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Low-power and High-speed SCFL-inverter Using Pseudomorphic InGaAs Channel High Electron Mobility Transistors

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Abstract: An SCFL (source coupled FET logic) -based ring oscillator was fabricated with pseudomorphic InGaAs channel high electron mobility transistors (HEMTs) with an extrinsic transconductance of 1.96 S/mm. A low power consumption of 26.9 mW/gate was obtained for the SCFL inverter along with a propagation delay time of 5.08 ps/gate. Low-power operation without sacrificing the propagation delay time is possible because of the low knee voltage of less than 0.3 V and the high threshold voltage of near zero volts of a HEMT. These results demonstrate the possibility of the large-scale integration of HEMTs using low-power and high-speed circuit configurations.

Keywords: InP, HEMT, pseudomorphic, SCFL inverter, ring oscillator

Classification: Electron devices

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1 Introduction

InP-based high electron mobility transistors (HEMTs) are promising devices for the ultra-high-speed ICs in communications systems. One way to improve HEMT performance such as transconductance (g_m) and current-gain cutoff frequency (f_T), is to use an $In_{0.53}Ga_{0.47}As/InAs/In_{0.53}Ga_{0.47}As$ composite channel or a strained In-rich InGaAs channel. This is because of their advantages over lattice-matched InGaAs channel in terms of electron mobility and saturation velocity [1]-[3]. Although the potential of these pseudomorphic structures has been clarified in terms of f_T and noise figures, device application has not been widely investigated. Along with high-speed operation, reducing the power consumption is crucial for the practical use of InP-based HEMTs in large-scale ICs. For lowering the power consumption, it is effective to assure the low knee voltage (V_{knee}) and the high threshold voltage (V_{th}) so as to reduce the supply voltage to circuits and the current level in ICs. We have successfully fabricated low-power and high-speed SCFL (source coupled FET logic)-based ring oscillator by employing pseudomorphic InGaAs channel, which results in low V_{knee} due to high electron mobility, and a thin layer structure, which results in high g_m and V_{th} due to the reduced distance (d) between the gate and two-dimensional electron gas (2DEG). In this paper, the characteristics of the fabricated pseudomorphic HEMTs (PM-HEMTs) and the relation between the propagation delay time (τ_{pd}) of the SCFL inverter and its power consumption are described.

2 Devices

The HEMT structure, which was grown by molecular beam epitaxy, comprises a 9-nm InP recess-etch-stop layer/InAlAs Schottky barrier layer and a 9-nm pseudomorphic InGaAs channel layer. From Hall measurement, the mobility of 1.00E+4 $cm^2/V \cdot s$ and sheet carrier density of 2.57E+12 cm^{-2} were obtained at room temperature. Schottky barrier diodes (SBDs), which are used as level-shifters in circuits, were grown on the HEMT layers along with another InP etch-stop-layer for device separation. A 9-nm pseudomorphic InGaAs channel was used in order to make the 2DEG thinner. Thus, maximum d was reduced to less than 18 nm to ensure high g_m and V_{th}.

The fabrication process is based on the monolithic integration technology of 0.1-μm-gate lattice-matched InAlAs/InGaAs HEMT-ICs [4, 5]. A gate footprint of 70-nm length was delineated by electron-beam direct writing. Current-voltage (I-V) characteristics of a fabricated 70-nm-gate HEMT are shown in Fig. 1 (a). An extrinsic g_m of 1.96 S/mm and V_{th} of -67 mV were obtained at drain-source bias (V_{DS}) of 0.6 V. The V_{knee} of less than 0.3 V is very low compared with that for a conventional lattice-matched InGaAs/InAlAs HEMT (LM-HEMT), which is $\sim$0.5 V. Large g_m was obtained even at low V_{DS} due to high electron mobility and reduced d (Fig. 1 (b)). Although g_m degraded at low V_{DS}, it is still larger than that of the LM-HEMT. Note that the degradation of g_m with increasing drain current (I_{DS}) was suppressed compared with the LM-HEMT. As for RF characteristics, a high f_T of 201

