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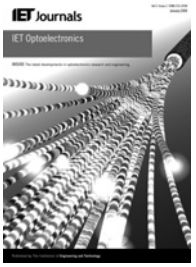

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Low-resistive sulphur-treated ohmic contacts to n-type InAsSb

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Abstract: The authors present low-resistive ohmic contacts to lattice-matched n-type InAsSb on n-GaSb substrates, which are suitable for GaSb-based devices. Using wet chemical treatment as a surface preparation in order to remove the native oxides and evaporating Ti/Pt/Au metals sequentially, specific contact resistivities as low as $5.6 \times 10^{-6}\ \Omega\,\text{cm}^2$ without any annealing are obtained. The resistivity decreases to $3.7 \times 10^{-6}\ \Omega\,\text{cm}^2$ after annealing at 350°C for 90 s.

1 Introduction

The GaSb material system is of particular interest for optoelectronic devices in the mid-infrared wavelength range. In the past, developments on semiconductor lasers [1–3], vertical-cavity surface-emitting lasers (VCSELs) [4, 5], light-emitting diodes (LEDs) [6], photodetectors [7] and high-speed microwave devices [8, 9] have been reported. For the successful operation of such devices, high-quality metal–semiconductor ohmic contacts with low specific contact resistivities (ρ_c) are important [10]. But, the GaSb material system inherently has several problems that make the formation of ohmic contacts difficult. For instance, this material system is very reactive to the atmospheric oxygen or water, which promotes the rapid formation of native oxides on the surface [11]. Besides, particularly in n-type GaSb, the problems of Fermi level pinning in the GaSb valence band [12] (which is, in fact, beneficial for ohmic contacts to p-type GaSb) and the low doping limit ($2.5 \times 10^{18}\ \text{cm}^{-3}$) for the commonly used Te dopant [13] impede to obtain high-quality ohmic contacts.

To date, the lowest value reported for contact resistances of unannealed ohmic contacts on n-GaSb is of the order of $10^{-4}\ \Omega\,\text{cm}^2$ or even higher. Few groups, for instance, Vogt *et al.* [14], Yang *et al.* [15] and Robinson and Mohney [16] formed ohmic contacts on n-GaSb with low contact resistances on the order of $10^{-6}\ \Omega\,\text{cm}^2$, but they applied high-temperature (300–400°C) annealing steps on their alloy contacts. However, high-temperature annealing may cause dopant diffusion [17] and even it might affect the active regions [18]. Therefore this work considers a low bandgap highly doped material to develop a low-resistive unannealed ohmic contact.

As a contact layer, n-type $InAs_{0.91}Sb_{0.09}$, a low bandgap material ($E_g = 0.296$ eV) and lattice-matched to GaSb ($E_g = 0.72$ eV) can be used. The use of this additional contact layer where the ohmic contacts will be formed on overcomes the above-mentioned problems. Because, at the surface of this material, the Fermi level is pinned near the conduction band [19] and it can be highly doped up to $1 \times 10^{20}\ \text{cm}^{-3}$ by using Te as a dopant [17]. In fact, high doping is necessary for the ohmic contacts in order to make the depletion region at the metal–semiconductor interface thin enough to enable carrier tunnelling [20]. This is displayed in Fig. 1 by the band diagram of the metal, the highly n-doped contact layer and the buffer layer underneath. The band structure was calculated using SimWindows (version 1.5.0) [21].

Lauer *et al.* [22] demonstrated Ti/Pt/Au-based contacts on the same contact layer using sputter etching in Ar^+ plasma. They found the resistivities as low as $5.1 \times 10^{-6}\ \Omega\,\text{cm}^2$, but this method involved the ion-induced damage of the contact layer surface during the longer sputter etching process.

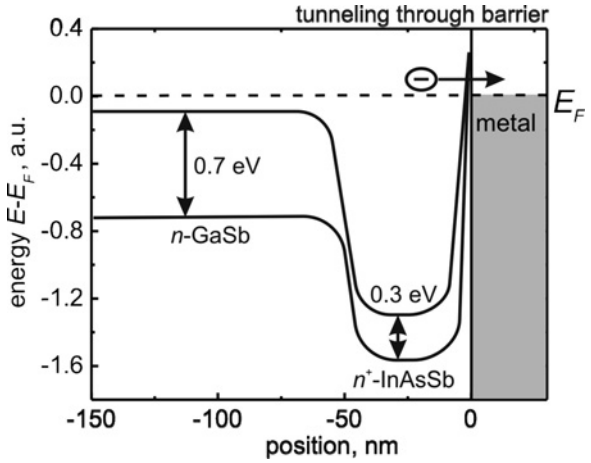

Figure 1 *Band diagram of metal/n^+-InAsSb/n-GaSb*

The dashed line indicates the Fermi level. The Schottky barrier at the metal–semiconductor interface is very thin, which enhances the tunnelling mechanism

