

# Submicron-Gate InP Power MISFET's with Improved Output Power Density at 18 and 20 GHz

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**Abstract**—Presented here are the microwave characteristics at 18 and 20 GHz of submicron-gate indium phosphide (InP) metal-insulator-semiconductor field-effect transistors (MISFET's) for high output power density applications. InP power MISFET's were fabricated with 0.7  $\mu\text{m}$  gate lengths, 0.2 mm gate widths, and drain-source spacings of 2, 3, and 5  $\mu\text{m}$ . The output power density was investigated as a function of drain-source spacing. The best output power density and gain were obtained for drain-source spacings of 3  $\mu\text{m}$ . At 18 GHz output power densities of 1.59 W/mm with a gain of 3.47 dB and a power-added efficiency of 20.0% were obtained for a drain-source spacing of 3  $\mu\text{m}$ . At 20 GHz output power densities of 1.20 W/mm with a gain of 3.17 dB and a power-added efficiency of 13.6% were obtained for a drain-source spacing of 3  $\mu\text{m}$ . The output power density is 2.7 times greater than has previously been measured for InP MISFET's at 18 and 20 GHz, and the power-added efficiency has also been increased. The output power density is also 50% better than recently reported for comparable gate width pseudomorphic HEMT's at 20 GHz. The power gain was stable to within 3.0% over 12 h, and the drain current variation during the same time was less than 5%.

## I. INTRODUCTION

INDIUM phosphide (InP) is a compound semiconductor with several material properties which make InP metal-insulator-semiconductor field-effect transistors (MISFET's) especially suited for power amplification at microwave and millimeter-wave frequencies. InP FET's should operate at higher frequencies than gallium arsenide (GaAs) FET's owing to the higher peak and saturation electron velocities of InP. InP is better for high-power applications since it has a 30% higher breakdown field and lower ionization coefficients than GaAs and a

55% higher room temperature thermal conductivity than GaAs [1].

The insulated gate of a MISFET also has several advantages for power amplification. Gate leakage current is virtually eliminated and larger positive gate voltages may be used, which provide both charge accumulation for higher channel current and higher gate-source and gate-drain breakdown voltages.

The disadvantage of an insulated gate on InP has been the dc drain current drift with time, which has been widely examined. Shokrani and Kapoor [2] have examined gate insulators with reduced dc drain current drift for InP power MISFET's, and drift mechanisms have been reviewed by Wager *et al.* [3]. The InP MISFET output power at microwave frequencies has been demonstrated to be more stable than the dc drain current [4].

The promise offered by InP MISFET material and device properties has been realized by record power densities in both the microwave and millimeter-wave region. Messick *et al.* [4] have demonstrated 4.5 W/mm at 9.7 GHz for InP MISFET's on n-type epitaxial layers using a 1.4  $\mu\text{m}$  gate length and a total gate width of 1 mm. Biedenbender *et al.* [5] and Shokrani *et al.* [6] have reported 2.4 and 2.7 W/mm, respectively, at 9.7 GHz for an all ion-implanted version of the above device. Others have reported lower output power densities from InP MISFET's with gate lengths from 1.2 to 0.3  $\mu\text{m}$  at frequencies up to 30 GHz [7]–[10]. The microwave performance of power FET's is affected by the device size, especially the gate length and the drain-source or drain-gate spacing [11]. However, no investigation of the microwave properties as a function of the drain-source spacing has been reported for InP power MISFET's.

Presented here are the microwave results from a new 0.7- $\mu\text{m}$ -gate-length InP power MISFET. The new design uses a submicron gate length for operation at high microwave frequencies and drain-source spacings of 2, 3, and 5  $\mu\text{m}$  to compare the effect of device size on output power. Current-voltage ( $I$ - $V$ ) characteristics are given at dc as well as power measurements at 18 and 20 GHz including output power density, power gain, and power-added efficiency ( $\eta_{\text{add}}$ ) as a function of drain-source

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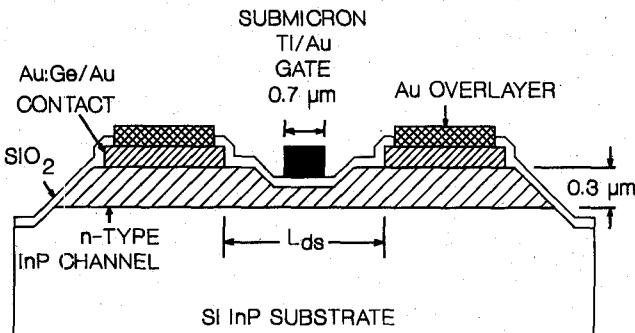


Fig. 1. Schematic cross section of a submicron-gate InP power MISFET.

spacing. The output power density, power gain, and power-added efficiency at 20 GHz as a function of drain voltage are presented. The variation of power gain and drain current with time is also examined.

