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Abstract

An investigation with the objective of improving n-type ohmic contacts to GaSb-based devices is described. This study involves a series of n-GaInAsSb and n-GaSb samples with varying doping, grown on both n-GaSb and semi-insulating GaAs substrates. These samples were fabricated into mesa-etched TLM structures, and the specific contact resistivity and sheet resistance of these layers as a function of majority electron concentration were measured. Extremely low specific contact resistivities of about 2×10^{-6} Ω-cm^2 and sheet resistances of about 4 $\Omega/\square$ are found for n-type GaInAsSb doped at about 3×10^{18} cm^{-3}.

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For applications ranging from high-speed electronics to optoelectronics, III-V antimonide-based compounds (including GaSb, GaInAsSb, and AlGaAsSb) have great potential. In these applications, high performance devices require low contact resistivity ohmic contacts. For example, the fill-factor of GaInAsSb/GaSb-based thermophotovoltaic (TPV) devices depends sensitively upon device series resistance, which is in turn dependant on the resistance due to the ohmic contacts. At present, device fabrication technology for the antimonides is at an early stage of development as compared to that for other III-V compounds, such as AlGaAs-GaAs. At the interface of GaSb, the Fermi level is pinned close to the valence band, so it is relatively more difficult to make low contact resistivity ohmic contacts to n-type GaSb than it is for the case of p-type GaSb. Previous work has focused on contacting directly to n-GaSb [1-6]. In the present work, we propose and demonstrate the utilization of n-type GaInAsSb as a contacting layer. An advantage of GaInAsSb as a contacting layer is that it can be lattice-matched to GaSb, and its smaller bandgap allows it to be directly incorporated into a device design, such as the base layer in a TPV p-n junction.

In this study, a series of samples with either n-type GaSb epilayers or n-type GaInAsSb epilayers (energy bandgap E_g~0.54 eV, lattice-matched to GaSb) was grown by organometallic-vapor-phase epitaxy (OMVPE) on both n-type GaSb substrates and on semi-insulating (SI) GaAs substrates [7]. The samples had epilayer thicknesses of 1 μm in the case of n-type GaInAsSb on n-type GaSb substrates, and 2 μm for samples grown on SI-GaAs substrates. The doping was varied from sample to sample in the range of low 10^{17} cm^{-3} to mid 10^{18} cm^{-3}, as will be described. The transfer length method (TLM), originally proposed by Shockley [8,9], was used to determine both the specific contact resistivity and sheet resistance of these samples. In this technique, the epilayers are mesa-etched down to the substrate material by wet chemical etching for electrical isolation. A ladder structure is fabricated on mesas by lift-off lithography and electron-beam metal evaporation, and appropriate alloy conditions are determined to make low resistance ohmic contacts. A Pd/Ge based metallization, similar to that employed in reference [1], was used to make shallow ohmic contacts to the thin n-type epilayers. The sequence of metals used in this study is Pd/Ge/Au/Pt/Au, with thicknesses of 70 Å/560 Å/230 Å /480 Å /2000 Å. By making measurements of the resistance between the differently spaced contacts on the ladder structure and measurements of end-resistance, both using a four-point probe setup, the specific contact resistivity and sheet resistance of the samples were extracted. A semiconductor parameter analyzer was used to collect the data, and approximately four hundred data points were collected for each current-voltage characteristic (for example, eight characteristics were collected for each ladder structure). These characteristics were fit to lines by the least-means-square fitting procedure, and the resistance was extracted from the fitted slopes.

In order to check the accuracy of TLM, additional samples were fabricated with metallization disks of varying diameters in order to compare TLM results with specific contact resistivity measured by the Cox-Strack method [10]. An n-type GaInAsSb sample grown on a SI-GaAs substrate was used to fabricate both TLM and Cox-Strack measurement structures. The doping of this sample was about 9.5×10^{17} cm^{-3}, and both samples were alloyed at 270° C for 60 seconds. In figure 1 (a) the ladder resistance measurements used in TLM determination of specific contact resistivity are shown, while in figure 1(b), disk resistance measurements used in Cox-Strack determination of specific contact resistivity are shown. Both techniques yield specific contact resitivities of about 1.3×10^{-5} Ω-cm^2, indicating excellent agreement between the two techniques.

