155- and 213-GHz AlInAs/GaInAs/InP HEMT MMIC Oscillators

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***Abstract*—We report on the design and measurement of monolithic 155- and 213-GHz quasi-optical oscillators using AlInAs/GaInAs/InP HEMT's. These results are believed to be the highest frequency three-terminal oscillators reported to date. The indium concentration in the channel was 80% for high sheet charge and mobility. The HEMT gates were fabricated with self-aligned sub-tenth-micrometer electron-beam techniques to achieve gate lengths on the order of 50 nm and drain-source spacing of 0.25 μm. Planar antennas were integrated into the fabrication process resulting in a compact and efficient quasi-optical Monolithic Millimeter-wave Integrated Circuit (MMIC) oscillator.**

I. Introduction

THE POTENTIAL of AlInAs/GaInAs High Electron Mobility Transistors (HEMT's) on InP substrates has been investigated extensively for low-noise and power applications at millimeter-wave frequencies (30–100 GHz), and the recent developments in HEMT materials growth [1], layer scaling [2], and electron-beam fabrication [3], have resulted in the fabrication of the world's highest cutoff frequency (f_t) transistors [4]. We have combined the AlInAs/GaInAs technology with integrated antennas to build a millimeter-wave quasi-optical oscillator. The design is based on the coplanar waveguide (CPW)-fed quasi-optical slot oscillators which has been investigated by Kormanyos [5], [6] and Moyer [7]. The uniplanar circuit requires no via holes and no backing ground plane and is compatible with the monolithic integration of high speed transistors. With the uniplanar approach, it is possible to put the InP oscillator on a high-resistivity silicon dielectric lens (silicon and InP have similar dielectric constants). The substrate lens simulates an infinite dielectric medium, eliminates power loss to substrate modes and makes the pattern nearly uni-directional [8]. Perhaps, the most important advantage of this approach is that the different designs at 150–550 GHz are independent of the substrate height and can all be integrated together on the same chip. This considerably reduces the fabrication time and cost per oscillator unit. The slot antenna impedance in this environment is accurately calculated using the space domain integral equation technique [9], and will not be discussed in this paper. Using this technique, we have succeeded in building 155- and 213-GHz oscillators while the maximum previously reported transistor oscillator performance has been limited to 131 GHz [10].

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II. Materials Development and Oscillator Fabrication

The epitaxial layers used in this work were grown in a Riber 2300 molecular-beam epitaxy (MBE) system, typically at a substrate temperature of 500°C, a growth rate of 600 nm/h, and a V/III beam equivalent pressure ratio of 40. Further details of these standard growth conditions can be found in [1]. Fig. 1 shows a diagram of the layer structure of the MBE material. The growth of the delta-doped, strained layer structures deviates from the standard conditions in several ways. The first is a reduction of the substrate temperature to 320°C, during and after the growth of the delta-doped layer in order to minimize the surface segregation of silicon atoms in AlInAs. By controlling the growth temperature in this fashion, we are able to improve the abruptness of the silicon profile and achieve an increase of approximately 20–30% in electron transfer efficiency [4]. The second modification is the use of a wider spacer thickness. In order to obtain a high mobility using delta doping, we increased the spacer thickness of the delta-doped structures from 2–6 nm. The last, but most important, is a lower substrate temperature during the growth of the pseudomorphic channel. We grew this layer at a substrate temperature of 440°C, as opposed to the standard 500°C, to prevent three-dimensional nucleation and misfit dislocation production. The resulting sheet charge and mobility were approximately $2.7 \times 10^{12}\mathrm{cm}^{-2}$ and $13000\ \mathrm{cm}^{2/v-s}$, respectively.

We employed a self-aligned-gate (SAG) process first proposed by Mishra *et al.* [12], which consists of five levels: 1) alignment marks, 2) device isolation, 3) T-shaped gate definition, recess, and metalization (Ti/Pt/Au), 4) ohmic definition, metalization (AuGe/Ni/Au) with the T-shaped gate serving as a shadow mask, and alloying, and finally, 5)

GaInAs: Si Cap	70 Å
AlInAs Schottky	200Å
AlInAs Spacer	60Å
GaInAs Channel 80Å 80% In 125Å lattice-matched	200Å
AlInAs/GaInAs superlattice	~400Å
AlInAs Buffer	2500Å
InP Substrate	

Fig. 1. Layer structure of the InP MBE material.

