Advanced mHEMT technologies for space applications

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***Abstract*—Heterodyne receivers operating at THz frequencies can detect rotation spectra of several spurious gases. These receivers typically use sub harmonic Schottky diode mixers, which need a low phase noise local oscillator (LO) input generated by frequency multiplication and amplification. THz radiometry requires broadband receivers with low noise temperatures which are necessary for high temperature resolutions. All these systems benefit from low-noise transistors working at millimeter-wave (MMW) frequencies.**

***Index Terms*—mHEMT, MMIC, sub-millimeter-wave, frequency multiplier, low-noise amplifier (LNA), mixer, voltage controlled oscillator (VCO)**

I. Introduction

The frequency range above 300 GHz is of growing interest for space applications. Many spectroscopic signatures of tri atomic molecules and other substances are present at sub-millimeter-waves (SMW). This offers the possibility to remotely analyze the atmosphere and surface composition of planets or their moons. Up to now, this frequency regime can be handled only by sub harmonic Schottky diode based mixers, but as demonstrated in this paper, metamorphic high electron mobility transistor (mHEMT) technology is becoming available. However, heterodyne systems at least need an LO signal with sufficient power, as there is a high conversion loss of passive frequency multiplication by hetero barrier varactors (HBVs) or Schottky-diodes. For high spectroscopic resolution a low phase noise sub harmonic LO-signal has to be generated, multiplied and amplified. These components operate at the millimeter wave range, and can be cost efficiently fabricated by mHEMT technology on GaAs wafers. Some MMIC components that have been already realized are presented at this paper.

II. Metamorphic HEMT Technology

The use of In-rich InGaAs channels in HEMTs has resulted in SMW amplifiers at 300 GHz and above [1], [2] which had been the domain of Schottky diodes just some years ago. Also HBTs have been used to cover this frequency range [3]. HEMTs can be grown pseudomorphically on InP or metamorphically on GaAs with comparable results. Metamorphic means, that the lattice constant of the GaAs substrate is changed by a quaternary buffer to a value needed by the active device on top. The generated dislocations do not degrade the electron transport mechanism in the field effect transistors. InP substrates have a better thermal conductivity but GaAs is more robust, cheaper and thus MMICs can be fabricated on larger wafers. At IAF, we have developed a mHEMT technology suitable for monolithic SMW integrated circuits (S-MMICs). As shown in Fig. 1, the e-beam defined T-shaped gate, which is defined by a four layer PMMA resist, has a length down to 35 nm.

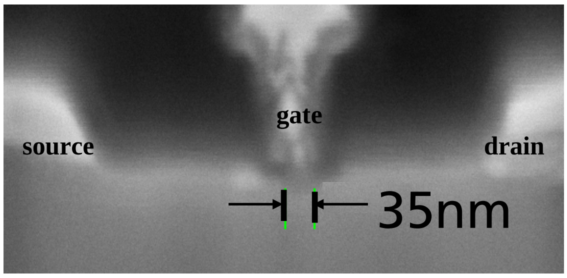

Fig. 1. Scanning electron microscopy of a 35 nm mHEMT cross-section.

The metamorphic HEMTs structure is grown by MBE on 4-inch GaAs wafers and has an $In_{0.80}Ga_{0.20}As$ channel with $In_{0.52}Al_{0.48}As$ barriers.

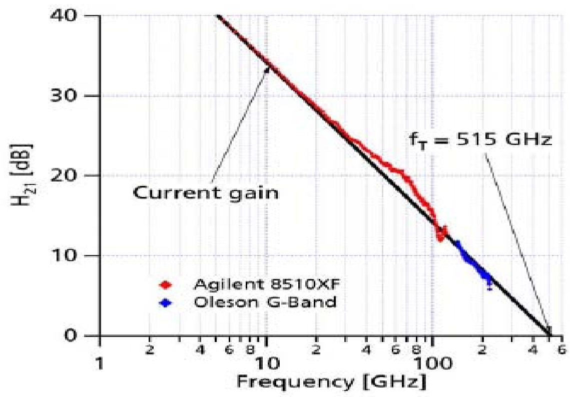

Fig. 2. Measured current gain of the 35nm mHEMT and extrapolated transit frequency.

