# 44 GHz HYBRID LOW NOISE AMPLIFIERS USING ION-IMPLANTED $In_xGa_{1-x}As$ MESFETs

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## ABSTRACT

Hybrid low noise amplifiers using ion-implanted $In_xGa_{1-x}As$ MESFETs with 0.25-micron T-gates have been developed at 44 GHz. The hybrid two-stage amplifier using these ion-implanted $In_xGa_{1-x}As$ MESFETs achieved a noise figure of 3.6 dB with an associated gain of 14.4 dB at 44 GHz. When two of these amplifiers were cascaded, the four-stage amplifier demonstrated a gain of 30.5 dB at 44 GHz and 37 dB at 40 GHz. These results, achieved using low cost ion-implantation techniques, rival the best HEMT results.

## INTRODUCTION

Ion implantation of the active device channel to fabricate MESFETs has long been recognized for its advantages in high density IC fabrication. The ability to selectively implant planar devices and integrated circuits, combined with excellent uniformity, high throughput and low cost, makes ion implantation extremely attractive for large scale production. Since Metal Organic Chemical Vapor Deposition (MOCVD) is a higher throughput material growth technique than Molecular Beam Epitaxy (MBE), ion implantation into MOCVD grown heterostructure materials is an attractive technique for combining the advantages of ion implantation with the high performance of heterostructure devices.

The ternary compound semiconductor InGaAs has demonstrated higher low-field mobility, higher doping capability, and better high-field transport properties than GaAs (1), (2). In the past, InGaAs has been used primarily in HEMT rather than MESFET structures because of the small bandgap of InGaAs material. Unlike HEMTs which have a layer of large bandgap material between the Schottky barrier gate and the active channel, MESFETs have the Schottky barrier gate in direct contact with the device channel. Consequently, the Schottky barrier gate on InGaAs has a low barrier height and a high leakage current. Consequently, the excellent transport properties of the InGaAs material is compromised by the inferior Schottky barrier contact. This problem can be solved by using a graded $In_xGa_{1-x}As$ device channel. As reported in references (3), (4), and (5), 0.5-micron gate-length graded $In_xGa_{1-x}As$ devices achieved an extrinsic transconductance of 460 mS/mm with a cutoff frequency, $f_t$, of 61 GHz. These results indicated that the microwave performance of ion-implanted InGaAs MESFETs is comparable to that of heterostructure devices with the same gate-length.

In this paper, we report hybrid low noise amplifiers using ion-implanted $In_xGa_{1-x}As$ MESFETs with 0.25-micron T-shaped gates operating at 44 GHz. These results represent the first low noise application of ion-implanted InGaAs MESFETs at 44 GHz and indicate that ion-implanted $In_xGa_{1-x}As$ MESFETs are the most suitable manufacturing technology for millimeter-wave low noise applications.

## MATERIAL GROWTH AND DEVICE FABRICATION

The $In_xGa_{1-x}As$ layer is grown on (100) GaAs substrates by using an EMCORE GS3300 MOCVD reactor. The $In_xGa_{1-x}As$ layer concentration used is graded from 18 percent at the substrate to 0 percent at the surface to improve the Schottky barrier gate and lattice match. The growth rate for these $In_xGa_{1-x}As$ layers is typically 2 micron/hour. The total thickness is 1600 A. The source materials for MOCVD growth are arsine, trimethylgallium, and ethyldimethylindium. After MOCVD growth, silicon ion implantation is used to dope the graded $In_xGa_{1-x}As$ layers to a peak carrier concentration of $1 \times 10^{18}$ $cm^{-3}$.

Standard MESFET processing techniques are used to fabricate 0.25-micron recessed T-gate MESFETs on the graded $In_xGa_{1-x}As$ wafers. The drain-to-source spacing is 2 microns with a gate-to-source spacing of 0.25 micron to reduce the source resistance. Device isolation is achieved by mesa etching. The source and drain regions are defined by optical lithgraphy, followed by AuGe/Ni/Au metal evaporation and ohmic alloy. The 0.25 micron T-gates are defined by a triple layer resist technique, followed by Ti/Pt/Au gate metallization on the recessed channel.

