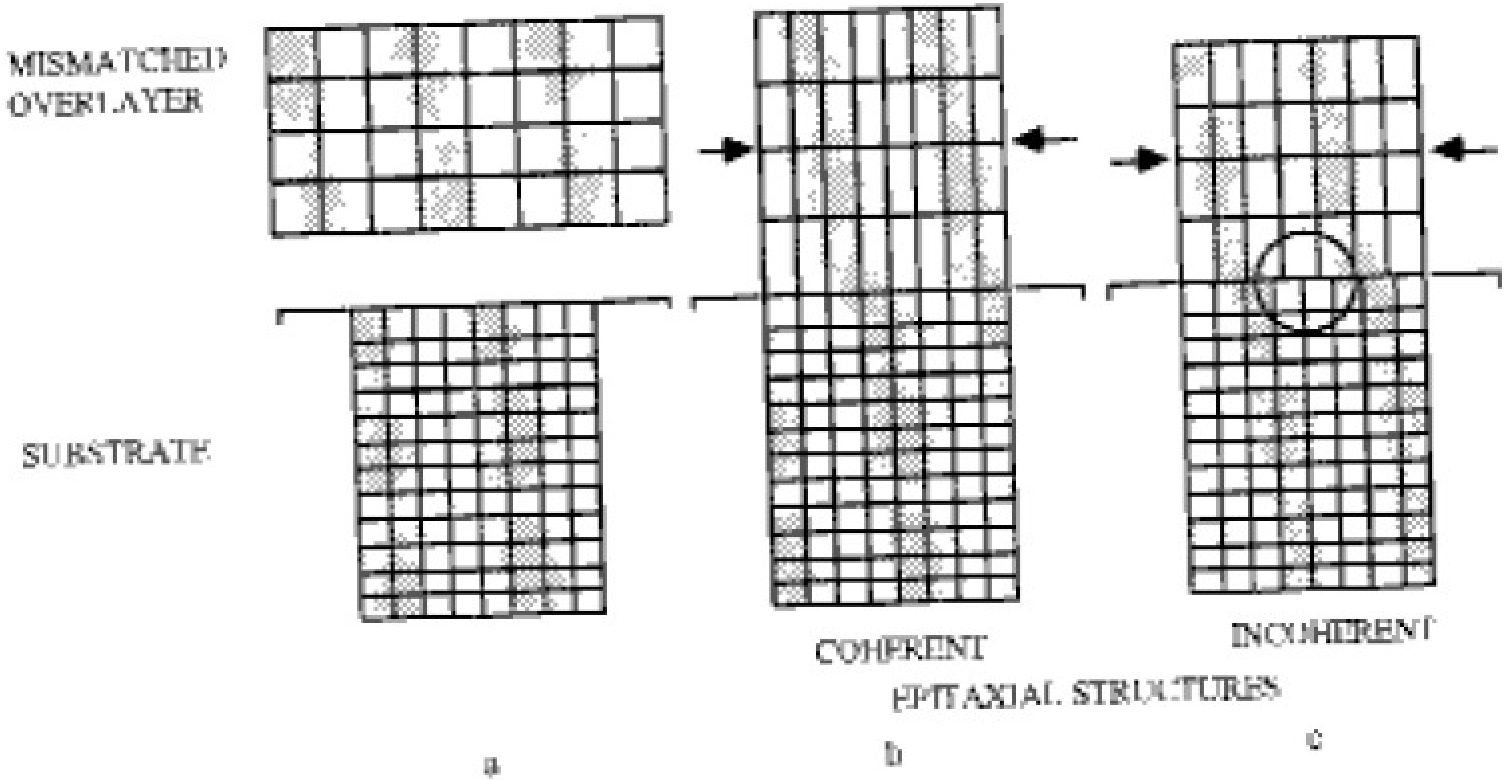
(c) Tension

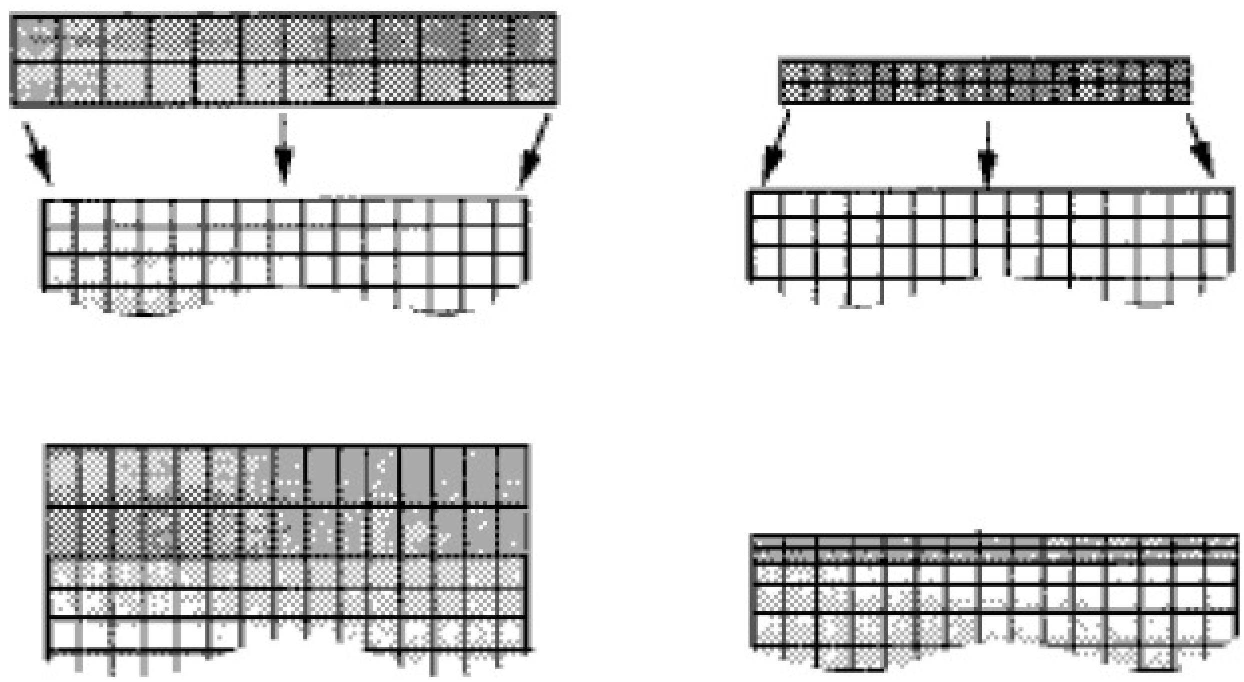
$$\sigma_{ij} = T\delta_{iy}\delta_{jy}$$



