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SMR/459-8

SPRING COLLEGE IN CONDENSED MATTER
ON
'PHYSICS OF LOW-DIMENSIONAL STRUCTURES'
(23 April - 15 June 1990)

PHONONS IN LOW DIMENSIONAL SYSTEMS

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These are preliminary lecture notes, intended only for distribution to participants.

Phonons in low dimensional systems

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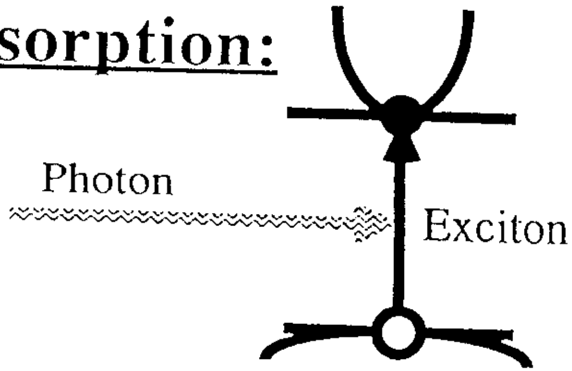
Absorption:



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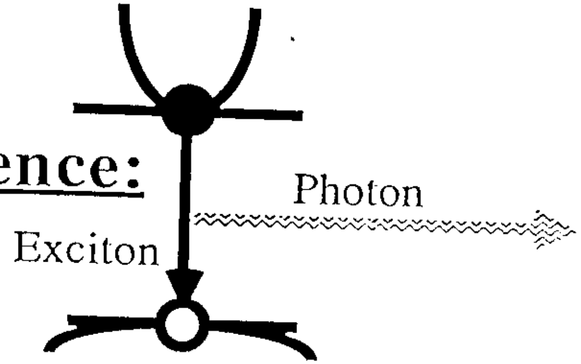

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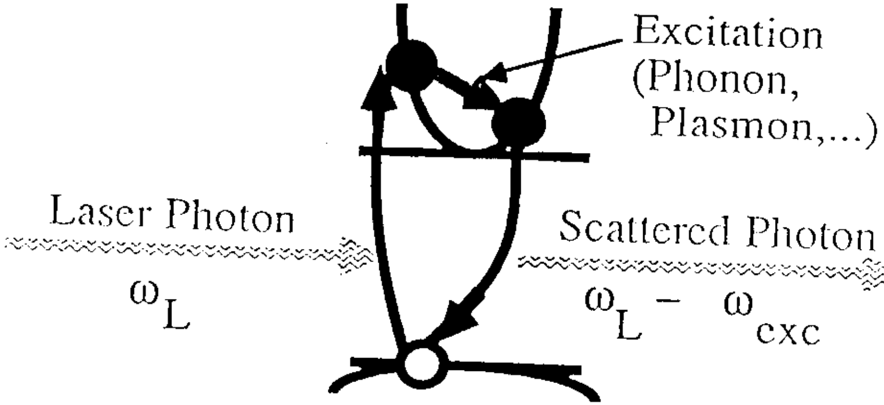
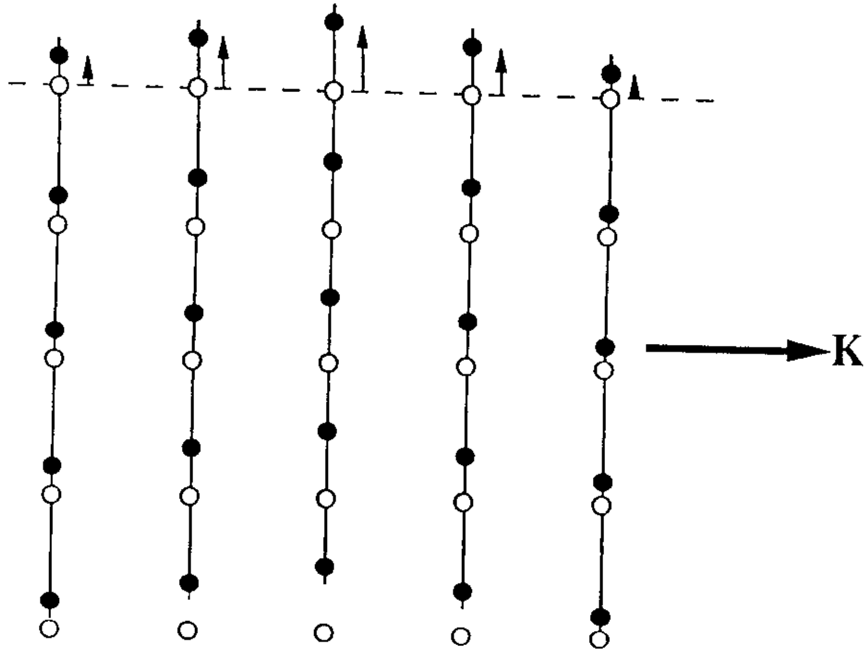
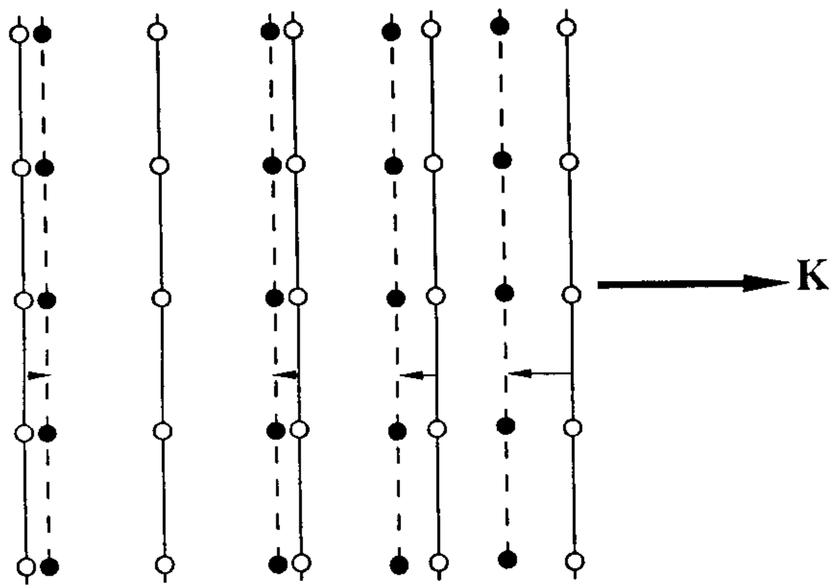
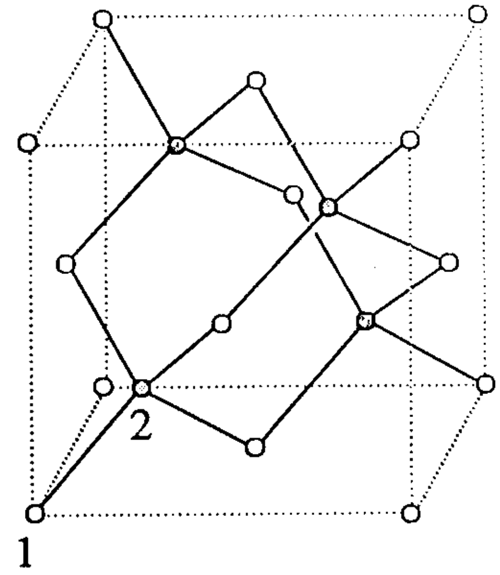


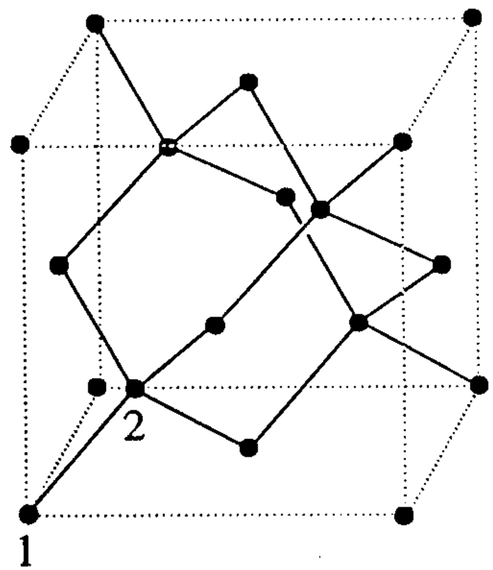


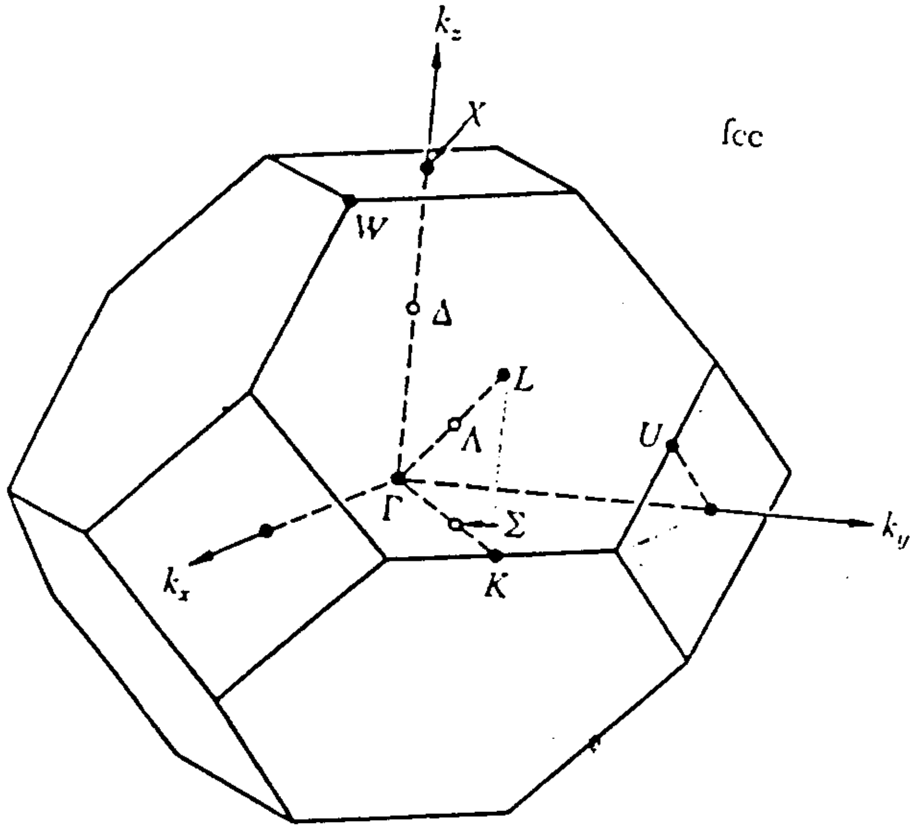


GaAs, AlAs



C, Si, Ge





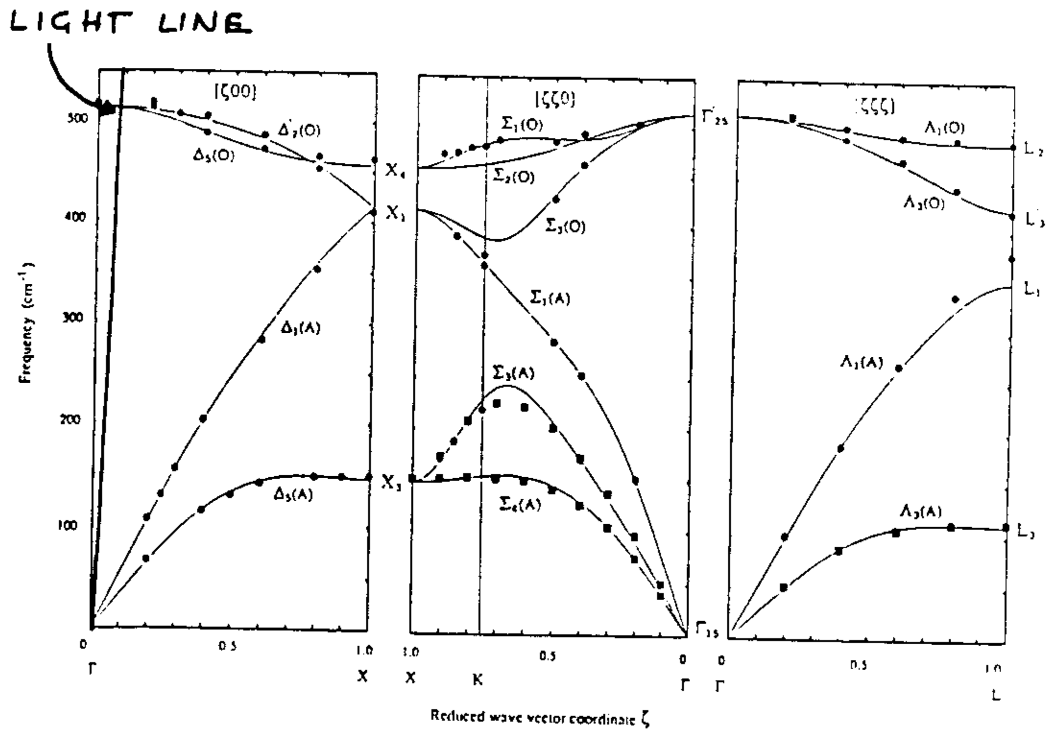
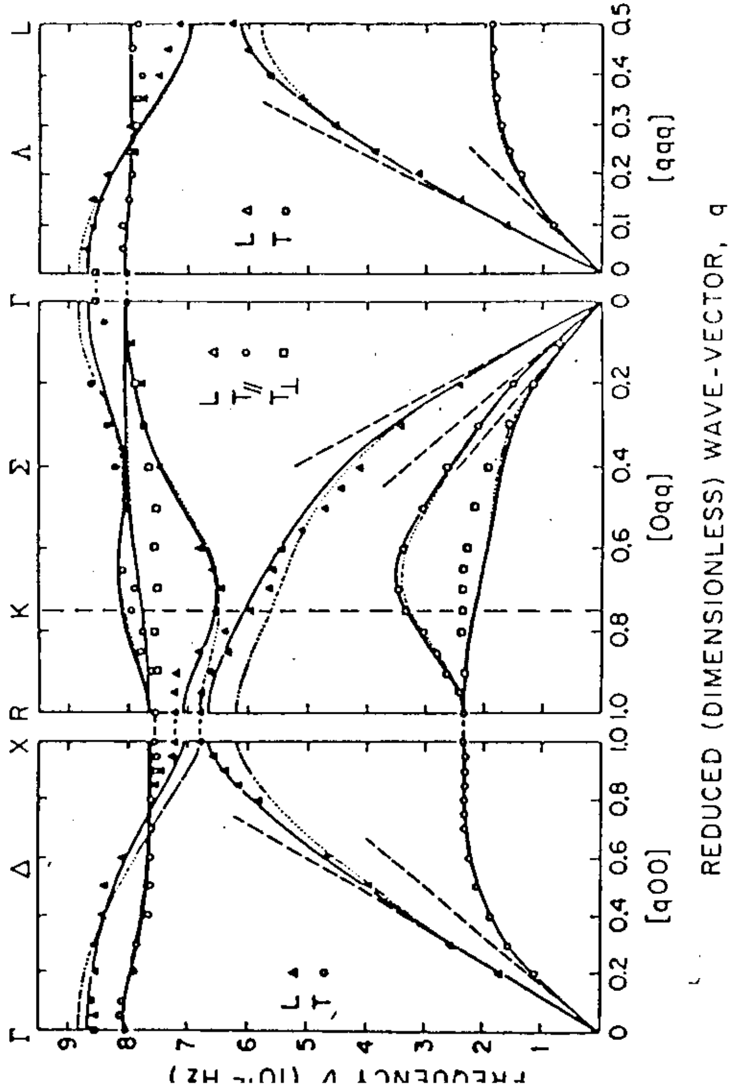
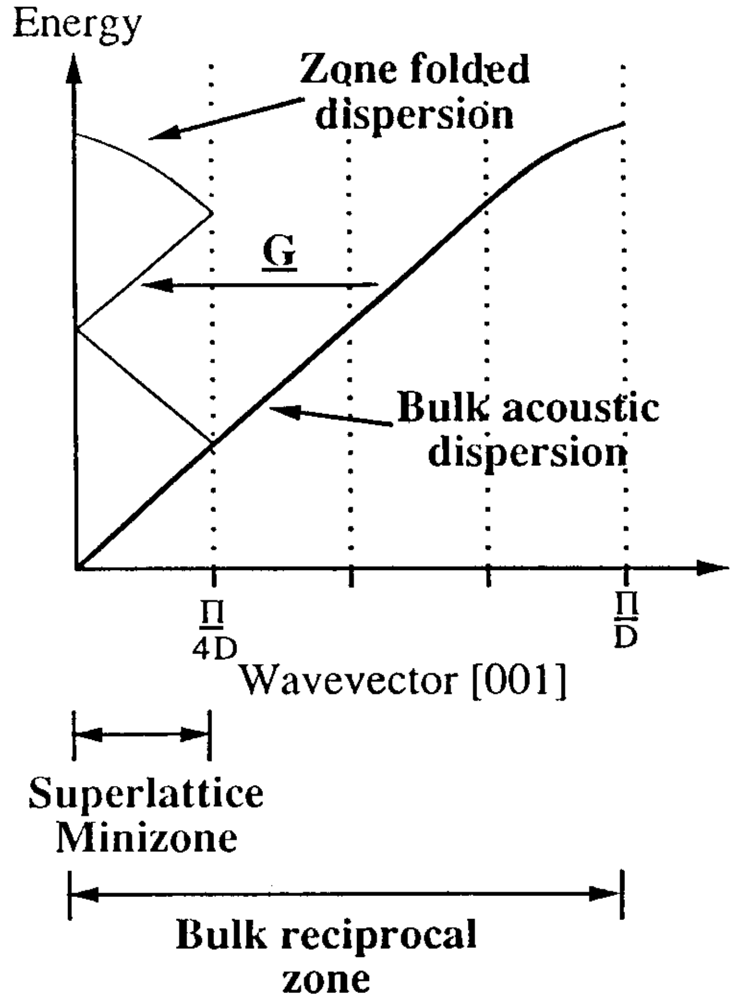
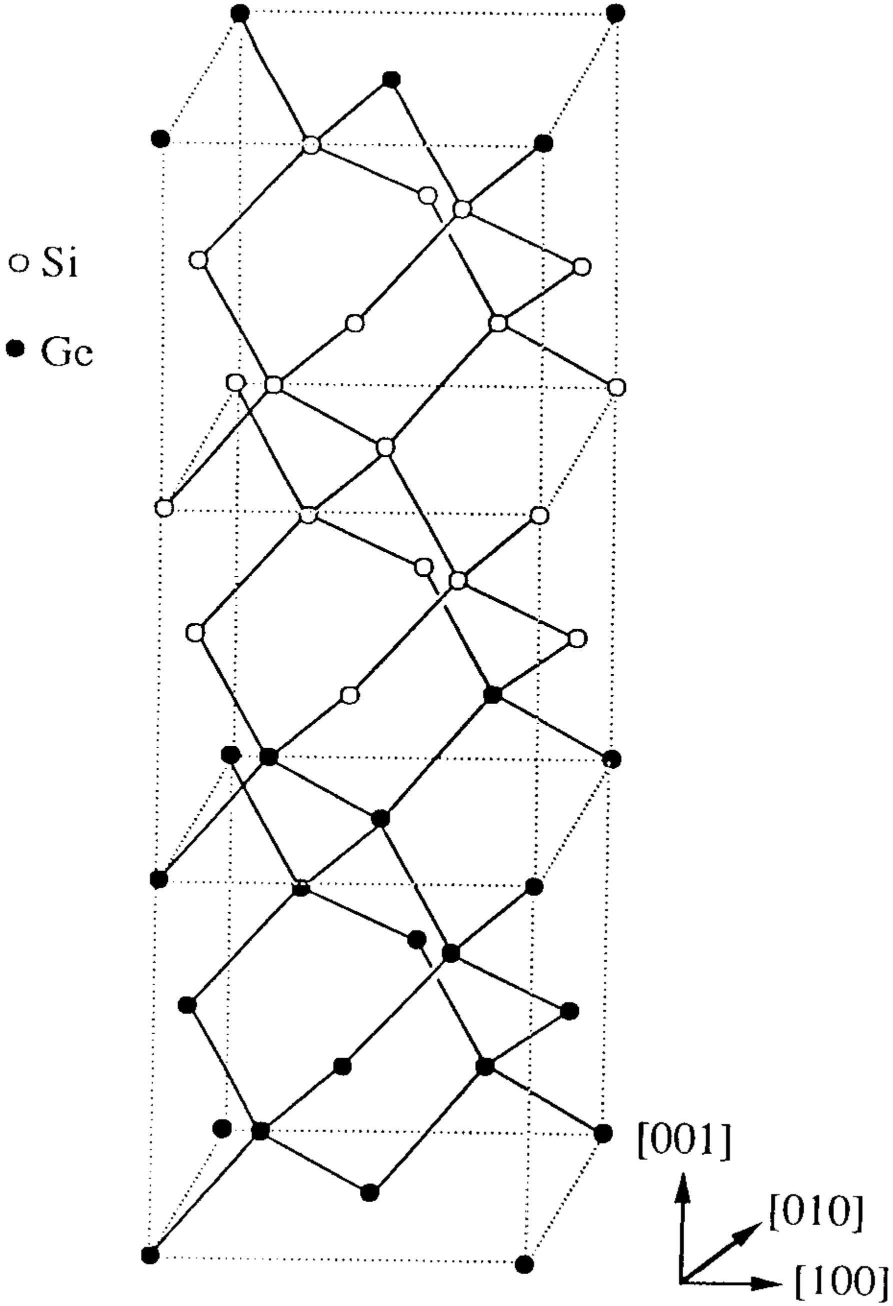


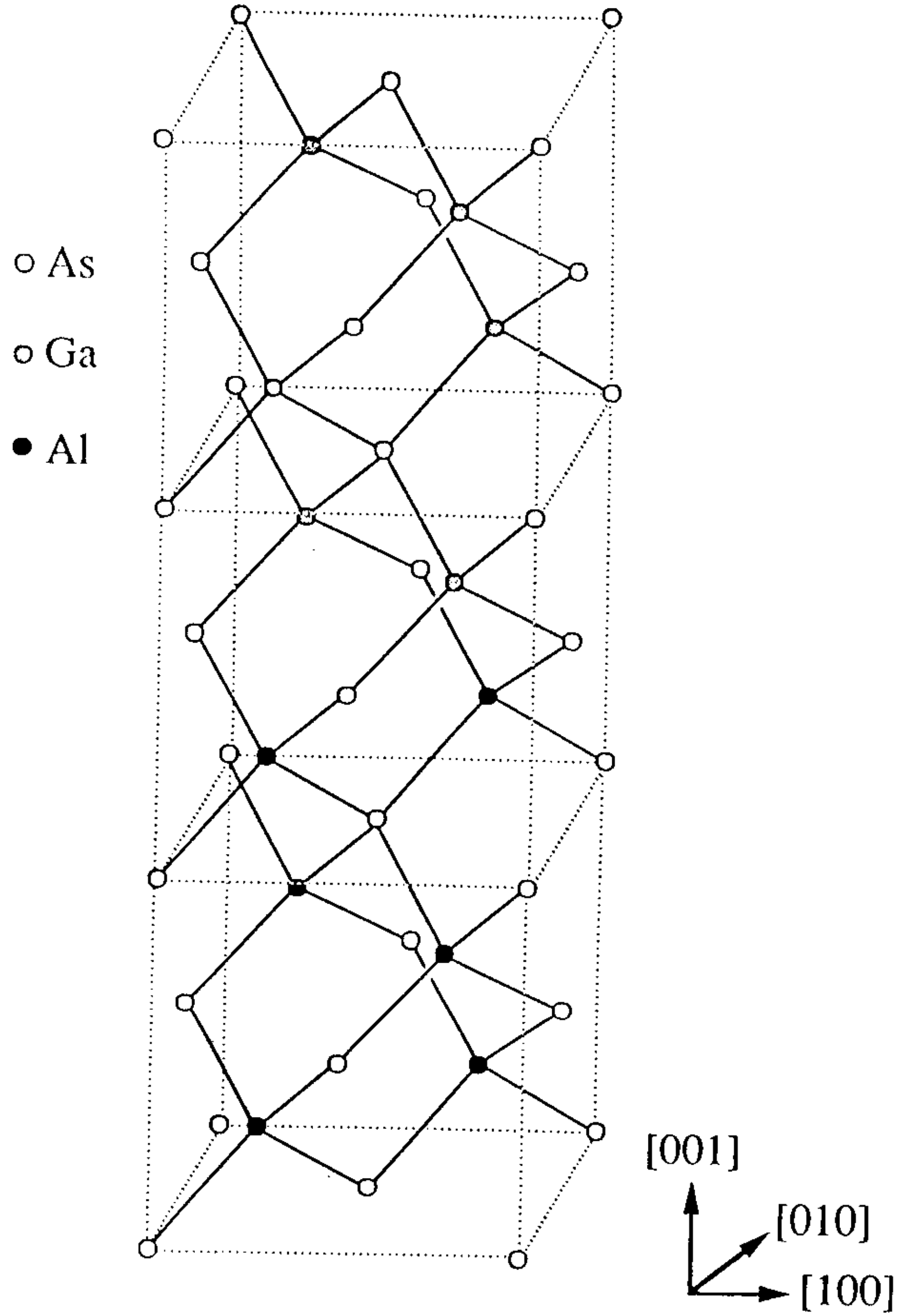
Figure 4.1 - Calculated bulk dispersion relations for silicon in the three primary symmetry directions. Data points are available experimental data from neutron scattering experiments (circles from [47,48], and squares from [49]).


REDUCED (DIMENSIONLESS) WAVE-VECTOR, q
[q00]
[0qq]
[qqq]


Energy
Zone folded dispersion
G
Bulk acoustic dispersion
Π/4D
Π/D
Wavevector [001]
Superlattice Minizone
Bulk reciprocal zone



