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# Optical properties improvement of GaSb epilayers through defects compensation via doping

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ABSTRACT

The optical properties of GaSb strongly depend on the defect types and concentration. Doping is an effective method to improve the optical properties by changing the native defect types and concentration. In this paper, the native defects related emissions were suppressed through defects compensation via Be-doping. The un-doped and Be-doped GaSb were fabricated by molecular beam epitaxy. Temperature- and excitation power-dependent photoluminescence were applied to investigate optical properties of GaSb epilayer. The Ga vacancy related emission disappeared after Be doping. This phenomenon can be explained by the defect compensation between Be atoms and Ga vacancy, which greatly reduced the concentration of native defects. To certify this theory, Te-doped GaSb was prepared. For Te-doped GaSb, $Te_{Sb}$ recombined with native defects and formed new complex defects, which enhanced the defects related emission peak. The investigation of optical properties of doped GaSb epilayer was great significant for practical application of GaSb-based devices.

## 1. Introduction

As the typical III-V semiconductors material, Gallium antimonide (GaSb), which has high hole mobility (850–10800 $cm^2$/Vs), low carriers effective masses, and small direct band gap, is of current scientific and technological interest [1,2]. It is a particularly suitable candidate for long wavelength lasers [3,4]. GaAs is a desirable substrate to fabricate III-V optoelectronic devices due to its lattice parameter, excellent semi-insulating, good thermal properties. In addition, GaAs substrates affords the possibility of integration for optoelectronic devices [5–7]. For this reason, hetero-epitaxy of GaSb material on GaAs substrate has attracted more and more attention.

However, the photoluminescence (PL) spectra of un-doped GaSb usually was dominated by defects emission [8]. In order to suppress defects emission, the surface passivation method has been demonstrated [9,10]. However, the surface passivation only eliminate the surface defects and cannot change the internal defects states. Doping was an effective way to eliminate internal defects, such as vacancy [11,12]. Nevertheless, the existent status of dopants and the interaction of dopants with native defects play an important role in the optical properties of GaSb. Understanding and identifying defects types and emission characteristics are crucial in improving photoluminescence performance.

In this paper, undoped, Be-doped and Te-doped GaSb epilayers were prepared by molecular beam epitaxy (MBE). Temperature- and excitation power-dependent PL measurements were applied to analyze the optical properties systematically. The experiment results revealed that Ga vacancy had been compensated effectively in Be-doped GaSb. On the contrast, new complex defects were introduced in Te-doped GaSb. The mechanism of defects compensation was explained in terms of defects movement and recombination.

## 2. Experiment

The undoped, Be-doped and Te-dope GaSb epilayers were deposited on semi-insulating GaAs substrate. The thicknesses of all epilayer were 1μm. The growth temperature of GaSb was 600 °C. Before the growth process of GaSb epilayer, a 150 nm GaAs buffer layer was deposited on substrate at 620 °C to relax stress and filter dislocation. The crystal quality of samples was confirmed by X-ray diffraction (XRD) measurement. The carrier concentration and mobility were carried out by Hall Effect measurement. The temperature dependent PL was measured by laser spectroscopy at temperature range from 10 K to 300 K, A 655 nm laser was used as excitation source. InGaAs detector was used to detect the PL signal. The excitation dependent PL spectra were carried out with excitation power from 1 mW to 100 mW at 10 K.

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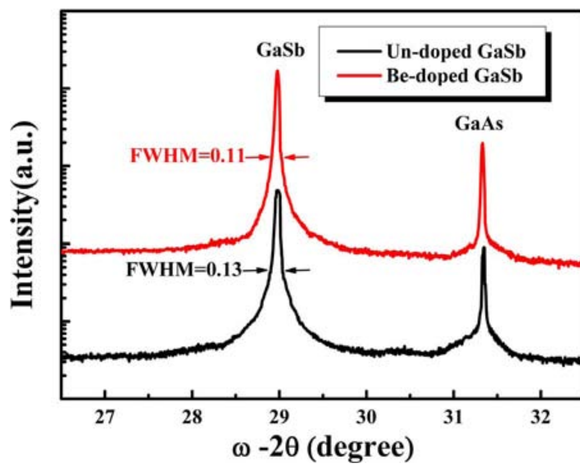


