High Performance InGaAs MOSFETs with an InGaP Interface Control Layer and ALD-Al_2O_3 Gate Oxide for RF Switch Applications

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Abstract

High performance InGaAs MOSFETs fabricated on GaAs substrate with an InGaP interface control layer and ALD-Al_2O_3 gate oxide were demonstrated. InGaAs buried channel MOSFETs exhibited a drain saturation currents of 250 mA/mm, maximum transconductance of 370 mS/mm, as well as a peak cutoff frequency of 105 GHz and maximum oscillation frequency of 180 GHz. A prototype RF switch using the InGaAs MOSFET technology showed an insertion loss of less than 1.8 dB and isolation of better than 20dB in the frequency range from 0.1GHz to 7.5GHz. The lowest insertion loss and the highest isolation can reach 0.27 dB and more than 68 dB respectively. The present work indicates that the InGaAs MOSFET technology has a great potential for high-end RF switch applications.

Introduction

GaAs-based high-electron-mobility-transistors (HEMTs) adopting an AlGaAs Schottky gate barrier have been widely applied for high-frequency and low-noise microwave monolithic integrated circuit applications due to the low effective mass and high saturation velocity in the InGaAs channel. However, GaAs HEMTs with the Schottky gate electrode suffers from high leakage current, which limits the input dynamic range, increases the noise figure, and prevents the large scale integration of these transistors [1]. In order to suppress the gate leakage current, insulating gate oxides were introduced between metal gates and InGaAs channel through different deposition techniques [2, 3]. The main obstacle for InGaAs MOSFETs is lack of high quality thermo-dynamically stable gate dielectrics. Recently, surface channel InGaAs MOSFETs with atomic layer deposited (ALD) Al_2O_3[4], HfO_2[5], ZrO_2[6] have shown improved interface passivation and thermal stability. Compared with InGaAs HEMTs, the effective channel mobility in surface-channel InGaAs MOSFETs is still relatively low due to the high interface trap density (D_{it}) at the oxide–InGaAs interface [7].

Combining high electron mobility and thermal stability, buried-channel InGaAs MOSFET is considered as one of the most promising high-mobility CMOS technologies for high performance logic applications [8, 9]. Buried channel $In_xGa_{1-x}As$ ($x<0.25$) MOSFETs with 3.5 nm InAlP native oxide as gate dielectric have exhibited a excellent interface quality and promising RF performance [10]. The limited drain current density might be attributed to low-Indium-content InGaAs channel and high conduction-band offset at InAlP barrier. In this work, buried-channel high-Indium-content $In_{0.4}Ga_{0.6}As$ MOSFETs with Si-doped $In_{0.49}Ga_{0.51}P$ interface control layer and ALD-Al_2O_3 gate oxide on SI-GaAs substrate were proposed and investigated for the first time. The fabricated InGaAs MOSFETs demonstrated decent interface quality, low gate leakage current, high breakdown voltage and excellent radio frequency (RF) characteristics for RF switch applications.

Device Fabrication and Characterization

The epitaxial layer is grown on a semi-insulating GaAs substrate using MBE technology. The structures consisted of 300 nm undoped $Al_{0.26}Ga_{0.74}As$ buffer layer, a 2/7/3 nm GaAs/$In_{0.4}Ga_{0.6}As$/GaAs strained quantum well channel, a 5 nm $In_{0.49}Ga_{0.51}P$ interface control layer (ICL) doped with silicon, and the n+ contact layer including a 50 nm GaAs cap layer and 10nm $In_{0.54}Ga_{0.46}As$ cap layer. The epi-structure shows a room temperature hall electron mobility of ~8000 cm^2/Vs (without GaAs/InGaAs cap layers).