In figure 2(a), measured contact resistivities are shown as a function of alloy temperature in an n-GaSb sample. The sample is fabricated using an n-GaSb epilayer, with a doping level of about 1.2×10^{18} cm^{-3}, grown on a SI-GaAs substrate. It is important to note that, in practice, only contact resistivities of less than about 2×10^{-3} Ω-cm^2 are truly ohmic, since their I-V characteristics are linear. Contact resistivities above 2×10^{-3} Ω-cm^2 are typically not ohmic, as their corresponding I-V characteristics are slightly nonlinear. However, the nonlinear characteristics are still fit to a linear relationship to obtain "effective" contact and sheet resistivities for contact resistivities above 2×10^{-3} Ω-cm^2. For n-GaSb samples, the minimum contact resistivity occurs at approximately 270 to 280 °C. For this highly doped sample the minimum contact resistivity obtained is about 1×10^{-5} Ω-cm^2. The n-GaSb epilayer sample is ohmic both before and after alloying, although specific contact resistivity can be reduced by more than one order of magnitude by alloying. Contact resistivity as a function of alloy temperature was also measured using n-GaSb samples with different doping levels, and also using samples fabricated using n-GaSb substrate material directly (n-GaSb substrate material typically has doping levels in the range of mid 10^{17} cm^{-3}). For all GaSb samples measured, independent of doping level, the minimum in contact resistivity occurs at the same temperature range, about 270 to 280 °C.

In figure 2(b), measured contact resistivities are shown as a function of alloy temperature for an n-GaInAsSb epilayer (with n-type doping level of about 3×10^{18} cm^{-3}) on a SI-GaAs substrate. The minimum contact resistivity occurs at a slightly lower temperature than for n-GaSb, namely, at a temperature of about 250 °C. The sheet resistance of the alloyed n-GaInAsSb epilayer is also considerably lower than that of the n-GaSb epilayers, typically about 4 Ω/□ instead of 12 Ω/□.

In figure 3(a), measured contact resistivities are shown for n-GaSb samples grown on n-GaSb substrates. The measured sheet resistances of these samples are shown in figure 3(b). In these figures, results are shown for both pre-alloy and post-alloy conditions. In this series, sample numbers 623 to 626 indicate samples whose epilayers have successively decreasing doping. Because the substrates are doped, Hall measurements do not give an accurate determination of epilayer doping levels. According to these measurements, GaInAsSb is a good material to make ohmic contacts to directly. The lowest contact resisitivity measured is for the most highly doped sample, 623. After alloying, the contact resistivity measured is about 8×10^{-6} Ω-cm^2. In practice, the sheet resistance has contributions from both the n-GaInAsSb epilayers and also the n-type GaSb substrate. Experimentally, it is not clear how to separate the contributions from the epilayer (of interest) and from the substrate (not of interest). This suggests the need to use SI-GaAs substrates to eliminate the effect of substrate conductivity. However, the drawback of using SI-GaAs substrates is that the GaSb-based epilayers are no longer lattice-matched.

In figures 4(a) and (b), the measured contact resistivity and sheet resistance are shown, respectively, for n-GaSb epilayers grown on SI-GaAs substrates. These data are plotted against the independently measured Hall doping level. Hall doping levels shown have not been corrected for multi-band conduction. Without the multi-band conduction correction, the doping levels reported here represent a lower bound on the doping level.

Contact resistivity of these samples follows the expected trend, i.e., it decreases as the doping level is increased, and the minimum contact resistivity measured for this set of samples is about 1×10^{-5} Ω-cm^2. The lowest sheet resistivities measured are about 12 Ω/☐. Also shown in the same figure are repeated measurements on the same samples measured several weeks after initial measurements were taken, and also repeated measurements on samples processed in a separate fabrication run. All of these measurements are nearly in perfect agreement, indicating both that the TLM technique used here is very reproducible, and that the Pd/Ge contacts to n-GaSb are stable over a period of (at least) weeks. In addition, it was found that the sheet resistance obtained using the Hall technique are in good agreement with those obtained by the TLM method (despite the fact that different contact metals were used in the Hall measurements), which is an indication of the consistency of the TLM method for measuring sheet resistance.