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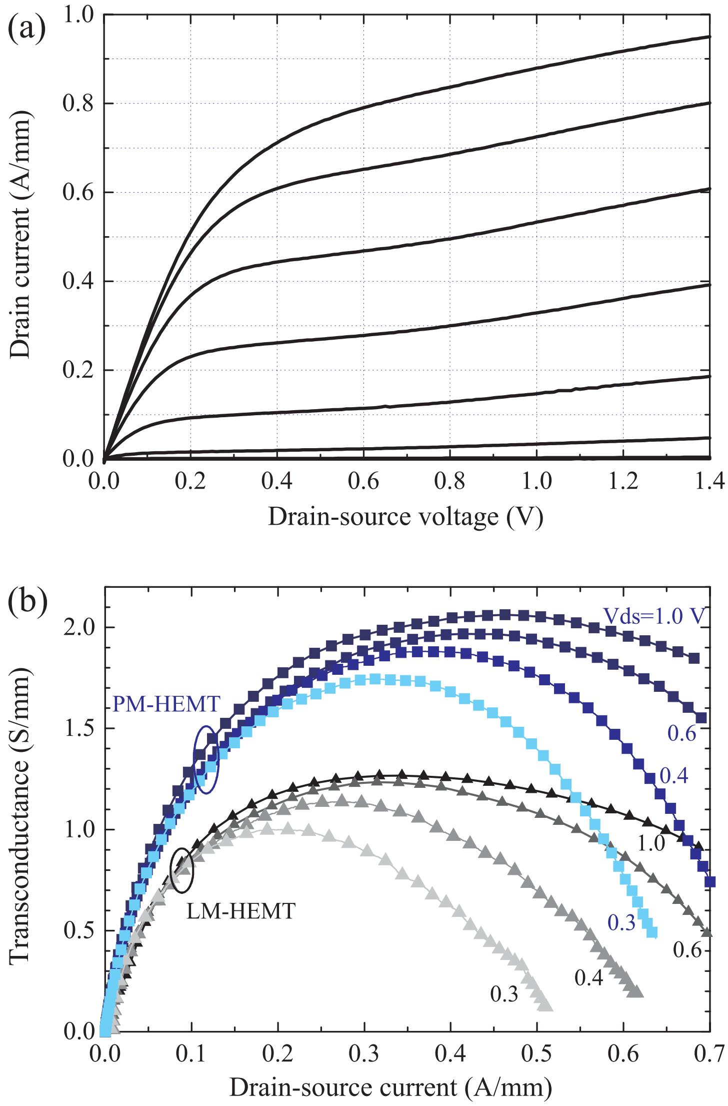

Fig. 1. (a) Current-voltage characteristics of a pseudomorphic InGaAs channel HEMT (PM-HEMT) with 70-nm gate length. Gate voltage ranges from 0.5 to -0.1 V in -0.1 V steps. (b) Transconductance dependence on drain-source current of PM-HEMT and lattice-matched InGaAs/InAlAs HEMT (LM-HEMT).

GHz and maximum operating frequency of 348 GHz were obtained for a 20-μm-gate-width HEMT from S-parameter measurement even at low V_{DS} of 0.6 V.

3 SCFL-based Ring Oscillators

Fabrication and measurement of a ring oscillator is an effective way to evaluate integration technology and the high-frequency performance of devices. The fabricated ring oscillator consists of 19 stages of conventional SCFL-inverters and an output buffer. The device counts in the circuit are 140 20-μm-gate-width HEMTs, 80 SBDs, and 40 resistors. The fundamental os-

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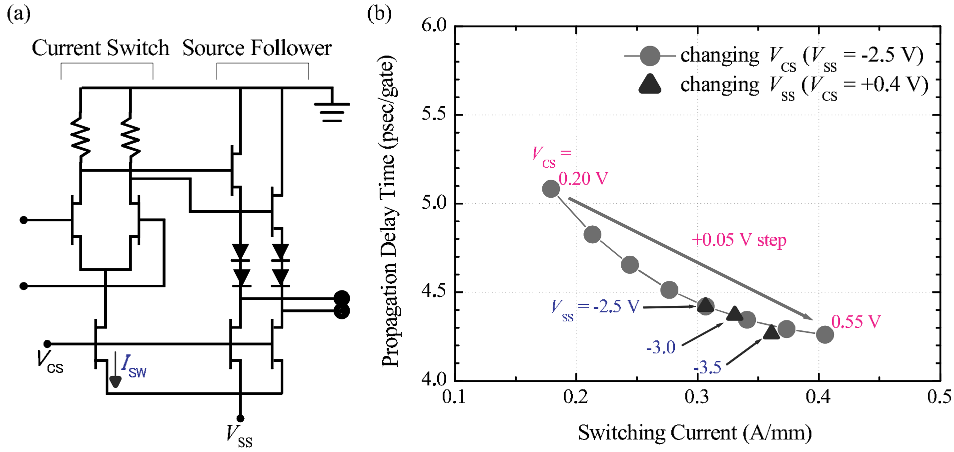

Fig. 2. (a) Circuit diagram of a stage of the fabricated ring oscillator. (b) Propagation delay time (τ_{pd}) of the ring oscillator. Red plots trace the change in V_{cs}, and blue ones that in V_{ss}. τ_{pd} is sensitive to the change in V_{cs} compared to V_{ss}.