The InGaAs MOSFETs were fabricated combining optical lithography and electron beam lithography to define the 100nm and 300nm T-gates. Device isolation and gate recess is performed by selective wet etching using H_3PO_4:H_2O_2:H_2O solution. The InGaP barrier layer was removed by hydrochloric acid solution. After recess, the wafers are pretreated by diluted hydrochloric acid solution and ammonia-based solution. 8~20 nm Al_2O_3 was then deposited by ALD as gate dielectric followed by a 400 ℃ post deposition annealing in a N_2 ambient. Then Ti/W/Ti/Au Gate metal were formed. Ni/Ge/Au/Ge/Ni/Au source and drain ohmic contact were deposited by e-beam evaporation. The sheet resistance and contact resistance of source and drain regions are determined to be only 100 Ω/square and 0.1 Ω·mm by using the transmission line method, which are much smaller than InGaAs channel MOS-HEMTs [1, 11] and MOSFETs [12, 13]. This is believed to be due to the $In_{0.54}Ga_{0.46}As$ cap layer and Si-doped $In_{0.49}Ga_{0.51}P$ barrier layer, which significantly lower the barrier height at source and drain. The devices have a 3 μm source–drain spacing with

the gate centering in the source–drain space, and the gate width is 150 µm. Fig. 1 shows the epitaxial structure and cross-section of 100nm-gate-length InGaAs MOSFETs.

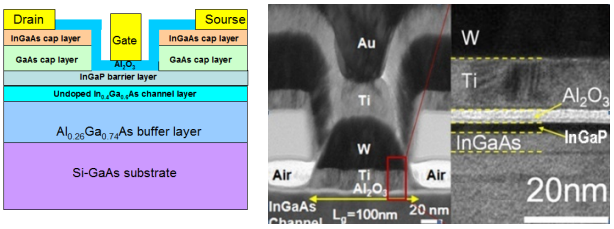

Fig. 1. Schematic cross-section of the 100nm InGaAs MOSFET.

Fig. 2 shows typical I-V characteristics for a 300 nm gate length InGaAs MOSFET with a gate bias from −2 to 3 V as a step of 0.5 V. The maximum drain current density is 250 mA/mm. A maximum extrinsic transconductance g_{max} of 370 mS/mm is achieved at V_{GS} = -0.1 V and V_{DS} = 2 V. R_{on} of transistors is about 0.72 mΩ·mm^2. The drain current I_{on}/I_{off} ratio of ~10^6 at V_{DS} = 50 mV and a sub-threshold slope (SS) of 220 mV/decade are obtained.

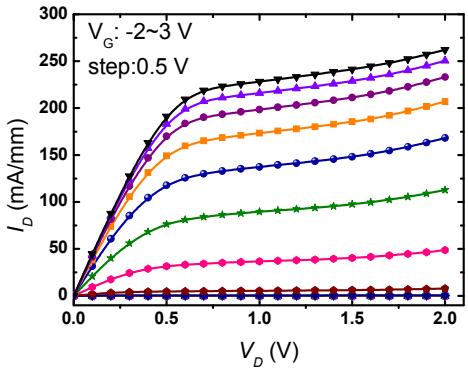

Fig. 2. Typical I–V characteristics for InGaAs MOSFETs.

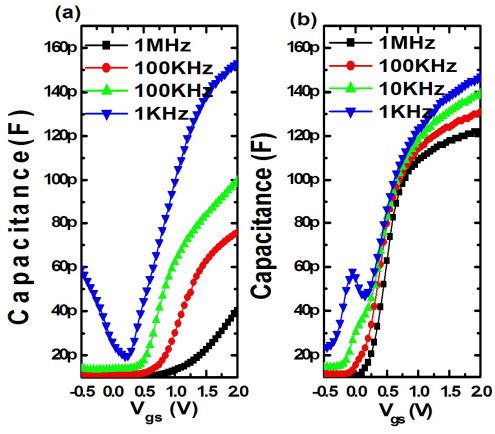

Fig. 3. Split CV of fabricated InGaAs MOSFETs without (a) and with (b) Si-doped $In_{0.49}Ga_{0.51}P$ interface control layer (ICL).

