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Effects of incident-light-intensity-dependent band gap narrowing on barrier heights of p-doped $Al_xGa_{1-x}As$/GaAs heterojunction devices

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HIGHLIGHTS

- Light-intensity causes zero VB offsets in low-barrier IR detectors at $T > 50$ K.
- PL shows band gap increase in undoped GaAs with illumination at $T = 25$ K.
- Undoped GaAs and p-AlGaAs are reluctant to BGN caused by incident light intensity.
- Undoped GaAs/p-doped $Al_{0.01}Ga_{0.99}As$ combination suitable for FIR/THz detectors.

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ABSTRACT

Band gaps of semiconductor materials are reduced due to band gap narrowing (BGN). Photoluminescence measurements on GaAs and AlGaAs thin films revealed a dependency of incident light intensity, and temperature in BGN in addition to the doping density. As a result, the valence band offset of p-doped GaAs/AlGaAs heterojunctions were reduced under illumination and high temperatures. We present evidence of incident-light-intensity causing barrier reduction at temperature >50 K causing zero valence band offsets in low-barrier heterostructures such as p-GaAs/$Al_{0.01}Ga_{0.99}As$, in addition to the dark-current increase by thermal excitations, causing the device failure at high temperatures.

1. Introduction

The motivation of this work is to understand the effects of incident photon intensity on p-doped heterojunction devices made with semiconductor materials. Carrier excitations cause changes in the occupied energy band levels in conduction or valence bands of a semiconductor material. For example, in highly n-doped semiconductors, electrons in the lower levels of the conduction band (CB) prevent carriers from further occupying those energy states; as a result, carriers have to occupy higher energy states. This phenomenon resemble an increase in the material's band gap known as the Burstein-Moss (BM) shift [1,2] when the band gap is extracted by optical methods such as absorption and photoluminescence (PL) spectra. Furthermore, band gap excitations in p-doped semiconductors cause electrons from valence band (VB) to inject on to empty states in CB. As a result, a phenomenon similar to B-M effect can be observed because the energies at the highest occupied energy level of the CB and the lowest unoccupied energy level of the VB are at further apart from where they were under dark conditions. Optoelectronic devices, based on band gap excitations or CB offset are affected by the BM effect.

Another phenomenon affecting the band offset of heterojunctions is the band gap narrowing (BGN). BGN is resulted by the ionized dopants in the doped materials, in addition to many-body interactions caused by carrier occupancy in the CB and the holes generated in the VB. Just as the occupancy of carriers in CB and VB are changing under different incident photon intensities BGN also changes based on the incident photon intensity. This implies that the occupied and unoccupied levels in CB and VB respectively will be shifted farther apart or closer to each other, depending on the magnitudes of difference between B-M and BGN under incident photon intensities. As a result, the band gap will either increase or decrease; therefore, BGN alters the response spectra of optoelectronic devices based on band gap excitations or VB offset.

Studies have revealed red shift in the response spectra due to BGN on p-doped GaAs/AlGaAs quantum well structures [3] and other types of optoelectronic devices [4]. Therefore, consideration of the BM effect and BGN effect is critical when designing detector structures for far infrared (FIR) and terahertz (THz) detection, as the detection mechanism in these devices is based on intra-band transitions of carries across small band offsets (barriers) or energy

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gaps. Additionally the BM and BGN effects can cause a significantly larger shift in the detectors' response range from its intended response range. In the case of large shift in a FIR/THz detector, the device may not function because the barrier becomes extremely small and the thermal excitations have increased.

In Section 2 we present the experimental methods, and in Section 3 we are presenting a comparison of band gap calculated by PL measured under different temperatures and with two different excitation light intensities for GaAs and AlGaAs films. Discussions in the next two sections are based on the BGN and BM effects observed and presented in Section 3. Section 4 provides a comparison of VB offsets, calculated for hypothetical GaAs/AlGaAs heterojunctions with different aluminum fractions, using band gaps obtained by PL for GaAs and AlGaAs thin films. This comparison of band offsets provide a good understanding of the way that the band offset of GaAs/AlGaAs heterojunctions will react to incident photon intensities. And finally, we compare our observations on band offset of low barrier devices with the reported results on a low barrier GaAs/AlGaAs heterojunction superlattice structures in literature by Matsik et.al. [5], and Rinzan et al. [6] in Section 5.

2. Material parameters and band gap calculation procedure

Three GaAs and two AlGaAs thin films were used in our study and were grown using molecular beam epitaxy on a semi-insulating GaAs substrate. The sample parameters are shown in Table 1. The sample GA116 is an undoped GaAs thin film, while the GA517 and GA818 are GaAs thin films, p-doped with beryllium to 5×10^{17} cm^{-3} and 8×10^{18} cm^{-3} respectively. The two AlGaAs thin films, labeled as AGA1 and AGA20, consist of aluminum fractions 1% and 20% respectively, and were p-doped to 3×10^{18} cm^{-3} with beryllium.

