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High-Performance InP-based HEMT's with a Graded Pseudomorphic Channel

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ABSTRACT

$Al_{0.48}In_{0.52}As/Ga_{1-x}In_xAs$ pseudomorphic HEMT's with very high gate and channel breakdown voltages were successfully fabricated. To improve the breakdown characteristics, graded pseudomorphic $Ga_{1-x}In_xAs$ and $Al_{0.2}In_{0.8}P$ were adoped as a channel and Schottky layer, respectively. Systematic studies reveal that the modification of the quantum-well channel by grading the composition considerably changes the channel breakdown (BV_{ds}) and output conductance (g_o) characteristics. HEMT's with graded $Ga_{1-x}In_xAs$ channel ($x = 0.7$ to 0.6) exhibited improved BV_{ds} (11 V) and g_o (40 mS/mm) compared with HEMT's with uniform composition ($x = 0.7$) in the channel ($BV_{ds} = 4$ V and $g_o = 80$ mS/mm).

INTRODUCTION

Recently, it has been demonstrated that the performance of AlInAs/GaInAs high electron mobility transistors (HEMT's) can be further enhanced by increasing the InAs mole fraction in the Ga1-xInxAs channel up to 0.80 [1,2]. However, as the InAs mole fraction increases in the Ga1-xInxAs channel (pseudomorphic GaInAs), devices suffer from large gate leakage current and low source-drain breakdown voltage [3]. These are due to the lower band gap of the pseudomorphic GaInAs material, which results in a deeper potential well close to the spacer layer and strong localization of the two-dimensional electron gas (2DEG) distribution function close to the spacer layer [4]. The strong localization of the 2DEG wave function results in not only a serious interface scattering but also in enhanced impact ionization in the high-field gate-drain region. In this work, a new $Al_{0.2}In_{0.8}P/Al_{0.48}In_{0.52}As/Ga_{1-x}In_xAs$ pseudomorphic HEMT is demonstrated. This structure has graded InAs mole fraction in the pseudomorphic $Ga_{1-x}In_xAs$ channel to modify the triangular-shaped potential well into an approximately rectangular shape as shown in Fig. 1. This will shift the maximum of the electron wave function from close to the interface to deeper inside the channel, which results in the reduction of interface scattering. Also, the alleviated electric field at the interface results in less impact ionization. An $Al_{0.2}In_{0.8}P$ ternary is used as a Schottky layer to increase the Schottky barrier height [5].

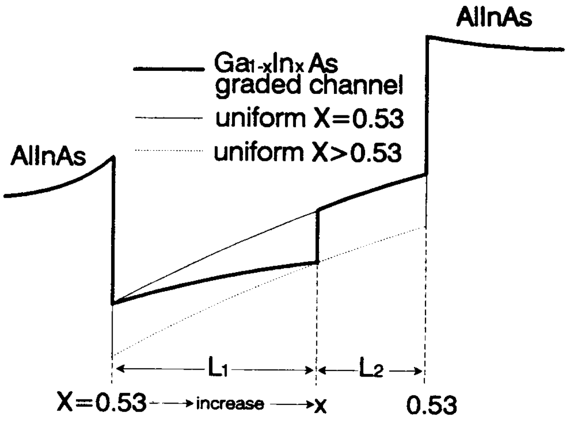

Fig. 1. Schematic band structure of graded channel HEMT (device D).

GROWTH AND DEVICE FABRICATION

The device structures (A-E) were grown by low-pressure OMCVD as shown in Fig. 2. All five device structures were identical except that the channel composition was changed in a systematic way. The total channel thickness remained at 300 Å. Devices A, B, and C had a uniform indium composition of 0.53, 0.6, and 0.7, respectively. On the other hand, devices D and E had a channel with the indium composition graded from 0.7 to 0.53 and from 0.7 to 0.6, respectively. The growth pressure was 76 Torr, and the growth temperatures were 625, 650, and 675°C for InP, $Al_{0.2}In_{0.8}P$, and $Al_{0.48}In_{0.52}As$, respectively. Lattice-matched $Ga_{0.47}In_{0.53}As$ was grown at 650°C, whereas a lower growth temperature, 615°C, was adopted for the strained channel layers. The mobilities of device structures at room temperature were 11,200 (A), 12,500 (B), 13,300 (C), 12,800 (D), and 13,100 (E) cm^2/V-s with similar carrier densities (2.5-2.7 x 10^{12} cm^{-2}).