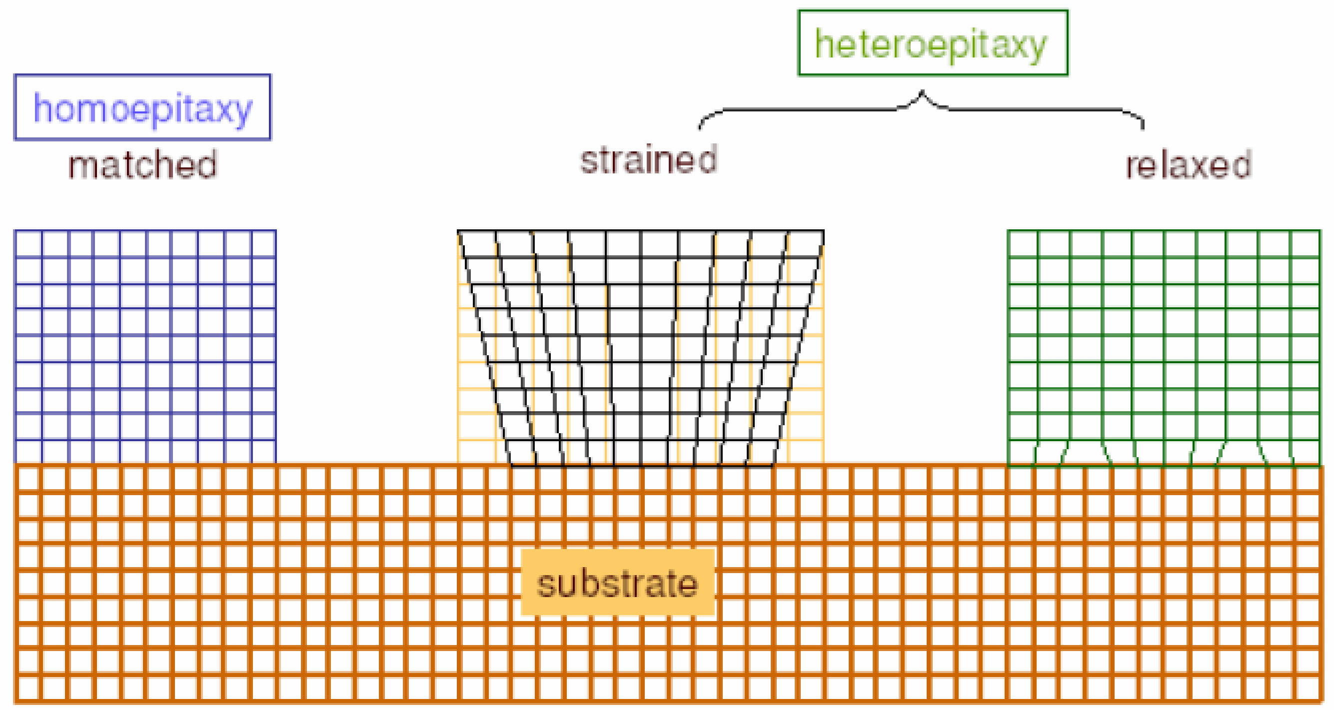




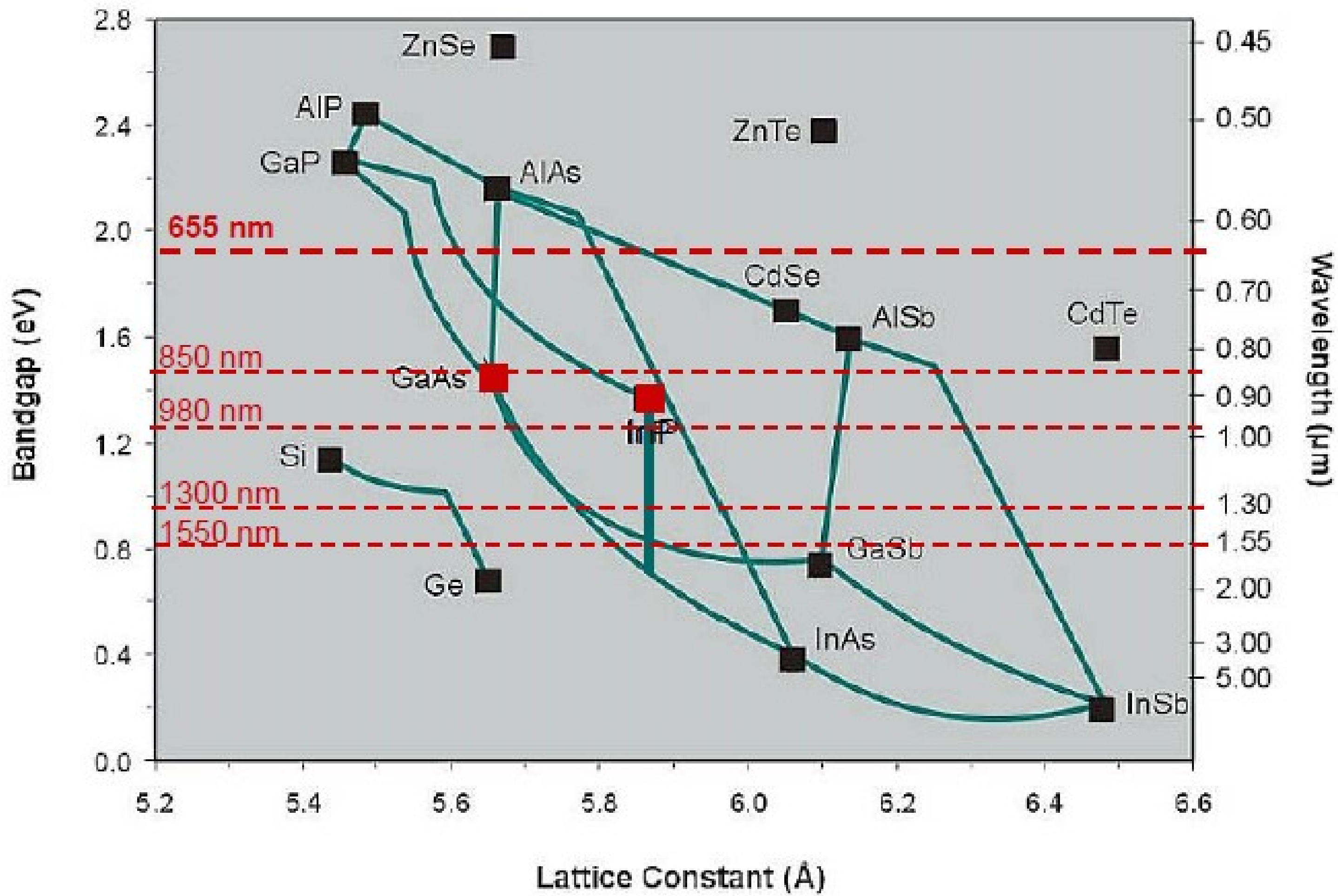

MISMATCHED
OVERLAYER
SUBSTRATE
COHERENT
INCOHERENT
EPITAXIAL STRUCTURES
a
b
c

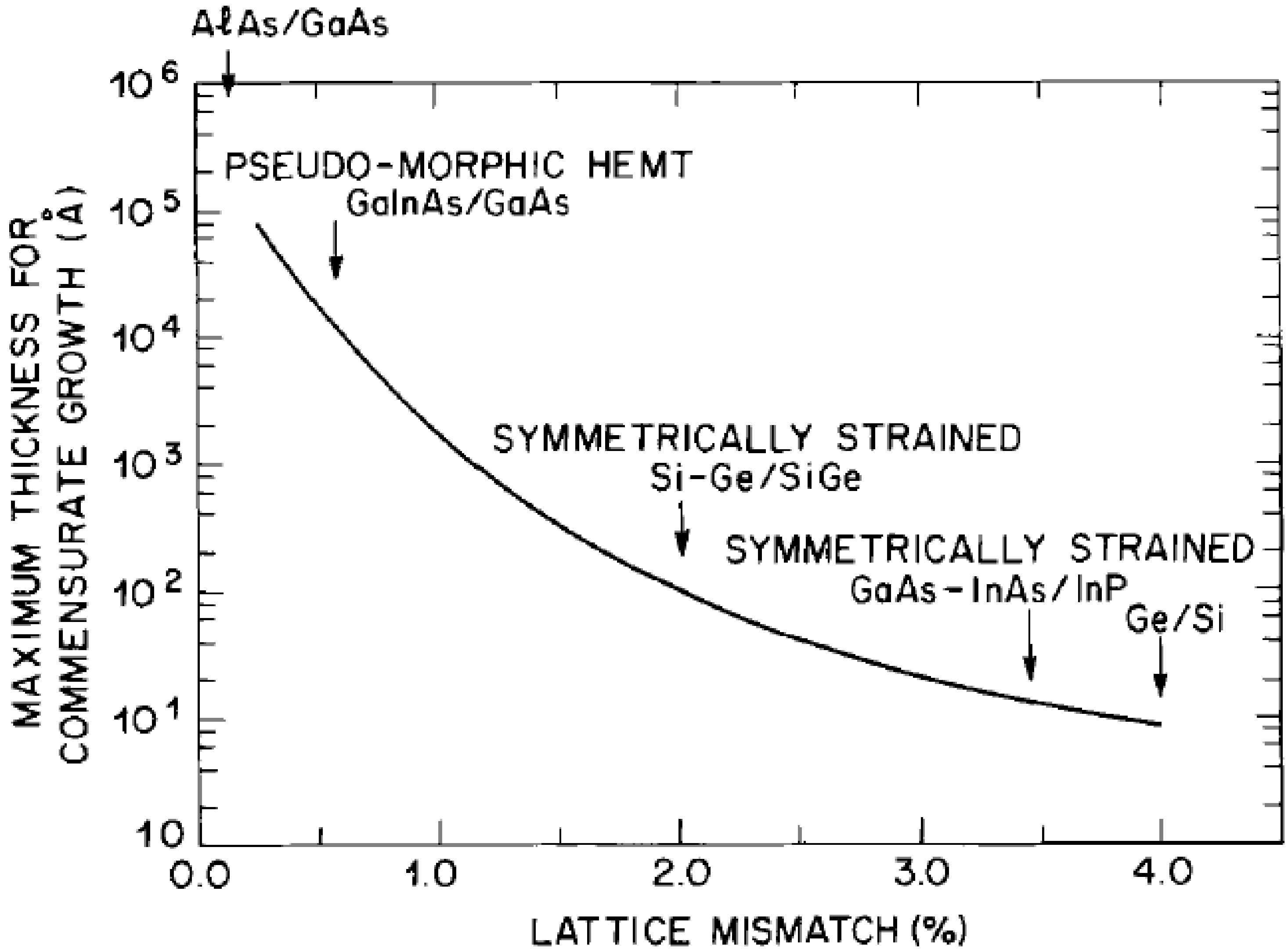


(a) (b)

