

Reduction of the unintentional background electron density in AlSb/InAs/AlSb quantum wells

C. Kadow,^a H.-K. Lin,^a M. Dahlström,^a M. Rodwell,^a A.C. Gossard,^a
B. Brar,^b G. Sullivan^b

^a*ECE Department, University of California, Santa Barbara, CA 93106-9560*

^b*Rockwell Scientific, Thousand Oaks, CA 91360*

Elsevier use only: Received date here; revised date here; accepted date here

Abstract

InAs quantum wells clad by AlSb barriers contain an unintentional electron density of approximately $1 \times 10^{12} \text{ cm}^{-2}$. This report concerns the compensation of these electrons by p-type modulation doping with Be. The electron concentration in the InAs quantum well decreases linearly with increasing Be doping as expected from lever rule arguments. Hall measurements show that the electron mobility increases with increasing electron concentration at temperatures between 10 K and 300 K. These findings need to be considered in the design of field-effect transistors based on this material system.

A1. Doping; A3. Molecular beam epitaxy; B1. Antimonides; B3. High electron mobility transistors

1. Introduction

InAs/AlSb quantum wells are of interest in high-frequency low-noise heterojunction field effect transistors (HFETs) [1,2]. This is mainly due to the high room-temperature electron mobility of $30,000 \text{ cm}^2/\text{Vs}$ and the large conduction band offset of 1.3 eV. Undoped InAs quantum wells contain an unintentional electron density of approximately $1 \times 10^{12} \text{ cm}^{-2}$. Important device parameters, such as the threshold voltage of HFETs, are directly related to the electron concentration in as-grown InAs quantum wells. Several groups have studied the origin of these electrons [3,4,5,6] and have found several sources: the surface, the InAs/AlSb interfaces and unintentional doping of the AlSb. In this report we address the reduction of this unintentional electron concentration. Our approach is based on p-type modulation doping. We investigate in detail how this approach affects the electron density and mobility at temperatures between 10 K and 300 K. Note that there is one report in the literature on InAs-based HFETs, in which Be-doping is used to reduce the threshold voltage [2].

2. Experiment

For this work several samples were grown by molecular beam epitaxy (MBE) using a Varian Gen II MBE machine. The fluxes of the group III elements and the Be dopants were provided by standard effusion cells. Both group V fluxes were generated by valved crackers. The sample temperature was measured with a pyrometer facing the growth front. The samples were grown metamorphically on (100) semi-insulating GaAs substrates. On top of an AlSb-based buffer [7], the device structures were deposited: First, a short-period AlSb/GaSb superlattice with an average Al content of 80% was grown at a temperature of 530°C. This superlattice was followed by a 300 Å AlSb back barrier, an 130 Å InAs quantum well, a 200 Å AlSb top barrier and a 75 Å GaSb cap layer, which were all grown at a temperature of approximately 490°C. Both interfaces of the InAs quantum well were forced to be InSb-like as described by Tuttle *et al.* [8]. Be modulation doping was introduced as a delta-doping sheet in the top barrier, setback by 50 Å from the quantum well. The Be doping levels were varied from no doping to $1.5 \times 10^{12} \text{ cm}^{-2}$. The Be-flux was determined from bulk doping calibrations in AlSb. Similar to previous reports [9], we find that Be is a well-behaved p-type dopant in AlSb. The doping efficiency of Be in AlSb was essentially identical to its doping efficiency in GaAs.

Samples were prepared for Hall measurements in van der Pauw geometry by cleaving square pieces from the wafers and alloying In contacts at their corners. Hall measurements were performed at temperatures between 10 K and 300 K in a closed-cycle cryostat.

3. Results

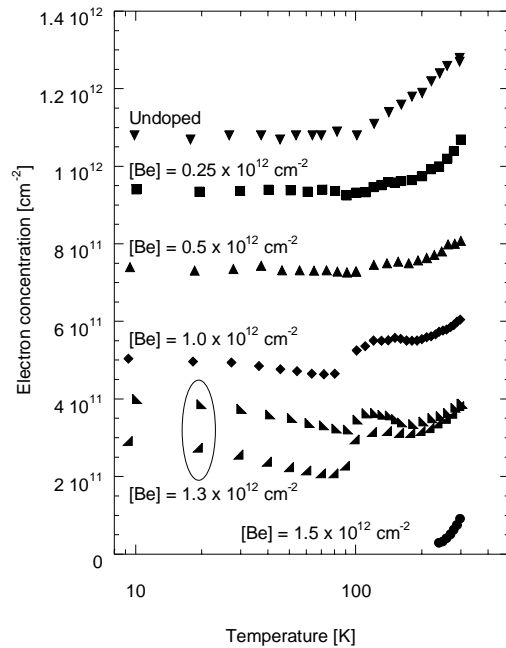


Fig. 1: Electron concentration for different temperatures and Be doping levels as determined by Hall measurements.

