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高性能磷化銦系列光電元件之研製

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Comprehensive investigations of various static and microwave performances on InAlAs/In_{x}Ga_{1-x}As/InP HEMTs with different channel designs, grown by the low-pressure metal organic chemical vapor deposition (LP-MOCVD) technique. The In_{x}Ga_{1-x}As channel structures include the linearity-graded channel (LGC) with x = 0.56 → 0.5, the lattice-matched channel (LMC) with x = 0.53, and the inverse linearly-graded channel (ILGC) with x = 0.5 → 0.56, respectively. In addition, the InP layer is adopted as the etching-stop layer to precisely maintain the same Schottky layer thickness and to improve the uniformity of the device threshold and the extrinsic transconductance characteristics. Improved carrier transport characteristics by employing the linearly-graded channel (LGC) have contributed to the superior extrinsic transconductance (g_{m}) of 346 mS/mm, unity-gain cut-off frequency (f_{t}) of 57 GHz, and maximum oscillation frequency (f_{max}) of 68.3 GHz for a gate dimension of 0.65 × 200 μm². Therefore, the LGC-HEMT is suitable for high-frequency and high-gain applications. On the other hand, the inverse linearly-graded channel structure has demonstrated superior linearity and wider current operating regime of 203 mA/mm at 300 K and better thermal coefficient of g_{m,max} (\partial g_{m,max}/\partial T) is -0.37 mS/mm-K and V_{th} (\partial V_{th}/\partial T) is
-0.5mV/K with increasing temperature due to reduce the scattering effect and improve carrier confinement capability. Consequently, the proposed ILGC-HEMT is suitable for high-temperature and good linearity applications.

### III. Introduction

Over the past years, heterostructure field-effect transistors (HFET’s) and heterostructure bipolar transistors (HBT’s) have been widely studied for high-power and high-frequency integrated circuit applications [5-8]. Particularly, InP-based HEMTs have demonstrated high-frequency and low-noise circuit applications due to their low effective electron mass, high low-field electron mobility, high electron saturation velocity and high sheet carrier densities in the InGaAs channel, as compared to those of GaAs-based HEMT’s. Nevertheless, the low energy-gap InGaAs compounds usually accompany with low impact-ionization threshold fields and kink effects, thus, considerably degrade the device performances, such as higher gate leakages, increased output conductance, and decreased off-state breakdown voltages. To resolve these problems, several approaches have been used, such as using an InP surface passivation layer over the InAlAs gate recess regions to suppress the ionized-hole current injected to the gate terminal to improve breakdown voltages [4, 5]. In addition, the InP layer is adopted as the etching-stop layer to precisely maintain the same Schottky layer thickness and to improve the uniformity of the device threshold and the extrinsic transconductance characteristics. Another way was to reduce the indium composition in the InGaAs channel to directly increase the impact-ionization threshold fields [6]. In this work, we present detailed comparison including DC, RF performances and temperature-dependence characteristics for δ-doped InAlAs/InxGa1-xAs/InP HEMT with linearity-graded channel and inverse linearity-graded channel. Experimentally, the linearity-graded channel improved device gain, current drive capability, gate leakages and output conductance characteristics. The HEMT with inverse linearity-graded channel demonstrates larger gate voltage swing and good thermal stability for high-temperature application.