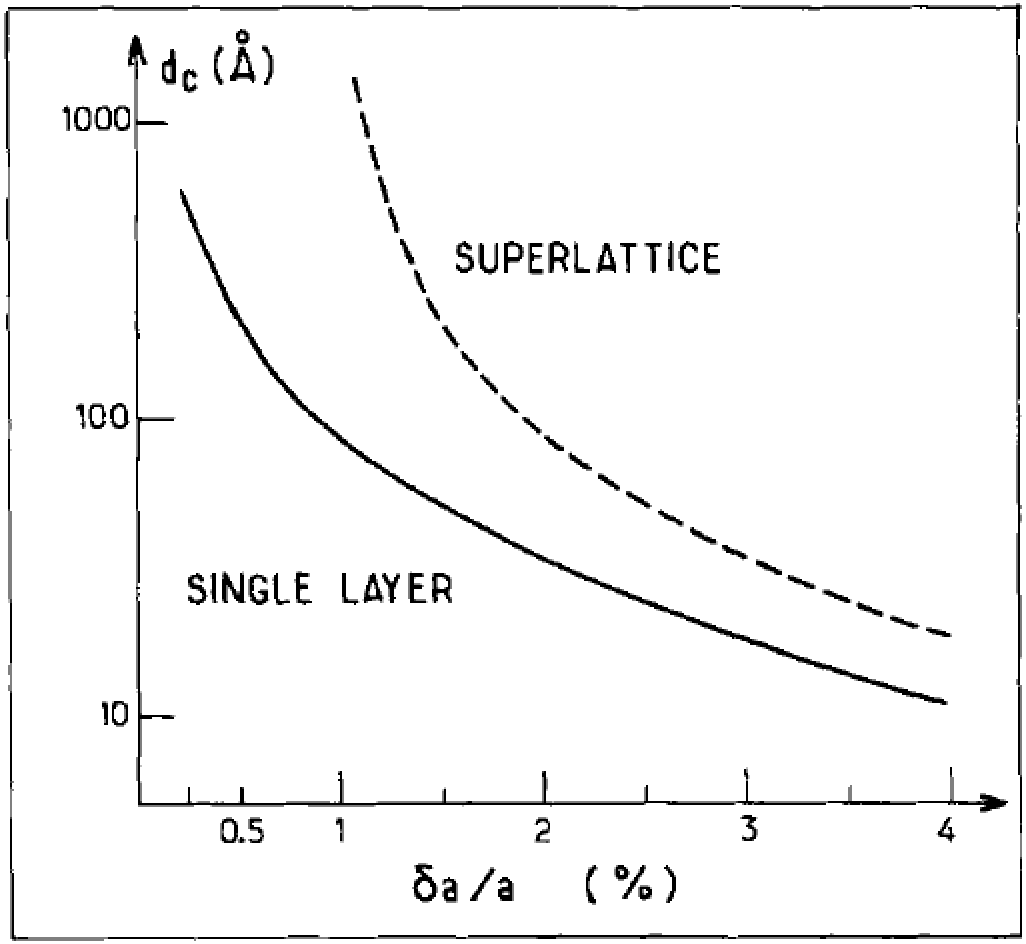

heteroepitaxy
homoepitaxy
matched
strained
relaxed
substrate

Materials Selection





AlAs/GaAs
PSEUDO-MORPHIC HEMT
GaInAs/GaAs
SYMMETRICALLY STRAINED
Si-Ge/SiGe
SYMMETRICALLY STRAINED
GaAs-InAs/InP
Ge/Si
MAXIMUM THICKNESS FOR COMMENSURATE GROWTH (Å)
10^6
10^5
10^4
10^3
10^2
10^1
10
0.0
1.0
2.0
3.0
4.0
LATTICE MISMATCH (%)



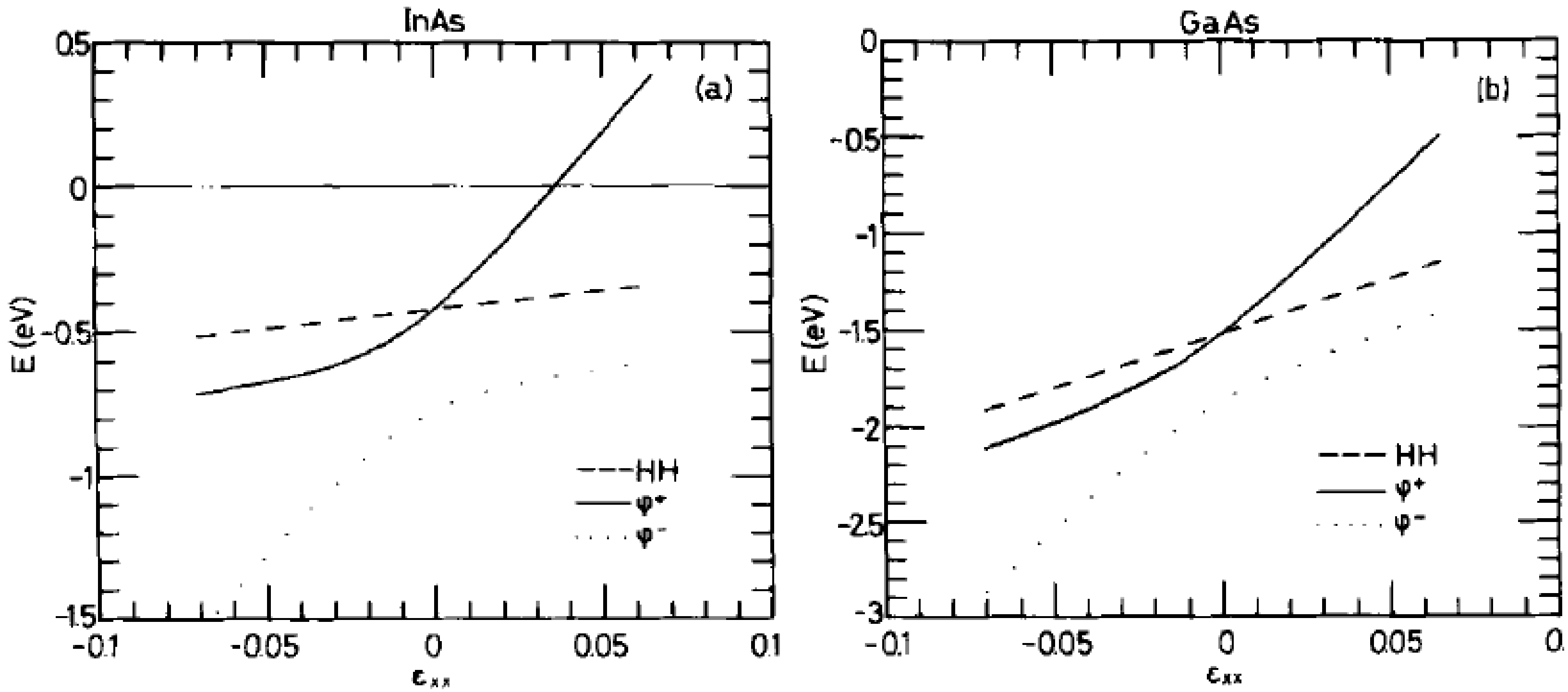
d_c (Å)
1000
100
10
SUPERLATTICE
SINGLE LAYER
0.5
1
2
3
4
$\delta a/a$ (%)

