Millimeter-Wave Power Performance of Ion-Implanted $In_xGa_{(1-x)}As$ on GaAs Metal Semiconductor Field-Effect Transistors

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Abstract— **Millimeter-wave power performance achieved by ion-implanted InGaAs–GaAs MESFET's with a gate length of 0.25 micron is described. When the device with a gate width of 150 micron was measured at 22 GHz, an output power of 95 mW, a power-added efficiency of 33%, and an associated gain of 7.3 dB were achieved. At an output power of 93 mW, a power-added efficiency of 25%, and an associated gain of 4 dB were obtained at 44 GHz. When the device with a gate width of 200 micron was measured at 60 GHz, an output power of 121 mW with 3 dB associated gain and 13% power-added efficiency were achieved.**

I. Introduction

The SOLID-STATE three-terminal power device at 20, 44, and 60 GHz is an important research area due to its application in the down-link, up-link and cross-link of satellite communication. The first result of 60 GHz amplifier using ion-implanted GaAs metal semiconductor field effect transistors (MESFET's) achieving a small signal gain of 6 dB was reported in 1984 [1], but the device result lacked significant output power. Until 1988, GaAs power MESFET on MBE grown epitaxial layers with a gate width of 75 micron achieved 53-mW output power, 5.2-dB gain, and 34% power-added efficiency at 35 GHz [2]. Also in 1988, a power amplifier using GaAs MESFET on MBE grown epitaxial layers achieved 95 mW output power, 3.6-dB gain, and 11% power-added efficiency at 58 GHz [3]. This work reports the millimeter-wave power performance of ion-implanted InGaAs–GaAs MESFET's with 0.25 micron gates.

II. Material Growth and Device Fabrication

The InGaAs material was known to have higher peak drift velocity compared to GaAs material due to large energy separation between Γ and L valleys. The InGaAs material was grown directly on GaAs substrate by MOCVD technique. The InGaAs–GaAs material structure consisted of a 600-Å layer of $In_{0.18}Ga_{0.82}As$ direct deposited on GaAs substrate first and a 1000 Å layer of $In_xGa_{(1-x)}As$ with the indium composition linearly graded from $x = 0.18$ to $X = 0$ toward the surface. The gate-to-drain leakage The active channel was formed by ion implantation into the InGaAs layer and subsequent capless anneal to activate the implanted species (Si^{+28}). The channel implant is formed with a penetration depth of 1500 Å to achieve a peak carrier concentration of $1 \times 10^{18} cm^{-3}$. The surface implant (n^+ layer) is achieved with a penetration depth of 600 Å to achieve a peak carrier concentration of 2×10^{18} cm^{-3}. Electron-beam direct write lithography was used to define the 0.25 micron "*T*" shaped gates with a width of 150 and 200 microns. The Ti–Pt–Au gate metal was evaporated after recess etch. The drain to source spacing was 2 microns with the gate offset toward the source to reduce source resistance.

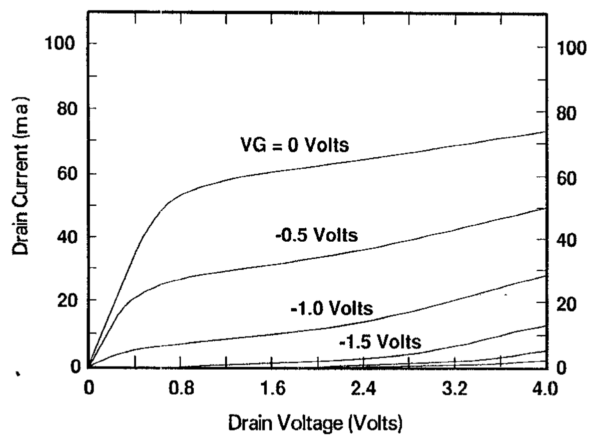

Fig. 1. I-V characteristics of ion-implanted InGaAs–GaAs MESFET with a 0.25 x 150 micron gate.

III. DC and RF Device Performance

The drain current versus gate voltage for a typical 0.25 x 150 micron implanted InGaAs MESFET is shown in Fig. 1. The drain to source voltage was swept from 0 to 4 V while the gate voltage was stepped at −0.5 V per step. The transconductance is 437 mS/mm and current density is 480 mA/mm at zero gate bias and V_{ds}=2 V. The gate to drain breakdown voltage is greater than 7 V.