$(Si)_6/(Ge)_6$

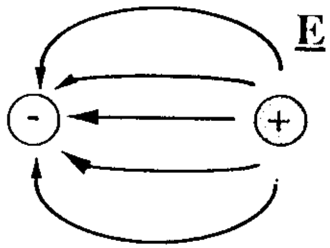


$(GaAs)_3/(AlAs)_3$

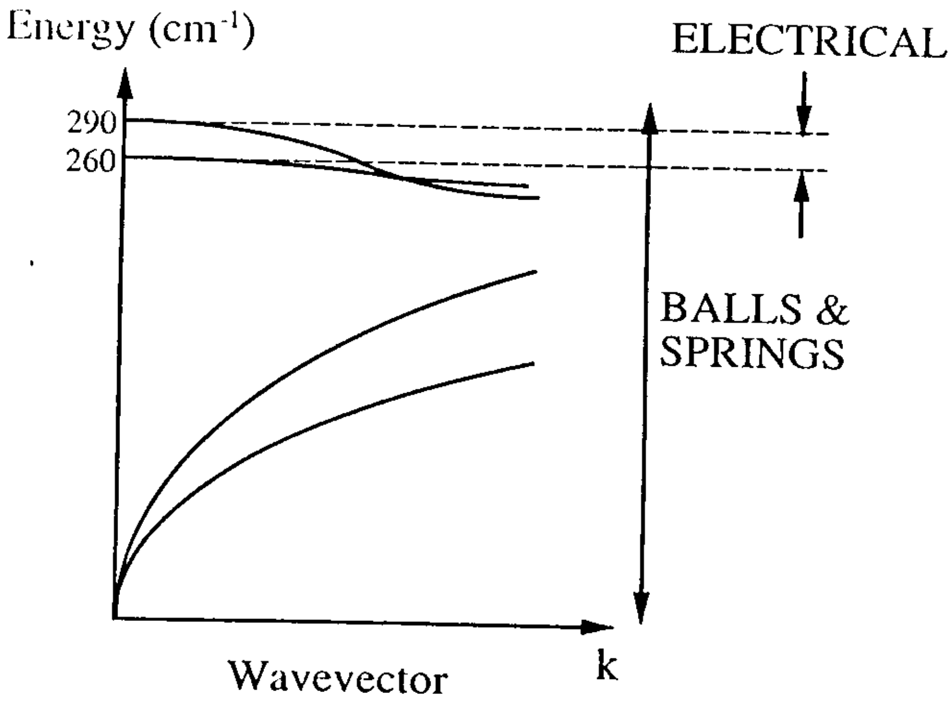
1.) BALLS & SPRINGS

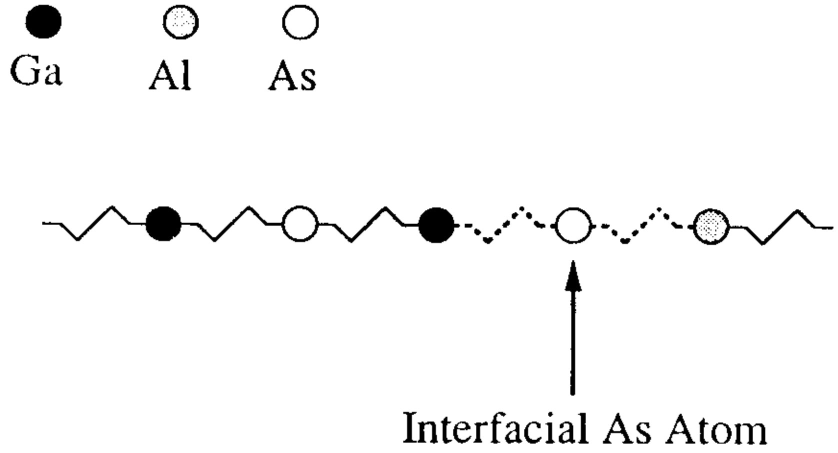
STRONG

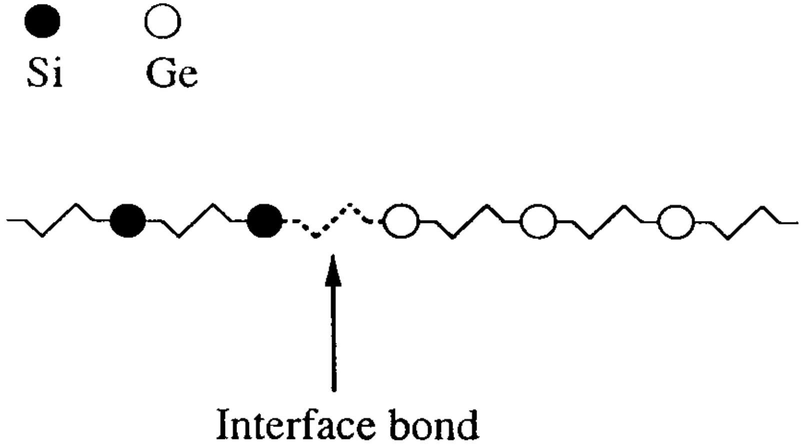
2.) ELECTRICAL



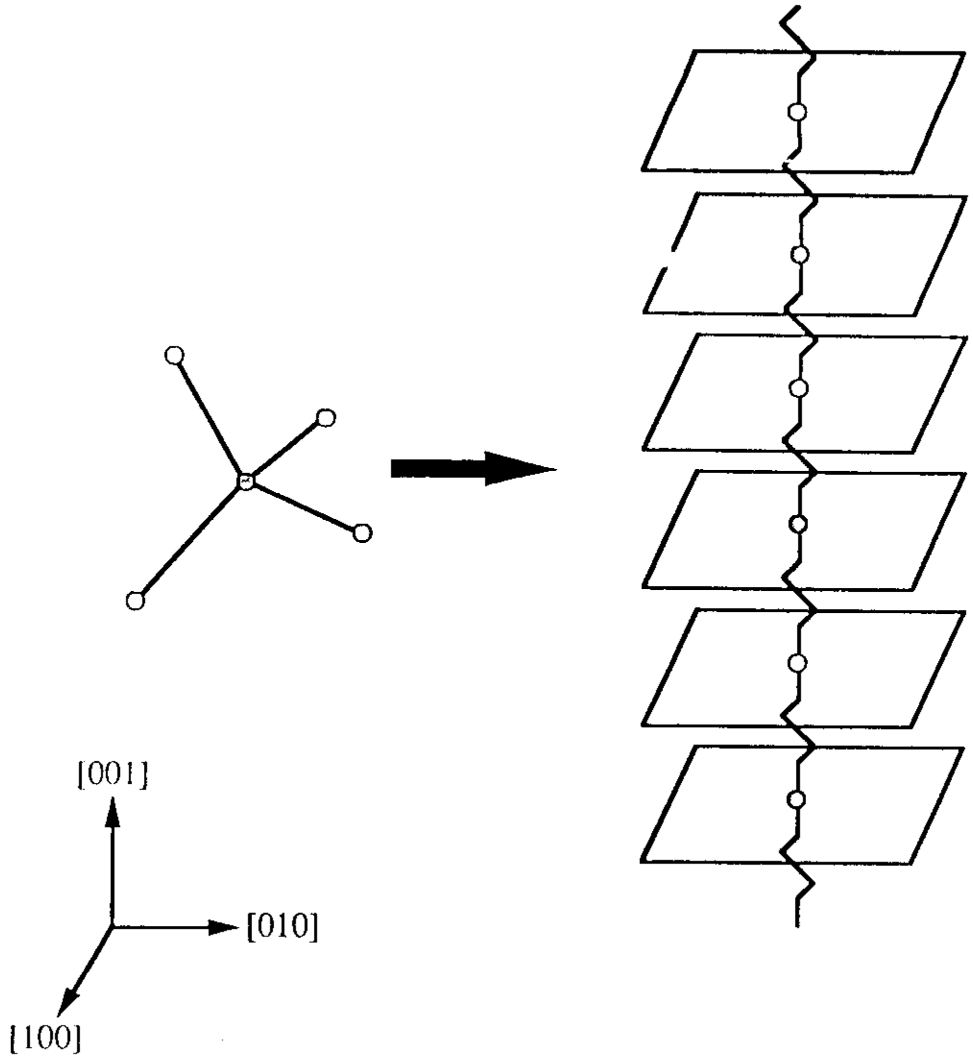
PERTURBATION

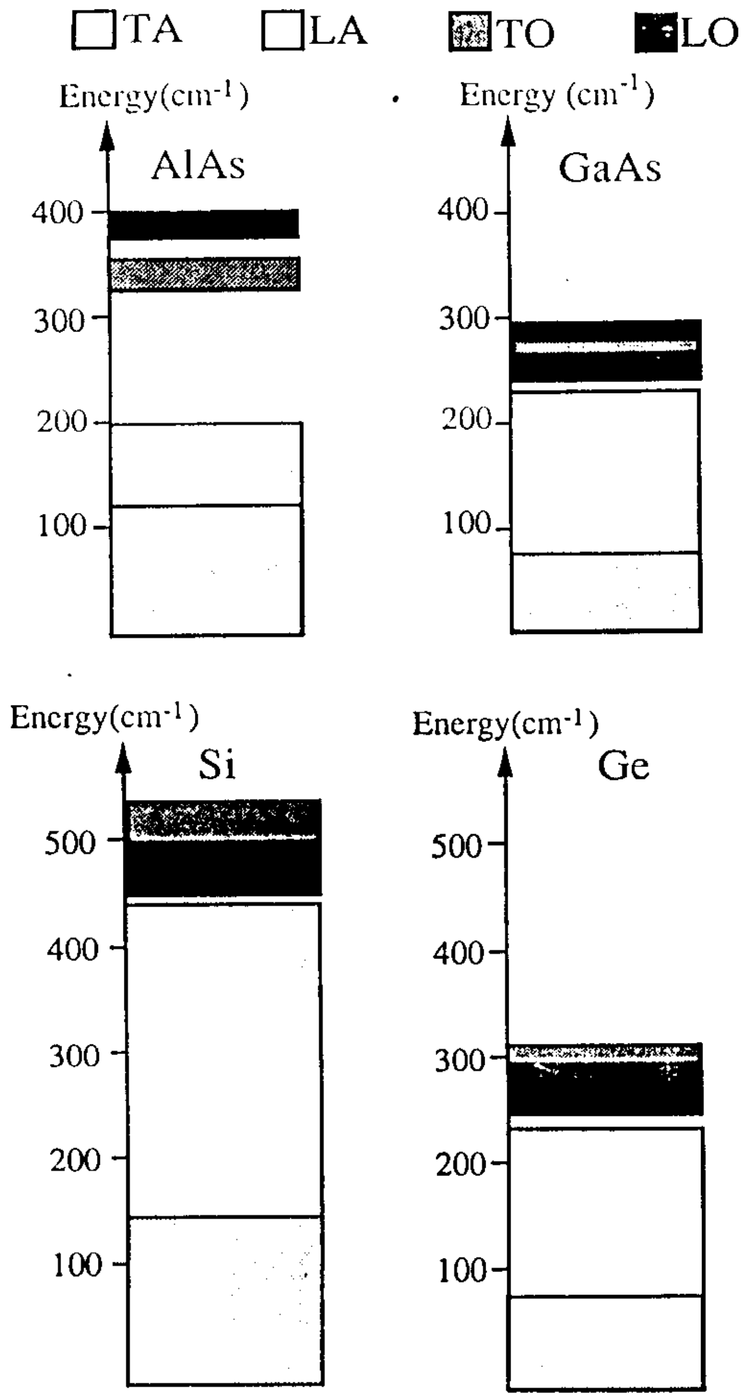






Linear chain model





Acoustic Phonons in superlattices

From Rytov;

$$\cos(Qd) = \cos\left(\omega \frac{d_a}{v_a}\right)\cos\left(\omega \frac{d_b}{v_b}\right) - \left(1+\frac{\alpha^2}{2}\right)\sin\left(\omega \frac{d_a}{v_a}\right)\sin\left(\omega \frac{d_b}{v_b}\right) \quad (1)$$

Where $d=d_1+d_2$ and Q is the superlattice wavevector and

$a = |\rho_a v_a - \rho_b v_b| / \sqrt{(\rho_a v_a \rho_b v_b)}$

For the case where the acoustic modulation of the superlattice is small (α=0) (1) reduces to;

$$Qd = \frac{\omega}{d}\left(\frac{d_a}{v_a} + \frac{d_b}{v_b}\right) \quad (2)$$

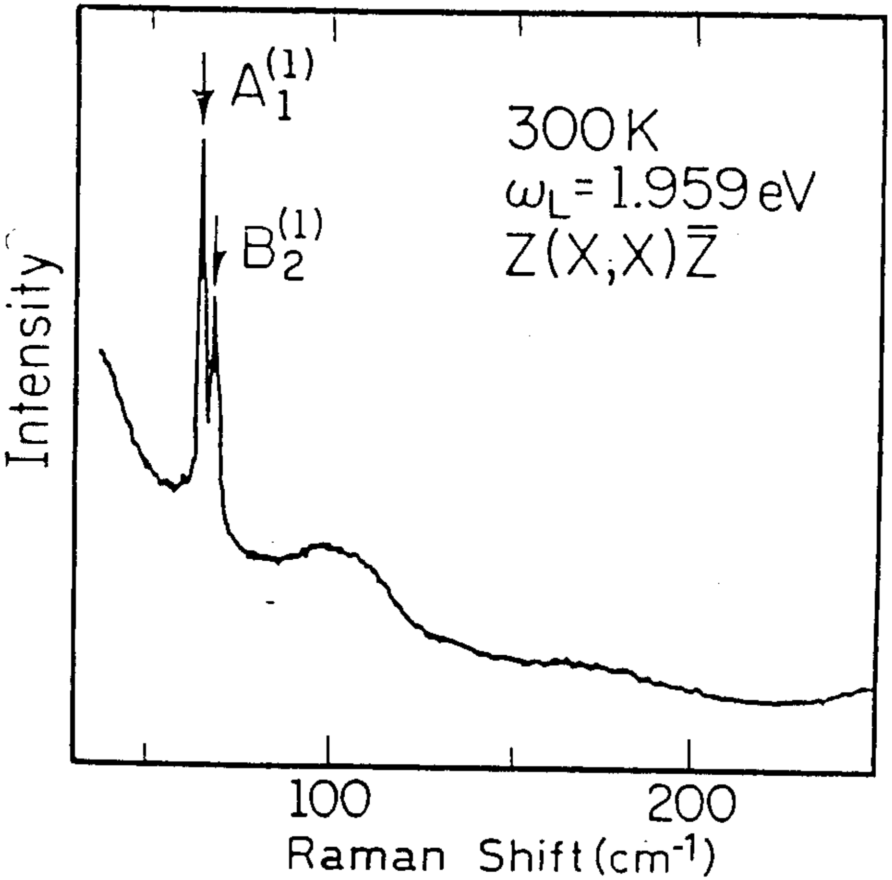
using $v_g=\frac{d\omega}{dq}$, we find that the average velocity of acoustic waves through the superlattice ,v_s is;

$$v_s=\frac{v_1 v_2}{x v_1+(1-x)v_2} \quad (3)$$

Where $x=d_b/d$.

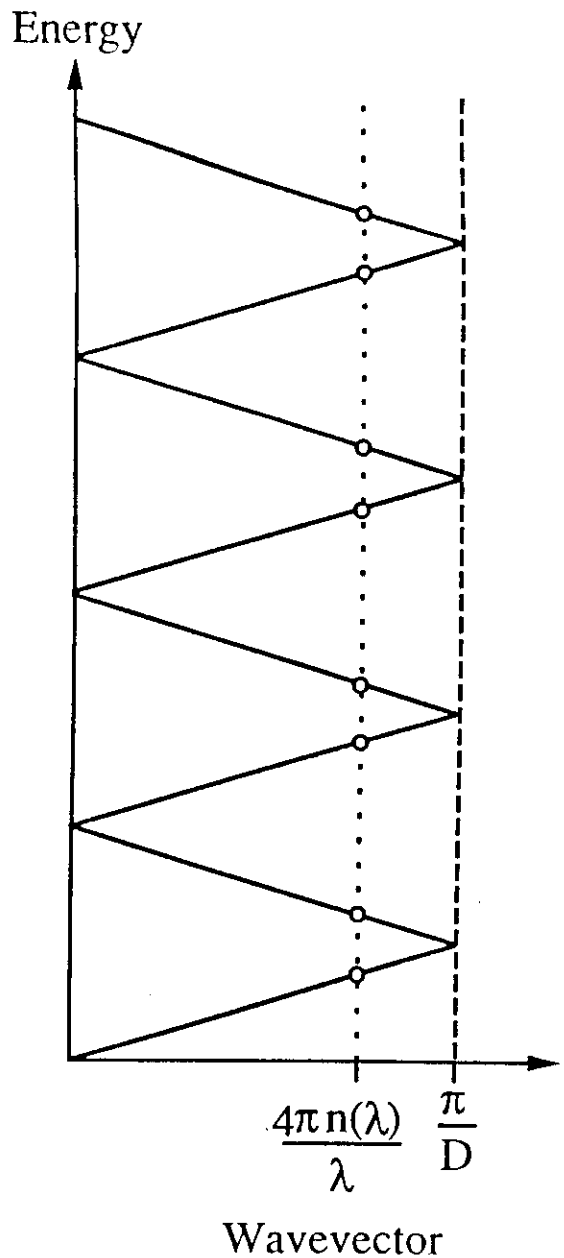
$$\Delta\Omega^2 = \alpha^2 \frac{v^2}{d^2}\sin^2 \pi \left\{\frac{x v_1 - (1-x)v_2}{x v_1 + (1-x)v_2}\right\} \quad (4)$$

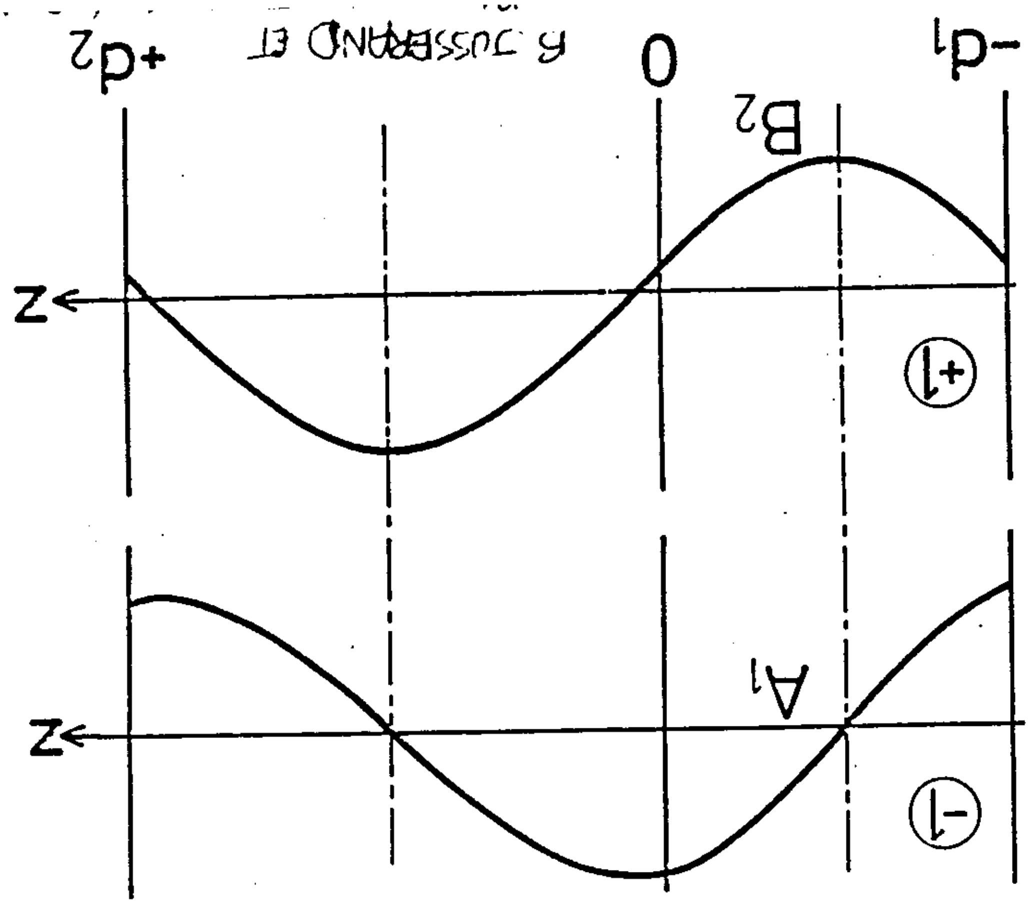
The gap at the zone centre being $2\Delta\Omega$.



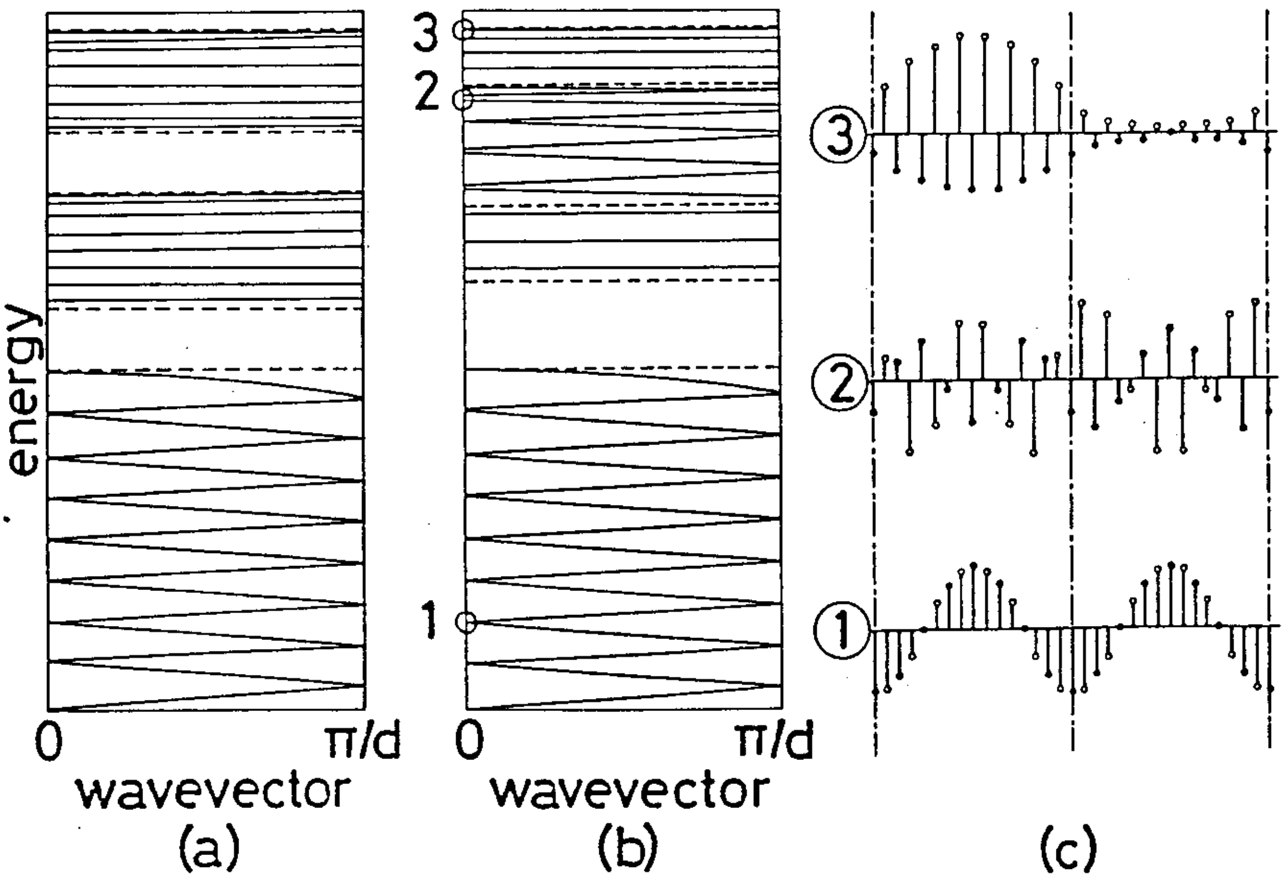
COLVARD. P.R.L 43
298 (1980)

3.28



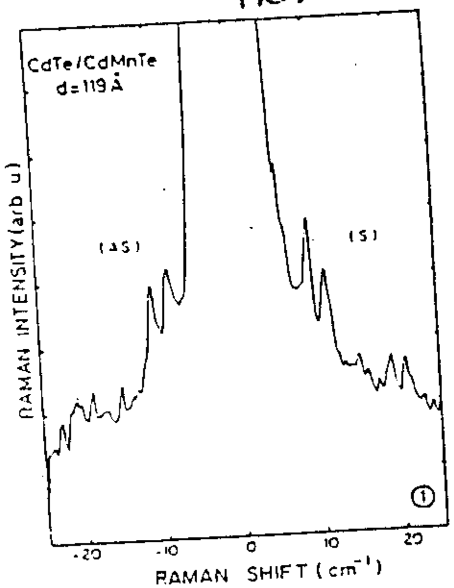


+d2
0
-d1
z
B2
A1
+1
-1

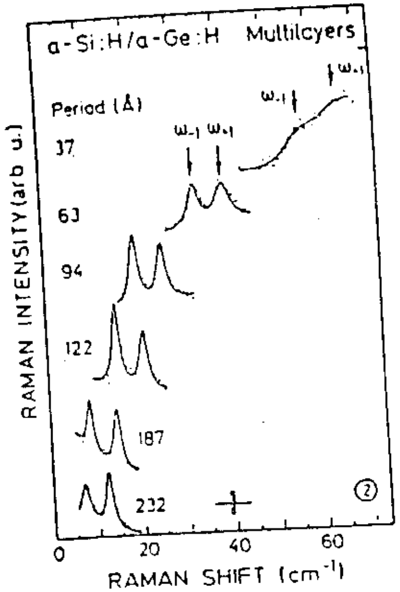


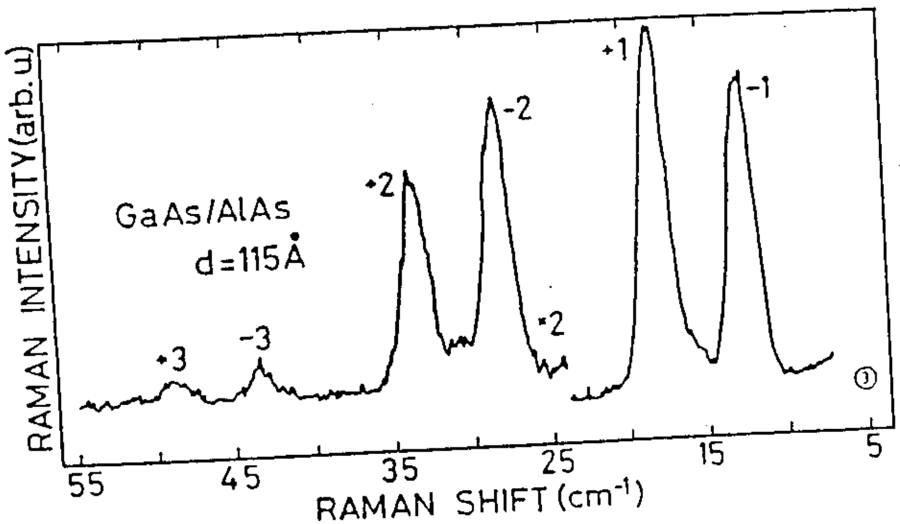
energy
0
π/d
wavevector
(a)
1
2
3
(b)
(c)

S. VENUGOPOLAN
ET APL 45 974
1987

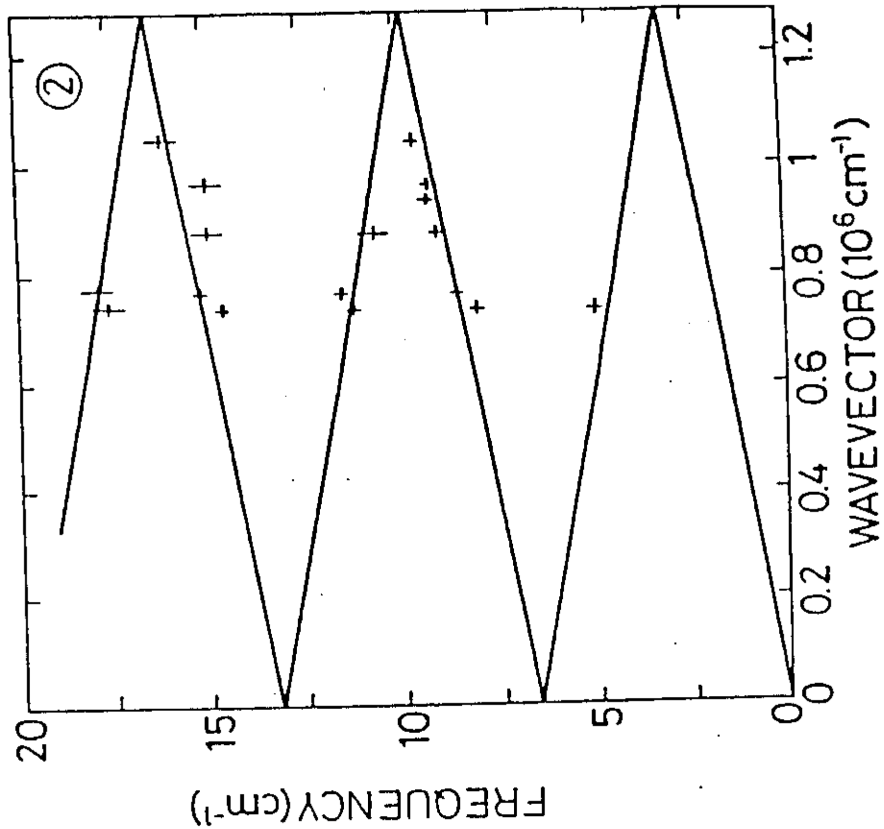


P.V. SANTOS ET AL
P.R.B 36 3325 (FB7)

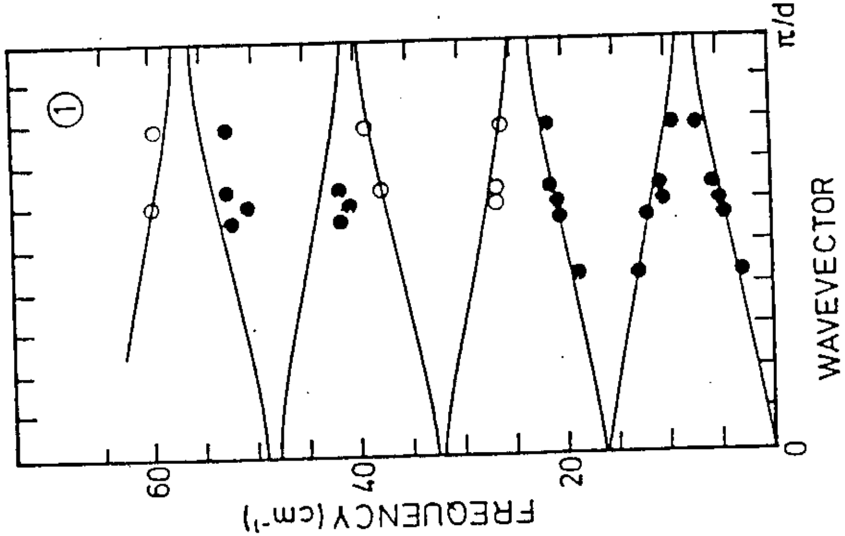




B JUSSERAND ET AL
... 1988 (AR?)
3.29

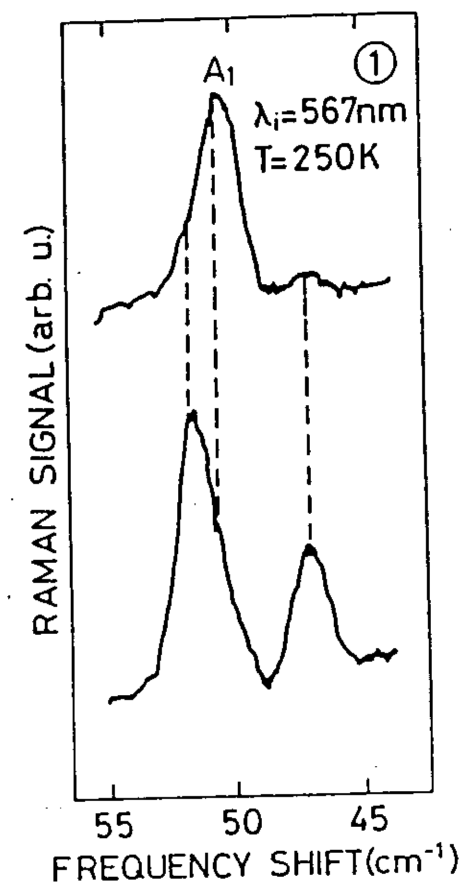


JUSSERAND ET AL APL 42 444 (1983)

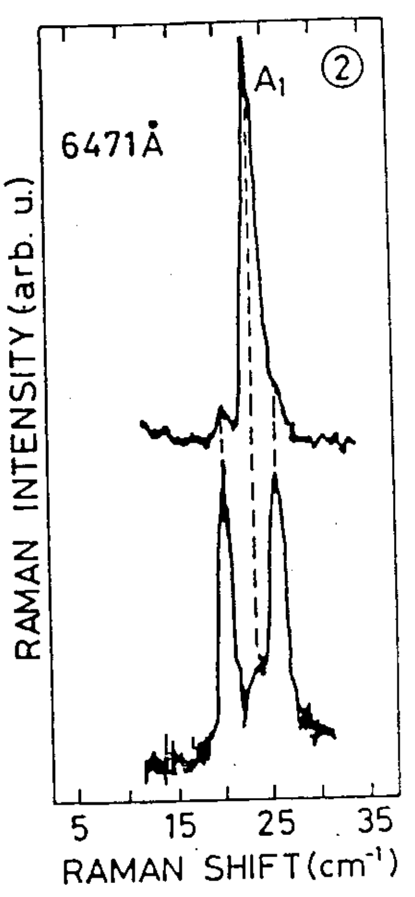


BRUGGER ET AL. SUPER. + MICROS. 2

3.30



JUSSERAND ET AL P.R.B.
33 2897 (1986)



SANTOS ET AL
PRB 36 4858 (1987)

