Photo-modulation spectroscopy of GaBiAs /GaAs layers grown by MBE

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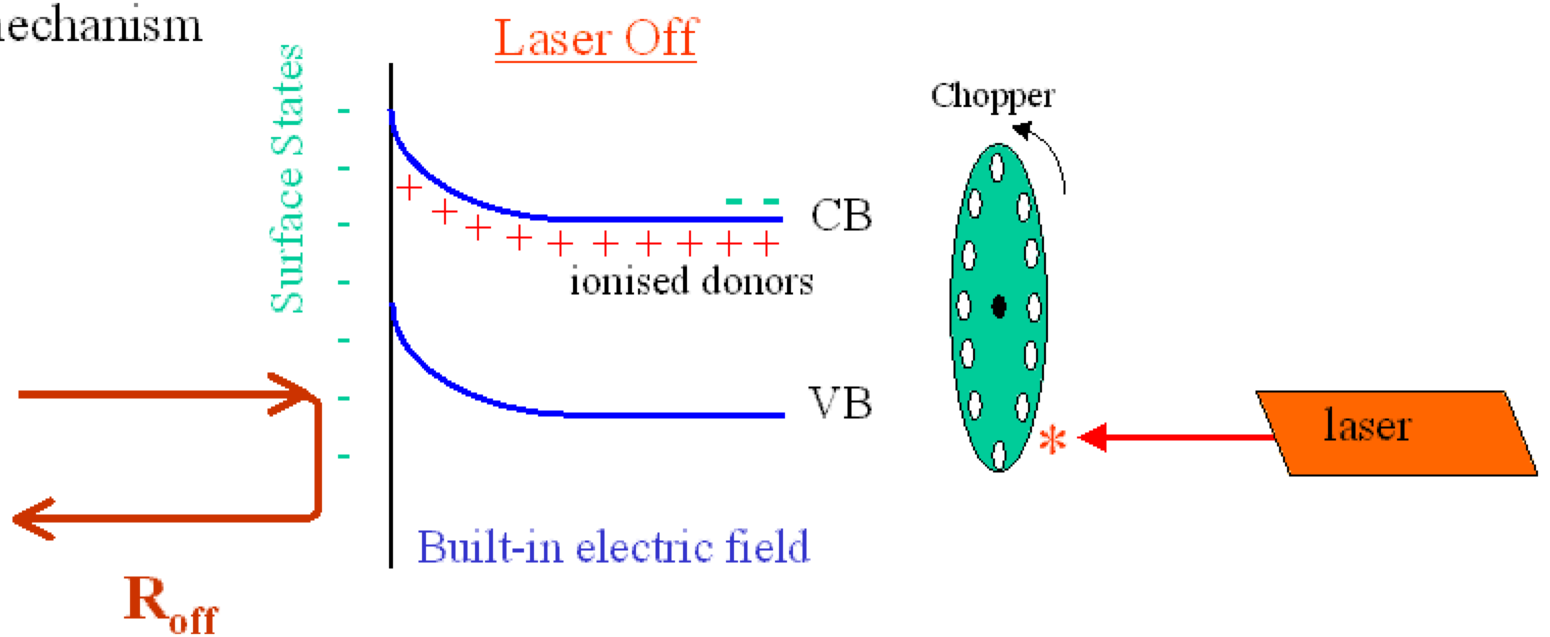
• What is modulated reflectance?

- Measure sample's reflectance **R** as a function of λ, while it is being modulated by <u>external periodic perturbation</u> : e.g. electric field (Electro-modulated reflectance - **ER**).

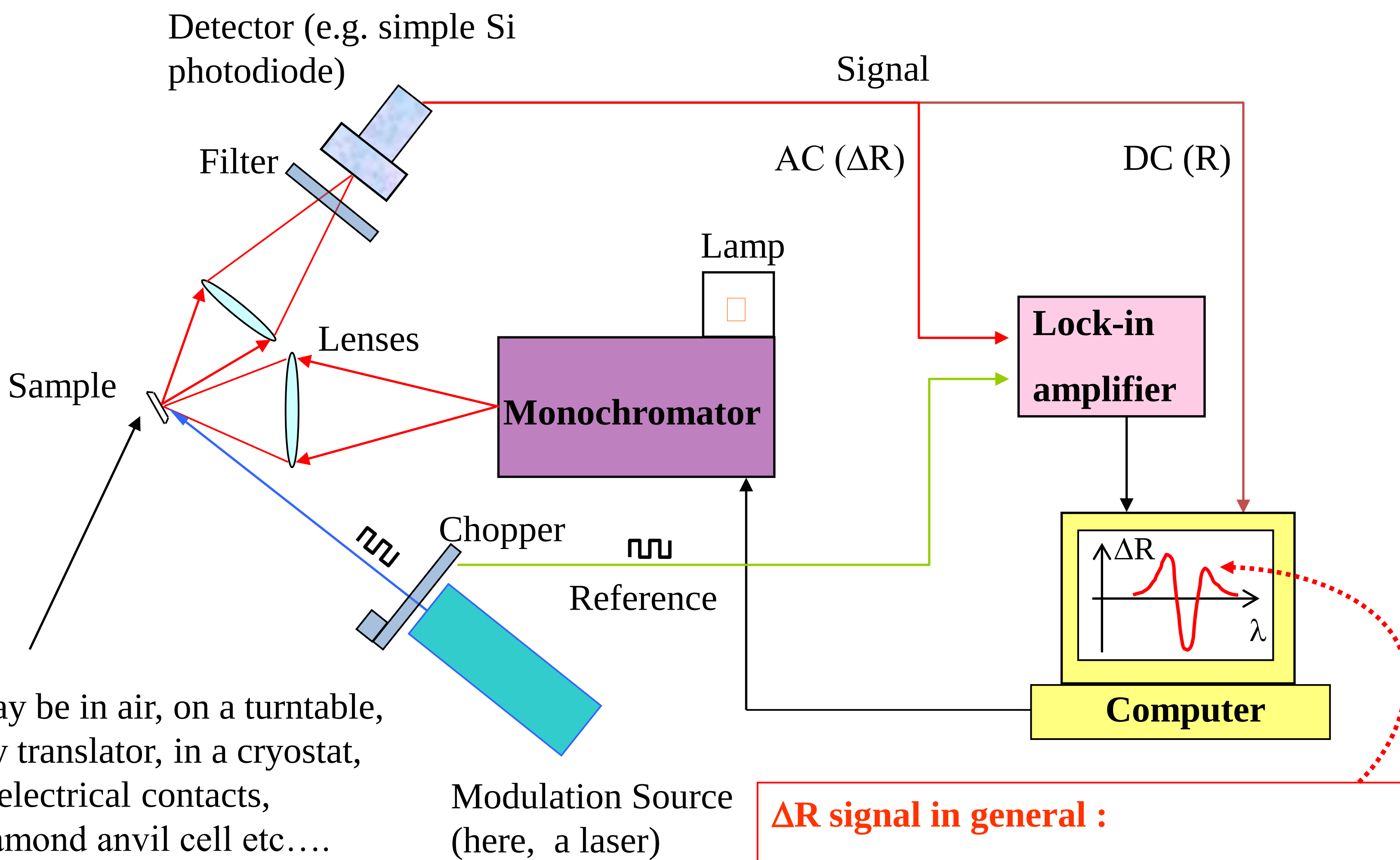
- Using a chopped pump laser beam gives especially useful **<u>Photo-modulated Reflectance</u> (PR)** : <u>non-destructive</u>, <u>non-contact</u> form of ER.

