An $In_{0.15}Ga_{0.85}$ As/GaAs Pseudomorphic Single Quantum Well HEMT

J. J. ROSENBERG, M. BENLAMRI, P. D. KIRCHNER, J. M. WOODALL, AND G. D. PETTIT

Abstract—**This letter describes high electron mobility transistors (HEMT's) utilizing a conducting channel which is a single $In_{0.15}Ga_{0.85}As$ quantum well grown pseudomorphically on a GaAs substrate. A Hall mobility of 40 000 $cm^2/V \cdot s$ has been observed at 77 K. Shubnikov-de Haas oscillations have been observed at 4.2 K which verify the existence of a two-dimensional electron gas at the $In_{0.15}Ga_{0.85}As$/GaAs interface. HEMT's fabricated with 2-μm gate lengths show an extrinsic transconductance of 90 and 140 mS/mm at 300 and 77 K, respectively—significantly larger than that previously reported for strained-layer superlattice $In_xGa_{1-x}As$ structures which are nonpseudomorphic to GaAs substrates. HEMT's with 1-μm gate lengths have been fabricated, which show an extrinsic transconductance of 175 mS/mm at 300 K which is higher than previously reported values for both strained and unstrained $In_xGa_{1-x}As$ FET's. The absence of $Al_xGa_{1-x}As$ in these structures has eliminated both the persistent photoconductivity effect and drain current collapse at 77 K.**

I. INTRODUCTION

OVER THE PAST several years, interest in heterojunction devices for high-speed digital and microwave applications has increased dramatically. The vast majority of the reported heterojunction FET devices utilize $Al_xGa_{1-x}As$/GaAs heterojunctions in which electrons are transferred from the heavily doped $Al_xGa_{1-x}As$ to the narrower bandgap GaAs. This heterojunction system is used despite the fact that heavily doped $Al_xGa_{1-x}As$ tends to have a high density of deep levels including the so-called *DX* center. These traps are often cited as the cause of the persistent photoconductivity effect [1] and drain current collapse [2] at reduced temperatures. The primary motivation for using the $Al_xGa_{1-x}As$/GaAs system is that $Al_xGa_{1-x}As$ is latticed matched to GaAs over the entire compositional range. This allows for the formation of high-quality heterojunctions which are not dominated by misfit dislocations which can arise when a lattice-mismatched pair of semiconductors is used.

As predicted by van der Merwe [3] and demonstrated by several authors [4], [5], a lattice-mismatched layer can be grown sufficiently thin so that the mismatch is accomodated entirely as elastic strain. In this situation the interface between the materials is essentially free from misfit dislocations and the thin layer is *pseudomorphic*. This suggests that heterojunction systems other than $Al_xGa_{1-x}As$/GaAs might be useful for devices provided that only a thin layer of one of the materials is needed. In this letter we report on HEMT's which utilize an $In_{0.15}Ga_{0.85}As$/GaAs heterojunction in which electrons are transferred from the heavily doped GaAs to the narrower bandgap $In_{0.15}Ga_{0.85}As$ (which is grown pseudomorphically on a GaAs substrate). The $Al_xGa_{1-x}As$ is eliminated from the device and no persistent photoconductivity or drain current collapse is observed. We find that the extrinsic transconductance (per unit gate width) of FET's fabricated on pseudomorphic $In_{0.15}Ga_{0.85}As$ is significantly larger than that of previously reported nonpseudomorphic strained layer $In_xGa_{1-x}As$ devices [6] having a 2-μm gate length (noting that the maximum 300 and 77 K transconductances of 84 and 140 mS/mm obtained in [6] were from a multi-quantum well structure which was simultaneously gated from top and bottom, thereby doubling its effective channel width). The transconductance of the pseudomorphic devices improves with decreasing temperature. We have also performed magnetotransport measurements at 4.2 K which verify the existence of a two-dimensional electron gas at the $In_{0.15}Ga_{0.85}As$/GaAs interface. The onset of Shubnikov-de Haas oscillations at fairly low magnetic field (0.5 T) suggests high mobility ($\geq 100\,000$ $cm^2/V \cdot s$) and reasonably good uniformity. Lastly, we have fabricated 1-μm gate-length HEMT's having 300 K transconductance as high as 175 ms/mm, which is to our knowledge the highest yet reported for any $In_xGa_{1-x}As$ FET utilizing either strained *or* unstrained $In_xGa_{1-x}As$. These data suggest that pseudomorphic material can be grown which has electronic properties which are comparable to unstrained material, and that heterointerfaces between lattice-mismatched materials can be formed such that they are not dominated by misfit dislocations.

