Inverted-type InAlAs/InGaAs MOSHEMT with Regrown Source/Drain Exhibiting High Current and Low On-resistance

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Abstract

Selectively regrown n^{++} $In_{0.53}Ga_{0.47}As$ source/drain by MOCVD was incorporated in inverted-type InAlAs/InGaAs MOSHEMTs on GaAs substrates. A low ohmic contact resistance of 0.008Ω·mm and a regrowth interface resistance of 0.027Ω·mm were determined by TLM measurements. The thermal stability of the inverted epitaxial HEMT structure after source/drain regrowth was investigated using Van der Pauw Hall measurements. A 450nm gate-length device exhibited a high drive current of 1132mA/mm at Vds=0.5V, with an ultra-low on-resistance of 350 Ω·µm. A high peak effective mobility of 5130 $cm^2/V{\cdot}s$ was extracted, indicating excellent electron transport properties.

INTRODUCTION

As Si CMOS devices scale into the sub-22nm regime, severe short channel effects and power-dissipation constraints lead to huge challenges. To maintain high switching speed while lowering power consumption, high on-current at low supply voltages is required for future generations of novel transistors. III-V high-mobility channel FETs are currently under intensive investigation for such applications and various device architectures have been explored. Inversion-channel InGaAs MOSFETs with Al_2O_3 [1], Al_2O_3/GGO[2], or Al_2O_3/Y_2O_3 [3] as gate dielectric have yielded impressive performance. However, due to the limitation of source/drain dopant activation after ion implantation, the access resistance of these devices is usually large. InAlAs/InGaAs buried channel or quantum-well structure is another attractive candidate because of its superior electron mobility and flexible heterostructure engineering. 30nm gate-length InAlAs/InGaAs HEMT with promising logic figures of merit has been reported [4]. But conventional HEMTs with recessed gates are undesirable for VLSI application due to the large footprint. One emerging alternative device design is to incorporate regrown source/drain for ohmic contact, thereby eliminating gate-recess etching in the meantime. Using this approach, InGaAs buried channel [5] and surface channel [6,7] quantum well devices on InP substrates have been demonstrated, and maximum drain current exceeding 2000 mA/mm with low on-resistance was reported [7]. In this work, selectively regrown n^{++} $In_{0.53}Ga_{0.47}As$ source/drain was applied in inverted-type $In_{0.53}Ga_{0.47}As$ MOSHEMTs metamorphically grown on GaAs substrates by MOCVD. The epitaxial quality of the regrown source/drain was assessed by AFM, Van der Pauw Hall measurements and TLM characterization. Depletion mode InGaAs MOSHEMTs were fabricated and device drive current at low supply voltages, on-resistance as well as effective mobility were extracted and analyzed.

MATERIAL GROWTH AND DEVICE FABRICATION

Inverted-type InAlAs/InGaAs metamorphic HEMT structures were grown on exact-(100) oriented GaAs substrates in an Aixtron AIX-200/4 MOCVD system. Si delta-doping was inserted in the InAlAs buffer 15nm below the InGaAs channel. The full epi-structure is shown in Fig. 1. High resolution XRD was used to determine alloy compositions in the layers. Room-temperature Hall measurements gave an electron mobility of $5890cm^2/V{\cdot}s$ and a sheet carrier density of $3.2\times10^{12}/cm^2$, which combined into a sheet resistance of 330Ω/sq.

A gate-last non-self-aligned process was developed to fabricate MOSHEMTs with regrown source/drain regions. A 100nm SiO_2 film was first deposited by PECVD on the as-grown HEMT as regrowth mask. The source/drain regions were exposed by wet etching down to the InGaAs channel. 60nm n^{++} InGaAs with an electron concentration of $4.5x10^{19}cm^{-3}$ was regrown in the exposed source/drain regions by MOCVD at 600˚C, using TEGa, TMIn, TBA and SiH_4 as precursors. The SiO_2 mask was removed by BOE subsequently. Mesa wet etching was then performed for device isolation. After 10% diluted HCl cleaning for 2min and $(NH_4)_2S$ passivation for 5min, the sample was loaded into an Oxford OpAL ALD system immediately. In-situ TMA pretreatment using twenty cycles of TMA/Ar was conducted, and 8nm Al_2O_3 was deposited (300˚C using TMA and water as precursors) as gate dielectric, followed by post deposition annealing in H_2 at 380ºC for 30 min in the ALD chamber to improve the oxide quality. Then, source/drain contact holes were opened and ohmic contact metal (Ni/Ge/Au/Ge/Ni/Au) was deposited. Ti/Au gate metallization was the final fabrication step. The cross-section view of the InGaAs MOSHEMT after process is depicted in Fig.1. Fig.2 (a, b, c) show the surface morphology of InP buffer on GaAs substrate, inverted InGaAs HEMT, and the regrown InGaAs source/drain, respectively. There was no change in smoothness (RMS of (a) and (b)) with the additional growth of the metamorphic HEMT structure on the InP buffer. But the regrown region showed a slight increase in roughness. The device gate/channel length was defined by the separation between the raised InGaAs source/drain, as illustrated in Fig.2(d).