- Periodically-excited carriers → modulate internal **<u>E</u>**-fields → modulate complex dielectric fn $\varepsilon_1 + i\varepsilon_2 \rightarrow \Delta\varepsilon_1, \Delta\varepsilon_2 \rightarrow$ differential changes **ΔR** in reflectivity **R** → **PR signal = ΔR/ R**

Basic PR mechanism



Schematic of typical Modulated Reflectance Setup

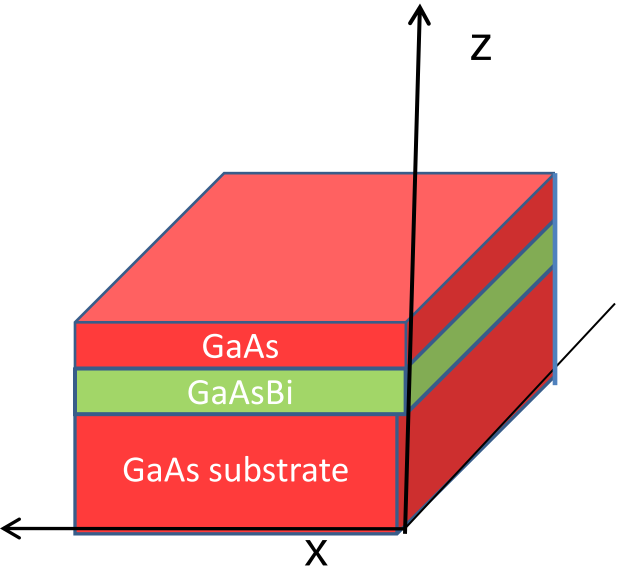


May be in air, on a turntable, x-y translator, in a cryostat, in electrical contacts, diamond anvil cell etc….

ΔR signal in general :

- **oscillatory & derivative-like,**
- **centred on critical-point energy of sample**