As shown in Fig. 3, the frequency dispersion of the split C-V curves of InGaAs MOSFETs with $In_{0.49}Ga_{0.51}P$ ICL is much smaller than that without InGaP ICL. This phenomenon may be resulted from two reasons: one is that the MBE grown InGaP/InGaAs interface is superior to the ALD-Al_2O_3/InGaAs interface. Another is the Si-doped $In_{0.49}Ga_{0.51}P$ layer separates the InGaAs channel from Al_2O_3 interface. The density of interface traps states, extracted from the High-Low frequency method, at Al_2O_3/InGaP interface for InGaAs MOSFETs with InGaP ICL is below 1×10^{12} /cm^2·eV, which is one order of magnitude lower than the case without InGaP ICL.

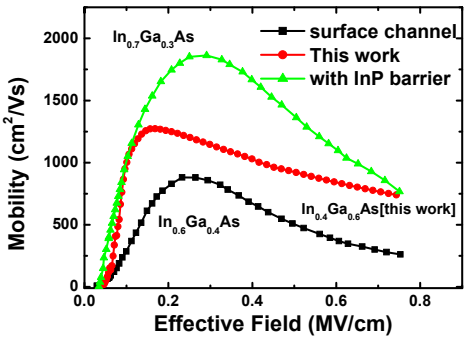

Fig. 4. Effective channel mobility for InGaAs MOSFETs.

Fig. 4 shows the effective channel mobility of the buried channel $In_{0.4}Ga_{0.6}As$ MOSFETs with 5nm InGaP ICL, the surface channel $In_{0.4}Ga_{0.6}As$ MOSFETs and the InP-based $In_{0.7}Ga_{0.3}As$ MOSFETs buried channel with 4 nm InP barrier layer measured by split C-V method by using the devices with gate length of 20 µm. It is well known that higher Indium content results higher electron mobility, it is observed that the peak effective channel mobility for $In_{0.4}Ga_{0.6}As$ MOSFETs with InGaP ICL is 1266 cm^2/V-s, which is much larger than surface channel $In_{0.6}Ga_{0.4}As$ MOSFETs. InP-based buried channel $In_{0.7}Ga_{0.3}As$ MOSFET with InP ICL gives the highest effective channel mobilities.

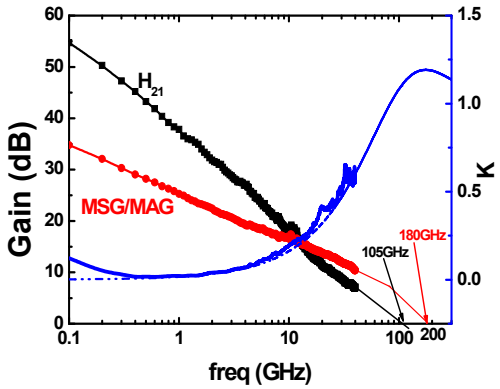

Fig. 5. Current gain and unilateral power gain versus frequency for the 100 nm × 150 µm InGaAs MOSFETs.

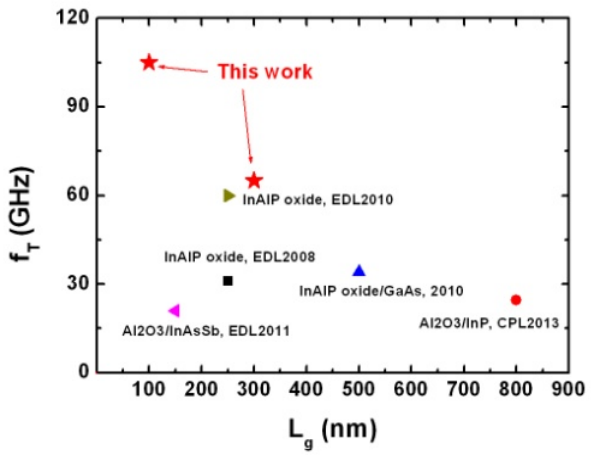

Fig. 6. f_T versus gate length in comparison with the InGaAs MOSFETs on GaAs substrate previously reported by other groups.

