Novel high mobility \( \text{Ga}_{0.51}\text{In}_{0.49}\text{P}/\text{GaAs} \) modulation-doped field-effect transistor structures grown using a gas source molecular beam epitaxy

Z. P. Jiang, P. B. Fischer, S. Y. Chou, and M. I. Nathan

Department of Electrical Engineering, University of Minnesota, Minneapolis, Minnesota 55455

(Received 15 August 1991; accepted for publication 25 January 1992)

A standard \( \text{Ga}_{0.51}\text{In}_{0.49}\text{P}/\text{GaAs} \) modulation-doped field-effect transistor (MODFET) structure and a novel \( \text{Ga}_{0.51}\text{In}_{0.49}\text{P}/\text{GaAs} \) MODFET structure where the \( \text{Ga}_{0.51}\text{In}_{0.49}\text{P} \) spacer layer was replaced by an undoped \( \text{Al}_{0.3}\text{Ga}_{0.7}\text{As} \) layer were grown using a gas source molecular beam epitaxy. The Hall mobility of the novel MODFET’s structures are 6600 and 36 400 cm\(^2\)/Vs at room temperature and 77 K, respectively, which are more than twice as high as that in the ordinary \( \text{Ga}_{0.51}\text{In}_{0.49}\text{P}/\text{GaAs} \) MODFET’s structure. The mobility is attributed to better carrier confinement and smoother heterointerface. Furthermore, it is found that both ordinary and novel MODFET’s structures have small photo-persistant conductivity effects at low temperatures and that the FETs made in these materials had no threshold voltage shift at low temperatures after illumination.

\( \text{GaInP} \) lattice matched to \( \text{GaAs} \) is an attractive material system for many electronic and optoelectronic device applications. \( \text{Ga}_{0.51}\text{In}_{0.49}\text{P} \) has a direct energy band gap of 1.9 eV and can emit light in the visible range. Furthermore, the \( \Gamma-L \) valley separation in \( \text{Ga}_{0.51}\text{In}_{0.49}\text{P} \) was estimated to be as large as 300 meV, which is possibly large enough to place the donor complex (DX) centers above the \( \Gamma \) valley. Therefore, this material is attractive for high-speed and high-performance device applications.

Previously, several groups have reported observation of a two-dimensional electron gas (2 DEG) in the \( \text{GaInP}/\text{GaAs} \) heterostructures grown by metalorganic chemical vapor deposition (MOCVD).\(^4\) MOCVD has also been used to fabricate modulation-doped field-effect transistors (MODFETs).\(^5\) Gas source molecular beam epitaxy (MBE) systems have been used to grow thick \( \text{GaInP} \) on \( \text{GaAs} \) and \( \text{GaInP}/\text{GaAs} \) superlattices,\(^6\) but not MODFET’s structures.

In this paper we report the first growth of \( \text{GaInP}/\text{GaAs} \) MODFET structures using a gas source MBE system, and the first growth of a novel \( \text{GaInP}/\text{GaAs} \) MODFET structure where the undoped \( \text{Ga}_{0.51}\text{In}_{0.49}\text{P} \) spacer layer was replaced by an undoped \( \text{Al}_{0.3}\text{Ga}_{0.7}\text{As} \) layer. We will show that the 2DEG mobility in the novel structure is enhanced by more than two times. In addition, we show that both ordinary and novel MODFET structures exhibited only a small PPC effect at low temperatures and that the field-effect transistors made in these materials had no threshold voltage shift at low temperatures after illumination.