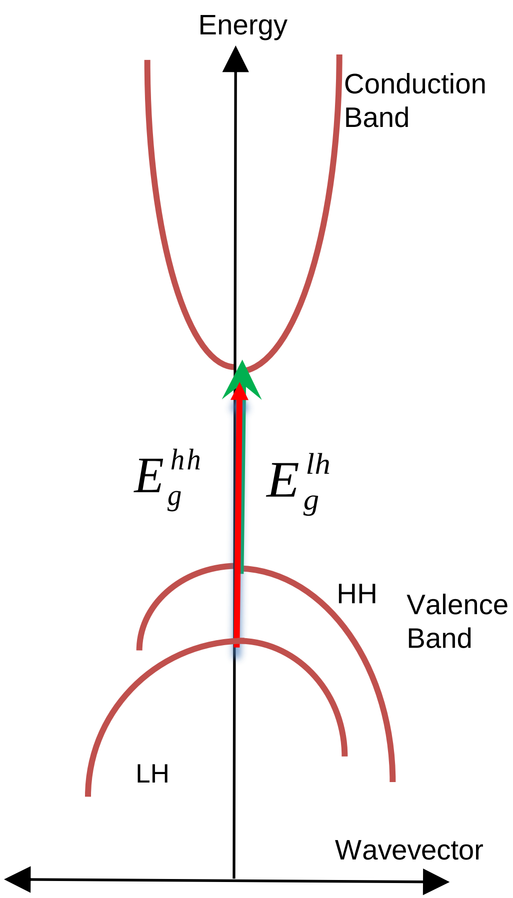
GaBiAs/GaAs – sample info

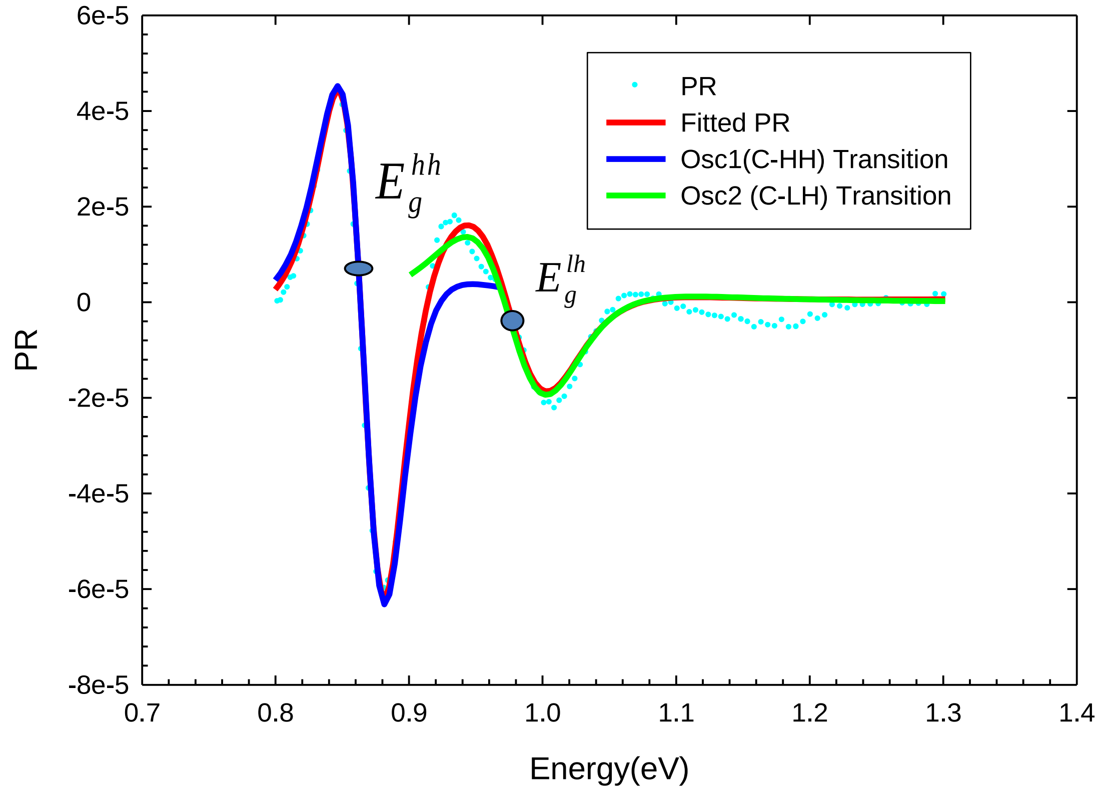


sample	Bi%	Thickness of GaBiAS layer(nm)	GaAs Cap(nm)
R1835	2.3	40	300
R1829	4.5	30	uncapped
R1923	8.5	30	-------------
R1914	10.4	30	-------------

Z- axis is the growth direction

Obtaining the band gap transitions from PR





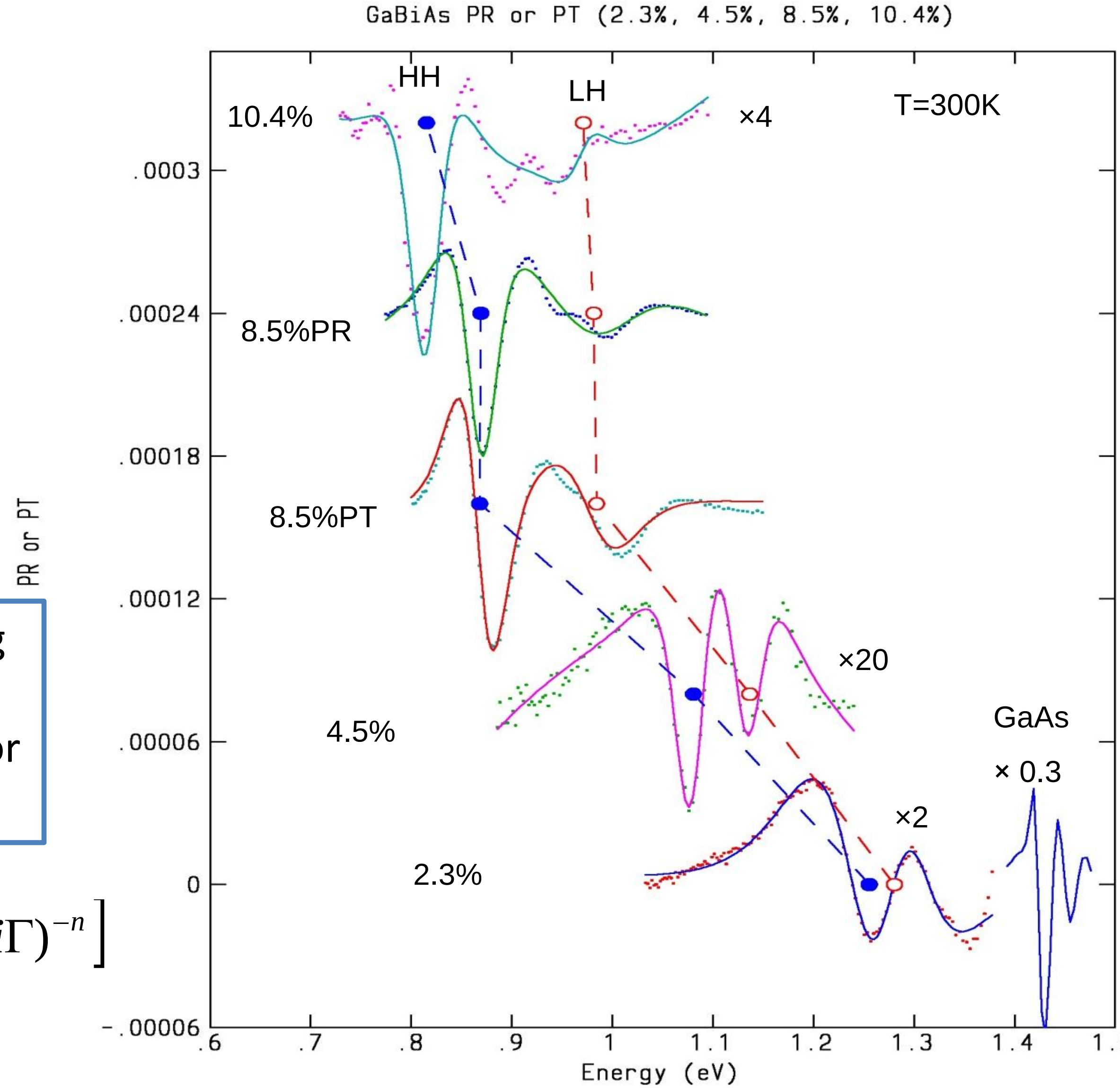
PR Spectra of GaBiAs Layers with 2.3%<Bi<10.4% For Bandgap Transition

514nm/153mW
Ar ion laser
Chopped at 333 Hz

InGaAs Detector

PR/PT line shapes fitted using a sum of two Aspnes third derivative functional forms for HH and LH [2] :

$$\Delta R / R = \mathrm{Re}\left[Ce^{i\theta} (E - E_g + i\Gamma)^{-n} \right]$$