100nm-gate-length InGaAs MOSFETs gives a peak cut off frequency (f_T) of 105 GHz and maximum oscillation frequency (f_{max}) of 180 GHz, as shown in Fig. 5. For 300nm-gate-length InGaAs MOSFETs, f_T= 65 GHz and f_{max}= 155 GHz are measured. Fig.6 shows the cut off frequencies (f_T) obtained from our 100nm and 300nm InGaAs MOSFETs at different gate lengths comparing with other group's data. As we can see, the newly developed InGaAs MOSFETs technology demonstrated a great potential for RF applications.

RF Switch Application

Fig. 7 shows photo-micrograph of RF switch device based on our 300nm-gete-length InGaAs MOSFET technology and its equivalent circuit. An equivalent circuit of the MOSFET in the on-state is a simple resistor. In the off-state, it is replaced by a simple capacitor. The gate bias voltage controls on-state and off-state of the device. Source and Drain are used as signal transmission or receiving ports. As shown in Figure 8, the gate leakage current density of the InGaAs MOSFETs is less than 10^{-4} A/cm^2 in the gate voltage range from -8 V to +6 V. It is 3–5 orders of magnitude lower than the conventional InGaAs HEMTs.

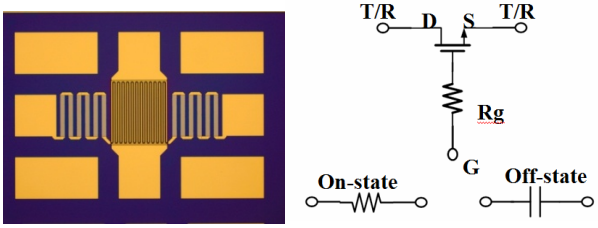

Fig. 7. Photo-micrograph for InGaAs MOSFET RF switch and its equivalent circuit.

The on-state at 2 V gate bias loss and off-state at -2 V gate bias isolation from 0.1 to 10 GHz are plotted in Figure 9. The InGaAs MOSFET RF switch shows insertion loss of less than 1.8 dB in the range from 0.1 GHz to 10 GHz, and the lowest insertion loss can reach 0.27 dB. A return loss of more than 15 dB can be achieved ranging from 0.1 to 10 GHz. As presented in Fig. 9(b), an isolation of higher than 20 dB in the range from 0.1 to 7.5 GHz can be achieved, and the highest isolation is more than 68 dB.

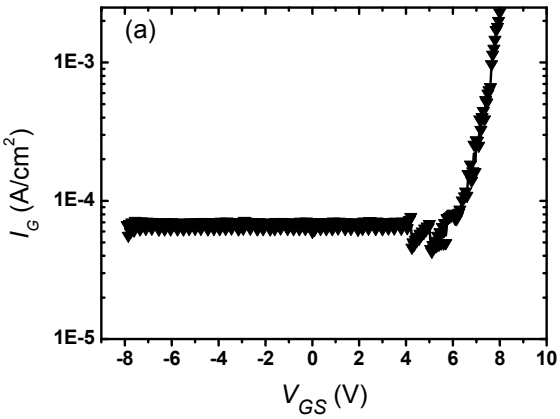

Fig. 8. Gate leakage characteristics of the RF switch.