In figures 5(a) and (b), the measured contact resistivities and sheet resistances are shown, respectively, for n-GaInAsSb epilayers grown on SI-GaAs substrates. These data are also plotted against the independently measured Hall doping level. Contact resistivity of these samples follows the same trend as for the n-GaSb samples, and the minimum contact resistivity measured for this set of samples is about 2×10^{-6} Ω-cm^2, about five times lower than the lowest measured for n-GaSb on SI-GaAs substrates [see figure 4(a)]. The lowest sheet resistance measured is about 4 Ω/☐ Both of these minimum resistivities were obtained for the most highly doped sample under an alloy temperature of about 250 °C. Other post-alloy results are also shown for samples alloyed at 270 °C. The n-GaInAsSb epilayers can be doped at a higher level than the n-GaSb epilayers, so that contacting the quaternary layer directly results in improved ohmic contacts (doping levels of about 3×10^{18} cm^{-3} for the quaternary instead of about 1×10^{18} cm^{-3} for GaSb). This is the first report of extremely low resistivity ohmic contacts to n-GaInAsSb.

From a device standpoint, it is of interest to determine whether the Pd/Ge metallization remains shallow after alloying. One technique to check this, which is of immediate relevance from a device viewpoint, is to fabricate shallow p-n junction devices for metallization test structures. Therefore, two GaSb-based p-n junctions were grown. On an n-GaSb substrate, a 3-μm thick p-GaSb layer, with a doping level of 2.2×10^{18} cm^{-3}, was grown (p-on-n structure). On a p-GaSb substrate, a 1-μm thick n-GaSb layer, with a doping level of 1×10^{18} cm^{-3}, was grown (n-on-p structure). Mesa-etched square diodes with dimensions of 300×300 μm were fabricated. The same Pd/Ge metallization used in the TLM study was used for both the n-type and p-type contacts, which were deposited on the front-sides and backsides of the samples. The fabrication sequence for both samples was such that the n-type ohmic contact was deposited and alloyed first, so that the p-type metal was entirely not alloyed (which is also a consistency check that the p-type Pd/Ge ohmic contacts do not require alloying).

Current-voltage characteristics are measured for the mesa diodes using the four-point probe technique, and are shown in figure 6(a) for the p-on-n structure, and in 6(b) for the n-on-p structure. In both characteristics, it is clear that the drift-diffusion regime, corresponding to diode ideality factor A of close to 1, occurs for both the n-on-p and p-on-n structures (diode ideality is approximately 1.3 for voltages between 0.4 to 0.5 V). At positive voltages below this regime, the ideality factor is close to or greater than 2 due to effects such as surface recombination [11] and shunt resistance, while at higher forward biases, the ideality factor is again close to 2 due to effects such as high injection and series resistance. The fact that the drift-diffusion regime appears similar in the cases of p-on-n and n-on-p structures indicates that the n-type Pd/Ge ohmic contacts are likely not diffusing though the junction after alloying, i.e., that the contacts are shallow (at least less than 1 μm alloy depth).

In summary, a study of specific contact resistivity and sheet resistance as a function doping level in n-type GaSb and n-type GaInAsSb is reported. Extremely low specific contact resistivities of about 2×10^{-6} Ω-cm^2 and sheet resistances of about 4 Ω/□ are found for n-type GaInAsSb doped at about 3×10^{18} cm^{-3}. GaSb-based p-n junctions using the Pd/Ge scheme were also fabricated to show that the ohmic contact scheme is shallow for n-type GaSb.

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Figure Captions

Figure 1. (a) Resistance as a function of distance between contacts d, used for TLM method, in n-GaInAsSb sample grown on SI-GaAs. (b) Resistance as a function of inverse disk radius, used for Cox-Strack method, of same sample in (a).