Fig. 2. Cross-section of 50-nm T-shaped gate.

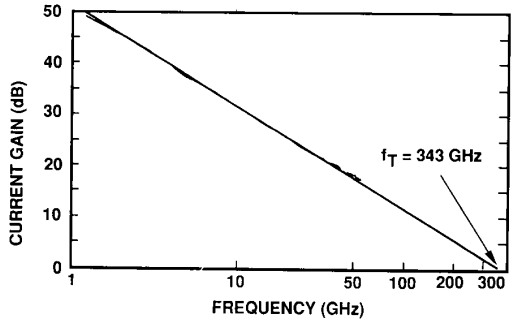

Fig. 3. HEMT short-circuit current gain versus frequency. The measurements are made to 50 GHz and extrapolated thereafter.

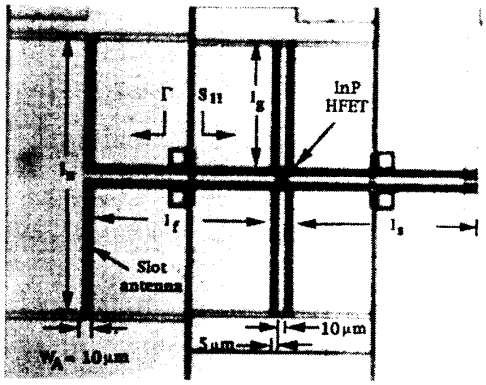

Fig. 4. The fabricated InP 155-GHz MMIC oscillator. The slot antenna is to the left. The dark areas outline the InP substrate.

overlay. We defined the sub-0.1-μm gates in a bi-layer of PMMA/P(MMA-MAA) electron-beam resist using a Phillips EBPG-4 electron-beam lithography system operating at 50-kV acceleration voltage. The resulting drain-to-source spacing is approximately 0.25 μm. Fig. 2 shows the cross-section of a 50-nm T-shaped gate after the deposition of the self-aligned ohmic metal. The addition of the ohmic metal reduces its resistance from approximately 1500–1000 Ω/mm, which is the lowest resistance ever reported for a 50-nm-long gate [4]. Typical peak extrinsic transconductance for the final wafer lot was approximately 1400 mS/mm for a 50-μm device measured after all the MMIC fabrication steps, with an associated *extrinsic* short-circuit current-gain extrapolated cutoff frequency, f_T, of approximately 340 GHz (Fig. 3). The extrapolated maximum oscillation frequency ($f_{\max}$) at -6 dB/octave for an *intrinsic* 50-μm device is 740 GHz.

The processing of the circuits begins with the ohmic contacts, other than the device ohmics, which are defined by lifting off AuGe-Ni-Au metallurgy. Second is the isolation implant, used to define the active area of the transistors, achieved by use of boron ions. Next is the self-aligned-gate (SAG) process, which is described above, followed by the device ohmic step, wherein the gate itself acts as a mask for the ohmic metal, also described in the previous section. Next is the perimeter etch, where we etch down to the InP substrate everywhere except in the device itself, to provide a very high resistance dielectric for the slot antenna and the cpw transmission line. DC biasing of the transistor is made possible by slits in the ground plane which isolate the gate, drain and source (see Fig. 4 for the completed MMIC oscillator). These slits are capacitively bypassed to create an uninterrupted ground plane for the RF circuit. Following that is the metal overlay, which defines the device electrodes, the transmission lines, slot antennas and the ground planes. Then, the capacitor dielectric layer is formed. The dielectric material is 0.22 μm of silicon monoxide (SiO). The post-metal fabrication step then defines the top plates and, hence, the size of the capacitors. Finally, the span metal step is used to fabricate the air-bridges from the capacitors as well as the plated metal on the transmission lines and ground plane.

III. Oscillator Design

The oscillator design follows the reflection amplifier approach presented in [12]. Computer optimization is applied at the source and gate terminals to maximize the reflection coefficient at the gate of the device which is connected to the slot antenna. The antenna impedance is used as a parameter in the oscillator design, and therefore the matching networks