80Å	Si-GaInAs
120 Å	$Al_{0.2}In_{0.8}P$
55 Å	Si-AlInAs
500 Å	AlInAs
Channel ($Ga_{1-x}In_xAs$) x = 0.53 (A), 0.60(B), 0.70 (C), x = 0.70→0.53 (D), x = 0.70→0.60 (E)	
500 Å	Fe-AlInAs
S. I. InP Substrate	

Fig. 2. Cross-section of the device structures investigated.

A standard 0.5 µm gate FET processing was employed to fabricate the devices on the epitaxial wafers. The source-drain spacing was 3 µm. For the mesa process, two different selective wet etchants were used sequentially. In order to remove the $Ga_{0.47}In_{0.53}As$ cap layer, a $H_3PO_4/H_2O_2/H_2O$ solution was used. This etchant has high selectivity for $Al_{0.2}In_{0.8}P$, only attacking $Ga_{0.47}In_{0.53}As$. After the cap layer was removed, the $Al_{0.2}In_{0.8}P$ and $Al_{0.48}In_{0.52}As$ layers above the channel layer were etched by a H_3PO_4/HCl solution which has high selectivity for $Ga_{1-x}In_xAs$, only attacking $Al_{0.2}In_{0.8}P$ and $Al_{0.48}In_{0.52}As$. The channel layer and $Al_{0.48}In_{0.52}As$ buffer were etched by a $H_3PO_4/H_2O_2/H_2O$ solution again. Ohmic contact was realized using Ni/Ge/Au/Ti/Au (80/220/800/150/600 Å) metals alloyed by a 350°C rapid thermal annealing for 10 s. For the gate recess, a selective recess was carried out by using a diluted $H_3PO_4/H_2O_2/H_2O$ etchant to etch only the $Ga_{0.47}In_{0.53}As$ cap (etch rate: ~300 Å/min). This technique provides an uniform threshold voltage distribution, very flat maximum g_m plateau for the wide range of gate bias and high yield. Finally, a Ti/Au (1000/2800 Å) gate metal was evaporated.

EXPERIMENTAL RESULTS

All five devices had excellent Schottky diode characteristics. This is due to a high bandgap (~1.8 eV) of the high-quality $Al_{0.2}In_{0.8}P$ Schottky layer. Fig. 3 shows the gate diode characteristics of the graded pseudomorphic HEMT (Device E) with $Al_{0.2}In_{0.8}P$ as a Schottky layer.

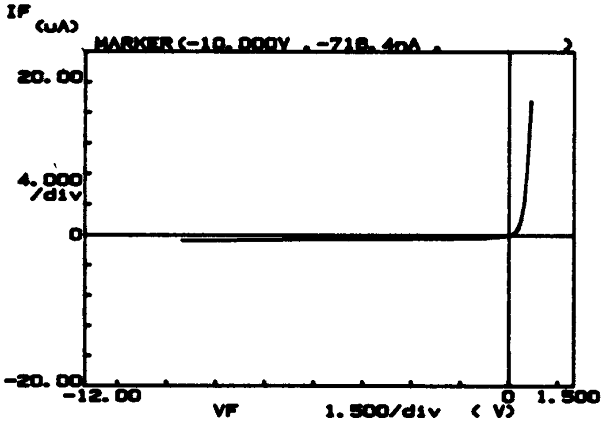

Fig. 3. $Al_{0.2}In_{0.8}P$ Schottky diode characteristics of device E (0.5 x 100 μm^2 gate). The gate-drain breakdown voltage was higher than 15 V.

The measured gate reverse leakage current was ~7 μ A/mm at V_{gs} = -10.5 V and the breakdown voltage at 1 mA/mm of gate current was approximately -15 V. In comparison, typical gate breakdown voltages of conventional $Al_{0.48}In_{0.52}As$/ $Ga_{0.47}In_{0.53}As$ HEMT's fabricated in our laboratory are in the range of -5 to -7 V. The high gate breakdown voltage indicates that the undoped $Al_{0.2}In_{0.8}P$ Schottky layer is of high quality. The Schottky barrier height was deduced from C-V measurements to be approximately 0.9~1.0 eV which is much higher than that of conventional $Al_{0.48}In_{0.52}As/Ga_{0.47}In_{0.53}As$ HEMT's (ϕ_b = 0.65 eV) [6].