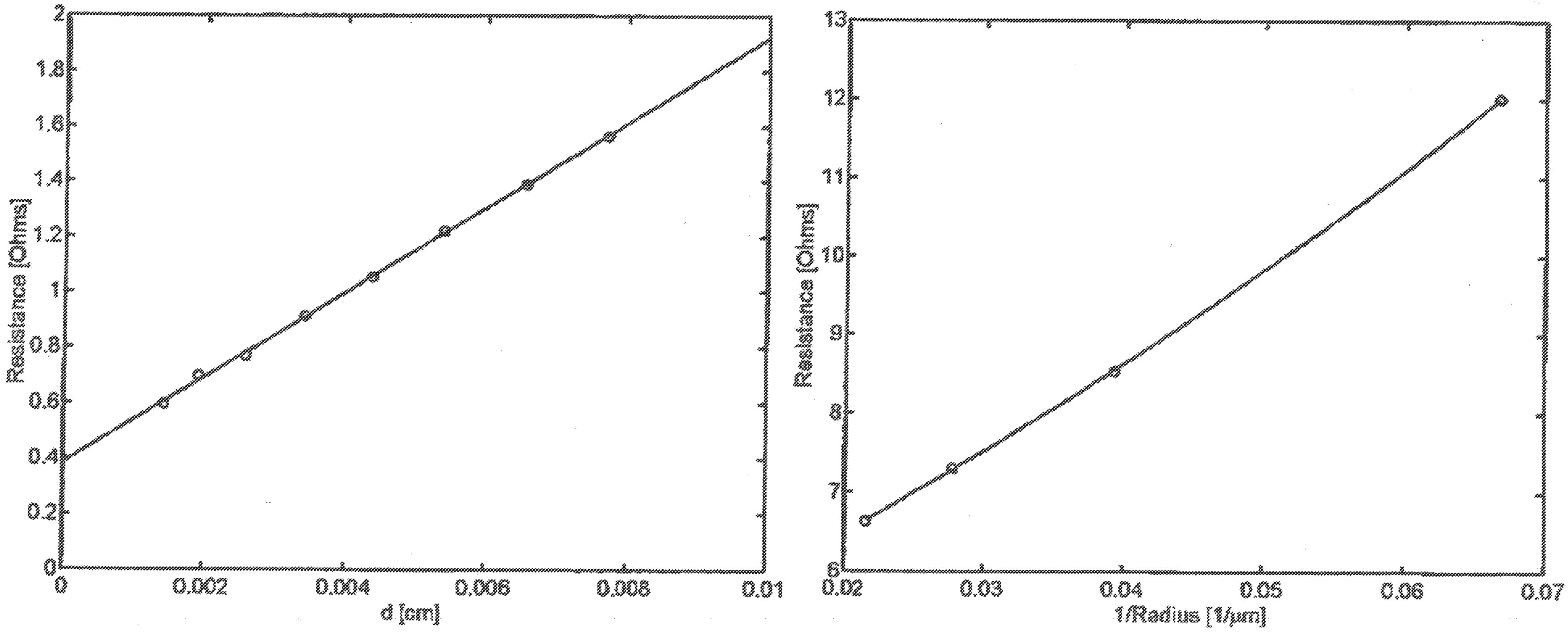
Figure 2. (a) Specific contact resistivity as a function of alloy temperature for four n-GaSb samples. (b) Specific contact resistivity as a function of alloy temperature for n-GaInAsSb sample.

Figure 3. (a) Specific contact resistivity of n-GaInAsSb samples on n-GaSb substrates. Increasing sample number corresponds to decreasing doping level in the n-type GaInAsSb epilayer. (b) Sheet resistance of n-GaInAsSb samples on n-GaSb substrates. In (a) and (b), circles represent pre-alloy data, while squares represent post-alloy data.

Figure 4. (a) Specific contact resistivity as a function of electron concentration for n-GaSb samples on SI-GaAs substrates. Electron concentration was measured by Hall, and is not corrected for multi-band conduction. (b) Sheet resistance as a function of electron concentration for n-GaSb samples on SI-GaAs. In (a) and (b), circles and stars represent pre-alloy data, while squares, diamonds, and triangles represent post-alloy data.

Figure 5. (a) Specific contact resistivity as a function of electron concentration for n-GaInAsSb samples on SI-GaAs substrates. Electron concentration was measured by Hall, and is not corrected for multi-band conduction. (b) Sheet resistance as a function of electron concentration for n-GaInAsSb samples on SI-GaAs. In (a) and (b), circles represent pre-alloy data; squares represent post-alloy data after alloying at 270° C for 60 seconds; and diamonds represent post-alloy data after alloying at 250° C for 60 seconds.

