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0.05-μm-Gate InAlAs/InGaAs HEMT and Reduction of Its Short-Channel Effects

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Lattice-matched InGaAs HEMTs with a gate length of 0.05 μm are fabricated and their short-channel effects are investigated. To make a sub-0.1-μm gate, the opening shape of the gate-footprint is controlled by employing a bi-layer dielectric film system and RIE side-etching. It is found that reducing the thickness of both the channel and the barrier to around 100 Å is indispensable for reducing the short-channel effects in the sub-0.1-μm-gate-length region. The device shows a current gain cutoff frequency of 300 GHz.

1. Introduction

InAlAs/InGaAs HEMTs on InP substrates have shown excellent high-frequency performance such as f_T>200 GHz[1], NF=1.2 dB at 94 GHz[2]. Furthermore, they are considered to be the most promising devices for enabling the handling of millimeter-wave and transmission speeds of more than 40 Gb/s in future communication systems. The relationship between f_T and gate length (L_g) suggests that f_T can be still increased by shortening L_g to less than 0.1-μm[3]. However, there have been no discussions with regard to the short-channel effects in such ultra short-channel regions. This paper reports the short-channel effects of a lattice-matched InAlAs/InGaAs HEMT on InP for the gate-length region from 0.5 to 0.05 μm, and discusses device designs for reducing the short channel effects.

2. Device structure

The lattice-matched InAlAs/InGaAs modulation-doped heterostructures shown in Fig. 1 were grown by MBE on semi-insulating InP substrates. The doping density of the n^+-InAlAs carrier supply layer was 1×10^{19} cm^{-3} and its thicknesses was 50 Å. An n^+-InGaAs/n^+-InAlAs cap structure was used for obtaining non-alloyed ohmic contacts made of Ti/Pt/Au. The InGaAs channel at the mesa-sidewall was selectively recessed to avoid direct contact between the gate metal and the channel, and to reduce the gate-leakage current[4].

A T-shaped gate structure was formed by using EB lithography for the footprint delineation, and optical lithography for the top portion of the gate. To make L_g shorter than 0.1 μm, it is necessary to control the opening shape of the dielectric film for the footprint of the gate. This is because it is difficult to fill the gate metal into the groove when the opening aspect ratio is larger than one[5]. To avoid this problem, a bi-layer dielectric film system composed of SiN and SiO_2 was used and the opening shape was controlled by RIE side-etching in the SiN film.

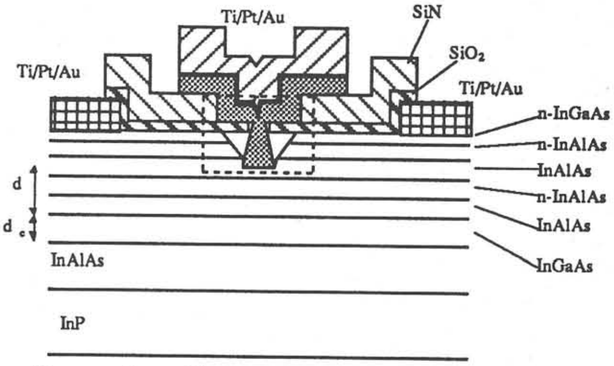

Figure 1. Gate structure of an InAlAs/InGaAs HEMT with a 0.05-μm-gate length.

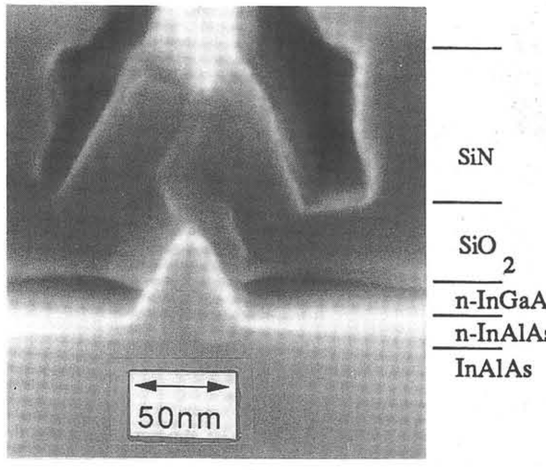

Figure 2. SEM photograph of a 0.05-μm-T-shaped gate. The view corresponds to the part indicated by dashed lines in Fig. 1

This technique achieved a footprint size of 0.05 μm in the SiO_2 film and an opening width of 0.15 μm in the SiN film. A cross-sectional view of the footprint of the T-shaped gate is shown in Fig. 2.

