Optically-Detected Magnetic Resonance of Excitons Localized at As Doping Sheets in AlSb

E.R. Glaser, T.A. Kennedy, B.R. Bennett, B.V. Shanabrook, and L.A. Hemstreet

Naval Research Laboratory, Washington, D.C., 20375-5347

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BACKGROUND

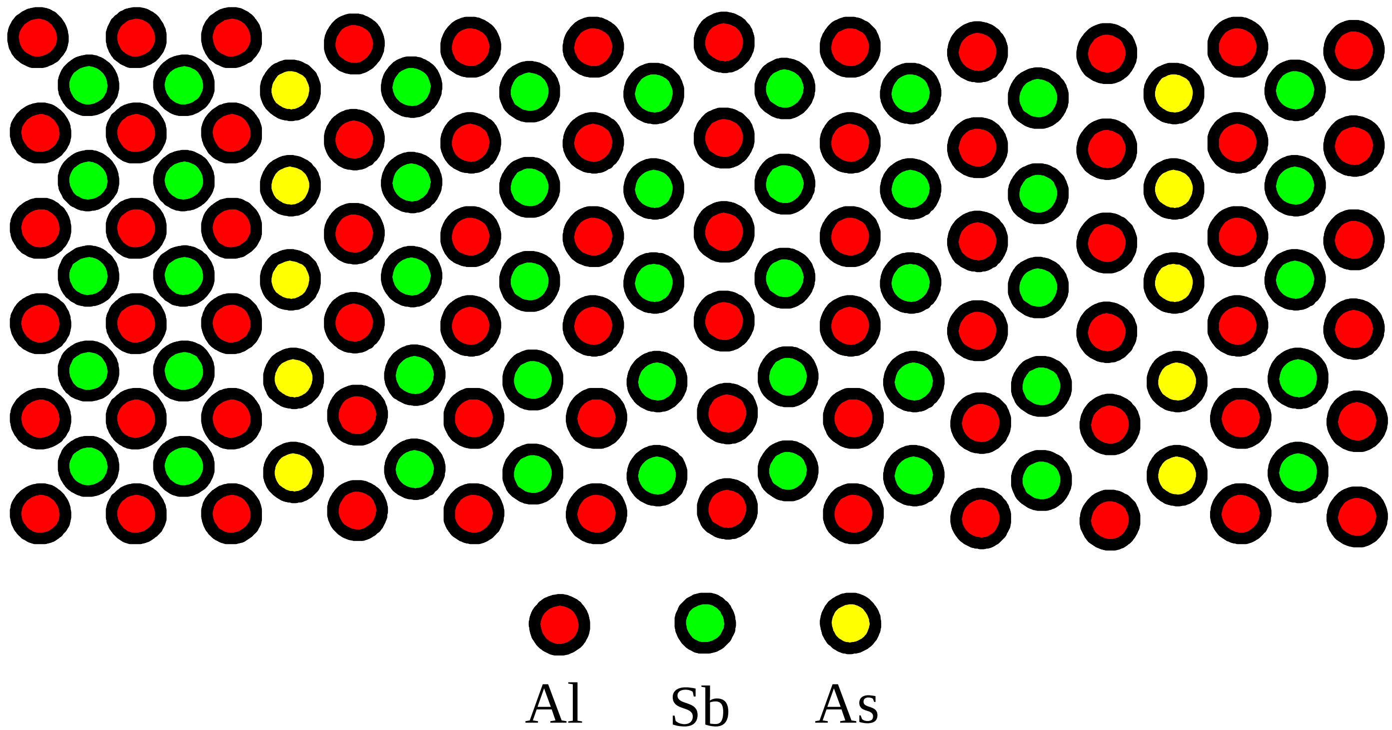
As monolayers inserted in AlSb barriers of InAs/AlSb high-speed FETs result in enhancement of 2D electron concentrations

PROBLEM

Origin of the carriers has not been established (As_{Al} antisites have been suggested as the source of the donors)