## II. EXPERIMENTAL

Fig. 1 shows a schematic cross section of a submicron-gate InP MISFET. The InP MISFET design was based on the structure recently reported by the authors [5]. The InP MISFET's investigated in this work had gate lengths of 0.7  $\mu\text{m}$ . The gate length was reduced compared with the previous structure [5] to provide higher transconductance and power gain for better operation at higher frequencies [12]. The length of the channel recess was 1  $\mu\text{m}$ . The new MISFET design included three devices with drain-source spacings ( $L_{DS}$ ) of 2, 3, and 5  $\mu\text{m}$ . The InP MISFET's with  $L_{DS} = 5 \mu\text{m}$  were included since these devices have been reported to provide record output power densities at 9.7 GHz [4]. A drain-source spacing of 5  $\mu\text{m}$  is also similar to values used for GaAs MESFET's to provide good breakdown voltages and high reliability at 15 GHz [12] as well as high total output power at 20 GHz [13]. The  $L_{DS} = 2$  and 3  $\mu\text{m}$  devices were included since at higher frequencies lower gate-source and gate-drain parasitics are often necessary despite the lower breakdown voltages possible as device size decreases [11].

The total gate width of the devices was 0.2 mm. Two individual gates with widths of 100  $\mu\text{m}$  were connected in parallel to obtain the total gate width of 0.2 mm. An individual gate width of 100  $\mu\text{m}$  was used to minimize the gain degradation that can occur for large widths as frequency increases. The same individual gate width has recently been reported for pseudomorphic power HEMT's at 20 GHz [14]. A large average spacing of 114  $\mu\text{m}$  between individual gates was used to allow enough room for wire bonds to the individual drain and gate regions. The large gate-to-gate spacing provides the benefit of a low thermal impedance and minimizes the temperature rise [15]. The devices were designed with ten 100- $\mu\text{m}$ -wide gates and several gate bonding pads available to provide various total gate widths of up to 1 mm [4]. The total area of each device was 0.5 mm  $\times$  1.4 mm.

The starting substrate material used for InP MISFET's was a 2-in.-diameter semi-insulating (Fe-doped) InP wafer. The surface orientation of the substrate was  $\langle 100 \rangle$  with a 2° misorientation to the closest  $\langle 110 \rangle$  directions. Initial cleaning of the InP was done using a sequence of trichloroethylene, acetone, and methanol for degreasing. After degreasing, the InP was rinsed in deionized H<sub>2</sub>O (DI H<sub>2</sub>O), followed by a solution of 1:1 DI H<sub>2</sub>O:HF for surface oxide removal and a final DI H<sub>2</sub>O rinse and nitrogen blow-dry. Additional details of the InP cleaning procedure have been previously described by Valco *et al.* [16], [17].

The InP layers used for the fabrication of the MISFET's have been grown by low-pressure metal organic vapor phase epitaxy (MOVPE) in a commercial AIXTRON AIX 200 horizontal reactor of the type widely used for industrial compound semiconductor production. The design and the variety of processes for which this reactor type have been applied are described elsewhere [18].

A 0.3- $\mu\text{m}$ -thick n-type epitaxial layer with a carrier concentration of  $3 \times 10^{17} \text{ cm}^{-3}$  was grown directly on the semi-insulating substrate by MOVPE without an unintentionally doped buffer layer, as shown in Fig. 1. As precursors for the preparation of the InP epitaxial layer, trimethylindium (TMIn) and 100% concentrated phosphine (PH<sub>3</sub>) were used. For n-type doping, silicon was incorporated in the layers by introducing diluted SiH<sub>4</sub> (2% in H<sub>2</sub>) as a source material into the growth atmosphere. The TMIn was transported from a stainless steel cylinder thermostated at 17°C. The cylinder was electronically pressure controlled for extremely stable evaporation rates. The carrier gas in the reaction cell was Pd diffused H<sub>2</sub>.

All gas flows were accurately controlled by electronic mass flow controllers and pneumatically operated valves. For extremely sharp interface formation all precursors were switched by a zero dead volume high-speed vent/run switching manifold.

For obtaining highly pure and uniform semiconductor layers on large substrate surfaces the application of low-pressure growth processes with high gas velocities has been proven to be advantageous. The reactor included an electronic control unit for the chamber pressure. The present work has been performed on a static susceptor.

For obtaining pure and uniform InP layers the growth temperature was adjusted at 600°C, the reactor pressure was held at 15 torr, and the total flow rates were adjusted to achieve a gas velocity of 2.2 m/s. The growth rate for the bulk layer was 2.5  $\mu\text{m}/\text{h}$  at a TMIn pressure of 3 mtorr and a V/III ratio of 500. At the target doping for the epitaxial layer,  $3 \times 10^{17} \text{ cm}^{-3}$ , the electron mobility at 77 K was 5000  $\text{cm}^2/\text{Vs}$ . The crystalline properties of the grown layer were excellent, as shown by a FWHM of less than 15" of the  $\langle 004 \rangle$  Bragg reflection line in the DCXD spectrum. The surface morphology was featureless in optical microscopy.