## DEVICE CHARACTERISTICS

The DC device performance of a typical 0.25 X 50 micron $In_xGa_{1-x}As$ MESFETs showed a maximum extrinsic transconductance of 480 mS/mm at a drain current of 520 mA/mm and a drain bias of 1.5 volts (Figure 1). The $f_t$ is typically 101 GHz.

The two-stage hybrid amplifier design was based on the 0.25 X 100 micron device equivalent circuit shown in Figure 2. The element values shown in this figure were derived from the 0.5 to 25 GHz S-parameter data by using a Fletcher-Powell optimization algorithm to fit this model to the measured data. The device used for this modeling was biased at 75% Idss and Vds = 1.8 volts. Based on this model, the device is unconditionally stable for frequencies above 42 GHz and the $f_{max}$ is 115 GHz (Figure 3).

The above S-parameter measurements were made using an HP8510 automatic network analyzer and Cascade microwave probes. The ANA was calibrated using the impedance standard substrate (ISS), and an "open circuit" condition (lifting the probes). No correction for parasitic capacitances was made.

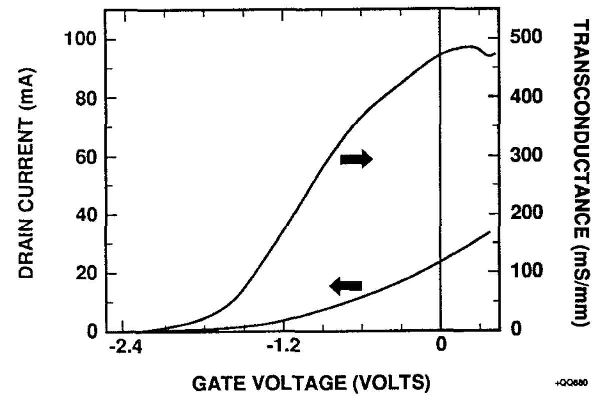


*Figure 1. DC transconductance and drain current of 0.25 x 50 micron ion-implanted* $In_xGa_{1-x}As$ MESFET.

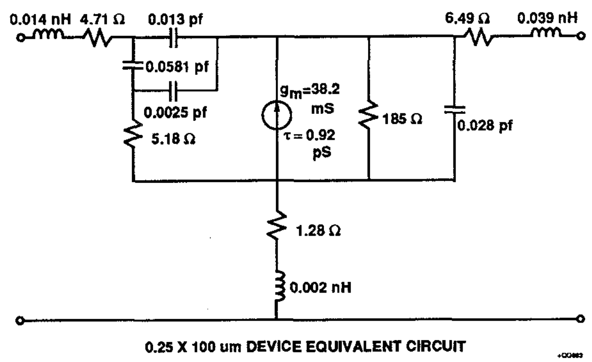


*Figure 2. Equivalent circuit element values of 0.25 x 100 micron ion-implanted* $In_xGa_{1-x}As$ MESFET.

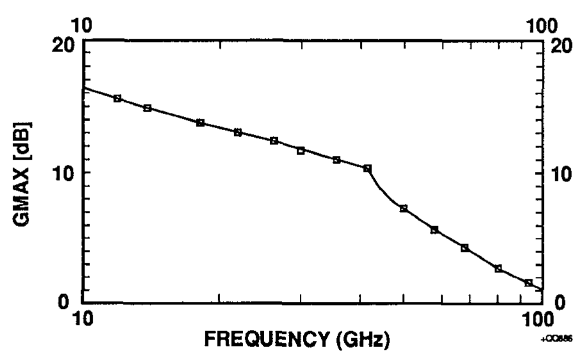


*Figure 3. Maximum available gain of the 0.25 x 100 micron ion-implanted* $In_xGa_{1-x}As$ MESFET.

## CIRCUIT DESIGN

A schematic showing the basic topology of the two stage amplifier is shown in Figure 4. In this single-ended approach, the microstrip circuit elements are used to realize low-pass matching networks. The interstage and input/output networks were designed to provide a nominally flat gain of 14 dB over the 40 to 46 GHz band. The simulated gain performance of this amplifier is shown in Figure 5. This circuit was fabricated using 10 mil thick fused silica substrates on a Thermcon carrier (Figure 6). Excluding the mounting ears, the overall dimensions of the carrier are 98 X 312 mils. This two-stage amplifier was tested in a waveguide-below-cutoff test fixture with integral waveguide-to-microstrip E-field probe transitions. The insertion loss of two of these back-to-back transitions is approximately 1 dB over the 40 to 46 GHz band.