**Fig. 1.** The X-ray diffraction spectra of un-doped and Be-doped GaSb epilayers.

## 3. Results and discussions

The XRD measurement was performed at room temperature to study crystal quality of the undoped and Be-doped epilayer, as shown in Fig. 1. Two peaks can be observed in each spectrum. The peaks at low Bragg angle were consistent with the GaSb zinc blende crystal structure. The other peaks originated from GaAs substrate. The Bragg angle of GaSb epilayer and GaAs substrate were about 29.00 and 31.33. The full width of half maximum (FWHM) of GaSb diffraction peaks were 0.13 and 0.11 degree for undoped and Be-doped GaSb, respectively. A qualitative comparison of the crystal quality belonging to different samples can be obtained by comparing the FWHM. Our results indicated that the crystal quality of Be-doped GaSb was better than undoped GaSb, which attributed to defects density decrease via Be doping.

GaSb usually exhibit p-type conduction was attributed to native defects, such as, Ga vacancy ($V_{Ga}$) and anti-site defect ($Ga_{Sb}$) [13]. Carriers in GaSb were restricted by these defects. This result in broaden of FWHM and decrease of intensity. In order to improve the optical properties of GaSb, the native defects should be eliminated [14]. The Zn element was commonly used as dopant to improve carriers performance and enhance emission properties of p-type GaSb [15]. The characteristics of $Zn_{Ga}$ acceptor had been actively investigated by many researchers [16]. However, the Be atom, which has smaller radius, was considered as another promising candidate to obtain high crystal quality and carriers performance p-type GaSb [17,18]. In this work, Be was used as dopant to eliminate Ga vacancy defect. Ga vacancy was compensated by Be atoms, which enhanced the hole concentration. The carrier concentration of Be-doped GaSb was $3.39 \times 10^{18}$ cm$^{-3}$. Compare to undoped GaSb of $1.0 \times 10^{18}$ cm$^{-3}$, it had significantly increase.

Photoluminescence has been proven an effective way to investigate the optical properties of semiconductor materials, to provide information of band-to-band emission, excitonic recombination, and transitions involving impurity levels. The optical characteristics of undoped and Be-doped GaSb were systematic investigated by PL. The temperature-dependence PL spectra of undoped GaSb and Be-doped GaSb, which were carried out from 10 K to 300 K under a laser excitation of 100 mW, were shown in Fig. 2. The 10 K PL spectrum of undoped GaSb was dominated by a broad emission band located at 0.771 eV, which was attributed to $V_{Ga}Ga_{Sb}$ defect and acceptor B emission [19,20]. The FWHM at 10 K was 70 meV. An extra peak located at 0.789 eV was observed when the temperature increased to 100 K. With further increase temperature, the spectra of undoped GaSb were dominated by the peak at high energy side. For Be-doped GaSb, a narrow peak was observed located at 0.795 eV. The emission peak had red shift with the temperature increasing. The FWHM of PL spectrum at 10 K was 14 meV. It was less much than undoped GaSb.