A Riber-32P gas source MBE was used to grow all of the samples. In order to grow \( \text{GaInP} \) lattice matched to \( \text{GaAs} \), we first used the \textit{in situ} reflection high-energy electron diffraction (RHEED) oscillations to calibrate the growth rates of \( \text{GaP} \) and \( \text{InP} \). The growth rate of \( \text{GaP} \) was calibrated by growing \( \text{GaAs} \) on a \( \text{GaAs} \) substrate, assuming the rate for growing \( \text{GaAs} \) for a given \( \text{Ga} \) flux is the same as that for \( \text{In} \). The growth rate of \( \text{InP} \) was calibrated by growing \( \text{InAs} \) on \( \text{GaAs} \) using a known \( \text{GaAs} \) growth rate and assuming that the \( \text{InAs} \) growth rate for a given \( \text{In} \) flux is the same as that for \( \text{InP} \). A single crystal x-ray diffraction measurement showed that, using the growth rates obtained from the RHEED oscillations, an 800-nm-thick layer of \( \text{GaInP} \) grown on a \( \text{GaAs} \) substrate had a lattice mismatch less than \( 1 \times 10^{-3} \). The GaP growth rate was readjusted according to the the x-ray center trappng and reduction or elimination of persistent photocconductivity (PPC) at low temperatures, making \( \text{GaInP} \) a favorable material to replace \( \text{AlGaAs} \) in the \( \text{AlGaAs}/\text{GaAs} \) heterostructures. Previously, several groups have reported observation of a two-dimensional electron gas (2 DEG) in the \( \text{GaInP}/\text{GaAs} \) heterostructures grown by metalorganic chemical vapor deposition (MOCVD)\(^2\) and chlorine vapor phase epitaxy.\(^4\) MOCVD has also been used to fabricate modulation-doped field-effect transistors (MODFETs).\(^5\) Gas source molecular beam epitaxy (MBE) systems have been used to grow thick \( \text{GaInP} \) on \( \text{GaAs} \) and \( \text{GaInP}/\text{GaAs} \) superlattices,\(^6\) but not MODFET’s structures.
TABLE I. Hall measurement data for the ordinary and novel MODFET's structures at 300 and 77 K. The electron mobility in the novel structure is twice that of the ordinary structure in both cases. Both devices were cooled down in the dark for the 77 K measurements.

<table>
<thead>
<tr>
<th>Device</th>
<th>Hall data at 300 K (dark)</th>
<th>Hall data at 77 K (before illumination)</th>
<th>Hall data at 77 K (after illumination)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\mu_H$ (cm$^2$/V s)</td>
<td>$n_e$ (cm$^{-2}$)</td>
<td>$\mu_H$ (cm$^2$/V s)</td>
</tr>
<tr>
<td>Ga$<em>{0.51}$In$</em>{0.49}$P/Ga$<em>{0.51}$In$</em>{0.49}$P/GaAs &quot;ordinary&quot; MODFET</td>
<td>3200</td>
<td>9.8 $\times$ 10$^{11}$</td>
<td>17 700</td>
</tr>
<tr>
<td>Ga$<em>{0.51}$In$</em>{0.49}$P/Al$<em>{0.3}$Ga$</em>{0.7}$As/GaAs &quot;novel&quot; MODFET</td>
<td>6600</td>
<td>5.3 $\times$ 10$^{11}$</td>
<td>38 200</td>
</tr>
</tbody>
</table>

6600 cm$^2$/V s and 5.3 $\times$ 10$^{11}$ cm$^{-2}$ for the novel MODFET structure with the undoped Al$_{0.3}$Ga$_{0.7}$As spacer. No PPC effects were seen in the samples at room temperature. The mobility in the ordinary MODFET structure is comparable to the value reported for a comparable structure grown by MOCVD. The mobility of the novel structure, however, is more than two times higher than that of the ordinary one.

The 77 K Hall measurements show that the mobility and carrier concentration for the ordinary MODFET structure are 17 700 cm$^2$/V s and 5.6 $\times$ 10$^{11}$ cm$^{-2}$ in dark and 15 600 cm$^2$/V s and 5.5 $\times$ 10$^{11}$ cm$^{-2}$ after illumination. For the novel MODFET structure, the mobility and carrier concentration are 38 200 cm$^2$/V s and 2.9 $\times$ 10$^{11}$ cm$^{-2}$ in dark and 36 400 cm$^2$/V s and 3.5 $\times$ 10$^{11}$ cm$^{-2}$ after illumination. The mobility in the novel MODFET structure is again more than two times higher than that in the ordinary structure and is 1.4 times better than the best mobility reported for a Ga$_{0.51}$In$_{0.49}$P/GaAs MODFET with a comparable Ga$_{0.51}$In$_{0.49}$P spacer grown by MOCVD.

We believe that the drastic improvement in mobility is partially due to better carrier confinement resulting from the larger conduction band offset. Recently, Chen et al. have shown that the conduction band offset at 25 K at a Ga$_{0.51}$In$_{0.49}$P/GaAs heterointerface is only 60 meV, which is about four times smaller than that at an Al$_{0.3}$Ga$_{0.7}$As/GaAs heterointerface. The improvement in mobility could also be due to a better and smoother heterointerface in the 2DEG channel. During the growth of the GaInP/GaAs interface, arsenic gas would be purged first and phosphine would then be introduced, and the substrate temperature would be lowered from 590°C to 500°C. These changes could cause poor or rough interface. By replacing the GaInP spacer layer with AlGaAs, neither gas nor substrate temperature needs to be changed during the growth of the AlGaAs/GaAs interface which is critical to the mobility of the 2DEG, leading to a better interface.