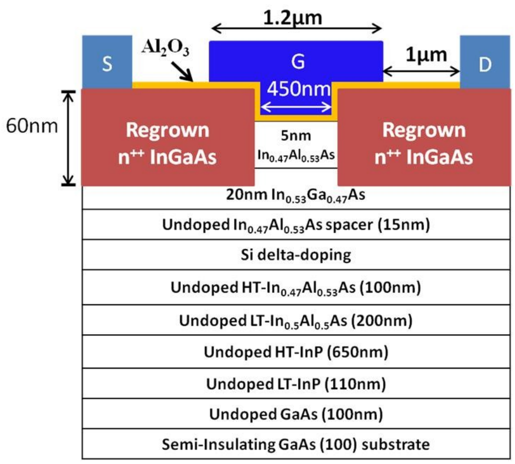

Fig. 1. Cross-section view of InGaAs MOSHEMT (LT-low temperature, HT-high temperature, note: figure not drawn to scale).

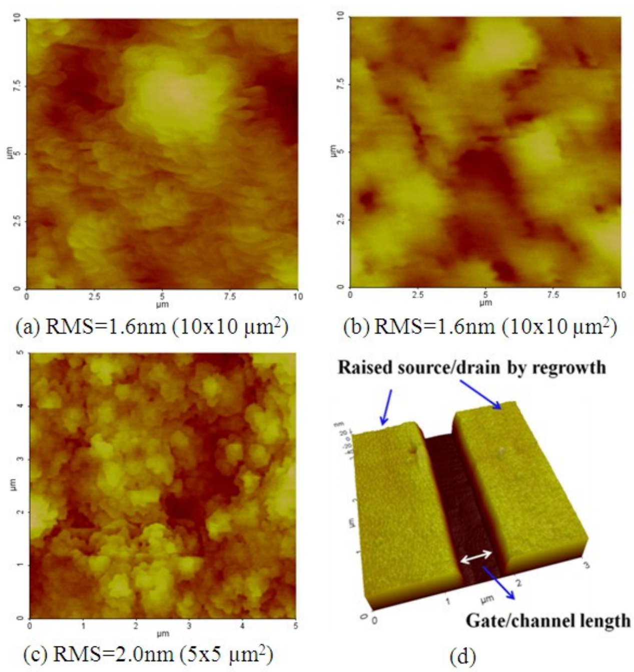

Fig. 2. AFM image of (a): InP buffer on GaAs substrate; (b): inverted InGaAs HEMT; (c): regrown InGaAs source/drain by MOCVD; and (d): Source-gate-drain surface profile after gate oxide deposition.

RESULTS AND DISCUSSION

To monitor the access resistance and intrinsic channel resistance after the gate-last process, two TLM patterns (TLM-1 and TLM-2) were designed with cross sections shown in Fig.3 (a) and (b) respectively. As measured from TLM-1, the regrown InGaAs exhibited a sheet resistance of 21Ω/□ (contribution from other layers was neglected) and the contact resistance of metal (Ni/Ge/Au/Ge/Ni/Au) on the regrown InGaAs was 0.008 Ω·mm. TLM-2 was used to deduce the contact resistance and the regrowth interface resistance in the MOSHEMT structure. It should be noted that the pad-to-pad spacing in TLM-2 was re-measured after metal deposition to take into account the undercut induced by wet-etching prior to regrowth. As shown in Fig.3(b), a contact resistance of 0.035 Ω·mm was obtained in the MOSHEMT structure, and the regrowth interface resistance was estimated to be 0.027 Ω·mm.