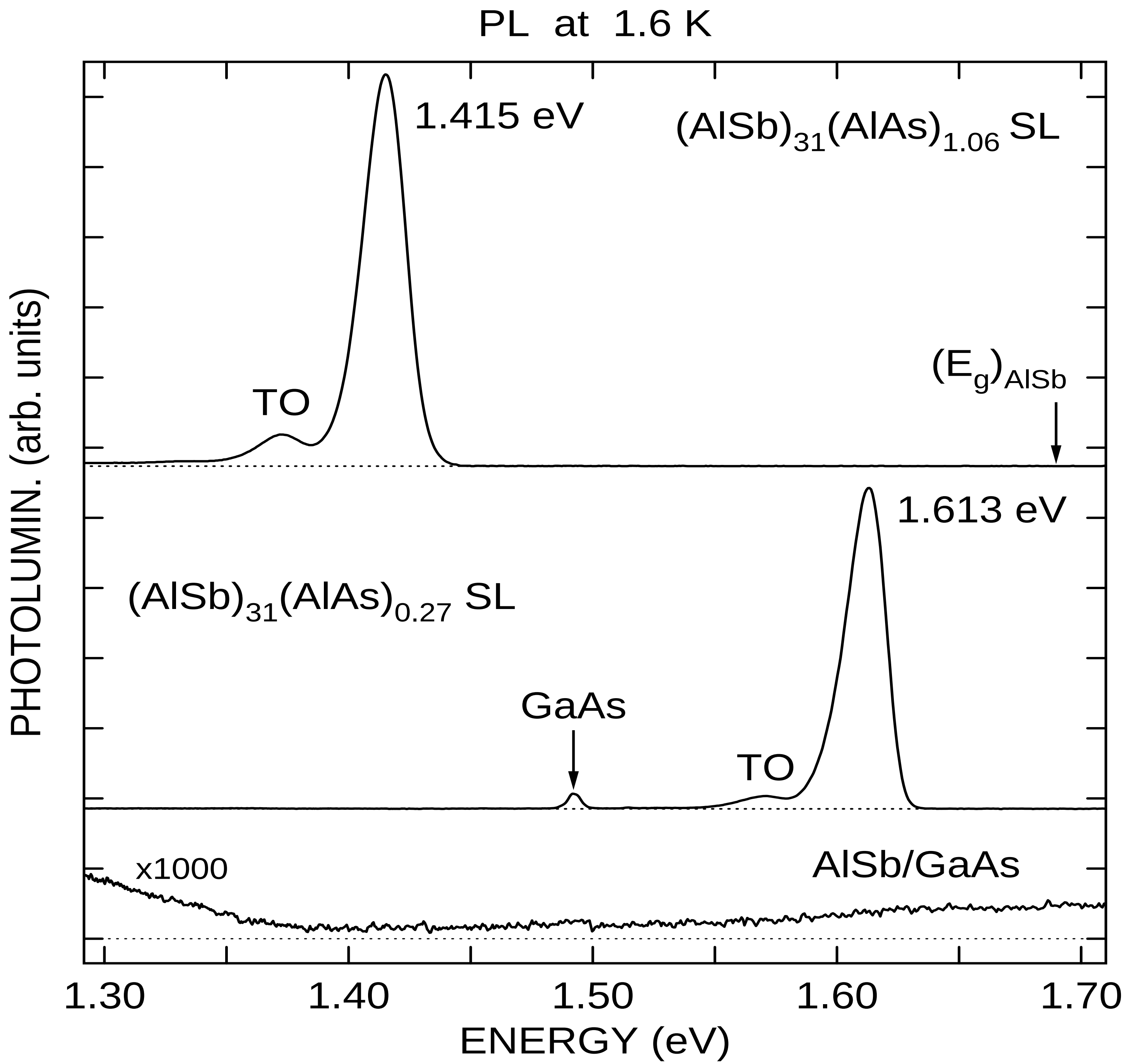
TEST STRUCTURES

Superlattices (SLs) composed of fractional or single monolayers (MLs) of AlAs separated by 8-49 MLs of AlSb grown on (001) GaAs by MBE



APPROACH

- Low-temperature Photoluminescence (PL)
- Optically-Detected Magnetic Resonance (ODMR) at 24 GHz
- Structural parameters of SLs determined from x-ray diffraction measurements (AlSb buffer layers are under an average in-plane biaxial compression of 0.08 ± 0.02 %)


PL at 1.6 K
1.415 eV
(AlSb)31(AlAs)1.06 SL
TO
(Eg)AlSb
1.613 eV
(AlSb)31(AlAs)0.27 SL
GaAs
TO
x1000
AlSb/GaAs
PHOTOLUMIN. (arb. units)
1.30
1.40
1.50
1.60
1.70
ENERGY (eV)