In order to further investigate the origin of emission peaks of

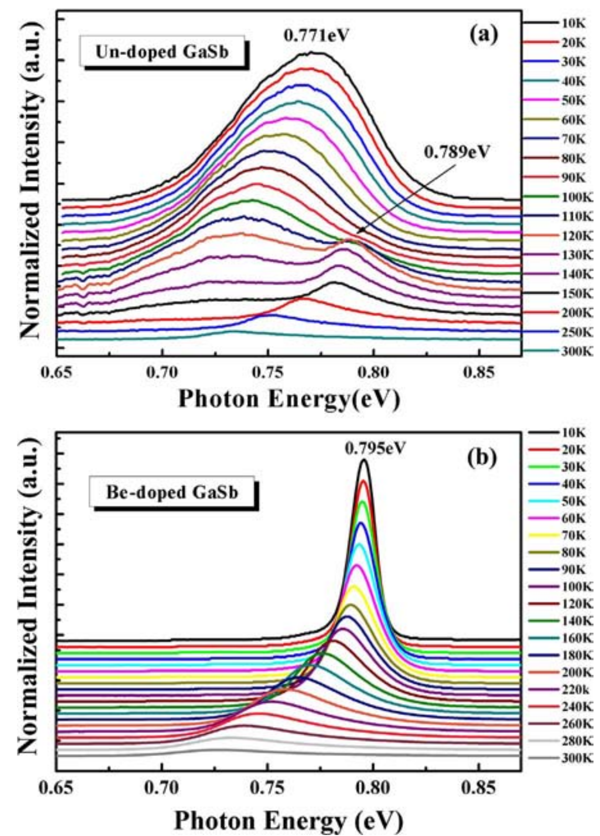


**Fig. 2.** Temperature-dependent PL spectra of GaSb (a) un-doped, (b) Be-doped.

undoped and Be-doped GaSb epilayers, temperature dependent emission peak position was analyzed. The model derived by K. P. O'Donnell and X. Chen was introduced to analyze the evolution. The relation between band gap and temperature was described by following equation [21]:

$$E_g(T) = E_g(0) - S < \hbar\omega > \left(\coth \frac{<\hbar\omega>}{2kT} - 1\right) \quad (1)$$

where $E_g(0)$ is the band gap at 0 K, $S$ is a dimensionless coupling constant and $<\hbar\omega>$ represents an average phonon energy involved the radiative recombination process [21]. The experimental and fitting results of temperature dependent emission peak positions were shown in Fig. 3. The experimental results agreed well with fitting curve in high temperature rage for undoped GaSb and all temperature rage for Be-

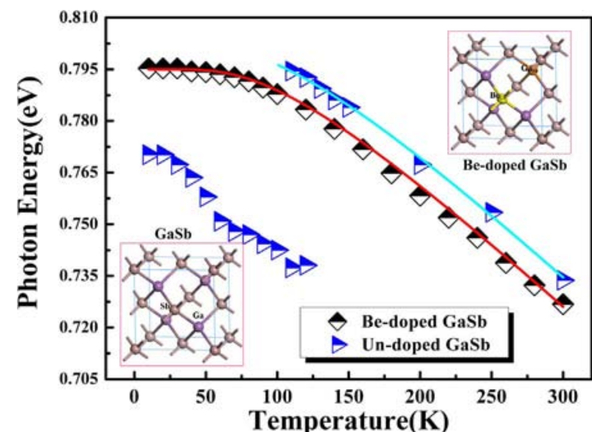


**Fig. 3.** Temperature dependent peak positions of un-doped and Be-doped GaSb. The solid lines represent the fitting curves. The inserts are crystal structure model of undoped and Be-doped GaSb.

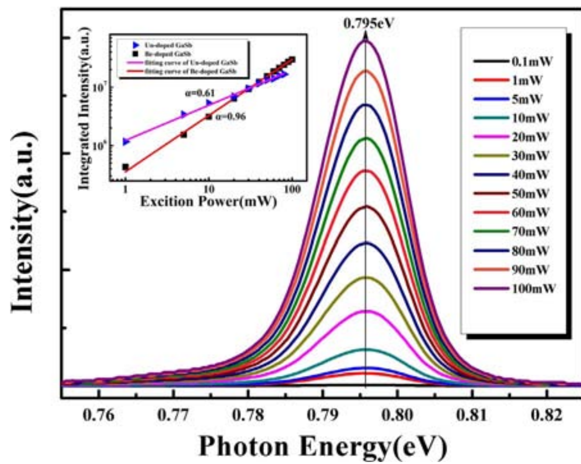


**Fig. 4.** Excitation power dependent PL spectra of Be-doped GaSb at 10 K. The insert was the fitting curves of Eq. (2) for undoped and Be-doped GaSb.

