



**AFRL-RX-WP-TM-2010-4192**

**COLLABORATIVE RESEARCH AND DEVELOPMENT  
(CR&D)**

**Delivery Order 0071: Magneto-Transport Measurements on  
Nanostructured Semiconductors**

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**Universal Technology Corporation**

**NOVEMBER 2007**

**Final Report**

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<b>1. REPORT DATE (DD-MM-YY)</b> November 2007		<b>2. REPORT TYPE</b> Final		<b>3. DATES COVERED (From - To)</b> 19 April 2007 – 14 September 2007	
<b>4. TITLE AND SUBTITLE</b> COLLABORATIVE RESEARCH AND DEVELOPMENT (CR&D) Delivery Order 0071: Magneto-Transport Measurements on Nanostructured Semiconductors				<b>5a. CONTRACT NUMBER</b> F33615-03-D-5801-0071	
				<b>5b. GRANT NUMBER</b>	
				<b>5c. PROGRAM ELEMENT NUMBER</b> 62102F	
				<b>5d. PROJECT NUMBER</b> 4349	
				<b>5e. TASK NUMBER</b> L0	
				<b>5f. WORK UNIT NUMBER</b> 4349LOVT	
<b>6. AUTHOR(S)</b> Said Elhamri				<b>8. PERFORMING ORGANIZATION REPORT NUMBER</b> S-531-071	
<b>7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)</b> Universal Technology Corporation 1270 North Fairfield Road Dayton, OH 45432-2600				<b>9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)</b> Air Force Research Laboratory Materials and Manufacturing Directorate Wright-Patterson Air Force Base, OH 45433-7750 Air Force Materiel Command United States Air Force	
<b>9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)</b> Air Force Research Laboratory Materials and Manufacturing Directorate Wright-Patterson Air Force Base, OH 45433-7750 Air Force Materiel Command United States Air Force				<b>10. SPONSORING/MONITORING AGENCY ACRONYM(S)</b> AFRL/RXOB	
				<b>11. SPONSORING/MONITORING AGENCY REPORT NUMBER(S)</b> AFRL-RX-WP-TM-2010-4192	
<b>12. DISTRIBUTION/AVAILABILITY STATEMENT</b> Approved for public release; distribution unlimited.					
<b>13. SUPPLEMENTARY NOTES</b> PAO Case Number: 88ABW-2010-1202; Clearance Date: 16 Mar 2010. Report contains color.					
<b>14. ABSTRACT</b> This research in support of the Air Force Research Laboratory Materials and Manufacturing Directorate was conducted at Wright-Patterson AFB, Ohio from 19 April 2007 through 14 September 2007. Temperature-dependent resistivity and Hall effect at a fixed field value of 0.5 T, variable-magnetic field Hall effect at temperatures below 20 K, and Shubnikov-de Haas measurements have been performed on InAs/GaSb quantum wells and superlattice and on AlGaIn/GaN heterostructures. The goal of the studies performed on InAs/GaSb superlattices, which were grown on a GaSb substrate, was to determine the impact of various growth conditions on the background carrier density and mobility. The work on the InAs/GaSb quantum wells, which were grown on a GaAs substrate, was aimed at evaluating the transport properties of these structures which were grown by a procedure that produces interface misfit formation to completely relax the lattice mismatch resulting from growing GaSb directly on GaAs. The purpose of the investigation of AlGaIn/GaN materials was to study the impact of a thin AlN interlayer, inserted between AlGaIn and GaN layers, on the transport properties of this heterostructure. While further work is still needed in each of the three projects, important achievements have been obtained in each of the areas. In this report, we highlight preliminary results in each of the three projects.					
<b>15. SUBJECT TERMS</b> Hall Effect, Shubnikov-de Haas, InAs/GaSb superlattice, AlGaIn/GaN, Heterostructure, Quantum Hall					
<b>16. SECURITY CLASSIFICATION OF:</b>			<b>17. LIMITATION OF ABSTRACT:</b> SAR	<b>18. NUMBER OF PAGES</b> 20	<b>19a. NAME OF RESPONSIBLE PERSON (Monitor)</b> Mark Groff <b>19b. TELEPHONE NUMBER (Include Area Code)</b> N/A
<b>a. REPORT</b> Unclassified	<b>b. ABSTRACT</b> Unclassified	<b>c. THIS PAGE</b> Unclassified			