Hall measurements showed that the conduction was n-type for every sample at all temperatures between 10 K and 300 K. As shown in Figure 1, the electron concentration decreased with increasing Be doping at all temperatures. In the undoped and low-doped samples, the electron concentration is by and large independent of temperature at temperatures below approximately 100 K. At temperatures above 100 K, the electron concentration increases slightly with increasing temperature. This agrees with what has been reported before [3,4]. For the higher doping levels of $1.0 \times 10^{12} \text{ cm}^{-2}$ and $1.3 \times 10^{12} \text{ cm}^{-2}$, we find a slight temperature dependence at low temperatures. In the highest doped samples ($[\text{Be}] = 1.5 \times 10^{12} \text{ cm}^{-2}$), the carriers froze out at 230 K.

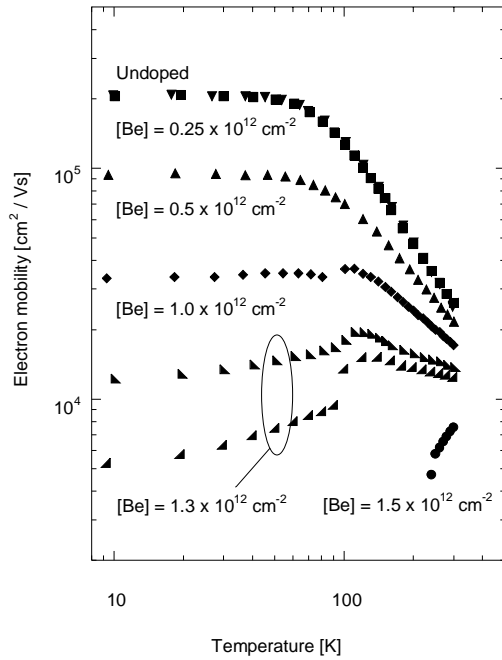


Fig. 2: Electron mobility for different temperatures and Be doping levels as determined from Hall measurements.

The electron mobilities of the same samples are shown in Figure 2. We find essentially identical data for the undoped sample and the sample with the lowest Be doping level of $2.5 \times 10^{11} \text{ cm}^{-2}$. For higher doping levels, the mobilities decrease at all temperatures with increasing Be doping.

Note that there are multiple curves for the Be doping level of $1.3 \times 10^{12} \text{ cm}^{-2}$. The two curves are measured on two different samples from the same wafer. The data from the two samples agree at room-temperature and differ at low temperatures. At this point, we attribute the variation to spatial non-uniformity of the wafer. From our experiments, we know that this variation is not due to multiple cooling cycles or photoconductive effects. Further experimentation is needed to clarify this issue.

4. Discussion

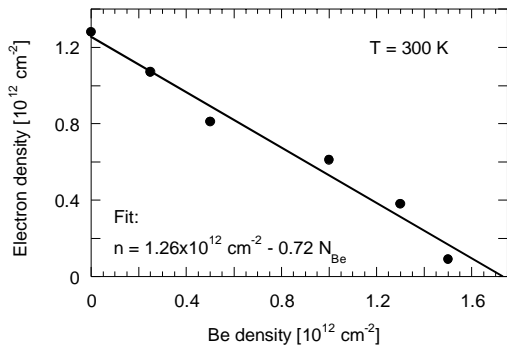
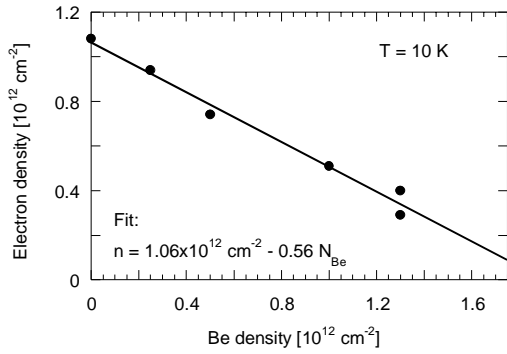
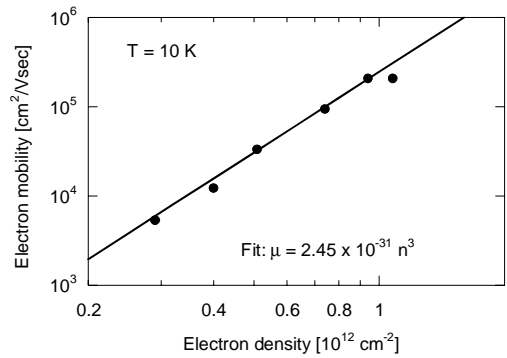


Fig. 3: Electron concentration as a function of Be doping at temperatures of 10 K and 300 K. The data are fitted with linear functions.