### IV. Material Growth and Device Fabrication

The studied structures were grown by the low-pressure metal organic chemical vapor deposition (LP-MOCVD) system on the Fe-doped semi-insulating InP substrates. Table I shows the epitaxial structures for the δ-doped In0.52Al0.48As/InxGa1-xAs/InP HEMT with linearly-graded channel (LGC-HEMT) and lattice match channel
(LMC-HEMT) and inverse linearly-graded channel (ILGC-HEMT). The same 50-nm thick In$_{0.52}$Al$_{0.48}$As buffer layers were grown on the Fe-doped semi-insulating (S.I.) InP substrate in all samples. Upon the buffer, a 12-nm thick undoped and a graded In$_x$Ga$_{1-x}$As channel layer, with $x = 0.56$ $\sim$ 0.5 linearly decreasing from the channel/spacer interface to the buffer/channel interface for the LGC-HEMT, undoped In$_{0.53}$Ga$_{0.47}$As channel for LMC-HEMT and a inverse linearity graded In$_x$Ga$_{1-x}$As channel, with $x = 0.5$ $\sim$ 0.56 linearly increase from the spacer/channel interface to the interface channel/buffer for the ILGC-HEMT, respectively. Then a 5-nm thick undoped In$_{0.52}$Al$_{0.48}$As spacer, followed by the silicon planar doping layer ($4 \times 10^{12}$ cm$^{-2}$), a 15-nm thick undoped In$_{0.52}$Al$_{0.48}$As Schottky layer, a 2.5-nm thick undoped InP layer, and finally a 50-nm thick Si-doped ($1 \times 10^{19}$ cm$^{-3}$) In$_{0.53}$Ga$_{0.47}$As capper layer. Though the channel structure varies for the LGC-HEMT, LMC-HEMT and ILGC-HEMT, the effective indium composition and layer thickness of the channel were maintained to be 0.53 and 120 Å, respectively. All the above three device structures were prepared under the same growth conditions to investigate the influences of the respective channel design. In addition, the undoped InP layer was inserted to serve as a gate-recess etching-stopper to improve the gate leakages. The output conductance ($g_{dd}$), and the voltage gain ($A_v$). Standard photolithography, lift-off and the rapid thermal annealing (RTA) techniques were employed for both device fabrications. AuGe/Ni alloys were used for the source and drain ohmic contacts, onto which Au was evaporated to reduce the contact resistance. Gate recess was performed by employing the H$_3$PO$_4$/H$_2$O$_2$/H$_2$O selective etching solution between the InGaAs capper and the InP layer. Pt/Au alloys were deposited on the undoped InP Schottky layer as the gate electrode. The gate length was 0.65 μm with the drain-to-source spacing of 4 μm. Mesa etching was further performed down to the buffer layer to reduce the substrate leakages.

V. Experimental Results and Discussions

Hall measurements have been conducted after removing the cap layers of the device structures under a magnetic field of 5000 Gauss. Table II lists the Hall measurement results of the studied LGC-HEMT, LM-HEMT and ILGC-HEMT, including the two-dimensional electron gas (2DEG) concentration ($n_s$), the electron mobility ($\mu_n$) and the product of carrier mobility and square of carrier concentration at 300 K (77 K), respectively. Since the sheet carrier of 2DEG ($n_s$) can be described as [28]:

$$n_s = \sqrt{\frac{2eN_f}{q}(\Delta E_c - E_{F2} - E_{F1}) + N_f d_i^2 - N_{d} d_f^2} \ldots (1)$$
where $N_d$ is the donor concentration, $\varepsilon$ is the position-dependent dielectric constant, $\Delta E_C$ is conductance band discontinuities at the heterojunction, $E_{F2}$ is the difference between the conduction band edge and the Fermi energy in InAlAs, $E_{Fi}$ is the Fermi level, $d_i$ is the thickness of the spacer layer. In this work, since three structures have the same donor concentration and Shottky layer, the 2DEG concentration would be determined by $\Delta E_C$. The LGC-HEMT has the large conductance band discontinuities ($\Delta E_C$) of 0.54 eV at the spacer/channel interface resulting highest 2DEG concentration compared with LMC-HEMT and ILGC-HEMT. As shown in Table II, the carrier concentration increases lightly and the mobility decreases quickly as temperature increases. The ILGC-HEMT demonstrates the highest carrier mobility at 77 K and 300K due to the inverse linearly-graded channel structure would shift the 2DEG closer to the channel/barrier interface where higher indium composition with lower effective mass was designed lead to the increased separating distance of the 2DEG from the $\delta$-doping ions would greatly improve the scattering effect, which can be observed from the significant improvement on carrier transport at 77 K.