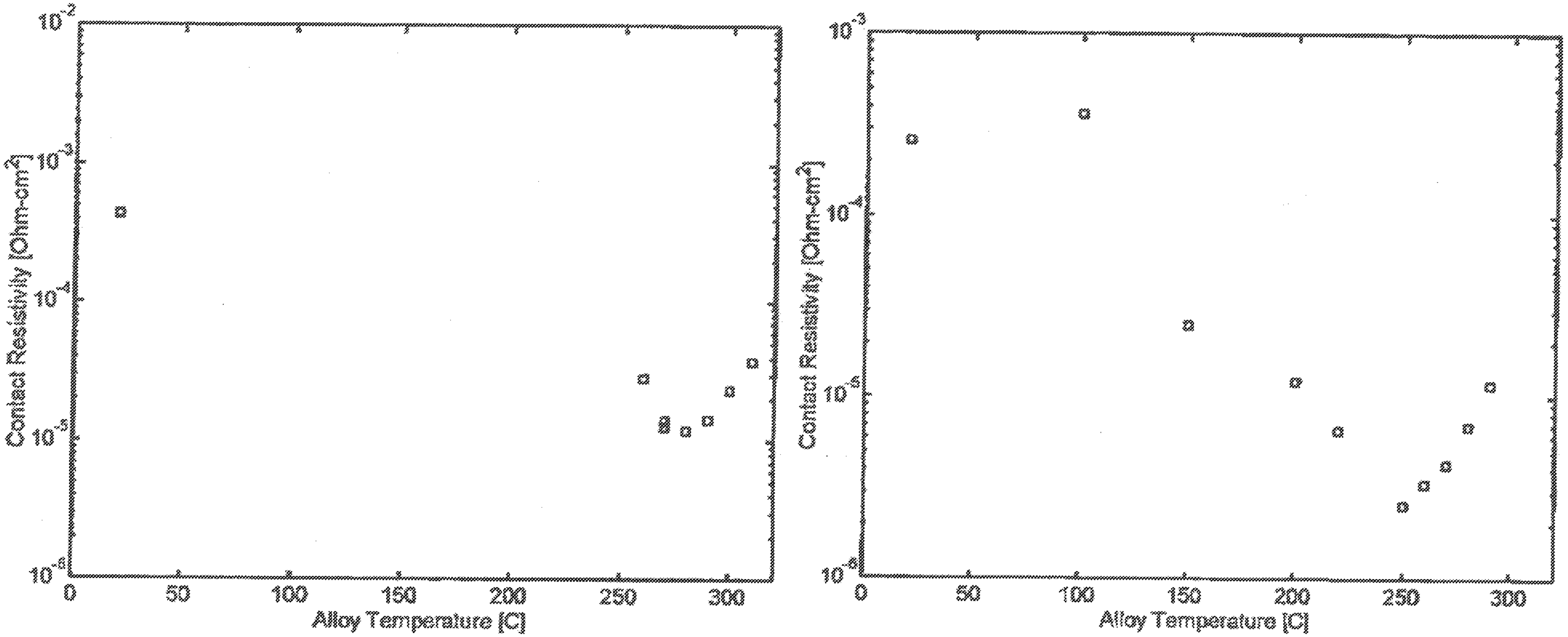
Figure 6. (a) Current-voltage characteristic of p-on-n GaSb p-n junction. (b) Current-voltage characteristic of n-on-p GaSb p-n junction.


Resistance [Ohms]
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
0
0.002
0.004
0.006
0.008
0.01
d [cm]
Resistance [Ohms]
6
7
8
9
10
11
12
13
0.02
0.03
0.04
0.05
0.06
0.07
1/Radius [1/μm]

(a)

(b)