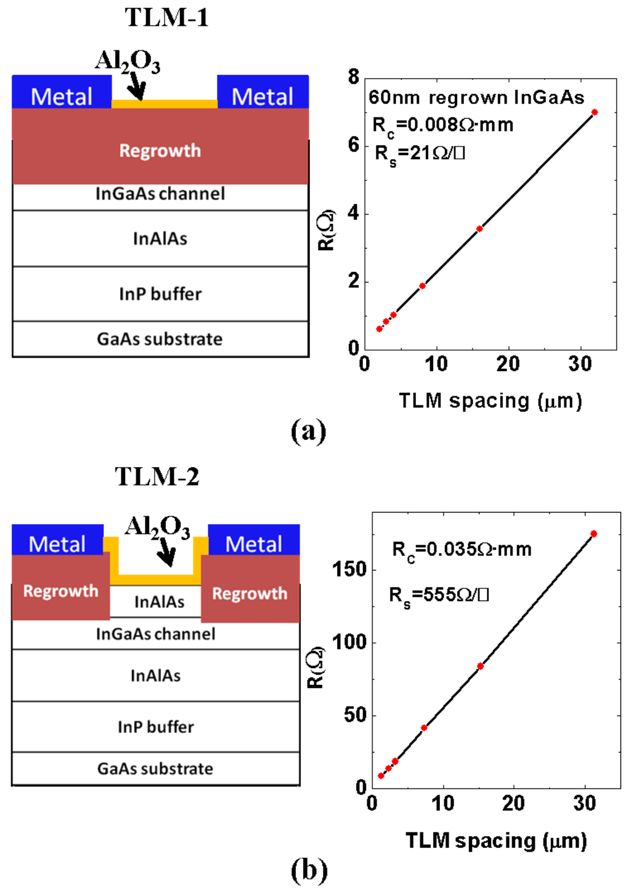

Fig. 3. TLM patterns for extraction of contact resistance and sheet resistance.

In order to investigate the thermal stability of the inverted HEMT structure through source/drain regrowth, another as-grown HEMT sample was covered by 100nm SiO_2 and annealed at 600°C in MOCVD to simulate the regrowth process. After that, SiO_2 was removed and Hall measurement was performed. The obtained 2DEG density (N_S), mobility (μ) and sheet resistance (R_S) were normalized by that of the as-grown samples, respectively. As shown in Fig.4, around 20% increase of sheet resistance was observed, due to the slight degradation of 2DEG density and mobility. This might be caused by impurity interdiffusion from the SiO_2 during the high temperature regrowth.

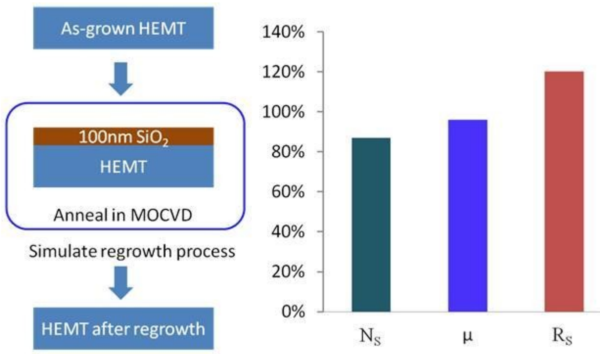

Fig. 4. Hall measurement result of HEMT after source/drain regrowth (normalized by the data of as-grown HEMT).

Fig.5 presents the output characteristics of a 450nm gate-length device. A maximum drain current of 1132mA/mm at a small drain bias of Vds=0.5V was obtained. The raised source/drain with high doping level resulted in an ultra-small on-resistance of 350Ω·μm. Fig.6 shows a comparison of on-current at Vds=0.5V of recently reported high-performance InGaAs transistors. Surface channel [1,3,8] and buried channel [5] InGaAs MOSFET, as well as inverted-type HEMT [4] and MOSHEMT [6,7] are all included. Compared with all these transistors grown on InP substrates, the device reported in this work showed excellent current delivering capability, which reflects the high quality growth of metamorphic devices lattice-matched to InP on GaAs substrates [9] and selective InGaAs regrowth by MOCVD.

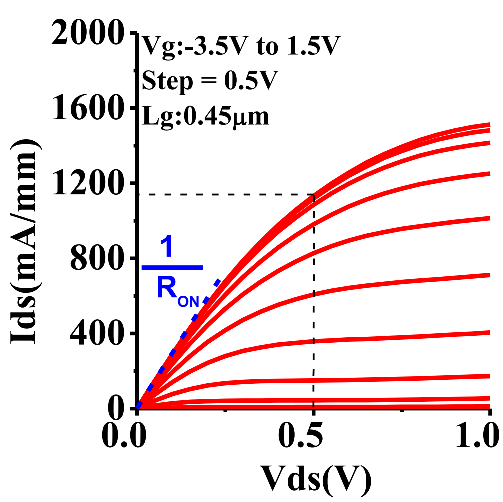

Fig. 5. Output characteristics of 450nm gate-length MOSHEMT (The dashed line: Ids=1132mA/mm @Vds=0.5V)