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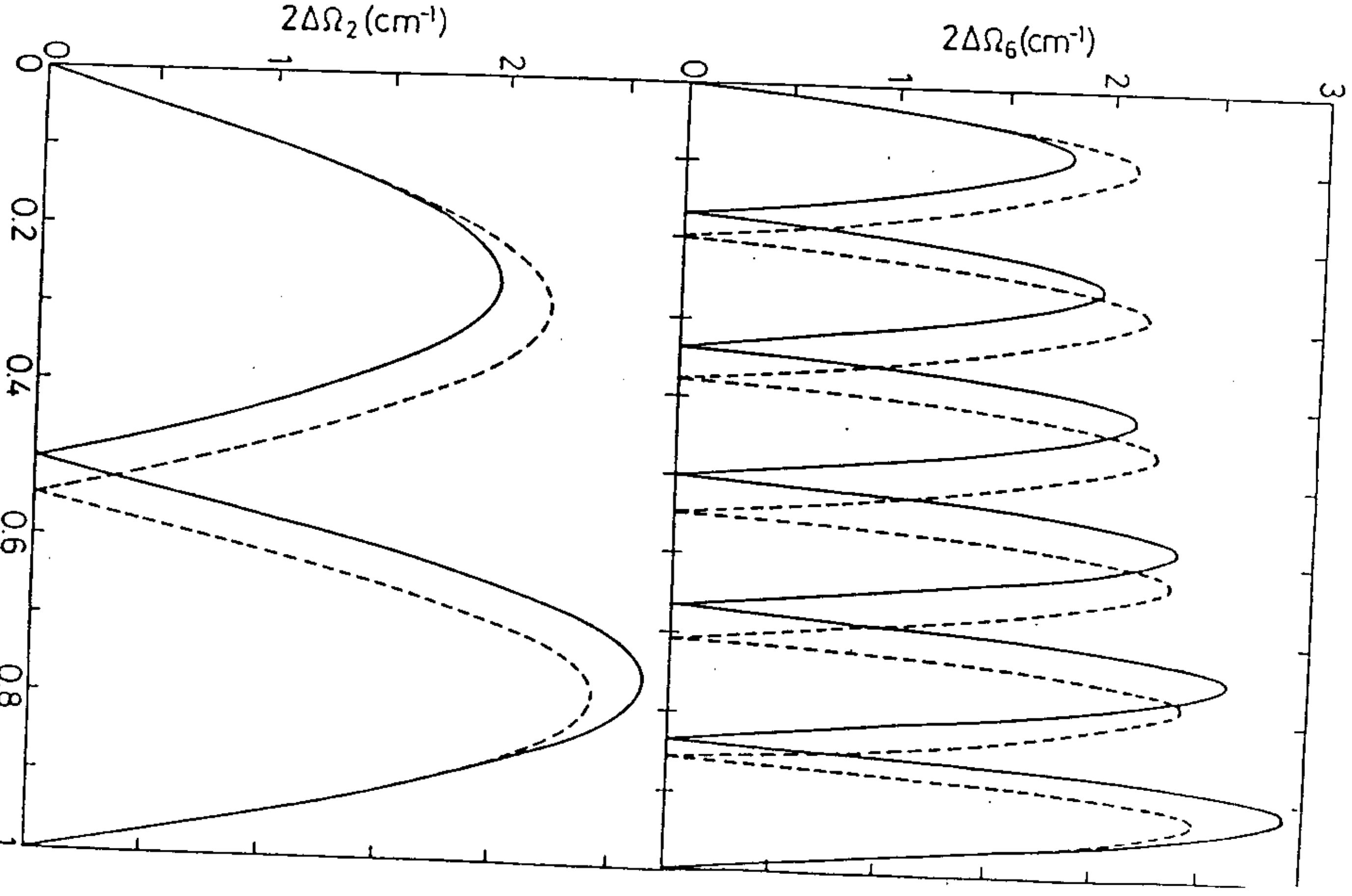
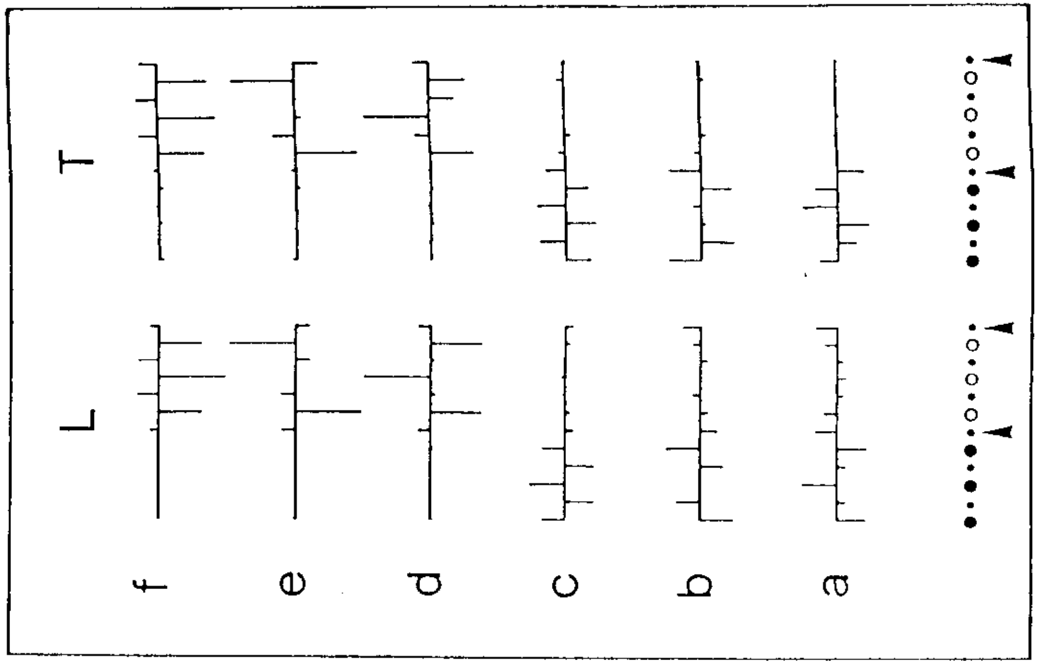


R. JUSSERAND, M. CARDONA

E. MOLINARI ET AL. SUPERLAT + MICROS. 2, 397, (1986)



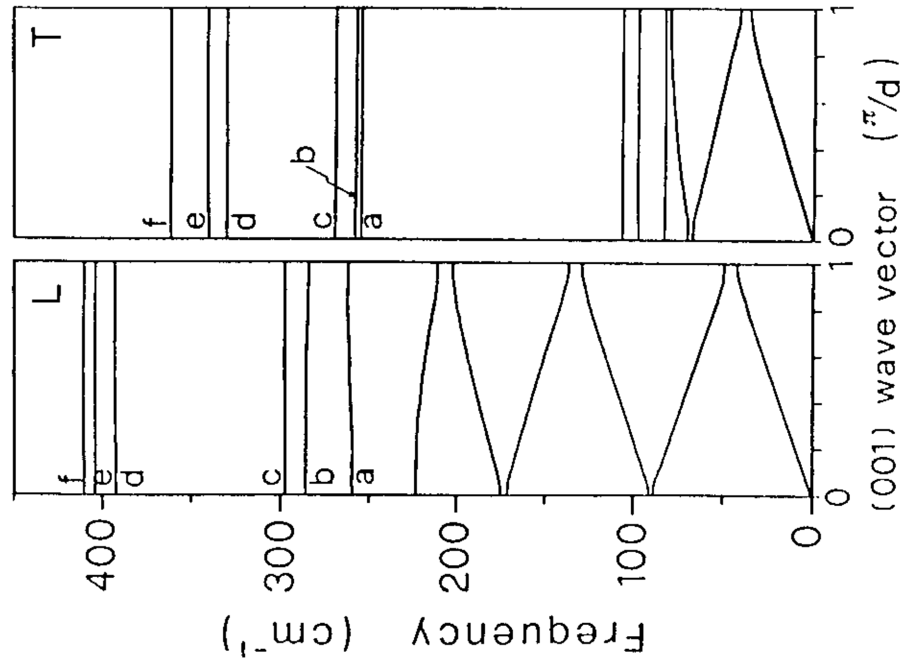
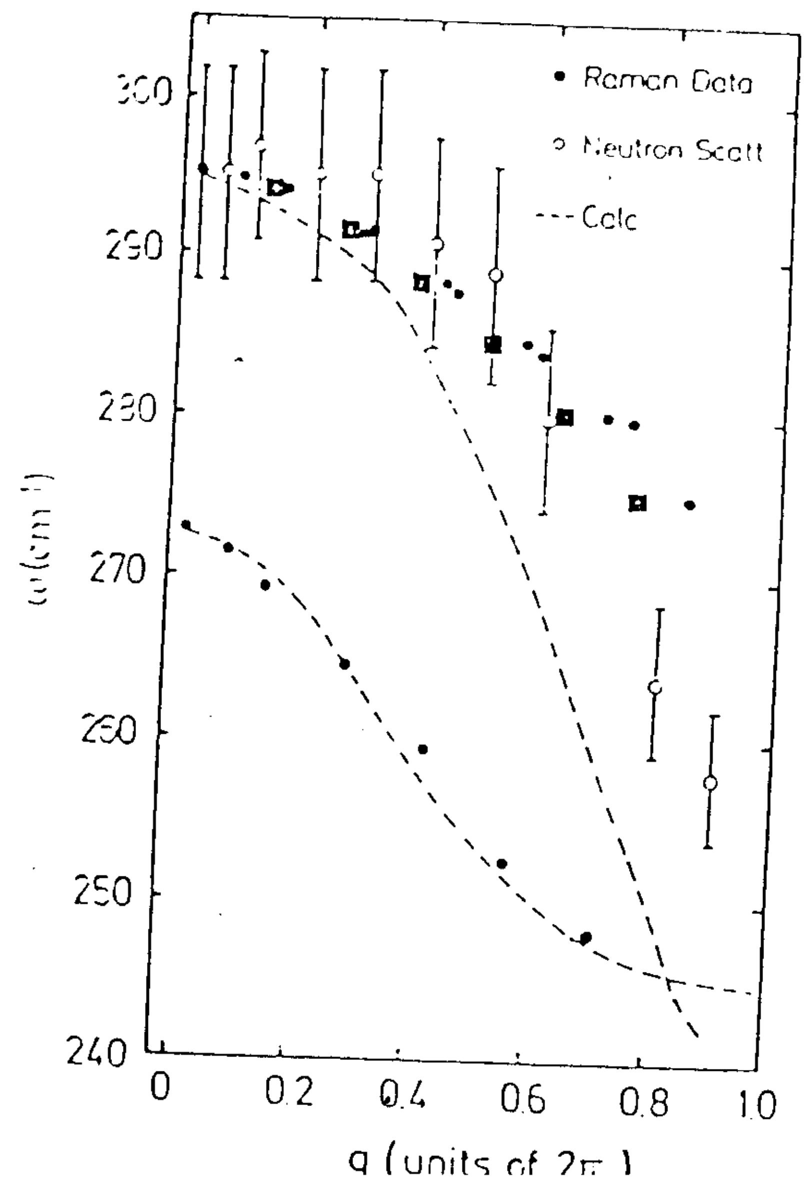


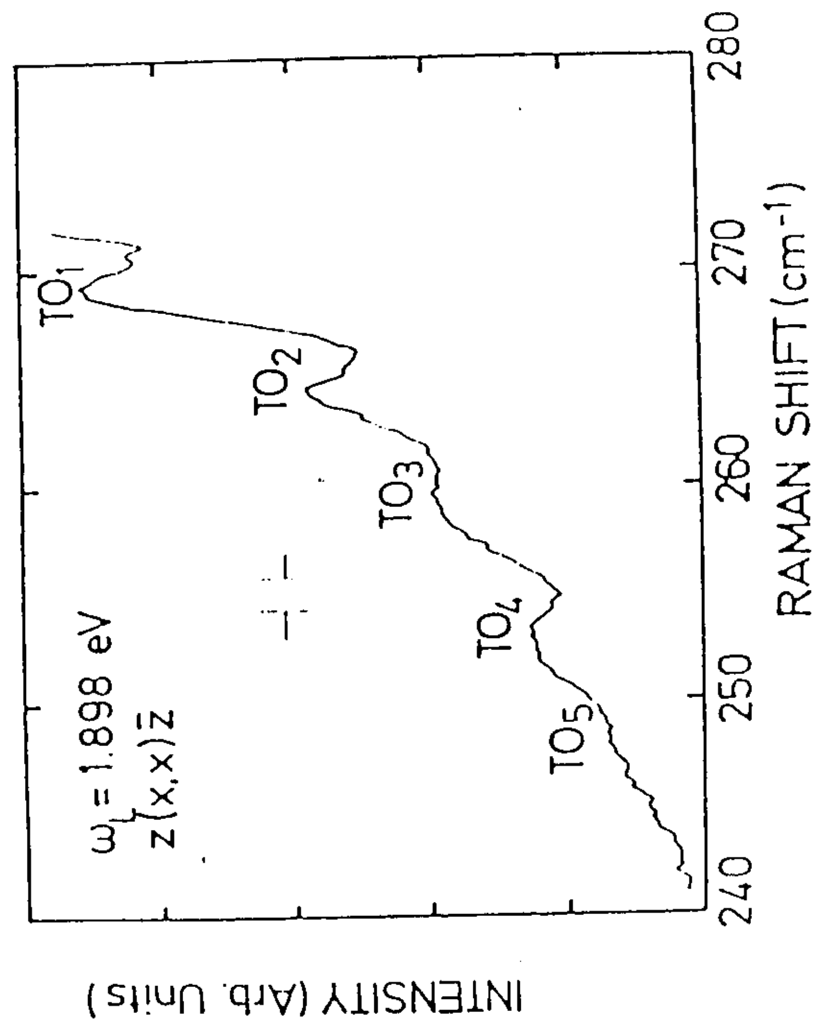
Fig.1. Longitudinal and transverse frequency dispersion along the (001) direction for the $(GaAs)_3(AlAs)_3$ superlattice (d = 3 a). The corresponding displacement amplitudes at Γ for modes a-f are shown in Fig.2.

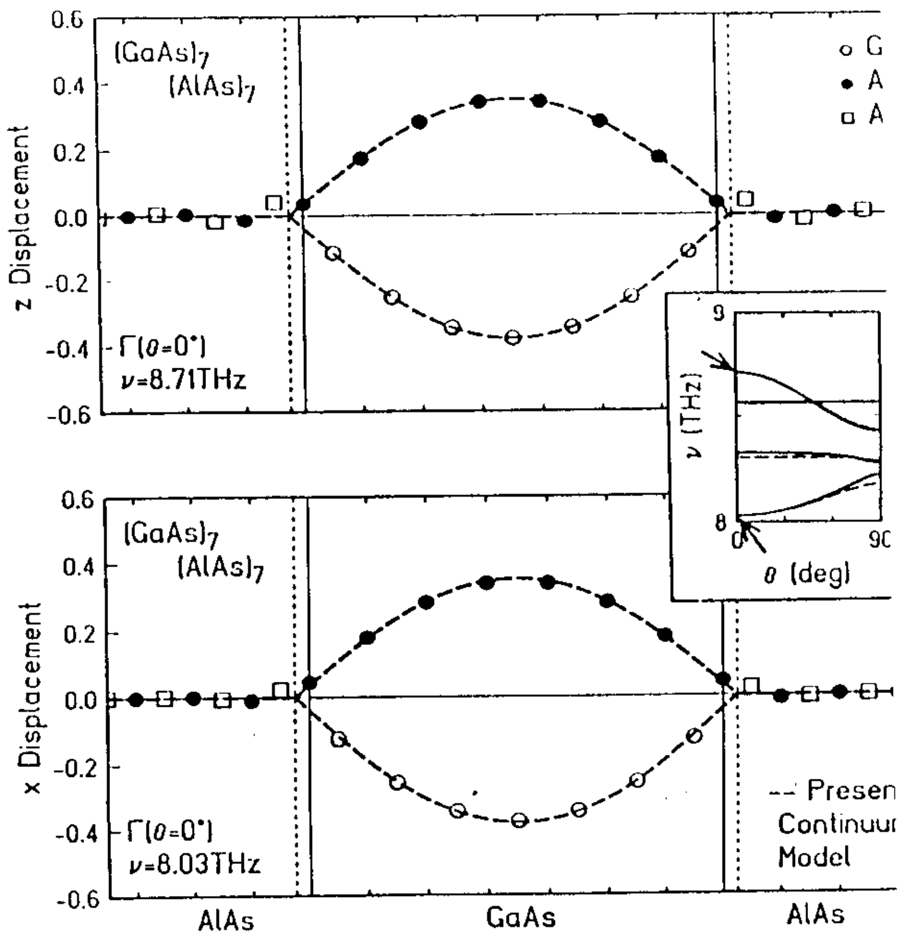
AK SOOD DAE SOL STATE PHYS. SYMPOSIUM, DEC 27-30 1985 NAGPUR INDIA.

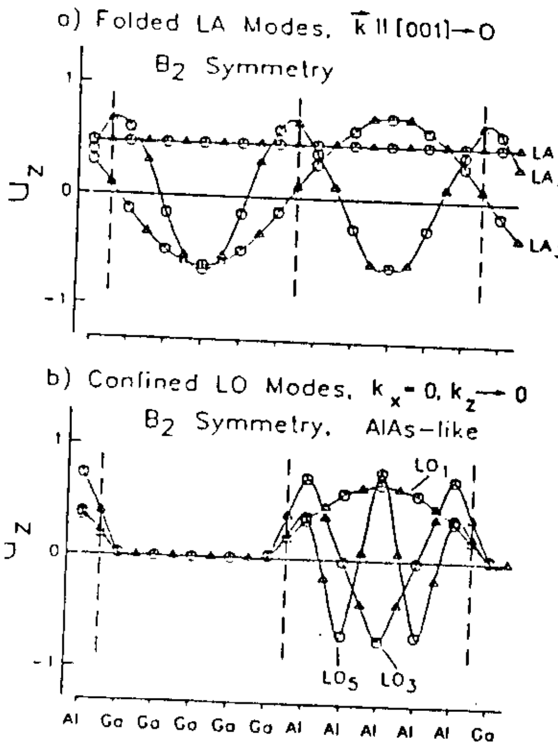


T. TSUCHIYA ~~AND~~ ETA P.R.B (1989)

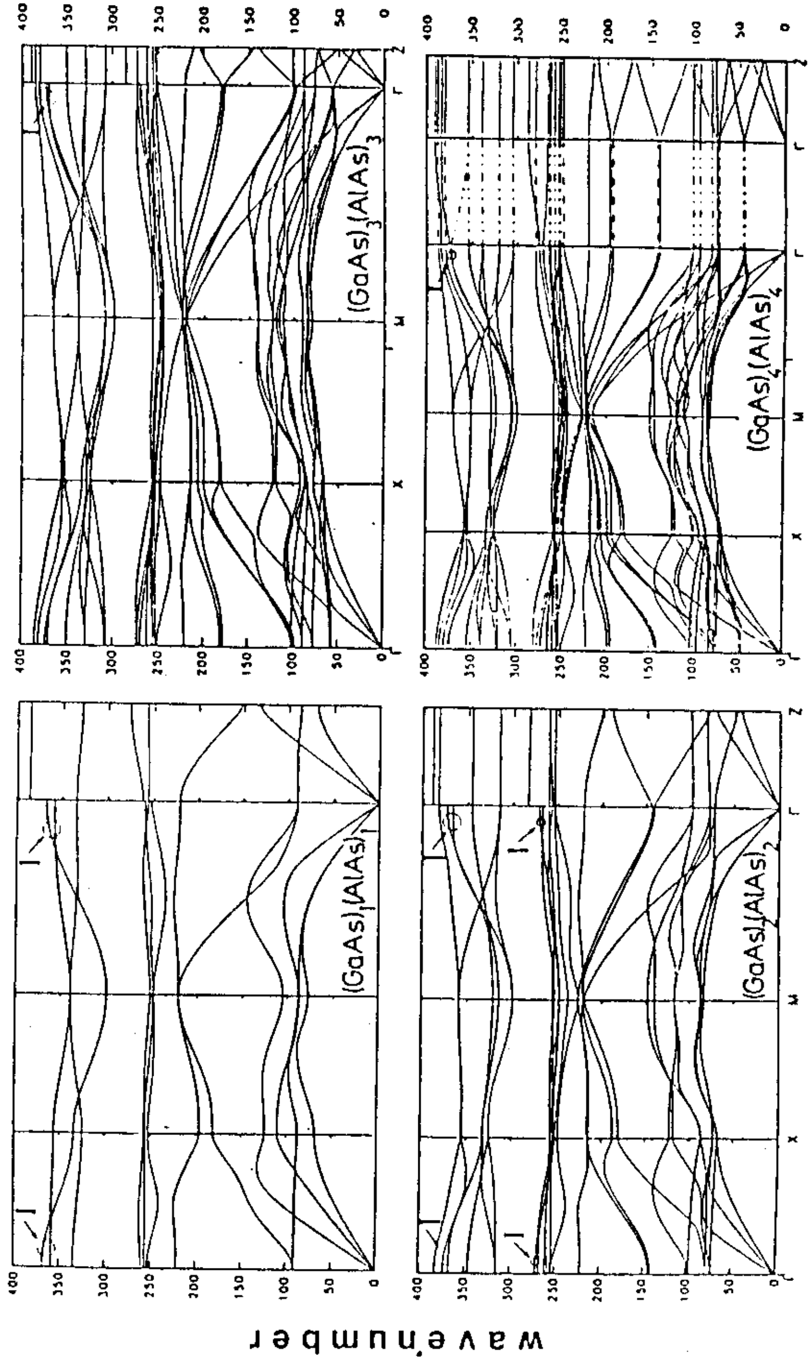
A K. SOOD IBID





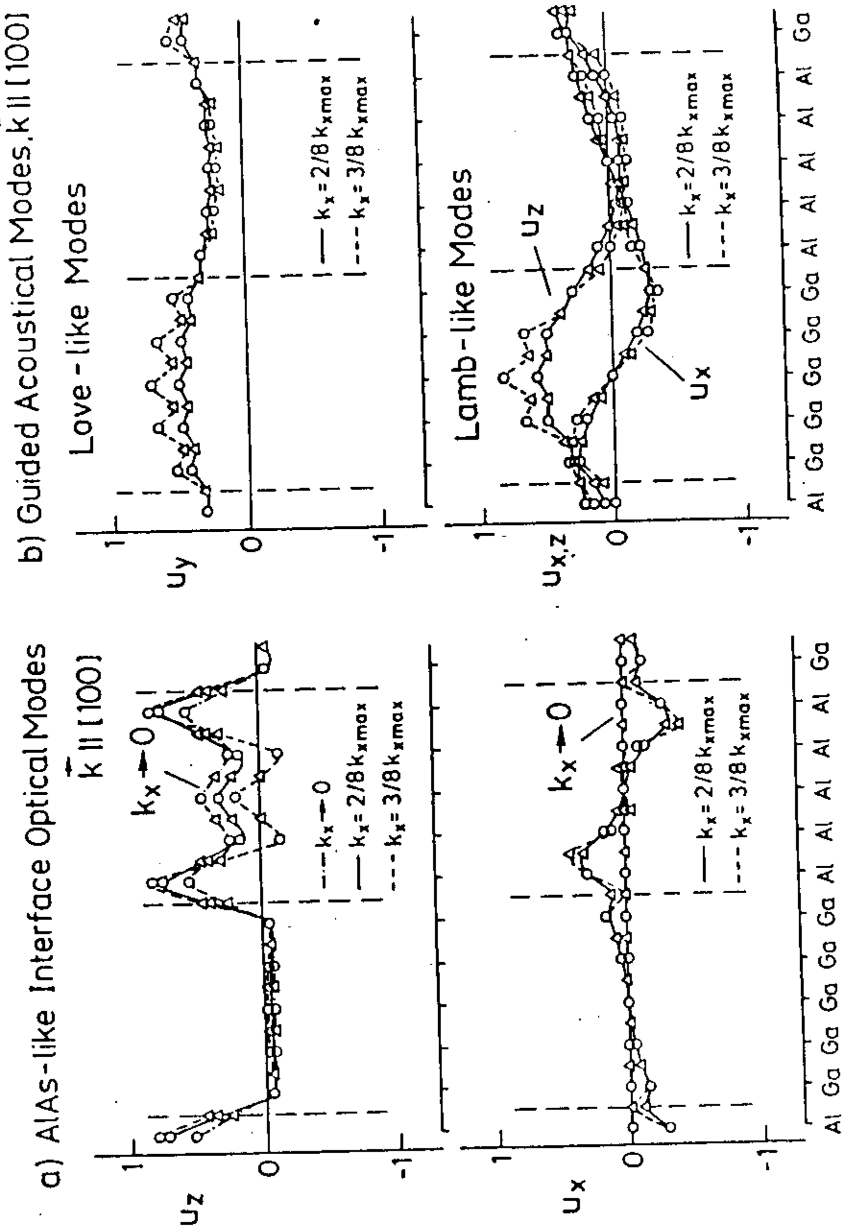


RICHTER AND
STRAUCH S.S.C 64 287 (1987)