Fig. 2 illustrates cross sections of the fabrication sequence for the InP MISFET's. Step (a) of Fig. 2 shows

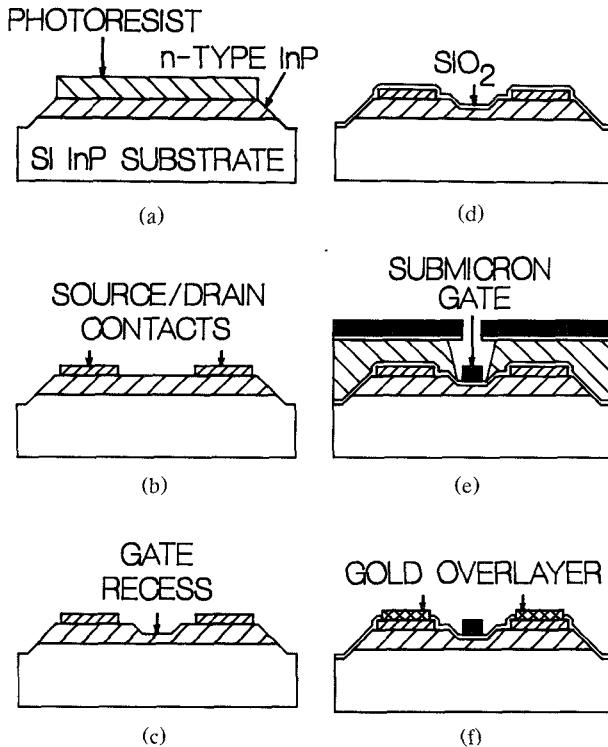


Fig. 2. Fabrication process cross sections for a submicron-gate InP power MISFET.

photolithography for the mesa isolation etch. Mesa etching was done using 10 wt% HIO<sub>3</sub> in DI H<sub>2</sub>O. Step (b) of Fig. 2 shows the source and drain ohmic contacts. The metal patterns were defined by a lift-off technique. The ohmic contacts consisted of a 1500 Å Au:Ge layer and a 1000 Å Au overlayer alloyed at 405°C for 1½ min. Step (c) of Fig. 2 shows the active channel gate recess. A photoresist mask was used during etching in 30:1 DI H<sub>2</sub>O:HBr with 1 drop of H<sub>2</sub>O<sub>2</sub> for each 20 ml of solution.

Step (d) of Fig. 2 shows the silicon dioxide gate insulator deposition. The silicon dioxide films were made by direct plasma-enhanced chemical vapor deposition (PECVD) using a Technics Planar-Etch II-A plasma reactor, operated at 13.56 MHz with automatic matching. Prior to insulator deposition, native oxides on the InP surface were etched using 10:1 DI H<sub>2</sub>O:HF for 30 s. After the native oxide etch the substrate was immediately loaded into the deposition chamber to minimize native oxide growth. Prior to film deposition the chamber was baked at 250°C for 1 h to reduce oxygen and carbon contamination. The silicon dioxide deposition temperature was 250°C. The flow rates used during deposition were 55 sccm nitrous oxide and 23 sccm silane, and the deposition pressure was 350 mtorr. The RF power used was 50 W, corresponding to a power density of 85 mW/cm<sup>2</sup>. Additional details of the silicon dioxide deposition on InP as well as the resulting native oxides and MIS device electrical properties are reported elsewhere by Shokrani and Kapoor [2]. After deposition the gate insulator was annealed at 300°C for 1 h in pure H<sub>2</sub>.

A 1000 Å gate insulator thickness was reported by Biedenbender *et al.* [5] for a 1.4-μm-gate-length InP power MISFET at 9.7 GHz. A thinner dielectric can be expected for smaller gate lengths and higher frequencies. A gate insulator thickness of 700 Å has been used by Gardner *et al.* [9] up to 20 GHz and by Saunier *et al.* [10] at 30 GHz. The gate insulator thickness used in this investigation was 630 Å. The saturation current density was measured to be ≈1 A/mm after the gate recess and gate insulator deposition and anneal. Saunier *et al.* [10] have reported the same saturation current density for millimeter-wave operation.

Step (e) of Fig. 2 shows the gate metal and submicron lithography for the InP MISFET's. The submicron lithography was a variation of the multilevel portable-conformable-mask technique [19]. A thick bottom resist (≈1.1 μm) was used to planarize the gate region. A 1000 Å layer of SiO<sub>2</sub> was deposited on the bottom resist by e-beam evaporation. Finally, a thin (≈2000 Å) resist was spun on the e-beam oxide. The thin top imaging resist was exposed using a 0.5 μm mask and developed. The pattern was transferred to the e-beam SiO<sub>2</sub> using a CF<sub>4</sub>/O<sub>2</sub> plasma etch. Because of the isotropic nature of the plasma used, the feature size obtained in the SiO<sub>2</sub> layer increased to 0.7 μm. The bottom resist was opened using an oxygen plasma, and the remaining e-beam oxide layer defined the gate during a subsequent metal evaporation and lift-off. The gate metal was 200 Å Ti and 4000 Å Au. Bonding pads to the submicron gates were patterned in a separate, conventional lift-off lithography and were also Ti/Au.