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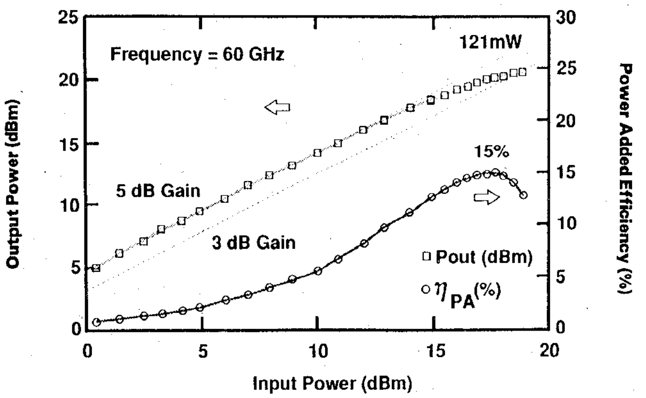

Fig. 2. Output power and power-added efficiency of a 0.25 x 200 micron-gate MESFET measured at 60 GHz versus input power. Device was tuned for the maximum output power.

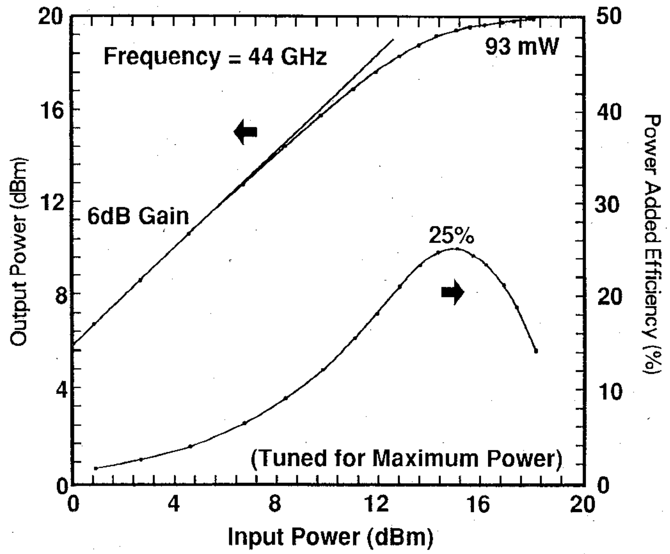

Fig. 3. Output power and power-added efficiency of 0.25 x 150 micron-gate MESFET's measured at 44 GHz versus input power. Device was tuned for the maximum output power.

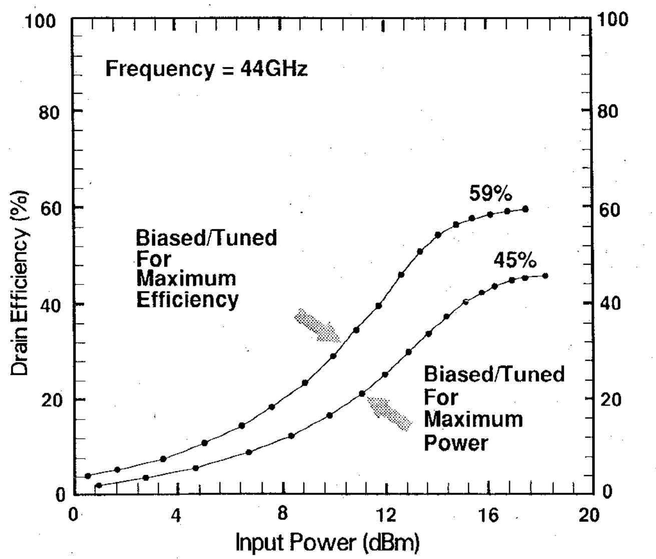

Fig. 4. 44 GHz drain efficiency of a 0.25 x 150 micron gate ion-implanted InGaAs–GaAs MESFET.

