

Novel high mobility Ga_{0.51}In_{0.49}P/GaAs modulation-doped field-effect transistor structures grown using a gas source molecular beam epitaxy

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

A standard Ga_{0.51}In_{0.49}P/GaAs modulation-doped field-effect transistor (MODFET) structure and a novel Ga_{0.51}In_{0.49}P/GaAs MODFET structure where the Ga_{0.51}In_{0.49}P spacer layer was replaced by an undoped Al_{0.3}Ga_{0.7}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 cm²/V s at room temperature and 77 K, respectively, which are more than twice as high as that in the ordinary Ga_{0.51}In_{0.49}P/GaAs MODFETs 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-persistent conductivity effects at low temperatures and that the FETs made in these materials had no threshold voltage shift at low temperatures after illumination.

GaInP lattice matched to GaAs is an attractive material system for many electronic and optoelectronic device applications. Ga_{0.51}In_{0.49}P has a direct energy band gap of 1.9 eV and can emit light in the visible range. Furthermore, the Γ -L valley separation in Ga_{0.51}In_{0.49}P was estimated to be as large as 300 meV,¹ which is possibly large enough to place the donor complex (DX) centers above the Γ valley and therefore lead to less DX center trapping and reduction or elimination of persistent photoconductivity (PPC) at low temperatures, making GaInP a favorable material to replace AlGaAs in the AlGaAs/GaAs heterostructures. Previously, several groups have reported observation of a two-dimensional electron gas (2 DEG) in the GaInP/GaAs heterostructures grown by metalorganic chemical vapor deposition (MOCVD)^{2,3} and chloride 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 GaInP on GaAs and GaInP/GaAs superlattices,^{6,7} but not MODFET's structures.

In this paper we report the first growth of GaInP/GaAs MODFET structures using a gas source MBE system, and the first growth of a novel GaInP/GaAs MODFET structure where the undoped Ga_{0.51}In_{0.49}P spacer is replaced by an undoped Al_{0.3}Ga_{0.7}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 GaInP lattice matched to GaAs, we first used the *in situ* reflection high-energy electron diffraction (RHEED) oscillations to calibrate the growth rates of GaP and InP. The growth rate of GaP was calibrated by growing GaAs on a GaAs substrate, assuming the rate for growing GaAs for a given Ga flux is the same as that for GaP. The growth rate of InP was measured by growing In_{0.24}Ga_{0.76}As on GaAs using a known

GaAs growth rate and assuming that the InAs growth rate for a given In flux is the same as that for 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 GaInP grown on a GaAs substrate had a lattice mismatch less than 1×10^{-3} . The GaP growth rate was readjusted according to the x-ray diffraction measurement while the InP growth rate was kept unchanged, and then the second sample with an 800-nm-thick layer of GaInP on GaAs was grown. The second x-ray diffraction measurement showed that the second sample had a lattice mismatch less than 1×10^{-4} . The substrate temperatures during the growths were 590 °C for the GaAs buffer layer and 490 °C for the GaInP layer. The growth rate was 0.25 $\mu\text{m}/\text{h}$ for GaAs and 0.47 $\mu\text{m}/\text{h}$ for Ga_{0.51}In_{0.49}P. The thick GaInP layer was doped with Si at a concentration of $1 \times 10^{17} \text{ cm}^{-3}$ in order to measure mobility. Hall mobility of the second bulk GaInP sample was 900 and 3500 cm²/V s at room temperature and 77 K, respectively, which are comparable to similar GaInP/GaAs samples grown by MOCVD, gas source MBE, liquid phase epitaxy, and MBE.⁶

After obtaining the near lattice match growth conditions, two MODFET's structures were grown immediately. The first MODFET's structure consists of a 0.5 μm GaAs buffer layer, a 10-nm-thick layer of undoped Ga_{0.51}In_{0.49}P, a 40-nm-thick layer of Ga_{0.51}In_{0.49}P doped with $1 \times 10^{18} \text{ cm}^{-3}$ Si, and a 10-nm-thick GaAs cap layer doped with $2 \times 10^{18} \text{ cm}^{-3}$ Si. The second MODFET's structure was identical to the first except the undoped Ga_{0.51}In_{0.49}P layer was replaced with undoped Al_{0.3}Ga_{0.7}As of the same thickness. The AlGaAs layer in the second MODFET's structure and the cap layer were grown at 590 °C and 500 °C, respectively.