## I. InAs/GaSb superlattice Project: The role of interface roughness scattering

The goal of this task is to study the impact of the various MBE growth methods on the background carrier density and mobility. Since our samples are grown on a GaSb substrate, it was imperative that we first establish the impact of the substrate on the transport parameters of our superlattices. A study of how the mobility, carrier density, and resistivity of the GaSb substrate vary as a function of temperature revealed that at temperatures below 20 K, the substrate freezes out. As can be seen in Figure 1 (a)-(c), this result indicates that for superlattices grown on GaSb a study to compare superlattices grown under different conditions has to be performed at temperatures below 20 K. While this Figure makes clear that at temperatures above 20 K the contribution of the substrate can not be ignored and in fact will quickly dominate conduction as the sample temperature rises, it also assures that at 10 K we can be confident that the contribution of the substrate to the overall conduction in our samples is insignificant.

After establishing the role of the substrate, we studied the impact of the InAs layer width,  $L$ , on the mobility of our superlattices. Since InAs is the channel material, theory predicts that, for samples where interface roughness scattering is the dominant scattering mechanism, the mobility would exhibit a power law relationship with respect to the width,  $L$ , ( $\mu \sim L^6$ ).<sup>1</sup> Though many other studies, performed by different research groups, aimed at confirming this power law relationship have shown various results,<sup>2-5</sup> our study clearly confirms that this relationship is obeyed in our samples as can be seen in Figure 2 which shows that our 10 K Hall mobility data is very well fitted with the power law dependence given by :

$$\mu = (6.32 \times 10^{-8})L^{6.20},$$

where the mobility is in  $\text{cm}^2/\text{Vs}$  and the InAs layer width  $L$  is in angstroms. The solid line is the best fit to our Hall mobility data obtained at 10 K.

*Since the mobility of our superlattices does indeed follows the  $L^6$  ( $\mu \sim L^{6.20}$ ), power law dependence on the well width, we conclude that interface roughness scattering is the dominant scattering mechanism in our samples at low temperatures.*

## **II. AlGaN/GaN on Silicon: Impact of an AlN interlayer**

The purpose of this project was to determine the influence of inserting a very thin (10Å) AlN layer between GaN and AlGaN on the transport behavior. Basically, the project was to compare the transport properties of the conventional AlGaN/GaN heterostructure (Structure A) to those of the new AlGaN/AlN/GaN heterostructure (Structure B). Structure details on the two samples, which were both grown on silicon by MOCVD, are provided in Figure 3.

The results of the variable temperature Hall effect measurements for both samples are presented in Figure 4 where the carrier density ( $n$ ) is plotted as a function of  $1000/T$  ( $K^{-1}$ ). The temperature dependence of the mobility ( $\mu$ ) for the two structures is shown in the inset. The temperature variation of carrier density and mobility for both samples is similar and is indicative of the presence of a high quality two dimensional electron gas (2DEG) in each structure. Clearly, the insertion of the AlN interlayer resulted in an increase in both  $n$  and  $\mu$  in the entire temperature range studied. However, its impact on  $\mu$  is more significant. At 300 K,  $n$  and  $\mu$  in structure A were  $8.57 \times 10^{12} \text{ cm}^{-2}$  and  $1523 \text{ cm}^2/\text{Vs}$ ; whereas those for structure B were  $10.03 \times 10^{12} \text{ cm}^{-2}$  and  $1937 \text{ cm}^2/\text{Vs}$ , respectively. While the density in both structures remained relatively unchanged over the 10 K- 300 K ranged studied, the mobility increased to  $6032 \text{ cm}^2/\text{Vs}$  and  $10700 \text{ cm}^2/\text{Vs}$  for structures A and B at 10 K, respectively. The lack of a temperature variation of  $n$  with  $T$  is a good indicator that parallel conduction is absent in our structures. The large increase in the mobility is believed to be due to the presence of the AlN

interlayer in structure B. The AlN layer appears to eliminate or reduce alloy scattering which is an important scattering mechanism, especially at low temperatures, in the conventional AlGaN/GaN structures regardless of the substrate type used for growth. The larger conduction band offset between AlN and GaN leads to a much stronger confinement of the 2DEG, inhibiting the penetration of the wave function into the AlGaN layer, which results in reduced alloy scattering.<sup>6,7</sup>