Figure 1

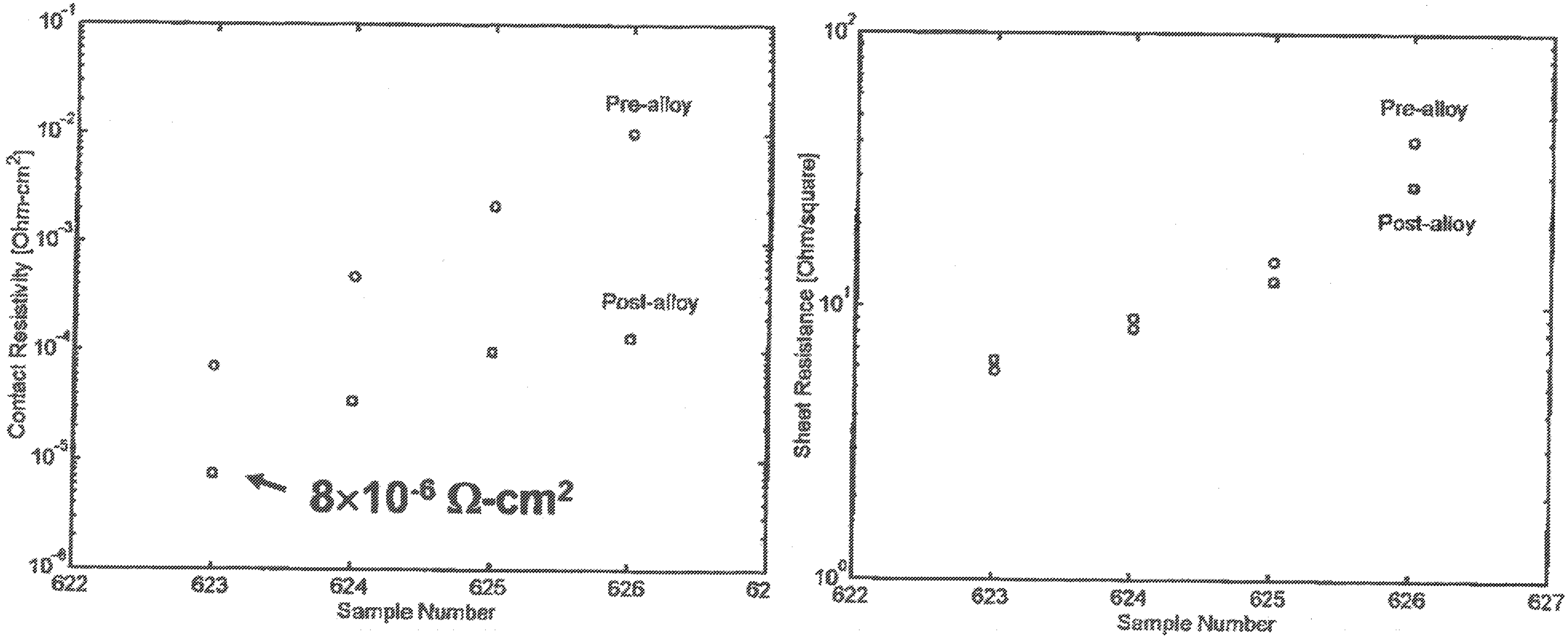


(a)

(b)

