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Annealing Study of Al/GaSb Contact with the Use of Doppler Broadening Technique

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Using a monoenergetic positron beam, annealing study of the Al/n-GaSb system was performed by monitoring the Doppler broadening of the annihilation radiation as a function of the positron implanting energy. The S-parameter against positron energy data was successfully fitted by a three-layer model (Al/interface/GaSb). The annealing out of the open volume defects in the polycrystalline Al layer was revealed by the decrease in the S-parameter and the increase in the effective diffusion length of the Al layer. For the as-deposited samples, a $\sim$ 5 nm interfacial region with S-parameter larger than those of the Al overlayer and the bulk was identified. After the 400°C annealing, this interfacial region extends to over 40 nm and its S-parameter dramatically drops. This is possibly due to the new phase formation at the interface. Annealing behaviors of S_{B} and $L_{+,\mathrm{B}}$ of the GaSb bulk showed the annealing out of positron traps (possibly the V_{Ga}-related defect) at 250°C. However, a further annealing at 400°C induces the formation of positron traps, which are possibly of another kind of V_{Ga}-related defect and the positron shallow trap GaSb antisite.

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1. Introduction

Gallium antimonide is a narrow direct bandgap semiconductor suitable for fabricating high frequency electronic devices and is also the basic material for fabricating a variety of lattice matched optoelectronic materials operating in the wavelength range of 0.8–4.3 μm [1]. Although, making metal rectifying contacts to the semiconductor material is crucial to device fabrication, studies on this issue on GaSb are relatively little as compared to those of GaAs or InP. Moreover, fabricating reliable GaSb Schottky contact is not easy because of the Fermi level pinning close to the valence band [2], and the insulating interfacial layer at the boundary [3]. Aluminum (Al) has been reported in some studies to be a good candidate for fabricating rectifying contact with n-type melt grown GaSb ($p \sim 10^{18}$ cm^{-3}) [3–8], although the rectifying properties were not consistent in all of the studies. With the use of monoenergetic positron beam, Doppler broadening technique has been used to study various metal–semiconductor interfaces (examples see Refs. [9–13]). In the present study, Al contacts onto liquid encapsulated Czochralski grown Te-doped n-type GaSb samples ($n \sim 10^{18}$ cm^{-3}) have been made by electron beam evaporation. Depth profile of S-parameter was obtained by varying positron energies up to 15 keV and thus the interfacial properties of the Al/n-GaSb contact, as well as its annealing behavior, were investigated.

2. Experimental

The GaSb wafer used is Te-doped liquid encapsulated Czochralski (LEC) grown n-GaSb purchased from Wafer Technology, U.K. Samples (dimensions $\sim$ 1 cm $\times$ 1 cm) cut from the wafer were etched in HCl and then rinsed in deionized water. A 0.8 mm diameter Al circular disc was then deposited onto the sample surface in an electron beam evaporator at the pressure of 10^{-5} Torr. Al/n-GaSb samples with Al thicknesses of 100 nm and 200 nm were fabricated. The Al film thickness of the sample was measured by the quartz crystal film thickness monitor. Annealing of samples was performed in a forming gas ($N_2 : H_2 = 80\% : 20\%$) atmosphere for a period of 30 minutes. The slow positron implantation measurements were carried out with the monoenergetic positron beam located in the University of Science and Technology of China (USTC). Positrons with energies up to 15 keV were implanted into the samples and the corresponding annihilation γ radiation spectra were collected with an HPGe detector system. Each spectrum contains a total count of 1×10^5 under the 511 keV annihilation peak. The Doppler broadening of the annihilation γ ray radiation was monitored by the S-parameter, which is defined as the ratio of the central region area to the total area under the annihilation peak. The window width of the central region was chosen such that the obtained S-parameter is close to 0.5, and was thus set at a width of 1 keV on both sides of the 511 keV peak. The data was then analyzed by the source code VEPFIT [14].