Figure 1 shows the common-source current-voltage characteristics of the all devices at room temperature, respectively. The high resistivity and high energy-gap of the In$_{0.52}$Al$_{0.48}$As barrier layer is intended to greatly reduce the electron injection into the buffer layer and to suppress the substrate leakage resulted in good pinch-off characteristics have been achieved in the three devices. As illustration in Fig. 1, the drain current density increases with increasing drain-source voltage due to the increased electric field resulted from impact ionization effect within the InGaAs channel regime for LMC-HEMT and ILGC-HEMT. Nevertheless, $I_{DSS}$ is nearly independent of $V_{DS}$ attributed to the improved impact ionization effect. Since the higher In-composition InGaAs compounds will have the lower impact-ionization coefficients, the LGC-HEMT was designed to have lower indium composition at the channel/barrier interface to improve its high-field kink effects. The electrons, as depleted farther away from the gate at decreased gate biases, will move to the InGaAs channel region with lower In-composition and wider energy-gap and, consequently, greatly improve the impact ionization-related kink effects of LGC-HEMT. Therefore, the LGC-HEMT improves significantly impact ionization effect lead to lower output conductance ($g_d$) of 3.8 mS/mm compared with 9.3 mS/mm for LMC-HEMT and 12.4 mS/mm for ILGC-HEMT. The measured gate voltage was $V_{DS} = 2$ V and $V_{GS} = 0$ V for LGC-HEMT and LMC-HEMT and
-0.15 V for ILGC-HEMT to maintain identical current density, $I_{DS} = 120$ mA/mm.

Figure 2 indicates the extrinsic transconductance ($g_m$) and saturation drain-source current density ($I_{DSS}$) on gate-source voltage ($V_{GS}$) on the applied gate bias at $V_{DS} = 2$ V at elevated temperatures, ranging from 300 to 500 K for LGC-HEMT, LMC-HEMT, and ILGC-HEMT, respectively. As a gate voltage is applied, the Eq (1) must be replaced by

$$n_s = \frac{\varepsilon}{q(d + \Delta d)}(V_G - V_{off})$$

then

$$V_G - V_{off} = \frac{q(d + \Delta d)n_s}{\varepsilon}$$

Therefore, the drain saturation current and extrinsic transconductance can be described as:

$$I_{DS} = \frac{\varepsilon qW}{2L(d + \Delta d)}(V_G - V_{off}) = \frac{q^2W(d + \Delta d)}{2Le}\mu n_s^2$$

$$g_m = \frac{\partial I_{DS}}{\partial V_{GS}} = \frac{\varepsilon qW}{(d + \Delta d)L}(V_G - V_{off}) = \frac{W}{L}\mu n_s,$$  

where $\Delta d$ is effective 2DEG position from spacer/channel interface, $d$ is the distance from gate to spacer/channel interface and $\varepsilon$ is the position-dependent dielectric constant. The Table Ⅲ lists $g_{m,max}$, $I_{D, max}$, $V_{th}$, $g_d$ and $A_v$ at 300 K and 500K. Obviously, the LGC-HEMT has demonstrated the highest $g_{m,max}$ characteristics of 363mS/mm, since most of the electron population located

within the interface between In$_{0.56}$Ga$_{0.44}$As and InAlAs spacer. The shortest separation distance between gate electrode and the 2DEG ensures the highest $g_{m,max}$ performance of LGC-HEMT, as compared to those of LMC-HEMT and ILGC-HEMT. In addition, the LGC-HEMT also exhibits the maximum drain current density of 360mA/mm. From Eq. (4), we observed the drain current is determined by product of carrier mobility and square of concentration and the value is $1.22 \times 10^{29}$ for LGC-HEMT which is higher than $1.17 \times 10^{29}$ for ILGC-HEMT at 300 K lead to the maximum drain current drive capability of LGC-HEMT. As discussed in Fig. 1, the LGC-HEMT presents the lower $g_d$ by diminishing impact ionization effect. Defining the intrinsic voltage gain can be described as:

$$A_v = g_m \cdot r_o = \frac{g_m}{g_d}$$

The LGC-HEMT has demonstrated higher $g_m$ of 358 (260) and lower $g_d$ of 3.8 (9.8) under $V_{GS} = 0$ V and $V_{DS} = 2$ V resulting in the higher voltage gain of 91.2 (26.5) at 300 (500) K as compared to those of LMC-HEMT at $V_{GS} = 0$ V and $V_{DS} = 2$ V and ILGC-HEMT at $V_{GS} = -0.15$ V and $V_{DS} = 2$ V, as shown in Table Ⅲ.

Figure 3 indicates the $g_{m,max}$ and $V_{th}$ characteristics as a function of the ambient temperatures up to 500 K, at $V_{DS} = 2$ V. The $g_{m,max}$ and $I_{D, max}$
decreases with increasing temperature due to the $g_m$ and $I_D$ is directly depend on proportional to carrier concentration and carrier mobility as shown in Eq (4) and (5). The carrier concentration increases as temperature increases. However, the carriers suffering from the phonon scattering and carrier-carrier scattering mechanisms lead to the mean free length is limited at high temperature. Therefore, the carrier mobility decreased resulting in the product of carrier concentration and carrier mobility decreased at high temperature. The ILGC-HEMT exhibits obviously smaller variations of $g_m$ and the thermal coefficient of $g_{m,max}$ ($\frac{\partial g_{m,max}}{\partial T}$) and $I_{D,max}$ ($\frac{\partial I_{D,max}}{\partial T}$) are -0.37 mS/mm-K and -0.345 mA/mm-K for ILGC-HEMT that is more stable than -0.505 mS/mm-K and -0.44 mA/mm-K for LGC-HEMT and -0.46 mS/mm-K and -0.42 mA/mm-K for LMC-HEMT, respectively. This is because the carriers are accumulated near the channel/buffer interface and the increased separating distance of the 2DEG from the $\delta$-doping ions greatly improve scattering lead to degradation of mobility is the smaller at high temperature. Beside, the threshold voltages ($V_{th}$) are determined by the extrapolated intercepts of $(I_{DSS})^{1/2}$ vs. $V_{GS}$ curves. The threshold shift ($\Delta V_{th}$) from 300 K to 500 K and thermal coefficient of $V_{th}$ ($\frac{\partial V_{th}}{\partial T}$) are -0.23/ -0.19/ -0.10 V and -1.15/ -0.95/ -0.5 mV/K for LGC/LMC/ILGC-HEMT. The electrons within the channel, after gaining sufficient energies at high temperatures, tend to surpass over conduction-band discontinuities. These carriers will likely result in the excessive substrate leakages at high temperatures \[11\] lead to achieve pinch-off more difficult. The ILGC-HEMT has larger conductance band discontinuity ($\Delta E_C = 0.54$ eV) at the channel/buffer interface by using the inverse linearity-graded channel designed resulting in better carrier confinement capability within the channel at high temperature. Experimentally, the ILGC-HEMT demonstrated better thermal stability characteristics within the temperature regime from 300 K to 500K.

Define the gate-voltage swing (GVS) as the width of transconductance plateau of a 10% reduction from the value of $g_{m,max}$, the ILGC-HEMT has demonstrated a larger GVS of 0.65 V with the corresponding current regime of 203 mA (31 mA $\leq I_{DSS} \leq 234$ mA) than those of 0.4 V and 133 mA (44 mA $\leq I_{DSS} \leq 177$ mA) in the LMC-HEMT and 0.5 V and 167 mA (70 mA $\leq I_{DSS} \leq 237$ mA) in the LGC-HEMT, respectively, as shown in Fig. 2. Furthermore, the linearity current operating regime at 500 K is still 149 mA for ILGC-HEMT higher than 85 mA for LMC-HEMT and 124 mA for LGC-HEMT. For a conventional LMC-HEMT device, the $\mu$ is constant and only $\Delta d$ in Eq. (5) dependent on the gate bias. Therefore,
the transconductance will drop quickly due to the increased $\Delta d$ with the decreased gate bias. Nevertheless, for the inverse linearity-graded channel structure as indicated in Table I, since the indium composition was designed to vary linearly from 0.5 at spacer/channel interface to 0.56 at channel/buffer interface, the 2DEG pushed by the gate bias towards higher $\mu$ regime will compensate the increase of $\Delta d$ in Eq. (5) to keep high transconductance and demonstrate the wide-GVS performance. The experimental results demonstrate superior linearity of ILGC-HEMT, can significantly improve the inter-modulation of high-frequency signals, and further resolve the distortion problems for high-frequency applications.

