InGaAs MESFET's for Millimeter-Wave Low-Noise Applications

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***Abstract*—It is reported that excellent device performance and uniformity can be achieved with 0.25-μm gate InGaAs MESFET's fabricated by the mixed manufacturing technology of MOCVD and ion implantation. An average f_t of 102 GHz with a standard deviation of 12 GHz is derived from the *S*-parameter measurements of 139 devices uniformly distributed on a 3-inch-diameter GaAs wafer. Two-stage low-noise amplifiers fabricated by using these InGaAs MESFET's demonstrate a typical noise figure of 3.6 dB with an associated gain of 14.4 dB at 44 GHz.**

TERNARY InGaAs materials epitaxially grown on GaAs and Si substrates have shown great potential for MESFET applications [1]. Important issues concerning the Schottky contact and limited channel thickness of the InGaAs MESFET's have also been investigated [2], [3]. In this work, we show that 0.25-μm gate MESFET's fabricated by using ion implantation into the MOCVD-grown InGaAs layers offer not only excellent device performance but also good uniformity across a 3-inch-diameter GaAs wafer. As the first low-noise application of the InGaAs MESFET's at 44 GHz, the measured performance of the *Q*-band two-stage low-noise amplifiers fabricated by using these InGaAs MESFET's rivals the best HEMT's results. Since MOCVD and ion implantation are manufacturing techniques with high throughput, this InGaAs MESFET approach has the advantage of possible volume production of high performance devices and circuits for millimeter-wave frequency band.

The InGaAs layer was directly grown on (100) GaAs substrates by MOCVD without any buffer structure. The active layer consisted of 1600 Å of $In_xGa_{1-x}As$ layer with the InGas mole fraction linearly graded from 15% at the InGaAs/GaAs heterointerface to 0% at the wafer surface. The graded InAs composition leads to better Schottky contact [3]. The growth rate for the InGaAs layer was typically 2 μm/hr at a growth temperature of 640 C, depending on the InAs composition. The MOCVD source materials were arsine, trimethylgallium, and ethyldimethylindium. Since ion implantation showed better uniformity of carrier concentration on 3-inch-diameter wafers in our laboratory, the MOCVD-grown InGaAs layers were implanted by silicon ions to a peak carrier concentration of $1 - 2 \times 10^{18}$ cm^{-3} and later annealed at 850 C for 30 min using capless anneal with an arsine overpressure. Currently we are modifying the MOCVD reactor to improve the in-situ doping uniformity, so that the extra step of ion implantation can be eliminated.

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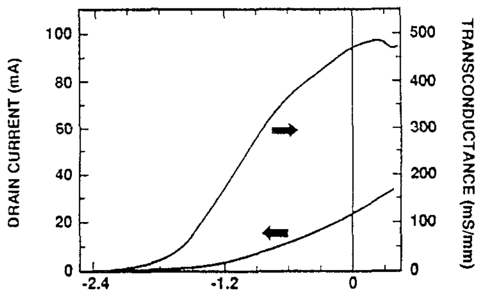

Fig. 1. Drain current and normalized transconductance versus gate voltage for 0.25-μm gate InGaAs MESFET. Drain bias voltage is 1.5 V.

Recess-gate MESFET processing techniques were used to fabricate 0.25-μm gate devices. Device isolation was achieved by mesa etching. The source and drain regions were defined by optical lithography with a spacing of 2 μm, followed by AuGe/Ni/Au metal evaporation. The nominally 0.25-μm gate, sitting in the middle of the channel, was defined by electron beam lithography. The channel was recessed by ~500 Å before Ti/Pt/Au gate metalization.

Fig. 1 shows the transconductance and drain current versus gate voltage for a typical 50-μm wide InGaAs MESFET. The maximum extrinsic transconductance is 480 mS/mm at a drain current of 520 mA/mm and a drain bias of 1.5 V. *The gate-to-drain breakdown voltage is about 5-6 V.* Device *S*-parameters were measured from 0.5-25 GHz by using a microwave probe station, while the devices were biased at zero gate voltage and a drain voltage of 1.5 V. The microwave probes were calibrated by impedance standard substrate (ISS) from Cascade Microtech. No correction was made for the parasitic capacitance, and therefore the measured results were extrinsic. The current gain and the maximum stable gain (MSG) at zero gate bias as a function of frequency for one of the best devices are shown in Fig. 2. The extrapolation of the current gain to unity using a −6 dB/Oct slope yields an extrinsic f_t of 126 GHz. In addition to high f_t, this device has excellent power gain, which is important for practical circuit application. The corresponding MSG at 12, 18 and 25 GHz is 17.4, 15.6 and 14.2 dB, respectively. At the same bias condition as previously described, a sampling of 139 devices uniformly distributed on a 3-inch-diameter wafer were measured for S-parameter by an automatic probe station to examine wafer scale uniformity. There were approximately 500 discrete devices in total on the wafer and no dc screening was performed before S-parameter measurements. Consistent device characteristics were implied by a very narrow f_t distribution as shown in Fig. 3. These extensive *S*-parameter measurements yield an average f_t of 102 GHz with a standard deviation of 12 GHz. These devices have dc transconductance ranging from 420 mS/mm to 500 mS/mm at the rf measurement bias point. The uniform f_t distribution on 3-inch GaAs wafers