Obviously, one has to be extremely careful in this method in order to minimise this surface damage by properly controlling the parameters like self-bias DC voltage, applied high voltage, flow of Ar gases and sputter etching time, which can make the contact surface oxide free and smooth prior to metal deposition. Small changes of these optimised parameters may lead to a bad ohmic contact. Moreover, a low resistance, $2.4 \times 10^{-8}\ \Omega\ \text{cm}^2$ unannealed ohmic contact on n-type $InAs_{0.66}Sb_{0.34}$ has been developed by Champlain *et al.* [23], which is highly strained to GaSb.

In this article, we have investigated an unannealed ohmic contact with low contact resistivity using a highly Te-doped n^+-InAsSb contact layer lattice-matched to GaSb. This configuration is suitable for GaSb-based devices, such as VCSELs for wavelengths above 2 μm, which have been demonstrated recently [4, 5]. The surface preparation procedure based on a significantly simplified wet chemical treatment prior to metallisation is also reported here.

2 Experimental procedure

The test samples used in this study consist of Te-doped n-GaSb substrate with doping concentration and resistivity of $1 \times 10^{18}\ \text{cm}^{-3}$ and 0.0024 Ω cm, respectively, followed by a 500 nm thick Te-doped ($3 \times 10^{18}\text{cm}^{-3}$) n-GaSb buffer layer and finally a 50 nm thick also Te-doped ($1 \times 10^{20}\ \text{cm}^{-3}$) n^+-$InAs_{0.91}Sb_{0.09}$ contact layer. All the layers were grown by conventional solid-source molecular beam epitaxy (MBE), where As_2 and Sb_2 were generated by valved cracker cells. For Te doping, Ga_2Te_3 was used.

After the growth, we defined circular mesas with 5–28 μm diameter using standard UV lithography and subsequent citric acid-based etching by which the topmost contact layer, InAsSb and a few nanometres of the GaSb buffer layer were removed. Then the mesas were covered with 150 nm of sputtered SiO_2 as a passivation layer. This layer was removed from the top of the mesas by a lift-off process to form circular contact openings. Before the metallisation step, sulphur-based surface preparation procedure was applied since it is known that highly reactive Sb-based materials, such as our topmost contact layer, n-InAsSb, get oxidised very quickly in the atmosphere. Taking this into account, a conventional wet chemical etching step, for example, 18.5% HCl dipping for 30 s was employed to remove the surface oxides and then for preventing the further formation of oxides, the samples were rinsed with aqueous $(NH_4)_2S$ solution (with pH = 9.5) at room temperature. Afterwards, the samples were blown dry with N_2 and promptly loaded into the electron beam metallisation chamber. At a base pressure of $\sim 10^{-6}$ mbar and under the control of a thickness monitor, Ti/Pt/Au were sequentially evaporated. This surface preparation method fits quite well with the investigation done by Robinson and Mohney [16], where they formed In-bearing ohmic contacts on n-GaSb.

The evaporated metal thicknesses for the top and backside contacts were 3/40/250 and 20/40/100 nm (Ti/Pt/Au), respectively. After the metal deposition, the contact pads were structured by metallisation lift-off process. The final test structure is shown schematically in Fig. 2, where the diameter of the point contact is denoted by D. The current–voltage (I–V) characteristics of the point contacts with different diameters were measured in a four-point probe measurement system. The contact resistivities (ρ_c) were then deduced by the experimental method described in [24], where the current spreading under the mesa has been included. To investigate the effect of annealing on the contact resistance, several samples were additionally annealed at 350°C for 90 s in a rapid thermal annealing (RTA) furnace under flows of 4 slm of N_2 and 1 slm of H_2.

3 Results and discussion

In order to see the influence of the sulphidation on the contact resistance, one sample was processed by only

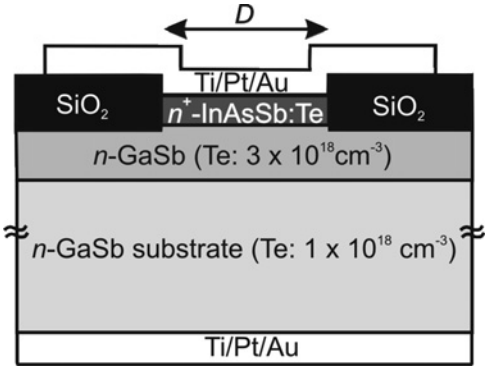

Figure 2 *Schematic cross-section of circular contact test devices*

The diameter of the device is denoted by *D*

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conventional HCl dipping without any sulphide treatment. As shown in Fig. 3, these test structures exhibit non-linear $I-V$ characteristics with high contact resistivities of $1.2 \times 10^{-4}\ \Omega\ cm^2$. In contrast, all the test devices processed by HCl dip followed by the sulphide dip exhibit good ohmic behaviour (Fig. 3, solid curve). In this way, the contact yielded a minimum specific contact resistance value of $5.6 \times 10^{-6}\ \Omega\ cm^2$ without any annealing.