12

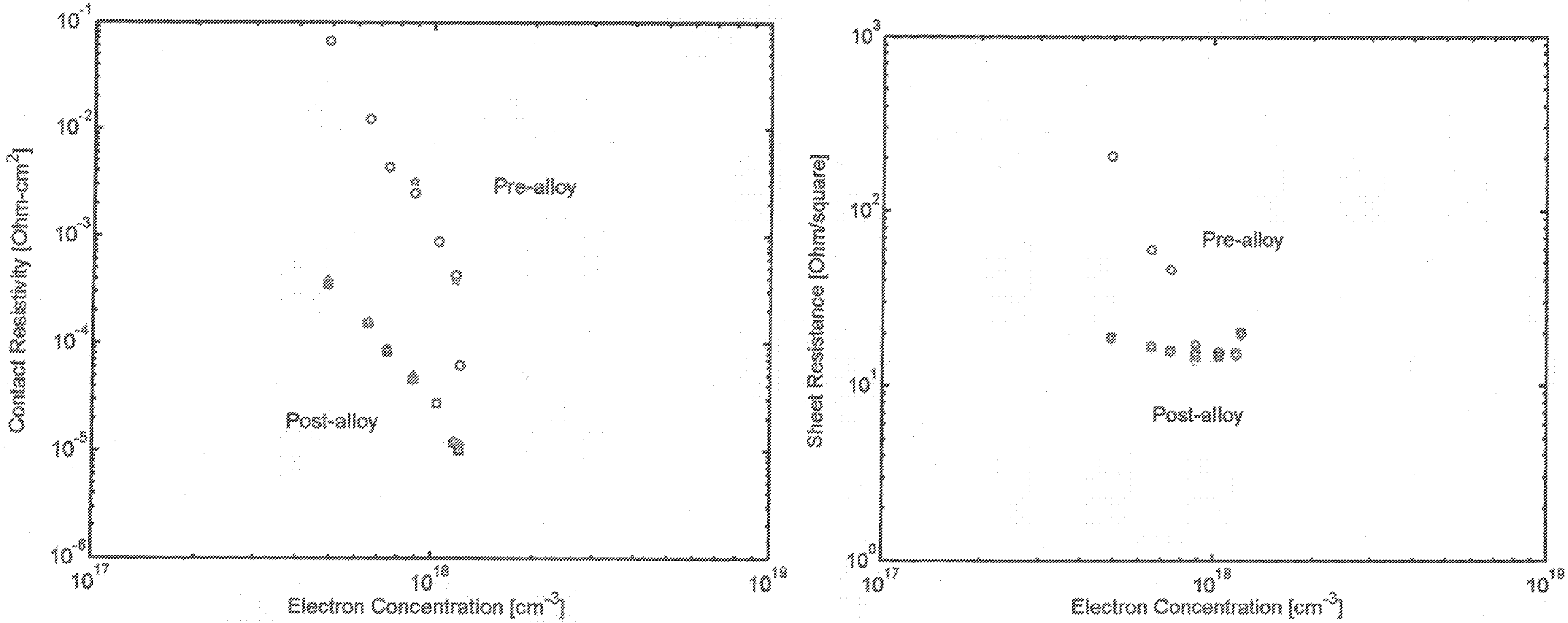
Figure 2


10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
Contact Resistivity [Ohm-cm^2]
Pre-alloy
Post-alloy
8×10^-6 Ω-cm^2
622
623
624
625
626
62
Sample Number
10^2
10^1
10^0
Sheet Resistance [Ohm/square]
Pre-alloy
Post-alloy
622
623
624
625
626
627
Sample Number

(a)

(b)