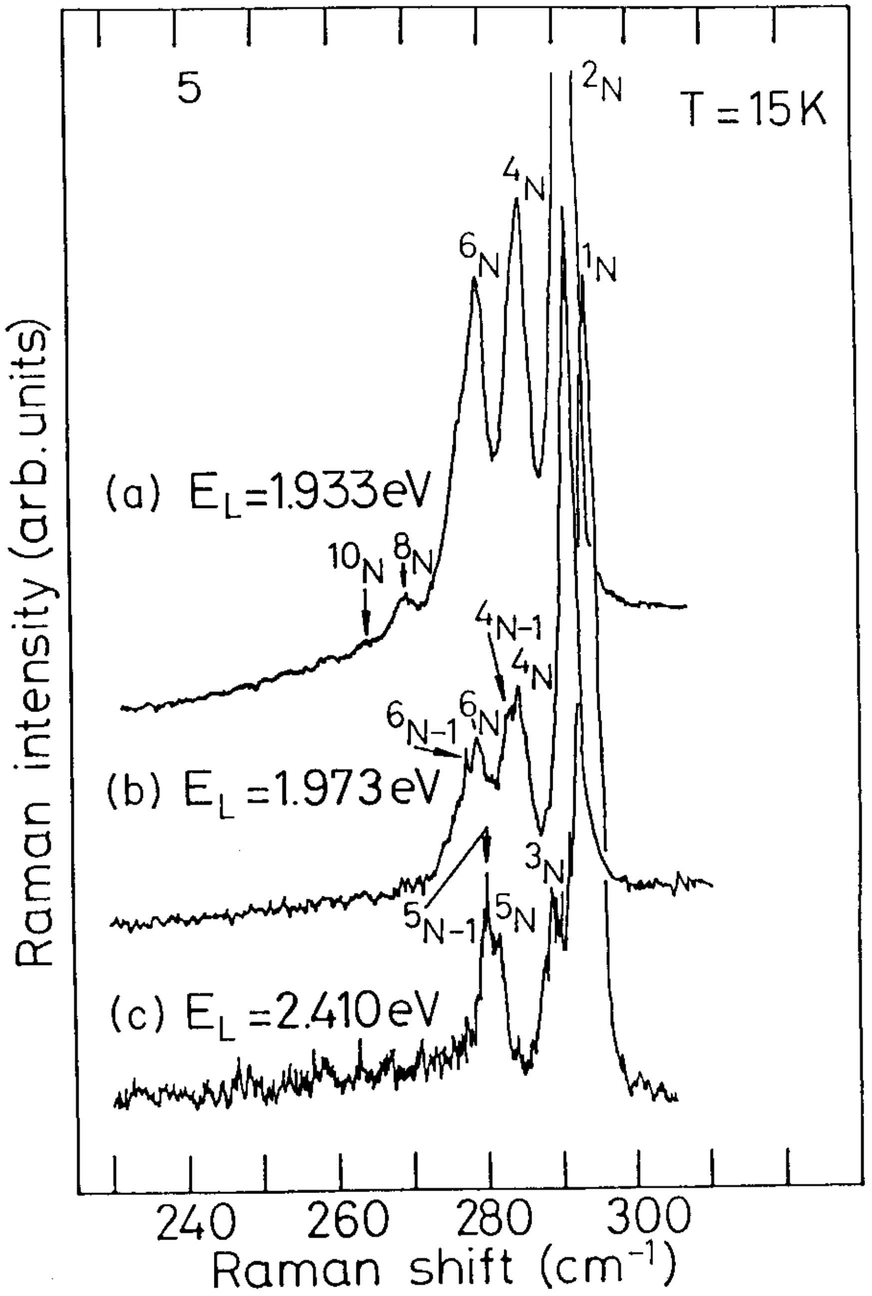


RICHTER ~~???~~ + STRAUCH, TOPICS IN APPLIED PHYSICS

3.20



RICHTER + STRAUCH SSC IBID



FASOL ET AL PRB 38 6056

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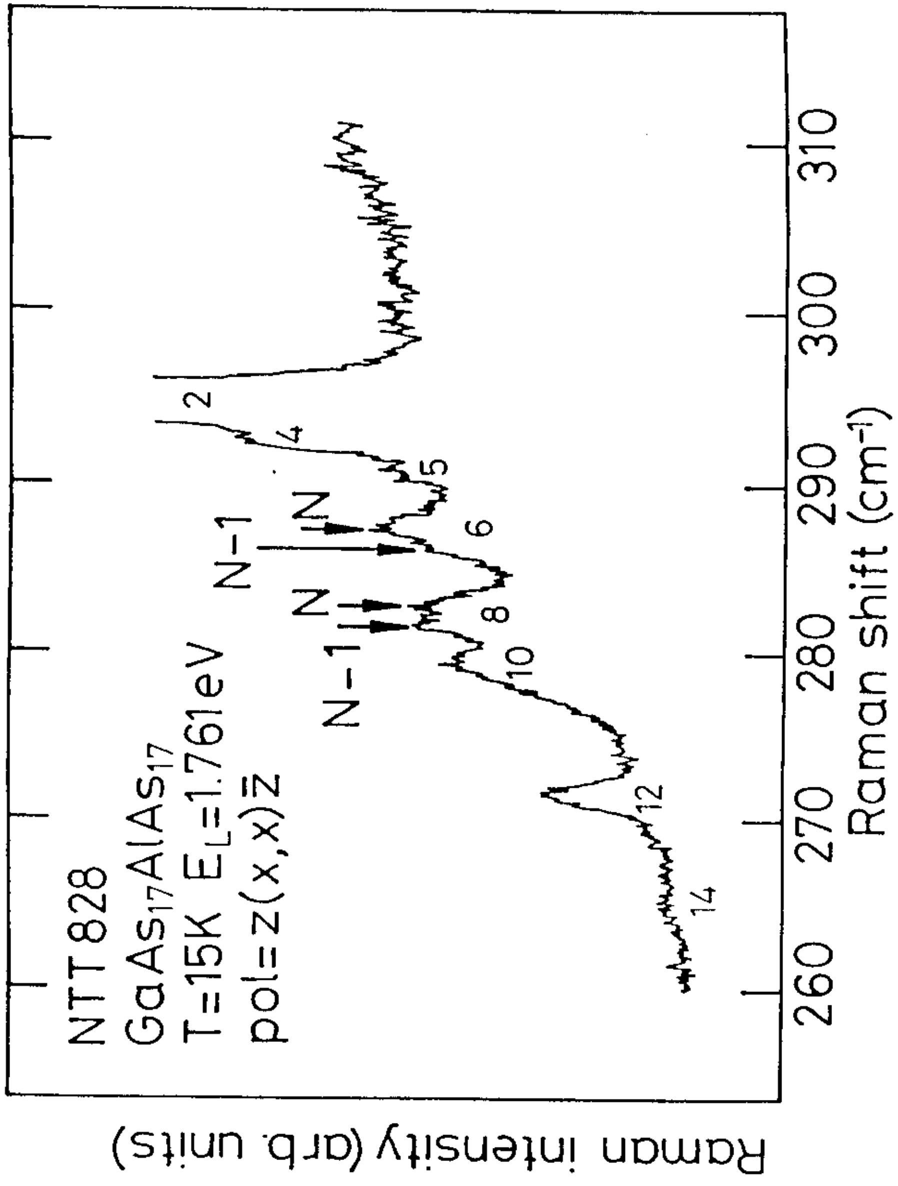
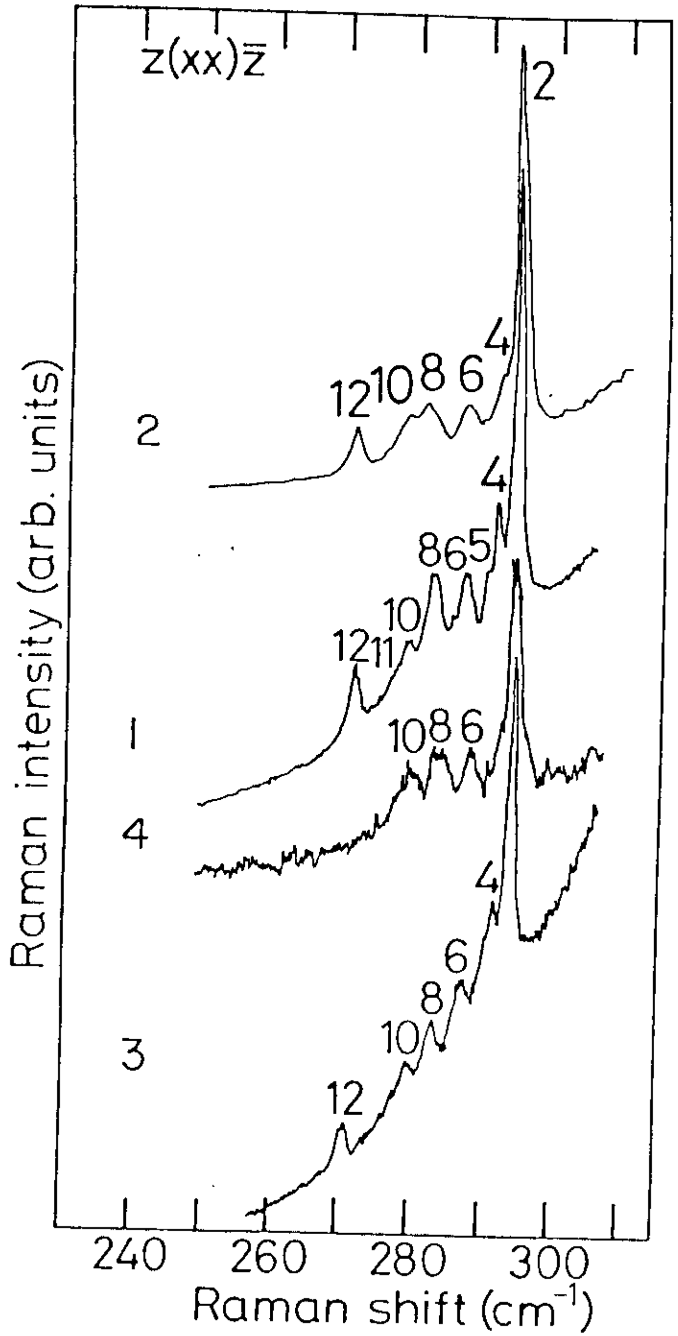
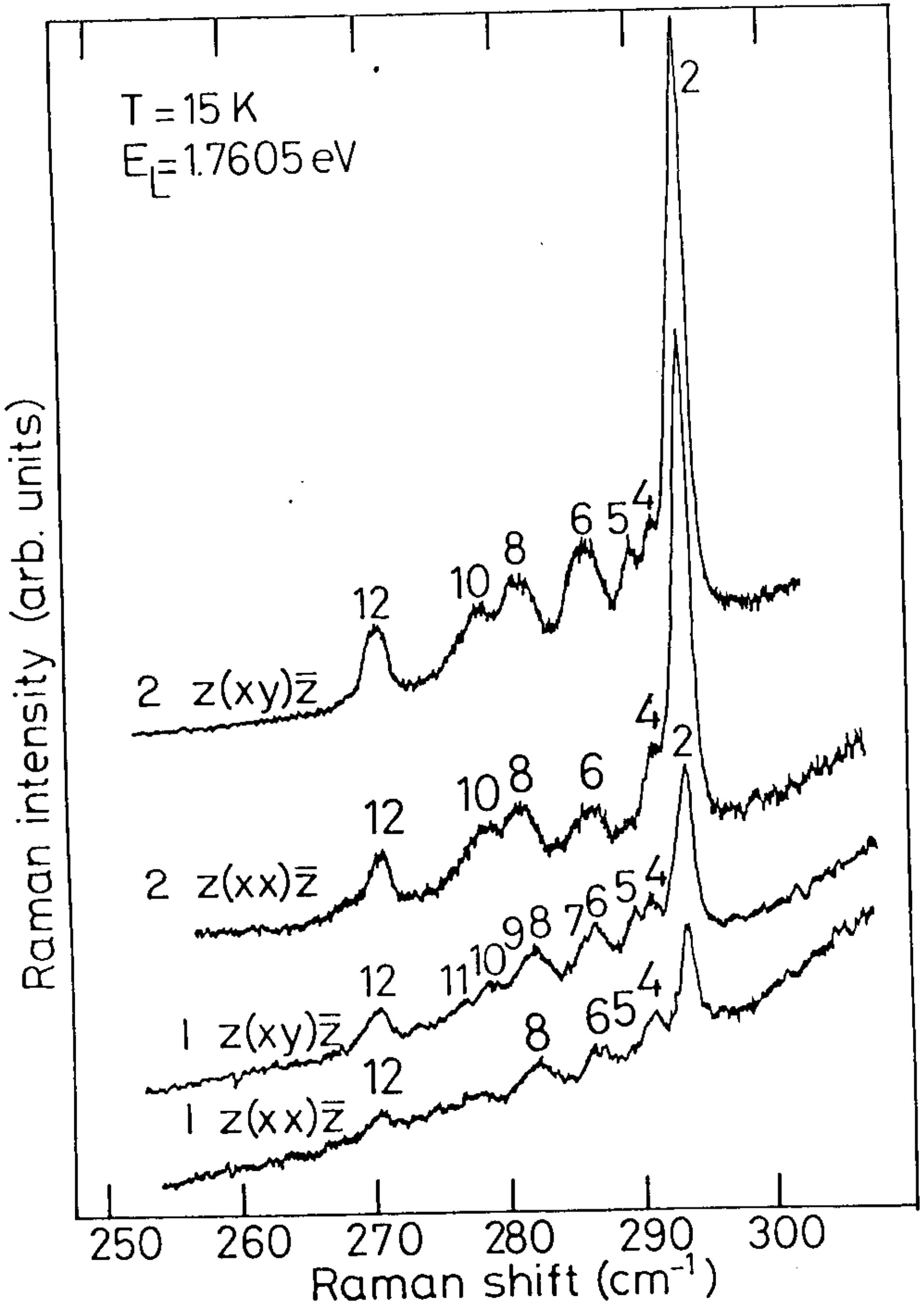




FASOL ET. AL VIBIDIUM

Sept B1588/BQS377B/Fasol/4/40



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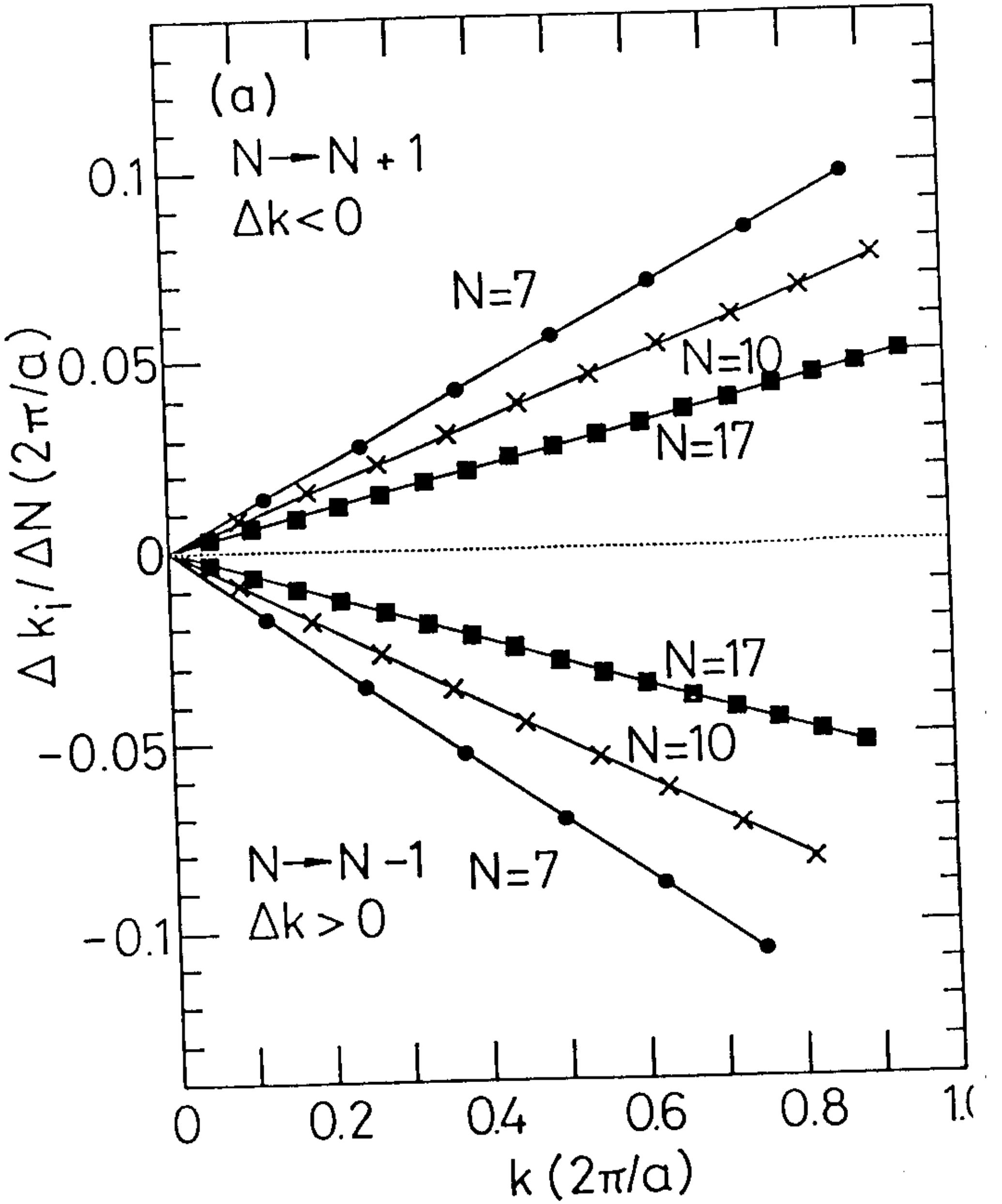

FASOL ET AL.

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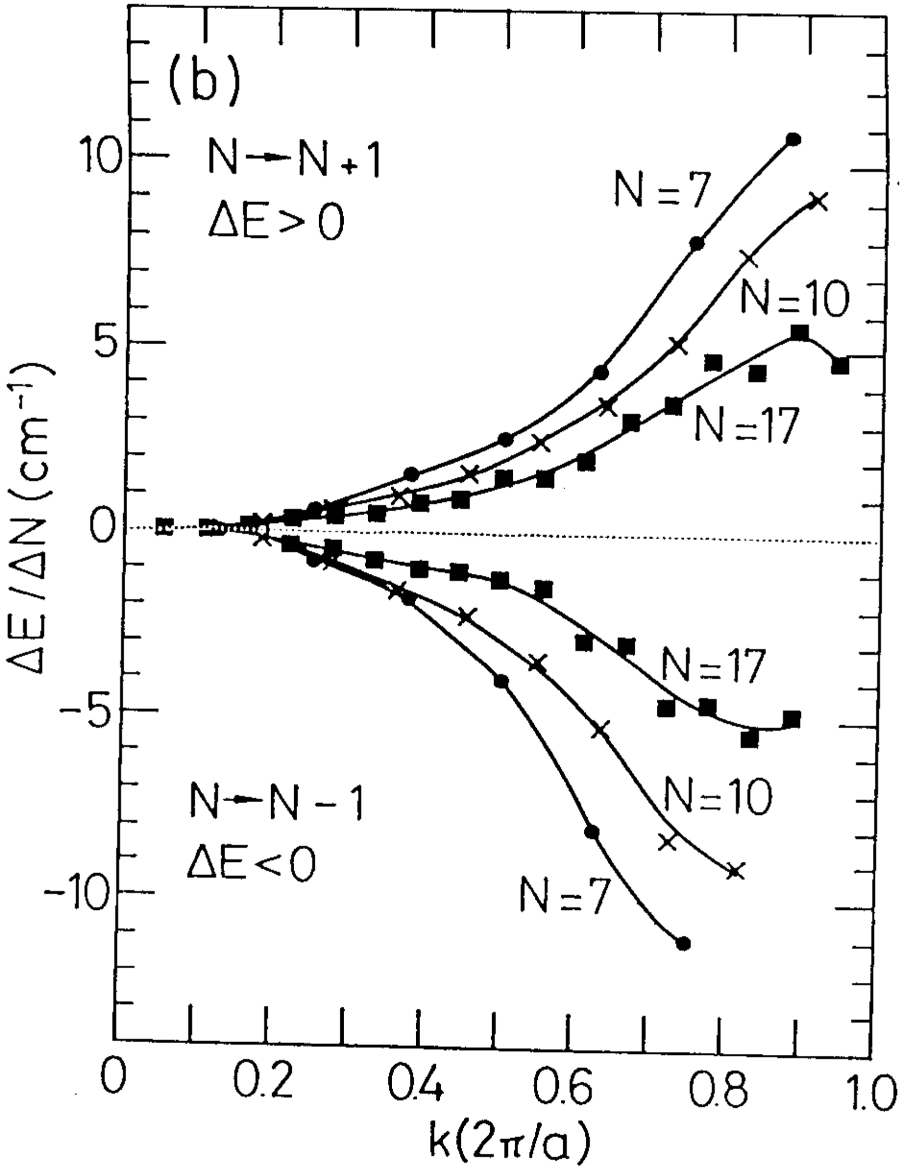

FASOL ET AL

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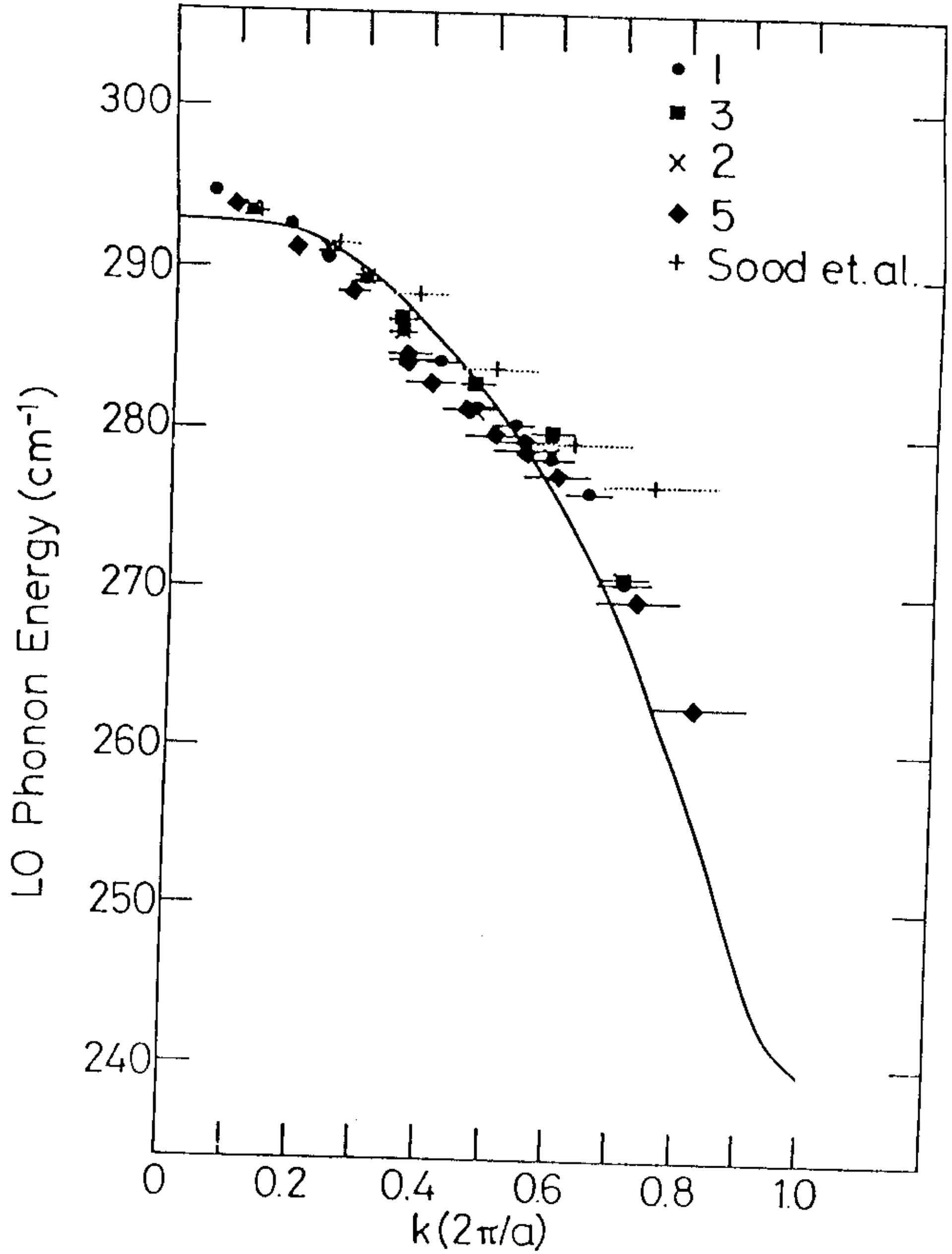

FASOL ET AL.

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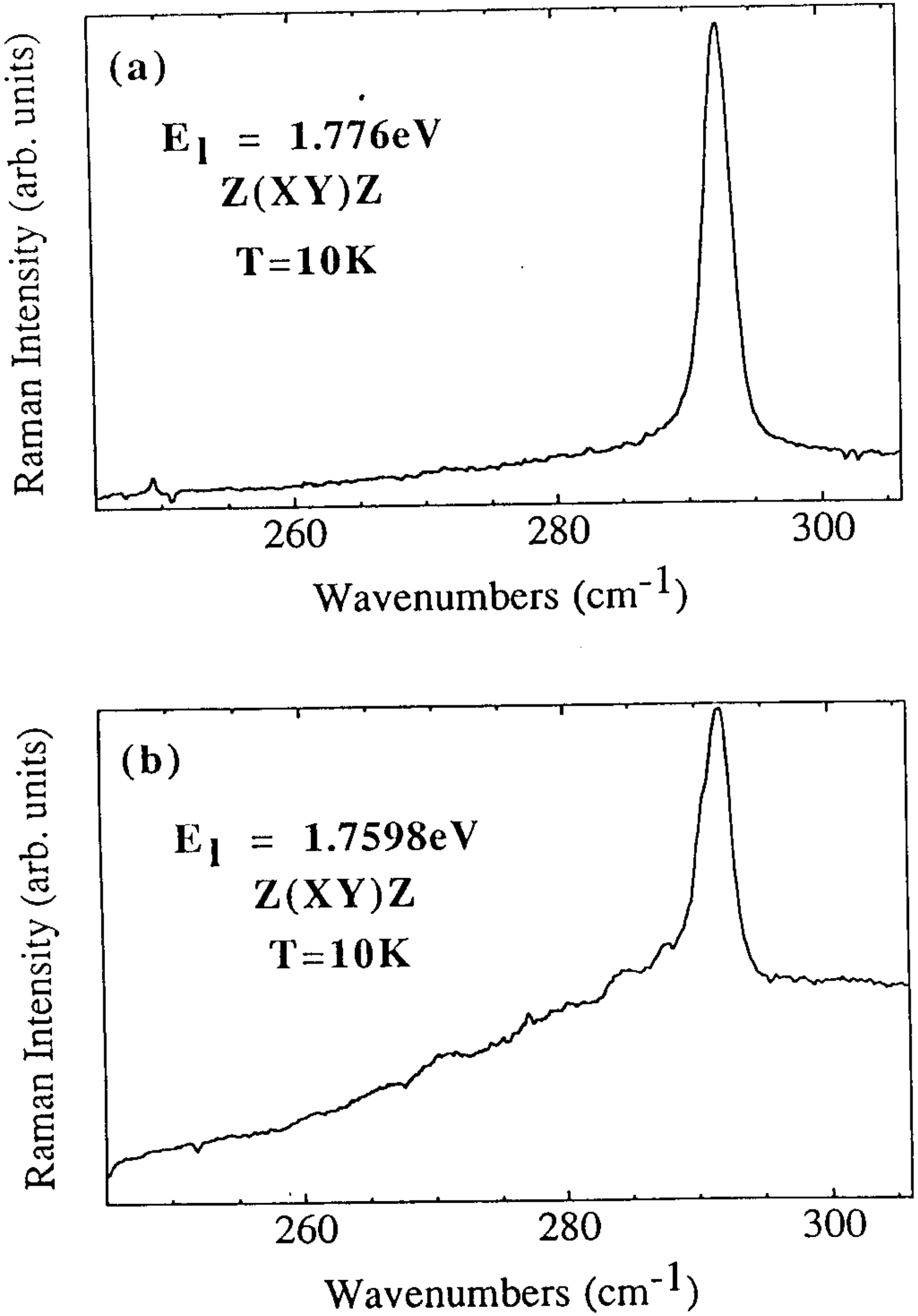
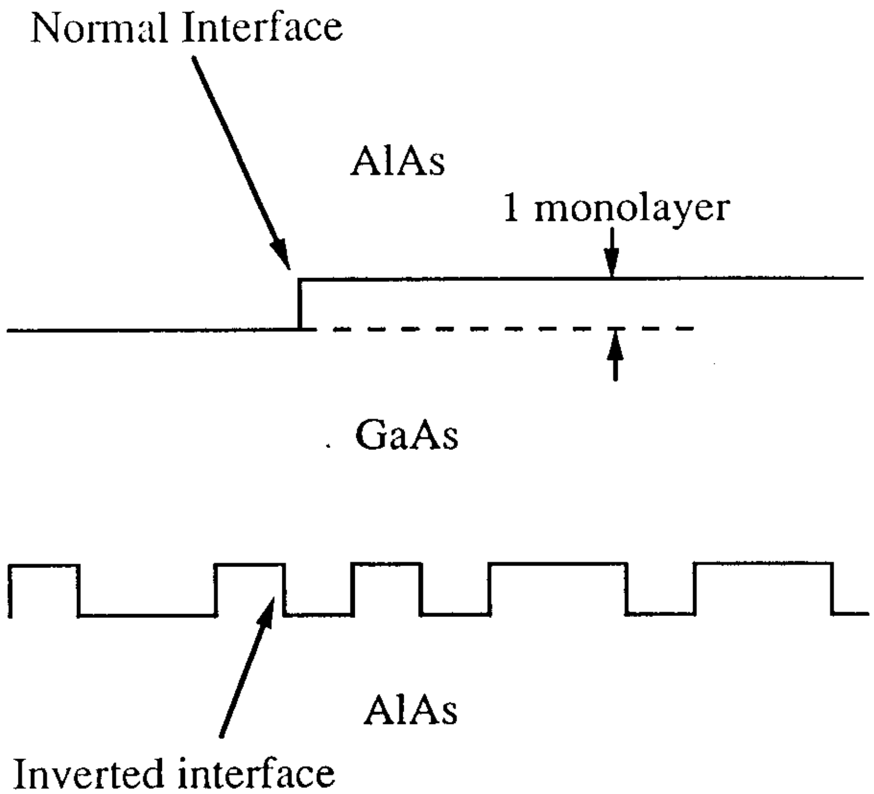
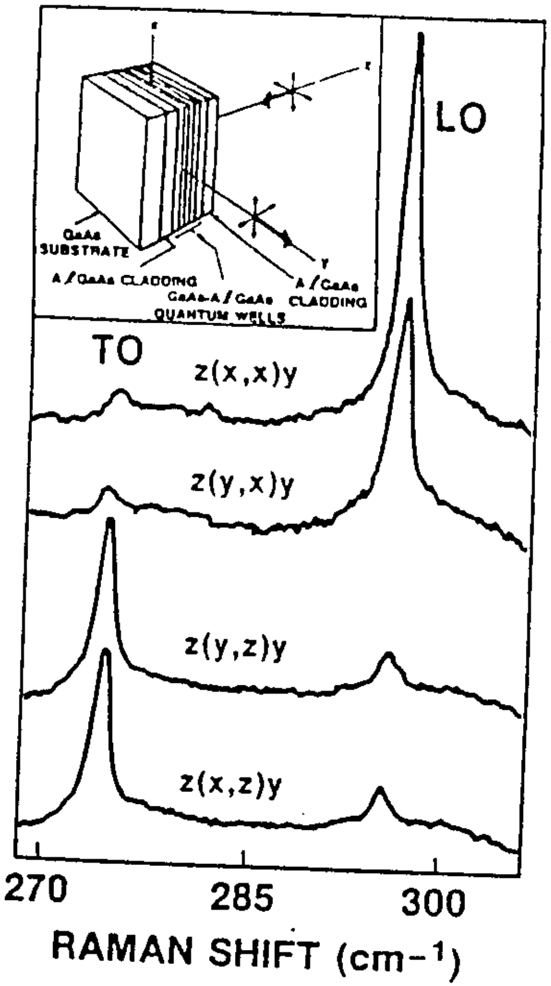




Normal interface coherence length ~ few μm

Inverted interface coherence length ~ 100Å



ZUCKER ET AL

PRL 53 1280 (1984)

3

Unit Cells for [001] Si/Ge and GaAs/AlAs superlattices

4k monlayers:

a || [1,1,0]   b || [$\bar{1}$,1,0]   c || [0,0,1]

4k+2 monlayers:

a || [1,1,0]   b || [$\bar{1}$,1,0]   c || a_0[0,2,N]

Where $N = n_1 + n_2$

Unit cells for D_{4h} superlattices

$(Si)_1/(Ge)_2 \Rightarrow \{(Si)_1/(Ge)_2 : (Si)_1/(Ge)_2\}$

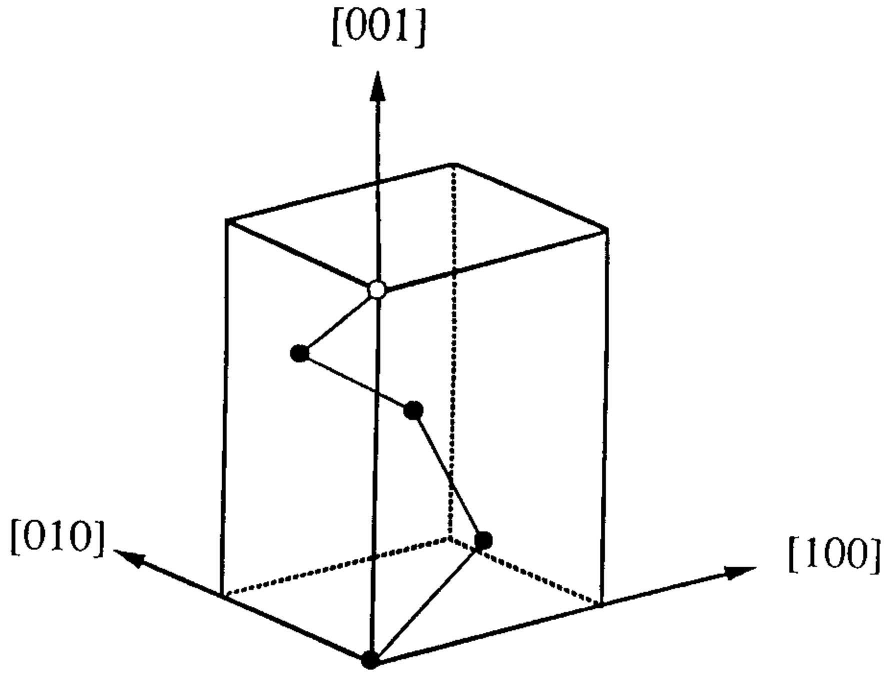
Symmetry in GaAs/AlAs and Si/Ge superlattices

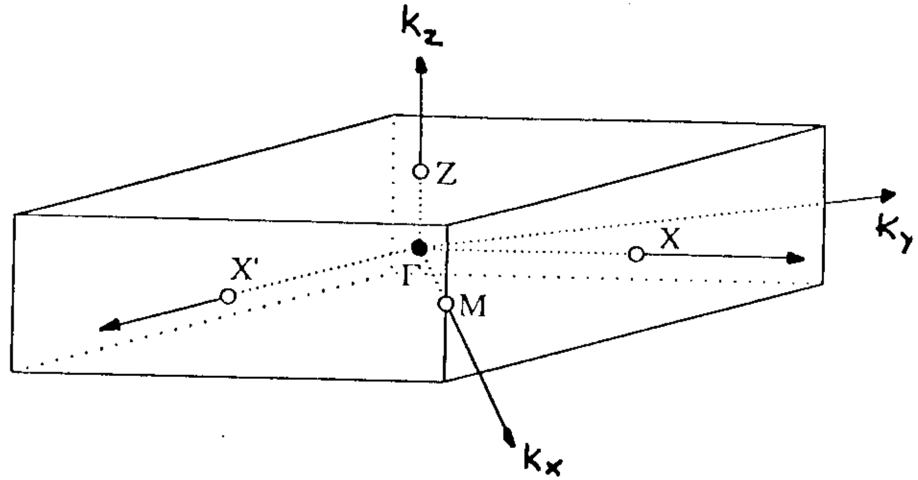
$(GaAs)_{n1}/(AlAs)_{n2}$	Space Group
$n_1 + n_2$; even	D_{2d}^5
$n_1 + n_2$; odd	D_{2d}^9

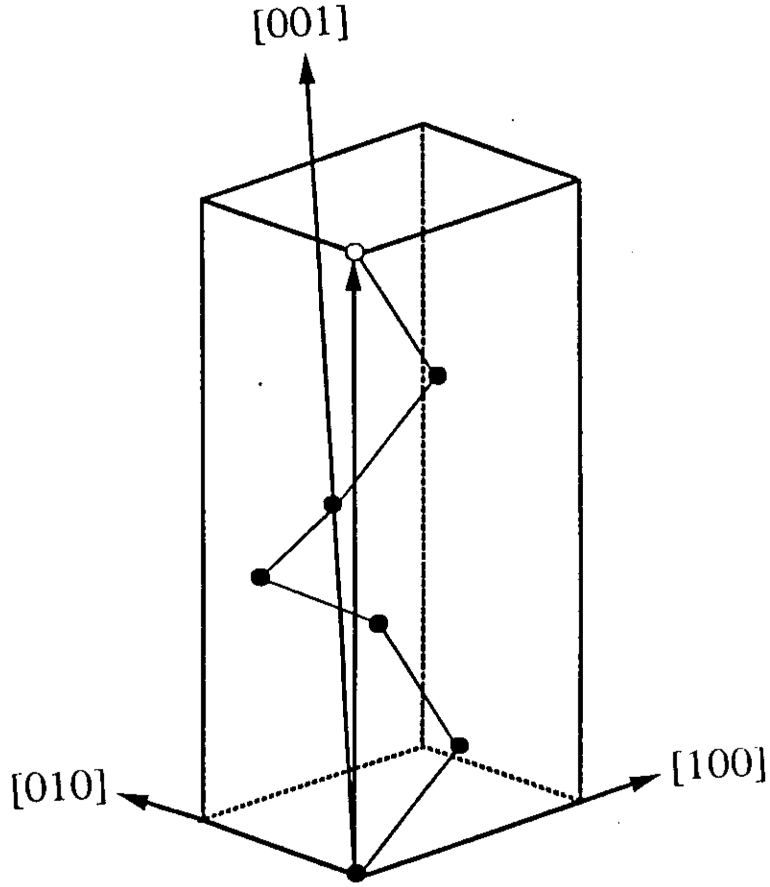
Table 1: The possible symmetries of [001] GaAs/AlAs superlattices.