doped GaSb. The <ℏω> of undoped and Be-doped GaSb were 27 meV and 26 meV, respectively, which were slightly smaller than phonon energy of GaSb reported in literatures (29 meV) [22]. It was attributed to lattice imperfection. The $E_g(0)$ of undoped and Be-doped GaSb were 0.803 eV and 0.795 eV. Hence, the peak at high energy side of undoped GaSb was exciton bound to $V_{Ga}Ga_{Sb}$ related emission and the peak of Be-doped GaSb was $Be_{Ga}$ defect related bound exciton emission [19]. The peak located at low energy side of undoped GaSb cannot agree with fitting curve. It is attributed to the native defects related localized carrier emission.

To further verify the origin of emission peak of Be-doped GaSb, the excitation dependent PL intensity were measured at 10 K, as shown in Fig. 4. The relation between PL integrated intensity and excitation power can be expressed as follow equation [23,24]:

$$I = \eta I_0^{\alpha} \quad (2)$$

where $I_0$ is the excitation power of the laser, $\eta$ is the emission efficiency, and the exponent $\alpha$ represents the radiative recombination mechanism. According to the fitting equation, the parameter $\alpha$ were equal to 0.96 and 0.61 for Be-doped GaSb and undoped GaSb. The fitting curve was shown in the insert of Fig. 4. The value of α was approximately equal to 1 mean that the origin of peak was excitonic recombination. For impurity or defect related emission, the value of α is less than 1 [23]. So, the peak of Be-doped GaSb was attributed to $Be_{Ga}$ related bound exciton emission at 10 K [19]. The peak of undoped GaSb was attributed to defects related emission.

According to above analyses, the compensation mechanism of native acceptors in Be-doped GaSb was proposed. It had been confirmed that Ga vacancy was the main native defect in undoped GaSb [12]. After Be-doping, Be atom recombined with Ga vacancy, the lattice site of Ga was occupied by Be atom. The structure model of Be-doped GaSb was shown insert of Fig. 3. Compared to undoped samples. the recombination of Ga vacancy and Be atom substantial decreased native defects concentration. The emission of native defect was suppressed. And then, the $Be_{Ga}$ related bound exciton transition was dominated in PL spectra. Due to decrease of vacancy concentration, the crystal quality of Be-doped GaSb was better than undoped GaSb, which was consist with XRD result.

Ga vacancy was eliminated and defect related emission was suppressed in Be-doped GaSb epilayer. To certify the impact of Be atom on suppression of defect emission, Te-doped GaSb was fabricated. To further study the emission characteristic of undoped GaSb and Te-doped GaSb, Gaussian fitting was used to analyze the emission spectrum at 10 K. The Gaussian fitting results (colored curves) were shown in Fig. 5. The emission peak of undoped GaSb was consisted of two parts. The peak located at 0.777 eV (green curve) come from the recombination of

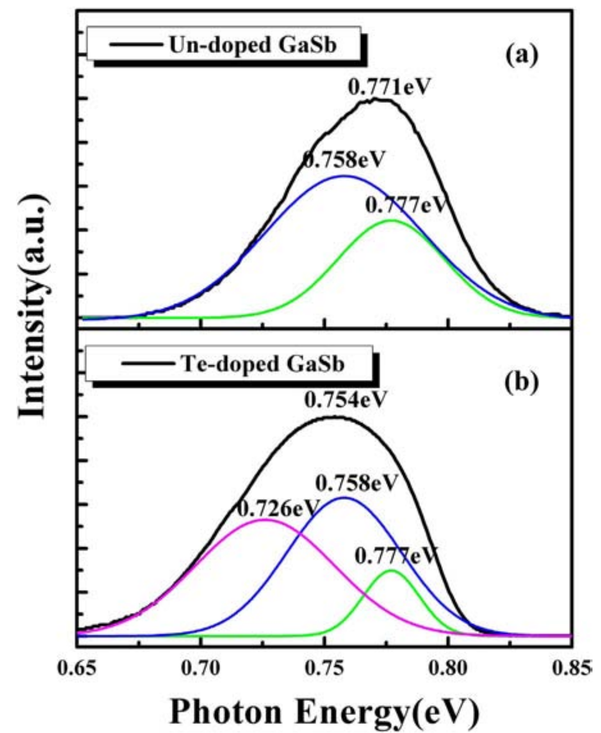


**Fig. 5.** Gaussian fitting (colored curves) of PL spectra of (a) Un-doped GaSb and (b) Te-doped GaSb at 10 K. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article)