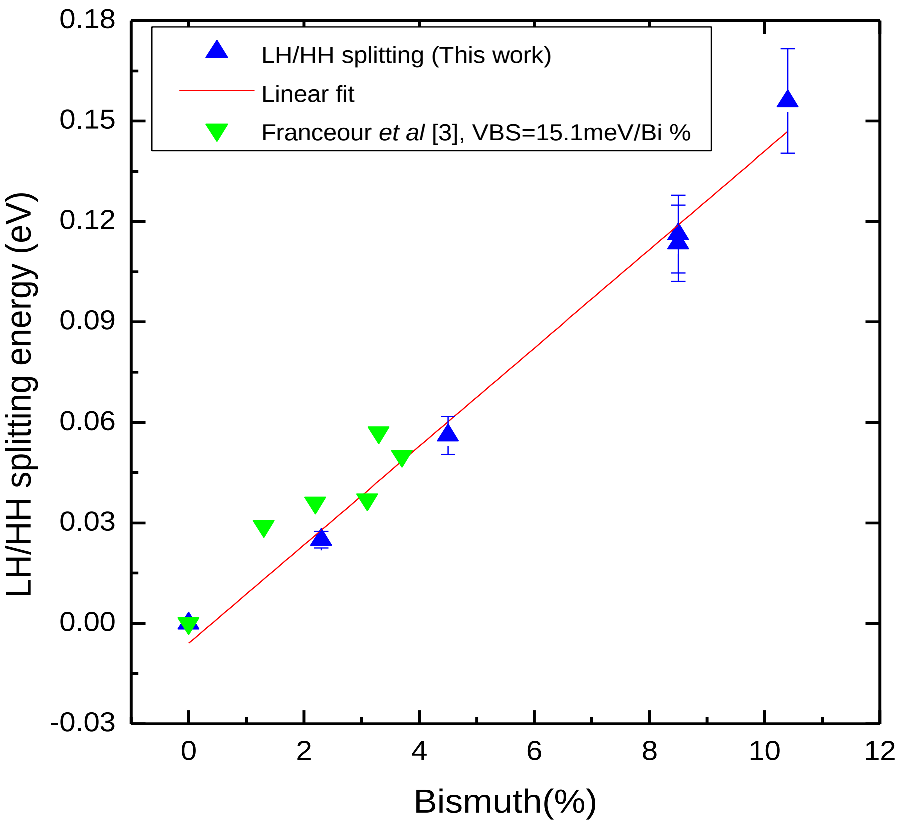


Strain induced Valence Band splitting (VBS)

- 30-40nm GaBiAs thin layers are under compressive strain, creating VBS

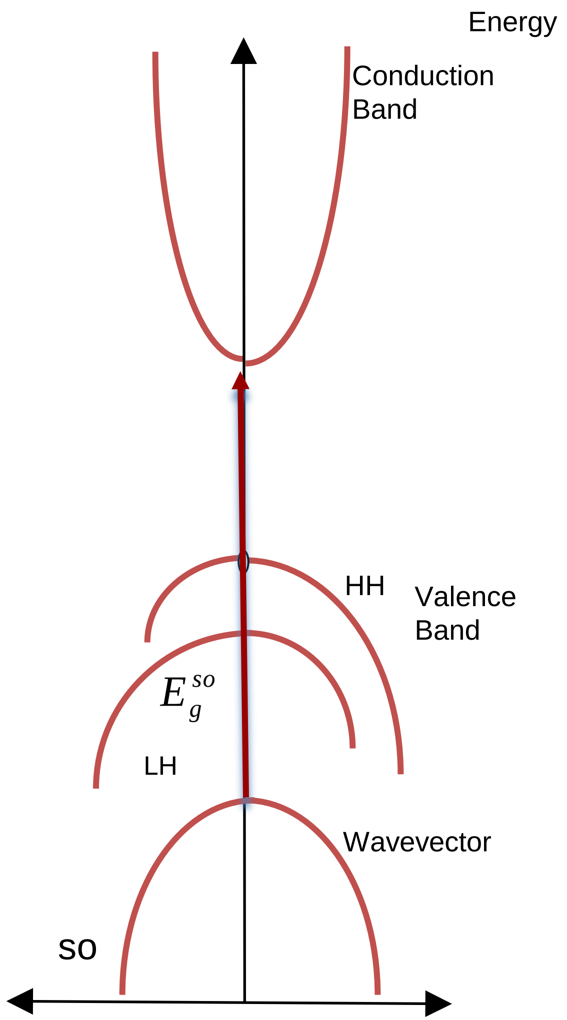
VBS changes at a rate on the order of 14.7meV/Bi% in good agreement with Franceour *et al* (15.1meV/Bi%)

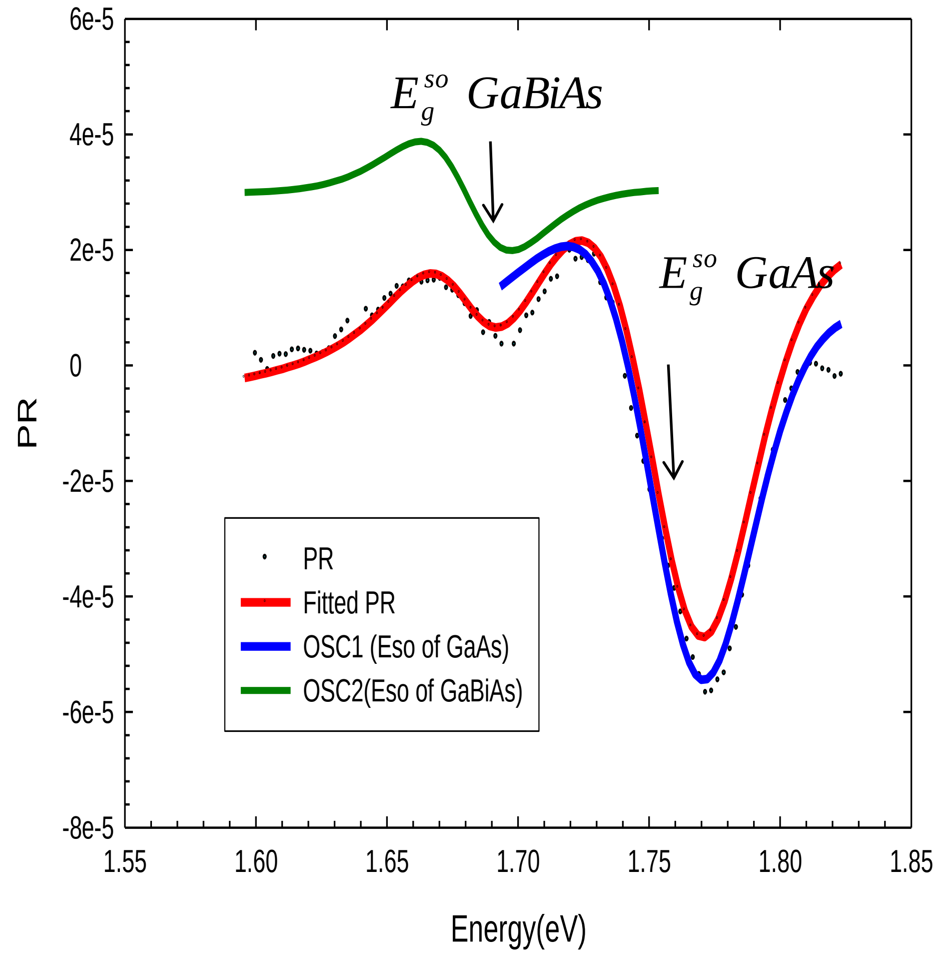
GaBiAs Valence Band Splitting from Fitted PR/PT



[3] S. Franceour, M.-J. Seong, and A. Mascarenhas ,S .Tixier ,M. Adamcyk, and T.Tiedje,Appl.Phys.Lett.82,22(2003).

