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Acceptors in undoped gallium antimonide

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ABSTRACT

Undoped GaSb materials were studied by temperature dependent Hall (TDH) measurements and photoluminescence (PL). The TDH data reveals four acceptor levels (having ionization energies of 7meV, 32meV, 89meV and 123meV) in the as-grown undoped GaSb samples. The 32meV and the 89meV levels were attributed to the Ga_{Sb} defect and the V_{Ga}-related defect. The Ga_{Sb} defect was found to be the important acceptor responsible for the p-type nature of the present undoped GaSb samples because of its abundance and its low ionization energy. This defect was thermally stable after the 500°C annealing. Similar to the non-irradiated samples, the 777meV and the 800meV PL signals were also observed in the electron irradiated undoped GaSb samples. The decrease of the two peaks' intensities with respect to the electron irradiation dosage reveals the introduction of a non-radiative defect during the electron irradiation process, which competes with the transition responsible for the 777meV and the 800meV PL peaks.

INTRODUCTION

Gallium antimonide is a narrow band gap III-V semiconductor having a high electron mobility and a small effective electron mass. It is suitable for fabricating high frequency electronic and long wavelength photonic devices. Moreover, GaSb is also the basic material having the lattice parameter which well matches various ternary and quaternary III-V compounds with bandgap varying from 0.3eV to 1.58eV [1,2]. Undoped Gallium antimonide is p-type in nature having the hole concentration of 10^{16}-$10^{17}cm^{-3}$ [1,2]. The residual acceptor is usually believed to be doubly ionizable [3], contain the structure of a vacancy and be related to Ga in excess. It has been attributed to have structures of V_{Ga}, Ga_{Sb} and $V_{Ga}Ga_{Sb}$. [1-5]. The residual acceptor was also thought to be involved in the transition resulting in the band A PL signal (~777meV), which was commonly found in photoluminescence and cathodoluminescence experiments [5-11].

We have studied the residual acceptor and the Ga vacancy in undoped GaSb with the use of positron lifetime technique and Hall measurement [12]. A 315ps lifetime component was identified in the as-grown and it was attributed to the V_{Ga}-related defect [12,13]. Correlation between the annealing of the V_{Ga}-related defect and the 777meV PL signal was also observed, for which they both anneal at 300°C [12]. However, it was also noticed that the hole concentration is independent of the annealing temperature up to 500°C. This implies the V_{Ga}-related defect identified in the lifetime measurement would not be the residual acceptor as it has already been annealed out at 300°C.

In the present study, we have studied the non-irradiated and the electron irradiated undoped GaSb samples with the use of TDH measurement and PL. We aim at identifying the shallow acceptors in the materials and searching for the correlation between signals obtained from different spectroscopies. Results obtained in the present study would also be compared with those of studying the thermal ionization of the V_{Ga}-related defect by the positron lifetime technique, which is also presented in the present MRS Fall Meeting 2003.

EXPERIMENT

The samples used in this study were cut from the liquid encapsulated Czochralski LEC grown undoped GaSb wafers (gasb042un and gasb342un) purchased from the MCP Wafer Technology Ltd., U.K. The thickness of the samples is 500μm and the hole concentration of the as-grown wafers at room temperature is $\sim 10^{17}cm^{-3}$. 1.7MeV electrons (with dosages of $10^{15}cm^{-2}$, $10^{16}cm^{-2}$ and $10^{17}cm^{-2}$) were irradiated on the samples cut from the wafer gasb042un. All the samples were degreased with acetone and ethanol and then rinsed by deionized water. Each of the annealing step was carried out in a forming gas atmosphere (N_2:H_2=80%:20%) for a period of 30 minutes.

The Hall measurements were performed with the Accent HL5500 Hall System attached to an Oxford liquid Helium cryostat operating at temperatures from 4-300K. The magnetic field was 0.505T in the measurements. Ohmic contacts were made by direct soldering In dots onto the samples surfaces with the Van der Pauw configuration.