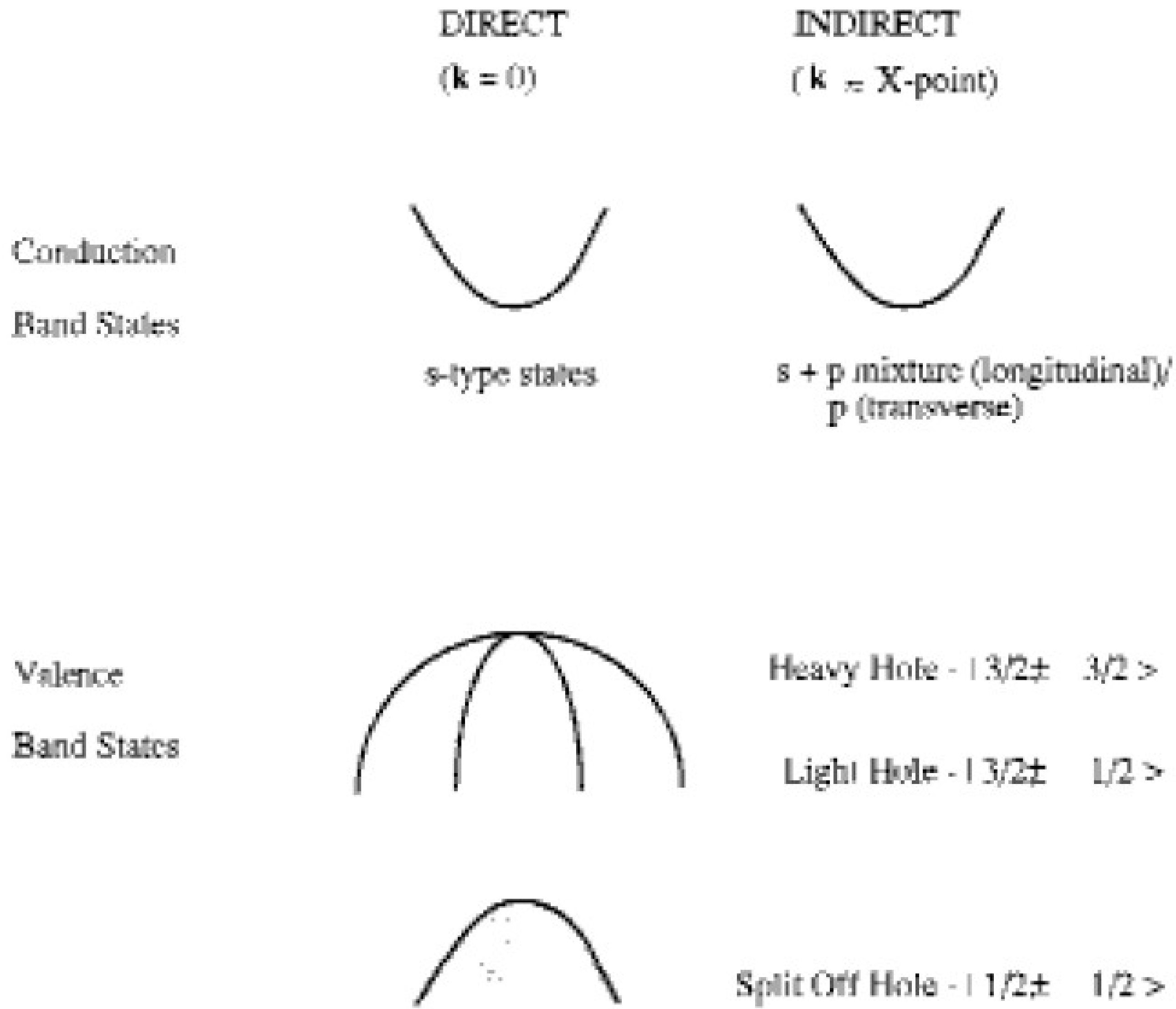
$$\begin{bmatrix} \sigma_{xx} \\ \sigma_{yy} \\ \sigma_{zz} \\ \sigma_{xy} \\ \sigma_{yz} \\ \sigma_{zx} \end{bmatrix} = \begin{bmatrix} C_{11} & C_{11} & C_{12} & 0 & 0 & 0 \\ C_{12} & C_{11} & C_{12} & 0 & 0 & 0 \\ C_{12} & C_{12} & C_{11} & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{44} & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{44} \end{bmatrix} \begin{bmatrix} e_{xx} \\ e_{yy} \\ e_{zz} \\ 2e_{xy} \\ 2e_{yz} \\ 2e_{zx} \end{bmatrix}.$$

$$e_{zz}^{\mathrm{A[B]}} = -\frac{2C_{12}^{\mathrm{A[B]}}}{C_{11}^{\mathrm{A[B]}}} e_{xx}^{\mathrm{A[B]}} \approx -e_{xx}^{\mathrm{A[B]}}. \qquad e_{xx}^{\mathrm{A}} - e_{yy}^{\mathrm{B}} = \delta a_0/a_0;$$

$$E_{\mathrm{el}} = \tfrac{1}{2}(d^{\mathrm{A}} e_{ij}^{\mathrm{A}} \sigma_{ij}^{\mathrm{A}} + d^{\mathrm{B}} e_{ij}^{\mathrm{B}} \sigma_{ij}^{\mathrm{B}})$$

$$a_{x,y} = \frac{a^{\mathrm{A}} d^{\mathrm{A}} \xi^{\mathrm{A}} + a^{\mathrm{B}} d^{\mathrm{B}} \xi^{\mathrm{B}}}{d^{\mathrm{A}} \xi^{\mathrm{A}} + d^{\mathrm{B}} \xi^{\mathrm{B}}}, \qquad \xi^{\mathrm{A[B]}} = (C_{11} + C_{12} - 2C_{12}^2/C_{11})^{\mathrm{A[B]}}$$


InAs
(a)
E (eV)
0.5
0
-0.5
-1
-1.5
-0.1
-0.05
0
0.05
0.1
εxx
HH
φ+
φ−
GaAs
(b)
E (eV)
0
-0.5
-1
-1.5
-2
-2.5
-3
-0.1
-0.05
0
0.05
0.1
εxx
HH
φ+
φ−


DIRECT
(k = 0)
INDIRECT
(k = X-point)
Conduction
Band States
s-type states
s + p mixture (longitudinal)/
p (transverse)
Valence
Band States
Heavy Hole - | 3/2± 3/2 >
Light Hole - | 3/2± 1/2 >
Split Off Hole - | 1/2± 1/2 >

$\|3/2, 3/2\rangle_z$	$\|3/2, 1/2\rangle_z$	$\|3/2, -3/2\rangle_z$	$\|3/2, -1/2\rangle_z$
$-(\hbar^2/2m_o)[(\gamma_1 + \gamma_2)\, k_\perp^2 + (\gamma_1 - 2\gamma_2)\, k_z^2]$	B	0	C
B^*	$-(\hbar^2/2m_o)[(\gamma_1 - \gamma_2)\, k_\perp^2 + (\gamma_1 + 2\gamma_2)\, k_z^2]$	C	0
0	C^*	$-(\hbar^2/2m_o)[(\gamma_1 + \gamma_2)\, k_\perp^2 + (\gamma_1 - 2\gamma_2)\, k_z^2]$	$-B^*$
C^*	0	$-B$	$-(\hbar^2/2m_o)[(\gamma_1 - \gamma_2)\, k_\perp^2 + (\gamma_1 + 2\gamma_2)\, k_z^2]$