electrons from ionized donor and holes from $V_{Ga}Ga_{Sb}$ related acceptor. The peak located at 0.758 eV (blue curve) was attributed to acceptor B [19]. However, the emission peak of Te-doped GaSb had great red shift. It was consisted of three parts. An extra peak located at 0.726 eV was observed besides the peaks at 0.777 eV and 0.758 eV. The peak at 0.726 eV (pink curve) originated from donor-accept pair (DAP) emission [25]. According to previous reports, the mechanism of defects formation and compensation was proposed in terms of defects movement and recombination during the Te doping process. Firstly, substitution defect ($Te_{Sb}$) formed due to Sb site occupied by Te atom. Subsequently, the $Te_{Sb}$ defect recombined with native defects ($V_{Ga}Ga_{Sb}$) and transformed to $V_{Ga}Ga_{Sb}Te_{Sb}$ compound acceptor defect [26]. With further increasing Te doping concentration, residual $Te_{Sb}$ donor defect density increased. We concluded that the peak at 0.726 eV originate from $Te_{Sb}$ donor-$V_{Ga}Ga_{Sb}Te_{Sb}$ accept pair emission.

The room-temperature (300 K) PL spectra of the un-doped, Be-doped and Te-doped GaSb were shown in Fig. 6. Compared to undoped

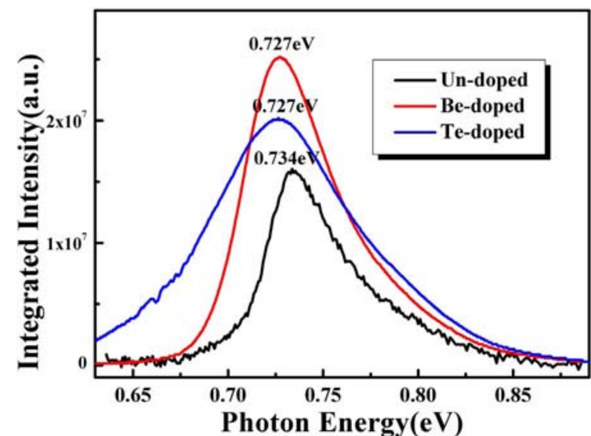


**Fig. 6.** Room temperature PL spectra of un-doped, Be-doped and Te-doped GaSb.

GaSb, the integrated PL intensity of Be-doped GaSb had been great enhanced. the FWHM had no significant change. The optical properties of GaSb had been improved after Be-doping. On the contrary, although the integrated PL intensity of Te-doped GaSb was also higher than undoped GaSb, the FWHM was broader than undoped GaSb. Its optical properties were degraded.

The comparison of PL results between undoped, Be-doped and Te-doped GaSb demonstrated that native defects was compensated via Be doping, but more complex defects were introduced by Te doping. The Be doping process eliminated the native defects and improved the PL characteristics of GaSb.

## 4. Conclusions

In summary, the structural and optical characteristics of GaSb epilayers with undoped, Be-doped have been investigated by XRD and PL measurements. All samples have well crystal quality according to XRD spectra. The improvement of PL after Be doping was obtained. For Be-doped GaSb, Be atom compensated with Ga vacancy. The PL spectra of Be-doped GaSb was dominated $Be_{Ga}$ related bound exciton emission at 10 K. It greatly reduced the concentration of Ga vacancy defects, which will eliminate the native defects emission and greatly decrease the FWHM. This results have proven that Be doping was an effective way to improve the optical performance of GaSb.

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