To further characterize our samples, we performed Shubnikov-de Haas (SdH) measurements at 1.2 K. These type of measurements are particularly suited for two dimensional electron gas as they can provide a wealth of information on the transport parameters; including the carrier density, effective mass, and scattering times. As can be seen from Figure 5, where the second derivative of the longitudinal resistance is plotted as a function of B, well-defined SdH oscillations are clearly present in both structures. However, at first glance, the amplitude of the oscillations for the AlGaN/GaN structure appear to be much larger, an indication that  $\tau_q$  for structure A is much longer than that of structure B which was not expected since the AlGaN/GaN structure had a lower Hall mobility. However, care must be exercised when comparing the amplitudes of SdH oscillations originating from different samples. Since the AlGaN/AlN/GaN sample had a higher carrier density, it will have a different number of Landau levels filled at any particular field B than the AlGaN/GaN sample. Therefore, a proper comparison must be made between amplitudes that correspond to the same Landau Level (filling factor). Our analysis revealed that though the quantum scattering is indeed higher for structure A, the difference between the quantum scattering times for the two structures is not as large as the data in Figure 5 indicates at first glance.

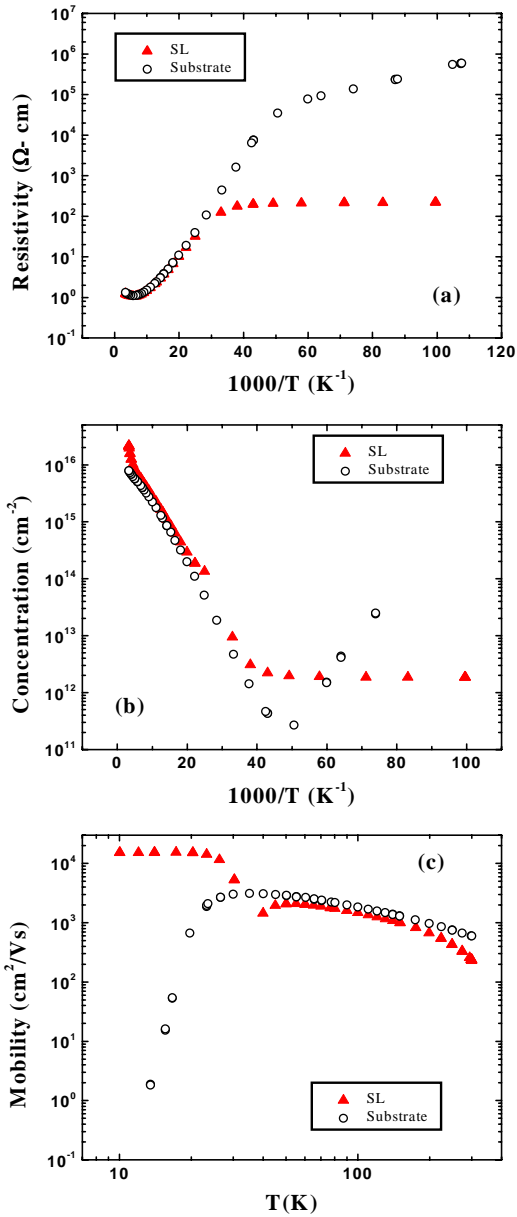
### III. InAs/GaSb quantum wells: An alternative growth method of InAs/GaSb on GaAs.

The overall goal of this project was to explore an alternative growth method for InAs/GaSb single quantum wells on a GaAs substrate. Basically the method uses a procedure which produces interface misfit formation to completely relax the mismatch between GaAs and GaSb lattices. The advantage of the method is it requires a thinner GaSb buffer layer compared to the most commonly used method for growing these quantum wells. My specific task was to conduct a transport characterization of the material.

