行政院國家科學委員會專題研究計畫成果報告

計畫題目: 砷化銦/砷化鋁銦應力補償之高速電晶體

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一、中文摘要：

本文敘述了有關 InAs channel HEMT 的直流和微波特性。在載子濃度為 2.7x10^{12} cm^{-2} 時，其室溫的電子遷移率高達 20200 cm^2/Vs；直流非本質跨導（DC extrinsic transconductance）經量測則為 714 mS/mm ，而 HEMT 閘極長度為 1μm時可獲得其截止頻率為 50 GHz。

而高 Hall mobility 和良好的元件特性與 $In_xAl_{1-x}As$ 的緩衝層設計有很大的關係，這層緩衝層也就是晶格常數從 $In_{0.52}Al_{0.48}As$ 結構變化到 $In_{0.75}Al_{0.25}As$ 結構的地方。在比較了分別由多層 $In_{0.52}Al_{0.48}As$ 單分子晶格、逐漸變化（step-graded）的 $In_xAl_{1-x}As$ 和均勻的$In_{0.75}Al_{0.25}As$ 所形成之三種緩衝層之後，我們發現了多層 $In_{0.52}Al_{0.48}As$ 單分子晶格組成的緩衝層效果最佳。

關鍵詞：HEMT、晶格常數、緩衝層

Abstract ---- **The dc and microwave performance of an InAs channel HEMT is reported. Room-temperature electron mobility as high as 20200 cm^2/Vs is measured, with a high carrier concentration of 2.7x10^{12} cm^{-2}. DC extrinsic transconductance of 714 mS/mm is measured and a unity-current-gain cut-off frequency of 50 GHz is obtained for a 1.1-μm gate length HEMT. The success of achieving superior Hall mobility and device performance is strongly dependent on the $In_xAl_{1-x}As$ buffer layer design that changes the lattice constant from lattice-matched $In_{0.52}Al_{0.48}As$ to $In_{0.75}Al_{0.25}As$. The multiple $In_{0.52}Al_{0.48}As$/InAs monolayer superlattices buffer achieves the best performance as compared to the step-graded $In_xAl_{1-x}As$ and the uniform $In_{0.75}Al_{0.25}As$ buffer.**

Keyword: HEMT, superior Hall mobility, lattice constant, buffer layer.

二、緣由與目的

RECENTLY, InP-based $In_{0.53+x}Ga_{0.47-x}As/In_{0.52}Al_{0.48}As$ pseudomorphic high-electron-mobility-transistors (HEMT's) [1]-[6] have demonstrated superior high-frequency performance relative to other field-effect transistors (FET's) at equal gate length (Lg). It is shown both theoretically and experimentally that the performance can be further improved with increasing In composition in the $In_{0.53+x}Ga_{0.47-x}As$ channel, which are due to the lower electron effective mess, higher electron mobility and peak velocity, and better carrier confinement in the quantum well. Therefore record high unity-current-gain cut-off frequency (f_T) and f_T-Lg product of 340 GHz [2] and 57 GHz-μm [1] have been achieved in $In_{0.8}Ga_{0.2}As$ channel and $In_{0.77}Ga_{0.23}As/In_{0.25}Ga_{0.75}As$ strain compensated channel, respectively. It is expected that the high-speed performance can be further improved if an InAs channel is used. However, the large lattice-mismatch between InAs channel and InP substrate is beyond the capability of our previous reported strain-compensated design [1], [7], [8], and three-dimensional (3-D) growth is generated. This rough growth front not only increases the interface roughness but also decreases both electron mobility and velocity, which may result in a degraded device performance.

In this letter, we present the successful growth of InAs channel HEMT structure. Room-temperature mobility of 20200 cm^2/Vs is measured, with a carrier concentration of 2.7 x 10^{12} cm^{-2}. The merit of the InAs channel design is further confirmed by the high f_T of 50 GHz in a 1.1-μm device. Both the mobility and f_T are improved to the previous strain compensated $In_{0.8}Ga_{0.2}As/In_{0.25}Ga_{0.75}As$ channel design.