cillating frequency (f_0) monitored by a spectrum analyzer was 5.177 GHz, which corresponded to τ_{pd} of 5.08 ps/gate. And the minimum power consumption of 26.9 mW/gate was obtained for V_{ss} = -2.5 V and V_{cs} = 0.20 V. Fig. 2 shows (a) the circuit diagram of a stage of the fabricated ring oscillator and (b) the dependences of τ_{pd} on the switching current (I_{SW}) with changing supply voltage (V_{SS}) and gate-source bias (V_{CS}) of the HEMT for the current source in the inverter. Here, I_{SW} is defined as the I_{DS} of the above-mentioned HEMT, and it is principally controlled by V_{CS}. I_{SW} also depends on V_{SS} because V_{DS} changes with V_{SS}. The increased I_{SW} effectively reduces τ_{pd} when I_{SW} increases with V_{CS}, because increasing I_{SW} enables the HEMTs to be operated with large g_m and improves the inverter's drivability (Fig. 1 (b)). Thus, minimum τ_{pd} of 4.26 psec/gate with power consumption of 60.8 mW/gate was obtained for V_{ss} = -2.5 V and V_{cs} = 0.55 V. Increasing V_{ss} hardly contributes to reducing τ_{pd}, and only causes an increase of power consumption. As g_m has a week dependence on V_{DS}, the change of V_{ss} does not improve the inverter's drivability (Fig. 1 (b)).

Next, we consider the reason that low power operation was achieved without any penalty in τ_{pd} compared with the conventional ring oscillator fabricated with the LM-HEMTs (Fig. 3). From the electrical characteristics shown in Fig. 1 (b), it was found that larger g_m is always obtained with lower I_{DS} for PM-HEMT compared to LM-HEMT, and g_m is markedly degraded at low V_{DS} for LM-HEMT. In other words, decreasing I_{SW} and V_{SS} causes poor inverter's drivability for LM-HEMT. Therefore, I_{SW} and V_{SS} should be maintained for high-speed operation of the conventional ring oscillator. In contrast, PM-HEMTs have large g_m even at low I_{DS} and V_{DS} so as to reduce I_{SW} and V_{SS} along with maintaining τ_{pd}.

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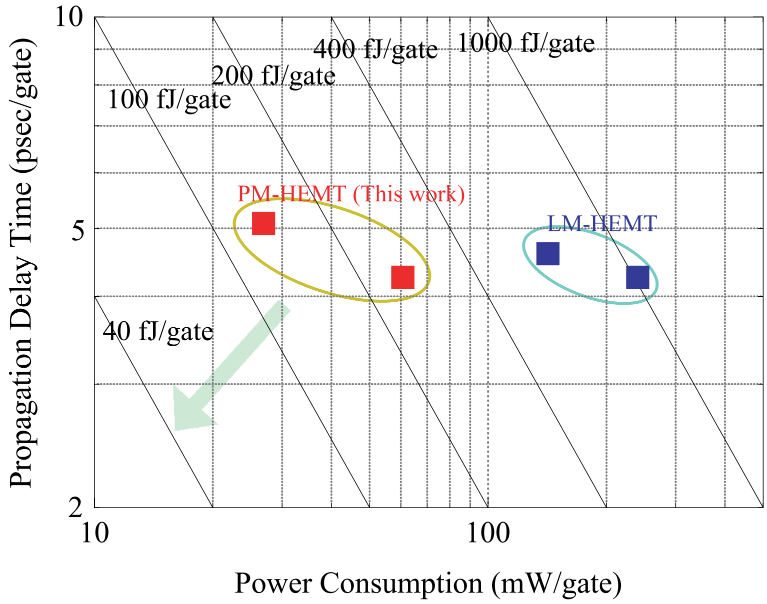

Fig. 3. τ_{pd} and power consumption of ring oscillators. τ_{pd} for PM-HEMT-based ring oscillator (this work) is shown with red plots and τ_{pd} for LM-HEMT-based one is shown with blue plots.

4 Summary

A ring oscillator was successfully fabricated with pseudomorphic InGaAs channel HEMTs and SBDs. A fabricated HEMT exhibited an extrinsic transconductance of 1.96 S/mm and a current-gain cutoff frequency of 201 GHz. From the measurement of the ring oscillator, low power consumption of 26.9 mW/gate was obtained along with 5.08 ps/gate propagation delay time of the SCFL inverter. Both large g_m and high V_{th}, which were obtained by employing a pseudomorphic InGaAs channel and a thinner Schottky-barrier/channel layer structure, contribute to the low-power operation of the SCFL inverter. Although further improvement of both τ_{pd} and power consumption is necessary, the presented demonstration suggests the possibility of the large-scale integration of HEMTs and a configuration of low-power and high-speed circuits.

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