High-Power High-Speed $Ga_{0.51}In_{0.49}P/In_xGa_{1-x}As$ Doped-Channel FET's

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Introduction

The *first* $Ga_{0.51}In_{0.49}P/In_xGa_{1-x}As$ ($0 \le x \le 0.22$) doped-channel FET's (DCFET's) grown by GSMBE exhibiting excellent dc and microwave characteristics were successfully fabricated. A high g_m of 306 mS/mm, a high f_t of 21.7 GHz and a high f_{max} of 53.4 GHz were achieved at 300 K for a $Ga_{0.51}In_{0.49}P/In_{0.2}Ga_{0.8}As$ DCFET with a 1 μm-long gate. This device also showed a very high maximum current density (630 mA/mm) and a very high drain-source operating voltage (13 V). These values were quite high compared with other works of InGaAs channel DCFET's and HEMT's with same gate length. Moreover, wide and flat characteristics of g_m, f_t and f_{max} versus drain current (or gate voltage) were attained for all DCFET's. Power performance of $Ga_{0.51}In_{0.49}P/In_{0.2}Ga_{0.8}As$ DCFET's, $Al_{0.3}Ga_{0.7}As/In_{0.2}Ga_{0.8}As$ DCFET's and HEMT's were calculated. It is found that $Ga_{0.51}In_{0.49}P/In_{0.2}Ga_{0.8}As$ DCFET's provides the largest power among the three devices. These results demonstrate that high transconductance, high linearity, high speed and high output-power could be achieved by using $In_xGa_{1-x}As$ and $Ga_{0.51}In_{0.49}P$ as the channel and insulator materials, respectively.

I. Background

High electron mobility transistors (HEMT's) have demonstrated excellent performance in low-noise applications[1]. As for high-power applications, the heterostructure FET's (HFET's) based on an InGaAs pseudomorphic channel have shown extremely good power performance at millimeterwave frequencies due to high-current handling capability, high transconductance (g_m), and good electron confinement by the potential well [2],[3]. It has been demonstrated that the current-drivability and g_m of metal/i-AlGaAs/n-InGaAs/i-GaAs quantum well MISFET's with doped InGaAs channel were higher than those of metal/i-AlGaAs/i-InGaAs/n-GaAs quantum well MISFET's with undoped InGaAs channel [3]. Therefore, we would like to study the performance of the metal/i-GaInP/n-InGaAs/i-GaAs doped-channel FET's (DCFET's). There are several advantages by using the GaInP/InGaAs/GaAs material system compared with AlGaAs/InGaAs/GaAs system : 1) the etching selectivity between $Ga_{0.51}In_{0.49}P$ and GaAs is very high and therefore gate recess will stop at the undoped $Ga_{0.51}In_{0.49}P$ layer automatically and exactly, which means high uniformity and yield [4]; 2) the reliability should be better since $Ga_{0.51}In_{0.49}P$ has very low reactivity with oxygen [4],[5]; and 3) the 1/f noise is lower due to smaller surface recombination [6]. Hence, in this paper, we report the peformance of the $Ga_{0.51}In_{0.49}P/In_xGa_{1-x}As/GaAs$ DCFET's and compared them with other works of InGaAs channel DCFET's and HEMT's.

II. Experimental Details

The $Ga_{0.51}In_{0.49}P/In_xGa_{1-x}As$ DCFET structure shown in Fig. 1(a) was grown by GSMBE. First, a 5000 Å undoped GaAs buffer layer was grown on a (100) GaAs semi-insulating substrate, followed by a 150 Å $In_xGa_{1-x}As$ n channel layer (3×10^{18} cm^{-3}, Si doped). Then a 200 Å undoped $Ga_{0.51}In_{0.49}P$ insulator layer was grown on top of the active channel. Finally, a 400 Å n^+ GaAs cap layer was grown. Conventional optical lithography and mesa type wet etching technique were used to fabricate the $Ga_{0.51}In_{0.49}P/In_xGa_{1-x}As$ DCFET's [7]. After the GaAs cap layer was selectively etched, 1 μm-long, 150 μm-wide Ti/Pt/Au (500 Å/500 Å/6000 Å) traditional gates were evaporated and defined by a lift-off process. The recess length between gate-drain and gate-source were 2 μm and 1 μm, respectively, as shown in Fig. 1(a). Fig. 1(b)