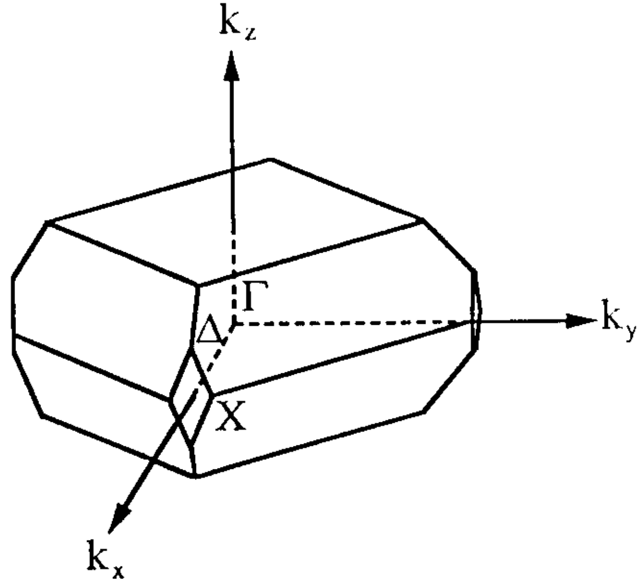
$(Si)_{n1}/(Ge)_{n2}$	Space Group
$n_1 = n_2 = 1$	T_d^2
n_1; odd n_2; odd	
$n_1 + n_2 = 4\kappa$	D_{2d}^5
$n_1 + n_2 = 4\kappa+2$	D_{2d}^9
n_1; even, n_2; even	
$n_1 + n_1 = 4\kappa$	D_{2h}^5
$n_1 + n_1 = 4\kappa + 2$	D_{2h}^{28}
n_1, n_2; even/odd or odd/even	D_{4h}^{19}

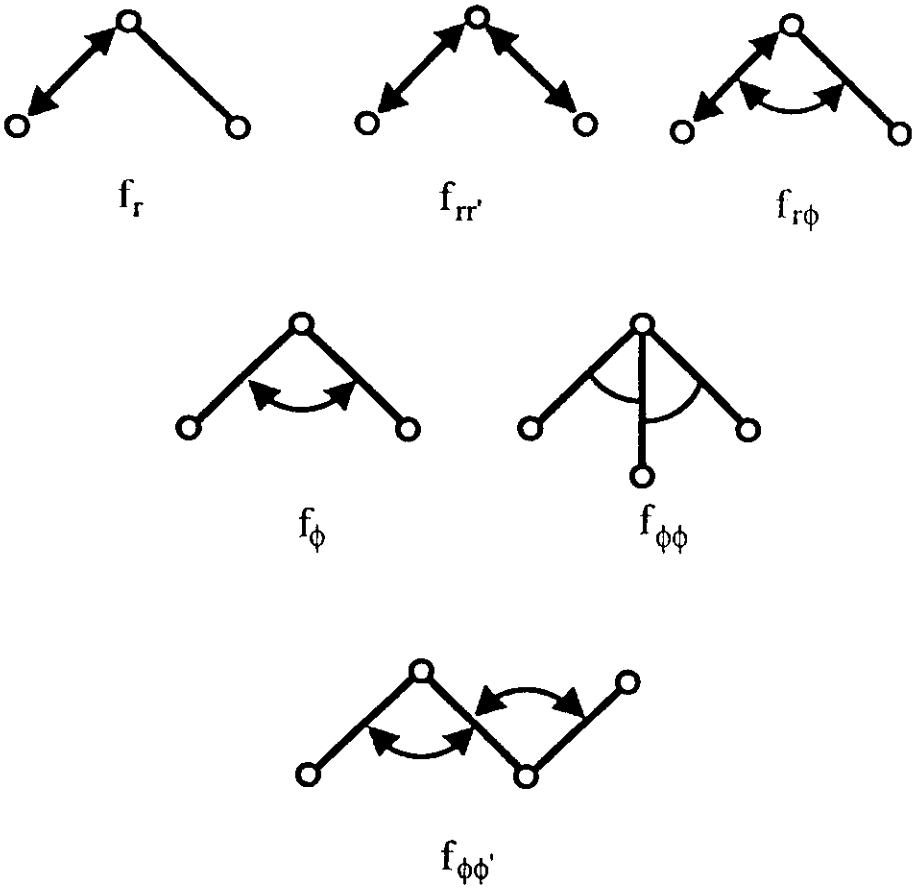
Table 2: The possible symmetries of the Si/Ge [001] superlattices.

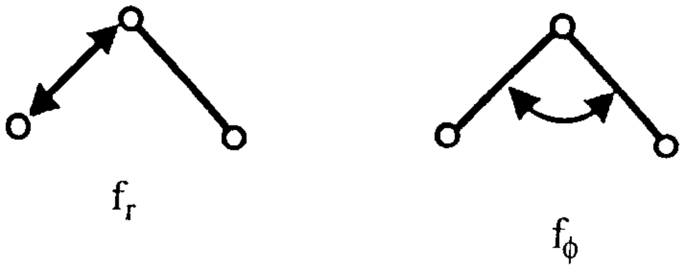

[001]
[010]
[100]


kz
Z
X'
Γ
X
M
ky
kx


[001]
[010]
[100]

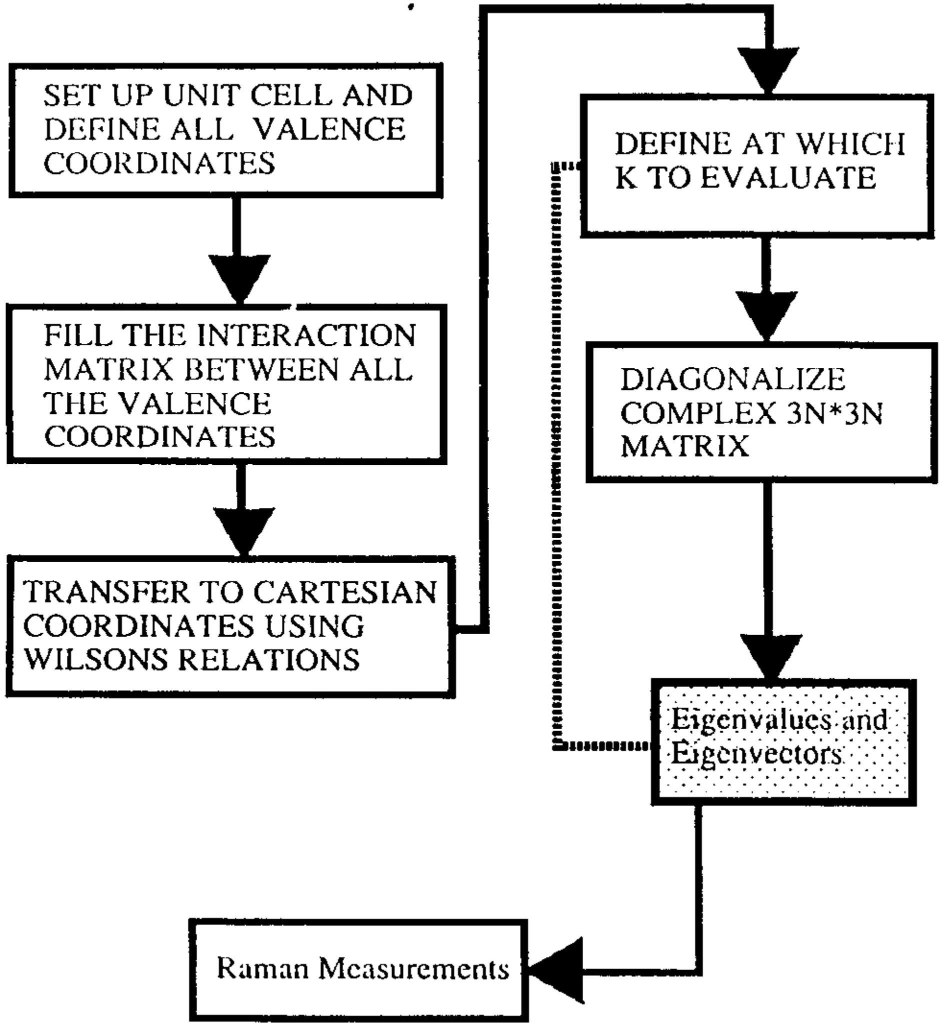

k_z
k_y
k_x
Γ
Δ
X

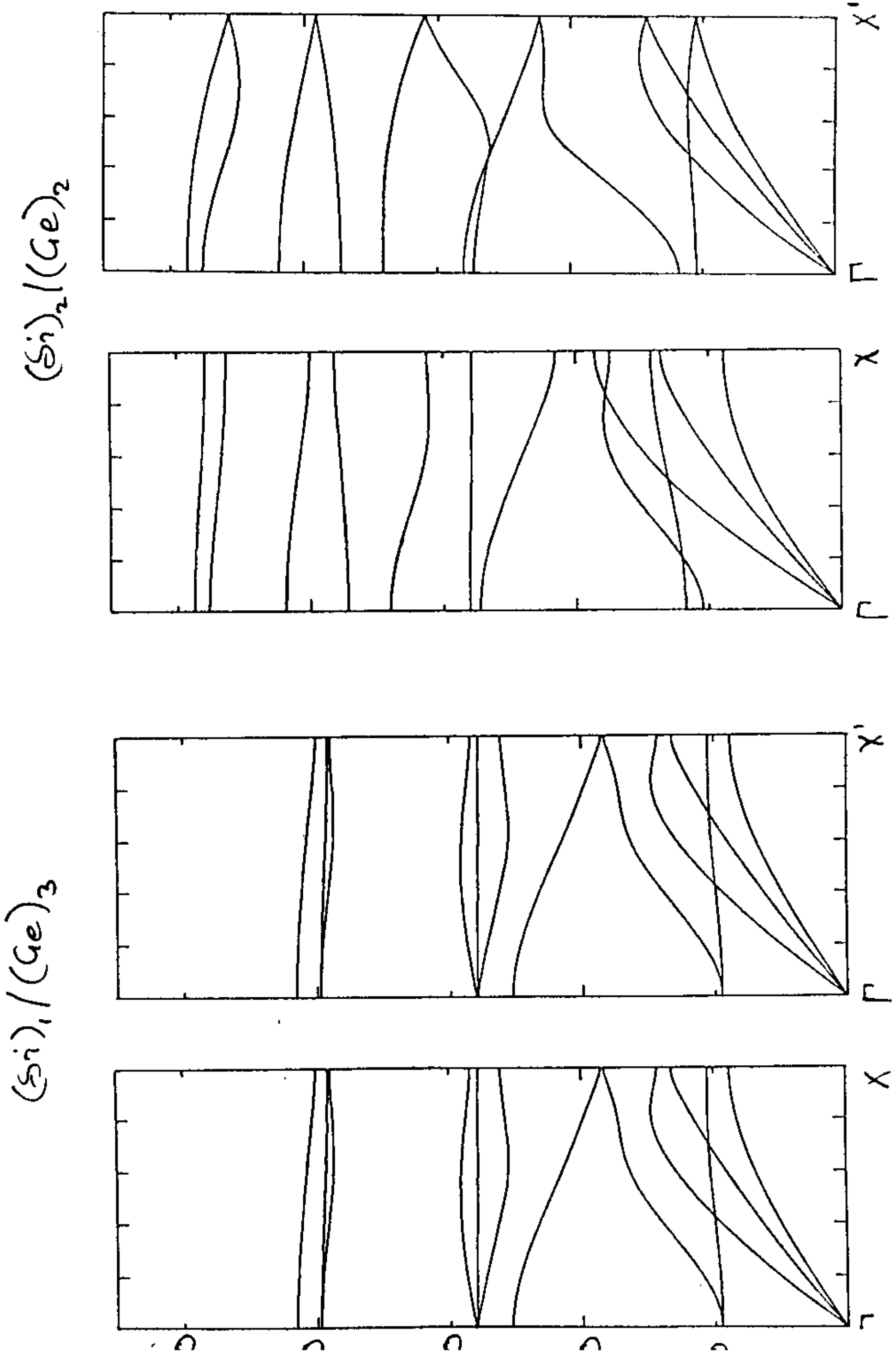




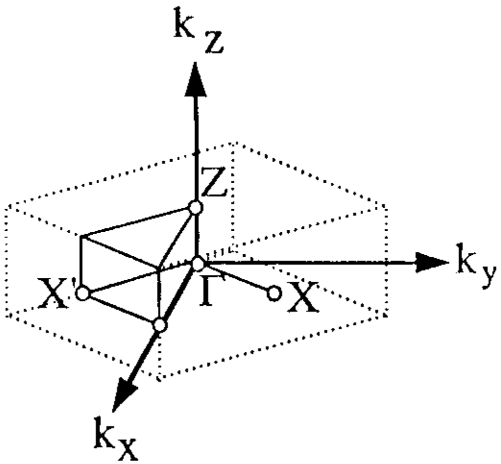
Keating model interactions

Valence force Method

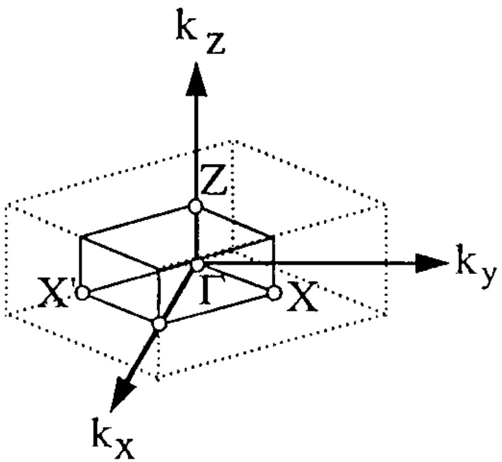


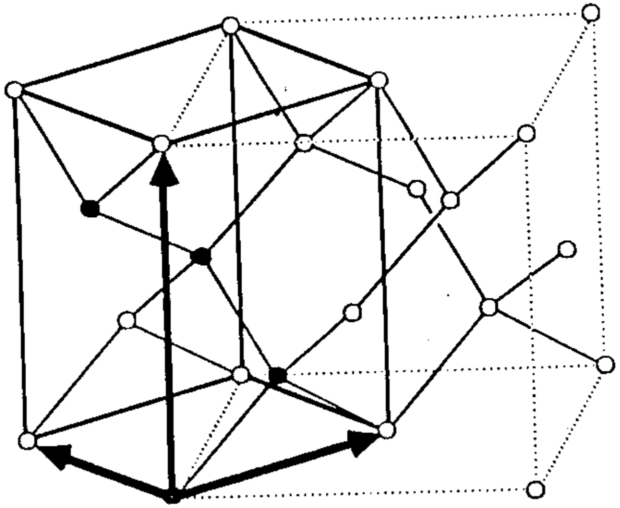


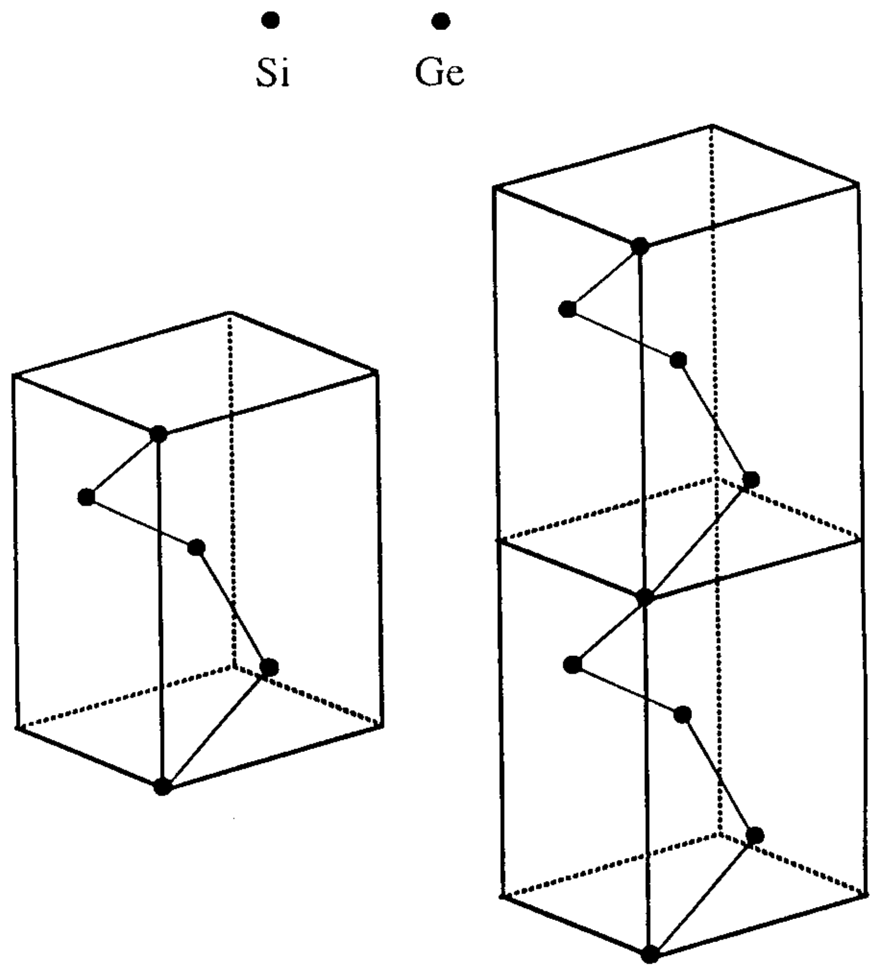
'rimitive
one for D_{2d}



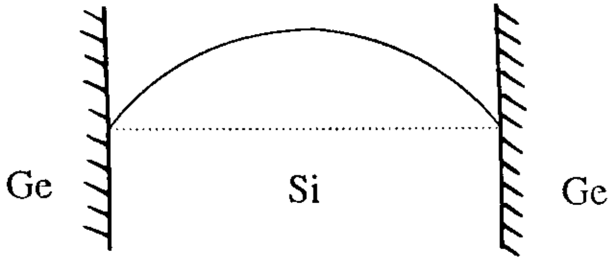
Primitive
:one for D_{2h}



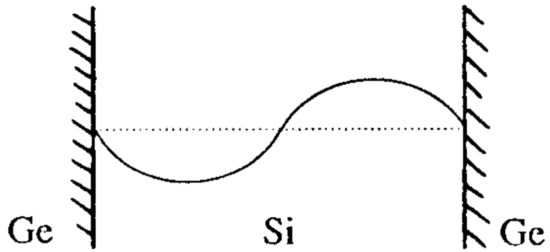




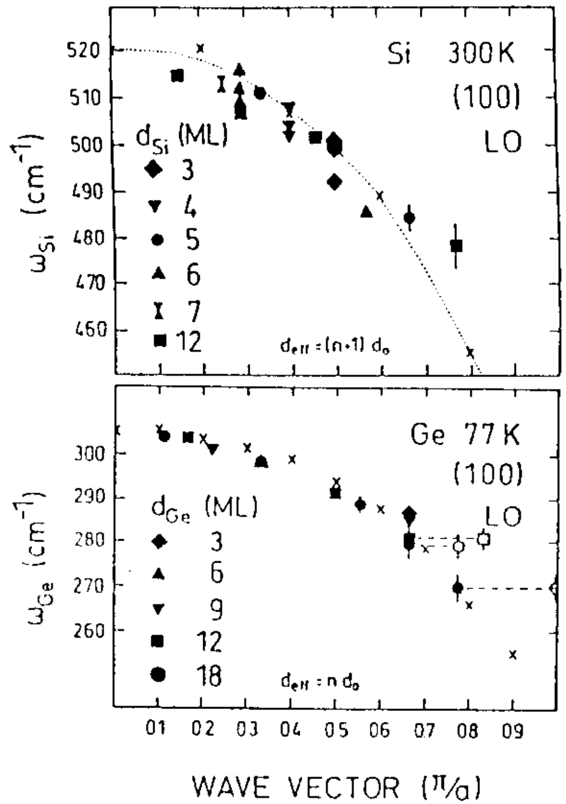
$(Si)_2/(Ge)_2$ $(Si)_4/(Ge)_4$



n=1



n=2



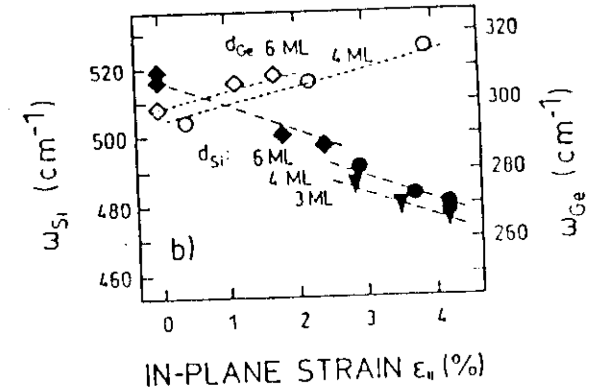
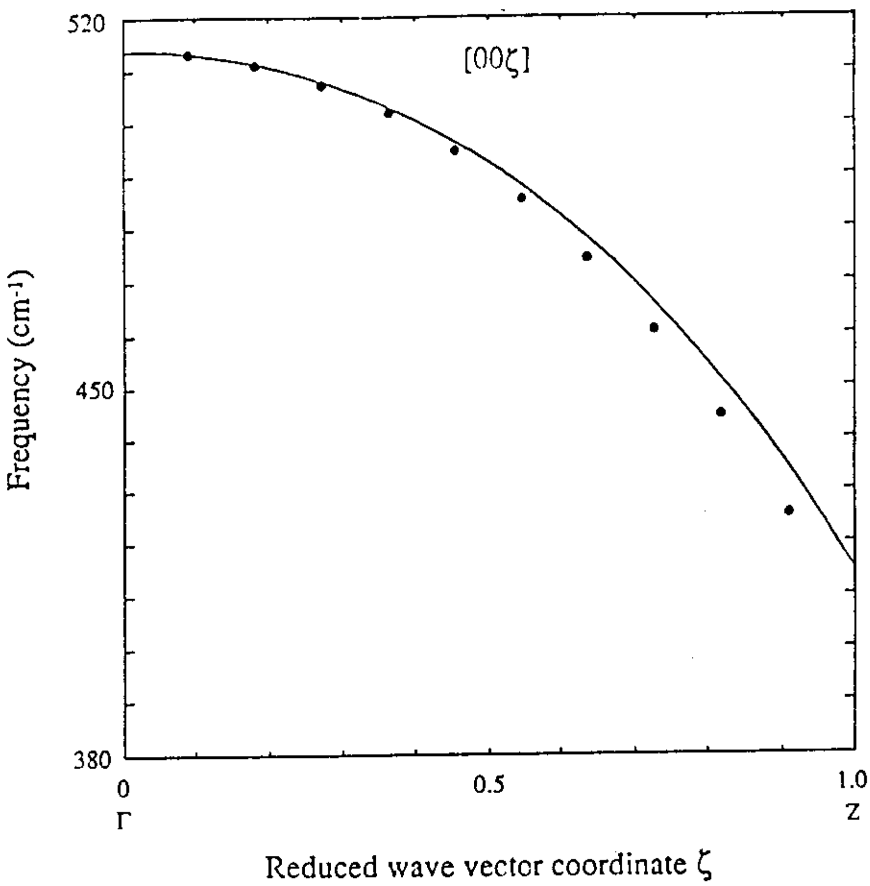


Fig 2
FRIESS ET AL S.S.C 73 P203 (1990)

Fig 5



GHANBARI, ET AL. SSC.
70 1025 (1989)

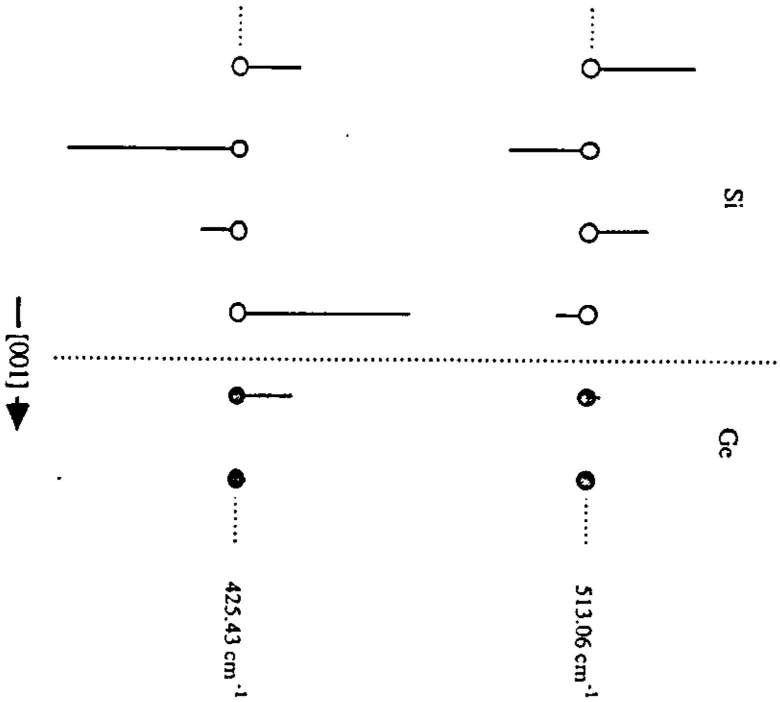
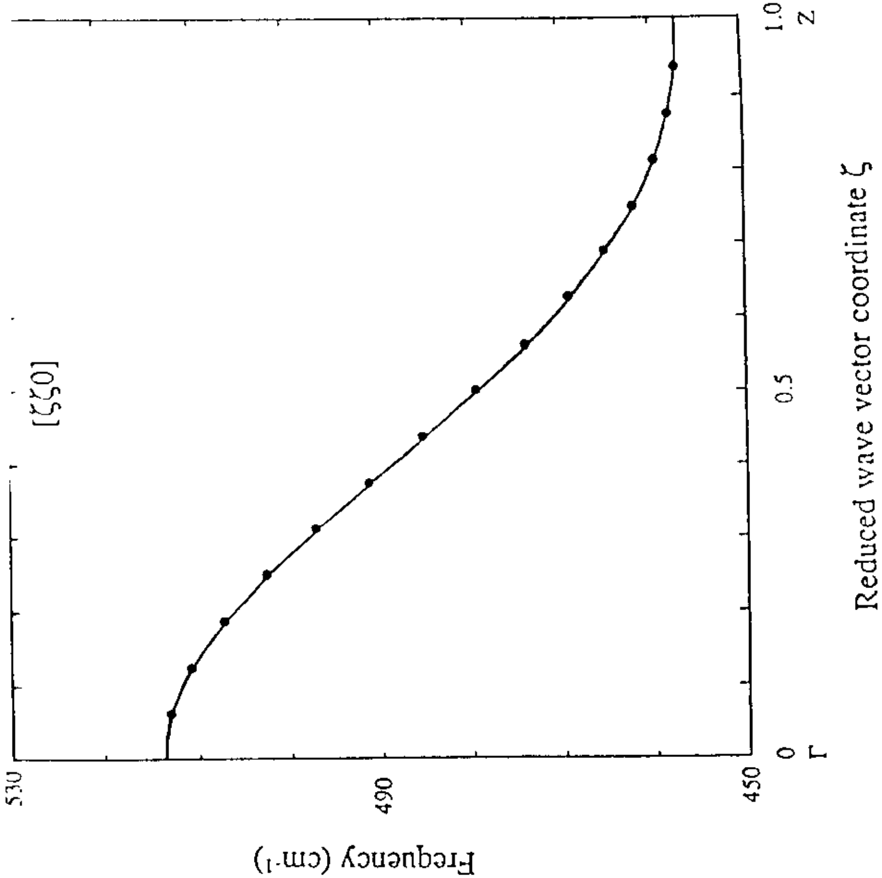