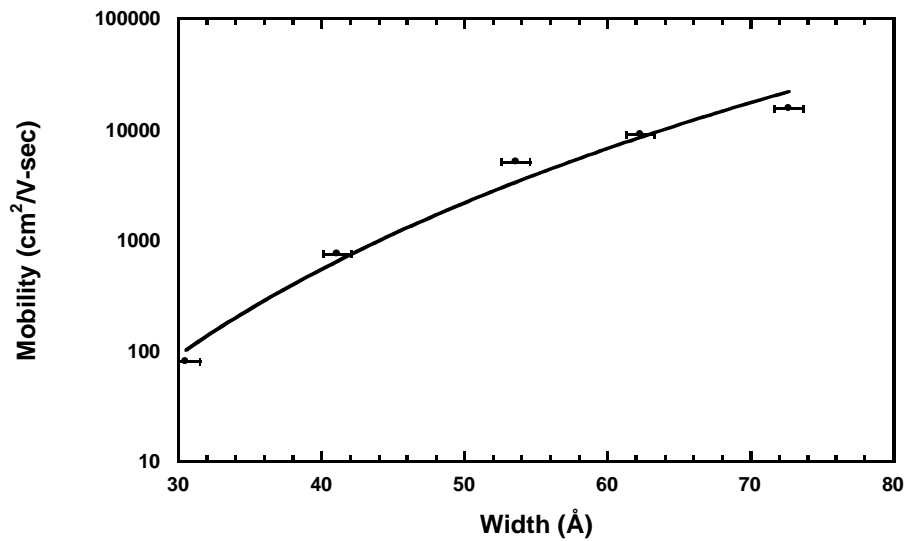
The results of the variable temperature Hall effect measurements are summarized in Figure 6 which shows how the carrier density and mobility vary with the temperature as the sample was warmed from 10 to 300 K. The temperature variations of both  $n$  and  $\mu$  are indicative of a two dimensional electron gas as they are both insensitive to  $T$  at low temperatures. At 300 K, the mobility and the carrier density were  $13900 \text{ cm}^2/\text{Vs}$  and  $2.3 \times 10^{12} \text{ cm}^{-2}$ . At 10 K the mobility increased to  $21600 \text{ cm}^2/\text{Vs}$  while the carrier density decreased to  $6.92 \times 10^{11} \text{ cm}^{-2}$ . The mobility peaked at  $\sim 60 \text{ K}$  where it was calculated to be roughly  $25000 \text{ cm}^2/\text{Vs}$ .

To characterize the sample further, magnetoresistance data was collected at 1.2 K in fields up to 8 T. These measurements indicated the presence of well defined Shubnikov-de Haas oscillations in the longitudinal resistance,  $R_{xx}$ , and well defined quantum Hall plateaus in the transverse resistance,  $R_{xy}$ . These results, shown in Figure 7, clearly confirm the presence of a high quality 2DEG in this structure. The carrier density of the 2DEG obtained from the SdH oscillations was roughly  $5.4 \times 10^{11} \text{ cm}^{-2}$  which is slightly lower than the value of roughly  $6 \times 10^{11} \text{ cm}^{-2}$  obtained from the low field Hall data. Though the difference between the two numbers is very small, it might be an indication that a small amount of parallel conduction is present in our sample. However, the presence of well defined plateaus is a very good indication that even if