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is the schematic conduction-band diagram of the $Ga_{0.51}In_{0.49}P/In_{0.2}Ga_{0.8}As$ DCFET's. Because the gate is sitting directly on the *undoped* high bandgap $Ga_{0.51}In_{0.49}P$ insulator layer (1.92 eV) with reasonably high Schottky barrier (0.87 eV) [8] and conduction band discontinuity at the $Ga_{0.51}In_{0.49}P$ $/In_{0.2}Ga_{0.8}As$ heterojunction is also large (~ 0.36 eV) [8],[9], higher gate turn on voltage, breakdown voltage and current drivability, as compared to MESFET's and HEMT's, can therefore be expected. The measured gate turn on voltage of $Ga_{0.51}In_{0.49}P$ $/In_{0.2}Ga_{0.8}As$ DCFET's was 1.05 eV. This value is comparable to that (1.0 eV) of $Al_{0.3}Ga_{0.7}As$ $/In_{0.2}Ga_{0.8}As$ DCFET's and better than that (0.65 eV) of $Al_{0.3}Ga_{0.7}As/In_{0.2}Ga_{0.8}As$ HEMT's [10].

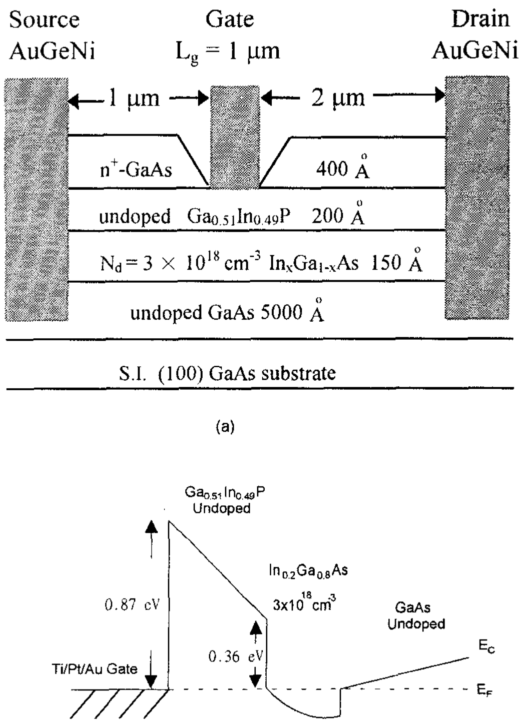


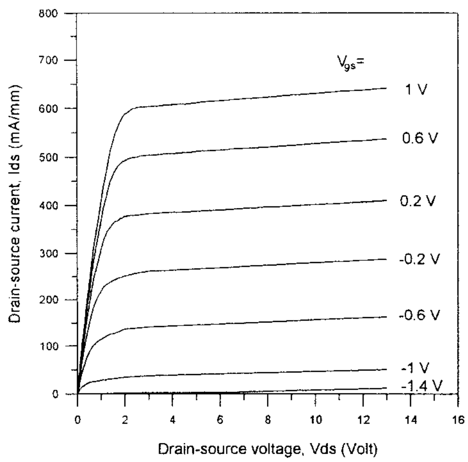
Fig. 1(a) Device cross-section of $Ga_{0.51}In_{0.49}P/In_xGa_{1-x}As$ DCFET's and (b) conduction band diagram of the $Ga_{0.51}In_{0.49}P/In_{0.2}Ga_{0.8}As$ DCFET's.