Effective mobility (μ_{eff}) was extracted as a function of channel electron density using a combination of C-V and I-V measurement [10]. Specifically, the channel carrier density was determined from C-V measurement of 100μm diameter ring capacitor at 1MHz, while drain conductance was obtained from the I-V curve at Vds=50mV of the 450nm gate-length MOSHEMT. The resultant mobility/carrier concentration data are shown in Fig.7. Although the μ_{eff} extracted from short channel devices is usually underestimated when compared to that extracted from long channel devices, a high peak μ_{eff} of 5130 $cm^2/V{\cdot}s$ was still obtained in this work. Fig.7 also includes the μ_{eff} of $In_{0.53}Ga_{0.47}As$ quantum well devices reported in the literature. Our results of inverted $In_{0.53}Ga_{0.47}As$ MOSHEMTs on GaAs substrate are favorably comparable to that of $In_{0.53}Ga_{0.47}As$ surface channel [8] or buried channel (with InP barrier) [11] MOSFET on InP substrates.

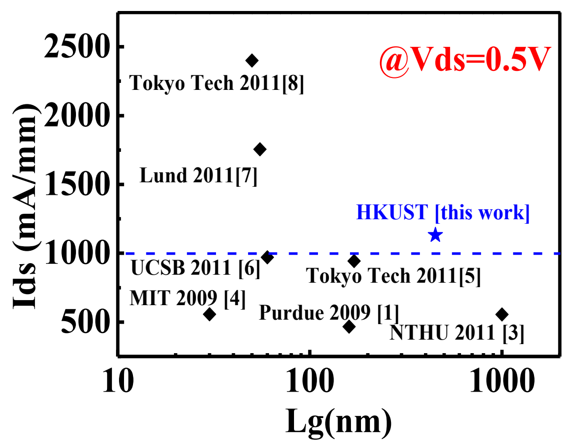

Fig. 6. Comparison of on-current at a drain bias of Vds=0.5V. (The dashed line: Ids=1000mA/mm)

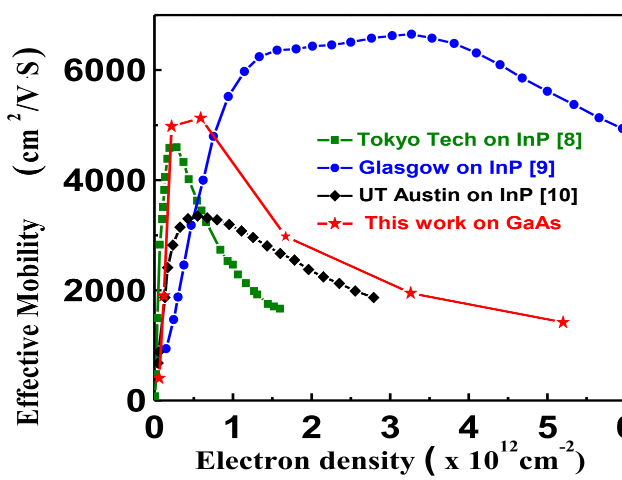

Fig.7. Comparison of effective mobility in this work with that of $In_{0.53}Ga_{0.47}As$ surface channel (Tokyo Tech.[8]), $In_{0.53}Ga_{0.47}As$ buried channel with InAlAs barrier (Glasgow Univ.[10]), and $In_{0.53}Ga_{0.47}As$ buried channel with InP barrier (UT Austin [11]) MOSFETs.

CONCLUSIONS

Inverted-type InGaAs MOSHEMTs on GaAs substrates featuring regrown source/drain by MOCVD were demonstrated. The contact resistance, regrowth interface resistance as well as transistor channel resistance were deduced to assess the feasibility and advantage of incorporating souce/drain regrowth in InGaAs MOSHEMT. A high on-current of 1132mA/mm at Vds=0.5V has been achieved. Compared with other surface channel or buried channel InGaAs MOSFETs on InP substrates, the device in this work showed excellent current delivering capability and comparable effective mobility.

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ACRONYMS

MOSHEMT: Metal-Oxide-Semiconductor High-Electron -Mobility-Transistor
MOCVD: Metalorganic Chemical Vapor Deposition
TLM: Transmission Line Method
FET: Field Effect Transistor
XRD: X-ray Diffraction
PECVD: Plasma-Enhanced Chemical Vapor Deposition
TEGa: triethylgallium
TMIn: trimethylindium
TBA: tertiarybutylarsine
BOE: Buffered oxide etch
ALD: Atomic Layer Deposition
TMA: trimethylaluminium
RMS: Root Mean Square
2DEG: Two-Dimensional Electron Gas