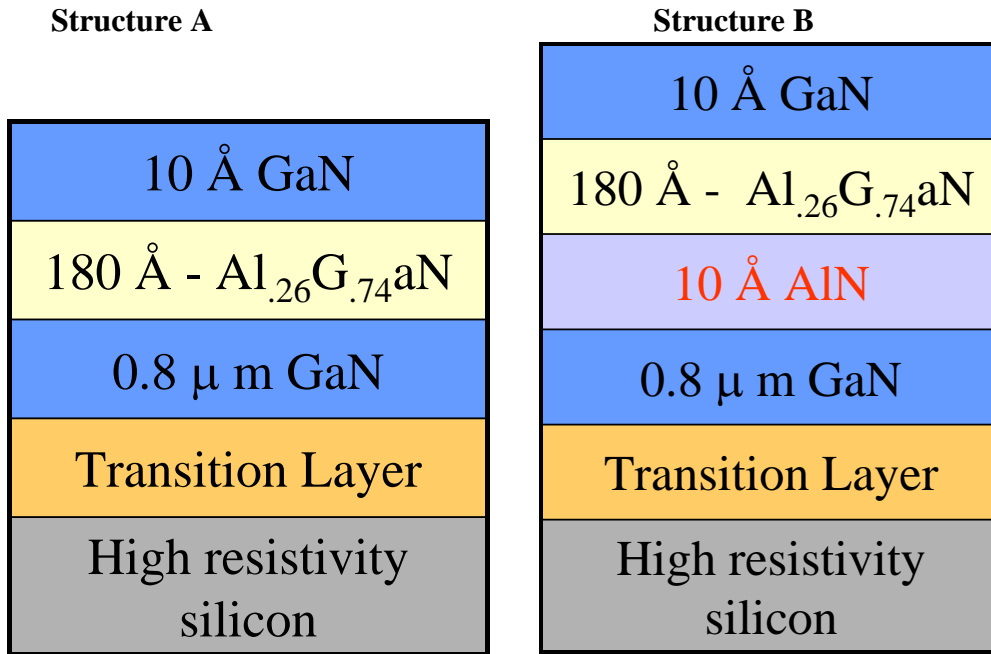
some parallel conduction might be present, its overall contribution to conduction in our sample is not significant. The data in Figure 6 clearly indicates the presence of a high quality 2DEG in our structure.



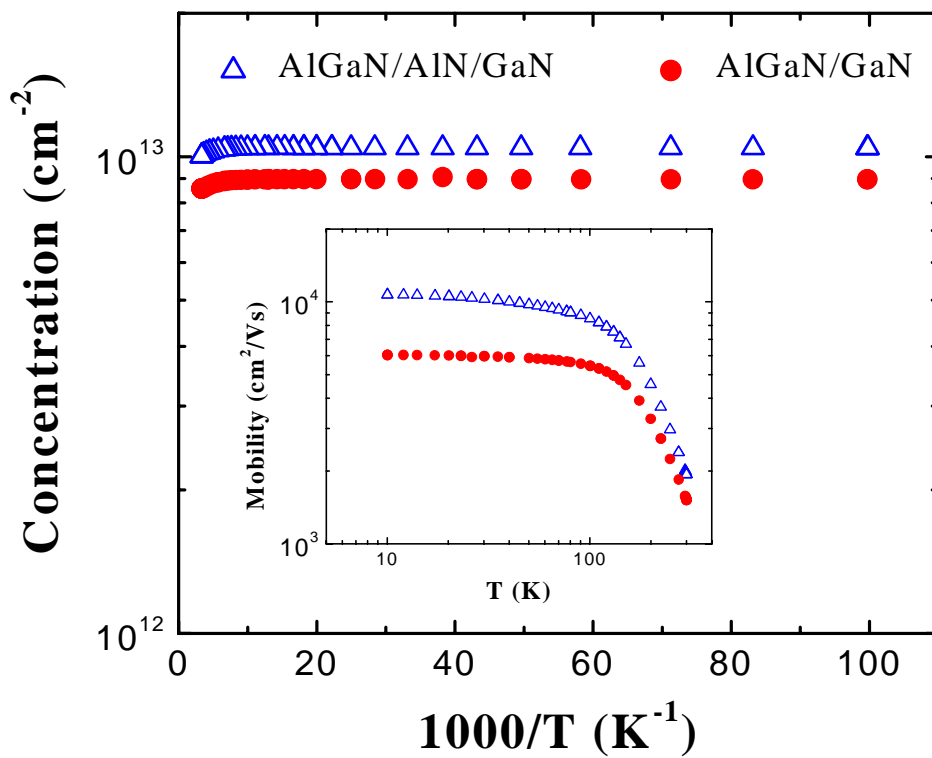
**Figure 1:** A comparison of the resistivity (a), carrier density (b) and mobility (c) of the GaSb substrate and a superlattice to show that at 10 K, the contribution to conduction from the substrate is insignificant.