III. Results and Discussions

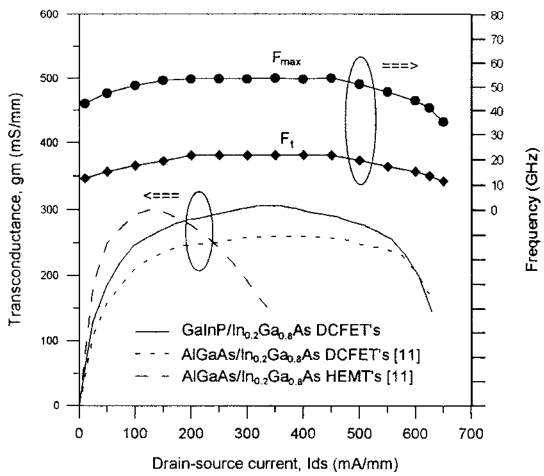
A. DC Characteristics

I-V characteristics of $Ga_{0.51}In_{0.49}P/In_xGa_{1-x}As$ ($0 \leq x \leq 0.22$) DCFET's were measured with an HP4156 precise semiconductor parameter analyzer. Typical drain-source current (I_{ds}) versus drain-source voltage (V_{ds}) characteristics of an x=0.20 DCFET is shown in Fig. 2(a). Note that the device could be operated up to I_{ds} = 630 mA/mm and V_{ds}=13 V at V_{gs}=1V. This is attributed to the high-quality *undoped* high-bandgap $Ga_{0.51}In_{0.49}P$ insulator layer, which could sustain a very high breakdown field at the gate edge nearest to the drain. A peak g_m of 306 mS/mm was also achieved at V_{ds} = 3 V. The output conductance (g_{ds}) at V_{gs}= 0 V was 2.1 mS/mm and therefore a high dc gain ratio (g_m/g_{ds}) of 147 was obtained. The I_{ds} dependence of g_m for $Ga_{0.51}In_{0.49}P/In_{0.2}Ga_{0.8}As$ DCFET's and $Al_{0.3}Ga_{0.7}As/In_{0.2}Ga_{0.8}As$ DCFET's and HEMT's [11] were shown in Fig. 2(b). As can be seen clearly, the characteristics curve of g_m versus I_{ds} for $Ga_{0.51}In_{0.49}P/In_{0.2}Ga_{0.8}As$ DCFET's and $Al_{0.3}Ga_{0.7}As/In_{0.2}Ga_{0.8}As$ DCFET's extended not only to higher I_{ds} values but also exhibited flatter g_m characteristics with wider drain bias current conditions, namely, 365 mA/mm for $Ga_{0.51}In_{0.49}P$ $/In_{0.2}Ga_{0.8}As$ DCFET's and 360 mA/mm for $Al_{0.3}Ga_{0.7}As/In_{0.2}Ga_{0.8}As$ DCFET's in contrast with 150 mA/mm for $Al_{0.3}Ga_{0.7}As/In_{0.2}Ga_{0.8}As$ HEMT's. The " width " of flat region was defined as the difference of two current densities corresponding to 10% drop from the maximum g_m. The above results demonstrated that doped-channel MIS-like structure indeed could achieve higher current drivability and better linearity [7],[11].

Due to the high etching selectivity between GaAs cap layer and $Ga_{0.51}In_{0.49}P$ insulator layer, the standard deviation of the threshold voltage of our fabricated DCFET's was low to 50 mV. This value was comparable to that (60 mV) of GaInP/AlGaAs/InGaAs HJFET's fabricated by selective wet etching and less than one sixth of that of the conventional AlGaAs/InGaAs HJFET's [12], indicating great potential in using a highly-selective etching technique for high-uniformity and high-yield device production. Recent reports have shown that GaInP/GaAs devices guarantee a mean time to failure (MTTF) of 10^8 hours (at a junction temperature of 125 °C) [4] and at least 10^6 hours at a junction temperature of 200 °C [5], which is enough for a 25-year lifetime requirement of a practical system and suggests high reliability of GaInP/GaAs devices. From the above results, $Ga_{0.51}In_{0.49}P/In_xGa_{1-x}As$ material system should be a good alternate to AlGaAs/InGaAs system.
Table I summarizes the dc characteristics of $Ga_{0.51}In_{0.49}P/In_xGa_{1-x}As$ ($0 \leq x \leq 0.22$) DCFET's with 1.0 μm-long gate at room temperature. We observed an enhancement of $g_{m,ext}$ from 180



(a)



(b)

Fig. 2(a) Typical I_{ds} v.s.V_{ds} characteristics of the $Ga_{0.51}In_{0.49}P/In_{0.2}Ga_{0.8}As$ DCFET and (b) g_m, f_t and f_{max} v.s. I_{ds} characteristics of $Ga_{0.51}In_{0.49}P/In_{0.2}Ga_{0.8}As$ DCFET's.