This striking difference might be because of a residual oxide layer at the metal–semiconductor surface of the conventional HCl-dipped sample [11]. On the other hand, it is expected that by the sulphide passivation process, the dangling bonds at the contact surface are terminated in the form of S–In, S–As and S–Sb [25], which leads to a reduced ohmic contact since it allows the intimate contact between the metal and semiconductor.

Another pronounced feature that needs to be addressed is the annealing effect on the contact resistance. According to our investigation, annealing has a strong influence on the backside n-contact and results in lowering the contact resistivity. However, the current spreads out in the 500 μm thick substrate and therefore the influence of the bottom contact of the test structure is negligible.

To obtain the optimum surface passivation time, one-quarter GaSb wafer was splitted into six pieces where all the processing steps up to the metallisation lithography were kept same. All the pieces were dipped into 18.5% HCl for 30 s and then dipped into the alkali 3.5% $(NH_4)_2S$ (pH = 9.5) at room temperature by varying the passivation time. The results are illustrated in Fig. 4 showing that the contact resistivity decreases with time up to 40 s and then rises again. The increase in contact resistance with time can be because of the thicker sulphide layer formed during the passivation, which prohibits the intimate contact between metal and semiconductor. On the other hand, samples with very low passivation time, for example, 4, 20 and 30 s, also show higher contact resistance. As a possible reason, the reaction time between semiconductor surface and sulphide solution to replace the oxygen atoms by sulphur atoms at the semiconductor surface might not be sufficient making the surface sensitive to further oxidation by ambient air. In contrast to these findings, Robinson and Mohney [16] found a good ohmic contact to n-GaSb using a very short sulphide passivation time, that is, 5 s.

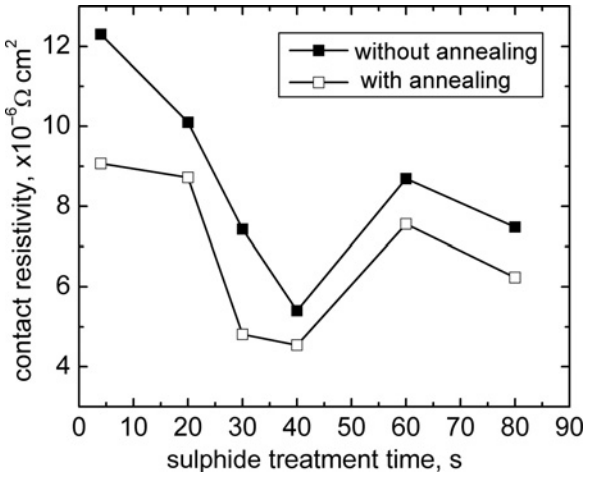

Figure 4 *Contact resistivities with varying sulphide treatment time at constant 3.5% $(NH_4)_2S$*

In addition, we also investigated the effect of the concentration of the $(NH_4)_2S$ solution on the contact resistance as displayed in Fig. 5 showing that the contact resistance increases with the concentration above 3% $(NH_4)_2S$. Apparently, the thick sulphide layer formed following passivation is not favourable when an ohmic contact is desired. Probably, the thick sulphide layer gets formed at the metal–semiconductor surface with the higher concentration causing the higher contact resistance. This is also in good agreement with the result of Robinson and

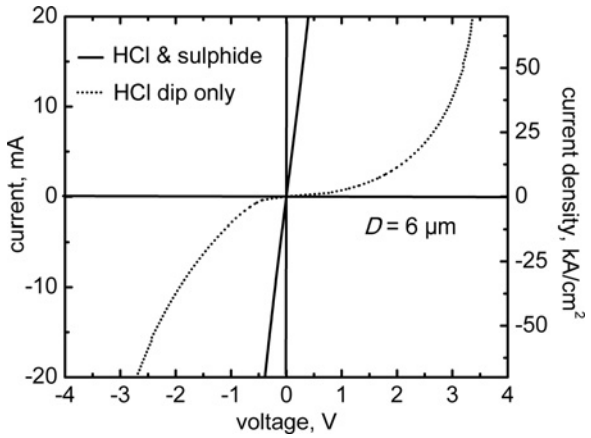

Figure 3 *I–V characteristics without annealing of the samples processed by HCl dip and sulphide (solid curve) and only HCl dip (dotted curve), respectively*