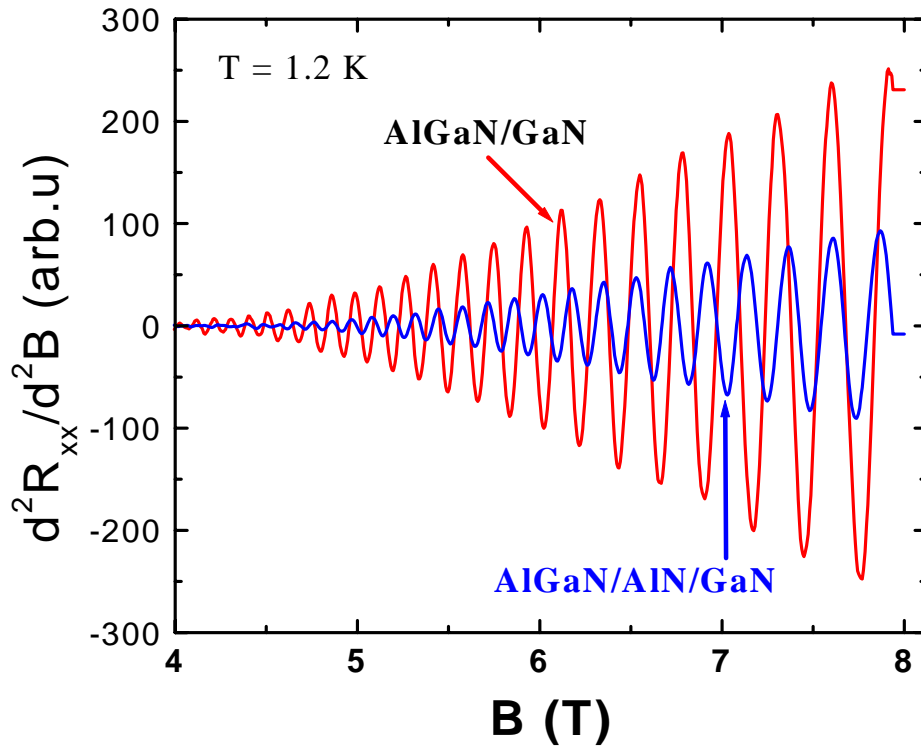
**Figure 2:** The 10 K Hall mobility in cm<sup>2</sup>/Vs of the superlattices as a function of the InAs Well width L is in angstroms. The line is represents the best fit.



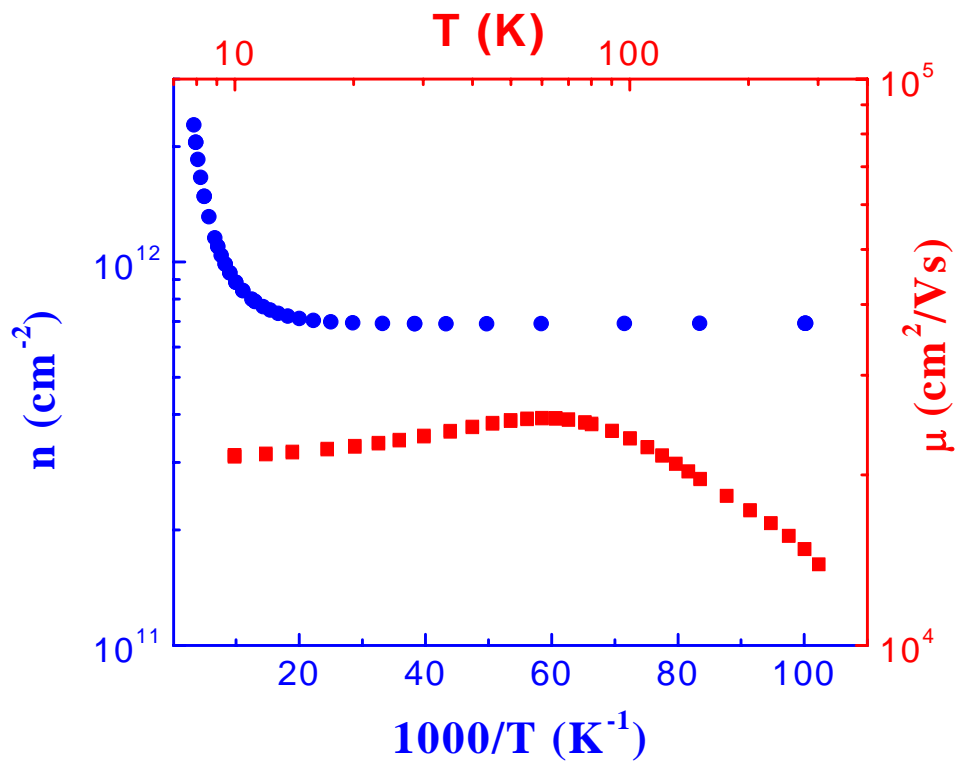
**Figure 3:** Layer-schematic of the two structures used in this study. Structure A is the conventional structure while Structure B contains the AlN interlayer.