Step (f) of Fig. 2 shows openings etched in the SiO<sub>2</sub> to the source and drain contact regions. A 4000 Å Au overlayer was deposited in the openings to assist the current handling of the devices and to ensure easy wire bonding. The InP samples were thinned to ≈100 μm to decrease the thermal impedance of the devices, and were scribed into individual MISFET's. A 200 Å Ti layer and a 4000 Å Au overlayer were deposited on the sample back to aid heat dissipation.

Microwave power measurements for the completed InP MISFET's were obtained using a test fixture with the microstrip input and output circuits shown in Fig. 3. The dc bias was applied through an RF choke consisting of a high-impedance transmission line in series with low-impedance radial stubs. The RF choke was designed for bias currents up to 1.5 A. External chip capacitors across microstrip gaps were used as dc blocks near the test fixture input and output. The circuit design was optimized using commercially available software from 20 to 40 GHz for a wide range of operation. To accommodate the range of device impedances resulting from different drain-source sizes and operation at different frequencies, impedance matching was done empirically using external metal stubs close to the transistor.

The microstrip circuits were epoxied to a gold-plated brass block. The transistors were mounted on a metal ridge between the input and output circuits. Electrical

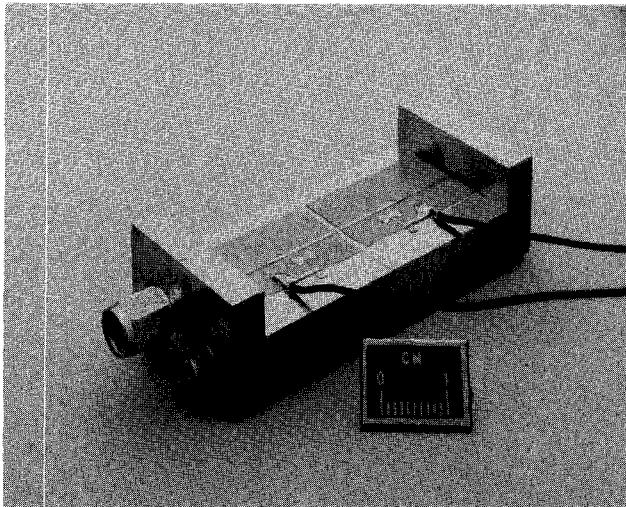


Fig. 3. Photograph of microwave test fixture with coax-to-microstrip launchers.

connections to the gate and drain were made by 1-mil-diameter wire bonds to the input and output microstrips, respectively. An electrically and thermally conductive silver-loaded epoxy was used for mounting the device and electrical connection to the source. Electrical connections between the test fixture microstrip and measurement system were made using 2.4 mm coax-to-microstrip launchers with a frequency range up to 50 GHz. Fig. 3 shows the test fixture with the coax-to-microstrip launchers. Fig. 4 shows a test fixture with a mounted transistor.

A calibration fixture to account for test fixture insertion loss was made with a microstrip through line in place of the transistor. Power measurements of InP MISFET's reported below have been corrected for the minimum calibration fixture insertion loss measured using external tuning at 18 and 20 GHz.

### III. RESULTS

Fig. 5 shows a typical  $I-V$  characteristic for an InP power MISFET with  $L_{DS} = 2 \mu\text{m}$  and  $W = 0.2 \text{ mm}$ . The gate voltage ranges from 0 to  $-10 \text{ V}$  in 1 V steps. The extrinsic transconductance is at least  $75 \text{ mS/mm}$  for gate voltages greater than  $-4 \text{ V}$ . The zero-gate-voltage saturation current is  $\approx 1 \text{ A/mm}$  at a drain voltage of 5 V. The transconductance and current density are representative values for all devices. For  $L_{DS} = 3$  and  $5 \mu\text{m}$ , the saturation drain voltage increases, as expected, with device size to  $\approx 3.8$  and  $\approx 4.1 \text{ V}$ , respectively. As reported elsewhere, the InP MISFET channel current cannot be pinched off in the normal curve tracer dc sweeping mode [2], [4], [6], [10]. However, previous results have shown that the channel can be pinched off using a curve tracer which applies the gate voltage in 80  $\mu\text{sec}$  pulses [4], [5], [10], [20]. The absence of pinch-off in the dc mode or at low frequency is attributed to electron trapping in states at the silicon dioxide-InP interface which do not respond to higher frequency (e.g. 80  $\mu\text{s}$  pulses) signals [10], [20]. Similar decreases in drain current using pulsed gate volt-