Table I
DC characteristics of $Ga_{0.51}In_{0.49}P/In_xGa_{1-x}As$ ($0 \le x \le 0.22$) DCFET's with 1.0 μm-long gate.

In content	x=0	x=0.15	x=0.20	x=0.22
$g_{m,ext}$ (mS/mm)	180	350	306	275
$I_{ds,\,max}$ (mA/mm)	465	575	630	585

mS/mm for x=0 - 350 mS/mm for x=0.15 DCFET's. However, $g_{m,ext}$ values dropped to 306 mS/mm for x=0.20 and 275 mS/mm for x=0.22 DCFET's. The optimum performance of $Ga_{0.51}In_{0.49}P/In_xGa_{1-x}As$ DCFET's is obtained with the x value ranging between x=0.15 and x=0.20 for 150 Å thick $In_xGa_{1-x}As$ channel layer and 200 Å thick $Ga_{0.51}In_{0.49}P$ insulator layer.

B. Microwave Characteristics

Microwave on wafer S-parameters, for 1.0 μm-long gate $Ga_{0.51}In_{0.49}P/In_xGa_{1-x}As$ ($0 \le x \le 0.22$) DCFET's were measured from 45 MHz to 26.5 GHz with an HP8510C network analyzer. Fig. 3 shows the current gain cut-off frequency (f_t) and maximum oscillation frequency (f_{max}) of x = 0.20 $In_xGa_{1-x}As$ channel DCFET's were 21.7 and 53.4 GHz respectively under the bias conditions of V_{ds} = 3 V and V_{gs} = 0 V. The f_t (21.7 GHz) of $Ga_{0.51}In_{0.49}P/In_{0.2}Ga_{0.8}As$ DCFET's was higher than those of $Al_{0.3}Ga_{0.7}As/In_{0.2}Ga_{0.8}As$ DCFET's (12 GHz) and HEMT's 14.5 (GHz) with 1.0 μm-long gate [10]. Moreover, the f_{max} (53.4 GHz) of our $Ga_{0.51}In_{0.49}P/In_{0.2}Ga_{0.8}As$ DCFET was comparable to those of $Al_{0.3}Ga_{0.7}As/In_{0.2}Ga_{0.8}As$ DCFET's (50 GHz) and HEMT's (50 GHz) with 1.0 μm-long gate [10]. The higher f_t performance of our $Ga_{0.51}In_{0.49}P/In_{0.2}Ga_{0.8}As$ DCFET versus $Al_{0.3}Ga_{0.7}As/In_{0.2}Ga_{0.8}As$ DCFET (with same insulator thickness 200 Å) was mainly attributed to higher g_m due to higher mobility (3090 cm^2/V-sec for our DCFET versus 1810 cm^2/V-sec for $Al_{0.3}Ga_{0.7}As/In_{0.2}Ga_{0.8}As$ DCFET) [10]. The mobility difference could be due to different growth techniques used. Though the mobility of our $Ga_{0.51}In_{0.49}P/In_{0.2}Ga_{0.8}As$ DCFET was lower than that (3800 cm^2/V-sec) of $Al_{0.3}Ga_{0.7}As/In_{0.2}Ga_{0.8}As$ HEMT, the g_m of our DCFET's was still larger than its due to the higher product of mobility and sheet charge density. Moreover, the lower gate-source and gate-drain capacitances of our $Ga_{0.51}In_{0.49}P/In_{0.2}Ga_{0.8}As$ DCFET (C_{gs} = 2023.2 fF/mm and C_{gd} = 157.8 fF/mm versus C_{gs} = 3030 fF/mm and C_{gd} = 190 fF/mm of $Al_{0.3}Ga_{0.7}As/In_{0.2}Ga_{0.8}As$ DCFET and C_{gs} = 2850 fF/mm and C_{gd} = 250 fF/mm of $Al_{0.3}Ga_{0.7}As/In_{0.2}Ga_{0.8}As$ HEMT) also benefit the high f_t performance.

