1. Introduction
The performance of GaAs-based p-HEMTs can be improved by increasing the In composition (x) of InGaAs channel layers due to the improved confinement and mobility of two-dimensional electron gas in the channel layer. However, the In composition and the thickness of the strained InGaAs channel layer used for conventional GaAs-based p-HEMTs have been restricted below approximately 0.22 and 120 Å, respectively, due to the limitation of the critical layer thickness of the highly strained InGaAs layer. To exploit the improved transport property of the highly strained InGaAs channel layer, special techniques for the growth of high-quality InGaAs layers having a reduced dislocation density are required. A metamorphic buffer growth technique is one of the techniques used for the growth of the high-quality InGaAs layers having the In composition in excess of 0.33 [1]. A patterned substrate growth is another technique to grow high-quality and highly strained InGaAs layers. Using this technique, growth of thick (more than 10 times thicker than the critical layer thickness) InGaAs layers having a reduced misfit dislocation density was reported [2]. The technique was also successfully applied for devices requiring highly strained InGaAs layers, resulting in improved device performances [3]. In this paper, we compare the performances of the InGaP/InGaAs p-HEMTs (x=0.22–0.40) grown on patterned and non-patterned GaAs substrates.

2. Characterization of The InGaP/InGaAs p-HEMTs
The InGaP/InGaAs (x=0.22, 0.33, 0.40) p-HEMT structures, shown in Fig. 1, were grown by using a V80H-10k compound source molecular beam epitaxy at 500 °C. The thickness of the channel layers for x values of 0.33 and 0.40 are approximately 50% and 150% in excess of the critical layer thickness (the Matthews and Blakeslee limit), respectively. For the patterned substrate growth, approximately 2,500 Å high mesa patterns (area = 50x60 μm²) used for the device active area were formed on the GaAs substrates before the epitaxial layer growth. Transistors having a 1.5x50 μm² gate were fabricated using a conventional optical lithography. DC characteristics (transconductance and drain saturation current) of the p-HEMTs grown on patterned and non-patterned substrates are shown in Fig. 2. The highly strained InGaP/InGaAs grown on non-patterned substrates showed degraded performances due to the increased dislocation density. The highly strained InGaP/InGaAs grown on patterned substrates showed the best performance. While the performance of the highly strained InGaP/InGaAs grown on non-patterned substrates degraded due to the increased dislocation density, it was still better than that of the InGaP/InGaAs grown on non-patterned substrates.

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InGaP/InGaAs p-HEMTs Having Channel Layers Over the Critical Layer Thickness Grown on Patterned GaAs Substrates

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![InGaP/InGaAs p-HEMTs](image-url)

**Fig. 1.** Epitaxial layer structures of the InGaP/InGaAs p-HEMTs.

**Fig. 2.** Normalized transconductances and drain saturation currents (at V_g=0V) of the InGaP/InGaAs p-HEMTs.
Microwave performances ($f_T$ and $f_{max}$) of the highly strained InGaP/In_{0.33}Ga_{0.67}As p-HEMTs grown on patterned substrates and the conventional InGaP/In_{0.22}Ga_{0.78}As p-HEMTs grown on non-patterned substrates are compared in Fig. 3. Low-frequency noise performances of the InGaP/In_{0.33}Ga_{0.67}As p-HEMTs were characterized for the temperature range of 150 K - 440 K and for the frequency range of 1 Hz - 53 kHz. Figure 4 shows the room temperature low-frequency input noise spectral density ($S_n$) of the p-HEMTs as a function of the frequency measured at $V_{gs} = 0$ V and $V_{ds} = 2$ V. The noise level and the Hooge parameter of the InGaP/In_{0.33}Ga_{0.67}As p-HEMT grown on patterned substrate were approximately an order of magnitude smaller than those of the InGaP/In_{0.22}Ga_{0.78}As p-HEMT grown on non-patterned substrates. The low-frequency noise spectra showed pure $1/f$ noise behavior for most of the temperature and the frequency ranges investigated.

Microwave noise performance of the p-HEMTs were measured for the frequency range of 1-3 GHz. Figure 5 shows the minimum noise figure ($NF_{min}$) and the associated gain ($G_a$) of the p-HEMTs as a function of frequency measured at $I_{ds} = 1.5$ mA and $V_{ds} = 1$ V. The minimum noise figure of the InGaP/In_{0.33}Ga_{0.67}As p-HEMT grown on patterned substrates was lower than that of the InGaP/In_{0.22}Ga_{0.78}As p-HEMT grown on non-patterned substrates by more than 1 dB for most of the bias conditions.

Fig. 3. Dependence of $f_T$ and $f_{max}$ of the InGaP/In_{0.33}Ga_{0.67}As p-HEMTs on the gate-source bias voltage.

Fig. 4. Room-temperature low-frequency input noise spectra of the InGaP/In_{0.33}Ga_{0.67}As p-HEMTs.

Fig. 5. Frequency dependence of minimum noise figure and associated gain of the InGaP/In_{0.33}Ga_{0.67}As p-HEMTs ($I_{ds} = 1.5$ mA and $V_{ds} = 1$ V).

Fig. 6. Minimum noise figure and associated gain of the InGaP/In_{0.33}Ga_{0.67}As p-HEMTs as a function of the drain current ($f' = 2$ GHz and $V_{ds} = 1$ V).

4. Conclusions

Substantial improvements in device performances including DC ($g_m$ and $f_{ds,hu}$), microwave ($f_T$ and $f_{max}$), and noise characteristics of the InGaP/In_{0.33}Ga_{0.67}As p-HEMTs having a highly strained InGaAs channel layer (50% in excess of the critical layer thickness) are reported. The results indicate the potential of highly strained p-HEMTs grown on patterned substrates for use in high-performance device applications. Further studies on the dependence of the dislocation density on layer structure, growth temperature, and area of patterns are required to achieve high-quality In_{x}Ga_{1-x}As layers having a higher strain.

References