三、實驗方法

Our samples were grown in a molecular beam epitaxy (MBE) system. Typical growth rates were 0.8 μm/h for both $In_{0.53}Ga_{0.47}As$ and $In_{0.52}Al_{0.48}As$. The layer structure of InAs channel HEMT's is shown schematically in Fig.1, which consists of a 200-nm $In_{0.52}Al_{0.48}As$ lattice-matched to InP, a 200-nm $In_xAl_{1-x}As$ buffer, an active channel, a 4-nm $In_{0.52}Al_{0.48}As$ spacer, a 4-nm n^+-$In_{0.52}Al_{0.48}As$ donor layer, a 20-nm $In_{0.52}Al_{0.48}As$ Schottky layer and a 4nm n^+-$In_{0.75}Ga_{0.25}As$ ohmic contact layer. The active channel contains a 7-nm InAs layer, with two 1.5-nm $In_{0.75}Ga_{0.25}As$ interface smooth layers. The $In_xAl_{1-x}As$ buffer is used to transfer lattice constant from that of $In_{0.52}Al_{0.48}As$ to $In_{0.75}Al_{0.25}As$. Three buffers are designed to study the electron mobility and interface roughness: Structure I consists of a uniform $In_{0.75}Al_{0.25}As$; Structure 2 consists of a step-graded 60-nm $In_{0.59}Al_{0.41}As$/70-nm $In_{0.67}Al_{0.33}As$/70-nm $In_{0.75}$Al0.25As; Structure 3 consists of multiple $In_{0.52}Al_{0.48}As/InAs$ monolayer superlattices. Hall measurement was used to investigate the electron mobility and the carrier density of the HEMT structure. The HEMT's were fabricated by standard photolithography and lift-off techniques. Source and drain were formed by Ge/Au/Ni/Ti/Au (70/140/50/20/70-nm) ohmic contacts after mesa isolation. Next, the gate recess was carried out by a H_3PO_4: H_2O_2: H_2O slow etching solution. The recess was controlled by the source-drain currents. Finally, gate was formed by Ti (10-nm)/Au (300-nm) and device was completed by a second mesa etch to remove the overlap between gate and channel. The gate length was measured by a scanning electron microscope. Devices were measured by using a semiconductor parameter analyzer and a network analyzer.