- As Planes Induce Strong PL in AlSb
- Strong Dependence on the Amount of As in the ML
- Weak Dependence on SL Period
- Extremely weak PL from AlSb/GaAs reference sample

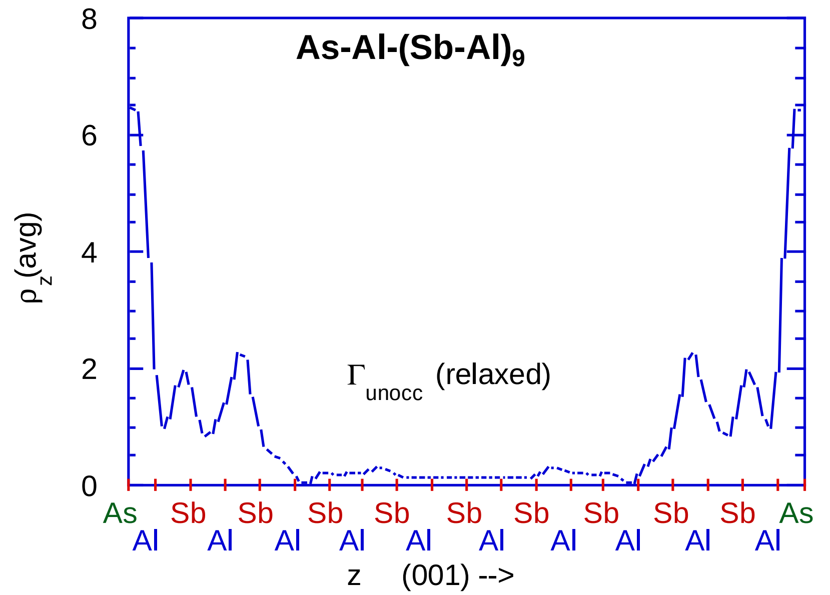
As Monolayer in AlSb

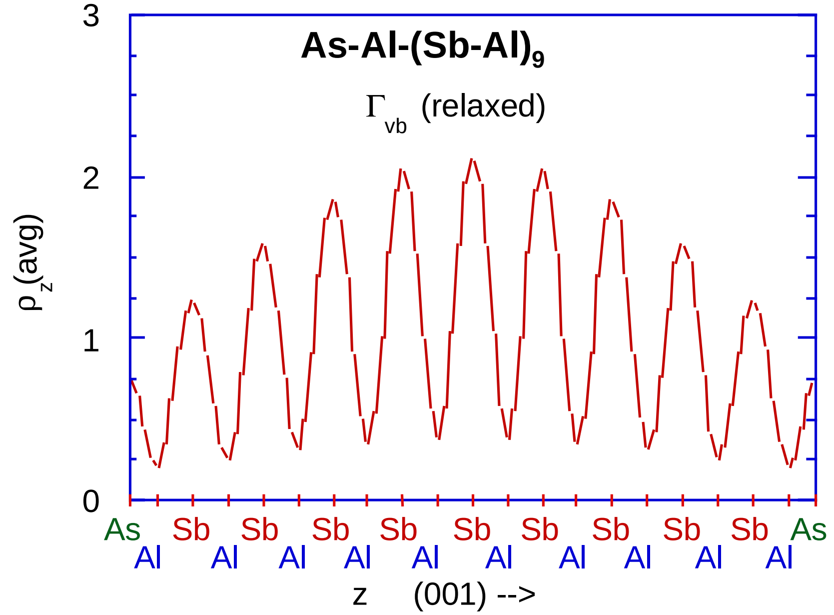
Theoretical Approach

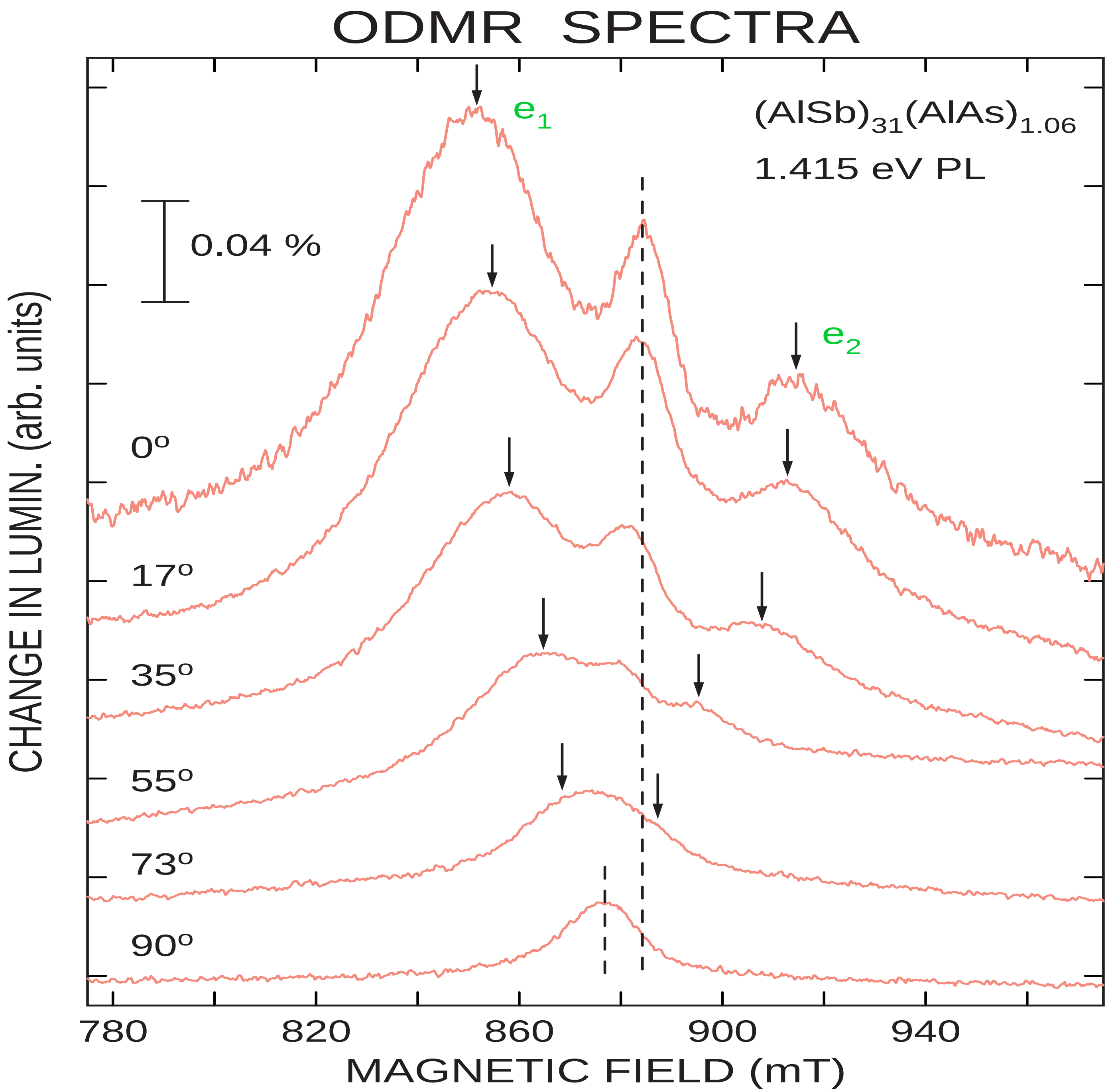
- Ab initio total energy calculations with norm-conserving pseudopotentials and plane wave basis
- 20 atom $AsAl–(SbAl)_9$ and $(SbAl)_{10}$ supercells
- Relaxation of Al–As interlayer separation

Key Results

- Lowest unoccupied level at Γ is lowered in energy into the bulk AlSb bandgap due to the As monolayer
- The energy lowering depends sensitively on the strain in the AlAs layer
- The energy lowering of the lowest unoccupied level at Γ is calculated to be 0.24 eV for an elastically strained Al–As layer
- The wavefunction associated with the unoccupied level in the gap is localized around the As doping sheet
- The highest occupied Γ_{vb} state is pushed away from the AlAs layers and has an enhanced probability in the AlSb layers
- Good agreement with the experimental PL data







ODMR SPECTRA
(AlSb)31(AlAs)1.06
1.415 eV PL
0.04 %
e1
e2
0o
17o
35o
55o
73o
90o
CHANGE IN LUMIN. (arb. units)
780
820
860
900
940
MAGNETIC FIELD (mT)