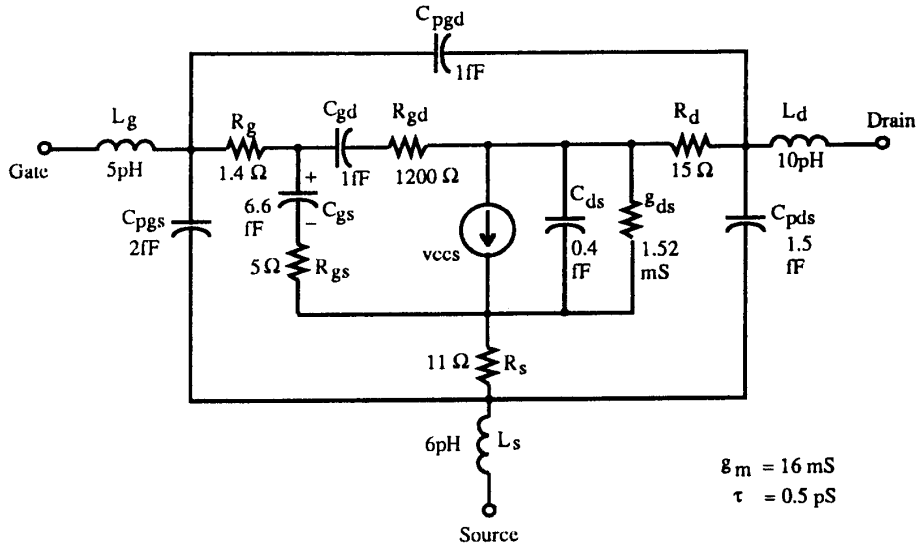

Fig. 5. Fitted small signal model for the scaled InP based HEMT with 0.05-μm gate length and 10-μm gate width (see text).

TABLE I
DESIGN PARAMETERS FOR THE TWO SUCCESSFUL MONOLITHIC MILLIMETER-WAVE OSCILLATORS. THE VALUES $L_g, \ldots$ ARE DEFINED IN FIG. 4

F* (GHz)	Lp,Cp**	g_m (mS)	l_s (μm)	l_g (μm)	l_f (μm)	l_a^{**} (μm)	$1/S_{11}$ (mag,ang)	Γ (mag,ang)
150	High	10	239	164.5	230.5	360	0.188, 164.4	0.595, 164
500	High	16	107	86.5	71	70	0.323, -147	0.897, -146.5

are minimized. This results in an oscillator circuit that is much smaller than a wavelength, typically 400 μm-square at 150 GHz and 100 μm-square at 500 GHz. All of the cpw lines in the oscillator design have a center conductor width of 10 μm and 5 μm gap giving an impedance of approximately 50 Ω and an effective dielectric constant of 6.7 on an InP substrate (calculated from a full-wave model). The loss in the cpw lines was taken into account in the design procedure and was estimated by extrapolating the data presented in [13]. A conservative value of 0.67 dB/mm at 60 GHz scaled with the square root of the frequency was used. The InP HEMT transistor has a 10 μm gate-width to result in favorable impedance levels at 150–500 GHz and to fit directly in the center conductor of the cpw line. This eliminates the need to model discontinuities in the cpw line at millimeter-wave frequencies.

Oscillator designs were carried out at frequencies from 150–550 GHz. To obtain a small signal model for the 10-μm transistor, a larger device with a 50 μm gatewidth was built and tested to 50 GHz (Fig. 3). The parasitics of the 50-μm device were stripped off and an intrinsic model was obtained for the 50-μm device. This intrinsic model was mathematically scaled to obtain the equivalent intrinsic model of the smaller 10-μm device (Fig. 5). The parasitic capacitances and inductances for the 10-μm model were determined using quasi-static techniques and the geometry of the 10μm device. Since this model was derived from measurements on a 50-μm device, a large uncertainty exists in the 10-μm device model parameters. The parasitic elements L_g, L_d, L_s, C_{pgs}, C_{pgd}, and C_{pds} associated with the extrinsic contact metalizations are known to about ± 4 pH or fF. Also, values of the intrinsic elements R_{gs}, C_{gs}, R_{gd}, C_{gd}, g_m, τ, C_{ds}, and g_{ds} are thought to be accurate to $\pm 20\%$. No independent confirmation of these estimates could be made since no S-parameter measurements were made on a 10 μm device.

We decided to "bracket" the oscillator designs. Due to the uncertainty existing in the device model, several designs were done at each frequency. The cases considered were with parasitics at their nominal values (Low) and at twice these values (High). The intrinsic transconductance was also taken to be either 16 mS (nominal) or 10 mS (low). This resulted in 16 different designs covering the range of 150–550 GHz. The idea behind the above choices is that the parasitics at 150 GHz and above will be higher than these predicted by 50-GHz measurements due to charge accumulation at the edges of the conductors. The low value of the intrinsic g_m of 10 mS was chosen because it fits the DC measurements closer than the small-signal 50-GHz extrapolated value of 16 mS.

