行政院國家科學委員會專題研究計畫期中進度報告

高性能磷化銦系列光電元件之研製

計畫類別：個別型計畫
計畫編號： NSC93-2215-E-006-007-
執行期間：93年08月01日至94年07月31日
執行單位：國立成功大學微電子工程研究所

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報告類型：精簡報告
處理方式：本計畫可公開查詢

中華民國94年05月12日
1. 中文摘要
在本計劃中，我們利用第一年磊晶經驗，在磷化銦基板上，成長高性能的高電子移動率電晶體，同時我們也成功地研製出一系列不同通道的 In0.52Al0.48As/In0.6Ga0.4As 高電子移動率電晶體。由於良好的載子侷限能力及低溫成長 In0.52Al0.48As 的能障層，因此元件顯示出高轉導值、低漏電流、高崩潰電壓及高線性度的操作區域。實驗可得，漸變式通道可以改善閘極電壓擺幅以及較大線性操作電流，另一方面，通道為 In0.6Ga0.4As 的元件，在閘極長度為 1.5 μm 下，外質轉導值可高達 302 mS/mm。

2. English Abstract
In this year, we have researched and fabricated the InP-based high electron mobility transistors by using the epitaxial grown data in the first year of this project. High-linearity In0.52Al0.48As/In0.6Ga0.4As HEMT_s have been successfully fabricated by low-pressure metal organic chemical vapor deposition (LP-MOCVD). The studied devices exhibit high transconductance, low leakage current, high breakdown, and high-linearly operational regime due to good carrier confinement well as the low temperature growth In0.52Al0.48As barrier layer significantly suppresses buffer leakage current. Experimentally, linear operation current regime and gate voltage swing are improved in the structure utilizing a compositionally graded In0.6Ga1-xAs channel due to the compositionally graded In0.6Ga1-xAs channel enhance the device carrier mobility and confinement. An extrinsic transconductance as high as 302 mS/mm at gate length of 1.5 μm is achieved for the In0.6Ga0.4As channel structure.

Keyword：InP based HEMT ; InAlAs/InGaAs heterostructure; LP-MOCVD

3. Introduction
The potential performance high electron mobility transistors (HEMTs) have been conclusively demonstrated excellent high-frequency and low-noise performance because of the superior transport properties. InP-based HEMTs have superior electronic transport properties to GaAs-based structures due to the large Γ-L band separation, low effective mass, high low-field electron
mobility, high electron saturation velocity, and high sheet carrier densities in the InGaAs channel [1]-[5]. Recently, great interest in the strained AlGaAs/In_{x}Ga_{1-x}As and In_{0.52}Al_{0.48}As/In_{x}Ga_{1-x}As (x > 0.53) heterostructures has been demonstrated. Provided that such layers are kept below a certain critical thickness the lattice mismatch can be incorporated as a biaxial strain and no misfit dislocations are generated. Thus, an In-rich pseudomorphic In_{x}Ga_{1-x}As channel with lower effective electron mass, higher mobility, and higher conduction-band discontinuities (ΔE_C) at AlGaAs/In_{x}Ga_{1-x}As and In_{0.52}Al_{0.48}As/In_{x}Ga_{1-x}As heterointerfaces can be achieved in the heterostructures [6]-[10]. Unfortunately, the lower energy-gap In_{x}Ga_{1-x}As may induce lower impact ionization field in the In_{x}Ga_{1-x}As channel layer under high electric field and the device performances, including leakage current, output conductance, voltage gain, and on-state breakdown voltage degrade considerably. Moreover, the drawback in the narrow constant transconductance regions may limit the transistor to be used in the applications of digital circuits in the future cellular/PCS phones. In the work, we propose In_{0.52}Al_{0.48}As/In_{x}Ga_{1-x}As high electron mobility transistors with various In_{x}Ga_{1-x}As channels. Experimentally, high transconductance and high-linearity characteristics along with good breakdown characteristics are obtained in the studied In_{0.52}Al_{0.48}As/In_{x}Ga_{1-x}As HEMTs.

4. Experiment Results

The studied structures were grown by low-pressure metal organic chemical vapor deposition (LP-MOCVD) system on Fe-doped SI-InP substrates. The detail epitaxial layers of the studied In_{0.52}Al_{0.48}As/In_{x}Ga_{1-x}As HEMT_s are shown in Fig. 1. The In_{x}Ga_{1-x}As channel compositions of the studied MC-HEMT, GC-HEMT, and PC-HEMT are designed as uniformly lattice-matched In_{0.53}Ga_{0.47}As, compositionally graded In_{x}Ga_{1-x}As from channel/barrier interface of x = 0.6 to spacer/channel of x = 0.53, and uniformly pseudomorphic In_{0.6}Ga_{0.4}As, respectively. The reactor pressure was hold at 100 mbar. The deposition temperatures are 640 °C for InP and In_{x}Ga_{1-x}As, 680 °C for In_{0.52}Al_{0.48}As barrier, and 720 °C for In_{0.52}Al_{0.48}As spacer, donor and, Schottky layers. Trimethylindium (TMIn), trimethylaluminum (TMA), trimethylgallium (TMGa), arsine (AsH3), and phosphine (PH3) were used as the In, Al, Ga, As, and P sources, respectively. Disilane (Si2H6) was adopted as the n-type source. The uniformity in layer thicknesses of InP, In_{0.52}Al_{0.48}As, and In_{x}Ga_{1-x}As under above growth conditions was ±5%. The lattice mismatch of In_{x}Ga_{1-x}As and In_{0.52}Al_{0.48}As were kept within ±500 ppm measured by X-ray diffraction. Standard photolithography, lift-off, and
rapid thermal annealing (RTA) techniques were employed for device fabrication. AuGeNi metal was used for source and drain ohmic contacts, on which Au was evaporated to reduce the contact resistance. Au was evaporated on the undoped InAlAs layer as Schottky contact metal. The gate dimension was $1.5 \times 100 \, \mu m^2$.