Fig 6



GHANBARI ET AL IBID

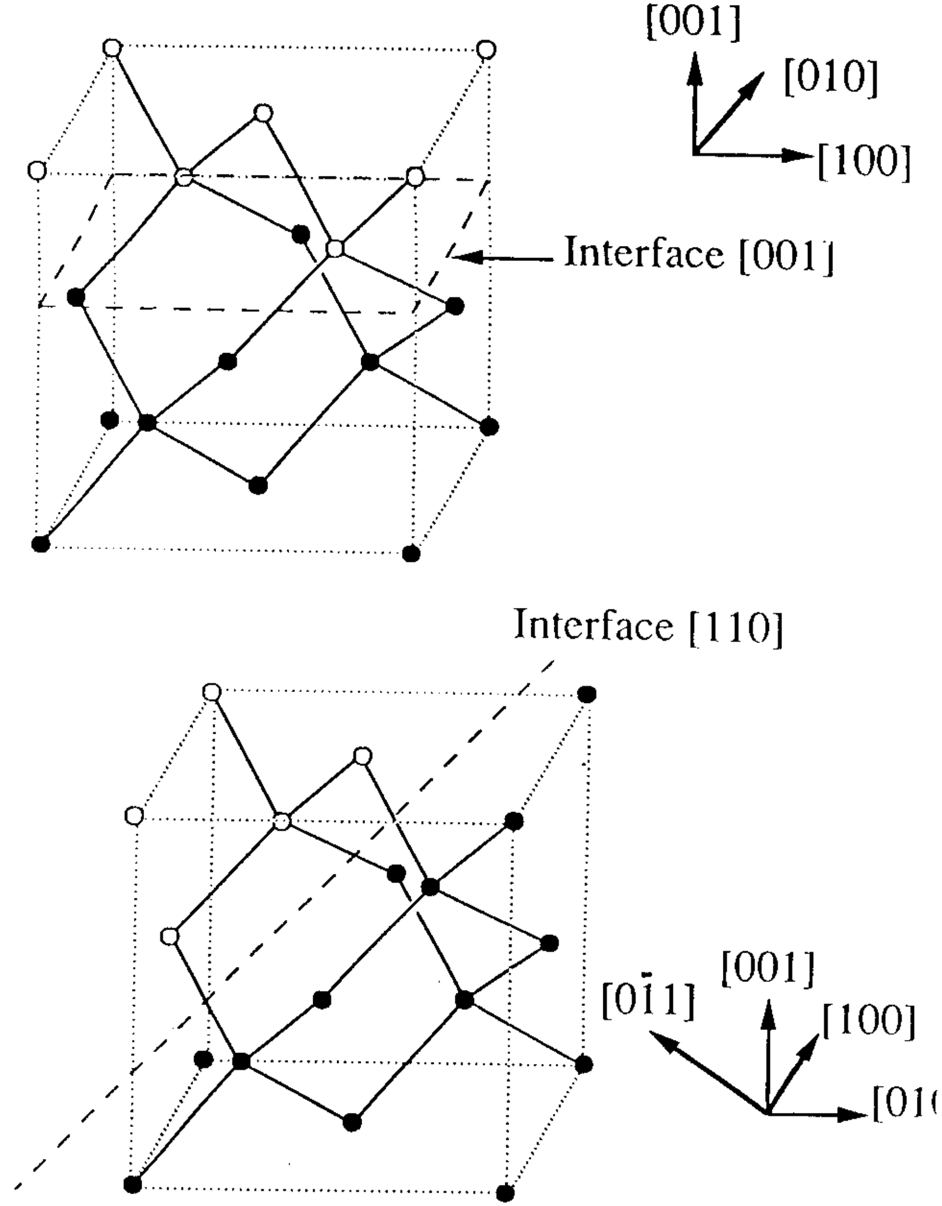
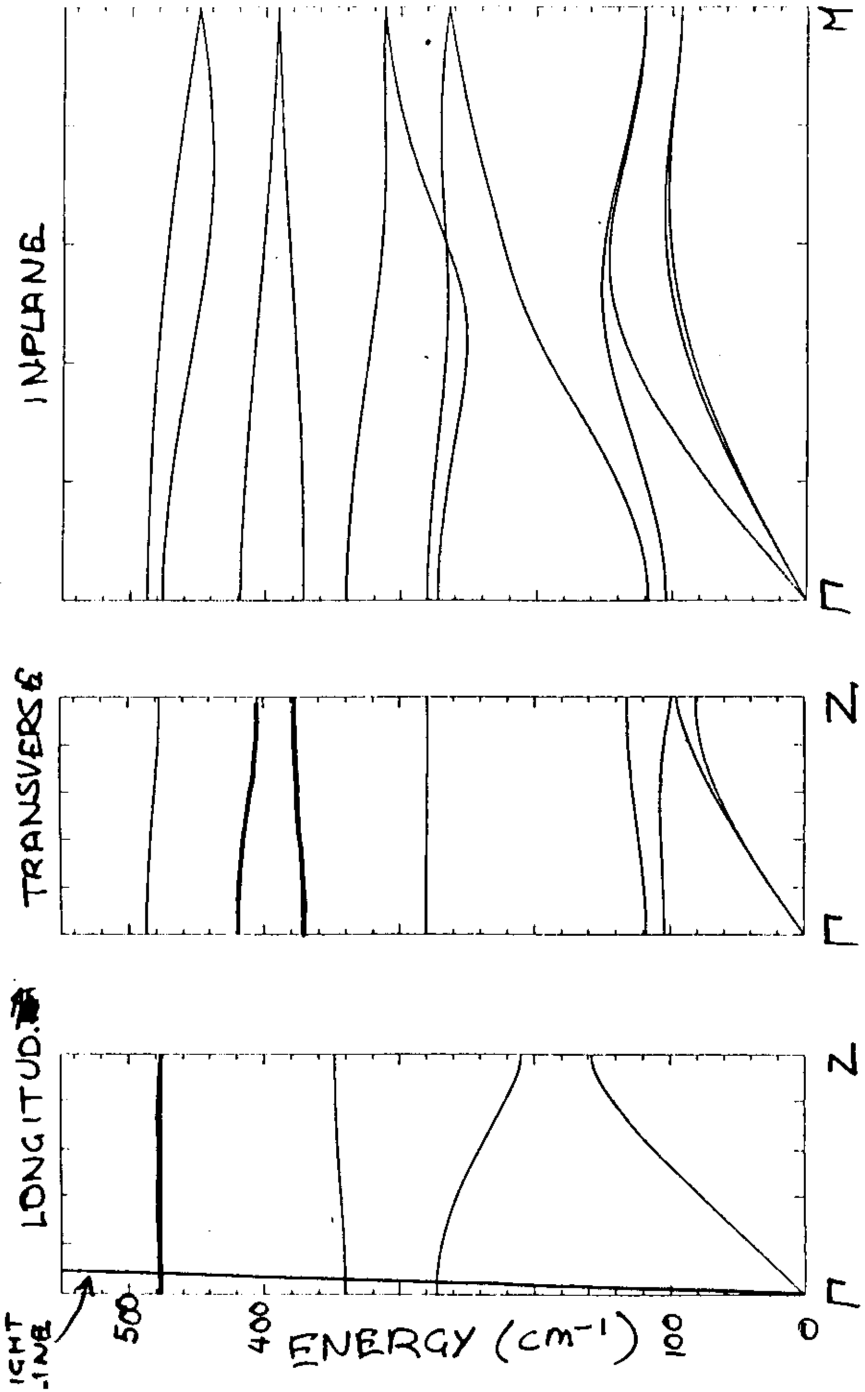
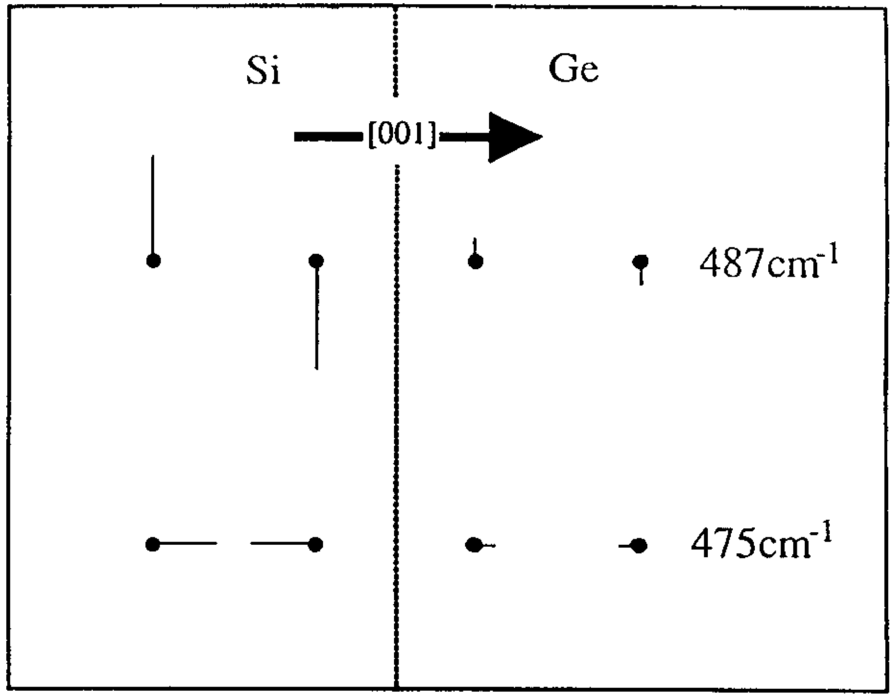
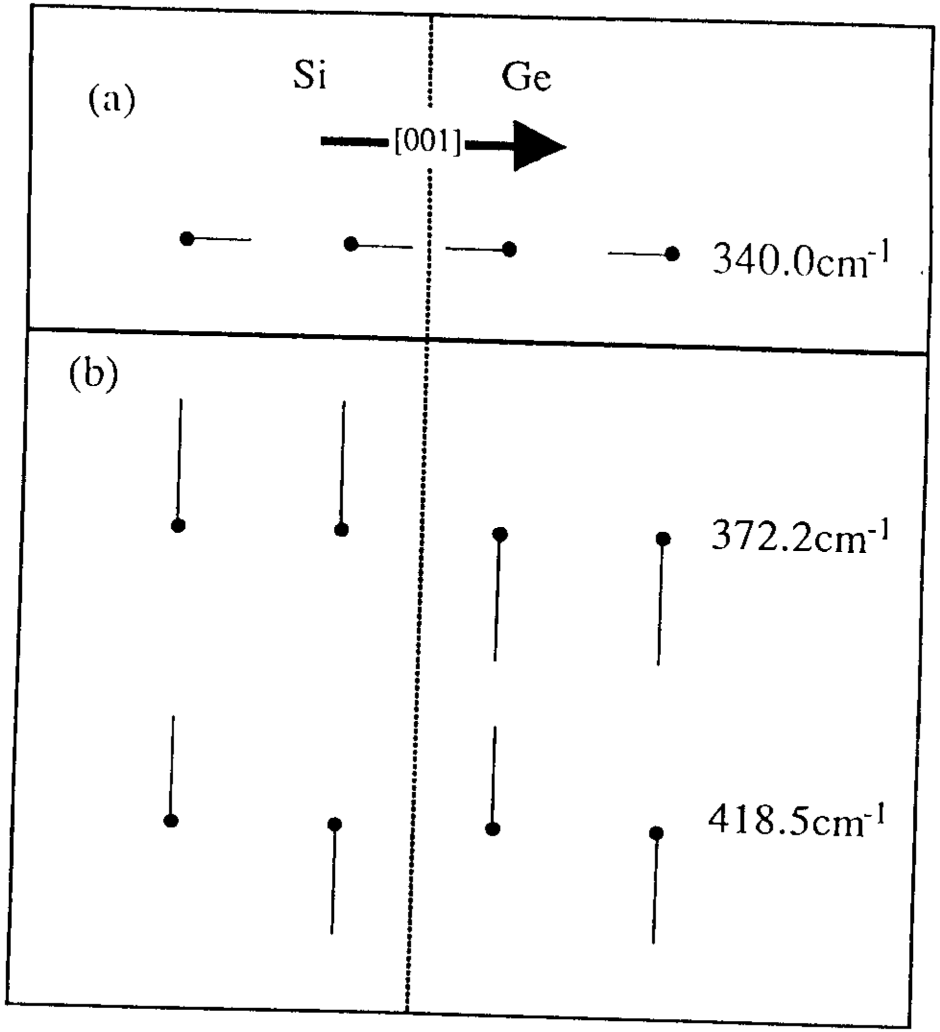


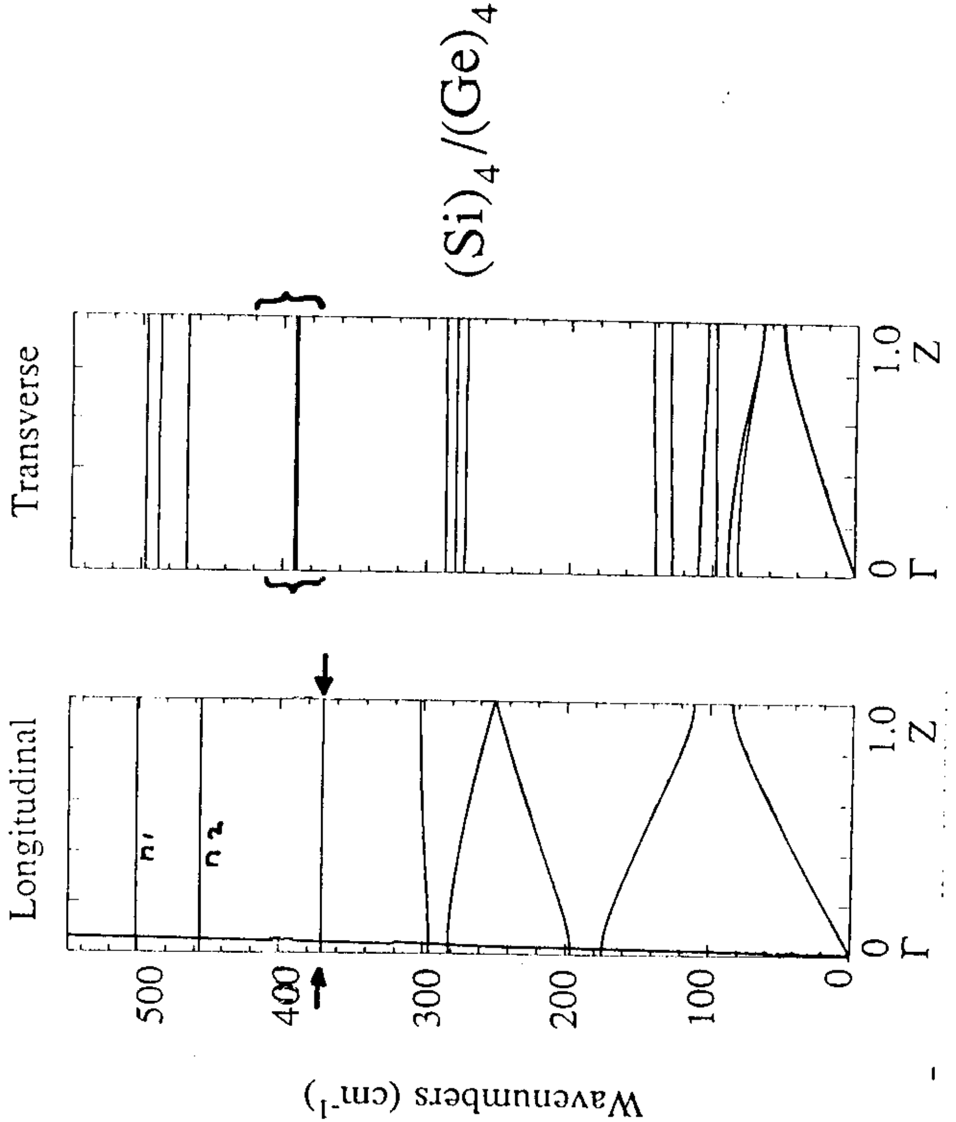
Fig 7

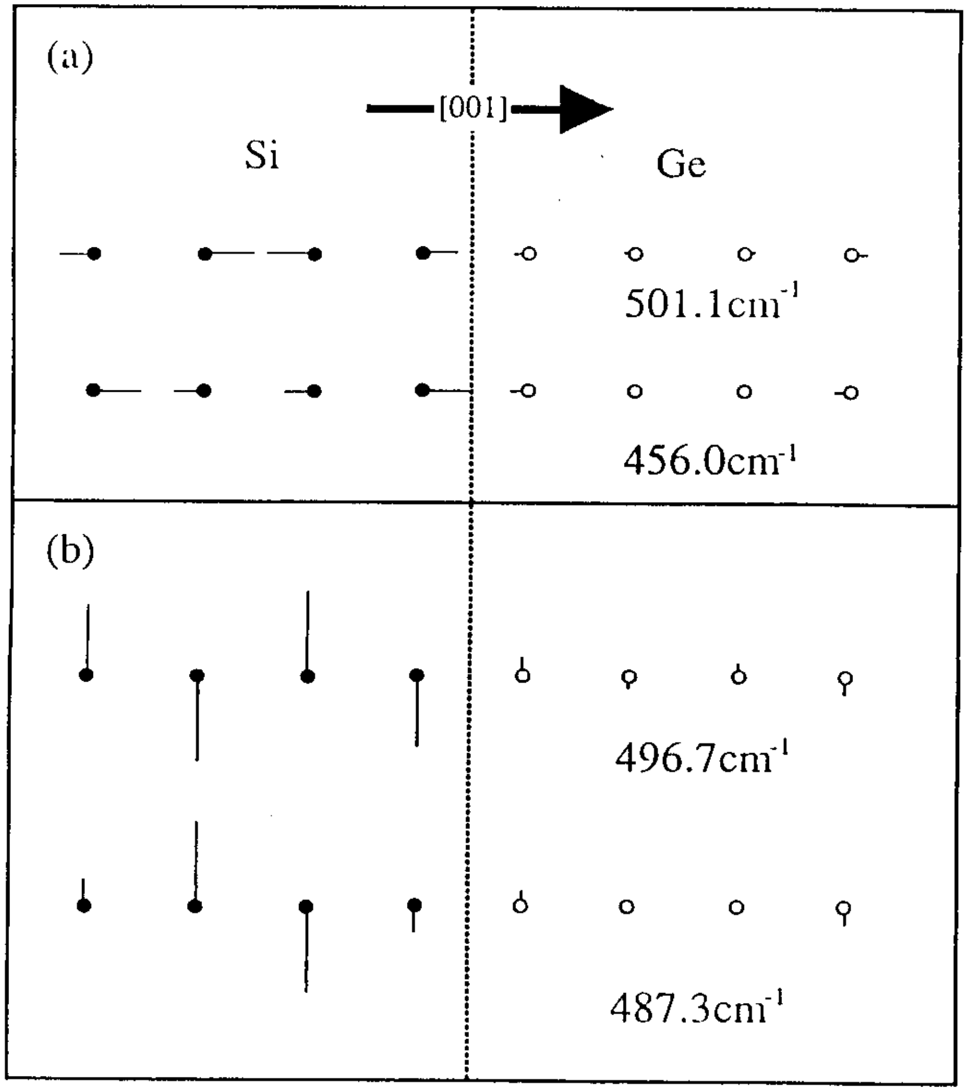

INPLANE
TRANSVERSE
LONGITUD.
M
Γ
Z
Γ
Z
Γ
500
400
ENERGY (cm-1)
100
0


Si
Ge
[001]
487cm-1
475cm-1

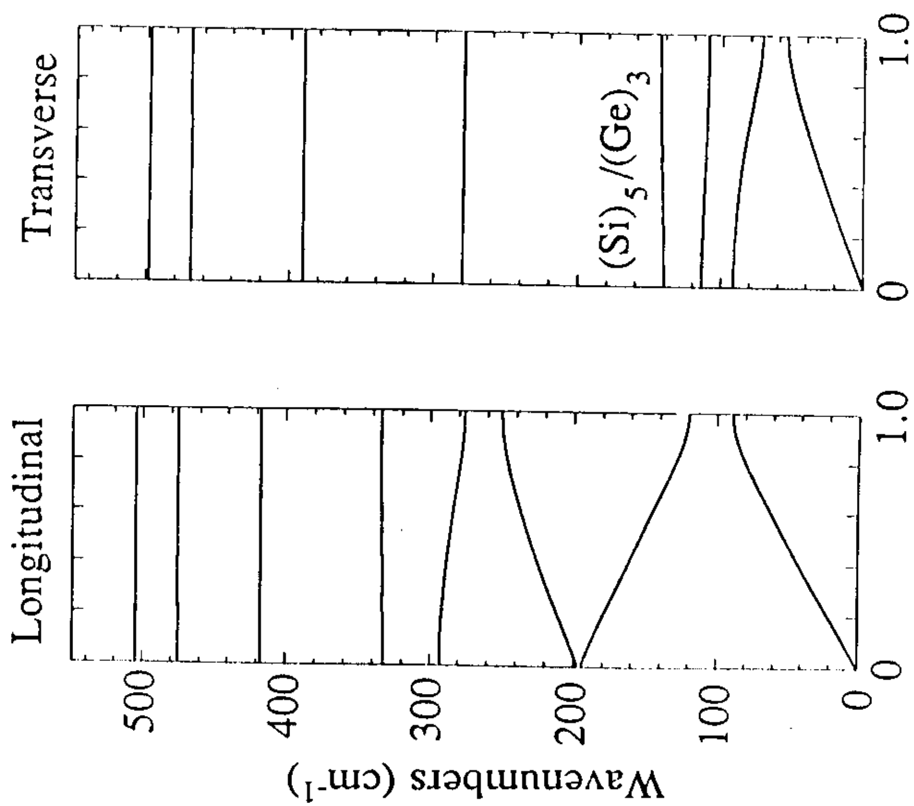

(a)
Si
Ge
[001]
340.0cm-1
(b)
372.2cm-1
418.5cm-1

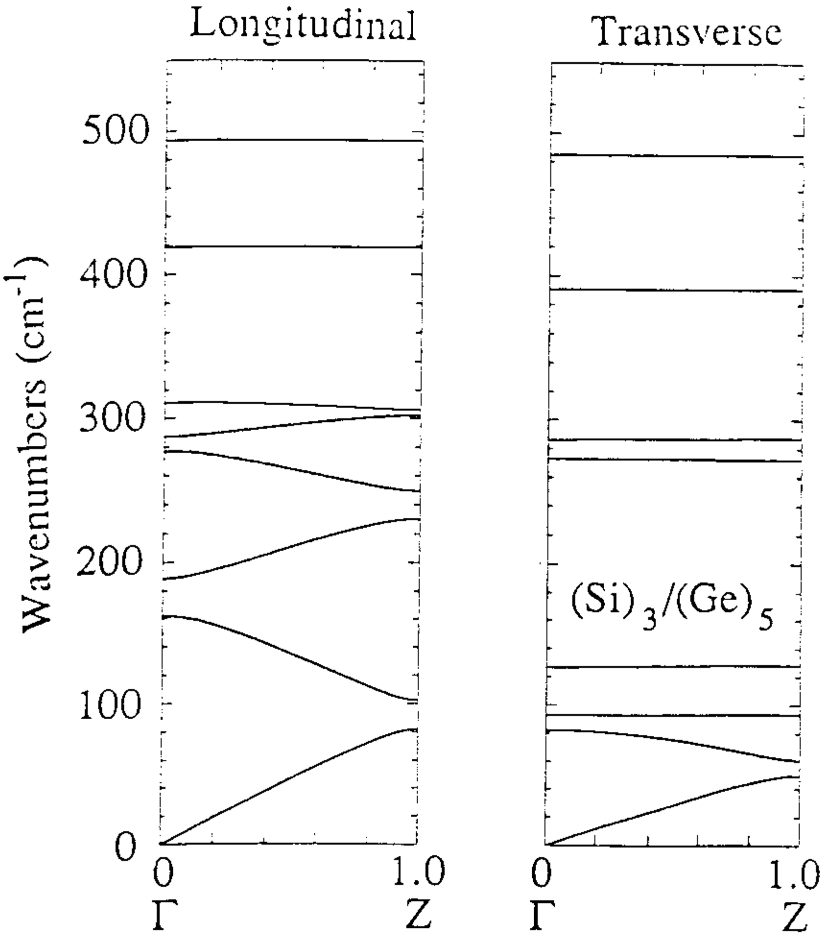
(Si)₂/(Ge)₂

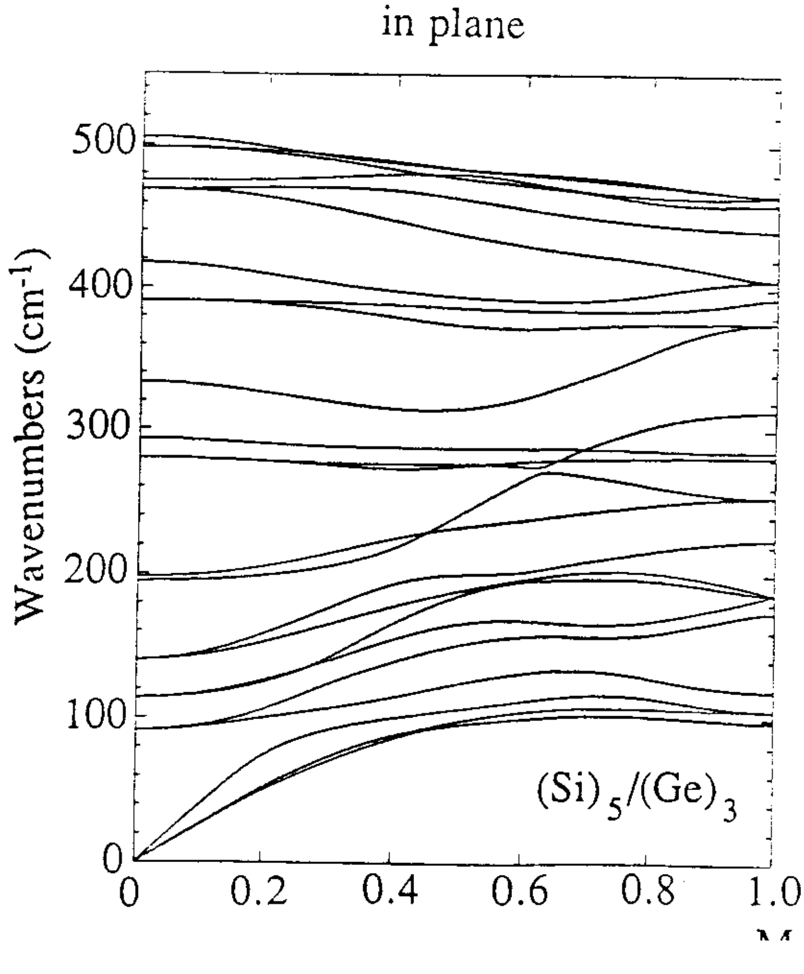

(Si)4/(Ge)4
Transverse
Longitudinal
Wavenumbers (cm-1)
500
400
300
200
100
0
Γ
Z
0
1.0


(a)
[001]
Si
Ge
501.1cm-1
456.0cm-1
(b)
496.7cm-1
487.3cm-1

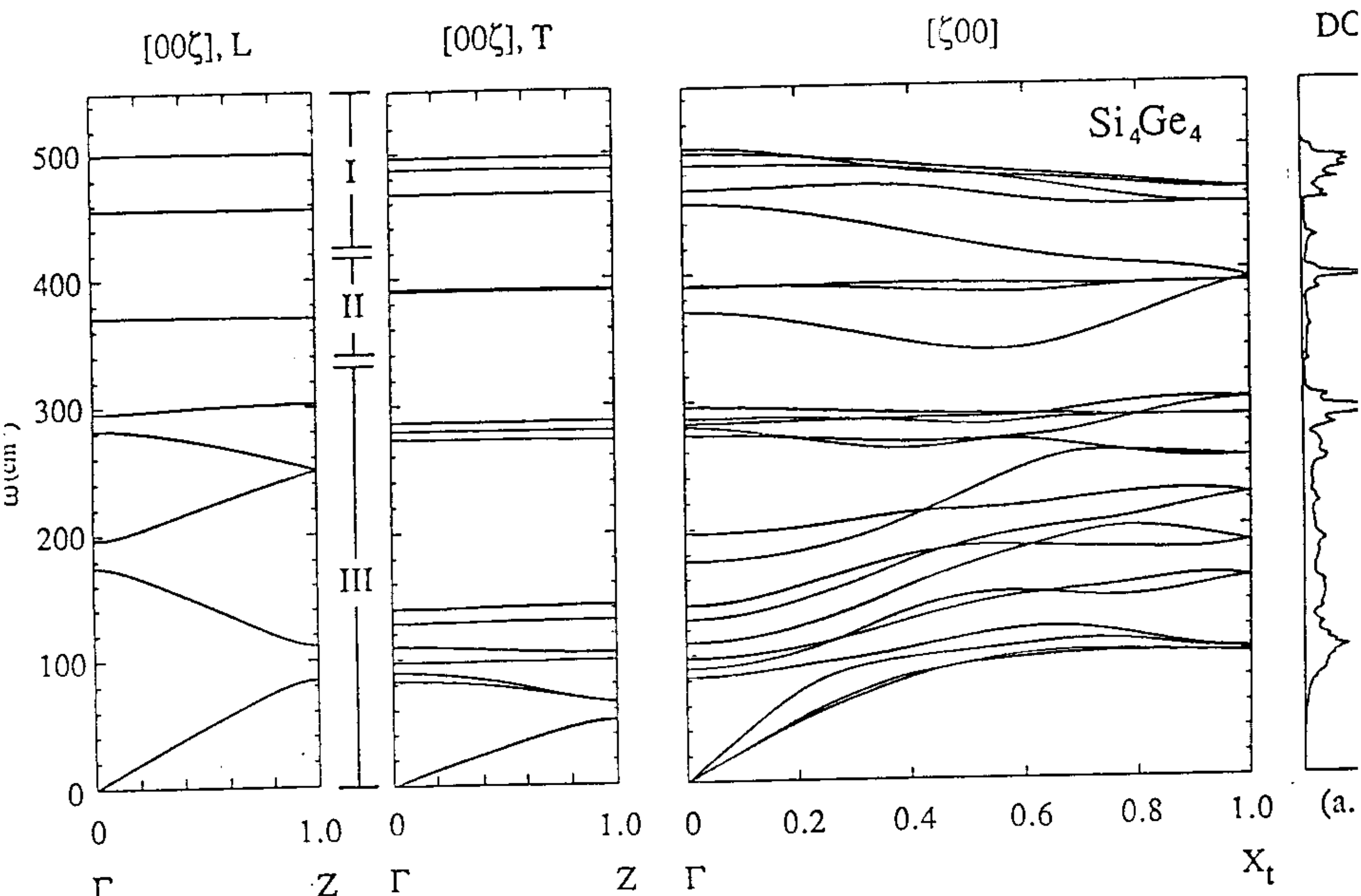
(Si)5/(Ge)3 on Si


Transverse
Longitudinal
(Si)5/(Ge)3
Wavenumbers (cm-1)
500
400
300
200
100
0
0
1.0
0
1.0

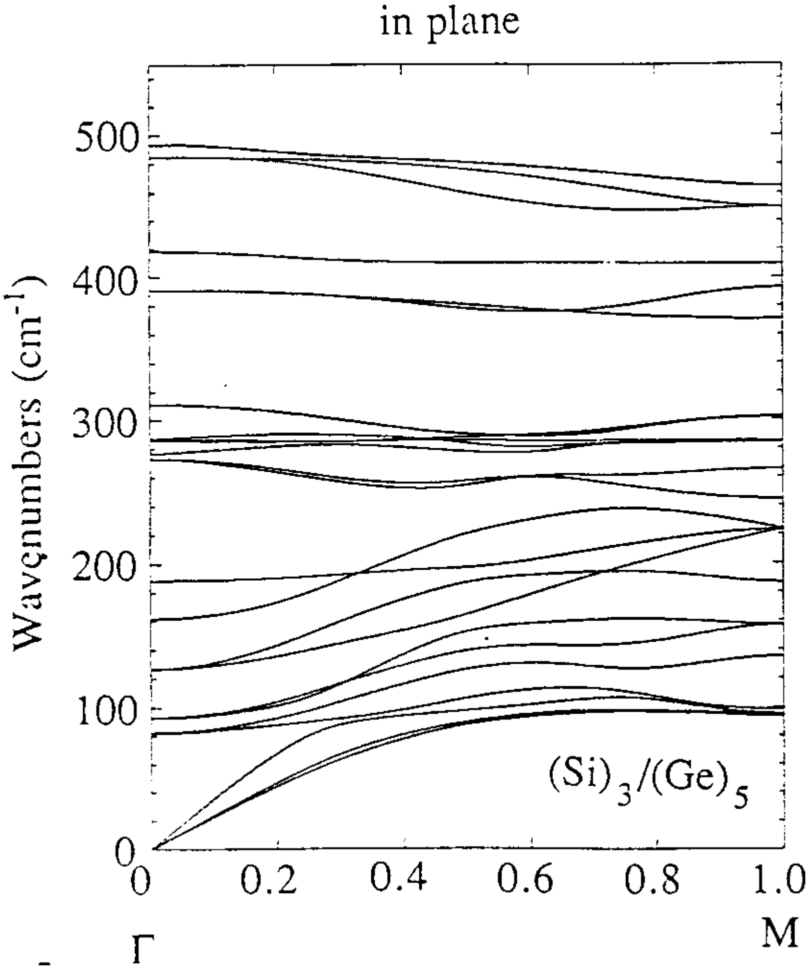

Longitudinal
Transverse
Wavenumbers (cm-1)
500
400
300
200
100
0
0
1.0
Γ
Z
(Si)3/(Ge)5


in plane
Wavenumbers (cm-1)
500
400
300
200
100
0
0.2
0.4
0.6
0.8
1.0
(Si)5/(Ge)3