MODFETs were also fabricated on each structure. Mesa isolation was performed using optical lithography and a two step wet etch process consisting of H$_2$SO$_4$/H$_2$O$_2$/H$_2$O for the GaAs cap layer and HCl/PH$_3$O$_4$ for the Ga$_{0.51}$In$_{0.49}$P layers. Optical lithography was again used to pattern Ni/Au/Ge contacts using a lift-off technique. The contacts were annealed at 420°C for 1.5 min. Transmission line measurements show that the resulting contact resistance is 4.0 Ω mm for the device fabricated on the standard MODFET structure and 5.4 Ω mm for the device fabricated on the novel structure. The gates were patterned using electron beam lithography with PMMA. The GaAs cap layer was removed with H$_2$SO$_4$/H$_2$O$_2$/H$_2$O prior to deposition and lift-off of Ti/Au (15 nm/35 nm).

Electrical measurements were performed on the devices at room temperature and at 77 K using an HP 4145B. Figure 1 shows the room-temperature current-voltage (I-V) characteristics of an ordinary and a novel GaInP/GaAs MODFET with gate lengths of 2 and 3 μm, respectively, and a drain-to-source spacing of 4.5 μm. The extrinsic transconductances for these devices was only 60 and 46 mS/mm for the ordinary and novel MODFETs, respectively, due to the large contact resistances. The threshold voltage of the devices were measured at 77 K by fixing the $V_{DS}$ at 50 mV and sweeping the gate voltage. Within experimental resolution, no threshold voltage shift was observed at 77 K after illuminating either structure. This observation is in agreement with the Hall mobility data from the standard MODFET since a decrease in the carrier concentration of $1 \times 10^{10}$ cm$^{-2}$ would lead to a threshold voltage shift of approximately 3 mV that is below the 10 mV resolution of the measurement. The fact that no threshold voltage shift was observed in the novel MODFET contradicts the Hall measurements which indicated a carrier concentration increase of $6 \times 10^{10}$ cm$^{-2}$ and a theoretical threshold voltage shift of $-18$ mV after illumination, a measurable amount. One possible explanation is that the $D\times X$ center is very close to the $\Gamma$ valley, so that a small gate or drain current can easily move electrons into and out of the traps.

Conventional AlGaAs/GaAs MODFETs were also fabricated for comparison from a MODFET structure consisting of a 0.5 μm GaAs buffer layer, a 10-nm-thick layer of undoped Al$_{0.3}$Ga$_{0.7}$As, a 40 nm-thick layer of Al$_{0.3}$Ga$_{0.7}$As doped with $1 \times 10^{18}$ Si, and a 10 nm GaAs cap layer. The structures were grown using the same gas source MBE system and were fabricated using a similar fabrication sequence as the GaInP MODFETs. The threshold voltages of the devices were measured at 77 K by fixing $V_{DS}$ at 50 mV and sweeping the gate voltage before and after illumination with a red light-emitting diode. A threshold voltage shift of 80 mV was observed at 77 K after
In summary, an ordinary and a novel MODFET's structure were grown using a gas source MBE. The novel MODFETs' structure has an enhanced mobility more than two times higher than that in ordinary MODFETs. Such enhancement is attributed to a better 2DEG confinement and a better heterojunction interface. At low temperatures, Hall measurement of the two samples showed only a slight PPC effect. MODFETs were fabricated on the two structures and exhibited no threshold voltage shift at low temperatures after illumination.

We would like to thank Fred Williamson for technical assistance with MBE growth. The work was partly supported by IBM through a university research program and a Faculty Development Award, and by the Packard Foundation through a Packard Fellowship. P. B. F. would like to thank the Air Force for an Air Force Laboratory Graduate Fellowship.

FIG. 1. Room-temperature I-V characteristics of (a) a 2 μm gate Ga0.5In0.5P/GaAs MODFET with a GaAs1In0.49P spacer layer and (b) a 3 μm gate MODFET which is identical with the first except the Ga0.51In0.49P is replaced by an Al0.3Ga0.7As spacer layer.

illumination which can be explained by the presence of deep DX centers in the Al0.3Ga0.7As.