II. DEVICE FABRICATION

The layers from which the transistors and magnetotransport structures were fabricated were grown by molecular beam epitaxy (MBE). The starting substrates were undoped LEC GaAs (100). The following layers were grown sequentially: 1) 1-μm undoped GaAs buffer; 2) 200-Å undoped pseudomorphic $In_{0.15}Ga_{0.85}As$; 3) 150-Å undoped GaAs spacer layer; 4) 400-Å Si doped (2×10^{18} cm^{-3}) GaAs (see Fig. 1). The growth temperature was 550°C. The transistors and magnetotransport structures (Hall bars and Corbino disks) were fabricated using a mesa isolated process. The mesas were defined using conventional photolithography and an $H_2O:NH_4OH:H_2O_2$ etch. Ohmic contact metallurgy was deposited using a lift-off technique. The ohmic metallurgy consists of 1000-Å Au:Ge eutectic 250-Å Ni, capped with 2000-Å Au. The contacts were alloyed using a rapid thermal

---

Manuscript received May 20, 1985; revised July 12, 1985.

J. J. Rosenberg and M. Benlamri are with the Division of Engineering, Brown University, Providence, RI 02912.

P. D. Kirchner, J. M. Woodall, and G. D. Pettit are with the IBM T. J. Watson Research Center, Yorktown Heights, NY 10598.

0741-3106/85/1000-0491$01.00 © 1985 IEEE

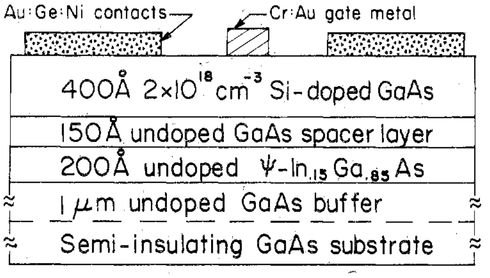

Fig. 1. Cross section of HEMT with pseudomorphic $\mathrm{In_{0.15}Ga_{0.85}As}$ channel layer (designated $\Psi - \mathrm{In_{0.15}Ga_{0.85}As}$).

cycle (40°C/s) alloying stage. The samples were rapidly heated to 475°C and cooled to room temperature. Following the ohmic contact formation, the gate/contact pad metallurgy was deposited using lift-off. The gate metallization consists of 100-Å of Cr, capped with 1500-Å of Au.

III. Results and Discussion

Room temperature and 77 K I-V characteristics for HEMT's having $W/L = 50$ μm/2 μm and a gate-source spacing of 4 μm are shown in Fig. 2. These characteristics were measured without illuminating the device. Neither persistent photoconductivity (PPC) nor drain current collapse at 77 K are observed, and the characteristics are essentially unaltered by illumination. The characteristics in Fig. 2 show a transconductance increase from ~90 mS/mm at 300 K to ~140 mS/mm at 77 K; an increase of over 50 percent. Note also that the characteristics show good turn-off behavior.

HEMT's having 1-μm gate lengths and 2-μm gate-to-source spacing were also fabricated. These transistors also showed good turn-off behavior, as well as no PPC or drain current collapse at 77 K. Transconductance of up to 175 mS/mm was observed at 300 K, although the transconductance improvement at 77 K was smaller for these devices (typically ~20 percent) than for the 2-μm gate-length devices. Much of the transconductance improvement in the 1-μm device can probably be attributed to a reduction in source resistance. The estimated source resistances (at 300 K) are ~6 Ω·mm and ~2 Ω·mm for the 2 and 1-μm devices, respectively. We believe (on the basis of the relatively small change in both linear region slope and transconductance at 77 K) that the ohmic contacts are limiting the 77 K performance of the 1-μm devices. Part of our ongoing study of these devices is directed at optimizing ohmic contacts to athis particular structure and material system.

In addition to the HEMT measurements, van der Pauw (VDP) and low temperature (4.2 K) magnetotransport measurements were made on the same layers from which the transistors were fabricated. VDP measurements showed typical room-temperature mobilities of ~4000 cm^2/V·s and 77 K mobilities as high as 40 000 cm^2/V·s with carrier densities of roughly 5×10^{11}/cm^2. Carrier densities were somewhat affected by illumination, but no persistent effect was observed at 77 K.

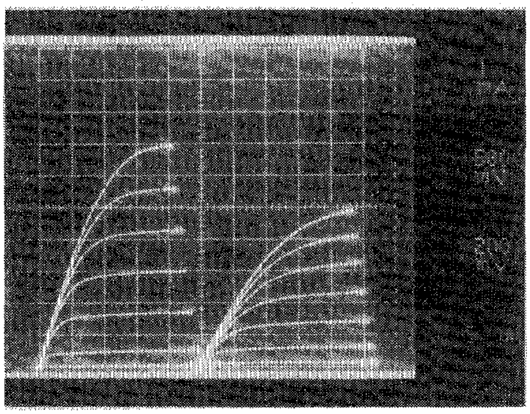

Fig. 2. HEMT I-V characteristics (no illumination). Left trace: 77 K, right trace: 300 K. Device dimensions are $W = 50$ μm, $L = 2$ μm gate-source spacing is 4 μm. Vertical sensitivity 1 mA/div; horizontal 0.5 V/div; gate drive 0.2 V/step.