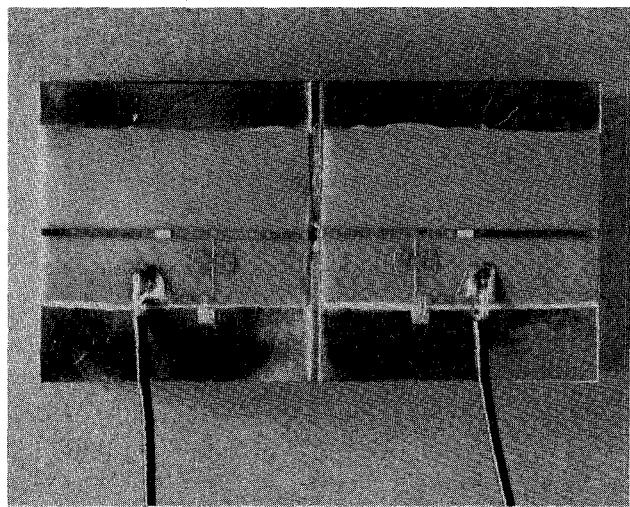


Fig. 4. Photograph of microwave test fixture with a mounted submicron-gate InP power MISFET.

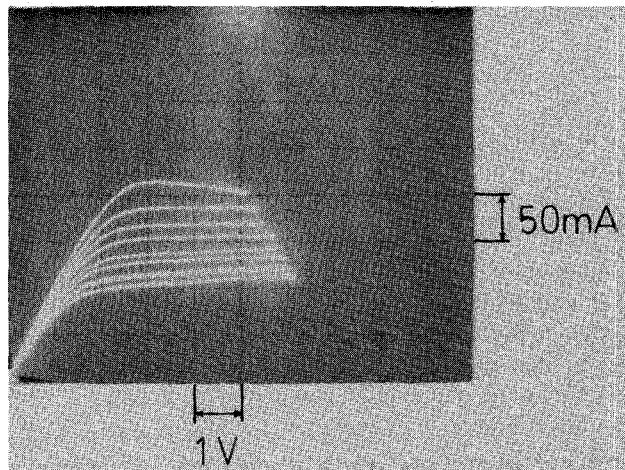


Fig. 5.  $I-V$  characteristics for a InP power MISFET with a  $0.2 \text{ mm}$  gate width and a  $2 \mu\text{m}$  drain-source space.

ages compared with dc sweeping have also been reported for GaAs power MESFET's [21].

The drain-source breakdown voltages for the  $I-V$  measurements in Fig. 5 are 6 V for  $L_{DS} = 2$  and  $3 \mu\text{m}$  and 8 V for  $L_{DS} = 5 \mu\text{m}$ . These voltages are comparable to the 6 V drain bias reported by Saunier *et al.* [10] for 30 GHz devices with  $L_{DS} = 1.5 \mu\text{m}$  and a drain current density of 1 A/mm. However, they are lower than the drain voltages of 9 to 18 V reported for other InP MISFET's between 4 and 20 GHz with drain current densities of 70 to 660 mA/mm [4]–[10]. The gate-drain and gate-source breakdown voltages are  $> 25 \text{ V}$  for all devices.

Parts (a) and (b) of Fig. 6 show measurements at 18 and 20 GHz, respectively, of output power density, power-added efficiency, and power gain as a function of  $L_{DS}$ . The gate width is 0.2 mm and the gate voltage is zero for all measurements. At both frequencies the output power density and power gain for conditions used to obtain high

