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Semi-Insulating, p-type, and n-type Doping in AlSb, GaSb, and AlSb/InAs by a Single Native Defect

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Theoretical and experimental studies on the conduction types and properties of the not-intentionally doped AlSb, GaSb, and InAs/AlGaSb material systems are presented. A single native defect model explains the mysterious semi-insulating, p-type, and n-type doping characters in these semiconductors even when they are not intentionally doped. The negative persistent photo-conductivity effect is also consistent with the present theory. It is predicted that semi-insulating $Al_{0.5}Ga_{0.5}Sb$ will become p-type under a hydrostatic pressure (p>100kbar).

High mobilities and unusual type-II band alignments make the lattice-matched GaSb/AlSb/InAs material system a good candidate for high speed electronics and quantum multifunctional devices beyond Si and GaAs. This relatively new system also brings about many unknown features and interesting physics not previously encountered. In this paper we shall present theoretical and experimental studies on the following apparent conduction anomalies in these materials when they are not-intentionally doped:[1,2] (1) bulk GaSb is p-type, (2) bulk AlSb is semi-insulating, (3) AlSb/InAs superlattices with thick InAs quantum wells are n-type, (4) AlSb/InAs superlattices with thin InAs quantum wells are semi-insulating. We propose that a single native defect, the anion site antisite defect ($Cation_{Sb}$) in GaSb or AlSb, is responsible for the above changing doping properties in the materials. We call this defect an X^A center.

The key physics is that this X^A center produces a deep level in the vicinity of the valence-band maximum (VBM) of the $Ga_{1-x}Al_xSb$ (Fig. 1). The deep level is p-like and has two holes and four electrons when it is

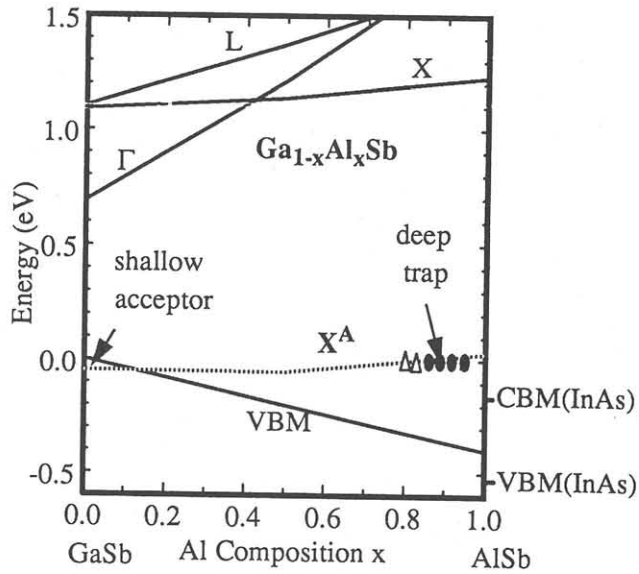

Fig. 1. Predicted Al composition dependences of the X^A level (dotted) and band edges of $Ga_{1-x}Al_xSb$ (solid). The X^A level is in the valence band when x<0.1 and the center is a shallow acceptor. When x>0.1, the X^A level is in the band gap and becomes a deep trap occupied by two holes (tragles) and four electrons (solid circles) when neutral.

1. G. Tuttle, H. Kroemer, and J. H. English, J. Appl. Phys. 65, (1989), 5239.
2. S. Ideshita, A. Furukawa, Y. Mochizuki, and M. Mizuta, Appl. Phys. Lett. 60, (1992), 2549.

neutral. In bulk GaSb, the X^A level lies in the valence band, so that the two holes will bubble up to the valence-band edge, doping GaSb p-type. When the Al composition x increases, the VBM moves down and gradually uncovers the X^A level which in turn becomes a deep trap for either holes or electrons, thus making AlSb semi-insulating. When a thick InAs quantum well is formed inside AlSb, the X^A level lies higher in energy than the InAs quantum well ground state. Electrons in the X^A level spill into the InAs layers, making InAs n-type. This is a case of remote "false valence" because an impurity that is expected to be an acceptor is, in fact, a remote donor, having an effective valence which is different from the expected one by up to six (the number of electrons that can be accommodated in a p-like deep level). As the InAs layer thickness becomes narrower, the conduction-band minimum of the AlSb/InAs superlattice (i.e., the ground state of the InAs quantum well) passes through the X^A level and the center becomes a deep trap again, making thin InAs quantum wells semi-insulating (Fig. 2).