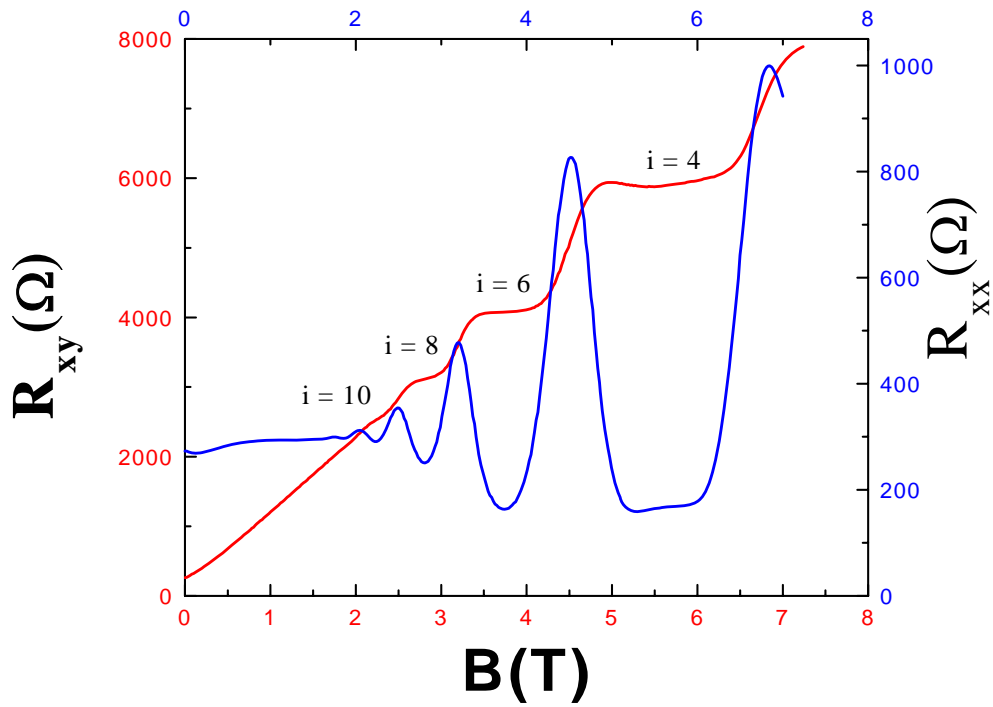
**Figure 4:** Variable-temperature carrier density and mobility as a function of  $1000/T$  for the two structures.



**Figure 5:** The second derivative of the longitudinal resistance,  $R_{xx}$ , for the two samples as a function of  $B$  at  $T = 1.2$  K. Data was smoothed to remove noise.



**Figure 6.** Temperature dependence of the carrier density (solid circles) and mobility (solid squares) obtained from the Hall and resistivity measurements. The mobility peaks at about 60 K.



**Figure 7.** Longitudinal magnetoresistance,  $R_{xx}$ , and the Hall resistance,  $R_{xy}$ , at  $T = 1.2\text{K}$ . The Hall data exhibits well defined plateaus and the magnetoresistance manifests well-defined Shubnikov-de Haas oscillations. The minimum in  $R_{xx}$  corresponding to the 10<sup>th</sup> filling factor is truncated due to instruments problems.

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