$(Si)_5 / (Ge)_3$
on Si

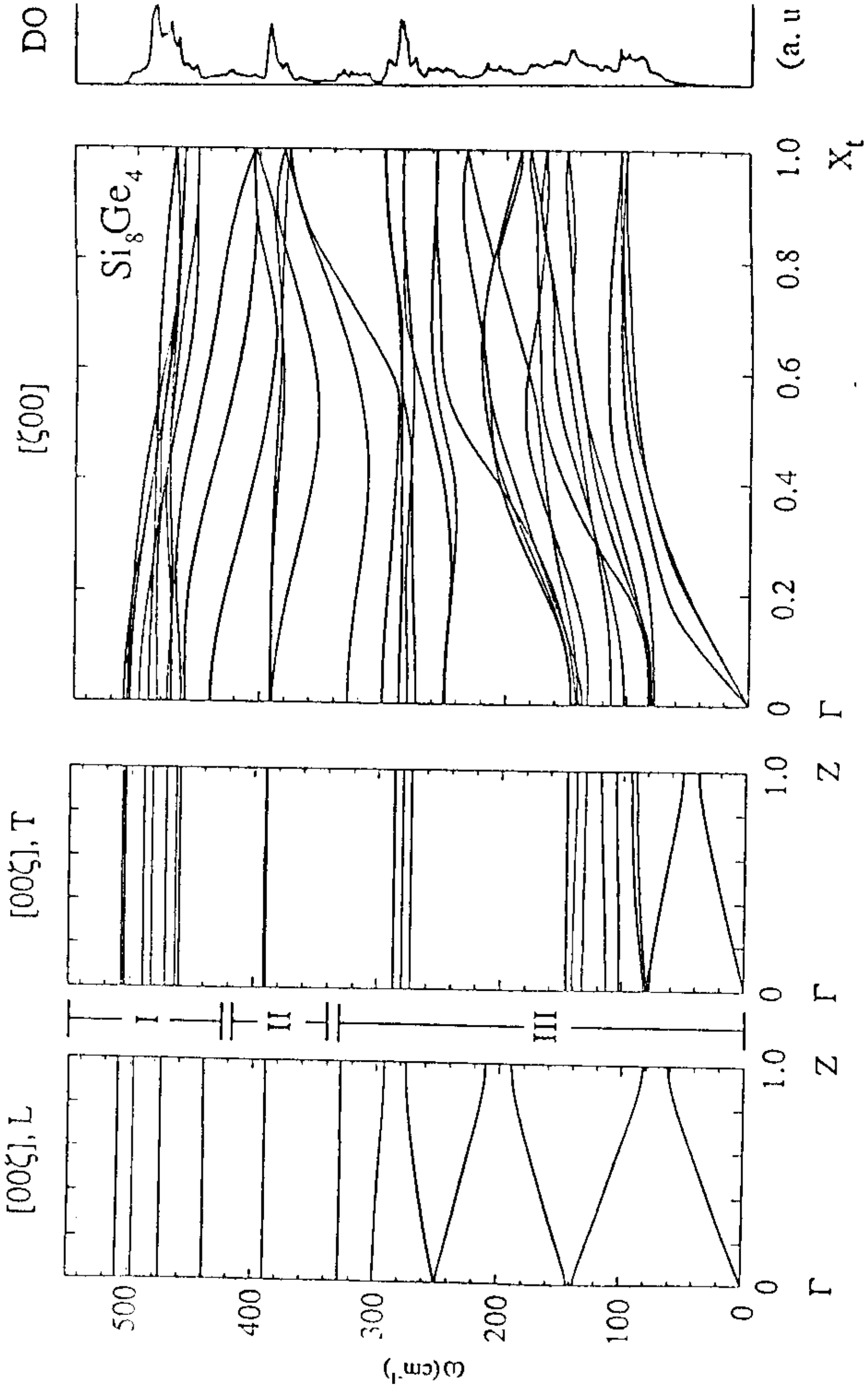


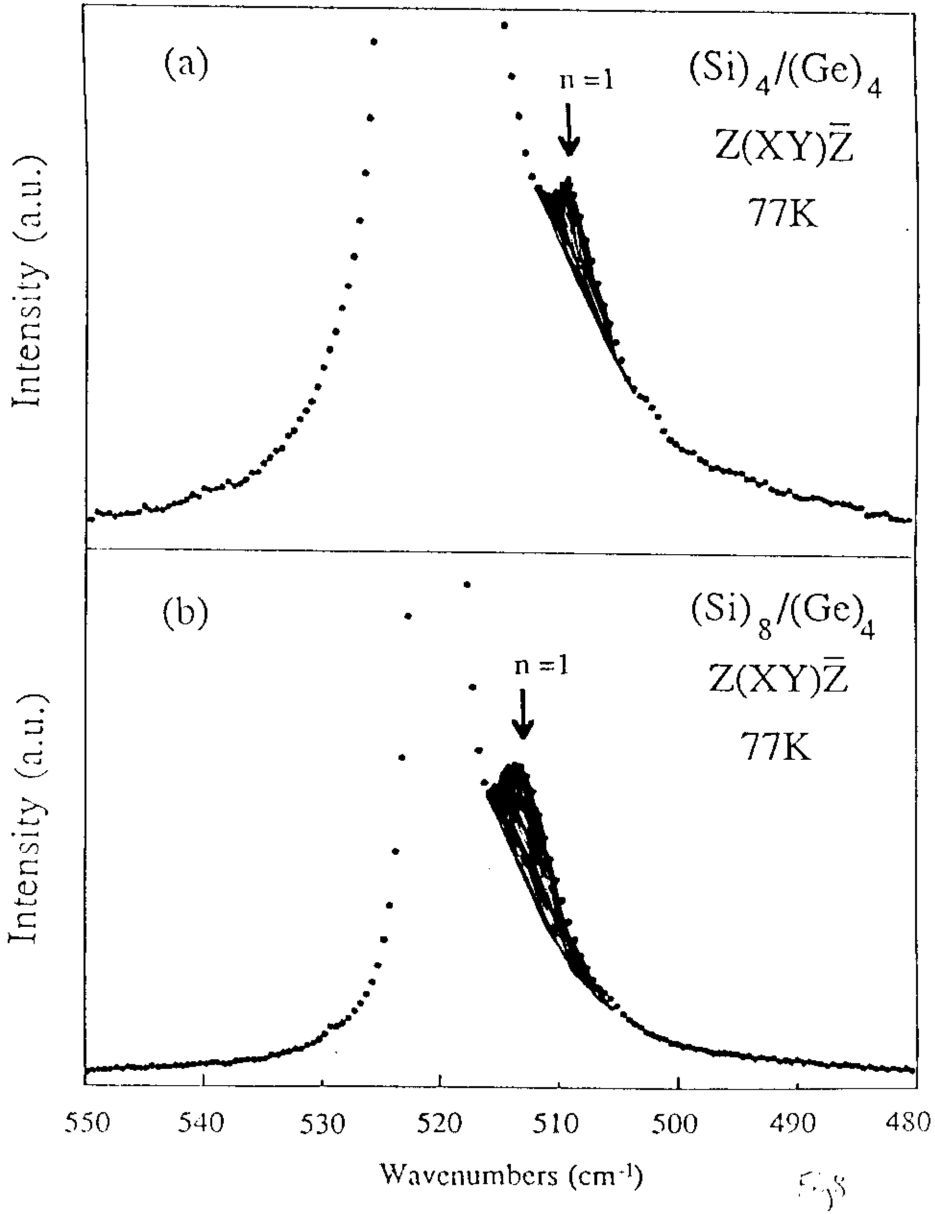
[redacted]

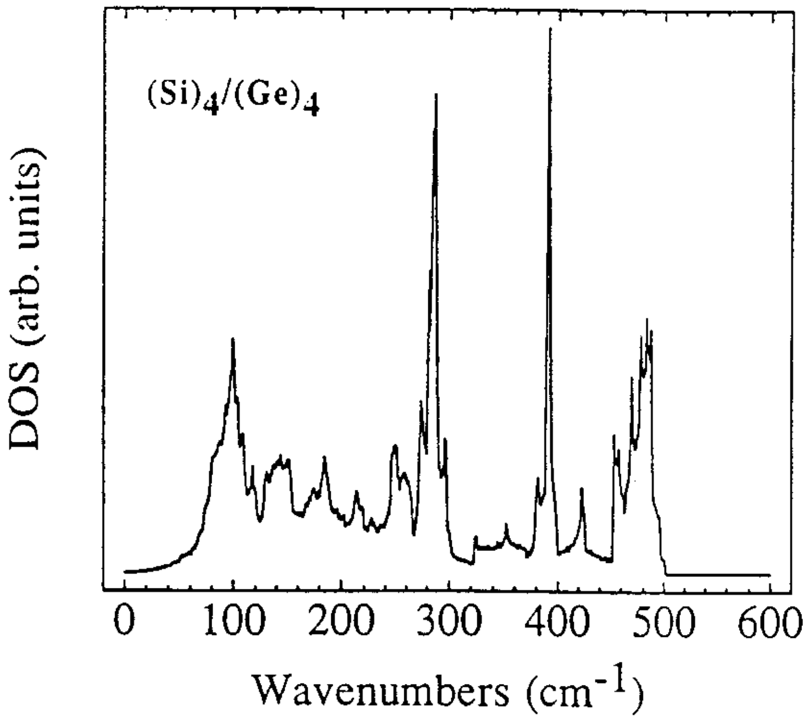


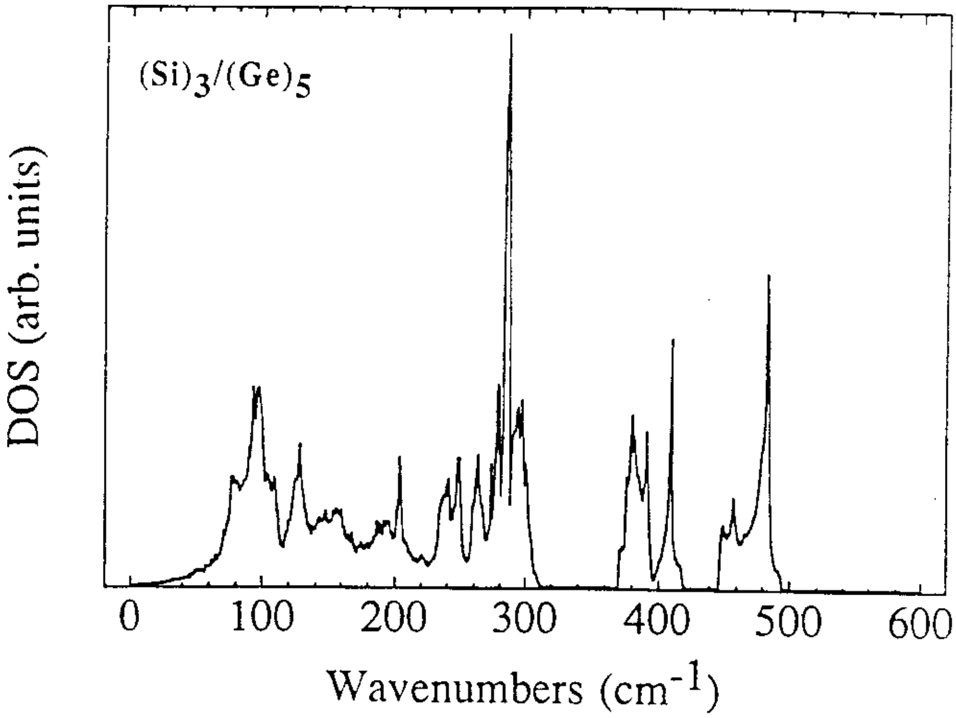
$(Si)_3 / (Ge)_5$.

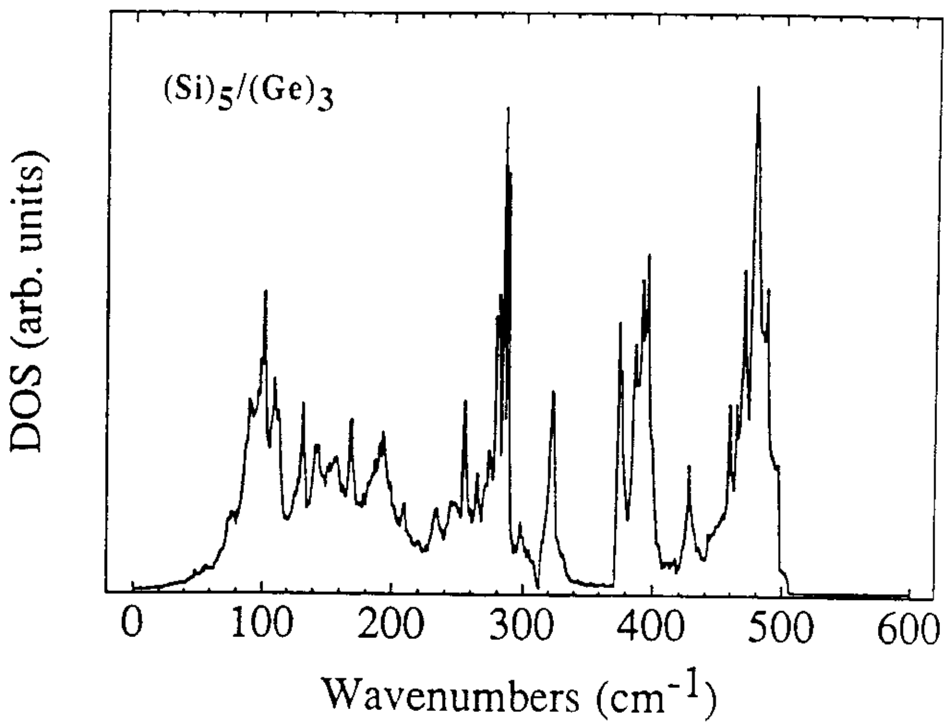
on Si

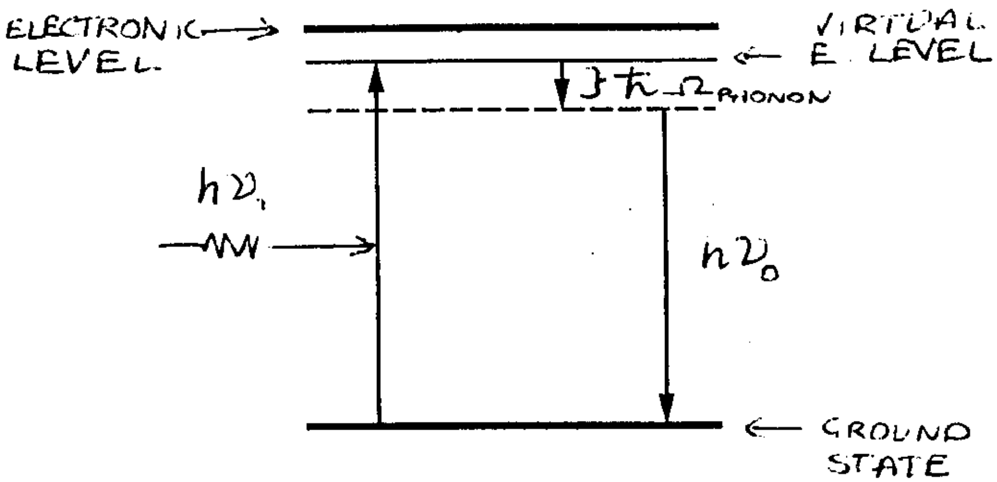

DO
(a. u
Si_8Ge_4
[ζ00]
X_t
[00ζ], T
[00ζ], L
I
II
III
Γ
Z
ω(cm⁻¹)
500
400
300
200
100
0
0.2
0.4
0.6
0.8
1.0

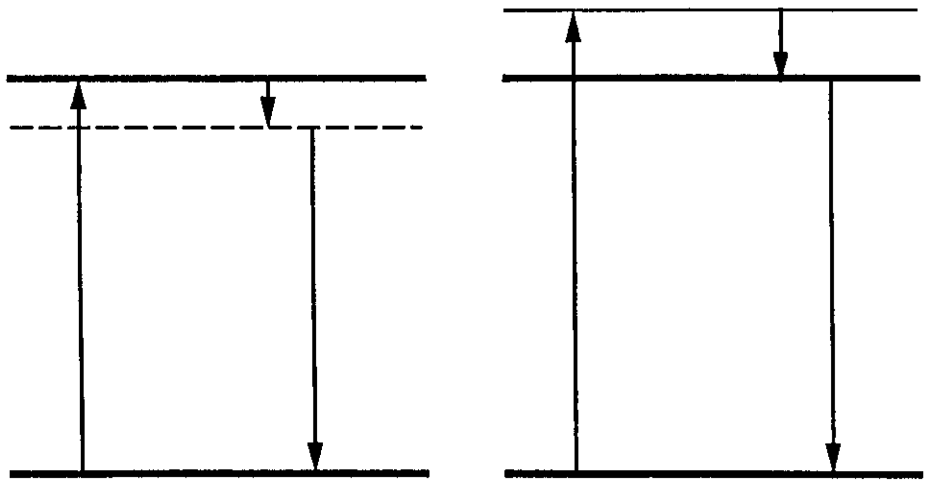

(a)
$(Si)_4/(Ge)_4$
$Z(XY)\bar{Z}$
77K
n =1
(b)
$(Si)_8/(Ge)_4$
$Z(XY)\bar{Z}$
77K
n =1
Intensity (a.u.)
Intensity (a.u.)
550
540
530
520
510
500
490
480
Wavenumbers (cm⁻¹)


(Si)4/(Ge)4
DOS (arb. units)
0
100
200
300
400
500
600
Wavenumbers (cm-1)

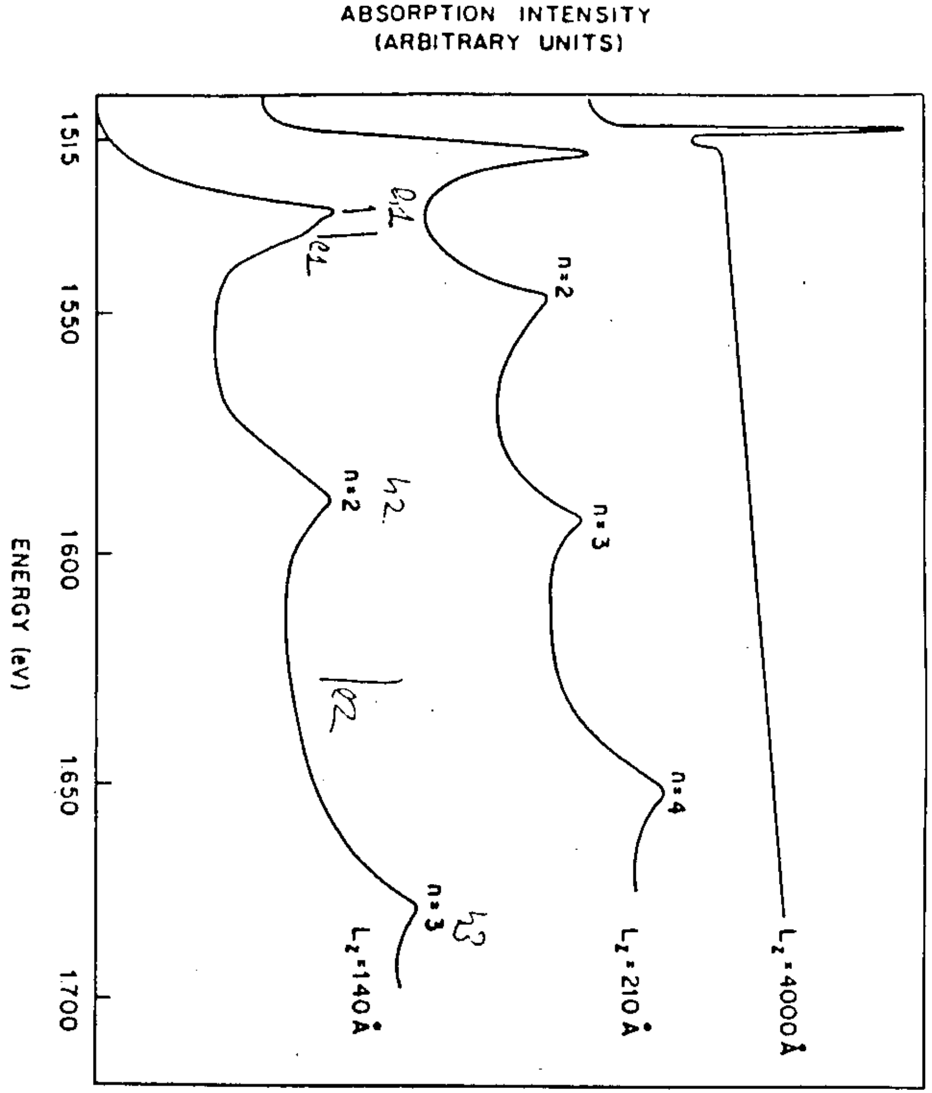

(Si)3/(Ge)5
DOS (arb. units)
0 100 200 300 400 500 600
Wavenumbers (cm-1)


(Si)5/(Ge)3
DOS (arb. units)
0 100 200 300 400 500 600
Wavenumbers (cm-1)

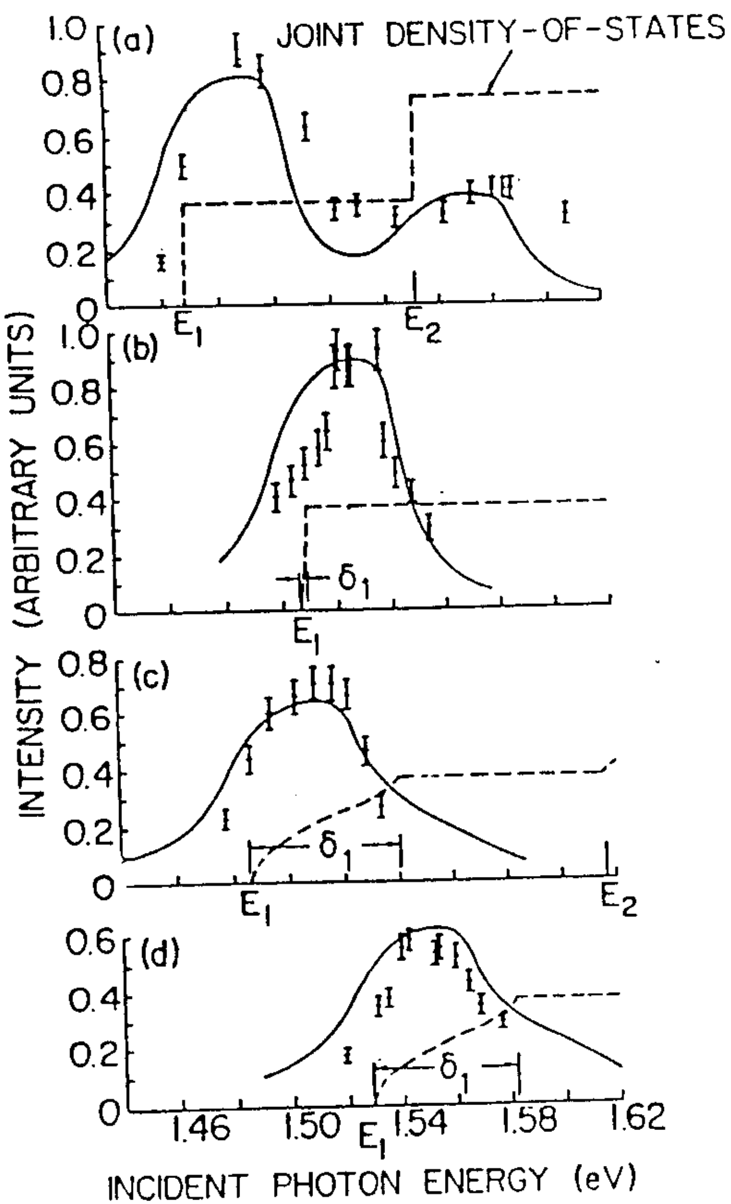




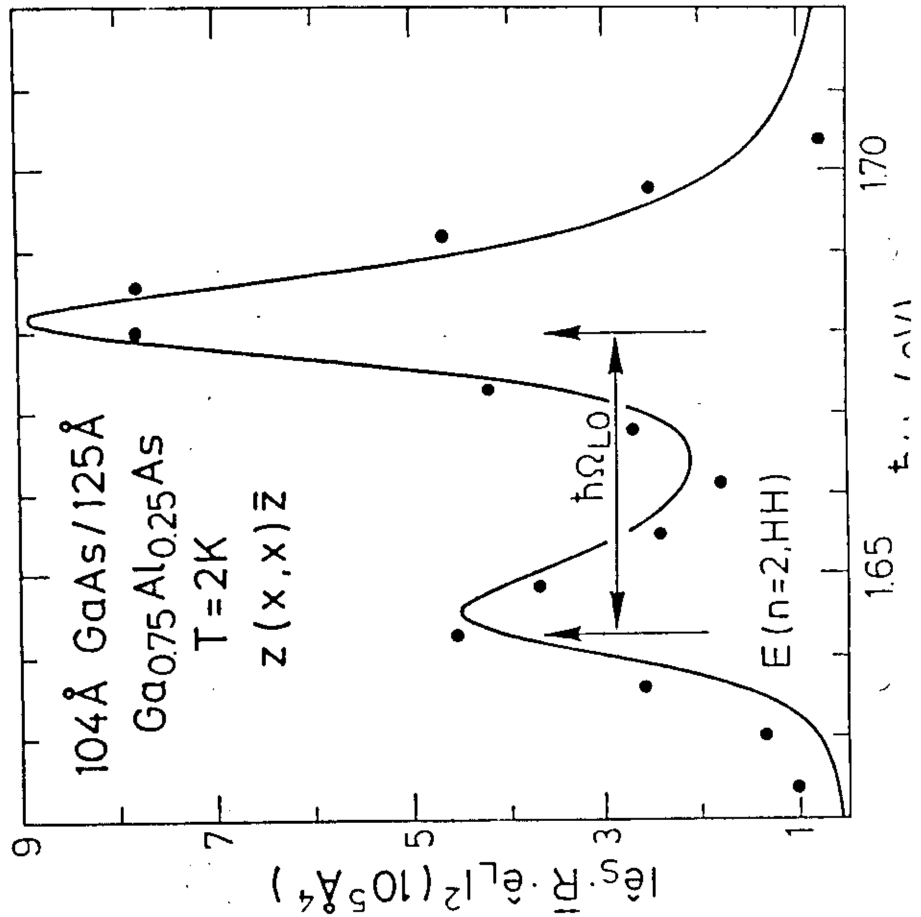
INGOING OUTGOING



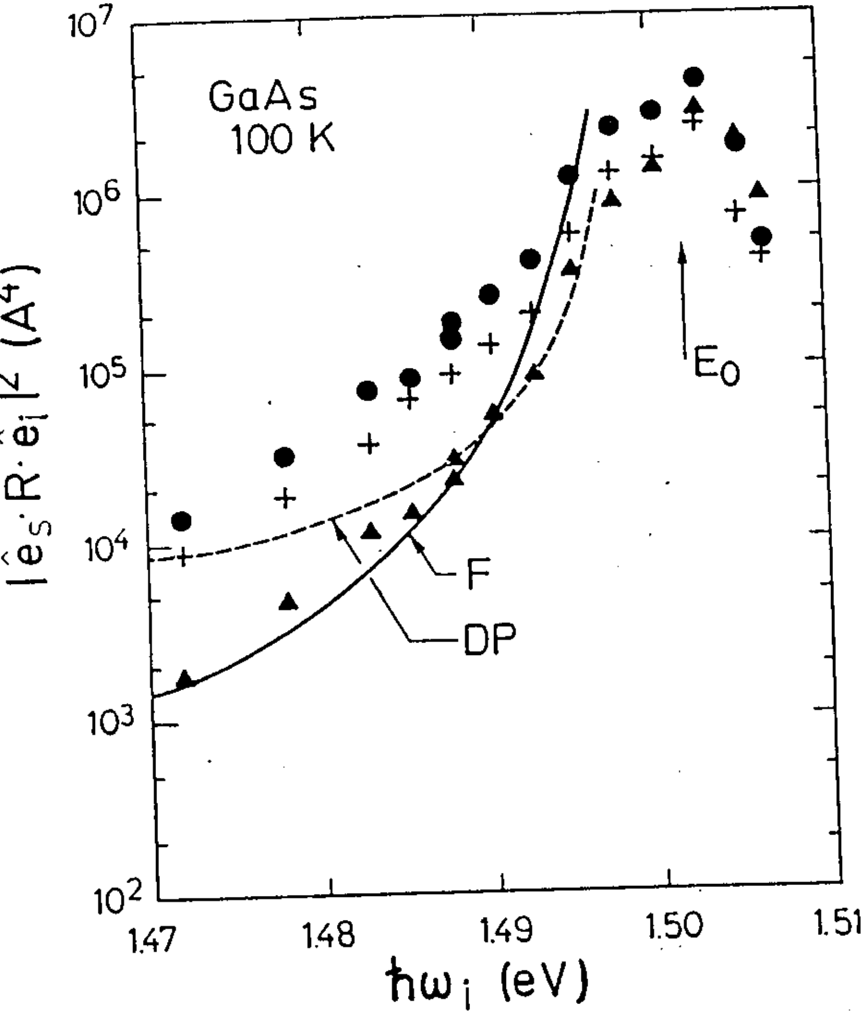
DINGLE ET. AL. P.R.L. 33 827 (1974)



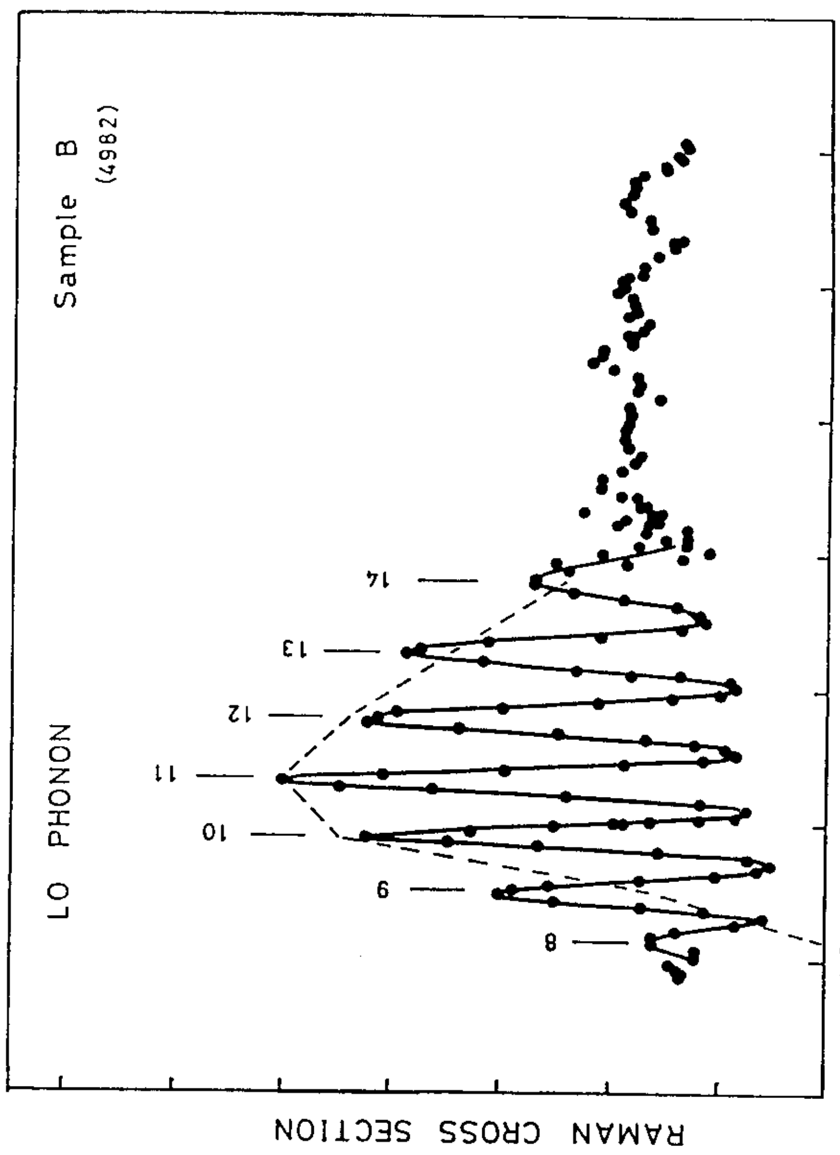
P MANDEL ET AL.



