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High-Performance InGaAs/InP Composite-Channel High Electron Mobility Transistors Grown by Metal-Organic Vapor-Phase Epitaxy

Hiroki Sugiyama, Toshihiko Kosugi, Haruki Yokoyama, Koichi Murata, Yasuro Yamane*, Masami Tokumitsu, and Takatomo Enoki

NTT Photonics Laboratories, *NTT Electronics Corporation

3-1, Morinosato Wakamiya, Atsugi-shi, Kanagawa 243-0198, Japan

Phone: +81-46-240-2778, Fax: +81-46-240-2872, E-mail: sugiyama@aecl.ntt.co.jp

1. Introduction

Millimeter-wave frequencies of over 100 GHz are recently attracting much interest for system applications, such as broadband wireless communication [1] and sensing/monitoring systems [2]. The excellent high-frequency and low-noise performances of InP-based high electron mobility transistors (HEMTs) have been demonstrated in these applications. However, they often suffer from low breakdown voltages caused by enhanced impact-ionization effects that take place in the narrow-bandgap InGaAs channel. For practical applications, the maximum available power of millimeter-wave integrated circuits (MMICs) is one of the key parameters for system design. Therefore, improvement of the breakdown characteristics of HEMTs is strongly required.

One of the effective approaches to increase breakdown voltages is the use of an InGaAs/InP composite channel (CC) [3, 4]. There are several reports on the performance of InGaAs/InP CC HEMTs [5, 6, 7]. However, the epiwafer growth issues and the practical feasibility of the devices, such as on-wafer uniformity and reliability, have hardly been discussed. The reduction of gate leakage current is also important for the improvement of breakdown characteristics. It has been reported that the use of high-Shottky-barrier material, such as InAlP, is effective [8, 9].

Recently, we have successfully fabricated InGaAs/InP CC HEMTs with an InAlP recess-etching-stopper layer. We confirmed the improvement of breakdown characteristics. Excellent high-frequency characteristics and on-wafer uniformity were obtained. We also confirmed the practical reliability of the devices under both on- and off-state bias-stress aging tests. In this paper, we report the high performance and the practical feasibility of the InGaAs/InP CC HEMTs with an InAlP recess-etching-stopper layer.

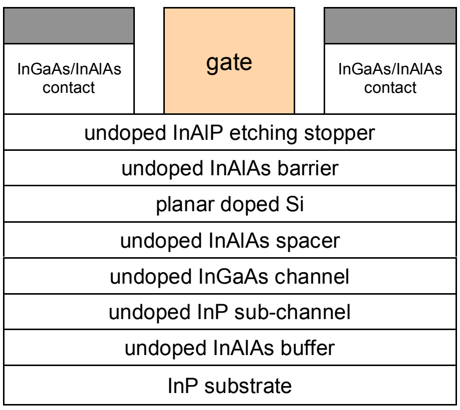
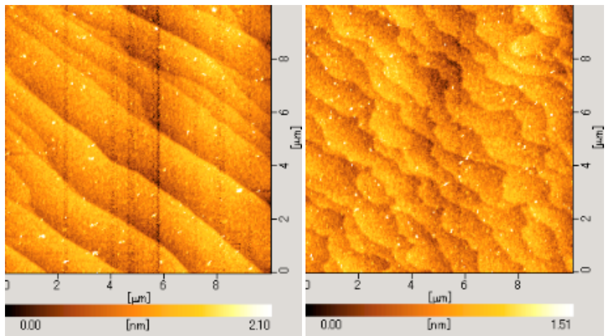


Fig. 1. Structure of InGaAs/InP composite channel HEMTs

2. Epitaxial Growth and Device Fabrication

InGaAs/InP CC HEMTs were grown on 3-inch semi-insulating InP substrates by metal-organic vapor-phase epitaxy (MOVPE). The layer structure of the HEMTs is shown in Fig. 1. The sheet carrier concentration (Ns) in the channel was controlled by planar Si doping. To



(a) (b)

Fig. 2. AFM images of the sample surfaces. (a) The top of InP sub-channel and (b) the top of InAlP recess-etching stopper.