ANALYSIS of ODMR

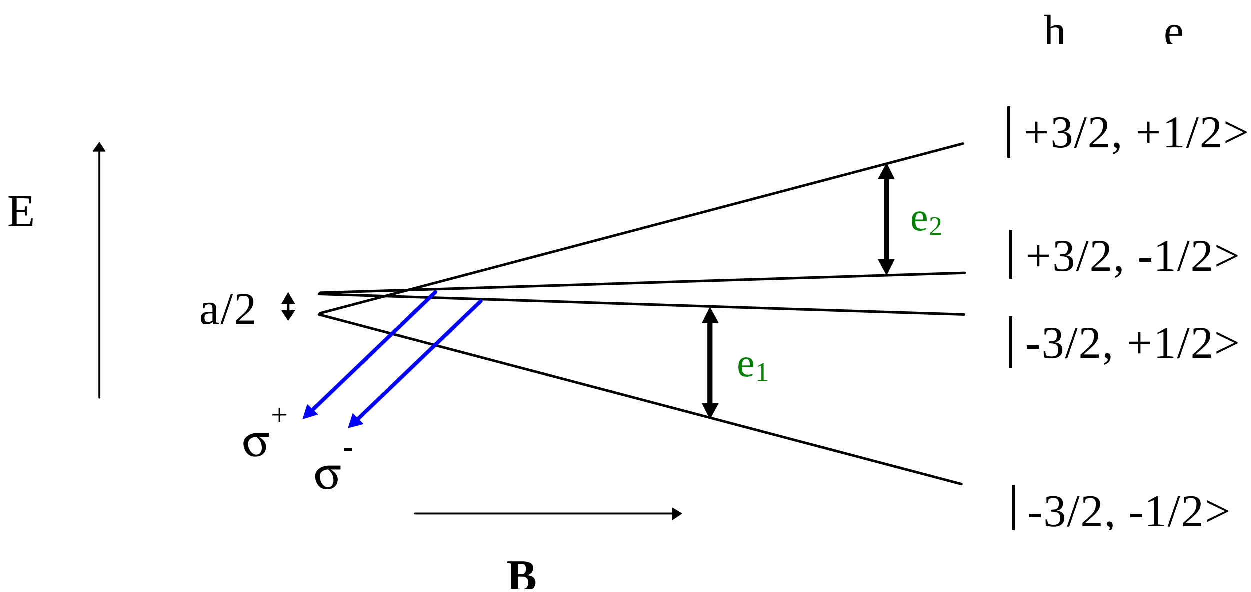
(similar to ODMR found on excitonic recomb. from type-II short-period GaAs/AlAs MQWs; see H.W. van Kesteren *et al.*, Phys. Rev. B **41**, 5283 (1990))