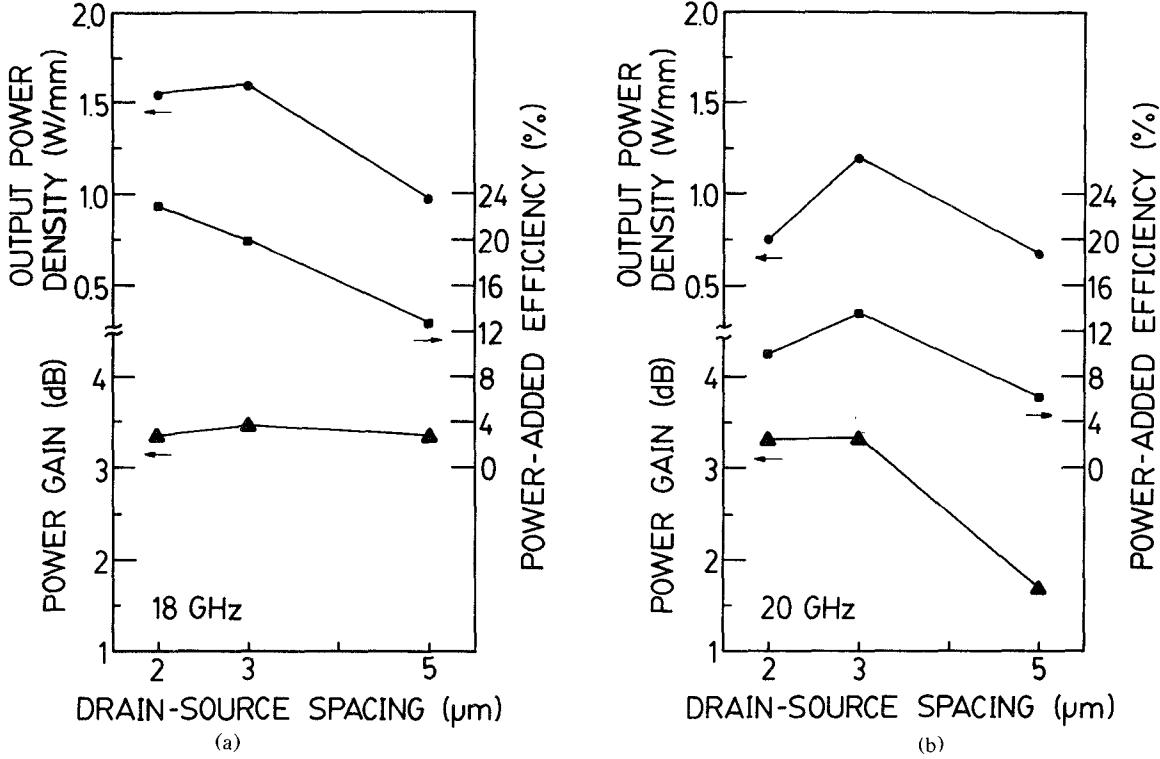


Fig. 6. Output power density, power gain, and power-added efficiency as a function of drain-source spacing at (a) 18 and (b) 20 GHz for a InP MISFET with a 3  $\mu\text{m}$  drain-source space.

output power are best for  $L_{DS} = 3 \mu\text{m}$ , second for  $L_{DS} = 2 \mu\text{m}$ , and lowest for  $L_{DS} = 5 \mu\text{m}$ .

In Fig. 6(a) at 18 GHz for  $L_{DS} = 2 \mu\text{m}$  the input power, drain voltage, and drain current density are 21.55 dBm, 6.0 V, and 603 mA/mm, respectively. For  $L_{DS} = 3 \mu\text{m}$  the input power, drain voltage, and drain current density are 21.55 dBm, 7.0 V, and 625 mA/mm, respectively. For  $L_{DS} = 5 \mu\text{m}$  the input power, drain voltage, and drain current density are 19.55 dBm, 7.0 V, and 589 mA/mm, respectively. The output power density for all device sizes is greater than previous measurements for InP MISFET's at 18 GHz [9]. For  $L_{DS} = 3 \mu\text{m}$  the output power density is up to 1.59 W/mm, which is better by a factor of 2.7. The total output power (up to 318 mW) is comparable to the total powers obtained from larger gate width InP MISFET's at these frequencies [9]. The power-added efficiencies of 23.0% and 20.0% for the  $L_{DS} = 2$  and 3  $\mu\text{m}$  devices, respectively, are also improvements for InP MISFET's measured at 18 GHz. The power-added efficiency for  $L_{DS} = 5 \mu\text{m}$  is 12.7% and is less than the value of 15.7% previously achieved at 18 GHz [9].

In Fig. 6(b) at 20 GHz for  $L_{DS} = 2 \mu\text{m}$  the input power, drain voltage, and drain current density are 18.63 dBm, 5.6 V, and 690 mA/mm, respectively. For  $L_{DS} = 3 \mu\text{m}$  the input power, drain voltage, and drain current density are 20.64 dBm, 7.0 V, and 654 mA/mm, respectively. For  $L_{DS} = 5 \mu\text{m}$  the input power, drain voltage, and drain current density are 19.65 dBm, 6.0 V, and 603 mA/mm. At 20 GHz the  $L_{DS} = 5 \mu\text{m}$  device has a low power gain less than 2 dB. However, there is more than 3 dB gain for

the  $L_{DS} = 3$  and 2  $\mu\text{m}$  devices, which again have output power densities better than reported for larger gate width InP MISFET's providing comparable total output power (up to 240 mW) at 20 GHz [9]. For  $L_{DS} = 3 \mu\text{m}$  the output power density is up to 1.20 W/mm, which is again better by a factor of 2.7 than previous measurements at 20 GHz. For  $L_{DS} = 3 \mu\text{m}$ ,  $\eta_{\text{add}}$  is improved to 13.6%. At 23 GHz the best gain that could be obtained for any of the devices was only 2.1 dB.

The reason for the best output power being available for  $L_{DS} = 3 \mu\text{m}$  is probably the trade-off between lower parasitics for smaller devices and higher breakdown voltages for bigger devices. Although parasitics are lower for  $L_{DS} = 2 \mu\text{m}$ , the drain voltage is higher for  $L_{DS} = 3 \mu\text{m}$ . At 18 GHz the output power is less for  $L_{DS} = 5 \mu\text{m}$  even though the drain voltage is the same as for  $L_{DS} = 3 \mu\text{m}$ . At 20 GHz the maximum drain voltage decreases for  $L_{DS} = 5 \mu\text{m}$ , and the power gain and output power are low.