The two-terminal gate-drain breakdown ($BV_{GD}$) and forward turn-on voltage ($V_{on}$) characteristics at room temperature of the studied InP HEMTs are shown in Fig. 4. The $BV_{GD}$ and $V_{on}$, defined at $I_G = 1$ mA/mm, are -19.2 V/0.88 V, -17.0/0.68 V and -15.7/1.35 V for LGC-HEMT, LM-HEMT and ILGC-HEMT, respectively. Since the gate leakage current consists of two major contributions: (1) the electron injection through thermionic-field emission (TFE) and tunneling mechanisms through the Schottky gate barrier; (2) the generation of hole current through the impact ionization in the channel $^{[9]}$. The LGC-HEMT was designed to have lower indium composition with lower impact-ionization coefficients at the channel/buffer interface to improve its high-field kink effects and diminish the ionized-hole current injected to the gate terminal. Therefore, higher breakdown voltages of the LGC-HEMT have been achieved at room temperature. On the other hand, the ILGC-HEMT presents highest turn-on voltage, possibly due to the carriers are farther away from the gate electrode as compared to the LMC-HEMT and LGC-HEMT, the increased separation distance has resulted in a higher series resistance within the inverse graded channel design, as can be observed in the different slopes of the forward I-V curves in the inset of Fig. 4.

Fig. 4 (b) shows the gate-drain breakdown and turn on voltage as a function of temperature from 300K to 500K. Since the Schottky barrier height decreases $^{[1]}$ and the electrons obtained enough thermal energy at high temperature, the probability of carrier injection or tunneling rose. The TFE/tunneling mechanisms manifest the increasing of gate current with increasing temperature. Therefore, the gate current couples with impact ionization and TFE/tunneling currents lead to the breakdown and turn on voltage decreased quickly as 300 K $\leq T \leq$ 400 K as shown in Fig. 7. The LGC-HEMT still demonstrates larger breakdown voltage but the variation of three device decreases with increasing
temperature. Additionally, as the temperature increases above 400 K, the carriers within the channel suffering from the phonon scattering and carrier-carrier scattering mechanisms couldn’t obtain sufficient thermal energy and to initiate the impact ionization (1). The TFE/tunneling effect is more significant compare than impact ionization at the ambient temperature. Therefore, the reverse gate leakage current is dominated by TFE/tunneling mechanism. A formulation of the WKB approximation for tunneling probability at the Schottky gate is given as [22]

\[
\Gamma_{\text{w}} = \exp \left[ -\frac{2}{\hbar} \int_{0}^{r} \sqrt{2m \left( \frac{\phi_b}{q} + \Phi_m - \phi(x) \right)} dx \right] \tag{7}
\]

where \( \Lambda^* \) is the effective Richardson constant, \( m_t \) is the tunneling mass, \( \phi_b \) is the barrier height, \( \Phi_m \) is the work function of metal, \( \phi \) is the electrostatic potential. The same InAlAs Schottky barrier layer and Pt/Au metal for three devices lead to the parameter of \( \phi_b, \Phi_m, m_t \) and \( \phi \) is similarity. Consequently, the breakdown voltage and turn-on voltage is similar for all devices as the temperature above 400K.

