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Organometallic Vapor Phase Epitaxy of n-GaSb and n-GaInAsSb for Low Resistance

Ohmic Contacts*

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Abstract

A comparison of n-GaSb and n-GaInAsSb epilayers for ohmic contacts in GaSb-based devices is studied. The epilayers were grown by organometallic vapor phase epitaxy and doped with Te. At similar electron concentrations, the atomic Te concentration, as determined by secondary ion mass spectroscopy, is more than 2 times higher in n-GaSb compared to n-GaInAsSb. In addition, the electron mobility is lower in n-GaSb than n-GaInAsSb at similar electron concentrations. The electron concentration saturates at about $1.3 \times 10^{18} \text{ cm}^{-3}$ for n-GaSb, but linearly increases for n-GaInAsSb. Pd/Ge/Au/Pt/Au metallization was studied for ohmic contacts. A specific contact resistivity of $1 \times 10^{-5} \Omega\text{-cm}^2$ for n-GaSb was measured. The specific contact resistivity can be greatly improved by contacting n-GaInAsSb, and a significantly lower specific contact resistivity of $2 \times 10^{-6} \Omega\text{-cm}^2$ for n-GaInAsSb was measured.

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1. Introduction

GaSb-based III-V semiconductors are of increasing interest for high-speed, low power electronics and mid-infrared optoelectronics and detectors. One of the many factors that must be considered in the design and fabrication of these devices is the electrical characteristic of these materials, since it can affect the specific contact resistivity of ohmic contacts and the bulk resistivity and thus device resistance. Of particular concern is the fabrication of n-type ohmic contacts with low specific contact resistivity, which can be difficult to achieve in n-GaSb because the Fermi level is pinned in the GaSb valence band. In recent studies, GaInAsSb/GaSb thermophotovoltaic (TPV) cells were monolithically series-interconnected using a common metallization scheme for both p- and n-ohmic contacts to GaSb [1,2]. In this configuration, ohmic contact was made to an n-GaSb layer that conducts current laterally through the device. It is important to achieve a low specific contact resistivity and low sheet resistance to achieve a high fill factor for these TPV devices.

The specific contact resistivity and sheet resistance are dependent in part by the carrier concentration of the bulk semiconductor, and it is important to be able to achieve a carrier concentration as high as possible. The maximum electron concentration in n-GaSb has been reported to be in the range between 1 to $2 \times 10^{18} \text{ cm}^{-3}$, whether the material is grown by organometallic vapor phase epitaxy (OMVPE) or molecular beam epitaxy [3-8]. However, higher electron concentrations would be more desirable. Therefore, this work considers n-GaInAsSb, lattice matched to GaSb, as an alternative alloy for making n-type ohmic contacts for GaSb-based devices. This alloy is a layer in the TPV device structure, and therefore does not add additional complexity to the growth of these device structures. The use of alloys other than the substrate material is routinely being used for InP-based materials in which p-InGaAs is used as the contact layer since a higher hole concentration can be attained in InGaAs compared to InP. In this study, a comparison of Te incorporation, electrical characteristics, and ohmic contact formation for n-GaSb and n-GaInAsSb epilayers grown by OMVPE is presented.

2. Experimental procedure

GaSb and GaInAsSb epitaxial layers were grown on both n-GaSb and semi-insulating (SI) GaAs substrates, (001) miscut 6° toward (1-11)B. Epilayers were grown on both types of substrates since earlier work indicated that the carrier concentration may be different on these

substrates even though the gas phase concentration is nominally the same [9]. Solution trimethylindium, triethylgallium, tritertiarybutylaluminum, tertiarybutylarsine, and trimethylantimony were used as precursors. Diethyltellurium (DETe), 10 ppm diluted in H_2 , was used as the n-type dopant and DETe mole fraction (MF) ranged from 5 to 100×10^{-9} . The layers were grown in a previously described vertical rotating-disk OMVPE reactor [10] with H_2 carrier gas flow rate of 10 slpm; reactor pressure of 150 Torr; and susceptor rotation rate of 250 rpm. GaSb was grown at 550 °C and V/III ratio of 1.6, while GaInAsSb was grown at 525 °C and V/III of 1.8. The alloy composition of GaInAsSb corresponds to a 300 K photoluminescence peak emission at 2.3 μm for epilayers that are nominally lattice-matched to GaSb.