Fig. 7 shows microwave power measurements at 20 GHz of output power density, power gain, and power-added efficiency as a function of drain voltage. The measurements are for a device with  $W = 0.2 \text{ mm}$  and  $L_{DS} = 3 \mu\text{m}$ . The maximum output power density at 20 GHz is 1.20 W/mm, with a corresponding gain of 3.17 dB and a power-added efficiency of 13.6%. The input power is 20.6 dBm; it is the highest examined at 20 GHz for this device and the gain in Fig. 7 is compressed for all drain voltages. The power gain,  $P_{\text{out}}$ , and  $\eta_{\text{add}}$  all increase with drain voltage. At 18 GHz the same device had a maximum

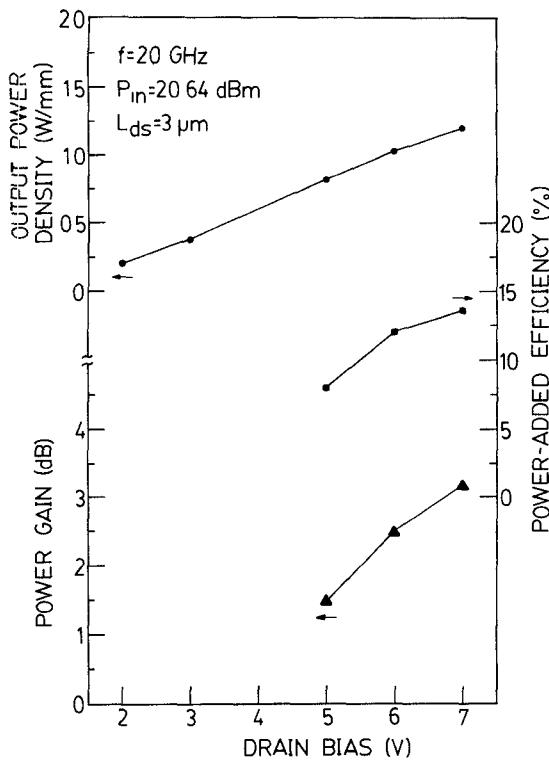


Fig. 7. Output power density, power gain, and power-added efficiency as a function of drain voltage at 20 GHz for an InP MISFET with a 0.2 mm gate width and a 3  $\mu\text{m}$  drain-source space.

output power density of 1.59 W/mm, with a corresponding gain of 3.47 dB and a power-added efficiency of 20.0% for a drain voltage of 7.0 V and  $P_{in} = 21.6 \text{ dBm}$ .

The drain current decreases with increasing microwave input power, as has been previously observed for InP MISFET's [4], [5], [10]. The saturation current density for the device in Fig. 7 at 18 and 20 GHz is 654 mA/mm for  $P_{in} = 20.6 \text{ dBm}$  and a drain voltage of 7.0 V. Typical decreases in drain current with microwave input power are 30% less than the zero-gate-voltage dc saturation current. The decrease in drain current with  $P_{in}$  has been attributed to a change in the charge status of states near the InP-insulator interface [4], [5], although a mechanism for the response of such states at the high frequencies involved is yet to be developed. Another possible cause of the decreased current is the nonlinear output characteristics that can occur as the device is driven into compression [22]. The lower drain current results in higher drain-source breakdown voltages compared with dc values. The maximum drain voltages that can be used with RF power applied are 8 V for  $L_{DS} = 2$  or 3  $\mu\text{m}$  and 9 V for  $L_{DS} = 5 \mu\text{m}$ . When high drain voltages are used to obtain maximum output power, a high input power must also be applied for a low drain current. Reducing  $P_{in}$  while a high drain voltage is applied results in increased current and thermal breakdown of the transistor. The change in drain current limits the range of  $P_{in}$  for measurements of  $P_{out}$  versus  $P_{in}$  under constant bias conditions.

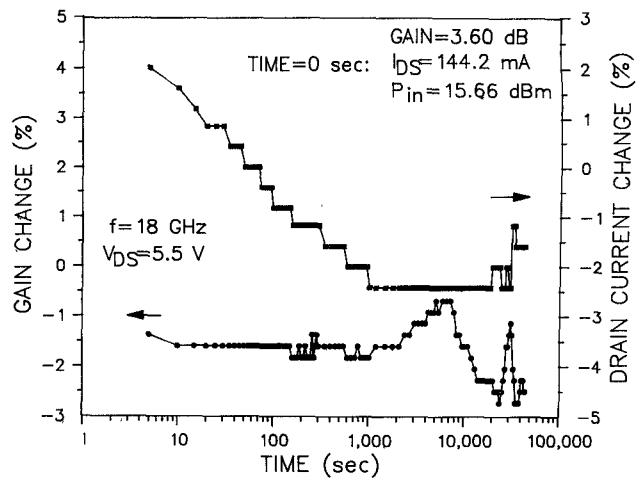


Fig. 8. Time dependence of power gain and drain current.