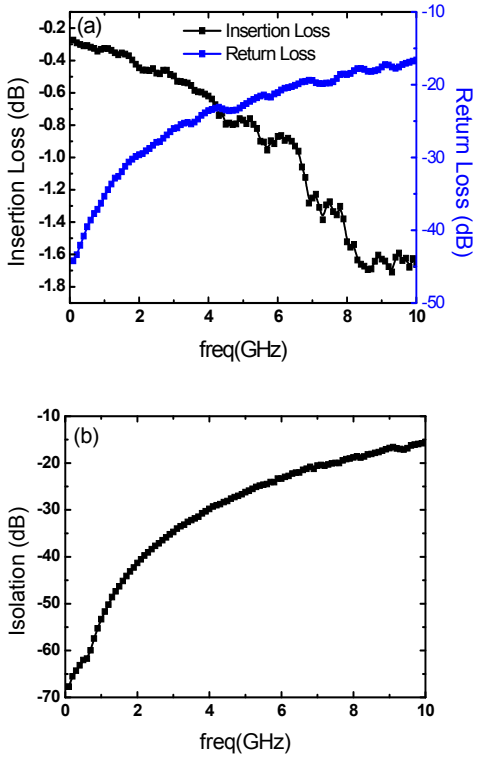

Fig. 9. (a) Insertion loss and Return loss of device in the on-state at 2V gate bias; (b) Isolation of device in the off-state at -2V gate bias.

The comparison of RF switch characteristics of InGaAs MOSFET and GaAs HEMT is shown in Table I. The insertion loss and isolation of this InGaAs MOSFET switch are 0.27

dB~0.49 dB and 68 dB~35 dB in frequency range from 0.1 GHz to 3 GHz which is better than conventional GaAs HEMT switches, respectively.

TABLE I
The comparison between this work and conventional GaAs HEMT switches in the range from 0.1 GHz to 3 GHz

Parameters	**This work**	Ref.[14]	Ref.[15]	Ref.[16]
Insertion loss (dB)	**0.27~0.49**	0.2~0.55	0.8~1	0.23~0.4
Isolation (dB)	**68~35**	46~20	64~31	42~31

CONCLUSIONS

InGaAs MOSFETs fabricated on GaAs substrate with an InGaP interface control layer and ALD-Al_2O_3 gate oxide was demonstrated. The proposed InGaAs MOSFETs exhibited excellent DC and RF performance. Comparing with GaAs HEMT, a prototype RF switch using the InGaAs MOSFET technology gives an encouraging insertion loss and isolation below 3 GHz. This work indicates that the InGaAs MOSFET technology has a great potential for high-end RF switch applications.

ACKNOWLEDGEMENTS

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REFERENCES

[1] H. C. Lin et al, Solid State Electronics, 68, 2012, pp27-31
[2] M.Passlack et al, IEEE Trans.ElectronDevices 44, 1997, pp214
[3] P.D.Ye et al,IEEE Electron Device Lett. 24, 2003, pp209
[4] Y. Q. Wu et al, IEEE Electron Device Lett. 30, 2009, pp700
[5] M. Egard et al, IEDM Tech. Dig. 2011, pp303.
[6] J. Huang et al, IEDM Tech. Dig. 2009, pp335.
[7] H C. Lin et al . Appl. Phys. Lett, vol. 91, 2007, pp. 212101
[8] Gu J J et al., Applied Physics Letters. 15 (2011) 152113
[9] Passlack M et al., IEEE IEDM 2007, 369
[10] H. Zhao et al, Appl. Phys. Lett. 94, 2009, pp103502
[11] K. Lee et al, IEEE Electron Device Lett, 26, 2005, pp864
[12] X. Li et al, IEEE Electron Device Lett. 25, 2004, pp722
[13] X. Xing et al, IEEE Electron Device Lett. 31, 2010, pp1214
[14] Hiroyuki Tosaka et al. IEEE RFIC Symposium, 2003: 519-522
[15] Kang-Ho Lee et al, IEEE APMC Proceedings, 2005, 2
[16] Wu Y C et al. IEEE Microwave & Wireless Components Letters, 2007, 17(2):133-135.

ACRONYMS

InGaAs: Indium Gallium Arsnide
MOSFET: Metal-Oxide-Semiconductor Field Effect Transistor
HEMT: High Electron Mobility Transistor
MBE: Molecular Beam Epitaxy
ALD: Atomic Layer Deposition
ICL: Interface Control Layer