3. Short-channel effects

Threshold voltage shift (ΔV_{th}) refers to the threshold voltage (V_{th}) of the 0.5-μm-gate device. This and the subthreshold swing (n_g) are used as indexes which characterize the short-channel effects. According to the analogy of the Si-MOSFET[6], n_g can be given by

$$I_{ds} \propto exp\left(\frac{V_{gs}}{n_g k_B T}\right) \tag{1}$$

$$n_g = 1 + C_D\left(\frac{d}{\varepsilon_B} + \frac{d_c}{\varepsilon_c}\right) \tag{2}$$

where I_{ds} is the subthreshold drain current, V_{gs} the gate-source voltage, k_BT the thermal voltage, C_D, the substrate capacitance, ε the dielectric constant, d the barrier thickness, and d_c the channel thickness. As found in these equations, it is necessary to reduce both d_c and d in order to reduce n_g. Hall measurements were used to experimentally obtain the limit for how thin the channel thickness of this growth system can be made. In this experiment, the doping density and thickness for the carrier supply layer was $1x10^{19}$ cm^{-3} and the spacer thickness was fixed at 20 Å. The dependencies of electron mobility and sheet carrier density on the InGaAs channel thickness were shown in Fig. 3. It is found that the channel can be thinned-down to 75 Å without significant degradation of the electron mobility at room temperature.

To investigate the short-channel effects, two HEMT structures were fabricated. One has a d_c of 300 Å and a d of 170 Å, and the other has a d_c of 150 Å and a d of 100 Å. The d was controlled by changing the gate-recess depth and estimated from the V_{th}. The V_{th} of the thick-channel (300 Å) and the thin-channel (150 Å) devices with a 0.5-μm-gate length were -0.63 and -0.14 V, respectively. Figure 4 compares the subthreshold characteristics of 0.08-μm-gate devices with thin and thick channels. The selective mesa-sidewall recess reduced the gate-leakage current, thus enabling us to investigate the subthreshold characteristics. As found in

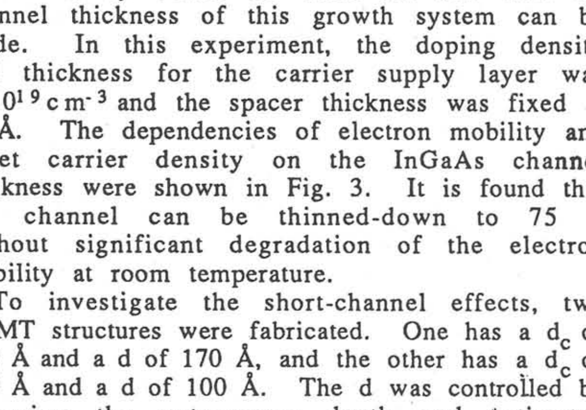

Figure 3. Dependences of electron mobility and sheet carrier density on channel thickness.

Fig. 4, the n_g of the thick-channel device is large, and its dependence on drain bias is strong. Figure 5 shows the dependencies of ΔV_{th} and n_g on the gate length for the thin- and thick-channel devices. It is obvious that the short-channel effects are much smaller for the thinner channel and barrier.

As discussed elsewhere[7-8], ΔV_{th} depends on the aspect ratio of the channel (a/L_g) where a is the effective channel thickness. Two-dimensional simulations[8] were carried out to clarify each advantage of the thin channel and barrier. In Fig. 5, simulated n_g and ΔV_{th} for three sets of d_c and d parameters [A:(300 and 170 Å); B:(150 and 170 Å); C:(150 and 100 Å)] are also plotted. It is clear that the thinner channel reduces both n_g and ΔV_{th}, and the thinner barrier mainly reduces ΔV_{th}.

If we take into account the effective L_g, which is longer than the physical L_g by 300 Å[3], the

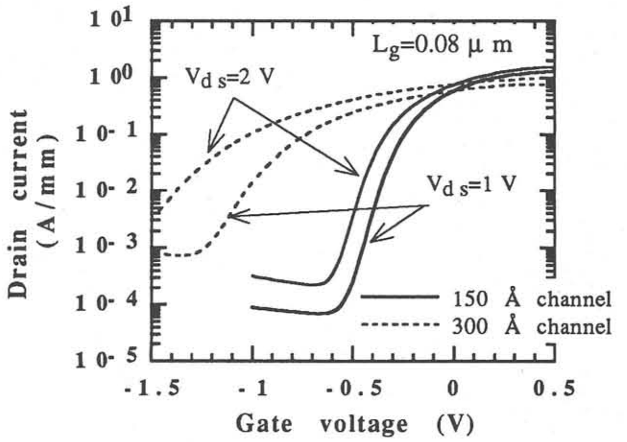

Figure 4. Subthreshold characteristics of 0.08-μm-gate InGaAs HEMTs.