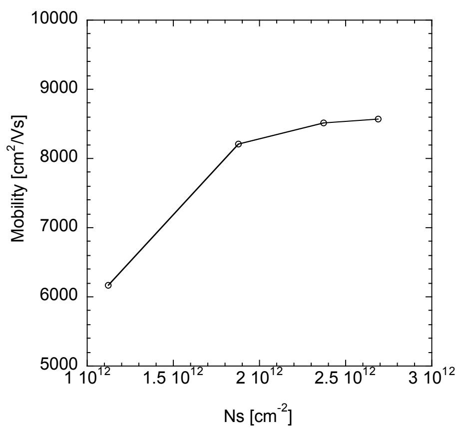


Fig. 3. Ns vs. mobility in the InGaAs/InP composite channel HEMTs.

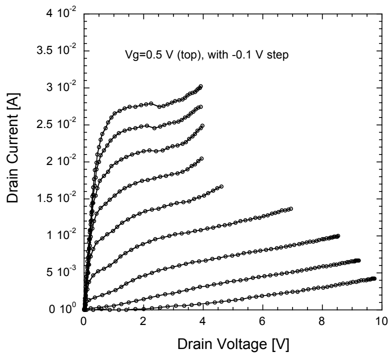


Fig. 4. Typical I-V characteristics of a fabricated 0.08-μm-gate HEMT with gate width of 2x20 μm.

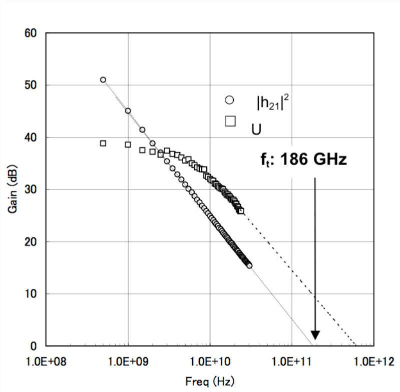


Fig. 5. Frequency dependence of current gain of a fabricated 0.08-μm-gate HEMT with gate width of 2x20 μm.

obtain excellent device characteristics, the quality of the In(Al)P/In(Ga, Al)As heterointerfaces must be high. Figures 2(a) and (b) shows typical atomic force microscope (AFM) images of the top of InP sub-channel and InAlP etching stopper, respectively, after removing InGaAs channel or contact layers by selective citric-acid-based wet etching. The atomically flat surfaces with monolayer steps in both images indicate the excellent flatness and abruptness of the interfaces. The Ns and mobility of the HEMT structures were measured at room temperature by the van der Pauw method after the contact layers had been removed [10]. Figure 3 shows the relationship between the Ns and mobility of the samples. The increase of the mobility with Ns suggests that the peak of the two-dimensional-electron gas population moves from the InP sub-channel to the InGaAs channel region as Ns increases. The devices were fabricated by our conventional production-level InP-based HEMT process [11]. The gate length was reduced to 0.08 μm to boost high-frequency characteristics.

3. Device Characteristics and Reliability

Figure 4 shows the typical I-V characteristics of the HEMTs at room temperature. The on-state breakdown voltage is around 4 V, which is about two times higher than that of conventional InGaAs-channel HEMTs. The off-state breakdown characteristics are also improved. Figure 5 shows an example of the frequency dependence of the current gain ($|h_{21}|^2$) and uni-lateral power gain (U), as determined from on-wafer S-parameter measurements. The

Table I. Typical performance of 0.08-μm-gate InGaAs/InP composite channel HEMTs on a 3-inch wafer (N=21).

	Average	Standard deviation
V_{th} (mV)	-319	16
g_m (S/mm)	1.25	0.047
f_t (GHz)	178	8
f_{max} (GHz)	~ 580	~ 60

extrapolation of $|h_{21}|^2$ and U gives a high current gain cutoff frequency (f_t) of 186 GHz and a maximum oscillation frequency (f_{max}) of around 580 GHz, respectively, at a drain-source bias (V_{ds}) of 1.1 V. Table I summarizes the performance of the devices on a 3-inch wafer. The standard deviations of the threshold voltage (V_{th}), transconductance (g_m), f_t and f_{max} are small enough and comparable to our production-level HEMTs [12, 13]. The device reliability was examined by an accelerated aging test. We confirmed that the time-dependent change of drain resistance under on- and off-state bias conditions were quite similar to those of our conventional InGaAs-channel HEMTs with long lifetime of over $1x10^6$ hours at 100 ˚C [14].

4. Summary

We have successfully fabricated InGaAs/InP CC HEMTs with excellent high-frequency characteristics, on-wafer uniformity, and reliability. These HEMTs are eminently suitable for practical power ICs for millimeter-wave systems.

Acknowledgements

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