Table 1 lists 2DEG carrier concentrations and mobility of the studied $In_{0.52}Al_{0.48}As/In_{x}Ga_{1-x}As$ HEMT’s obtained from Hall measurement at 77 and 300 K. For a compositionally uniform channel HEMT structure, MC-HEMT or PC-HEMT, the 2DEG accumulates near spacer/channel interface due to the attraction from the ionized donor at doped layer. For a compositionally graded channel HEMT structure, GC-HEMT, the compositionally graded $In_{x}Ga_{1-x}As$ channel shifts the 2DEG closer to the channel/barrier interface where higher indium composition is located. A lower effective mass and lower Coulomb scattering can be expected. Consequently, improved electron mobility especially at low temperature is obtained for GC-HEMT when compared with the fixed-composition channel structures, MCHEMT and PCHEMT. Figures 2(a), 2(b), and 2(c) show the common source current-voltage characteristics of the studied $In_{0.52}Al_{0.48}As/In_{x}Ga_{1-x}As$ HEMT’s at room temperature. The PC-HEMT and GC-HEMT show higher operation current due to the higher In composition of $In_{x}Ga_{1-x}As$ channel implying higher electron mobility in the channel, thus higher drain-source current ($I_{DS}$) is obtained. As illustrated in Fig. 2(c), under saturation region the drain-source current ($I_{DS}$) increases slightly with the bias of drain-source voltage ($V_{DS}$) due to the InGaAs channel impact ionization under high electric field. Low energy-gap of In-rich $In_{x}Ga_{1-x}As$ channel indices low impact ionization field under high electric field, thus higher output conductance ($g_{ds}$) is obtained in the studied PC-HEMT. The lower temperature growth InAlAs barrier layer has a higher resistivity and results in an improved isolation-related property of the device characteristics. In addition, the high resistivity and high energy-gap InAlAs barrier layer significantly suppresses the buffer layer leakage current and reduces electron injection into the buffer, thus good pinch-off characteristics are achieved in the studied devices. Figure 3 shows the gate-drain I-V characteristics of the studied $In_{0.52}Al_{0.48}As/In_{x}Ga_{1-x}As$ HEMT’s at room temperature. The gate-drain breakdown voltages (defined at $I_{GD}=1$ mA/mm) of the studied MC-HEMT, GC-HEMT and PC-HEMT are 14.8, 11.7, and 10.7 V, respectively. These high breakdown voltages are attributed to the use of the undoped high bandgap InAlAs Schottly layer as well as good carrier confinement in the $In_{x}Ga_{1-x}As$ channel.
The dependences of the extrinsic transconductance \( (g_m) \) and drain-source saturation current \( (I_{DS}) \) on the gate-source voltage \( (V_{GS}) \) of the studied \( \text{In}_{0.52}\text{Al}_{0.48}\text{As}/\text{In}_{x}\text{Ga}_{1-x}\text{As} \) HEMT’s measured at room temperature are shown in Fig. 4. The applied voltage is fixed at \( V_{DS} = 3 \) V. Obviously, good linearity properties and high transconductance are achieved in studied \( \text{In}_{0.52}\text{Al}_{0.48}\text{As}/\text{In}_{x}\text{Ga}_{1-x}\text{As} \) HEMT’s. The measured maximum transconductance \( (g_{m,max}) \) at room temperature of MC-HEMT, GC-HEMT and PC-HEMT are 208, 235 and 302 mS/mm, respectively. The corresponding gate-voltage swing \( (\text{GVS}) \) (defined at the drop of 10\% from the \( g_{m,max} \)) of the studied MC-HEMT, GC-HEMT and PC-HEMT are 0.6, 0.9, and 0.5 V, respectively. Figure 5 shows the dependences of the extrinsic transconductance \( (g_m) \) on the drain-source saturation current \( (I_{DS}) \) of the studied \( \text{In}_{0.52}\text{Al}_{0.48}\text{As}/\text{In}_{x}\text{Ga}_{1-x}\text{As} \) HEMT’s measured at room temperature. The applied voltage is fixed at \( V_{DS} = 3 \) V. The corresponding linear \( I_{DS} \) operation regime (defined at the drop of 10\% from the \( g_{m,max} \)) of the studied MC-HEMT, GC-HEMT and PC-HEMT are \( 121 \) \((-0.45 \text{ V} \leq V_{GS} \leq 0.15 \text{ V})\), \( 205 \) \((-0.8 \text{ V} \leq V_{GS} \leq 0.1 \text{ V})\) and \( 160 \) \((-0.35 \text{ V} \leq V_{GS} \leq 0.15 \text{ V})\) mA/mm, respectively. For a compositionally uniform channel HEMT structure, MC-HEMT or PC-HEMT, the carrier saturation velocity is assumed to be constant in the channel due to the same composition in the channel. As the reverse gate bias increasing the thickness from gate electrode to the effective 2DEG position increases, thus causes the transconductance to be decreased. Therefore, the transconductance after increasing with the reverse gate bias, peaks and then drops. For a compositionally graded channel HEMT structure, GC-HEMT, the compositionally graded \( \text{In}_{x}\text{Ga}_{1-x}\text{As} \) channel shifts the 2DEG closer to the channel/barrier interface where higher indium composition is located. Moreover, the carrier saturation velocity in the channel is no longer constant. Carrier saturation velocity increases with increasing indium composition in the graded \( \text{In}_{x}\text{Ga}_{1-x}\text{As} \) channel may further compensate for the tiny increase of the thickness from gate electrode to the effective 2DEG position. Transconductance can thus be kept constant over a wider range and improvements in gate-voltage swing and linear current operation regime are therefore achieved through the employment of a compositionally graded channel.