The microwave on-wafer S-parameter measurements have also been conducted from 0.5 to 40 GHz in a common-source configuration, by using the HP-8510B network analyzer. The the unity current gain cut-off frequency \( (f_i) \) and the maximum oscillation frequency \( f_{\text{max}} \) performances at \( V_{\text{DS}} = 2\text{V} \) have been indicated in Fig. 5 (a) at room temperature. The higher \( f_i \) \( f_{\text{max}} \) are 57 (68.3) GHz for LGC-HEMT at \( V_{\text{GS}} = 0\text{V} \), 42.3 (50.9) GHz for LMC-HEMT at \( V_{\text{GS}} = 0\text{V} \) and 52.9 (56.6) GHz for ILGC-HEMT at \( V_{\text{GS}} = -0.2 \text{V} \). Since the cutoff frequency \( (f_i) \), can be approximated as:

\[
f_i \approx \frac{g_m}{2\pi \left( C_{\text{dg}} + C_{\text{gs}} \right)} \tag{8}
\]

\[
f_{\text{max}} \approx \frac{f_i}{2\sqrt{R_i} \cdot g_d} \tag{9}
\]

where \( C_{\text{gs}} \) and \( C_{\text{gd}} \) is the capacitance of gate-source and gate-drain and \( R_i \) is the series resistance. Higher \( g_m \) and lower \( g_d \) result in better high-frequency performances. Higher \( f_i \) and \( f_{\text{max}} \) characteristics of LGC-HEMT than those of ILGC-HEMT and LMC-HEMT are obtained due to the improved transport characteristics and the shortened separation distance of the 2DEG population from gate electrode by considering the previously discussed \( g_m \) characteristics. Fig.5 (b) shows the \( f_i \) and \( f_{\text{max}} \) as a function of temperature form 300 K to 425 K. The \( f_i \) \( f_{\text{max}} \) are 52.4 (58.6) GHz at 425K for LGC-HEMT, 38.9 (42.8) for LMC-HEMT and 49.9 (51.3) for ILGC-HEMT. High-temperature \( f_i \) performance at 425 K maintains distinguished 94 % of that at 300 K of ILGC-HEMT. As illustrated in Fig. 5 (b), the lower degradation of \( f_i \) and \( f_{\text{max}} \) with increasing temperature is obtained for ILGC-HEMT due to the better thermal stability of \( g_{m,max} \). Therefore, based on the better linearity and thermal stability, the ILGC-HEMT
Microwave power characteristics were also investigated by using a load-pull ATN system, which provides a conjugate simultaneously matched input and load impedances for achieving an optimum power performance. The microwave power performances were measured at 5.8 GHz, with $V_{DS} = 2$ V and $V_{GS} = -0.25$ V at 300 K for studied InP HEMTs. Figure 6 shows the saturated output power ($P_{out}$), associated power gain ($G_a$) and the power-added efficiency (P.A.E.) versus the input power. The measured saturated output power, P.A.E., and the associated power gain are 12.24 (11.04/11.52) dBm, 43.2 (36.9/40.6) % and 20.53 (18.6/20.19) dB for the LGC-HEMT (LMC-HEMT/ILGC-HEMT), respectively. Together with the superior breakdown characteristics and current driving capability, the improved high power performances of the LGC-HEMT indicate its promising power applications.

VI. Conclusion

In summary, δ-doped In$_{0.52}$Al$_{0.48}$As/In$_x$Ga$_{1-x}$As/InP high electron mobility transistors with different channel designs, grown by the low-pressure metal organic chemical vapor deposition (LP-MOCVD) technique, have been successfully investigated. Influences on various DC, high-frequency, and high-temperature device characteristics of the linearity graded channel and inverse linearly graded In$_x$Ga$_{1-x}$As channel designs have been comprehensively discussed and compared with those of the conventional lattice-matched In$_{0.53}$Ga$_{0.47}$As channel. Due to the intrinsic high-speed property of the high In composition In$_{0.56}$Ga$_{0.44}$As channel design and the decreased separation distance between 2DEG and gate electrode, the LGC-HEMT exhibiting higher extrinsic transconductance, lower output conductance, higher voltage gain, and enhanced microwave performances, is suitable for high-frequency and high-gain applications. On the other hand, ILGC-HEMT has demonstrated superior linearity, wider GVS regime and extremely low thermal coefficient performances at high temperatures up to 500 K., due to the inverse linearly-graded In$_x$Ga$_{1-x}$As channel design. Consequently, the proposed ILGC-HEMT is suitable for high-temperature and good linearity applications.