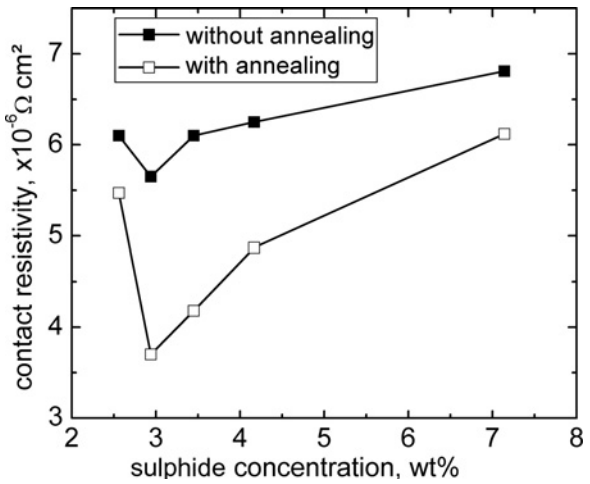

Figure 5 *Contact resistivities with varying sulphide concentrations at constant sulphide passivation time of 40 s*

Mohney [11]. Thus, by using 2.9% $(NH_4)_2S$ for 40 s as optimum sulphide treatment time, we found minimum contact resistivitiy values of approximately $5.6 \times 10^{-6}\ \Omega\ cm^2$ without any annealing and it improves to $3.7 \times 10^{-6}\ \Omega\ cm^2$ after annealing at 350°C for 90 s.

Note that we have not found any noticeable etching of the contact layer (InAsSb) while dipping in $(NH_4)_2S$ solution according to the result of Suyatin *et al.* [26]. However, it is observed that $(NH_4)_2S$-based solutions etch n- and p-GaSb at a steady rate [27].

Also, the sensitivity of the contact resistance on the Ti thickness was investigated. It has been found that the contact resistance decreases with decreasing Ti thickness. Therefore only 3 nm of Ti was evaporated at the topside in order to ensure good adhesion to the semiconductor surface. The reason for using Pt is to prevent the Au diffusion into the semiconductor. Its thickness does not have any influence on contact resistances but it ensures long-term thermal stability. The Au thickness also does not have any influence on contact resistances. The topside of 250 nm assures low mechanical damage on the contact pad while contacting with the probes.

The long-term stability of the contacts was also examined. The contact samples were left at ambient conditions for more than 2 months during which no reduction of the contact resistivities has been noticed.

Finally, the thermal stability of the contacts was checked by annealing the sample in N_2 ambient at 350°C for several hours. We did not find any deterioration of the contact resistance with annealing time as shown in Fig. 6. However, for annealing temperatures higher than 400°C, the degradation of the surface morphology at the backside became visible, because our backside contacts had to be formed on n-GaSb, which is affected at this high temperature. In addition, the degradation of the contact resistance started to appear at an annealing temperature of 450°C possibly because of Sb outdiffusion from the GaSb substrate. Additionally, also Au diffusion into the semiconductor takes place at such a high temperature in spite of the Pt diffusion barrier.

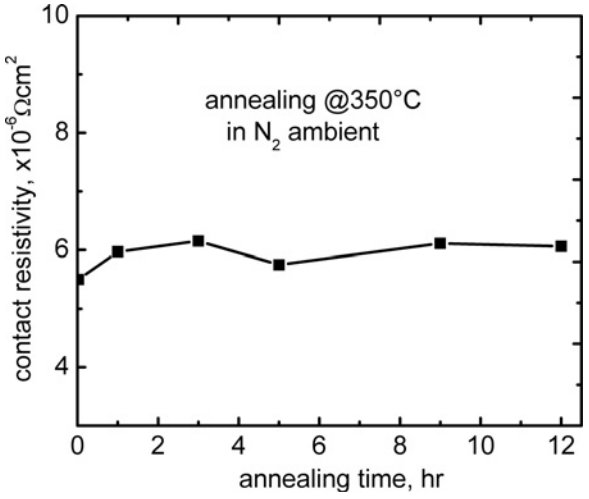

Figure 6 *Contact resisitivites of the Ti/Pt/Au contact on n^+-InAsSb for various annealing times*

4 Summary

In summary, we have investigated the fabrication of high-quality ohmic contacts to n-GaSb using a lattice-matched n^+-InAsSb contact layer. A simple surface preparation method using sulphidation prior to metallisation has been developed. Applying proper process parameters, n-contact resistances of 3.7×10^{-6} and $5.6 \times 10^{-6}\ \Omega\ cm^2$ are reproducibly obtained for annealed and non-annealed samples.

5 Acknowledgments

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