The two parts of Figure 3 show that the electron concentration decreases linearly with increasing Be concentration both at room-temperature and around 10 K. A linear dependence is indeed expected from straightforward lever-rule arguments. Note, however, that the slope is different at the two temperatures. We believe that the slope change is due to the fact that the electrons are due to different sources [3,4,5,6].



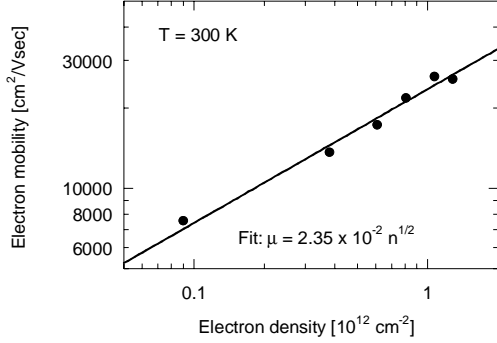


Fig. 4: Electron mobility as a function of electron density at temperatures of 10 K and 300 K. The data are fitted with power laws.

In Figure 4 we show the mobility as a function of the electron concentration for temperatures of 10 K and 300 K. The experimental data is fit well with power laws in both cases. At a temperature of 10 K, we find a cubic dependence. At room temperature, we find a square-root dependence.

The decrease in mobility with increasing Be doping level has two probable origins: First, the Be atoms cause ionized impurity scattering and second, the changing electron density changes the Fermi wavevector, which affects the relevant scattering mechanisms such as interface roughness scattering and phonon scattering. In the case of undoped InAs quantum wells, it has been shown that interface roughness scattering is the limiting scattering mechanism at low temperatures [7]. At room-temperature, the fact that the electron mobility is temperature dependent suggests a phonon scattering mechanism as the dominant scattering mechanism. We plan to publish a quantitative analysis in due course.

Regardless of the exact nature of the scattering mechanism, the reduction of the electron mobility with increasing Be doping level is reason for concern for its application to HFETs. After all, the high mobility is one of the main reasons for using InAs quantum wells in HFETs. It should be noted, however, that the exact requirements on the mobility depend on the application. For example, in small-signal applications, the electron velocity needs to be high at the operating point of the HFET. In addition, if the observed mobility reduction is determined by the change in Fermi wavevector rather than the scattering from Be atoms, it will be present in all InAs-based device.

5. Summary

In conclusion, we have demonstrated Be modulation doping as an effective way to control the channel charge in InAs quantum wells. A potential application is threshold control in InAs-based HFETs. Electron mobility and concentrations were studied at temperatures between 10 K and 300 K. The observed trade-offs between electron concentration and mobility need to be taken into consideration, when designing InAs-based HFETs.

6. Acknowledgements

This work was supported by the DARPA Antimonide-Based Compound Semiconductors Program under contract No. N66001-01-C-8032 (UCSB subcontract to Rockwell Scientific Corporation).

References:

- [1] J.B. Boos, W. Kruppa, B.R. Bennett, D. Park, S.W. Kirchoefer, R. Bass, and H.B. Dietrich, *Trans. Electron Devices* **45**, 1869 (1998).
- [2] Y. Zhao, M.J. Jurkovic, and W.I. Wang, *Solid-State Electron.* **42**, 57 (1998).
- [3] C. Nguyen, B. Brar, H. Kroemer, and J.H. English, *Appl. Phys. Lett.* **60**, 854 (1992).
- [4] C. Nguyen, B. Brar, H. Kroemer, and J.H. English, *J. Vac. Sci. Technol.* **B 10**, 898 (1992).
- [5] S. Ideshita, A. Furukawa, Y. Mochizuki, and M. Mizuta, *Appl. Phys. Lett.* **60**, 2549 (1992).
- [6] D.J. Chadi, *Phys. Rev. B* **47**, 13478 (1993).
- [7] M. Thomas, H.-R. Blank, K.C. Wong, and H. Kroemer, *J. Cryst. Growth* **175/176**, 894 (1997).
- [8] G. Tuttle, H. Kroemer, and J.H. English, *J. Appl. Phys.* **67**, 3032 (1989).
- [9] B.R. Bennett, W.J. Moore, M.J. Yang, and B.V. Shanabrook, *J. Appl. Phys.* **87**, 7876 (2000).