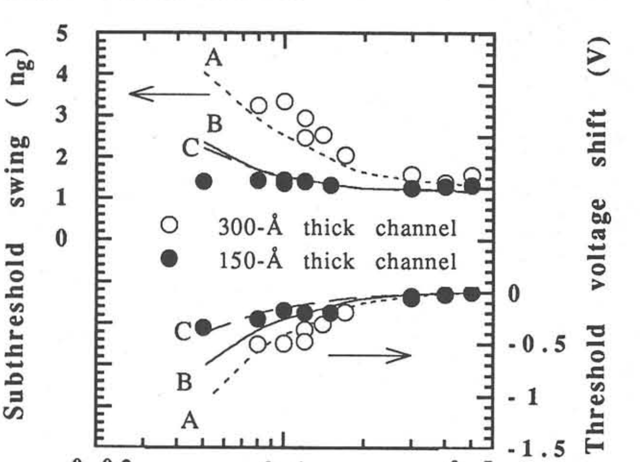

Figure 5. Gate length dependencies of subthreshold swing and threshold voltage shift. Curves show simulated short-channel effects for HEMTs with 300-Å d_c and 170-Å d (short dashed lines: A); 150-Å d_c and 170-Å d (solid line: B); 150-Å d_c and 100-Å d (long dashed line: C)

channel aspect ratio $[(d+d_c)/(L_g+\Delta L_g)]$ is about 1/3 for the 0.05-μm-gate device with the thin channel. Because the channel can be thinned-down to 75 Å as mentioned above, we will be able to reduce L_g down to 0.03 μm using 100-Å-thick barrier without any short-channel effects.

4. Device performance

The transconductance (g_m) and the drain conductance (g_d) of the thin-channel device with a 0.08-μm gate were 1100 and 69 mS/mm, respectively. The g_m/g_d ratio is 16. On the other hand, the values of the thick-channel device with the same gate length were 790 and 99 mS/mm, respectively. The ratio is only 8. From these data, it is definitely necessary to thin the channel and the barrier in order to obtain sub-0.1-μm-gate devices.

DC and RF measurements were carried out for the thin-channel device with a 0.05x150-μm^2-gate dimension. As shown in Fig. 6, the g_m and the g_d were 1280 and 85 mS/mm, respectively. The f_T of the device was 269 GHz. After selectively removing only SiN dielectric film using isotropic plasma etching, the value increased to 300 GHz due to smaller parasitic capacitance. Figure 7 shows the dependencies of the current gain ($|h_{21}|^2$), maximum available power gain (G_{max}), stability factor (K), and Mason's unilateral power gain (U_g) on frequencies up to 50 GHz. The f_{max} obtained by extrapolating the Ug with -20 dB/dec was estimated to be 235 GHz.

5. Conclusions

It is found that the short-channel effects of InAlAs/InGaAs HEMT can be reduced even in the 0.03-μm region by reducing thickness both of the channel and the barrier to approximately 100 Å. It is found that there is no significant degradation in the electron mobility in such a thin channel. It has been also demonstrated that 0.05-μm-gate InGaAs HEMT shows g_m of 1280 mS/mm, f_T of 300 GHz and f_{max} of 235 GHz.

It can be expected that 0.03-μm-gate InGaAs HEMTs can possibly handle millimeter and submillimeter waves and play important role in future communication system.

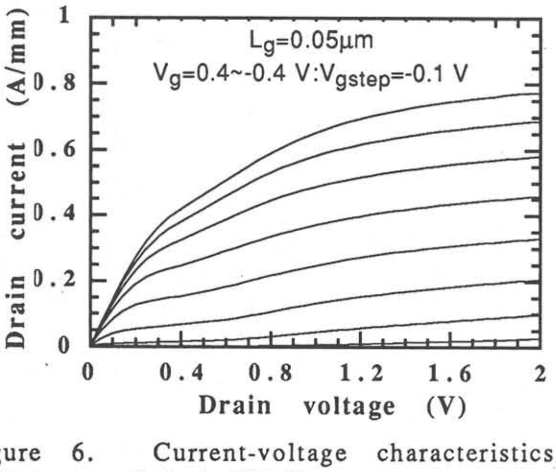

Figure 6. Current-voltage characteristics of 0.05-μm-gate InGaAs HEMT.

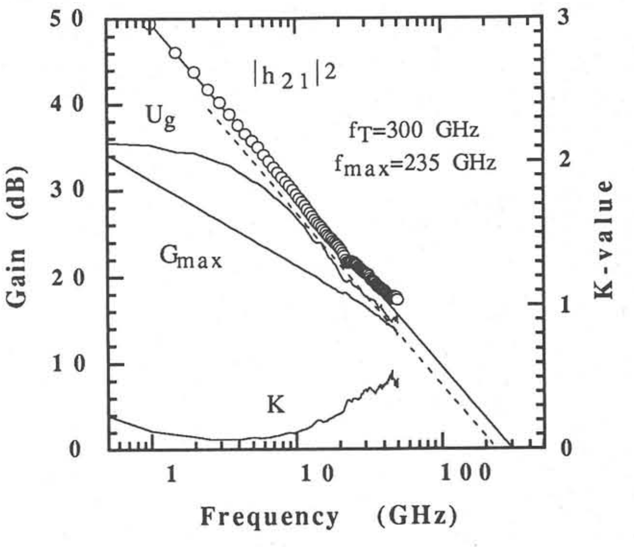

Figure 7. Frequency dependencies of current gain ($|h_{21}|^2$), unilateral power gain (U_g), available power gain (G_{max}), and stability factor (K) for a 0.05x150-μm^2-gate HEMT.

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