The current-gain cutoff frequency, f_t, for the MESFET's was obtained by extrapolating |H21| to unity gain with a -6 dB/octave slope. The MESFET with a 0.25 x 150 micron gate used in this work has a measured f_t = 90 GHz and $f_{\max}$ = 160 GHz at V_{ds} = 4.0 V. The peak measured f_t occurring at V_{ds} = 1.6 V is 104 GHz without correction and is estimated to be 131 GHz with pad capacitance (0.0169 pf) correction. The MESFET with a 0.25 x 200 micron gate used in this work has a measured f_t = 94 GHz and $f_{\max}$ = 165 GHz at V_{ds} = 4.0 V. A peak measured value of f_t = 112 GHz occurred at V_{ds} = 1.6 V without pad correction. All the devices tested here are nonpassivated FET's. The extrinsic transconductance g_m is 428 mS/mm and the standard deviation is 41 mS/mm. The average f_t is 102 GHz and the standard deviation is 12 GHz. The RF yield is better than 85%.

Three-section Q-band and V-band fixtures were used to test the MESFET devices. They consisted of two waveguide-to-microstrip transitions and a carrier containing the FET under test. The fixture transition loss measured on an HP8510 ANA was 0.25 dB per transition for Q-band and 0.35 dB for V-band. The E- and H-plane tuners had a loss of 0.14 dB per tuner for Q-band and 0.22 dB for V-band. There is no specific reason to choose 200 μm for 60 GHz operation other than we are interested in P_{out} > 100 mW.

The MESFET's with a 0.25 x 200 micron gate were tuned for maximum output power at 60 GHz where the dc-bias conditions were set with V_{ds} = 4.4 V and V_{gs} = -0.5 V. The output power and power-added efficiency versus input power are plotted in Fig. 2. A saturated power of 121 mW with 3-dB associated gain and 13% power-added efficiency was measured at 60 GHz. The reason for lower power-added efficiency is due to the unit gate width of 100 m that degrade the signal at 60 GHz.

The MESFET's with a 0.25 x 150 micron gate were tuned for maximum output power at 44 GHz where the dc-bias conditions were set at V_{ds} = 4 V and V_{gs} = -0.7 V. The output power and power-added efficiency versus input power are plotted in Fig. 2. An output power of 93 mW, an associated gain of 4 dB and a power-added efficiency of 25% were measured. A saturated output power of 97 mW was achieved at 44 GHz. The MESFET was then tuned for maximum power-added efficiency at 44 GHz where the dc-bias conditions were set at V_{ds} = 3.2 V and V_{gs} = -0.86 V. A maximum power-added efficiency of 33%, an output power of 65 mW and an associated gain of 4.5 dB were obtained at 44 GHz.

A similar 0.25 x 150 micron InGaAs–GaAs MESFET from the same wafer was evaluated at 22.25 GHz by MIT Lincoln Laboratory. When the device was tuned for maximum output power where the dc-bias conditions were set at V_{ds} = 4.3 V and V_{gs} = -0.62 V, an output power of 95 mW, a power-added efficiency of 33% and an associated power gain of 7.3 dB were achieved. When the same device was tuned for maximum power-added efficiency where the dc-bias conditions were set at V_{ds} = 3.8 V and V_{gs} = -1 V, an output power of 76 mW, a power-added efficiency of 41% and an associated gain of 7.8 dB were achieved.

The device drain efficiency at 44 GHz versus input power is plotted in Fig. 4. The drain efficiency can be as high as 45% for the maximum output power conditions and can be as high as 59% for the maximum power-added efficiency conditions. The drain efficiency is about the same for the devices measured at 22 and 44 GHz since the maximum output power of the devices is the same in both cases (93 mW at 44 GHz and 95 mW at 22 GHz). The difference is associated power gain (4 dB at 44 GHz and 7.3 dB at 22 GHz).

Hence, to improve the power-added efficiency for millimeter wave power devices, one has to improve the power gain of the devices and maximize the drain efficiency. Power gain of the MESFET's can be improved by using short unit gate widths and multiple gate fingers, for example, a unit gate finger of 50 micron instead of 75 micron at 44 GHz and a unit gate finger of 40–50 micron instead 100 micron at 60 GHz. Drain efficiency can be improved by increasing the breakdown voltage, decreasing the knee voltage, and optimizing the variation of drain current with gate voltage [4].

IV. Conclusion

In conclusion, we have characterized the ion-implanted InGaAs–GaAs power MESFET's achieving excellent output power, associated gain and power-added efficiency at 22 and 44 GHz for 0.25 x 150-micron MESFET's at 60 GHz for a 0.25 x 200-micron MESFET. These results demonstrate that the cost effective ion implantation technology is suitable for making power devices, amplifiers and monolithic integrated circuits in the millimeter-wave frequency range.

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