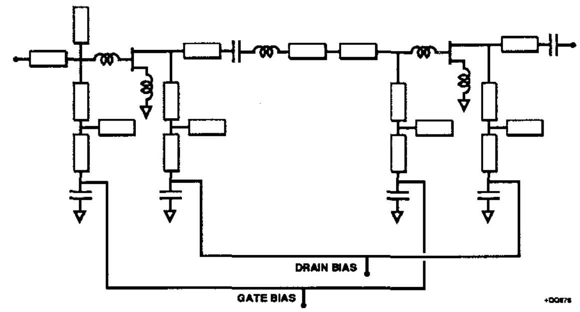


*Figure 4. Hybrid two-stage amplifier circuit schematic.*

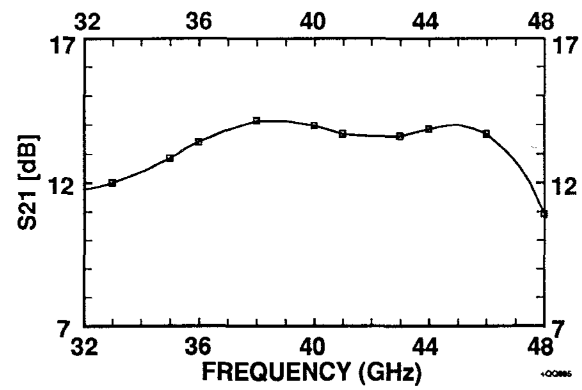


*Figure 5. Simulated gain performance of the two-stage amplifier.*

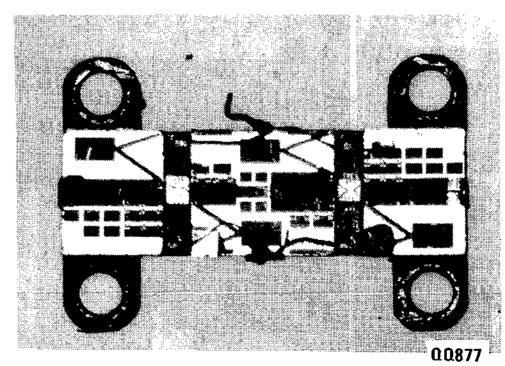


*Figure 6. Carrier assembly of the two-stage amplifier.*

## AMPLIFIER PERFORMANCE

The noise figure and associated gain of this amplifier are shown in Figure 7. For this data, the amplifier was biased at Vds = 2 volts and Ids = 59% Idss. Several amplifiers have

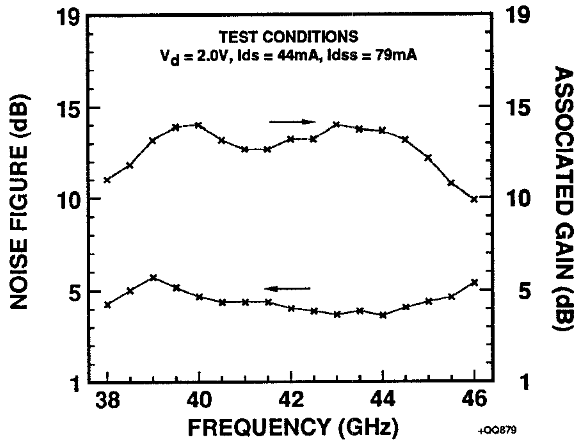


*Figure 7. Noise figure and associated gain of the hybrid two-stage amplifier.*

been tested to date and they all show similar results indicating the excellent repeatability of this approach. The gain ranges from 12.5 to 14.4 dB over the 39 to 44.5 GHz band. The noise figure of this amplifier at 44 GHz was measured to be 3.6 dB and the associated gain was 14.4 dB. These measurements are referenced to the carrier input/output interfaces with correction for the waveguide–to–microstrip transitions. This amplifier noise figure corresponds to a device noise figure of 2.8 dB at 44 GHz with the device biased at 59% Idss.

When two of these carriers were cascaded to form a four–stage amplifier, the gain of this amplifier (Figure 8) is 30.5 dB at 44 GHz and greater than 30 dB over the 38 to 45.5 GHz band. The gain is a maximum at 40 GHz with a value of 37.5 dB.