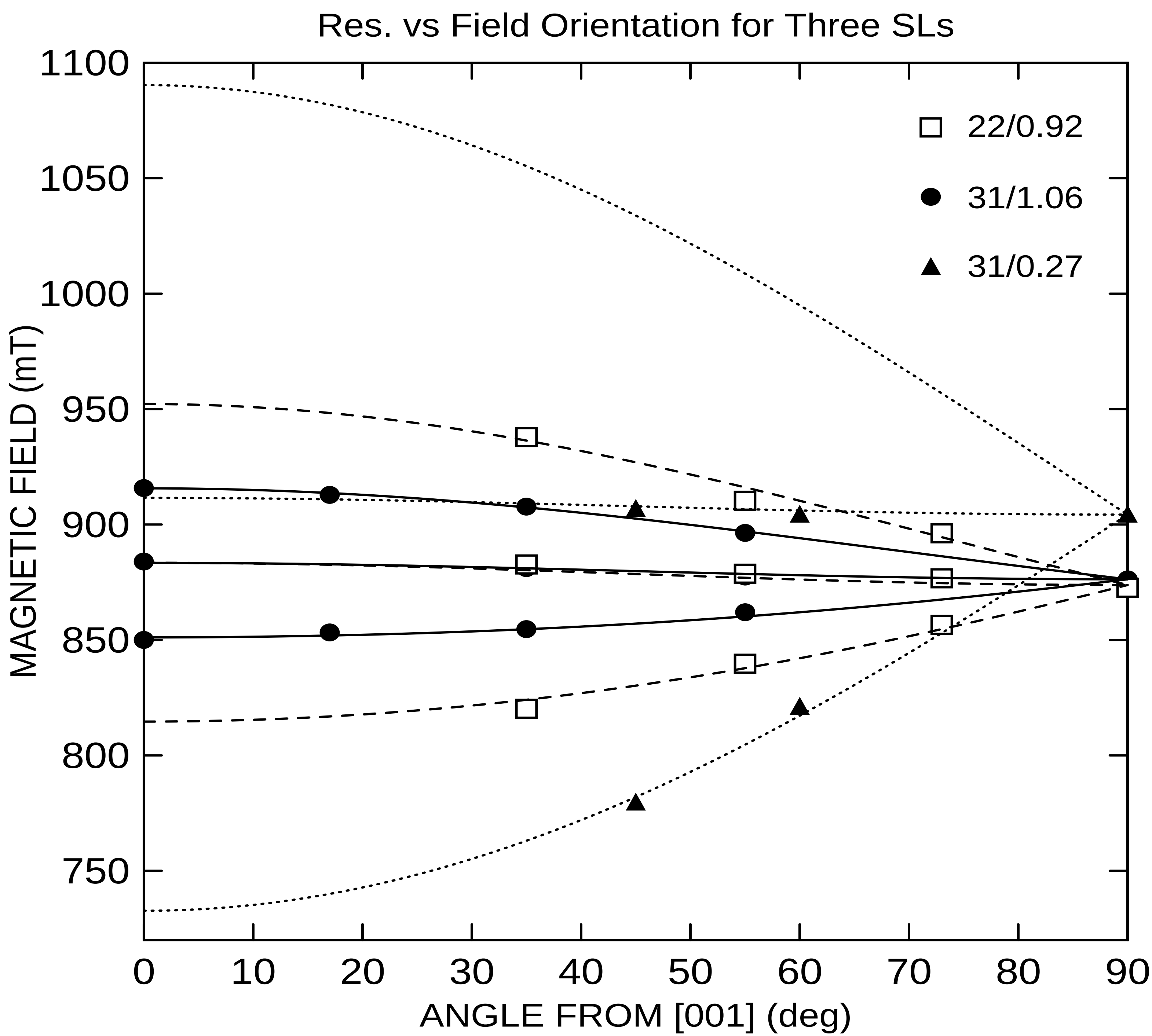
$$H = \mu_B g_e \, \mathbf{S} \bullet \mathbf{B} + \mu_B g_h \, \mathbf{J} \bullet \mathbf{B} + \mathbf{a} \, \mathbf{J} \bullet \mathbf{S}$$

Zeeman term for electron with spin 1/2

Zeeman term for hole with spin 3/2

electron-hole exchange with strength **a**





Res. vs Field Orientation for Three SLs
MAGNETIC FIELD (mT)
ANGLE FROM [001] (deg)
1100
1050
1000
950
900
850
800
750
0
10
20
30
40
50
60
70
80
90
22/0.92
31/1.06
31/0.27