Spin orbit splitting transition from PR



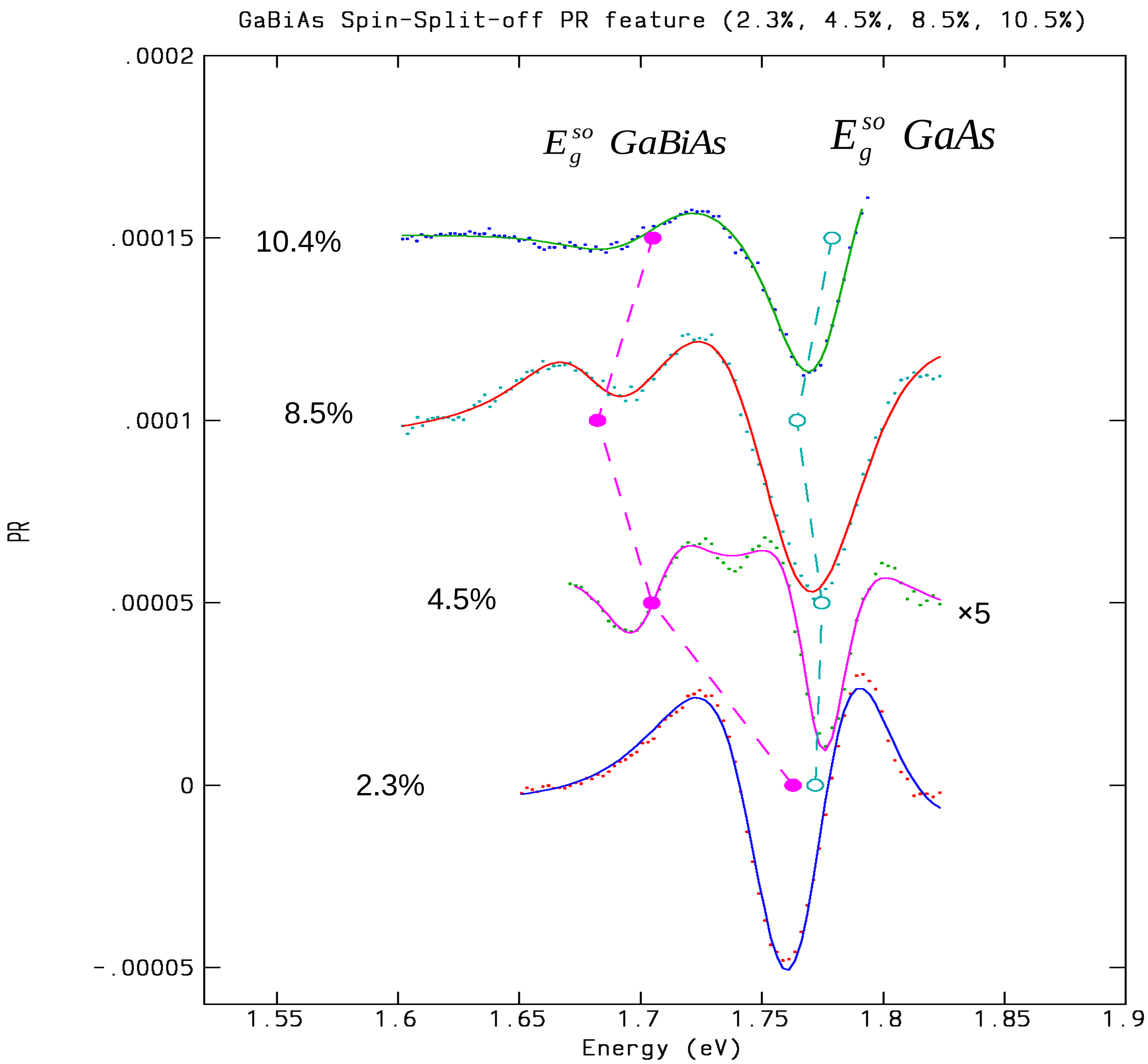


PR Spectra For Spin orbit splitting

Room Temperature

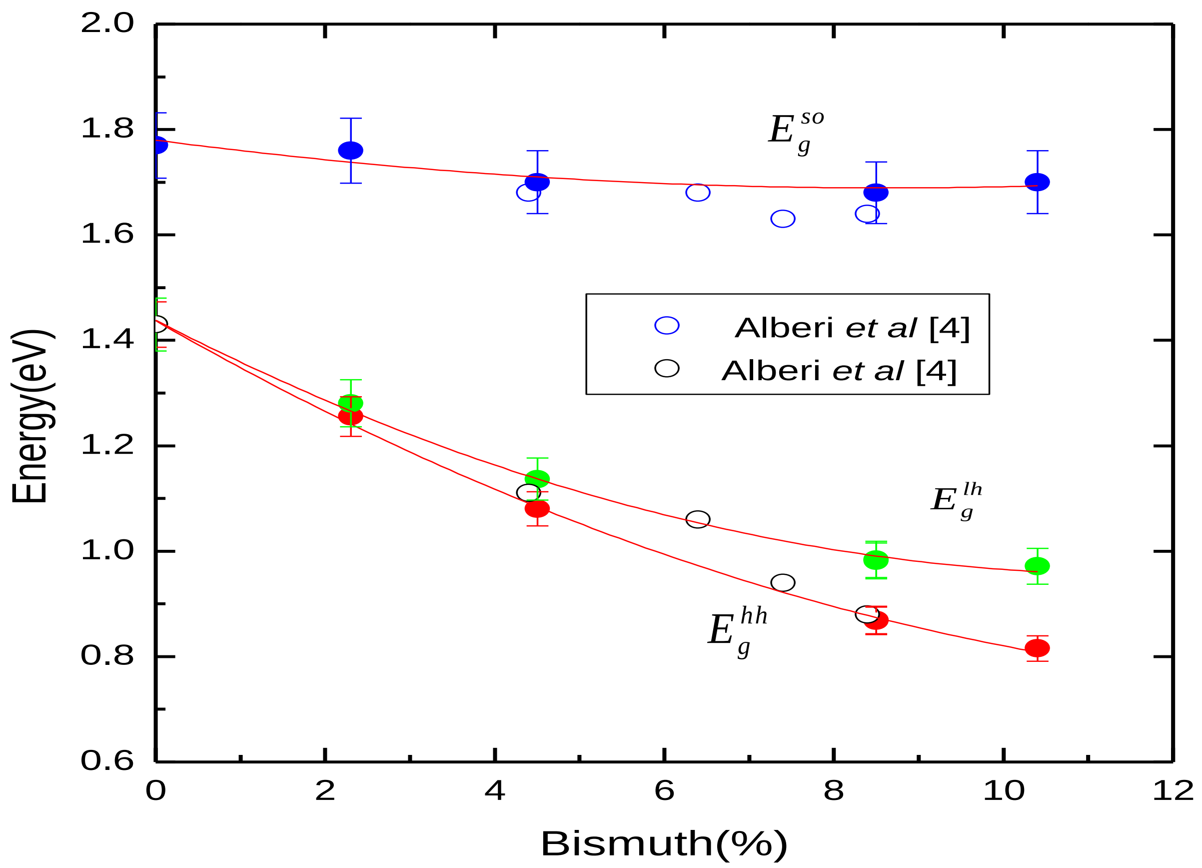
514nm/13.5mW laser Chopped at 333 Hz

Si detector



Reduction of Bandgap and Spin orbit Splitting with increase in Bismuth content

GaBiAs HH/LH and energies from fitting of PR/PT



[4] K. Alberi and O. D. Dubon, W. Walukiewicz and K. M. Yu ,K. Bertulis, and A. Krotkus ,Appl. Phys. Lett 91.051909(2007).

Strain Tensor Components

In plane strain (along x &y direction) and out of plane strain(z- axis,which axis of growth) are opposite