Reference:
3. Shinohara K, Yamashita Y, Endoh A, Watanabe I, Hikosaka K, Matsui T, and


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**Table I** The layer structures of the studied InAlAs/InGaAs/InP HEMTs.

<table>
<thead>
<tr>
<th>Layer</th>
<th>Thickness</th>
<th>LGC-HEMT</th>
<th>LMC-HEMT</th>
<th>ILGC-HEMT</th>
</tr>
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<tbody>
<tr>
<td>Cap</td>
<td>50 nm</td>
<td>$\delta^3\text{InGa}<em>{0.7}\text{Al}</em>{0.3}\text{As}$</td>
<td>$\delta\text{InGa}<em>{0.55}\text{Al}</em>{0.45}\text{As}$</td>
<td>$\delta\text{InGa}<em>{0.5}\text{Al}</em>{0.5}\text{As}$</td>
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<tr>
<td>Ech Stopper</td>
<td>2.5 nm</td>
<td>$\delta\text{InGa}<em>{0.5}\text{Al}</em>{0.5}\text{As}$</td>
<td>$\delta\text{InGa}<em>{0.5}\text{Al}</em>{0.5}\text{As}$</td>
<td>$\delta\text{InGa}<em>{0.5}\text{Al}</em>{0.5}\text{As}$</td>
</tr>
<tr>
<td>Source</td>
<td>15 nm</td>
<td>$\delta\text{InGa}<em>{0.5}\text{Al}</em>{0.5}\text{As}$</td>
<td>$\delta\text{InGa}<em>{0.5}\text{Al}</em>{0.5}\text{As}$</td>
<td>$\delta\text{InGa}<em>{0.5}\text{Al}</em>{0.5}\text{As}$</td>
</tr>
<tr>
<td>Current Stop</td>
<td></td>
<td>$\delta\text{InGa}<em>{0.4}\text{Al}</em>{0.6}\text{As}$</td>
<td>$\delta\text{InGa}<em>{0.4}\text{Al}</em>{0.6}\text{As}$</td>
<td>$\delta\text{InGa}<em>{0.4}\text{Al}</em>{0.6}\text{As}$</td>
</tr>
<tr>
<td>Spacers</td>
<td>5 nm</td>
<td>$\delta\text{InGa}<em>{0.5}\text{Al}</em>{0.5}\text{As}$</td>
<td>$\delta\text{InGa}<em>{0.5}\text{Al}</em>{0.5}\text{As}$</td>
<td>$\delta\text{InGa}<em>{0.5}\text{Al}</em>{0.5}\text{As}$</td>
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<tr>
<td>Channel</td>
<td>12 nm</td>
<td>$\delta\text{InGa}<em>{0.5}\text{Al}</em>{0.5}\text{As}$</td>
<td>$\delta\text{InGa}<em>{0.5}\text{Al}</em>{0.5}\text{As}$</td>
<td>$\delta\text{InGa}<em>{0.5}\text{Al}</em>{0.5}\text{As}$</td>
</tr>
<tr>
<td>Buffer</td>
<td>50 nm</td>
<td>$\delta\text{InGa}<em>{0.5}\text{Al}</em>{0.5}\text{As}$</td>
<td>$\delta\text{InGa}<em>{0.5}\text{Al}</em>{0.5}\text{As}$</td>
<td>$\delta\text{InGa}<em>{0.5}\text{Al}</em>{0.5}\text{As}$</td>
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**Table II** Hall measurement results at 77 K and 300 K for the LGC-HEMT, LMC-HEMT and ILGC-HEMT, respectively.