avec

$$B = 2\sqrt{3}(\hbar^2/2m_o)\gamma_3\, k_z\, (k_x - i k_y)$$

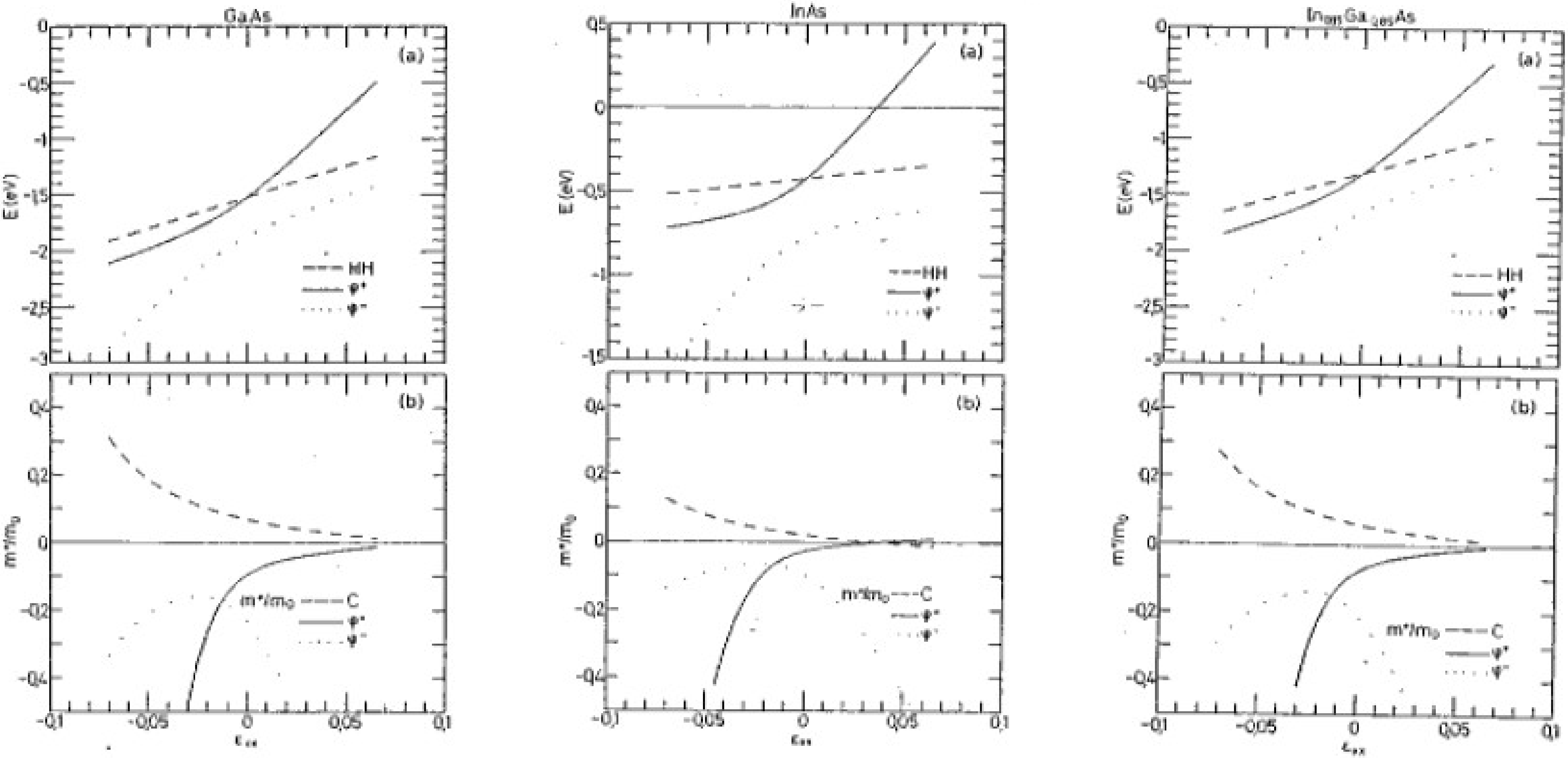
$$C = \sqrt{3}\, (\hbar^2/2m_o)[\gamma_2\, (k_x^2 - k_y^2) - 2\, i\, \gamma_3\, k_x k_y]$$