The gate recess is carried out by selective wet chemical etching, and the device isolation by mesa etching. Source and drain contact resistances are as low as 0.03 Ω·mm. The gate to drain and drain to source breakdown voltages are 2.0 V and 1.5 V, respectively. The peek transconductance at a gate

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voltage of +0.2 V was measured to be 2500 mS/mm, and the maximum drain current is 1600 mA/mm. As shown in Fig. 2, the current gain cutoff frequency f_T is extrapolated above 500 GHz. Details of the 35 nm mHEMTs have already been published by Leuther et al. [4]. A comparison of mHEMT devices with different gate length is shown in Tab. I.

TABLE I Electrical DC- and RF-Parameters of the IAF Metamorphic HEMT Technologies

	l_g = 100 nm	l_g = 50 nm	l_g = 35 nm
R_c	0.07 Ω·mm	0.05 Ω·mm	0.03 Ω·mm
R_s	0.23 Ω·mm	0.15 Ω·mm	0.1 Ω·mm
$I_{D, max}$	900 mA/mm	1200 mA/mm	1600 mA/mm
V_{th}	-0.3 V	-0.25 V	-0.3 V
$BV_{off\text{-}state}$	4.0 V	2.2 V	2.0 V
$BV_{on\text{-}state}$	3.0 V	1.6 V	1.5 V
$g_{m, max}$	1300 mS/mm	1800 mS/mm	2500 mS/mm
f_T	220 GHz	380 GHz	515 GHz
f_{max}	300 GHz	500 GHz	> 700 GHz
MTTF	3×10^7 h	2.7×10^6 h	n.a.

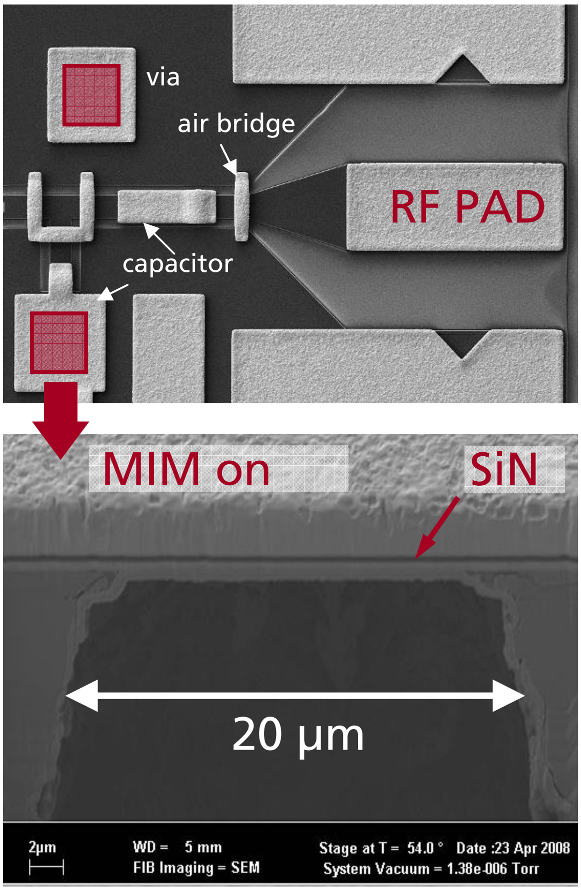

Fig. 3. Photo of a mHEMT MMIC. The top photo shows an output port with 14 µm ground to ground coplanar waveguides. The bottom photo shows a cross-section of an MIM capacitor on a 20 µm via hole.

We use grounded coplanar waveguides (GCPW) with different impedances from 30 to 70 Ohm on backside metalized 50 µm thinned wafers. A design library of passive and active devices has been implemented in Agilents ADS consisting of waveguides, MIM-capacitors, resistors, inductors, Schottky diodes and mHEMT devices. Details of an MMIC are shown in Fig. 3.

III. Integrated Circuits

Several MMICs have been realized using the above mentioned mHEMT technology. Depending on the MMIC frequency range, mHEMTs with 100 nm, 50 nm, or 35 nm gate length and grounded coplanar waveguides with ground to ground spacings of 14 µm or 50 µm have been used. All passive and active devices have been characterized up to H-band and a library of components like grounded coplanar waveguides, capacitors, T- and X-junctions, via holes, and RF pads were implemented in Agilents ADS, to build up IAFs circuit design library. Special care was carried out for the active devices models as published by Seelmann-Eggebert et al. [5].