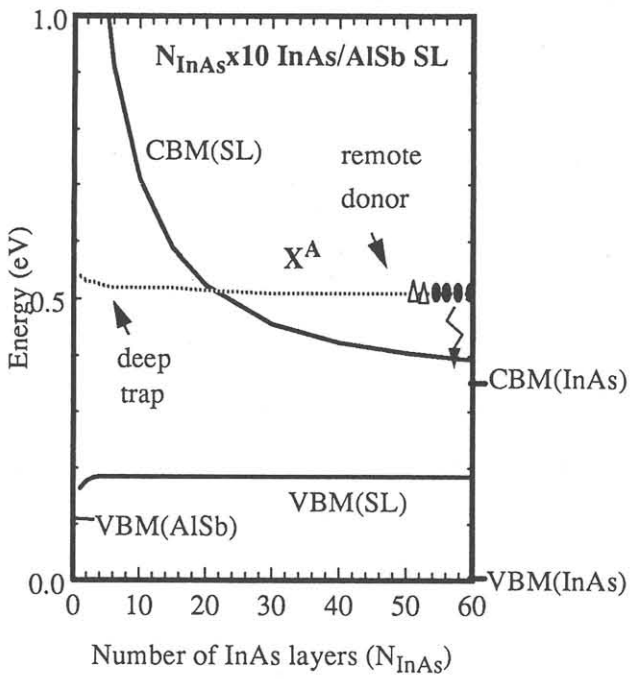

Fig. 2. Predicted InAs layer thickness dependences of the X^A level (dotted) and band edges (solid) of an N_{InAs}×10 InAs/AlSb superlattice. The X^A center is at the middle of the AlSb layers. When N_{InAs}>21, X^A has a level above the conduction-band minimum of the superlattice (CBM(SL)). Its four electrons become unstable and spill into the InAs quantum well, doping it n-type. For N_{InAs}<21, the X^A center is a deep trap.

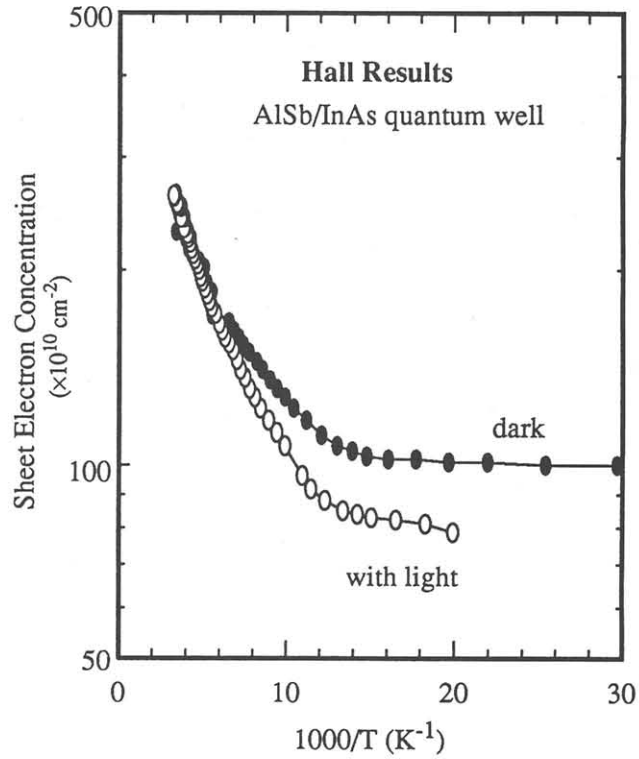

Fig. 3. Temperature dependences of electron concentrations in an AlSb/InAs quantum well in dark and with a red light. At low temperature, the electron concentration decreases with illumination. The decrease in electron concentration is persistent even when the light is turned off. This is called the negative persistent photoconductivity (NPPC) effect as opposed to the normal PPC effect associated with DX centers in GaAlAs.