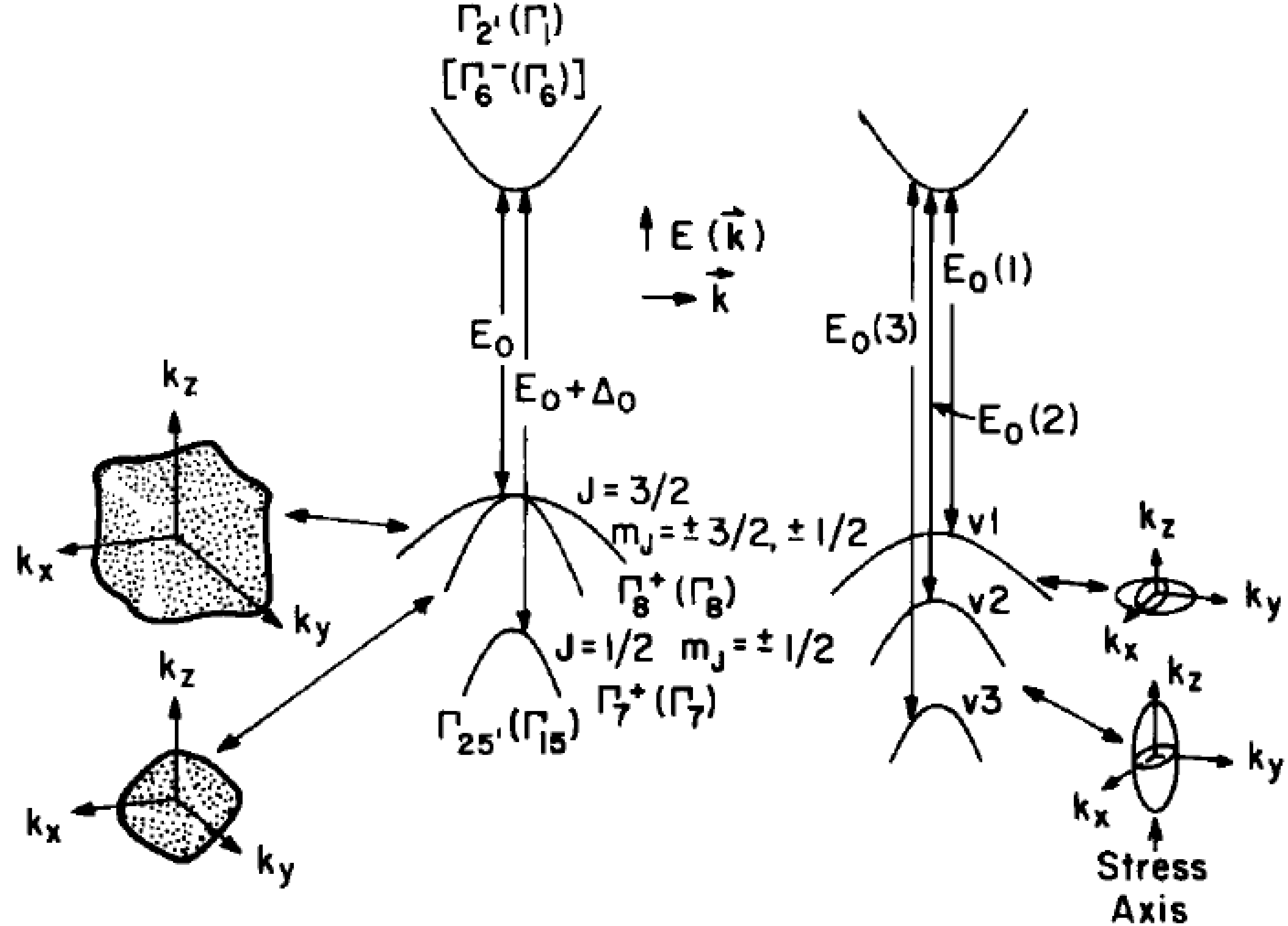
et $k_\perp^2 = k_x^2 + k_y^2$

dans GaAs, $\gamma_1 = 6.85$, $\gamma_2 = 2.10$, et $\gamma_3 = 2.90$

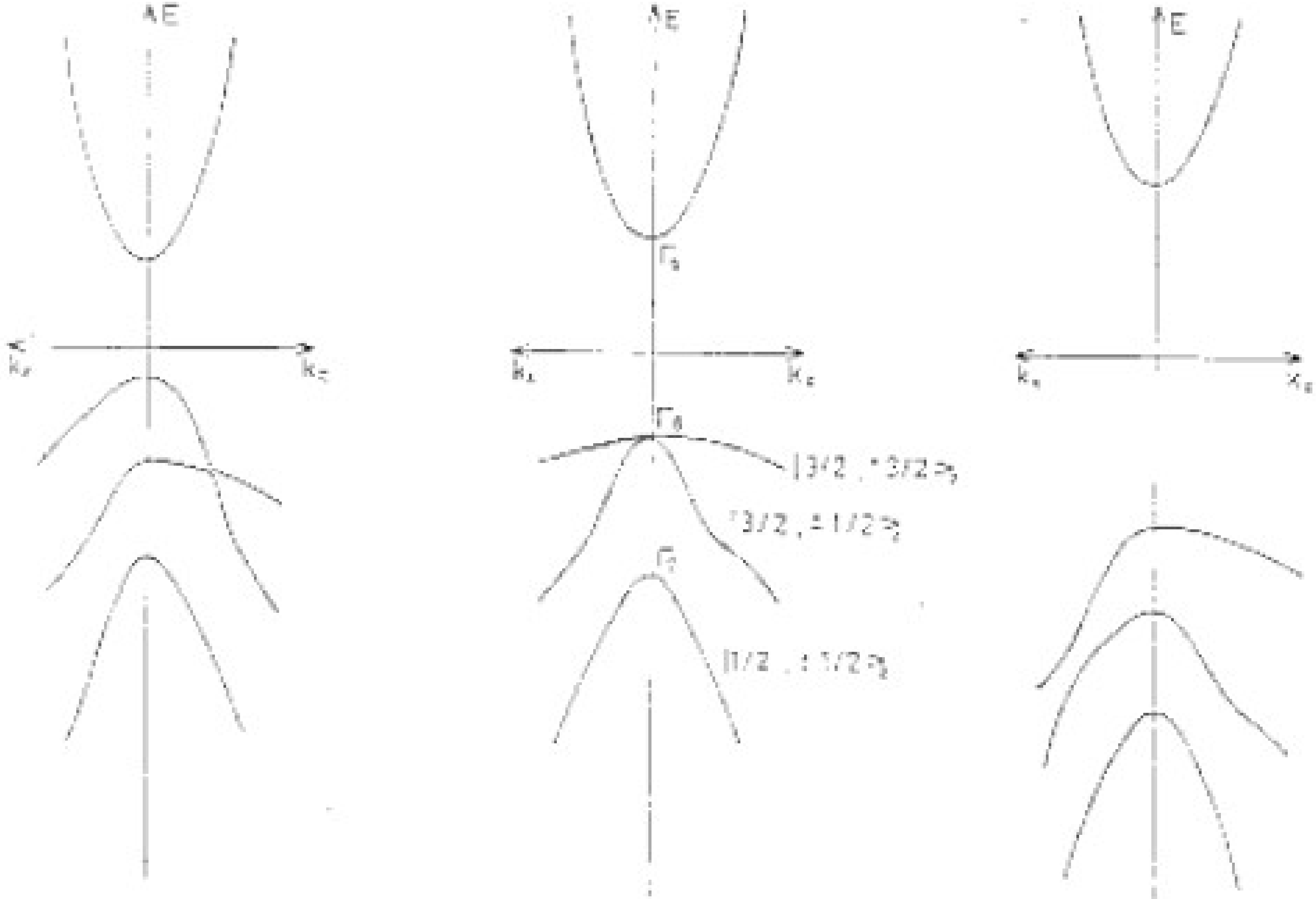
$S\uparrow$	$\vert 3/2, 3/2\rangle_z$	$\vert 3/2, 1/2\rangle_z$	$\vert 1/2, 1/2\rangle_z$
$E_g + C(\epsilon_{xx} + \epsilon_{yy} + \epsilon_{zz})$	0	0	0
0	$-a(\epsilon_{xx} + \epsilon_{yy} + \epsilon_{zz}) - b(\epsilon_{zz} - \epsilon_{xx})$	0	0
0	0	$-a(\epsilon_{xx} + \epsilon_{yy} + \epsilon_{zz}) + b(\epsilon_{zz} - \epsilon_{xx})$	$-\sqrt{2}b'(\epsilon_{zz} - \epsilon_{xx})$
0	0	$-\sqrt{2}b'(\epsilon_{zz} - \epsilon_{xx})$	$-\Delta - a'(\epsilon_{xx} + \epsilon_{yy} + \epsilon_{zz})$

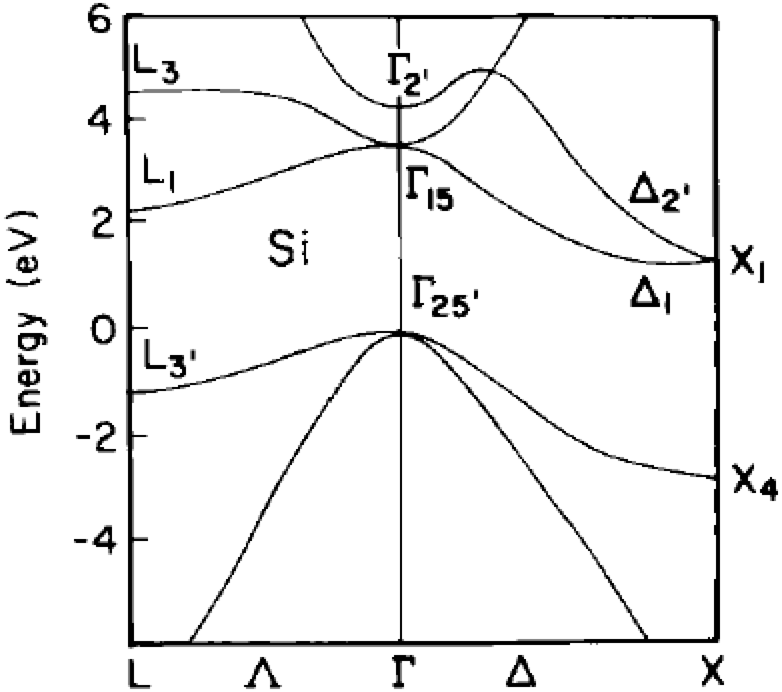
En général, on fait l'approximation $a = a'$, $b = b'$
dans les III-V, $C + a$ est de l'ordre de -8 eV, et b de -2 eV.

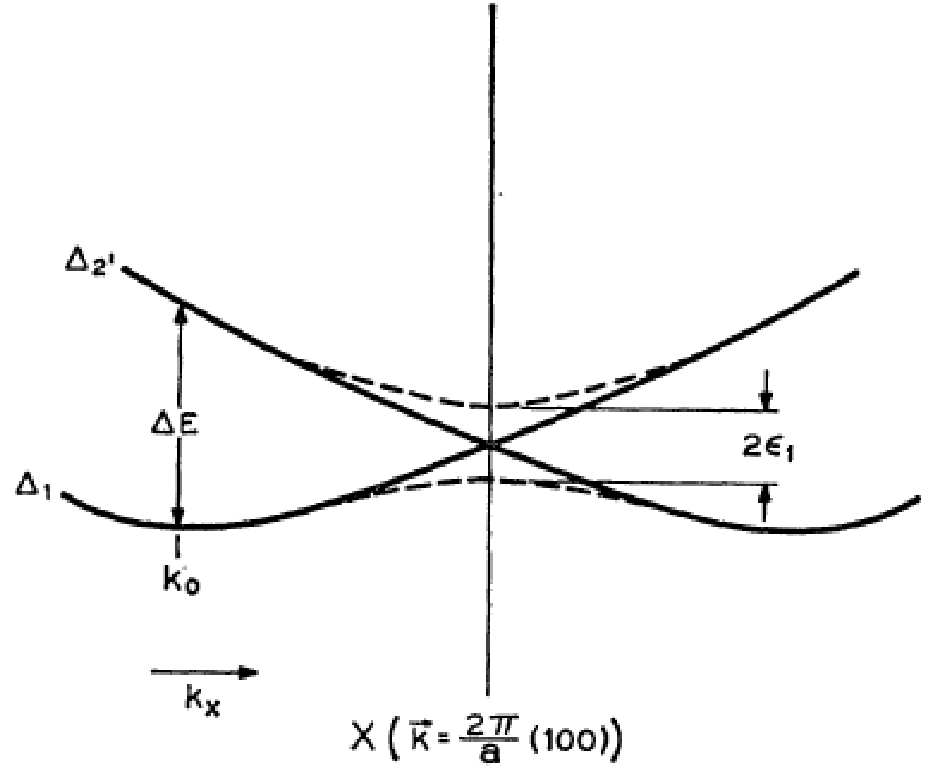

GaAs
InAs
(a)
(b)
E (eV)
m*/m0
HH
ψ+
ψ-
m*/m0 C
εxx



$\Gamma_{2'}(\Gamma_1)$
$[\Gamma_6^-(\Gamma_6)]$
E ($\vec{k}$)
$\vec{k}$
E_0
$E_0 + \Delta_0$
$E_0(1)$
$E_0(3)$
$E_0(2)$
k_z
k_x
k_y
J = 3/2
$m_J = \pm 3/2, \pm 1/2$
$\Gamma_8^+(\Gamma_8)$
J = 1/2 $m_J = \pm 1/2$
$\Gamma_7^+(\Gamma_7)$
$\Gamma_{25'}(\Gamma_{15})$
v1
v2
v3
Stress
Axis


E
k_x
k_z
E
Γ_6
k_x
k_z
Γ_8
$|3/2, \pm 3/2\rangle$
$|3/2, \pm 1/2\rangle$
Γ_7
$|1/2, \pm 1/2\rangle$
E





$$E_e(\mathbf{k}) = \delta_e + \frac{[k_x - k_0(e)]^2}{2m_{II}(e)} + \frac{k_y{}^2 + k_z{}^2}{2m_\perp(e)} + \alpha e_{yz} k_y k_z$$