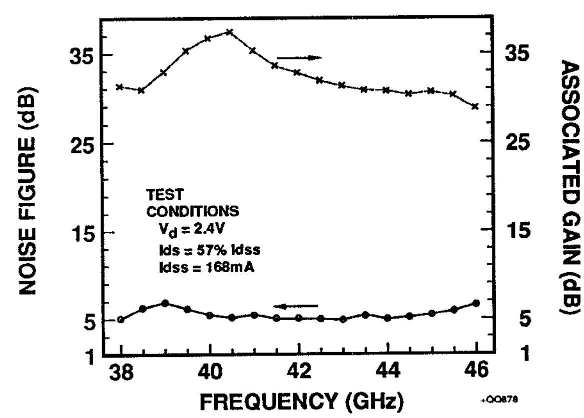


*Figure 8. Noise figure and associated gain of the cascaded hybrid four–stage amplifier.*

The amplifier result of 3.6 dB noise figure with 14.4 dB associated gain compares favorably with the state–of–the–art HEMT amplifiers reported in the literature for the 40 GHz frequency range. Berenz, et.al. (6) reported a single–stage 44 GHz monolithic low noise HEMT amplifier with a noise figure of 5 dB and an associated gain of 5.5 dB at 44.5 GHz. Yuen, et.al. (7) reported a single–stage HEMT low noise amplifier with a noise figure of 4 dB and an associated gain of 6.5 dB from 38 to 44 GHz.

## CONCLUSION

Hybrid low noise amplifiers using ion–implanted $In_xGa_{1-x}$ As MESFETs with 0.25–micron T–gates have been developed at 44 GHz. These results are the first low noise application of ion–implanted $In_xGa_{1-x}As$ MESFETs at 44 GHz and are comparable to those achieved by low noise HEMT amplifiers. These results clearly indicate that ion–implanted $In_xGa_{1-x}As$ MESFETs are the most suitable manufacturing technology for millimeter–wave low noise applications and that production of millimeter–wave MMICs is now possible with ion implantation into MOCVD grown heterostructure materials.

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## REFERENCES

(1) G.E. Stillman, L.W. Cook, T.J. Roth, T.S. Low, and B.J. Skromme, "High purity materials," in GaInAsP Alloy Semiconductors, T.P. Pearsall, Ed. New York, Wiley, 1982.

(2) T.H. Windhorn, L.W. Cook, and G.E. Stillman, "The electron velocity–field characteristics for n–$In_{0.53}$ $Ga_{0.47}As$ at 300 K," IEEE Electron Device Lett., Vol. EDL–3, pp. 18–20, Jan 1982.

(3) G.W. Wang, M. Feng, R. Kaliski, Y.P. Liaw, C. Lau, and C. Ito, "Millimeter–Wave Ion–Implanted Graded $In_xGa_{1-x}As$ MESFETs Grown by MOCVD," IEEE Electron Device Letters, Vol. 10, No. 10, pp. 449–451, October 1989.

(4) G.W. Wang, C. Ito, M. Feng, R. Kaliski, D. McIntyre, C. Lau, and V.K. Eu, "Heteroepitaxial $In_{0.1}Ga_{0.9}As$ Metal–Semiconductor Field–Effect Transistors Fabricated on GaAs and Si Substrates," Appl. Phys. Lett., Vol. 55, No. 15, pp. 1552–1554, October 9, 1989.

(5) M. Feng, G.W. Wang, Y.P. Liaw, R.W. Kaliski, C.L. Lau, and C. Ito. "Ion–Implanted $In_{0.1}$ $Ga_{0.9}As$ Metal–Semiconductor Field–Effect Transistors, on GaAs (100) Substrates, " Appl. Phys. Lett., Vol. 55, No. 6, August 7, 1989.

(6) J. Bernez, H.C. Yen, R. Esfandiari, K. Nakano, T. Sato, J. Velebir and K. Ip, "44 GHz Monolithic Low Noise Amplifier," IEEE 1987 Microwave and Millimeter–Wave Monolithic Circuits Symposium, pp. 15.

(7) C. Yuen, C. Nishimoto, S. Bandy, and G. Zdasiuk, "A Monolithic 40–GHz HEMT Low–Noise Amplifier," IEEE 1989 Microwave and Millimeter–Wave Monolithic Circuits Symposium, pp. 117.