Table II summarizes the RF characteristics of the $Ga_{0.51}In_{0.49}P/In_xGa_{1-x}As$ ($0 \le x \le 0.22$) DCFET's with 1.0 μm-long gate at room temperature. The optimum performance of f_t's and f_{max}'s both occured when the x value ranging between x=0.15 and x=0.20 for 150 Å thick $In_xGa_{1-x}As$ channel layer and 200 Å thick $Ga_{0.51}In_{0.49}P$ insulator layer.

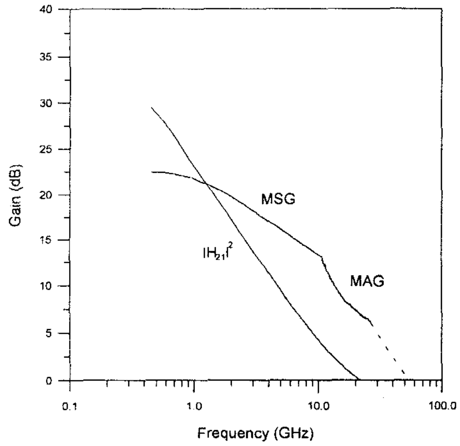


Fig. 3 Microwave characteristics of $Ga_{0.51}In_{0.49}P$/ $In_{0.2}Ga_{0.8}As$ DCFET's with 1 μm-long gate.

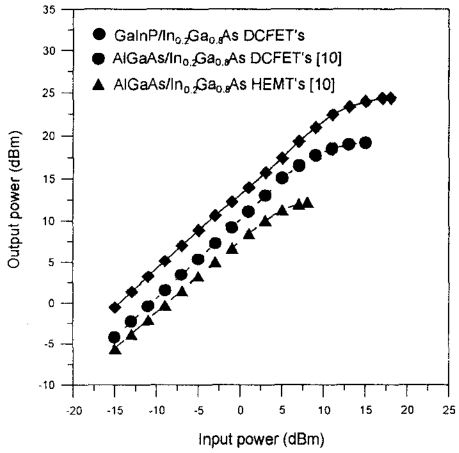


Fig. 4 Power performance of $Ga_{0.51}In_{0.49}P$/ $In_{0.2}Ga_{0.8}As$ DCFET's, $Al_{0.3}Ga_{0.7}As/In_{0.2}Ga_{0.8}As$ DCFET's and HEMT's at 2.4 GHz. (gate dimension: 1 × 100 μm^2)

Table II
RF characteristics of $Ga_{0.51}In_{0.49}P/In_xGa_{1-x}As$ ($0 \leq x \leq 0.22$) DCFET's with 1.0 μm-long gate.

In content	x=0	x=0.15	x=0.20	x=0.22
f_t (GHz)	17.6	23.3	21.7	19.1
f_{max} (GHz)	34.9	50.8	53.4	46.8

IV. Conclusions

In summary, the $Ga_{0.51}In_{0.49}P/In_xGa_{1-x}As$ DCFET's ($0 \leq x \leq 0.22$) grown by GSMBE were fabricated successfully and easily because of the high etching selectivity between $Ga_{0.51}In_{0.49}P$ and GaAs. Due to superior transport properties of $In_xGa_{1-x}As$ ($0.15 \leq x \leq 0.2$), high-quality *undoped* high bandgap $Ga_{0.51}In_{0.49}P$ insulator layer, large Schottky barrier and $Ga_{0.51}In_{0.49}P/In_xGa_{1-x}As$ conduction band-offset, high g_m, high current drivability, high operating voltage, high output-power and high-speed were achieved. Therefore, $Ga_{0.51}In_{0.49}P/In_xGa_{1-x}As$ ($0.15 \leq x \leq 0.2$) DCFET's will be very promising candidates for microwave power application.

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