Using 35 nm mHEMT devices, an H-band two-stage amplifier S-MMIC was designed to achieve broadband gain characteristic in combination with low noise figure. Fig. 4. shows the schematic cascode configuration of one utilized stage and Fig. 5 shows the chip photo of the realized circuit. Transistors with 2 x 10 µm gate width have been used for the compact coplanar layout. The on-wafer measured S-parameters of the amplifier are shown in Fig. 6, and a summary of the device performance is given in Tab. II. Further details of the circuit are published by Tessmann et al. [6].

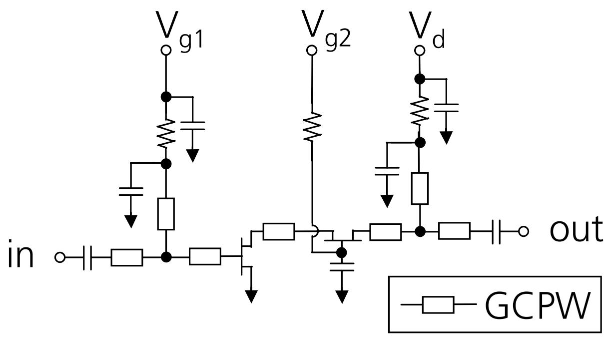

Fig. 4. Schematic circuit of one stage of the cascode amplifier.

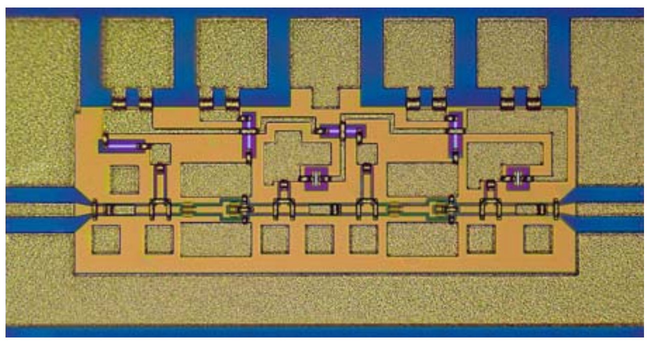

Fig. 5. Chip photo of the two-stage H-band cascode amplifier in 35 nm mHEMT technology.

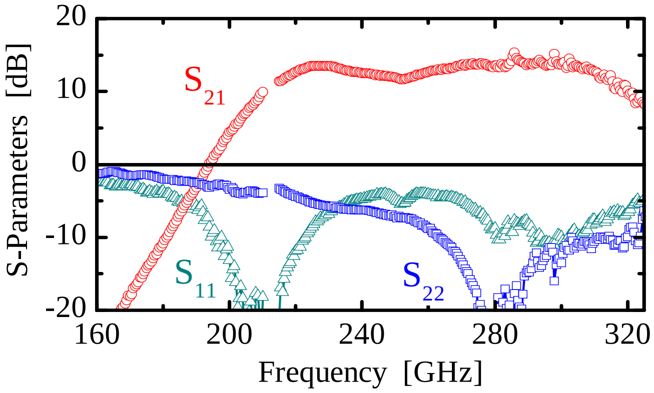

Fig. 6. On-wafer measured S-parameters of the two-stage H-band cascode amplifier S-MMIC from 160 to 325 GHz.

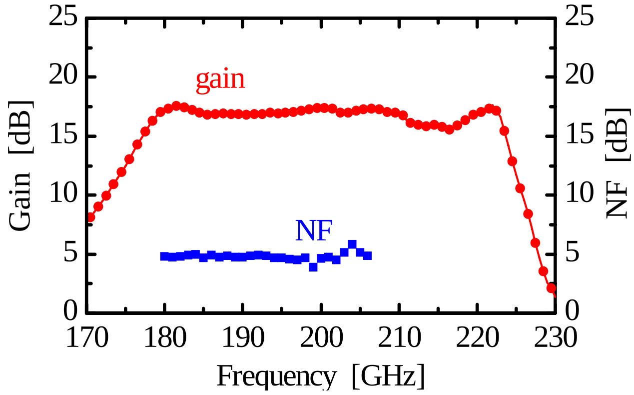

Fig. 8. On-wafer measured gain and noise figure (NF) of the four-stage 210 GHz low-noise amplifier MMIC.