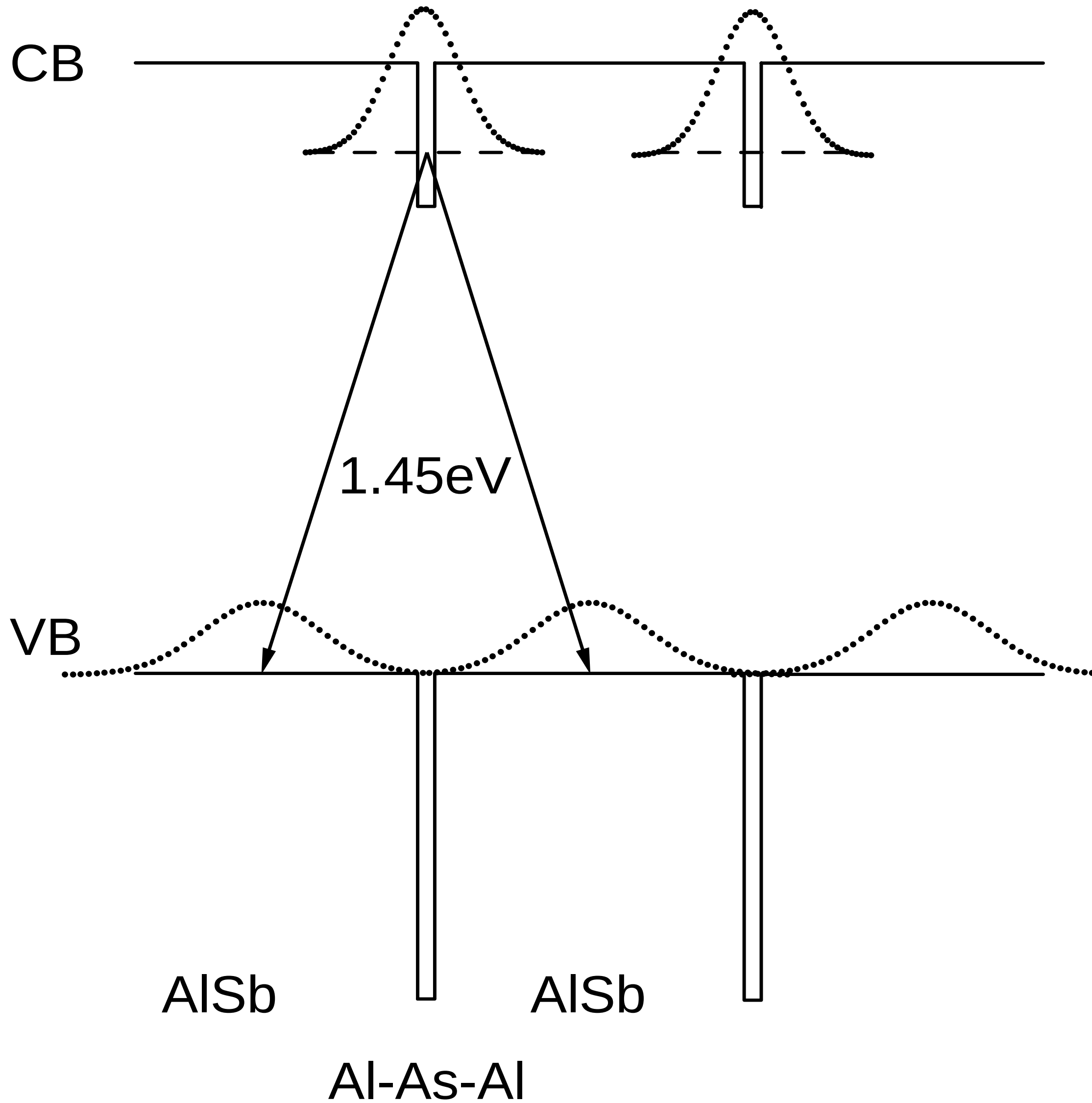
- Splitting between outer lines (e_1,e_2) exhibits cos(θ) dependence ⇒ electron coupled to a hole from the $J_z = \pm 3/2$ VB with $g_\perp \sim 0$

- These lines from SLs with ~1 ML of AlAs are electron spin transitions with $g_\equiv$ = 1.916 - 1.923 and $g_\perp$ = 1.934 - 1.944 split by an exchange interaction ($\Delta \equiv a/2$) of 3.4 - 8.0 μeV with the hole (Δ = 19.5 μeV for $(AlSb)_{31}(AlAs)_{0.27}$ SL !). Unsplit line described by the same g-tensor.

- g-values are between those for X-point EM donors/conduction electrons in AlAs and AlSb ⇒ Significant fraction of electron wavefunction lies at the AlAs ML, with some penetration into the AlSb layers

- $J_z = \pm 3/2$ holes are excluded to AlSb layers ⇒ follows from weak exchange coupling, state of strain, and charge separation generally required for observation of strong ODMR