Device		A	B	C	D	E
Channel	x	0.53	0.60	0.70	graded 0.70→0.53	graded 0.70→0.60
Channel	Å	300	200	150	200	200
Prechannel	Å	0	100	150	100	100
V_p	V	0.4	0.5	0.6	0.5	0.6
g_m	mS/mm	480	580	700	600	660
$I_{D(max)}$	mA/mm	370	640	700	600	650
BV_{ds}	V	7.5	5.0	4.0	8.0	11.0
Kink		None	Good	Poor	Good	Good
g_o	mS/mm	10	27	80	60	40
$AV_{(DC)}$		48	21	9	10	17
f_T	GHz	56	65	88	72	80
f_{axm}	GHz	70	86	110	105	165

Table1. Device characteristics of $Al_{0.2}In_{0.8}P$/ $AlInAs/Ga_{1-x}In_xAs$ HEMT's.

As summarized in Table 1, the transconductance (g_m) and current-gain cutoff frequency (f_T) significantly improved with the increase of the indium composition as expected. Device C had 46 % higher g_m (700 mS/mm) and 57 % higher f_T (88 GHz) than Device A. However, the channel breakdown voltage (BV_{ds}=4 V) and output conductance (g_o=80 mS/mm) of device C became considerably poorer. Therefore, the challenge is to modify the Device C structure to improve the BV_{ds} and g_o while keeping high g_m and f_T. Device E (graded x=0.7 to 0.6) showed g_m (650 mS/mm) and f_T (80 GHz) comparable to Device C, but exhibited dramatically improved BV_{ds} (11 V) and g_o (40 mS/mm) as shown in Fig. 4.

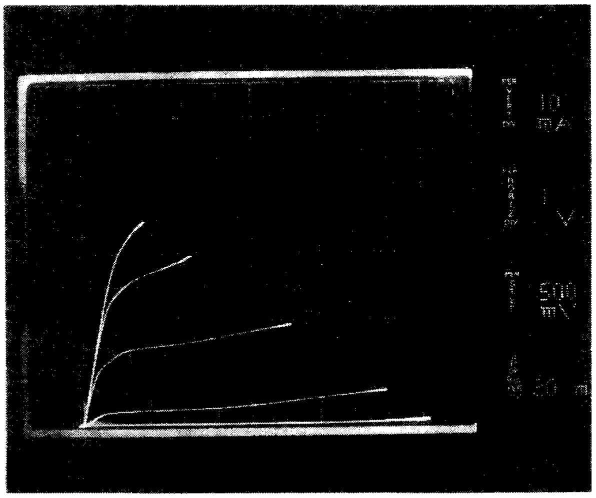

Fig. 4. I-V characteristics of device D (0.5 x 50 μm^2 gate).

Device E showed the largest BV_{ds}. Furthermore, the power-gain cutoff frequency (f_{max}) was highest, 165 GHz, with Device E (Fig. 5).

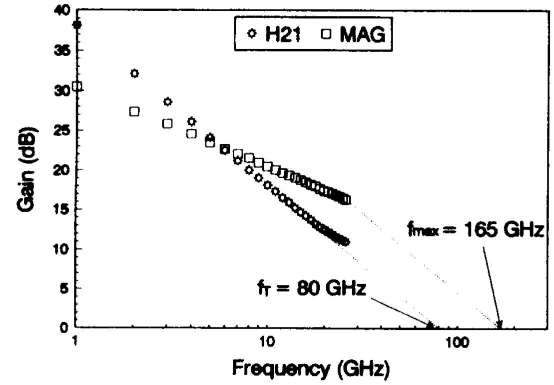

Fig. 5. RF current gain and power gain vs. frequency of device E

A self-consistent analysis has been utilized to investigate the conduction-band profile and carrier distribution in the quantum-well channels with a variety of indium composition as shown in (Fig. 6). The results clearly show that the composition grading modifies the channel structure such that a significant part of the carriers moves away from the top heterointerface and the electric field at the heterointerface is decreased, leading to the improvements of breakdown and output conductance characteristics.

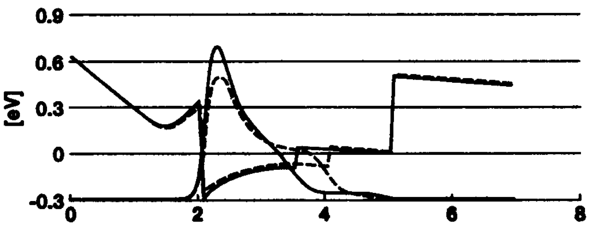

Fig. 6. Simulated conduction-band profile and carrier distribution. (Solid line:device C and dotted line:device D)

CONCLUSION

In conclusion, the studies demonstrated that the composition grading in the channel of InP-based pseudomorphic HEMT's significantly enhances the advantages of these devices. The Monte Carlo simulation is under study to understand the exact mechanism how the composition grading changes the device characteristics.

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