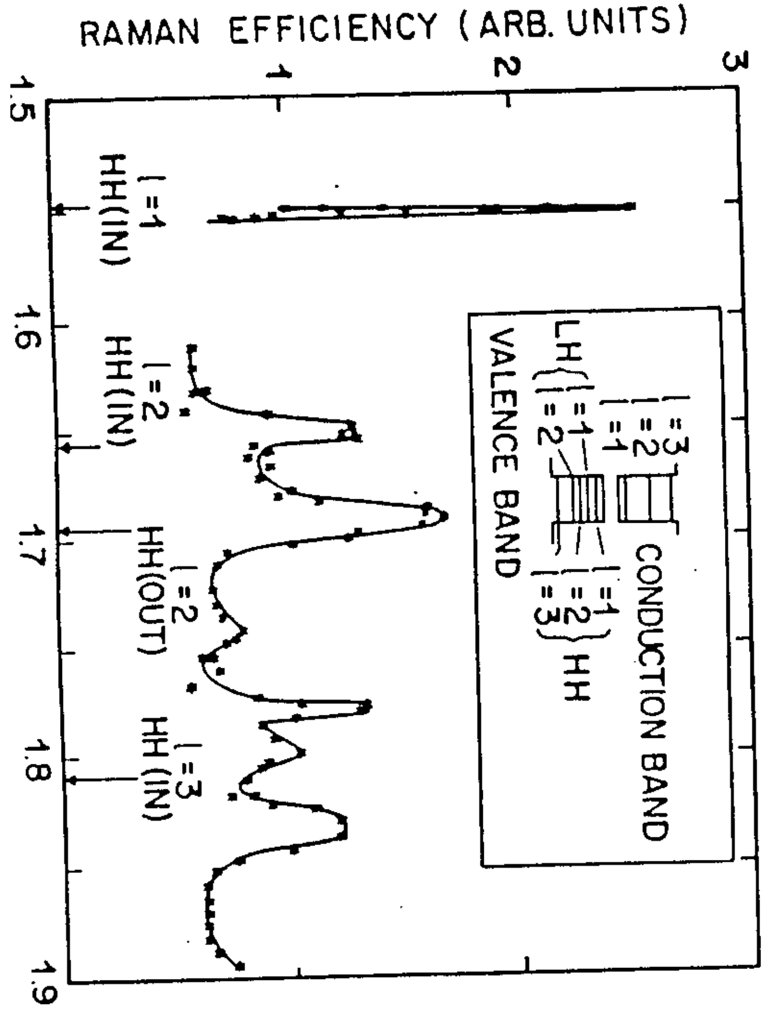
W. KAUSHKE ET AL
PRB 36 7469 (1987)



R M. MARTIN
PR.B 3 676 (1971)

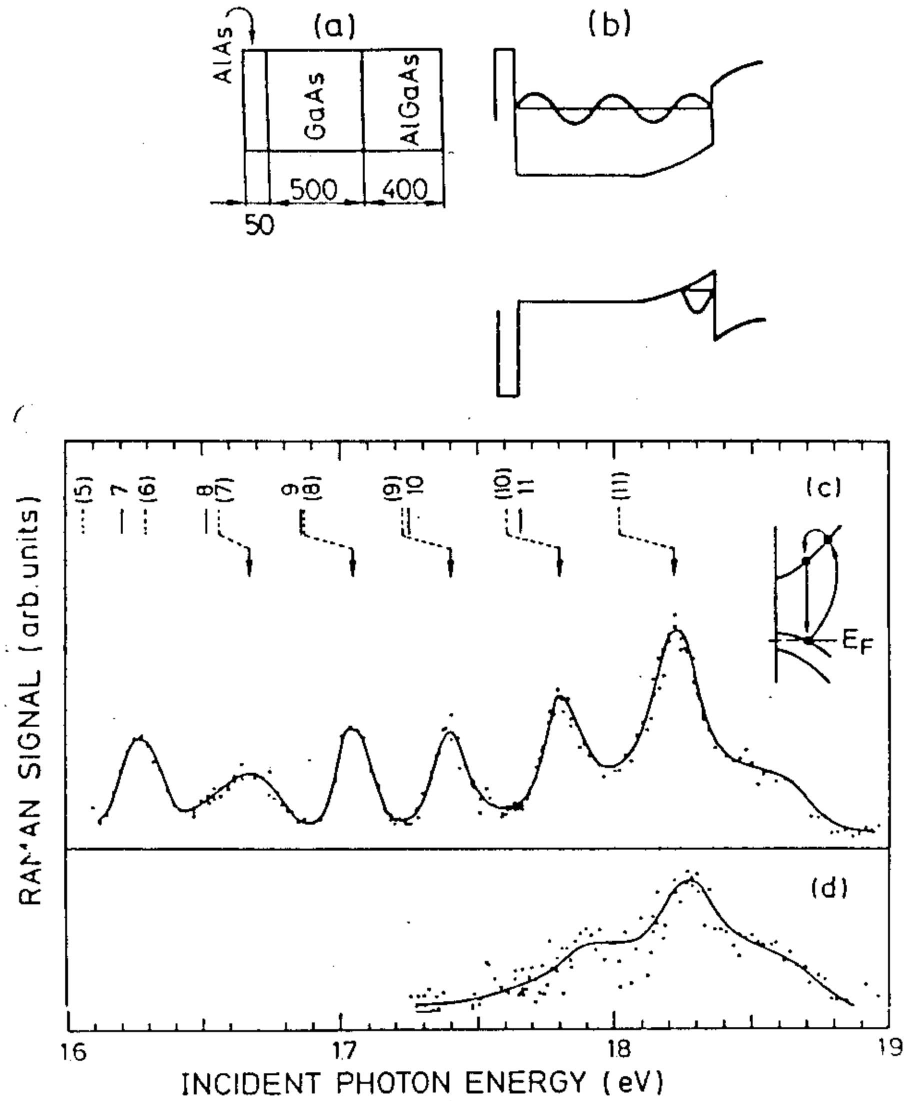


SUENOTO ET AL
PRB 27 1297



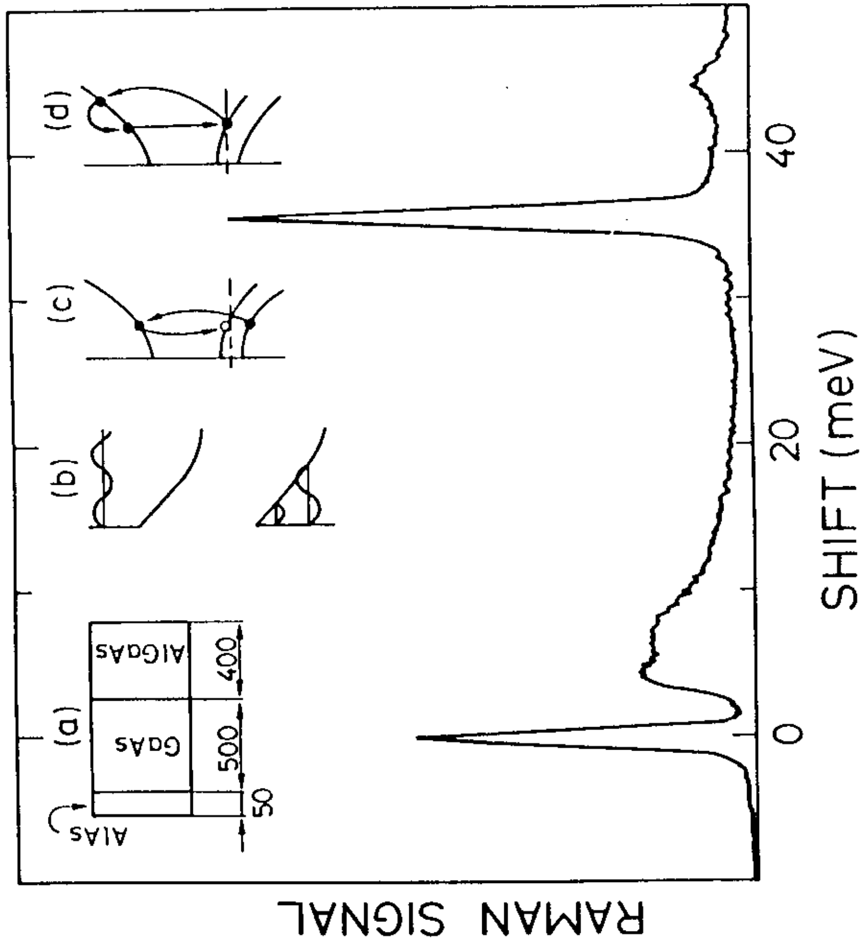
ZUCKER ET AL

P.R.L. 51 1293 (1983)

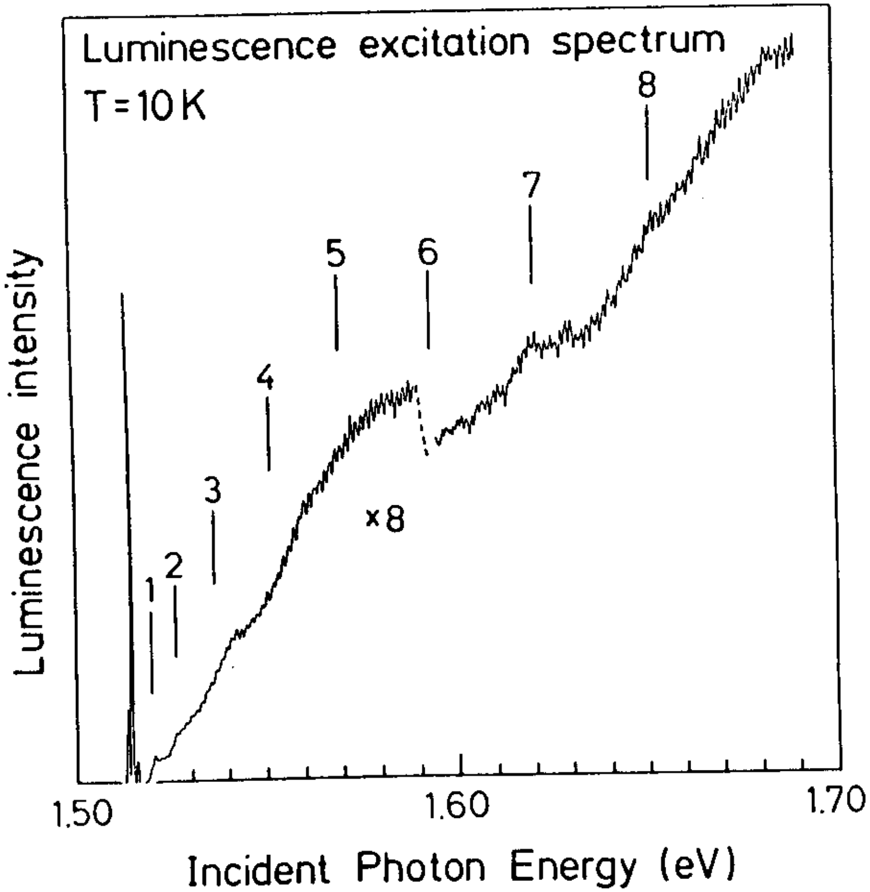


TSUEMOTO P.R.B 34 6034

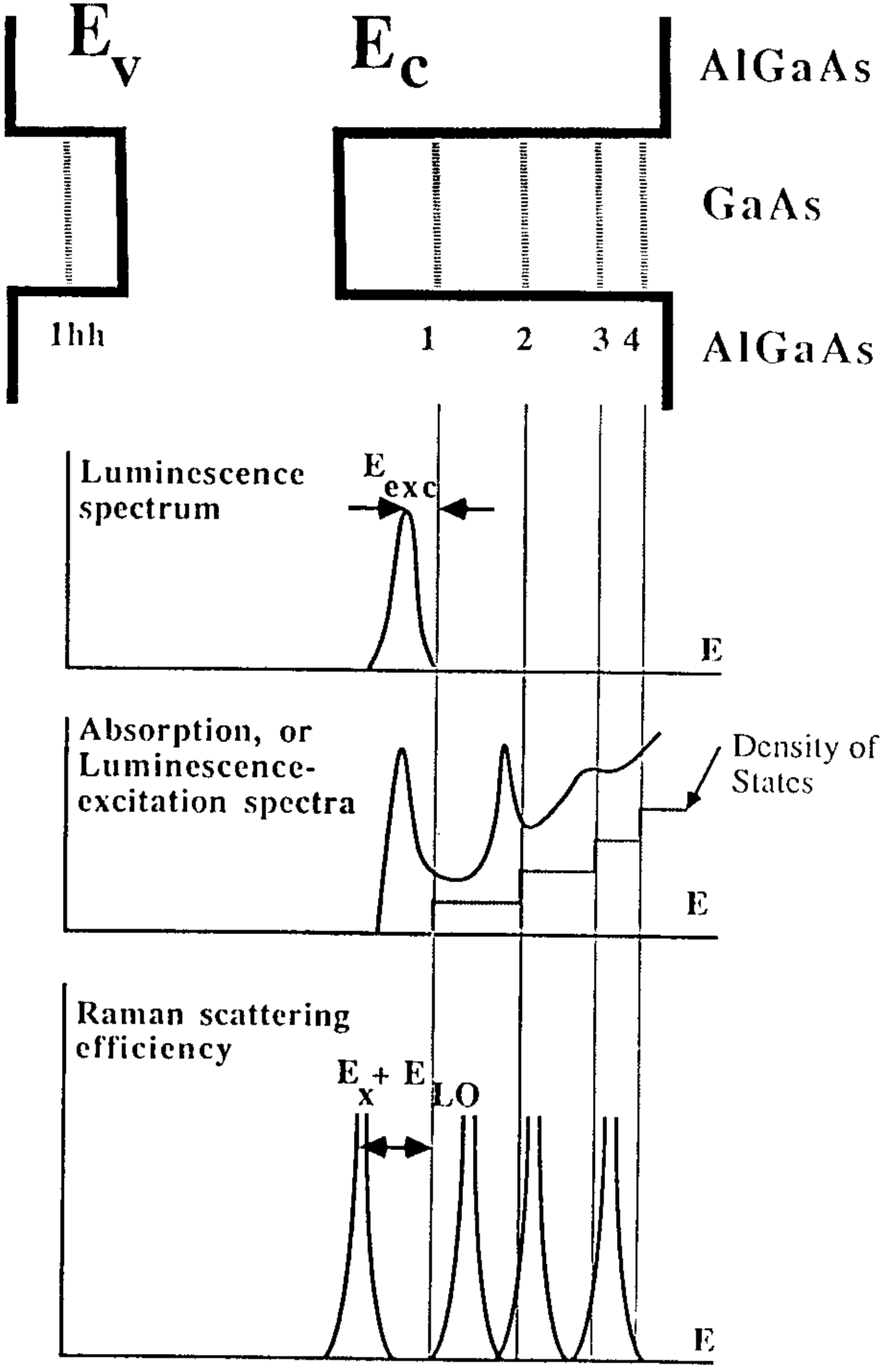
1986

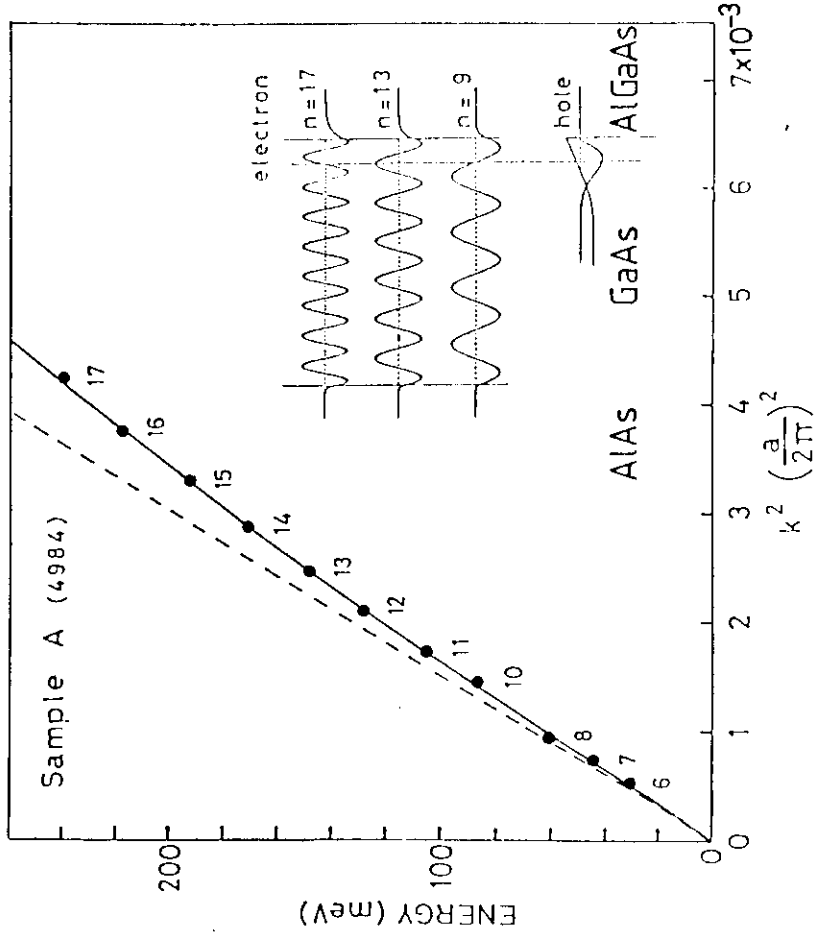


TSUEMOTO P.R.B. (1986) IBID



TSUEMOTO PRB (1988) IBID





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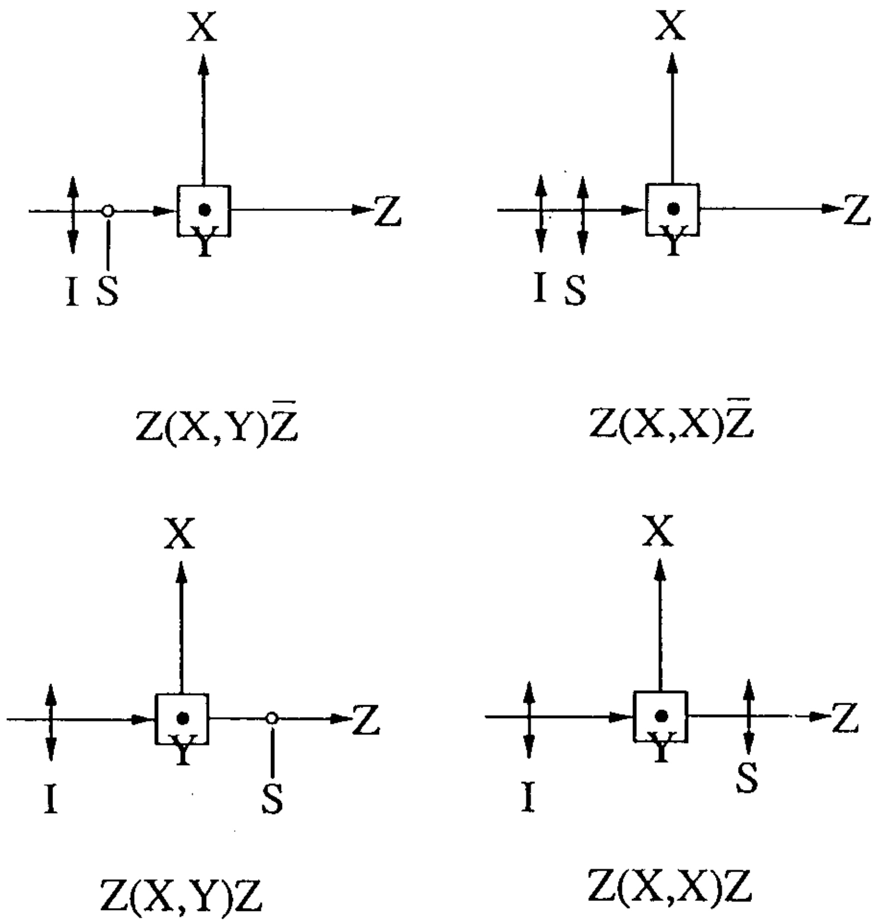
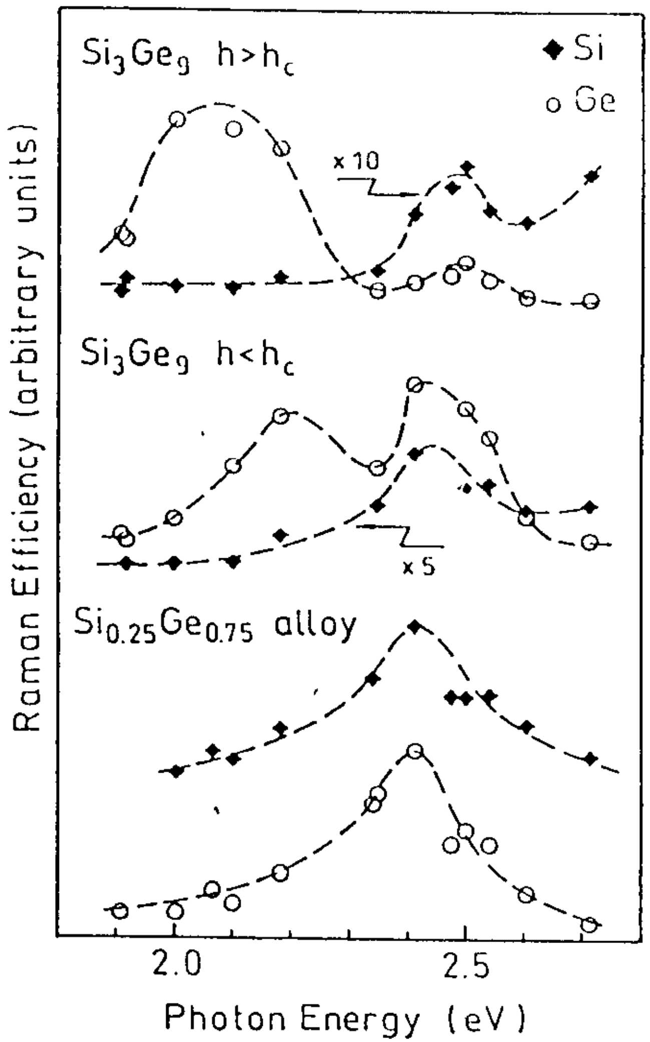
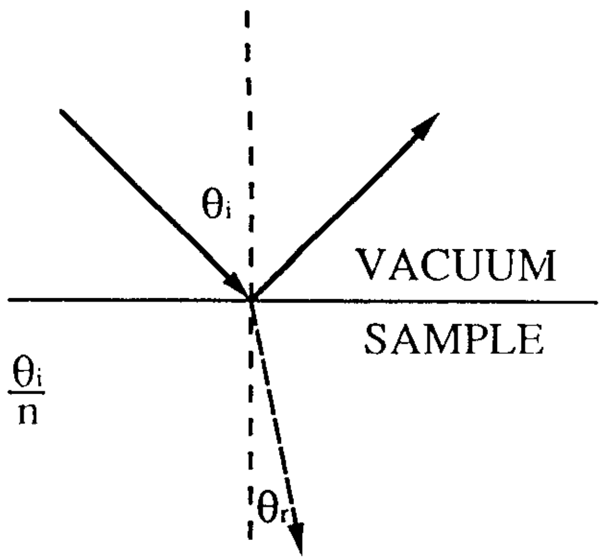


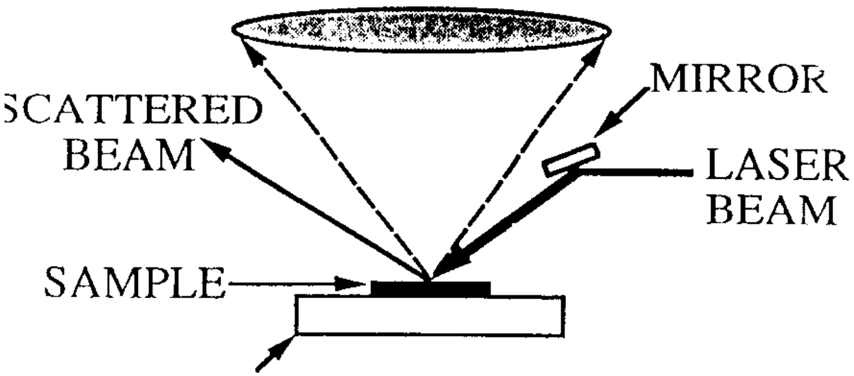


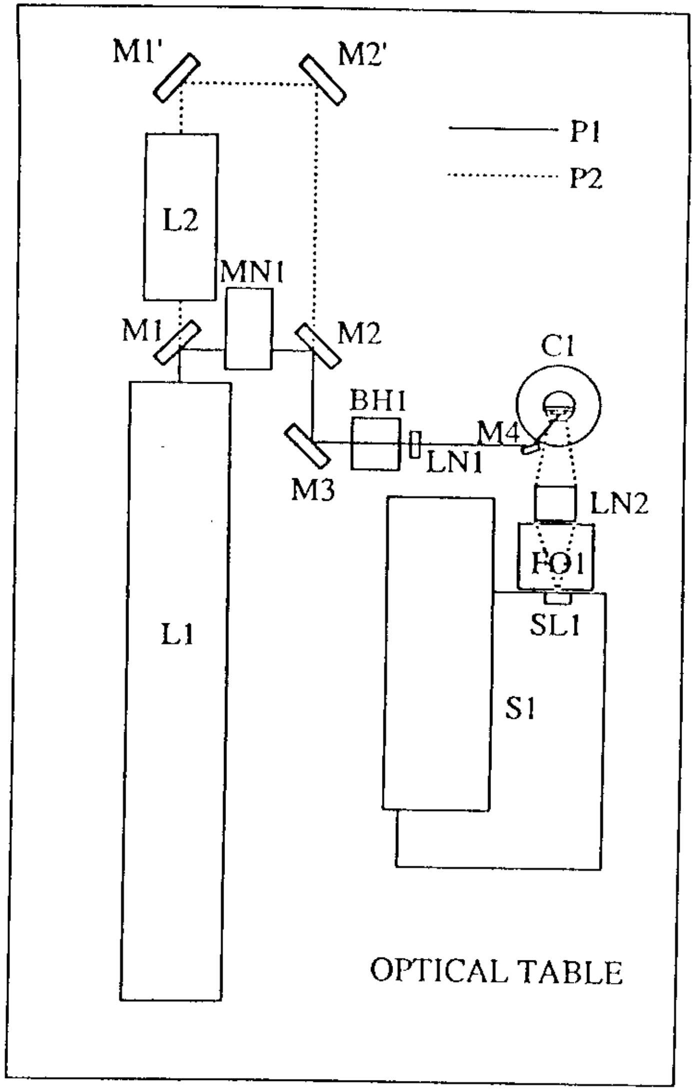
G ABSTREITER,
SPEC. SEM. MICROSTR.

Backscattering in practice

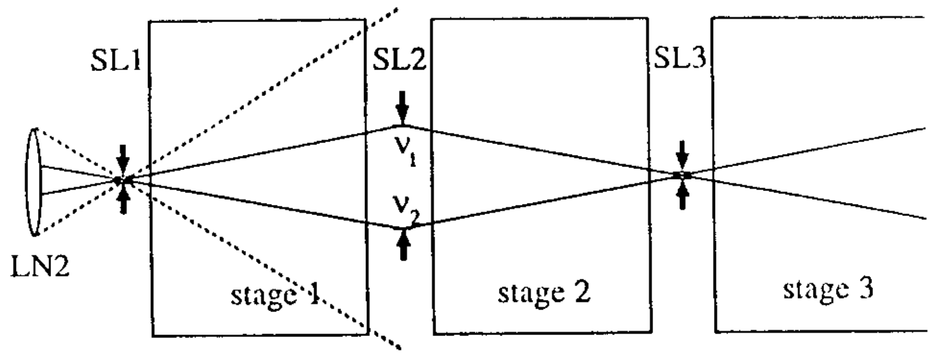


$$\sin\theta_r \approx \theta_r = \frac{\theta_i}{n}$$





(a) Double Subtractive Mode



(b) High Dispersion Mode