Van der Pauw patterns were fabricated on both MODFETs structures. The mobilities of two samples were measured at 300 and 77 K and are listed in Table I. The Hall measurements at room temperature show that the mobility and carrier concentration are 3200 cm²/V s and $9.8 \times 10^{11} \text{ cm}^{-2}$ for the ordinary MODFET structure, and

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.

Device	Hall data at 300 K (dark)		Hall data at 77 K (before illumination)		Hall data at 77 K (after illumination)	
	μ_H (cm ² /V s)	n_s (cm ⁻²)	μ_H (cm ² /V s)	n_s (cm ⁻²)	μ_H (cm ² /V s)	n_s (cm ⁻²)
Ga _{0.51} In _{0.49} P/Ga _{0.51} In _{0.49} P/GaAs "ordinary" MODFET	3200	9.8×10^{11}	17 700	5.6×10^{11}	15 600	5.5×10^{11}
Ga _{0.51} In _{0.49} P/Al _{0.3} Ga _{0.7} As/GaAs "novel" MODFET	6600	5.3×10^{11}	38 200	2.9×10^{11}	36 400	3.5×10^{11}

6600 cm²/V s and 5.3×10^{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.⁵ 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 cm²/V s and 5.6×10^{11} cm⁻² in dark and 15 600 cm²/V s and 5.5×10^{11} cm⁻² after illumination. For the novel MODFET structure, the mobility and carrier concentration are 38 200 cm²/V s and 2.9×10^{11} cm⁻² in dark and 36 400 cm²/V s and 3.5×10^{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.⁵

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.*⁸ 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, arsine 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 H₂SO₄/H₂O₂/H₂O for the GaAs cap layer and HCl/H₃PO₄ 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 H₂SO₄/H₂O₂/H₂O 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 before and after illumination with a red light-emitting diode. 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 1×10^{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 6×10^{10} cm⁻² and a theoretical threshold voltage shift of -18 mV after illumination, a measurable amount. One possible explanation is that the *DX* center is very close to the Γ 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 1×10^{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

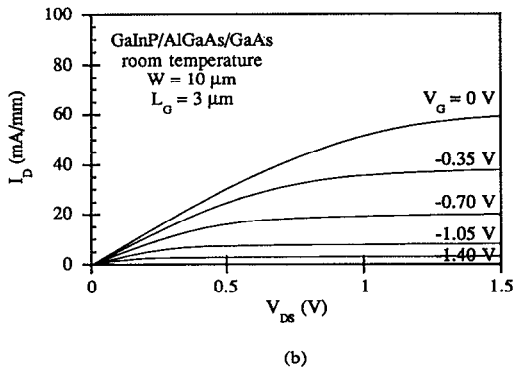
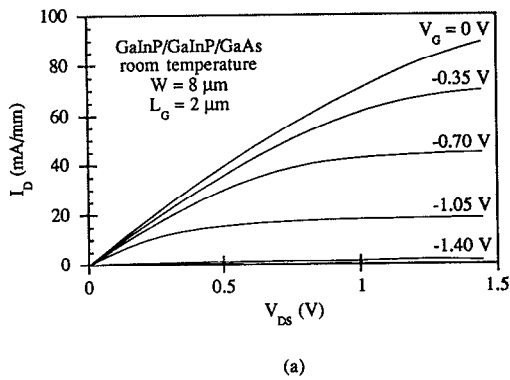


FIG. 1. Room-temperature I - V characteristics of (a) a $2\ \mu\text{m}$ gate $\text{Ga}_{0.51}\text{In}_{0.49}\text{P}/\text{GaAs}$ MODFET with a $\text{Ga}_{0.51}\text{In}_{0.49}\text{P}$ spacer layer and (b) a $3\ \mu\text{m}$ gate MODFET which is identical with the first except the $\text{Ga}_{0.51}\text{In}_{0.49}\text{P}$ is replaced by an $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$ spacer layer.

illumination which can be explained by the presence of deep DX centers in the $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$.

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.

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