IV. MILLIMETER-WAVE MEASUREMENTS

The InP chip containing all the oscillators from 150–550 GHz was positioned on a 2.54-cm-diameter elliptical silicon substrate lens for testing purposes and dc bias was applied to the oscillator-under-test using micropositioner dc probes. The

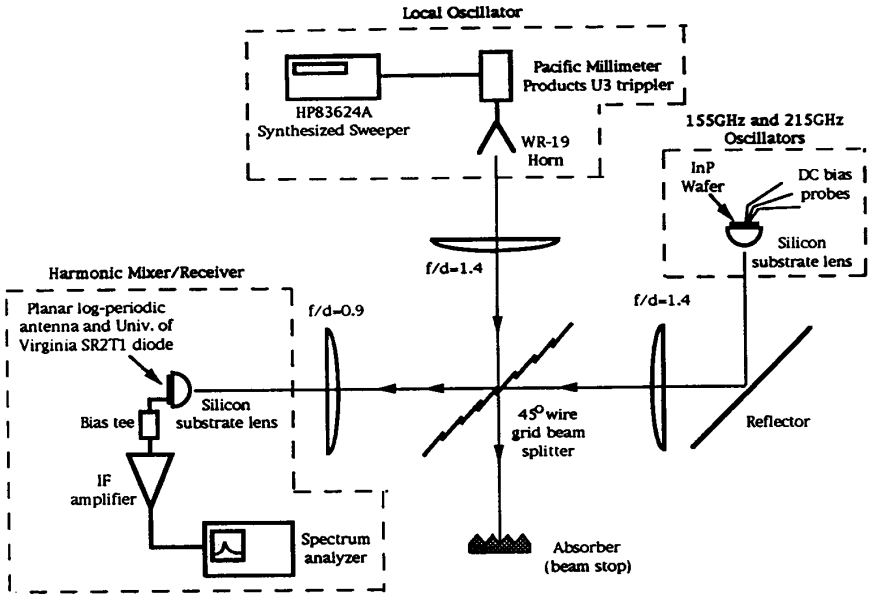

Fig. 6. Wideband quasi-optical harmonic mixer setup for accurate frequency determination and spectrum measurements.

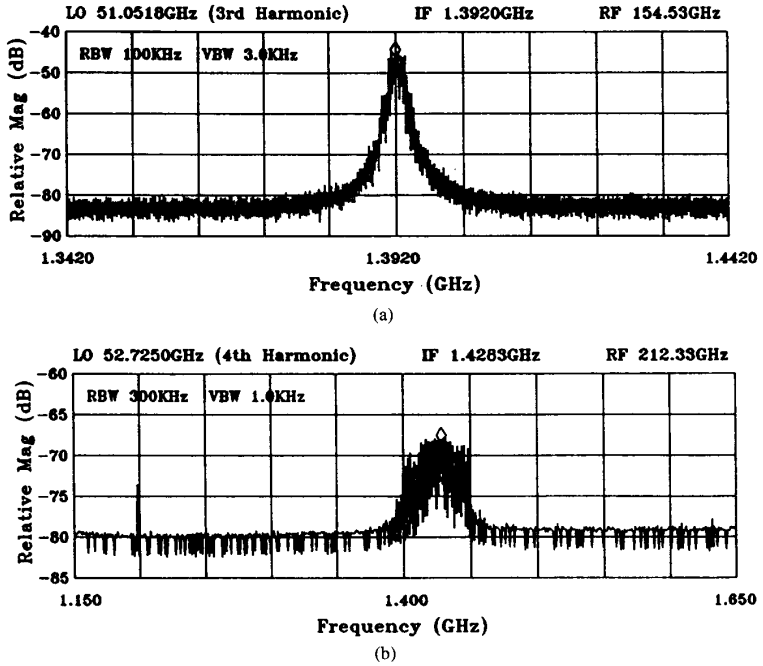

Fig. 7. Measured down converted spectrums of the (a) 155- and (b) 213-GHz oscillators.

millimeter-wave signal radiates from the lens to the quasi-optical measurement setup. There are no critical dimensions to control for the different test frequencies (oscillators) and this leads to a very simple test setup. Rough frequency measurements were obtained by aligning the silicon substrate in front of an InSb hot electron bolometer with an interferometer and mechanical chopper in the beam path. Two of the designs were found to oscillate with about 90% yield (Table I). The 150-GHz design case assuming high parasitics and 10 mS transconductance (150.H.10) oscillated near its design frequency generating an output signal at 155 GHz. The 500-GHz case assuming high parasitics and 16 mS transconductance (500.H.16) generated an output at an unexpected frequency near 213 GHz. The other 14 cases generated no output. This situation is not surprising considering the large uncertainty which exists in the 10-μm device model.