n-GaSb was grown directly on both n-GaSb and SI GaAs substrates, while n-GaInAsSb was grown on an u-GaSb buffer that was first deposited on the n-GaSb or SI GaAs substrate at 550 °C. Growth was interrupted after the buffer layer deposition to reduce the temperature to 525 °C, and subsequently n-GaInAsSb was grown. The buffer layer thickness was 0.1 μm for n-GaInAsSb on n-GaSb substrates, while it was 0.4 μm for layers grown on SI GaAs. The thicker buffer layer was used in order to reduce the contribution of electrically active defects that result from the lattice mismatch between the GaInAsSb and GaAs [11]. Nominally u-GaSb epilayers are p-type with hole concentration of $1.1 \pm 0.2 \times 10^{16} \text{ cm}^{-3}$ and mobility of $792 \pm 33 \text{ cm}^2/\text{V-s}$ at 300 K. At 77 K, the hole concentration is $2.8 \pm 0.6 \times 10^{15} \text{ cm}^{-3}$ and mobility is $4820 \pm 465 \text{ cm}^2/\text{V-s}$. These values of hole concentration are slightly higher and mobility values slightly lower compared to u-GaSb grown on (001) miscut 2° toward (101) SI GaAs substrates [12]. The n-doped epilayers are 2 to 3 μm

Carrier concentration and mobility were determined for n-GaSb and n-GaInAsSb grown on SI GaAs substrates. The measurements were made at 300 and 77 K from Hall measurements based on the van der Pauw method using a field of 10 KG. The atomic Te concentration was determined for n-GaSb and n-GaInAsSb grown on both SI GaAs and n-GaSb substrates, and was measured by secondary ion mass spectroscopy (SIMS) using a Cs^+ primary ion beam. Calibration of the absolute Te concentration is based on GaSb and GaInAsSb standards that were ion implanted with Te.

Contact resistivity and sheet resistance measurements were determined by the transfer length method (TLM) [13,14]. The experiments were performed on 2- μm -thick n-GaSb and n-

GaInAsSb epilayers grown on SI GaAs. The epilayers were etched down to the substrate to form mesa structures that were electrically isolated and a ladder structure was fabricated on the mesas by lift-off lithography. Pd/Ge-based metallization [1,15] was used for n-metallization and electron-beam evaporation was used to deposit Pd/Ge/Au/Pt/Au (7nm/56 nm/23 nm/48 nm/200 nm). The samples were alloyed at temperatures between 250 and 280 °C, as previously described [14].

3. Results and discussion

The electron and atomic Te concentration as a function of DETe MF are shown in Figures 1a and 1b for n-GaSb and n-GaInAsSb, respectively. The electron concentration for n-GaSb increases with DETe MF from $4.7 \times 10^{17} \text{ cm}^{-3}$ and saturates at $1.3 \times 10^{18} \text{ cm}^{-3}$, a behavior that is similar to previous reports [3-8]. The electron concentration for n-GaInAsSb linearly increases from 2.8 to $33 \times 10^{17} \text{ cm}^{-3}$ over the whole DETe range, and likely would increase further for higher DETe MF. However, the highest concentration in n-GaInAsSb is not fundamentally limited, but is experimentally constrained by the maximum DETe MF during OMVPE growth. (The lowest values of electron concentration for both alloys are experimentally constrained by the minimum DETe MF). Figure 1 also shows that the atomic Te concentration linearly increases with DETe MF for both n-GaSb and n-GaInAsSb epilayers, and that it is similar for epilayers grown either on a GaSb or SI GaAs substrate. Therefore, it may be assumed that Te incorporation is independent of the type of substrate and is not sensitive to lattice mismatch. The atomic Te concentration in GaSb is about five times higher than that in the GaInAsSb. This higher incorporation rate is likely related to the lower growth rate of GaSb at $1 \text{ } \mu\text{m/hr}$ compared to that of GaInAsSb at $5 \text{ } \mu\text{m/hr}$.

The atomic Te concentration is significantly higher than the electron concentration for n-GaSb. One possible explanation is that the 300 K Hall measurement is an underestimate of the total electron concentration. This is because the L valley lies close in energy to the Γ minimum, and thus carriers populate both the Γ and L valleys [16-17]. While this behavior particularly true for n-GaSb, where the Γ -L separation has been reported to be in the range 75 to 90 meV [17] it appears to be less significant for the GaInAsSb alloy. The electron concentration of n-GaSb at 77 K was as much as 60% higher compared that at 300 K. On the other hand, for n-GaInAsSb, it was less than 10% higher at 77 K compared to 300 K. These multi-band conduction effects,

particularly significant in n-GaSb, may be separated through magnetoresistance measurements, and are beyond the scope of this work.

To estimate Te activation, which is described by the ratio of the electron concentration to atomic Te concentration, the electron concentration that was measured at 77 K was used. This ratio ranges from 0.3 to 0.5 for GaSb, and from 0.7 to 0.8 for GaInAsSb. The lower activation for GaSb is due in part to the underestimate of the electron concentration as determined by Hall measurements, as discussed, but may also be due to deep donor levels or the formation of Ga_2Te_3 complexes [4].