3. Results and discussions

The S-parameter profiles of the as-fabricated Al/GaSb samples with 100 nm and 200 nm Al coverage are shown in Fig. 1a and b, respectively. In or-

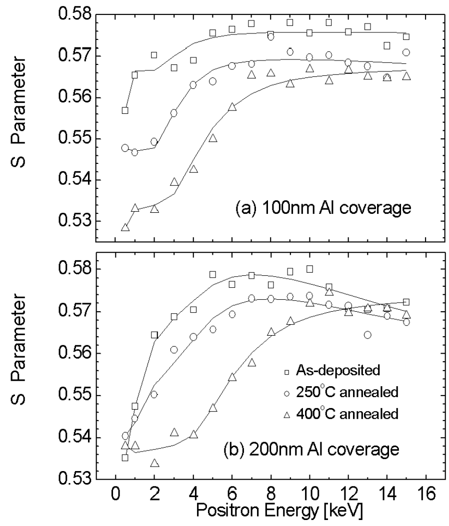

Fig. 1. The S-parameter measured as a function of the positron implanting energy for the Al/n-GaSb samples with 100 nm (a) and 200 nm (b) Al thicknesses. The solid lines represent the fitted curves using the Al/interface/GaSb model and the corresponding fitted parameters.

der to analyze the $S(E)$ data of the Al/GaSb system, we have employed the Al-interface-bulk three-layer model and thus the resultant S-parameter is given by: $S(E) = f_{\mathrm{Al}}(E)S_{\mathrm{Al}} + f_i(E)S_i + f_{\mathrm{B}}(E)S_{\mathrm{B}}$, where S_j and f_j are the S-parameters and the fractions, respectively, of positron annihilating in the corresponding layers of Al, interface, and GaSb bulk. The fitted results of the S-parameters and the effective positron diffusion lengths of the different layers are shown in Fig. 2. For both the as-deposited samples with 100 nm and 200 nm Al coverage, their fitted boundary positions agreed well with the expected values (i.e. the Al film thickness). The fitted curves for the different samples are shown in Fig. 1 and it is noticed that they give good representations to the experimental data. From Fig. 2, it is clearly shown that all the fitted S-parameters and L_+ have the similar annealing trends regardless of the samples' Al film thickness. For the Al overlayer, S_{Al} decreases with increasing temperature from 0.56–0.57 to ~ 0.537, while $L_{+,\mathrm{Al}}$ increases from several nm to ~ 50 nm. The Al film deposited by electron beam evaporation is polycrystalline with a grain size of about 100 nm [15]. The decrease in S_{Al} and the increase in $L_{+,\mathrm{Al}}$ with an annealing temperature increase are possibly due to the annealing out of positron trapping vacancies in the Al film. From Fig. 2b, for the interfacial region, the S_i has values of about ~ 0.59 with annealing temperature lower than 250°C. As the annealing temperature increases to 400°C, S_i abruptly drops to ~ 0.47 and the positron diffusion length increases from ~ 15 nm

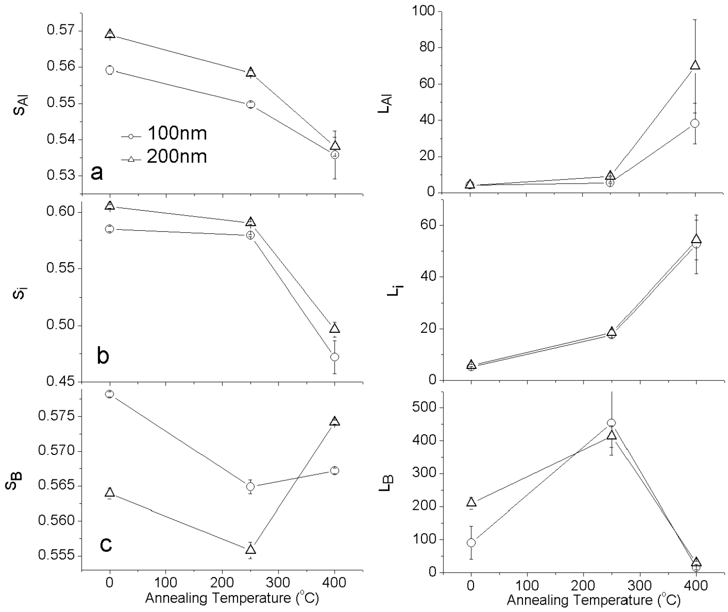

Fig. 2. The fitted values of the S-parameters and the positron diffusion length of the Al overlayer (a), the interfacial region (b), and the GaSb bulk (c) as a function of the annealing temperature. The fitting of the $S(E)$ data employed the three-layer model (i.e. the Al/interface/GaSb model).