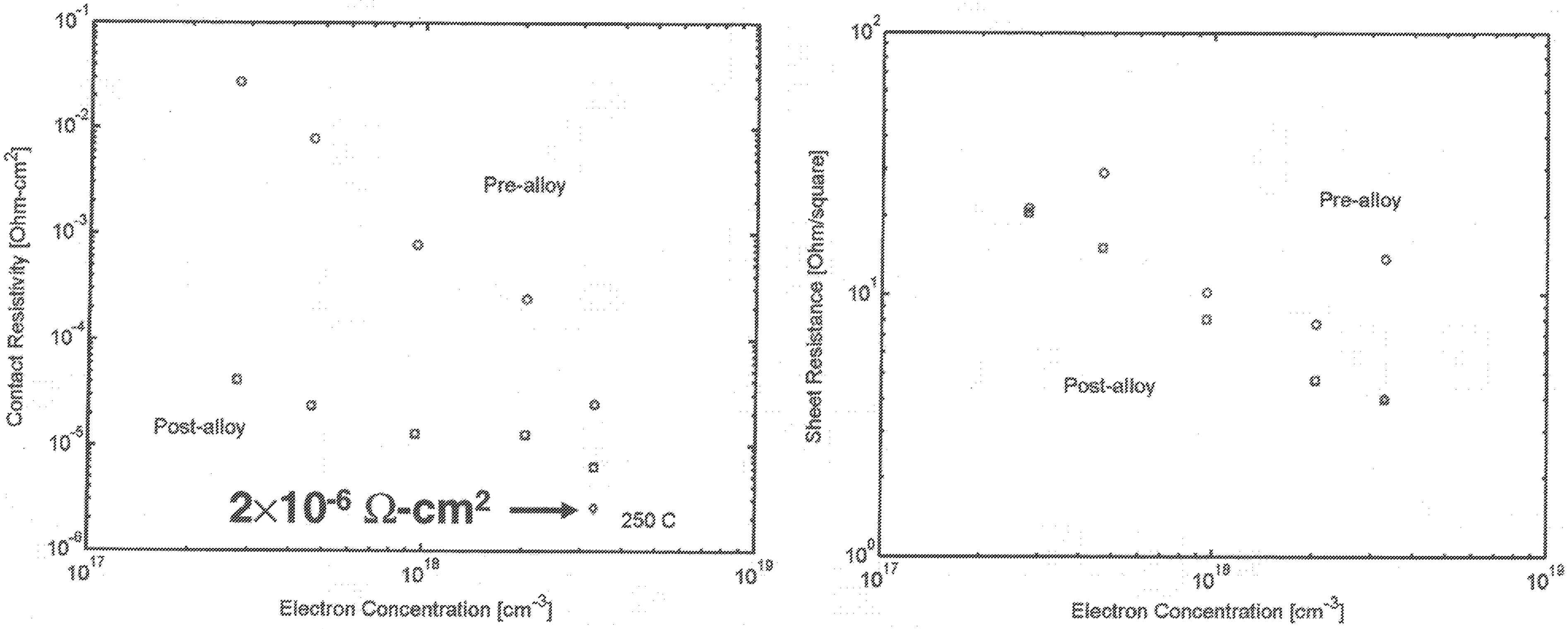
Figure 3



(a) **(b)**

14

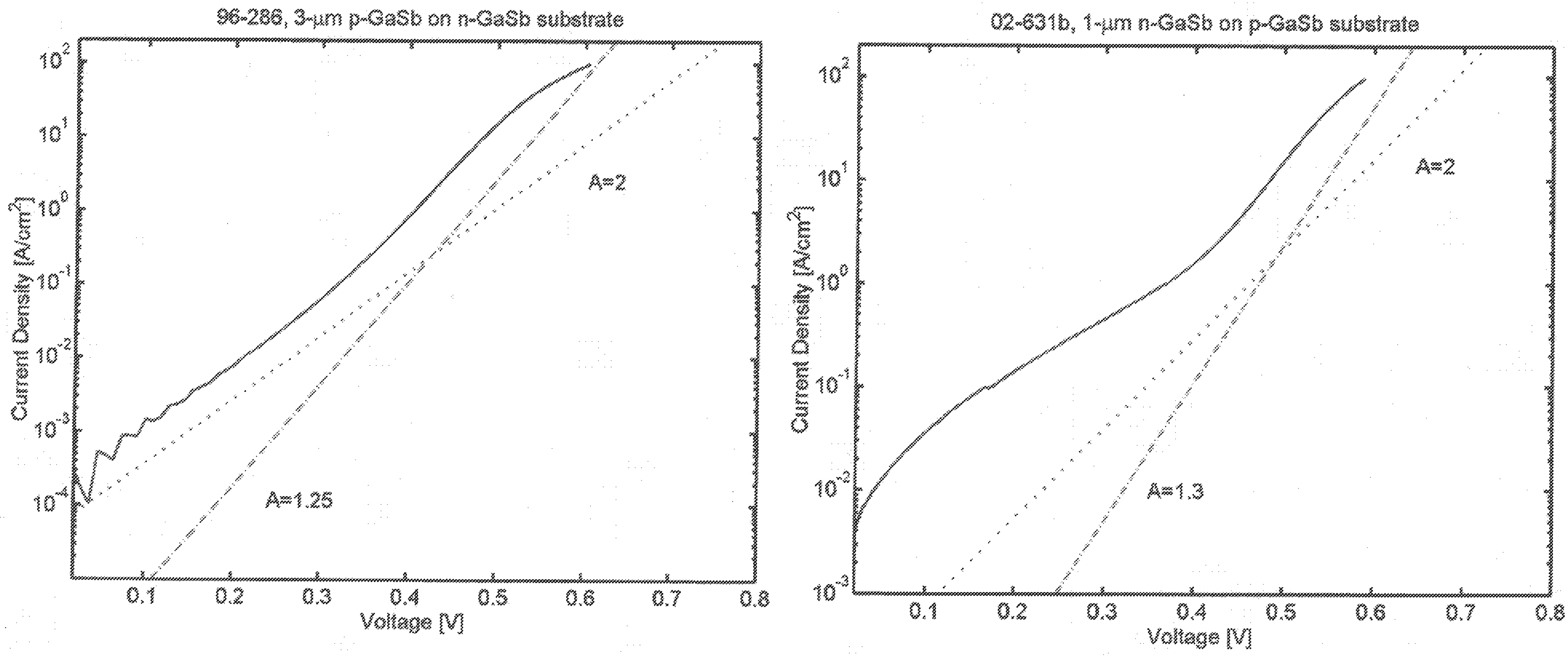
Figure 4


Contact Resistivity [Ohm-cm^2]
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
Pre-alloy
Post-alloy
2×10^{-6} Ω-cm^2 ⟶
250 C
10^{17}
10^{18}
10^{19}
Electron Concentration [cm^{-3}]
Sheet Resistance [Ohm/square]
10^{2}
10^{1}
10^{0}
Pre-alloy
Post-alloy
10^{17}
10^{18}
10^{19}
Electron Concentration [cm^{-3}]

(a)

(b)

Figure 5


96-286, 3-μm p-GaSb on n-GaSb substrate
Current Density [A/cm^2]
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
A=2
A=1.25
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
Voltage [V]
02-631b, 1-μm n-GaSb on p-GaSb substrate
Current Density [A/cm^2]
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
A=2
A=1.3
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
Voltage [V]

(a) **(b)**

Figure 6