J.C. Hensen et al., Phys. Rev. 138, A225 (1965)

$$\begin{bmatrix} v_1 k_x & \epsilon_1 + \dfrac{1}{m'} k_y k_z \\ \epsilon_1 + \dfrac{1}{m'} k_y k_z & -v_1 k_x \end{bmatrix} \begin{pmatrix} \xi \\ \bar{\xi} \end{pmatrix} = \epsilon(\mathbf{k}) \begin{pmatrix} \xi \\ \bar{\xi} \end{pmatrix}$$

$$\alpha = \frac{4\Xi_{u'}(k_0)}{-\Delta E} \frac{1}{m^2} \sum_l \frac{1}{E_{0l}} \langle \Delta_1 | p_y | \Delta_5^{y(l)} \rangle \times \langle \Delta_5^{y(l)} | p_z | \Delta_{2'} \rangle - \frac{1}{m} \left(\left(\frac{m}{m_\perp} \right)_{\Delta_1 k_0} - 1 \right)$$

$$\Xi_{u'}(k_0) = \langle \Delta_1 | D_{yz} | \Delta_{2'} \rangle_{k_0}$$

$$v_1 = (1/m) \langle X_1 | p_x | X_1 \rangle = -(1/m) \langle \bar{X}_1 | p_x | \bar{X}_1 \rangle$$

$$m_{11}/m = 0.9163 \pm 0.0004,$$

$$m_{\perp}/m = 0.1905 \pm 0.0001.$$

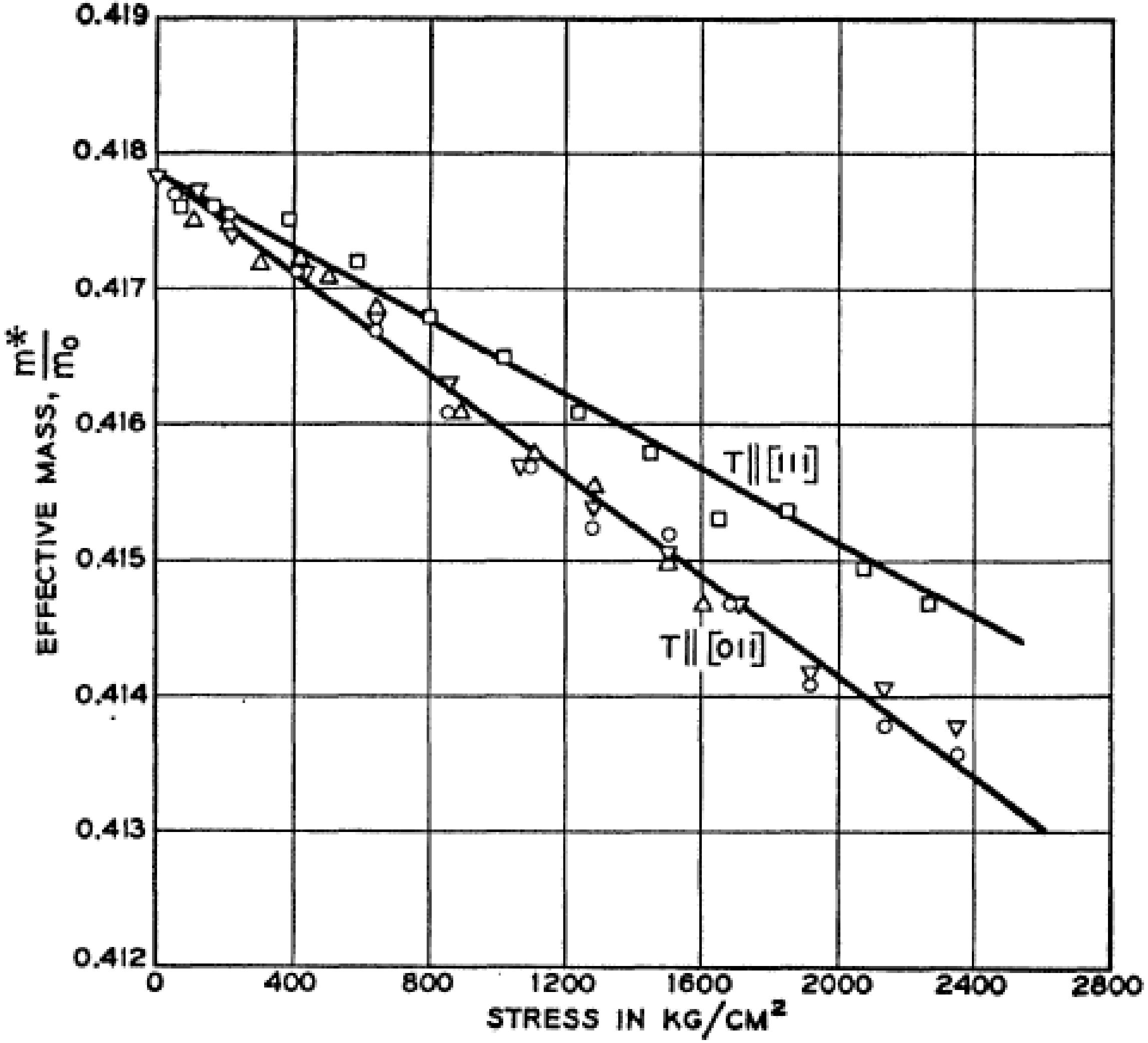


FIG. 4. Dependence of the electron effective mass ($H_0 \| [011]$) for the (001) ellipsoid on a uniaxial stress applied in turn to the [001] and [111] axes. In reference to Fig. 2 these measurements correspond, respectively, to case (b) with $\varphi = 0°$ and case (c) with $\theta = 90°$. The zero-stress effective mass is $(m_{\perp} m_{11})^{1/2} = (0.4178 \pm 0.0002)m$.

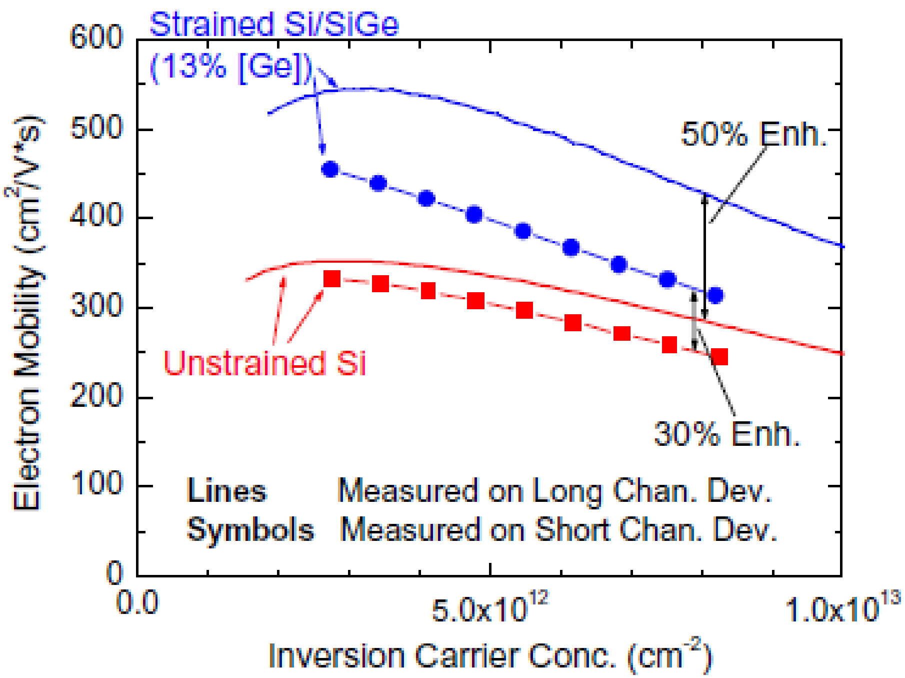


Fig. 1 Comparison of mobility in strained and unstrained Si devices. Mobility is extracted by the *dR/dL* method in short channel devices [2].

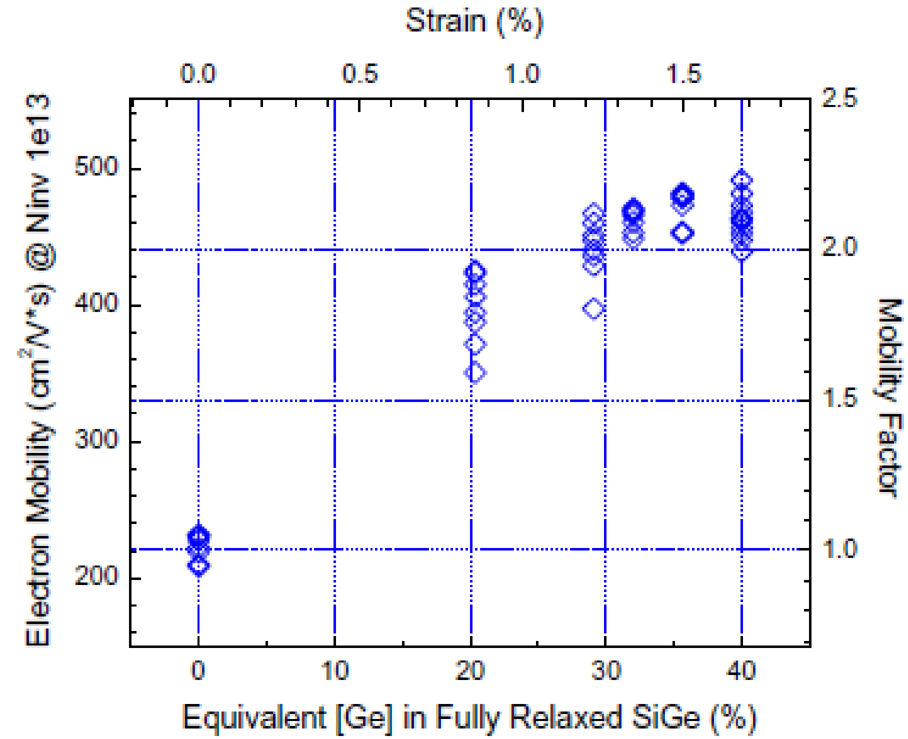


Fig. 2 NFET mobility at N_{inv} = 1e13 cm^{-2} as a function of strain. Electron mobility enhancement saturates at higher strain (ε>1.3%).