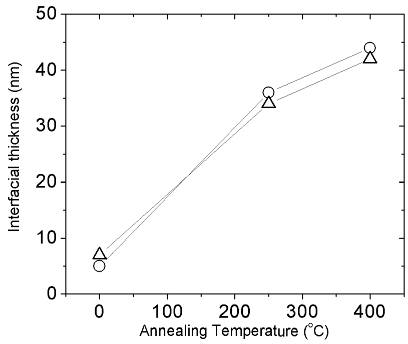

Fig. 3. The width of the interfacial region as a function of the annealing temperature. The triangles denote the 200 nm Al coverage, the circles — the 100 nm Al coverage.

to ~ 50 nm. From Fig. 3, the interfacial width increases from ~ 5 nm to ~ 45 nm after the 400°C annealing. At the first glance, the decrease in S_i and the increase in $L_{+,i}$ with increasing annealing temperature can be explained by the removal of positron trapping center. It is noticed after the 400°C annealing, the S_i decreases to the value of ~ 0.47, which is significantly smaller than those of S_{Al} and S_{B} at any annealing temperatures. However, at the same time, the value of $L_{+,i} \sim 50$ nm after the 400°C annealing is much smaller than the value of $L_{+,\mathrm{GaSb}} \sim 400$ nm after the 250°C annealing. This implies, despite the very low value of $S_i \sim 0.47$ after the 400°C annealing, there are a significant amount of positron traps in the interfacial region. This leads us to speculate that the dramatically drop of the S_i and the increase in the interfacial width upon annealing is also related to the formation of new phase at the interface originated to the inter-diffusion of atoms across the boundary, for which the new formed phase has a lower S-parameter. The Al/GaSb interface has been investigated by secondary ion mass spectroscopy (SIMS), Auger electron spectroscopy (AES) and soft X-ray photoemission spectroscopy although the results are divergent. Oueini et al. [16], Rouillard et al. [17], and Walters and Williams [4] have observed a significant atomic inter-diffusion across the Al/GaSb interface, and Poole et al. [18] have observed an abrupt Al/GaSb boundary. For the GaSb bulk layer, the S_B drops and the $L_{+,\mathrm{B}}$ increases from 100–200 nm to ~ 400 nm after the 250°C annealing. From Fig. 2, it is also noticed that after the 400°C annealing, the S_B increases despite the magnitudes of increase for the two samples with different thicknesses are different. Moreover, the $L_{+,\mathrm{B}}$ significantly reduces from ~ 400 nm to ~ 30 nm after the 400°C annealing. In our previous positron lifetime and temperature dependent Hall (TDH) studies of the electron irradiated LEC grown p-type GaSb [19, 20], two different kinds of $\mathrm{V_{Ga}}$-related defects having lifetimes of 280 ps and 315 ps were identified. These two components were attributed to the two $\mathrm{V_{Ga}}$-related defects having different microstructures rather than the same $\mathrm{V_{Ga}}$-related defect having different charge states and thus different degree of relaxation. The $\mathrm{V_{Ga,315ps}}$ intensity decreases and the $\mathrm{V_{Ga,280ps}}$ intensity increases with increasing annealing temperature while the annealing temperature is below 300°C. As the annealing temperature reaches 300°C, the $\mathrm{V_{Ga,315ps}}$ component disappears. Moreover, the concentration of the acceptor at $E_\mathrm{V} + 34$ meV increases from $\sim 2 \times 10^{17}$ cm^{-3} to 1.8×10^{18} cm^{-3} after the annealing at 400°C. This acceptor was attributed to the $\mathrm{Ga_{Sb}}$ antisite. The initial decrease in S_B and increase in $L_{+,\mathrm{B}}$ in the present study are possibly the resultant effect of the annealing out of $\mathrm{V_{Ga,315ps}}$ despite the creation of $\mathrm{V_{Ga,280ps}}$. The subsequent increase in S_B and the significant drop of $L_{+,\mathrm{B}}$ from ~ 400 nm to ~ 30 nm are possibly due to the generations of the $\mathrm{V_{Ga,280ps}}$ and the 34 meV acceptor which acts as positron shallow trap.

4. Conclusion

Al/n-GaSb interface was studied by Doppler broadening technique with the use of the monoenergetic positron beam. S-parameter profiles of the samples with different Al thicknesses (100 nm and 200 nm) were obtained. The $S(E)$ data were then fitted with the assumption of the Al/interface/GaSb model and the fitted results. The structural changes of the Al film, the interfacial region, and the GaSb bulk upon annealing were discussed.

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