The microwave characteristics of the studied \( \text{In}_{0.52}\text{Al}_{0.48}\text{As}/\text{In}_{x}\text{Ga}_{1-x}\text{As} \) HEMT’s were measured by an HP8510B network analyzer in conjunction with Cascade probes. The measured unity current gain cut-off frequencies \( (f_T) \) of MC-HEMT, GC-HEMT and PC-HEMT are 19, 22 and 22 GHz, respectively. In addition, the measured maximum
oscillation frequencies \( f_{\text{max}} \) are 28, 27 and 30 GHz, respectively.

5. Conclusion

In summary, we have investigated the influences of various \( \text{In}_x\text{Ga}_{1-x}\text{As} \) channels on device characteristics. MC-HEMT and GC-HEMT show good pinch-off, good saturation, and low output conductance characteristics due to good carrier confinement in the channel as well as the low temperature growth \( \text{InAlAs} \) barrier layer. In addition, GC-HEMT shows high-linearity operation current regime and large gate-voltage swing due to the compositionally graded \( \text{In}_x\text{Ga}_{1-x}\text{As} \) channel provide better carrier confinement. PC-HEMT shows high transconductance and current drivability due the high indium composition \( \text{In}_x\text{Ga}_{1-x}\text{As} \) channel which is expected high average carrier saturation velocity in the channel. Furthermore, good microwave characteristics are also obtained in the studied devices. Therefore, the studied \( \text{InAlAs}/\text{InGaAs} \) HEMTs are very suitable for high-power and high-linearity circuit applications.

Reference:


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| Table 1 2DEG carrier concentrations and mobility of the studied $\text{In}_{0.52}\text{Al}_{0.48}\text{As}/\text{In}_{x}\text{Ga}_{1-x}\text{As}$ HEMTs at 77 and 300 K |
|-----------------|-----------------|-----------------|
|                | MC MHEMT | GC MHEMT | PC MHEMT |
| Composition    | $x=0.53$ | $x=0.53-0.6$ | $x=0.6$ |
| $\text{In}_x\text{Ga}_{1-x}\text{As}$ | | | |
| Mobility       | 10500 | 11300 | 11700 |
| ($\text{cm}^2/\text{V.s}$) | at 300 K | | |
| Concentration  | 1.7 | 2 | 1.8 |
| ($10^{12}\text{ cm}^{-2}$) | at 300K | | |
| Mobility       | 41200 | 60000 | 52400 |
| ($\text{cm}^2/\text{V.s}$) | at 77 K | | |
| Concentration  | 1.4 | 1.7 | 1.7 |
| ($10^{12}\text{ cm}^{-2}$) | at 77K | | |
Fig. 1 The schematic cross-section of the studied $\text{In}_{0.52}\text{Al}_{0.48}\text{As}/\text{In}_{x}\text{Ga}_{1-x}\text{As}$ HEMTs

Fig. 2 The common source output I–V characteristics of (a) MCHEMT, (b) GCHEMT, and (c) PCHEMT.

Fig. 3 The two-terminal gate–drain I–V characteristics of the studied $\text{In}_{0.52}\text{Al}_{0.48}\text{As}/\text{In}_{x}\text{Ga}_{1-x}\text{As}$ HEMTs
Fig. 4 The measured drain–source saturation current and transconductance versus gate–source voltage of the studied $\text{In}_{0.52}\text{Al}_{0.48}\text{As}/\text{In}_{x}\text{Ga}_{1-x}\text{As}$ HEMTs.

Fig. 5 Transconductance as a function of the drain–source saturation current of the studied $\text{In}_{0.52}\text{Al}_{0.48}\text{As}/\text{In}_{x}\text{Ga}_{1-x}\text{As}$ HEMTs.