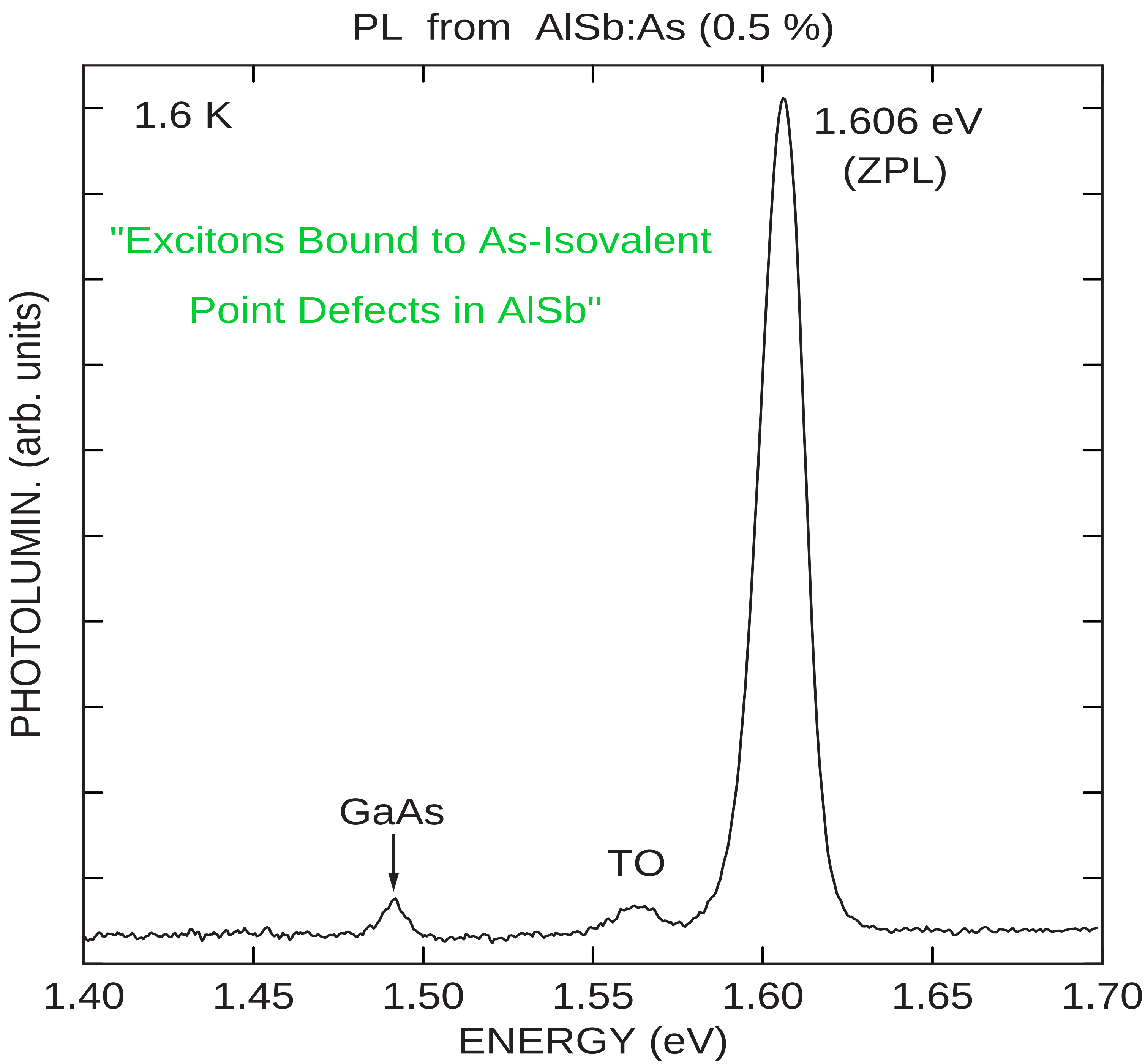
RECOMBINATION MODEL



(Band Offsets from W.A. Harrison and J. Tersoff, J. Vac. Sci. Technol. B**4**, 1

- Electron is strongly bound at the plane ⇒ this binding determines the PL energy
- Electron and Hole are bound to form the exciton ⇒ this binding is reflected in the exchange
- Exciton is localized at a fluctuation (“interface roughness”) in the ML ⇒ this localization provides the width of the PL line (~ 20 meV)

“Exciton Bound at an Isoelectronic Plane”
(see H.P. Hjalmarson, J. Vac. Sci. Technol. **21**, 524 (1982))


PL from AlSb:As (0.5 %)
1.6 K
1.606 eV
(ZPL)
"Excitons Bound to As-Isovalent
Point Defects in AlSb"
GaAs
TO
PHOTOLUMIN. (arb. units)
1.40
1.45
1.50
1.55
1.60
1.65
1.70
ENERGY (eV)

SUMMARY

- Strong PL bands found from $[(AlSb)_M(AlAs)_N]_{120}$ SLs
- ODMR reveals S=1/2 electron spin transitions split by an exchange interaction (Δ) of 3.4-19.5 μeV with $J_z = \pm 3/2$ VB holes
- Electron localized at AlAs ML and Hole excluded to AlSb
- Unknown donor-like defects do not compete favorably with As planes for photo-excited carriers
- As is an efficient electron trap in AlSb with $E_{loc.}$ ~ 55 meV in point defect limit (consis. with electronegativity values)