The PL measurements were carried out with the excitation of the 514.5nm line of an argon laser operating at a power of 500mW. The resolution is 0.5meV in our measurements. A double monochromator with focal length of 0.25m and input/output slit widths of 0.4nm was used to resolve the emitted light. An 800nm long-pass filter was used to prevent the second order signal entering the detector. All the PL measurements were performed at 10K with the samples mounted in an Oxford Instrument closed-cycle Helium cryostat. The 514.5nm excitation source was modulated to 20Hz with a mechanical chopper. The light was detected by a liquid nitrogen cooled InSb IR detector, for which the detector signal was passed to a lock-in amplifier.

RESULTS AND ANALYSIS

Results of temperature dependent Hall effect measurement (TDH)

TDH measurements were performed on the as-grown and the 300°C annealed non-irradiated samples cut from both the wafers. The data taken from 10K to 300K are shown in figure 1. Because of charge neutrality, the relation between the hole concentration p, the electron concentration n, the effective donor concentration N_D, the ionization energies E_{Ai} and the corresponding concentration N_{Ai} of acceptors is given by: [14]

$$p + N_D = n + \sum N_{Ai} \cdot \frac{1}{1 + g \cdot \exp\left(\frac{E_{Ai} - E_F}{kT}\right)} \qquad (1)$$

The data in figure 1 were fitted with equation (1) by taking g = 4 and n = 0. We have attempted fitting the data by assuming the models containing numbers of acceptors from one to four. It was found that the Hall data were not well represented by the one or the two acceptor model, but good fits were obtained by assuming the existence of three or four acceptors. The fitting parameters for the two models are shown in Table 1. Despite the fact that solely based on the data presented here, we cannot distinguish whether the 3 acceptor or the 4 acceptor is the correct model, it is noticed that the fitted parameters of the two shallower acceptors (i.e. A1 and A2) do not significantly depend on the choice of the three or four acceptor model. It is thus plausible to conclude the existence of the two acceptors at 7meV (A1) and 34meV (A2).

From Table 1, the concentration of A1 is too low to make significant contribution to the hole concentration of the undoped material. For the case of the acceptor A2, its concentration is 2-3×10^{17}cm^{-3} in the as-grown samples, which is the same as the room

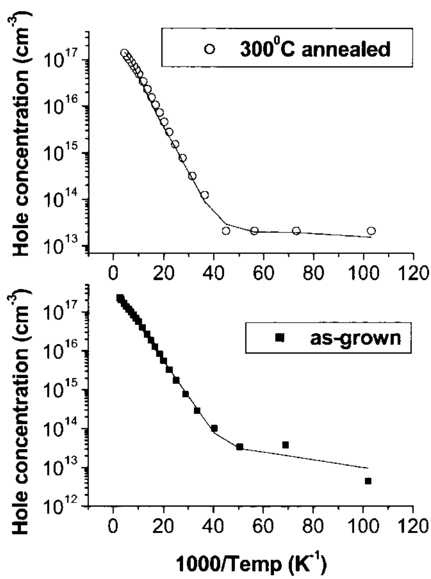

Figure 1 Hole concentration of the as-grown and 300°C annealed GaSb342 samples. Solid lines are fitted curves.

	GaSb342Un			
	as-grown		300°C annealed	
	3 acceptor	4 acceptor	3 acceptor	4 acceptor
E_{A1} (meV)	8	8	5	5
N_{A1} (cm^{-3})	3.0x10^{13}	3.0x10^{13}	2.0x10^{13}	2.0x10^{13}
E_{A2} (meV)	33	33	35	35
N_{A2} (cm^{-3})	2.0x10^{17}	2.0x10^{17}	1.8x10^{17}	1.8x10^{17}
E_{A3} (meV)	105	89	105	89
N_{A3} (cm^{-3})	9.1x10^{16}	6.5x10^{16}	4.5x10^{16}	1.2x10^{16}
E_{A4} (meV)		125		125
N_{A4} (cm^{-3})		3.3x10^{16}		4.3x10^{16}

Table 1 Fitted acceptor levels and concentrations of TDH data of as-grown and 300^{0}C annealed non-irradiated undoped GaSb samples. These fitted parameters are plotted as solid lines in figure 1 with equation 1.

temperature hole concentrations of the samples. Its ionization energy is small as compared to the other dominant acceptor and it is thermally stable up to the annealing temperature of 500°C. It is thus plausible to conclude the dominant residual acceptor responsible for the p-type conduction in the present samples is the E_{A2} acceptor. As the ionization energy (32meV) of A2 is close to that of the Ga_{Sb} acceptor $E(0/-)=E_V+0.04eV$ calculated by the first principle [16], the A2 acceptor is attributed to the Ga_{Sb} defect. The present conclusion that Ga_{Sb} is the dominant residual acceptor is consistent with the findings of Shaw [15] and Hakala et al [16].