四、研究與討論

The measured Hall data for three different $In_xAl_{1-x}As$ buffers are summarized in Table 1. Structure 1 with a uniform $In_{0.75}Al_{0.25}As$ buffer shows a degraded electron mobility of 5800 cm^2/Vs as compared to lattice-matched $In_{0.53}Ga_{0.47}As$ channel, which has a typical value of 10000-11000 cm^2/Vs [2], [8] at the same carrier density. This is due to the strain-induced 3-D growth and rough interface of $InAs/In_{0.52}Al_{0.48}As$. Although the step-graded $In_xAl_{1-x}As$ buffer (Structure 2) shows improved mobility of 11900 cm^2/Vs, this value is still far below the mobility of 15200 cm^2/Vs in a $In_{0.80}Ga_{0.20}As/In_{0.25}Ga_{0.75}As$ channel design [7], [8]. In contrast, significant improvement of electron mobility is achieved by using the multiple $In_{0.52}Al_{0.48}As/InAs$ monolayer superlattices buffer (Structure 3), and a mobility of 20200 cm^2/Vs is obtained. The measured carrier density of HEMT with $In_{0.52}Al_{0.48}As/InAs$ monolayer superlattice buffer is 2.7 x 10^{12} cm^{-2}, which is also the highest value as compared to the other two structures. The higher carrier density in this structure may be due to the reduced traps/deep levels in the $In_xAl_{1-x}As$ buffer, which is also confirmed from the negligible carrier density change between room temperature and 77 K. Possible reason for achieving good Hal data may be due to that the strained monolayer superlattice can preserve a relatively smooth growth front and reduced deep recombination levels. Similar effect was also reported in InAs/InGaAs short-period superlattice [8]. However, due to the limited improvement of 77 K mobility of 12800 (cm^2/Vs in InAs channel (Structure 3) to 123100 cm2/Vs in $In_{0.80}Ga_{0.20}As/In_{0.25}Ga_{0.75}As$ [7], [8], there is still interface roughness in $In_{0.52}Al_{0.48}As/InAs$ that limits the 77 K mobility We characteristics of a 1.1 x 50-μm^2 gate HEMT. The device did not show a complete pinch-off, which may be due to either the buffer leakage or the impact ionization in small bandgap InAs. However, it has also reported that the pinch-off characteristic is related to the gate recess, [1] and a low-temperature grown buffer can suppress the buffer leakage. Further detailed analysis is required to identify the leakage mechanism. The device has a peak extrinsic transconductance (g_m) of 714 mS/mm, and small kinks in I-V curves are only observed at low device currents. Because the measured extrinsic g_m is strongly related to the recess depth and gate-to-channel capacitance (Cgs) therefore RF measurement is required to further characterize the device performance. Microwave characterization was performed from 0.1 to 18 GHz using a CASCADE on-wafer probe and network analyzer. Fig.3 shows the calculated current gain (H_{21}) and maximum stable gain (MSG) from measured S-parameters. The device was biased at V_{ds} = 2.5 V and V_{gs} = -0.3 V. An extrapolated f_T of 50 GHz is obtained have used the structure of InAs channel with high electron mobility $InAs/In_{0.5}Al_{0.5}As$ buffer to fabricate devices. Fig.2 shows the room-temperature drain I-V from the 1.1-μm gate length device, which demonstrate the excellent RF performance of device. It is not surprising that the HEMT's fabricated using InAs channel have superior f_T, which is primary dominated by the small electron effective mass in InAs than that of $\mathrm{In_{0.53+x}Ga_{0.47-x}As}$ channel [1]-[6].

Result...We have investigated the InAs channel HEMT's grown on. The $\mathrm{In_{0.52}Al_{0.48}As/InAs}$ monolayer superlattice buffer achieves the best Hall mobility by changing the lattice constant from lattice-matched $\mathrm{In_{0.52}Al_{0.48}As}$ to $\mathrm{In_{0.75}Al_{0.25}As}$. Room-temperature electron mobility as high as 20200 $\mathrm{cm^2/Vs}$ is measured, with a high carrier concentration of 2.7×10^{12} $\mathrm{cm^{-2}}$. DC extrinsic transconductance of 714 mS/mm is measured and a f_T of 50 GHz is obtained for a 1.1-μm gate length HEMT.

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4 nm	**In$_{0.75}$Ga$_{0.25}$As**
20 nm	**In$_{0.52}$Al$_{0.48}$As**
4 nm	**n^{+}-In$_{0.52}$Al$_{0.48}$As**
4 nm	**In$_{0.52}$Al$_{0.48}$As**
1.5 nm	**In$_{0.75}$Ga$_{0.25}$As**
7 nm	**InAs**
1.5 nm	**In$_{0.75}$Ga$_{0.25}$As**
200 nm	**In$_x$Al$_{1-x}$As buffer**
200 nm	**In$_{0.52}$Al$_{0.48}$As**
	S.I InP

Fig. 1. Layer structure of In$_{0.52}$Al$_{0.48}$As/InAs/In$_{_}$Al$_{1__}$As pseudomorphic HEMT's. The In$_{_}$Al$_{1__}$As buffer changes In composition from 0.52 to 0.75: Structure 1: uniform In$_{0.75}$Al$_{0.25}$As; Structure 2: graded 60-nm In$_{0.59}$Al$_{0.41}$As/70-nm In$_{0.67}$Al$_{0.33}$As/70-nm In$_{0.75}$Al$_{0.25}$As; Structure 3: multiple InAs/In$_{0.52}$Al$_{0.48}$As monolayer superlattices.