$$\varepsilon_{xx} = \left(a_{GaAs} - a_{GaBiAs}\right) / a_{GaBiAs}$$

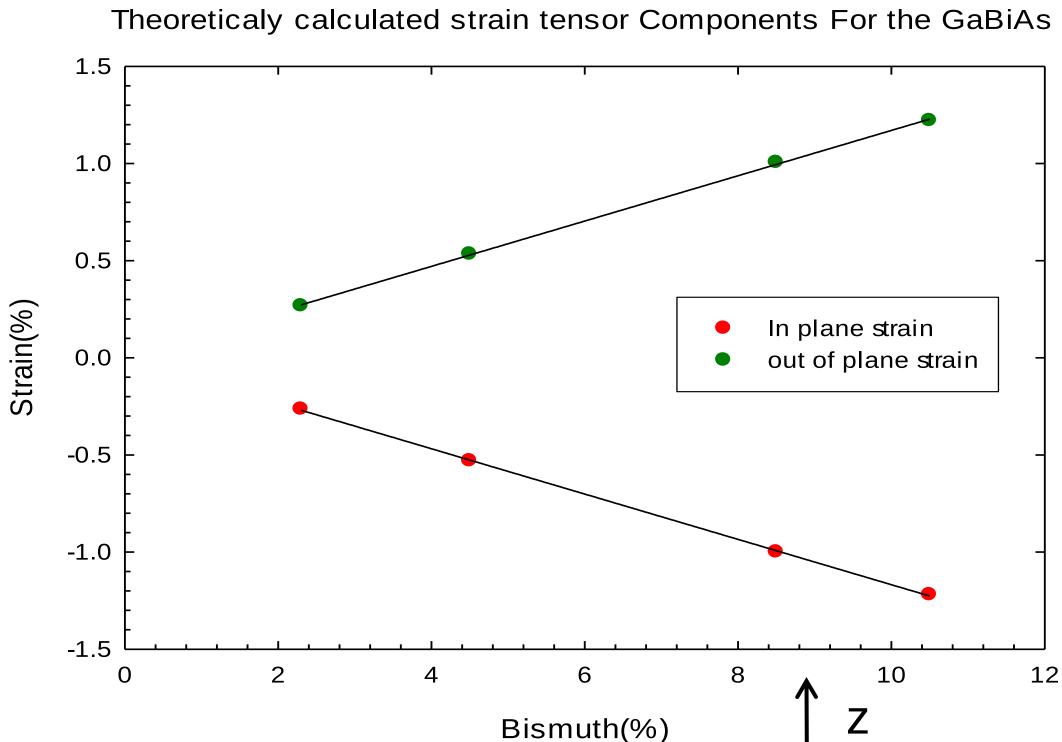
Where lattice constant of GaBiAs has been calculated by Vegard'Law

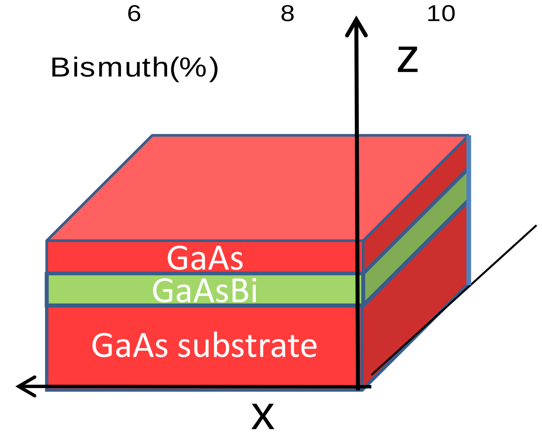
$$a_{GaBiAs} = (1-x)a_{GaAs} + x a_{GaBi}$$

$a_{GaBi} = 6.324\,A^0$ [5]

$$\varepsilon_{zz} = -\left(2c_{12} / c_{11}\right)\varepsilon_{xx}$$

$a_{GaAs} = 5.65325A^0$, $C_{11} = 12.21$ *and* $C_{12} = 5.66$ *of GaAs* [6]





[5] A. Janotti, Su-Huai Wei, and S. B. Zhang, Phys. Rev. B 65,115203(2003)

[6] I.Vurgaftman and J.R.Meyer,L.R.Ram-Mohan,J.Appl.Phys,89,p5825(2001)