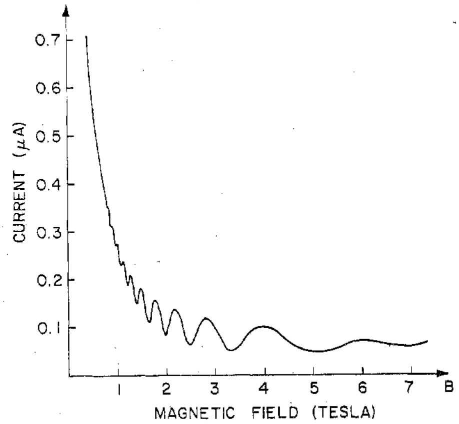

Fig. 3. Magneto conductance of an ungated annular FET (Corbino disk) at 4.2 K. AC drive voltage is 50 μV.

Magnetotransport measurements were made on a variety of structures at 4.2 K. Strong Shubnikov-de Haas oscillations characteristic of a two-dimensional electron gas were observed. Fig. 3 shows the magnetoconductance of a Corbino disk (ungated annular FET). The measurement was performed by applying a 50-μV ac signal (at 100 Hz), and measuring the ac current as a function of magnetic field (which was swept at 1 T/min). Oscillation in the conductance as a function of magnetic field could be observed with a normal field as low as 0.5 T. The uniformity implied by oscillations at this field intensity precludes the existence of a high density of misfit dislocations at the interface, since these dislocations are known to cause large variations in the local potential (due to fermi level pinning) [7]. These measurements indicate that the $\mathrm{In_{0.15}Ga_{0.85}As}$ layer is pseudomorphic, and that both the layer and the $\mathrm{In_{0.15}Ga_{0.85}As/GaAs}$ interface are of high quality.

IV. Conclusions

The results presented here have a number of implications. Firstly, devices fabricated on pseudomorphic $\mathrm{In_{0.15}Ga_{0.85}As}$ perform as well as those on unstrained $\mathrm{In_xGa_{1-x}As}$, and significantly better than those fabricated on nonpseudomorphic strained layer $\mathrm{In_xGa_{1-x}As}$. Secondly, pseudomorphic $\mathrm{In_xGa_{1-x}As}$ can be grown which has electronic properties comparable to unstrained $\mathrm{In_xGa_{1-x}As}$ and which forms a high-quality interface with GaAs. Pseudomorphic $\mathrm{In_{0.15}Ga_{0.85}As}$

HEMT's with fairly high transconductance (175 mS/mm at 300 K for 1-μm gate length) can be fabricated which do not show the persistent photoconductivity or drain current collapse often observed in $Al_xGa_{1-x}As/GaAs$ HEMT's. It is likely that further refinements in the structure and processing of the pseudomorphic $In_xGa_{1-x}As$ HEMT's can bring their transconductance up to that which is obtained in the best $Al_xGa_{1-x}As/GaAs$ HEMT's. More generally, this work suggests that pseudomorphic materials may be useful for practical devices, thereby increasing the number and variety of heterojunction systems available to device designers.

ACKNOWLEDGMENT

The authors gratefully acknowledge the support of the NSF Materials Research Laboratory through the use of the Brown University/MRL Microelectronics facility. We also wish to thank R. P. Smith for his help with the magnetotransport measurements.

REFERENCES

[1] T. J. Drummond, W. Kopp, R. Fischer, H. Morkoç, R. E. Thorne, and A. Y. Cho, "Photoconductivity effect in extremely high mobility modulation doped (Al,Ga)As/GaAs heterostructures," *J. Appl. Phys.*, vol. 53, p. 1238, Feb. 1982.

[2] R. Fischer, J. Timothy Drummond, J. Klem, W. Kopp, Timothy S. Henderson, D. Perrachione, and H. Morkoç, "On the collapse of drain *I-V* characteristics in modulation doped FETs at cryogenic temperatures," *IEEE Trans. Electron Devices*, vol. ED-31, p. 1028, Aug. 1984.

[3] J. H. van der Merwe, "Crystal intefaces. Part II. Finite Overgrowth," *J. Appl. Phys.*, vol. 34, no. 1, p. 123, Jan. 1963.

[4] Y. Sugita and M. Tamura, "Misfit dislocations in bicrystals of epitaxially grown silicon on boron-doped silicon substrates," *J. Appl. Phys.*, vol. 40, no. 8, p. 3089, July 1969.

[5] J. W. Matthews and A. E. Blakeslee, *J. Cryst. Growth*, vol. 32, p. 265, 1976.

[6] T. E. Zipparian, L. R. Dawson, G. C. Osbourn, and I. J. Fritz, "An $In_{.2}Ga_{.8}As/GaAs$ modulation doped superlattice FET," *IEDM Tech. Dig.*, 1983, p. 696.

[7] J. M. Woodall, G. D. Pettit, T. N. Jackson, C. Lanza, K. L. Kavanagh, and J. W. Mayer, "Fermi level pinning by misfit dislocations at GaAs interfaces," *Phys. Rev. Lett.*, vol. 51, p. 1783, 1983.