Figures 2 and 3 show the mobility and resistivity, respectively, as a function of the electron concentration at 300 K for n-GaSb and n-GaInAsSb. The mobility of n-GaSb is $3859 \text{ cm}^2/\text{V-s}$ at a carrier concentration of $3 \times 10^{17} \text{ cm}^{-3}$, and drops precipitously below $2000 \text{ cm}^2/\text{V-s}$ for concentrations above $1 \times 10^{18} \text{ cm}^{-3}$. Correspondingly, n-GaSb resistivity is a minimum at $1 \times 10^{18} \text{ cm}^{-3}$ and then increases for higher electron concentrations. This behavior may result from increased carrier scattering due to Te solubility limitations. On the other hand, the mobility of n-GaInAsSb is somewhat higher at $4707 \text{ cm}^2/\text{V-s}$ at $2.8 \times 10^{17} \text{ cm}^{-3}$; is still as high as $3535 \text{ cm}^2/\text{V-s}$ at $1 \times 10^{18} \text{ cm}^{-3}$ (interpolated); and the resistivity continues to decrease at the higher levels of electron concentration shown in Figure 3b. Therefore, lower values of resistivity can be attained for n-GaInAsSb compared to n-GaSb, and these are more than two times lower. Such lower values would be beneficial for minimizing sheet resistance in devices.

Figures 4 and 5 show specific contact resistivity and sheet resistance, respectively as a function of 300 K electron concentration for 2- μm -thick n-GaSb and n-GaInAsSb epilayers grown on SI GaAs. Specific contact resistivity decreases with increasing concentration, as expected. The minimum specific contact resistivity is about $1 \times 10^{-5} \Omega\text{-cm}^2$ for n-GaSb, while it is about five times lower at $2 \times 10^{-6} \Omega\text{-cm}^2$ for n-GaInAsSb. This low value for n-GaInAsSb is lower than the best value reported for n-GaSb [15]. The specific contact resistivity is lower for the n-GaInAsSb sample that was annealed at 250°C compared to the one annealed at 270°C . The lowest sheet resistance measured for n-GaSb is about $12 \Omega/\square$, while it is about $4 \Omega/\square$ for n-GaInAsSb. Since the sheet resistance for n-GaInAsSb is independent of alloy temperature, its value is dominated by properties of the bulk material. Furthermore, it was found that the sheet resistance values obtained using the Hall technique are in good agreement with those obtained by

TLM method, despite the fact that different contact metals were used in the Hall measurements. In additional studies, the sheet resistance is lower for thicker layers, as expected.

4. Conclusions

n-GaSb and n-GaInAsSb epilayers, doped with Te, were grown by OMVPE for studies of ohmic contacts in GaSb-based devices. A maximum concentration of $1.3 \times 10^{18} \text{ cm}^{-3}$ and $3.3 \times 10^{18} \text{ cm}^{-3}$, as determined by Hall measurements, was obtained for n-GaSb and n-GaInAsSb, respectively. While the electron concentration saturates at this level in n-GaSb, it is experimentally constrained for n-GaInAsSb epilayers, and higher electron concentrations can be expected. Electron mobility (resistivity) values are higher (lower) for n-GaInAsSb than n-GaSb, making the n-GaInAsSb an attractive material for making n-type ohmic contacts. Ohmic contacts were made to n-GaSb and n-GaInAsSb using a Pd/Ge-based metallization. The lowest values of specific contact resistivity were 1×10^{-5} and $2 \times 10^{-6} \Omega\text{-cm}^2$ for n-GaSb and n-GaInAsSb, respectively. It is anticipated that lower values of specific contact resistivity are possible with higher electron concentration in n-GaInAsSb.

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(a)

(b)

Figure 1. Electron and atomic Te concentration as a function of DTe MF for (a) n-GaSb and (b) n-GaInAsSb. Electron concentration is determined by Hall measurements at 300 K and has not been corrected for multi-band conduction. Te concentration is determined by SIMS.

(a)

(b)

Figure 2. Electron mobility as a function of electron concentration at 300 K for (a) n-GaSb and (b) n-GaInAsSb.

(a)

(b)

Figure 3. Resistivity as a function of electron concentration at 300 K for (a) n-GaSb and (b) n-GaInAsSb.

Figure 4. Specific contact resistivity as a function of electron concentration for (a) n-GaSb and (b) n-GaInAsSb on SI-GaAs. The circles in (b) represent samples that were alloyed at 270 °C, while the solid square is for a sample alloyed at 250 °C.

Figure 5. Sheet resistance as a function of electron concentration for (a) n-GaSb and (b) n-GaInAsSb on SI-GaAs. The circles in (b) represent samples that were alloyed at 270 °C, while the solid square is for a sample alloyed at 250 °C.