Strained Si for Sub-100 nm MOSFETs

K. Rim, L. Shi, K. Chan, J. Ott , J. Chu, D. Boyd, K. Jenkins, D. Lacey, P.M. Mooney,
M. Cobb, N. Klymko, F. Jamin, S. Koester, B.H. Lee, M. Gribelyuk, and T. Kanarsky
IBM SRDC, Research Division and Microelectronics Division
T. J. Watson Research Center, 1101 Kitchawan Road, Yorktown Heights, NY 10598, USA
Phone: +1-914-945-2946; Fax: +1-914-945-2141; e-mail: rim@us.ibm.com

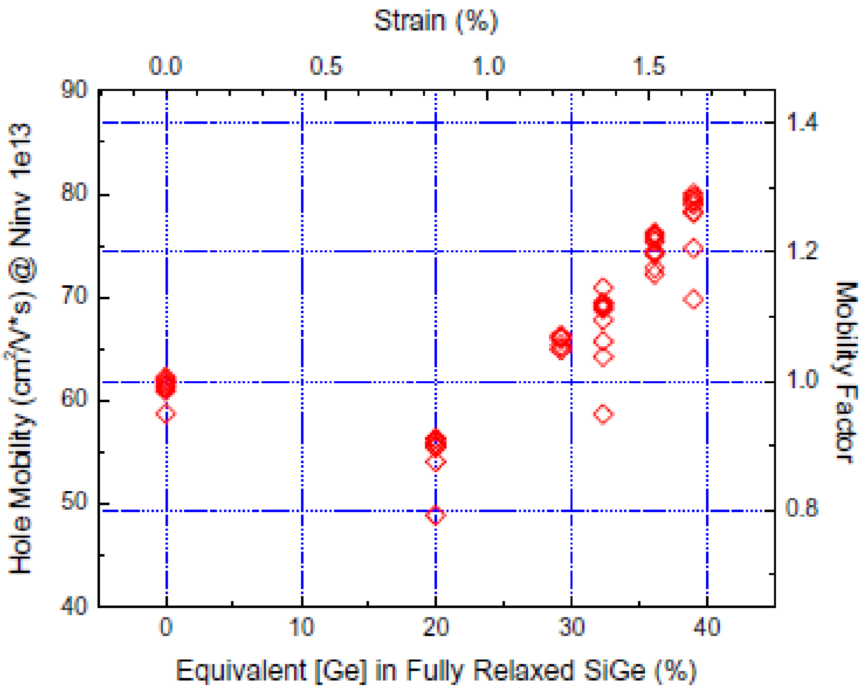


Fig. 3 PFET mobility at N_{inv} = 1e13 cm^{-2} as a function of strain. Sizable hole mobility enhancement requires high strain (ε>1.3%).

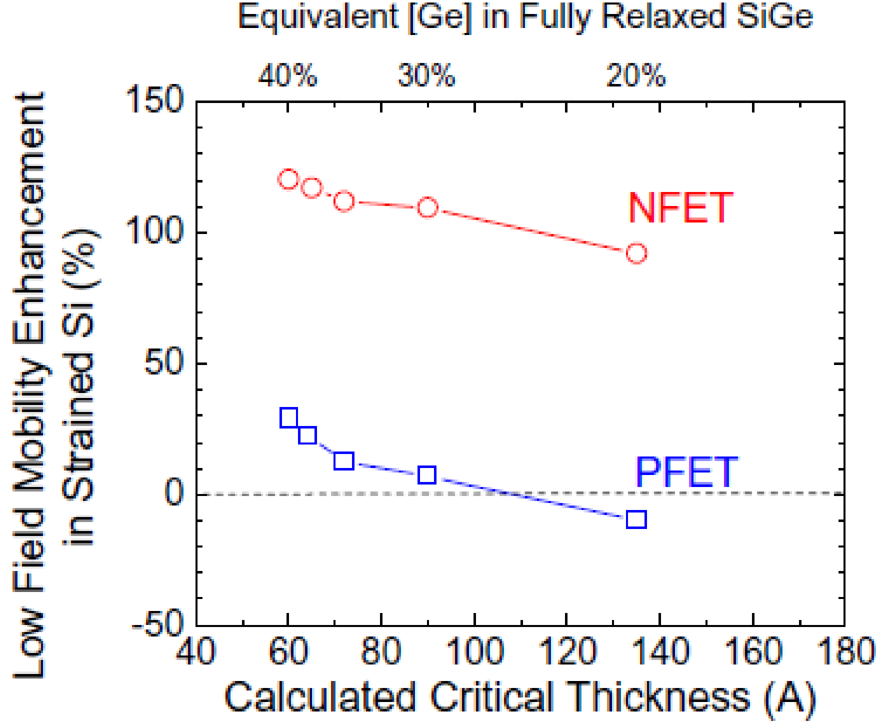


Fig. 4 Trade-off relationship between inversion mobility enhancement and theoretically calculated critical thickness from Matthews & Blakeslee (J. Cryst. Growth, vol 27, p. 118, 1974.)

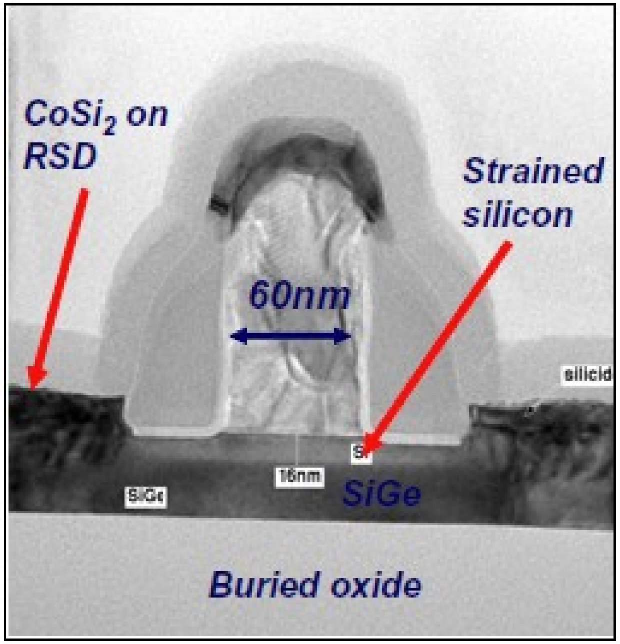


Fig. 5 TEM micrograph of a strained Si MOSFET fabricated on ultra-thin thermally mixed SGOI (TM-SGOI) [5].

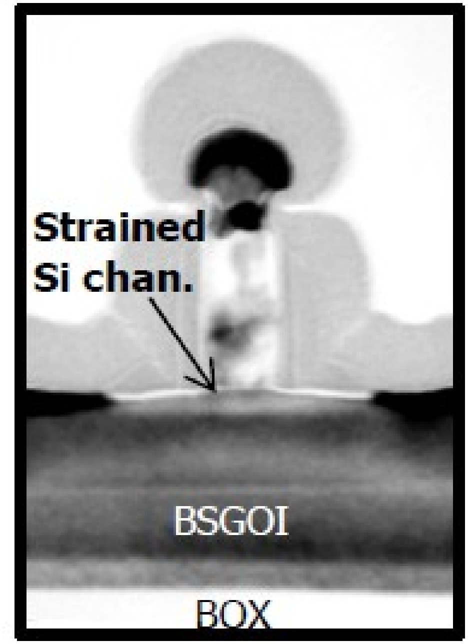


Fig. 6 TEM micrograph of a strained Si MOSFET fabricated on bonded SGOI (BSGOI).