The band gaps of the GaAs and AlGaAs thin film samples were calculated using PL spectra measured under different sample temperatures from 25 K to 300 K by mounting samples on the cold finger of a closed cycle refrigerator. An argon-ion laser (488 nm) was used as the excitation light source. PL were measured under two different excitation light intensities, $\sim$60 mW cm^{-2} and $\sim$250 mW cm^{-2}, to observe the impact of incident light intensity on the materials' band gap. The laser light intensities were calibrated using a silicon photo detector. Band gap of the material is calculated by selecting 5% of the PL peak maxima as described by Ref. [7]. The low energy edge of the PL spectrum gives the lowest energy difference between occupied level in CB and highest unoccupied level in VB, while the higher energy edge gives the energy difference between the highest occupied level in CB and lowest unoccupied level in VB [7].

The theoretical band gaps of the thin film samples under different temperatures were calculated using Eq. (1) [8].

$$\overline{E}_g = E_C - E_V - E_{BGN} = E_g(0) + \frac{\alpha T^2}{(\beta + T)} - E_{BGN} \tag{1}$$

where $\overline{E}_g$ is the total energy gap and E_C, E_V, E_{BGN}, are the CB, VB, and band narrowing energies respectively. $E_g(0)$ is the band gap energy at 0 K in electron volts (eV) for $Al_xGa_{1-x}As$. The two coefficients, $\alpha = -5.41 \times 10^{-4}$ eV K^{-1}, and $\beta = 204$ K for GaAs [9,10]. $E_g(0)$ is the direct band gap of $Al_xGa_{1-x}As$, and is calculated using Eq. (2) [9,11].

$$E_g(0) = 1.519 + 1.155x + 0.37x^2 \tag{2}$$

The temperature dependent Fermi energy level is calculated by Eq. (3) [10],

$$E_V - E_F = kT\left(\ln\left(\frac{p}{N_V}\right) + 2^{-3/2}\left(\frac{p}{N_V}\right)\right) \tag{3}$$

where E_V, E_F, k, p, and N_V are the valence band energy, Fermi energy, Boltzmann constant, doping density (cm^{-3}) and the density of states (cm^{-3}) in the valence band respectively. The temperature dependency of N_V for $Al_xGa_{1-x}As$ (for $x < 0.4$) was calculated by Eq. (4b) [11], by substituting, k, π, m_h^* (density of state effective mass), and h (plank constant) in Eq. (4a) [10].

$$N_V = 2\left(\frac{2\pi m_h^* kT}{h^2}\right)^{3/2} \tag{4a}$$

$$N_V = 4.82 \times 10^{15} T^{\frac{3}{2}} (0.51 + 0.25x)^{\frac{3}{2}} (\text{cm}^{-3}) \tag{4b}$$

Band gap narrowing of a material depends on four different interactions [12,13] caused by doping density of the material, (i) the exchange interactions, (ii) carrier-impurity interactions affect the majority carrier band, (iii) carrier–carrier or electron–hole interactions, and (iv) carrier impurity interaction affects in the minority carrier band. The band gap narrowing of p-doped $Al_xGa_{1-x}As$ is calculated by Eq. (5) [12,14], which gives E_{BGN} of 20.7 meV for GaAs ($x = 0$) with the doping density (p) of 5×10^{17} cm^{-3} at room temperature.

$$E_{BGN} = 9.71(1 + 0.09x)\left(\frac{p}{10^{18}}\right)^{\frac{1}{3}} + 12.19(1 + 0.42x)\left(\frac{p}{10^{18}}\right)^{\frac{1}{4}} + 3.88(1 - 0.23x)\left(\frac{p}{10^{18}}\right)^{\frac{1}{2}} \tag{5}$$

The band gaps calculated from PL measurements are compared with the band gap calculations with Eq. (1) to differentiate the changes in band gap due to incident light intensity. Additionally, PL data were also used to analyze the band offsets at GaAs/AlGaAs interfaces and band offset variations due to incident photon intensities. Even though various ratios, from 10:90 up to 50:50 can be found in literature as the VB:CB energy offset ratio in GaAs/AlGaAs heterostructures [9] we use 40:60 ratio in our calculations because the VB offset calculated by any other ratio will give a lower value for VB offset compared to the value given by a 40:60 ratio.

3. Burstein-Moss (BM) and band gap narrowing (BGN) effects on GaAs subjected to incident light intensities and temperature

Majority of GaAs/AlGaAs heterojunction optoelectronic devices has GaAs as the emitter and AlGaAs as barriers. Hence, the BM and BGN effects due to incident-light-intensity in GaAs and AlGaAs will directly affect the device response and performance. The variations in BM and BGN under different temperatures are well understood for GaAs and AlGaAs films. But, the incident-light-intensity dependence of the two effects under different temperatures, are not available in literature. Therefore, in this section, we present our observations of BM and BGN under different temperatures and with different incident-light-intensities for GaAs and AlGaAs, which should be useful in optoelectronic device designing.

3.1. Temperature effects on BM and BGN

Out observations of band gaps calculated for GA517 using Eq. (1) and PL under different temperatures as shown in Fig. 1. The

Table 1
Summary of sample parameters.

Sample	Material	Aluminum fraction (%)	Doping density (cm^{-3})
GA116	GaAs	–	Undoped
GA517	GaAs	–	5×10^{17}
GA818	GaAs	–	8×10^{18}
AGA1	AlGaAs	1	3×10^{18}
AGA20	AlGaAs	20	3×10^{18}