Results of Photoluminescence measurements

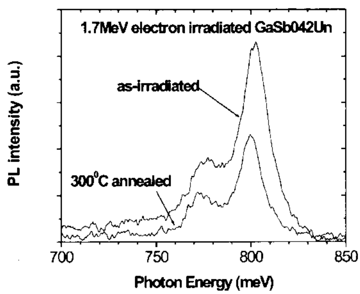

Figure 2 PL spectra of the as-irradiated and 300°C annealed electron irradiated (1.7MeVx10^{17}cm^{-2}) GaSb samples.

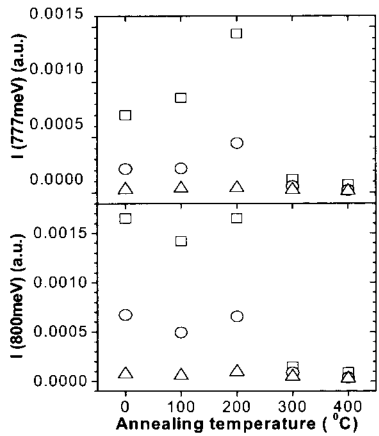

Figure 3 PL intensities of electron irradiated samples at different annealing temperatures. The square, circle and triangle represent the data obtained from 1.7MeVx10^{15}cm^{-2}, 1.7MeVx10^{16}cm^{-2} and 1.7MeVx10^{17}cm^{-2} samples respectively.

Electron irradiated GaSb samples were studied by PL at 10K and the results are shown in figure 2. Similar to the non-irradiated undoped samples, two significant PL peaks, namely at ~777meV and ~800meV, were observed in the PL spectra of the electron irradiated samples. The intensities of the two PL peaks as a function of the annealing temperature were measured and were shown in figure 3. The two peaks' intensities were observed to dramatically decrease after the 300°C annealing. This annealing behaviors are similar to the ~777meV and the ~800meV PL peaks found in the non-irradiated undoped GaSb samples. The 777meV signal (band A) was commonly found in most of the p-type GaSb materials and was found to be related to Ga in excess [6,9,10, 17]. The 777meV signal has been attributed to the conduction band/donor to the residual acceptor or the $V_{Ga}Ga_{Sb}$ defect transition. [5-11,17].

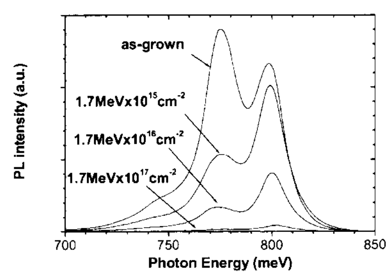

Figure 4 PL spectra of samples with various electron irradiation dosages before annealing.

The influence of the electron irradiation dosage on the intensities of the two PL peaks was also investigated and the results were shown in figure 4. From the figure, the peaks' intensities decrease with increasing dosage. This observation can be explained by the introduction of a non-radiative defect in the electron irradiation process. The newly formed non-radiative defect competes with the radiative transition that results in the PL signals and thus the two PL intensities decrease.

CONCLUSION

Acceptors in undoped GaSb materials were studied by the TDH measurements. Four acceptor levels having ionization energies of E_{A1}=7meV, E_{A2}=32meV, E_{A3}=89meV and E_{A4}=123meV were identified. The acceptors A2 and A3 were attributed to the Ga_{Sb} defect and the V_{Ga}-related defects respectively. Because of the abundance and the low ionization energy, the Ga_{Sb} defect was the most important residual acceptor responsible for the p-type conduction in the present samples. PL measurements on the electron irradiated samples revealed the introduction of a non-radiative defect, which compete with the radiative transitions responsible for the PL signals 777meV and 800meV.

ACKNOWLEDGEMENT

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