The oscillator frequencies were accurately measured and their spectrums were observed using a quasi-optical wideband harmonic mixer setup (Fig. 6). The harmonic mixer uses a back-to-back Schottky diode at the apex of a wideband log-periodic antenna. The antenna is placed is placed on a substrate lens to eliminate power loss to substrate modes. The harmonic mixer is pumped quasi-optically at 37–50 GHz (LO) thus resulting in a low conversion loss at 150–200 GHz (RF) [14]. A 45° beam splitter is used as a wideband diplexer for the LO an RF signal. The diplexer introduces a 3-dB loss in the LO and RF signal paths, but this is not detrimental for spectrum measurements. The measured down-converted spectrums of a 155- and a 213-GHz oscillator are shown in Fig. 7. The LO frequency was varied to observe both upper and lower sidebands and different IF frequencies were used to insure that the harmonic numbers and RF frequencies are correctly determined. To be certain that the observed signal corresponds to the fundamental oscillation frequency, the LO was adjusted to search for any signals at 1/2 and 1/3 of the oscillator frequency and no signals were observed.

The oscillator output power was estimated with a quasi-optical setup using calibrated waveguide diode detectors and a lock-in amplifier. The slot-oscillator power is determined from the amplitude of the received signal at the calibrated detector, the gain of the receiving horn antenna (23 dB), the directivity of the transmitting slot/lens antenna and by using the Friis transmission equation. The aperture efficiency of the slot oscillator on a substrate lens is 40%. This has been determined earlier from pattern measurements of a single slot antenna on a silicon substrate lens at 20 GHz [5] and includes the lens-air reflection loss of 1.9 dB. It is estimated that the maximum error in the power calculation is 25% with a 15% contribution from the calibrated waveguide detector and a ±10% contribution from the slot/lens antenna directivity. The total output power is found to be no less than 10-μW (±25%) for the 155-GHz oscillator and no less than 1 μW for the 213-GHz oscillator. The corresponding (minimum) dc to RF efficiencies are 0.13% at 155 GHz and 0.014% at 215 GHz. The 155-GHz power measurements are consistent with the fact that the transistor is very small with only a 10-μm gate width. The circuits were optimized for high loop gain and not maximum power, and there is a lot of uncertainty in the 10-μm device model. Also, the associated *extrinsic* short-circuit current-gain cutoff frequency (f_t) for a 10-μm transistor with high parasitics and low g_m is 135 GHz and the associated extrapolated maximum oscillation frequency ($f_{\max}$) is 400 GHz.

V. Conclusion

This paper presents the highest frequency achieved to-date for a InP millimeter-wave three-terminal device. Additional time spent on the modeling of these transistors could lead to better circuit designs that will enable this same technology to yield oscillators at 300 GHz and above. The inclusion of a cpw-fed planar slot antenna in the oscillator design enabled the fabrication of a large number of oscillators on a single InP chip and resulted in an easy system for testing purposes. A large number of these devices could be integrated together in quasi-optical power combining designs at millimeter wave frequencies to generate milliwatt power levels [15]. The successful development of these monolithic oscillators demonstrates the high frequency capabilities of the sub-micron gate InP based HEMT's which should also find applications as small signal millimeter-wave and submillimeter-wave amplifiers.

Acknowledgment

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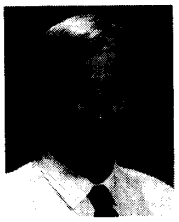

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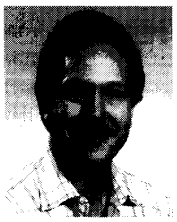

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Linda P. B. Katehi (S'81–M'84–SM'89), for a biography, see p. 83 of the January 1994 issue of this TRANSACTIONS.

Gabriel M. Rebeiz, (S'86–M'88–SM'93), for a biography, see page 545 of the April 1994 issue of this TRANSACTIONS.