Fig. 8 shows the power gain and drain current variation over a 12 h period. The measurements are at 18 GHz for an  $L_{DS} = 3 \mu\text{m}$  device. The microwave input power was set to an initial value of 15.66 dBm. The gate voltage was 0 V. At  $t = 0$  s the drain voltage was changed from 1.5 V to 5.5 V. The gain and drain current density at  $t = 0$  s were 3.60 dB and 721 mA/mm, respectively. The microwave power source had a power variation of 0.15 dB during the measurement time, so the power gain variation is shown instead of the output power variation to eliminate the effect of the input power variation. The power gain was stable to within 3.0%, which corresponds to an overall change of 0.13 dB. The drain current showed an initial increase of 2.0% and later decreased by as much as 2.4%. The power gain stability is slightly less than the output power stability of 2% over 167 h previously reported for 1.4- $\mu\text{m}$ -gate-length power MISFET's [4]. However, the drain current change is better than the value of 10% observed for the 1.4- $\mu\text{m}$ -gate-length MISFET's [4].

#### IV. SUMMARY

InP power MISFET's were fabricated with a 0.7  $\mu\text{m}$  gate length. Different device sizes were examined with gate widths of 0.2 mm and drain-source spacings of 2, 3, and 5  $\mu\text{m}$ . Current-voltage measurements at dc indicated extrinsic transconductances of up to 75 mS/mm. The drain-source breakdown voltages were 6 to 8 V. The gate-source and gate-drain breakdown voltages were  $> 25 \text{ V}$ . Power measurements at 18 and 20 GHz showed output power densities up to 2.7 times greater than previously observed at these frequencies for InP MISFET's, and the power-added efficiency was also improved. At 18 GHz for a drain-source spacing of 3  $\mu\text{m}$  the output power was 318 mW (1.59 W/mm) with a gain of 3.47 dB and a power-added efficiency of 20.0%. At 20 GHz for a drain-source spacing of 3  $\mu\text{m}$  the output power was 240 mW (1.20 W/mm) with a gain of 3.17 dB and a power-added efficiency of 13.6%. The output power density for the 0.2-mm-gate-width InP MISFET's here is 50% greater than the value of 0.8 W/mm recently reported at 20 GHz.

for 0.15-mm-gate-width pseudomorphic HEMT's with 0.25  $\mu\text{m}$  gate lengths [14]. InP power MISFET's have been previously shown to provide an output power density more than three times higher than the best GaAs power MESFET's at frequencies below 10 GHz [4], [23]. For comparison at 20 GHz a GaAs power MESFET with a total gate width of 4.8 mm has provided an output power density of 0.42 W/mm [13].

The best output power density and gain were obtained for drain-source spacings of 3  $\mu\text{m}$ . The maximum drain voltage was lower for 2  $\mu\text{m}$  drain-source space devices, as were the output power density and corresponding gain. Devices with a 5  $\mu\text{m}$  drain-source space had lower gain and output power density despite comparable maximum drain voltages to the 3  $\mu\text{m}$  drain-source space devices. The power gain was stable to within 3.0% over 12 h. The drain current variation was less than 5% during the same time period.

The gain was less than 3 dB and the output power density was low for gate widths greater than 0.2 mm. The total output power of the InP MISFET's here may be improved if the drain-source breakdown voltage can be increased through optimization of the device processing. Although excellent output power densities and power-added efficiencies have been achieved for gate widths of 0.2 mm, the maximum drain voltages that can be used are relatively low compared with most other InP MISFET's. Several parameters, including the drain saturation current resulting from the gate recess, channel thickness, and channel doping density, could be investigated to increase the drain-source breakdown voltages for the InP MISFET's here. Higher breakdown voltages may provide even better output power density and enhance the operation of larger gate width InP MISFET's for higher total power. The total output power may also be improved through the use of a different device topology for better power combining, such as the air bridge connections and source vias commonly used in commercial devices.

The use of an  $I-V$  measurement system capable of rapidly pulsing gate and drain voltages such as that recently reported for GaAs power MESFET's [24] would help elucidate the effects of surface and interface states as well as channel heating on the InP MISFET electrical properties. Such measurements should provide a better indication of the large-signal operation conditions at microwave frequencies and a better indication of the bias conditions for a desired class of amplifier operation. Small signal  $S$  parameters were not measured but would provide useful additional information for estimates of equivalent circuit elements and current gain cutoff frequency.

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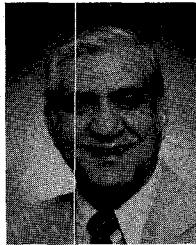
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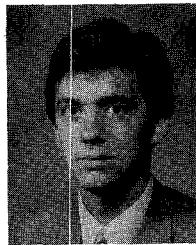
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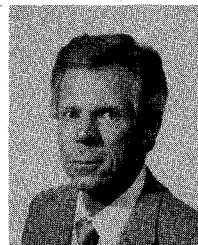


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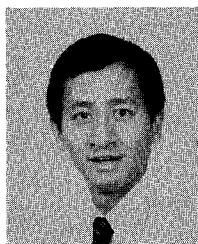
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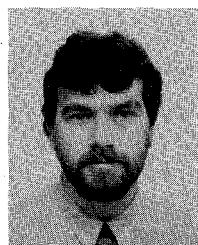
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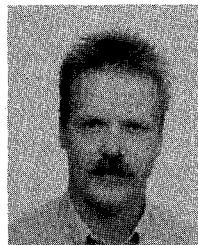
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