A negative persistent photo-conductivity (NPPC) has been observed in the $Ga_{1-x}Al_xSb$/InAs quantum well system (Fig. 3). The free electron concentration decreases when the sample is being illuminated at low temperature, and remains low even after illumination. This is opposite to the familiar PPC effect associated with the DX centers in $Ga_{1-x}Al_xAs$/GaAs[3], and is consistent with the fact that the X^A level lies at higher energy than the quantum well electronic ground state of the $Ga_{1-x}Al_xSb$/InAs system, while the DX center lies below the $Ga_{1-x}Al_xAs$/GaAs quantum well ground state. Hence, at low temperatures in the dark, most

3. See, for example, E. F. Schubert and K. Ploog, Phys. Rev. B 30, (1984), 7021.

electrons reside in the quantum well of the $Ga_{1-x}Al_xSb$/InAs system while in the case of $Ga_{1-x}Al_xAs$/GaAs, most electrons are trapped at the DX centers. Illumination transfers electrons from the $Ga_{1-x}Al_xSb$/InAs quantum well to X^A centers, and from the DX centers to the $Ga_{1-x}Al_xAs$/GaAs quantum well

We have also calculated the pressure dependences of the semi-insulating to p-type transition in bulk $Al_xGa_{1-x}Sb$[4] (Fig. 4). The X^A level is predicted to descend into the valence band of $Al_xGa_{1-x}Sb$ at about 90 kbar and 150 kbar for x=0.5 and x=1, respectively. This striking change of conductivity as a function of pressure can be used to test our proposed explanation of the peculiar doping characters in the GaSb, AlSb, and InAs/AlGaSb material system.

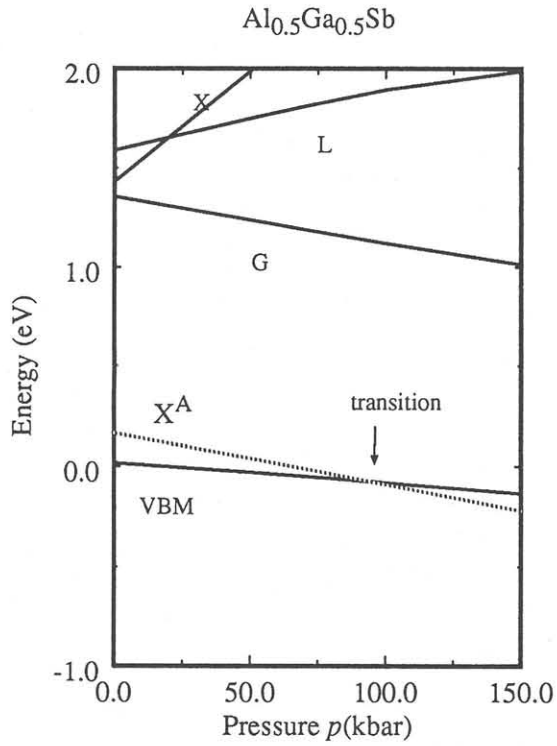

Fig. 4. Predicted pressure dependences of the X^A center level with respect to the band edges of bulk $Al_{0.5}Ga_{0.5}Sb$. The X^A level descends into the valence band for p>100 kbar and becomes electronically inert. When that happens, not-intentionally doped $Al_{0.5}Ga_{0.5}Sb$ will show p-type characteristics.

Detailed theoretical and experimental results on the quantum well thickness effects and alloy composition effects on doping properties of the $Ga_{1-x}Al_xSb$/InAs system will be presented in the symposium. We shall also discuss the related impact on high speed devices and quantum devices based on this material system.

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4. R. -D. Hong, D. W. Jenkins, S. Y. Ren, and J. D. Dow, Phys. Rev. B 38, (1988), 12549.