Strain Effects on Bandgap

- When $a_{epi} > a_{sub}$, then material is under compressive strain as for GaBiAs.
- Energy levels for the HH,LH and Spin orbit splitting states under strain are [7]

$$E_g^{hh} = \left(E_{go} + \delta E_H\right) + \delta E_S$$

$$E_g^{lh} = (E_{go} + \delta E_H) + \frac{1}{2}(\Delta_o - \delta E_s) - \frac{1}{2}\sqrt{\left(\Delta_o^2 + 2\Delta_o \delta E_s + 9\delta E_s^2\right)}$$

$$E_g^{so} = \left(E_{go} + \delta E_H\right) + \frac{1}{2}(\Delta_o - \delta E_s) + \frac{1}{2}\sqrt{\left(\Delta_o^2 + 2\Delta_o \delta E_s + 9\delta E_s^2\right)}$$

where

$$\delta E_s = b(\varepsilon_{zz} - \varepsilon_{xx})$$

$$\delta E_H = \left(a_c + a_v\right)(2\varepsilon_{xx} + \varepsilon_{zz}) = a(2\varepsilon_{xx} + \varepsilon_{zz})$$

b = shear deformation potential

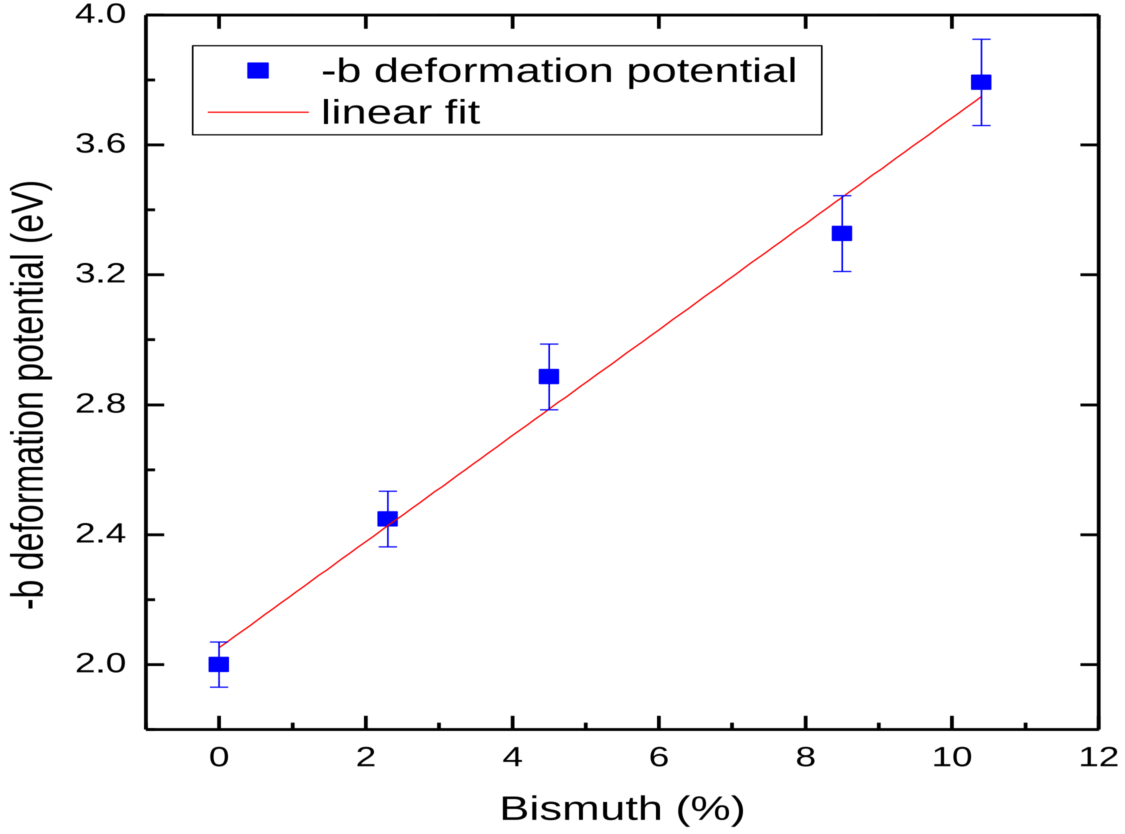
a_c = conduction band hydrostatic deformation potential
a_v = valence band hydrostatic deformation potential
a = $a_c + a_v$

By solving these equations and using our experimental results E_g^{hh}, E_g^{lh} *and* E_g^{so} we calculated the shear deformation potential 'b' for the GaBiAs as well as its unstrained bandgap E_{g0} and spin orbit splitting Δ_o.

[7] Pollak, F. H.''Effects of Homogeneous strain on the electronic and vibrational levels in semiconductors and semimetals'' Vol.32,ed.P.T.Pearsall(Academic, New York,1990)p.17

Shear Deformation Potential of GaBiAs

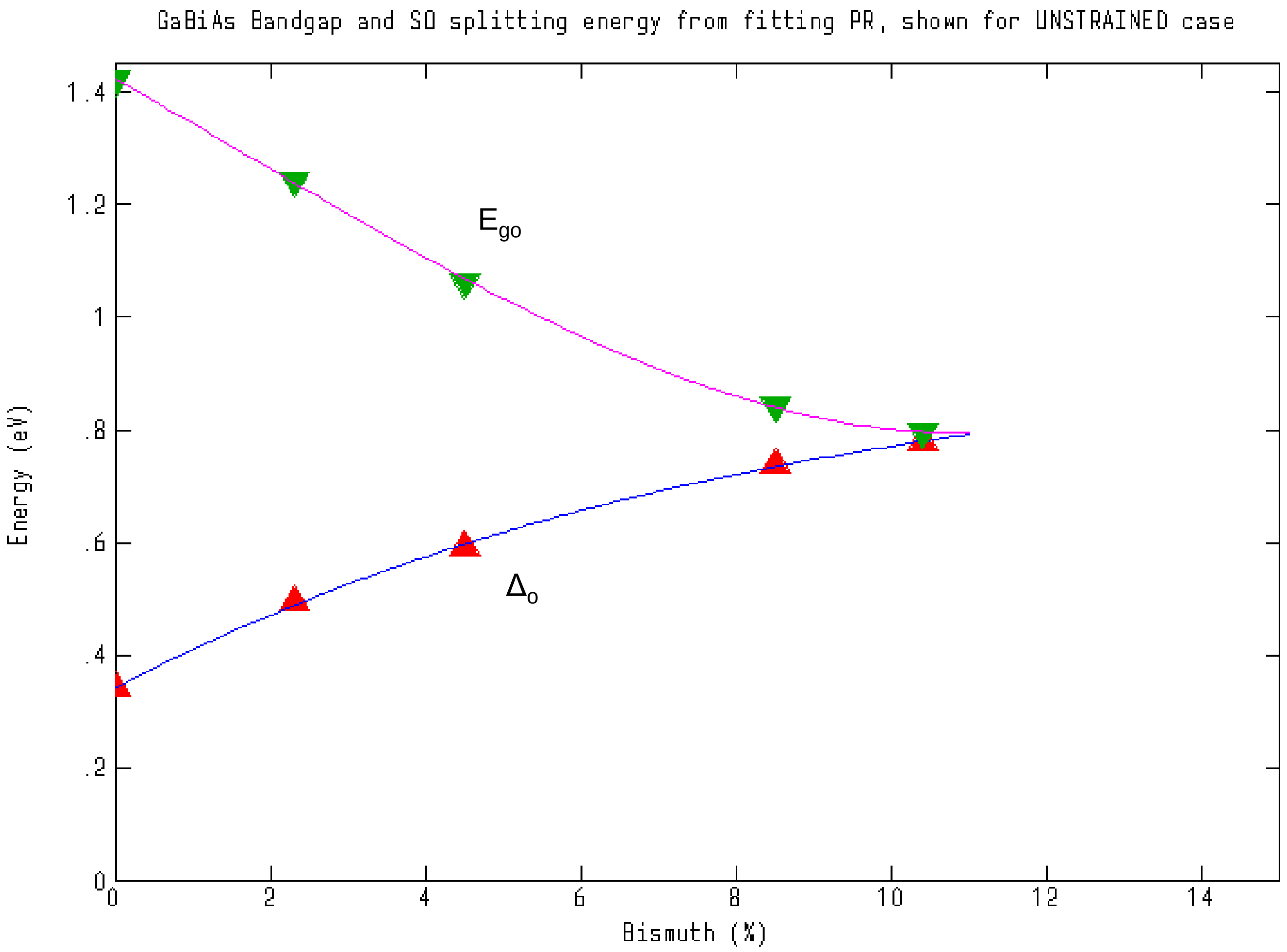
The deformation potential '–b' is calculated from the measurements of HH/LH splitting, spin orbit splitting energies and values of compressive strain in material