<table>
<thead>
<tr>
<th>Temperature</th>
<th>LGC-HEMT</th>
<th>LMC-HEMT</th>
<th>ILGC-HEMT</th>
</tr>
</thead>
<tbody>
<tr>
<td>K</td>
<td>300 K</td>
<td>77 K</td>
<td>300 K</td>
</tr>
<tr>
<td>$\mu$ (cm²/V·s)</td>
<td>8.654</td>
<td>3.052</td>
<td>8.491</td>
</tr>
<tr>
<td>$n_e \times 10^9$ (cm⁻³)</td>
<td>3.77</td>
<td>3.35</td>
<td>3.5</td>
</tr>
<tr>
<td>$\mu\cdot n_e \times 10^9$ (cm²/V·s)</td>
<td>1.22</td>
<td>3.42</td>
<td>1.84</td>
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Table III DC characteristics of the studied InP HEMTs at 300 K and 500 K, respectively.

<table>
<thead>
<tr>
<th>Temperature</th>
<th>LGC-HEMT</th>
<th>LMC-HEMT</th>
<th>ILGC-HEMT</th>
</tr>
</thead>
<tbody>
<tr>
<td>V_{DSS} (mS/mm)</td>
<td>346</td>
<td>262</td>
<td>295</td>
</tr>
<tr>
<td>I_{dss} (mA/mm)</td>
<td>298</td>
<td>260</td>
<td>292</td>
</tr>
<tr>
<td>V_{th} (V)</td>
<td>0.49</td>
<td>-0.72</td>
<td>-0.53</td>
</tr>
<tr>
<td>g_m (mS/mm)</td>
<td>3.8</td>
<td>9.8</td>
<td>9.1</td>
</tr>
<tr>
<td>A_r</td>
<td>91.2</td>
<td>26.5</td>
<td>31.6</td>
</tr>
</tbody>
</table>

Fig. 1 The common-source I-V characteristic for the studied InP HEMT with different channel structure at 300K.

Fig. 2(a) The extrinsic transconductance and saturation drain saturation density versus the applied gate-source bias with V_{DS} = 2 V at elevated temperatures, ranging from 300 to 500 K for LGC-HEMT.

Fig. 2(b) The extrinsic transconductance and saturation drain saturation density versus the applied gate-source bias with V_{DS} = 2 V at elevated temperatures, ranging from 300 to 500 K for LMC-HEMT.
Fig. 2(c) The extrinsic transconductance and saturation drain saturation density versus the applied gate-source bias with $V_{DS} = 2$ V at elevated temperatures, ranging from 300 to 500 K for ILGC-HEMT.

Fig. 3 The extrinsic transconductance ($g_{m,\text{ex}}$) and the threshold voltage ($V_{th}$) as a function of temperature for the studied InP HEMT from 300 K to 500 K.

Fig. 4(a) Two-terminal gate-to-drain breakdown characteristics for studied InP HEMT at 300 K, respectively. The inset shows the zoomed-in forward bias characteristics.

Fig. 4(b) The gate-drain breakdown voltage and turn-on voltage as a function of temperature for studied InP HEMT from 300K to 500K.
Fig. 5(a) Microwave characteristics for studied InP HEMT at 300 K with $V_{DS} = 2$ V. The gate voltage is 0 V for LGC-HEMT and LMC-HEMT and -0.25 V for ILGC-HEMT, respectively.

Fig. 5(b) Measured unity current gain cutoff frequency ($f_t$) and maximum oscillation frequency ($f_m$) as a function of temperature from 300K to 425 K.

Fig. 6 Room-temperature output power, power gain and power-added efficiency characteristics versus input power at 5.8 GHz, with $V_{DS} = 2$ V and $V_{GS} = -0.25$ V for studied InP HEMTs.