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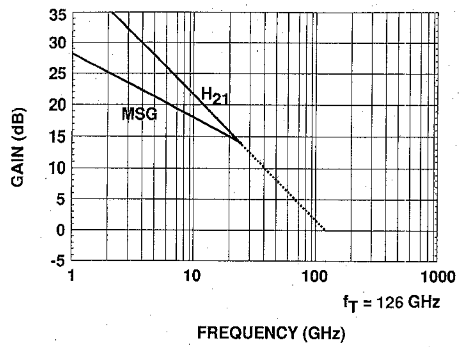

Fig. 2. Current gain (H_{21}) and maximum stable gain (MSG) as function of frequency at zero gate voltage and drain voltage of 1.5 V. Extrapolation of current gain yields an extrinsic f_t of 126 GHz.

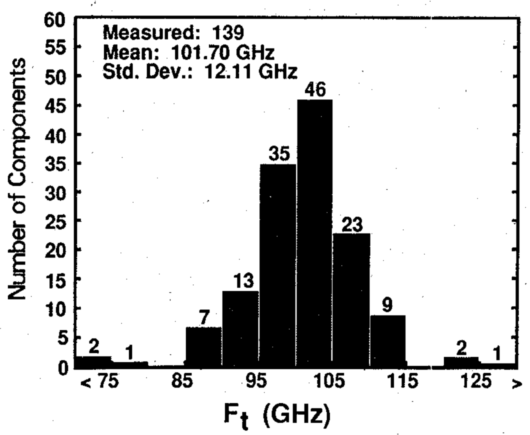

Fig. 3. f_t distribution of InGaAs MESFET's on 3-inch GaAs wafer. Average f_t is 102 GHz with standard deviation of 12 GHz.

indicates for the first time that high performance FET's with 100-GHz f_t can be produced in large quantities.

A hybrid two-stage low noise amplifier was constructed by using two 100-μm wide InGaAs MESFET's in order to test the device noise performance at 44 GHz. The input/output and interstage matching networks were designed to provide a nominally flat gain of 14 dB over the 40–46 GHz band. The microstrip matching circuits are fabricated on 10-mil thick fused silica substrates. Fig. 4 shows the measured noise figure and the associated gain of the amplifier as a function of frequency, when both stages of the amplifier were biased at a drain voltage of 2 V and a drain current of 59% Idss. The gain ranges from 12.5–14.4 dB over the 39–45 GHz band. AT 44 GHz, the noise figure of this amplifier is measured to be 3.6 dB with an associated gain of 14.4 dB. The amplifier noise figure corresponds to a device noise figure of 2.8 dB at 44 GHz with the device biased at 59% of Idss. Several amplifiers have been tested to date and they all showed similar results. The amplifier performance is currently limited by the carrier design in which both stages share the same external bias. As a result, the two MESFET's in the amplifier can not be biased separately to achieve the best noise and gain performance simultaneously.

These preliminary low noise results, nevertheless, compare favorably with the state-of-the-art HEMT amplifiers reported for

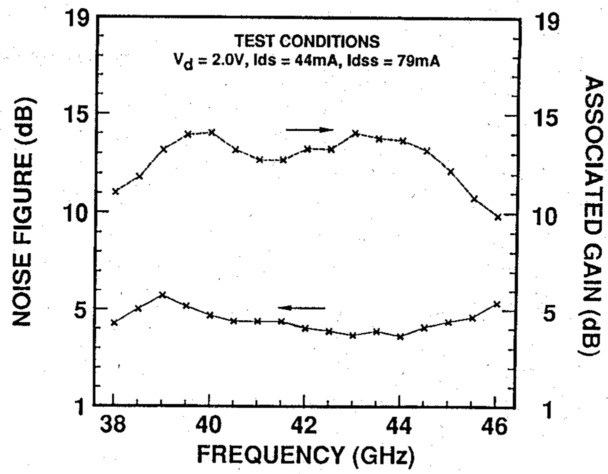

Fig. 4. Measured noise figure and associated gain of two-stage InGaAs MESFET amplifier as function of frequency.

the *Q* band. Berenz *et al.* reported a single-stage HEMT amplifier with a noise figure of 5 dB and an associated gain of 5.5 GHz at 44.5 [4]. Yuen *et al.* presented a single-stage low noise HEMT amplifier operating from 38–44 GHz with a noise figure of 4 dB and an associated gain of 6.5 dB [5].

In summary, two-stage low noise amplifiers using ion-implanted InGaAs MESFET's have been developed to demonstrate the first millimeter-wave application of these devices. The measured amplifier performance at 44 GHz are comparable to those achieved by the HEMT's. Furthermore, the excellent and uniform device performance obtained with 3-inch-diameter GaAs wafers clearly indicate that the ion-implanted InGaAs MESFET is a practical manufacturing technology for millimeter-wave devices and integrated circuits.

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