TABLE I
MEASURED HALL DATA FOR In$_{0.52}$Al$_{0.48}$As/InAs/In$_{_}$Al$_{1__}$As PSEUDOMORPHIC HEMT'S WITH DIFFERENT In$_{_}$Al$_{1__}$As BUFFER DESIGN

	Mobility (cm^2/Vs)		Carrier density (cm^{-2})	
In$_x$Al$_{1-x}$As	300K	77K	300K	77K
Structure 1	5,800	24,000	1.7x10^{12}	1.2x10^{12}
Structure 2	11,900	51,000	2.1x10^{12}	1.7x10^{12}
Structure 3	20,200	128,000	2.7x10^{12}	2.6x10^{12}

1. uniform In$_{0.75}$Al$_{0.25}$As
2. graded 60-nm In$_{0.59}$Al$_{0.41}$As/70-nm In$_{0.67}$Al$_{0.33}$As/70-nm In$_{0.75}$Al$_{0.25}$As
3. multiple InAs/In$_{0.52}$Al$_{0.48}$As monolayer superlattices

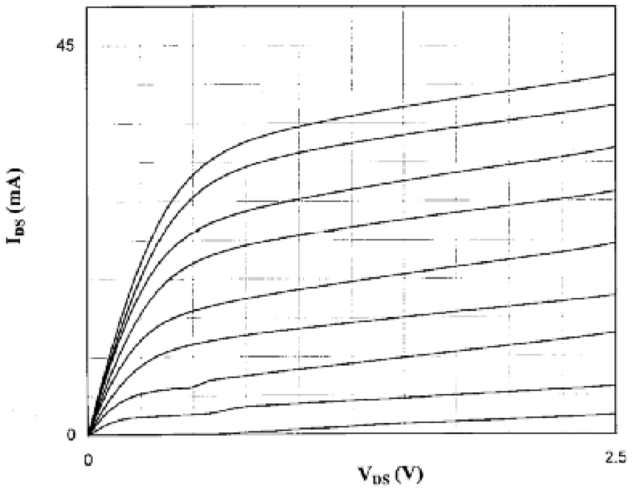

Fig. 2. I–V characteristics of a typical 1.1-μm In$_{0.52}$Al$_{0.48}$As/InAs/In$_{_}$Al$_{1__}$As pseudomorphic HEMT with multiple InAs/In$_{0.52}$Al$_{0.48}$As monolayer superlattices buffer ($V_{GS} = \_0.2$ V/step, 0.4-V top curve).

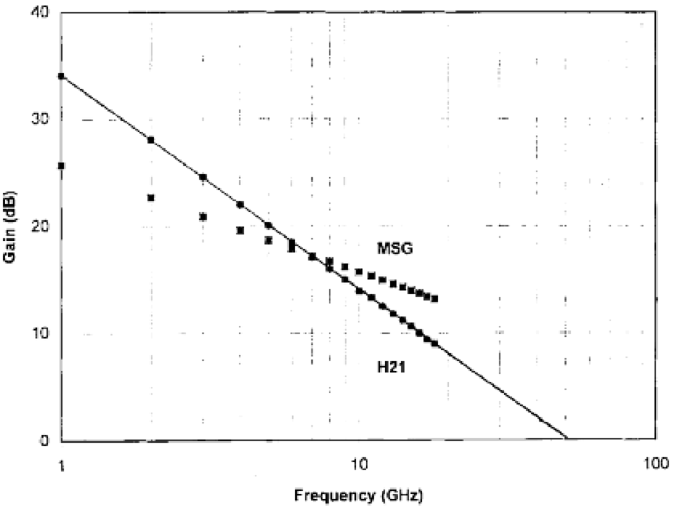

Fig. 3. Gain versus frequency for a typical 1.1-μm In$_{0.52}$Al$_{0.48}$As/InAs/In$_{_}$Al$_{1__}$As pseudomorphic HEMT with multiple InAs/In$_{0.52}$Al$_{0.48}$As monolayer superlattices buffer.