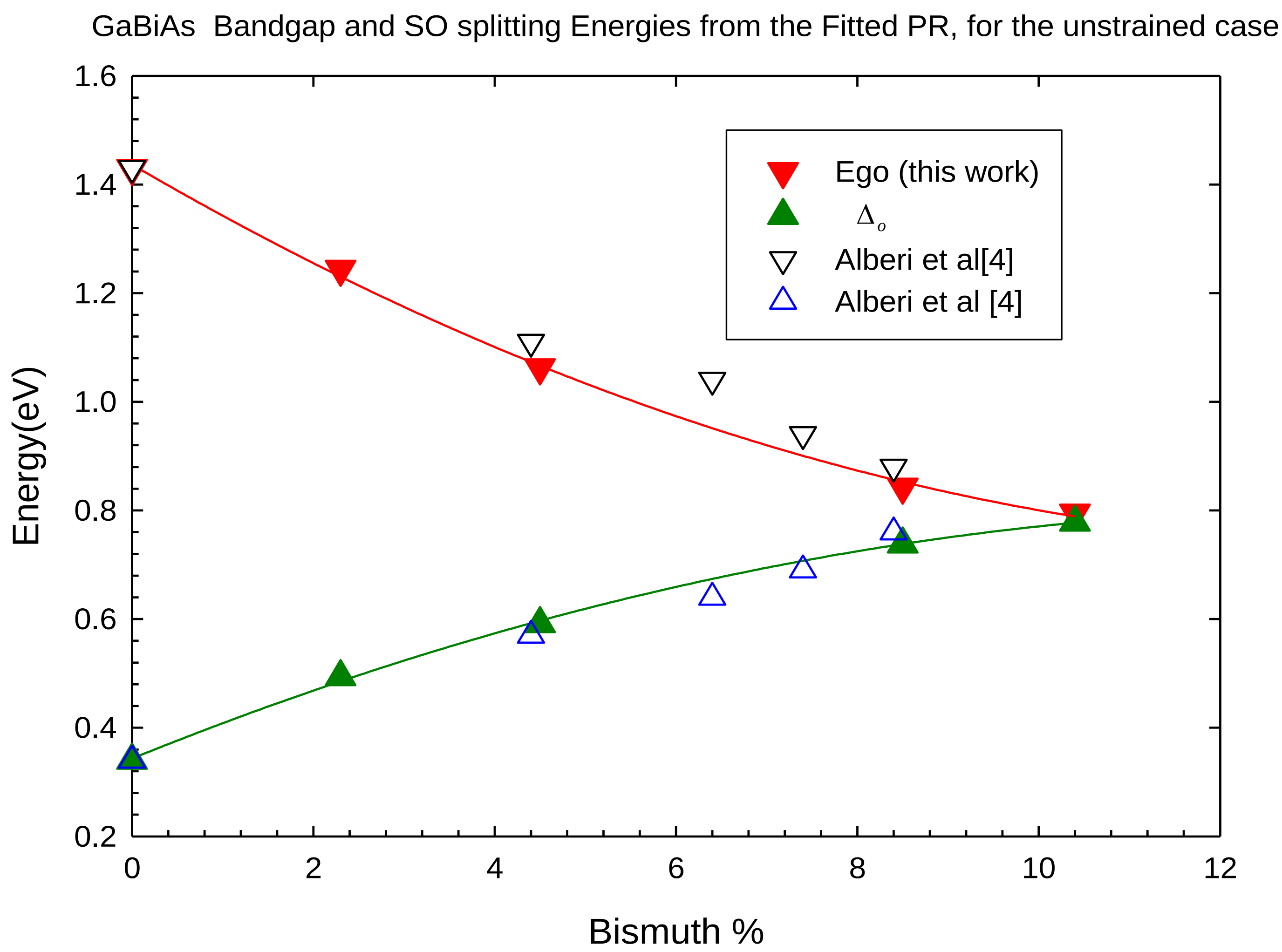
The rate of increase of magnitude of deformation potential is 163meV/Bi%

Resonance of unstrained Bandgap and Spin Orbit Splitting

By Using our experimental results of E_g^{hh}, E_g^{lh} and E_g^{so} ,calculated strain and deformation potential 'b' of GaBiAs ,we have calculated the unstrained bandgap E_{g0} and spin orbit splitting Δ_o.



Resonance of unstrained Bandgap and Spin Orbit Splitting



Conclusion

1. GaBiAs layers on GaAs experience compressive strain which creates a valence band splitting increasing at a rate on the order of 14.7meV/Bi%.
2. Magnitude of the shear deformation potential b for GaBiAs increases with a rate of ~163meV/Bi%
3. By using experimental E_g^{hh}, E_g^{lh} *and* E_g^{so} we have calculated the unstrained band gap and spin orbit splitting Δ_o, which become resonant with each other for bismuth fraction 10%<Bi< 12%.

Thanks