TABLE II AMPLIFIER PERFORMANCE

Bandwidth	220 … 320 GHz
Gain	13 dB
Input return loss @ 300 GHz	< -10 dB
Output return loss @ 300 GHz	< - 10 dB
Chip size	0.43 × 0.82 mm²

Furthermore an G-band four-stage low-noise amplifier MMIC was designed in 50 nm mHEMT technology with high gain at 210 GHz. A chip photograph of the realized four-stage low-noise amplifier MMIC is shown in Fig. 7. To achieve reasonable gain up to 220 GHz, the gate width of the common-source devices was chosen to be 2 × 10 µm.

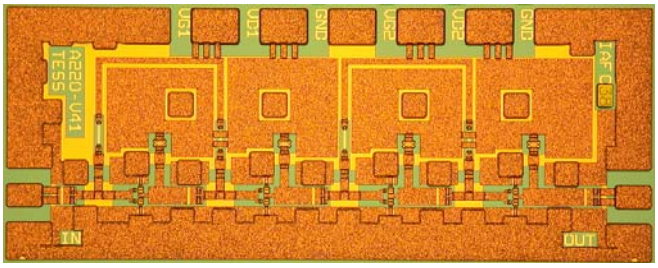

Fig. 7. Chip photograph of the four-stage 210 GHz low-noise amplifier MMIC fabricated in 50 nm mHEMT technology. The chip size is 0.65 × 1.5 mm².

The on-wafer measured small-signal gain of the MMIC is shown in Fig. 8. The LNA circuit achieved a linear gain of more than 16 dB. Furthermore, noise figure measurements were performed at room temperature (T = 293 K) from 180 to 206 GHz. The measured average noise figure of the low-noise amplifier was only 4.8 dB over the characterized frequency range. Details of the circuit are published by Tessmann et al. in [7].

Schottky diode detectors have been integrated for the mHEMT process using broadband impedance matching [8]. The diodes use the Schottky contact and epi-layers of the mHEMT which is not ideal for detectors, but enables easy integration. Different diode layouts have been analysed. Fig. 9 shows the voltage response at 135 GHz for a detector with shorted source and drain of a 100 nm mHEMT with 12.5 µm gate width as well as a design with 1.25 µm² square shaped diodes. The lower response of the mHEMT diode is due to higher ratio of edge length to contact area which degrades the n-factor. These detectors can be integrated with LNAs enabling single chip direct detection radiometer MMICs and are working at zero bias.

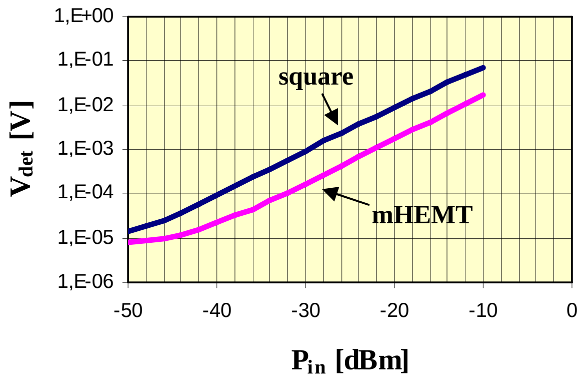

Fig. 9. Detector voltage response versus input power at 135 GHz for a 100 nm mHEMT with shorted source and drain and 12.5 µm gate width, in comparison to a design with 1.25 µm² square shape at zero bias.

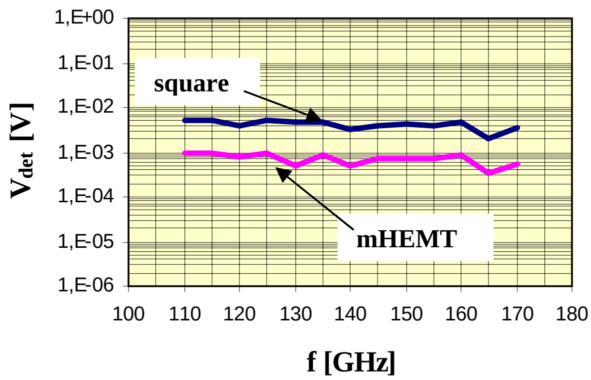

Fig. 10. Detector voltage response at an input power of -23 dBm versus frequency for a 100 nm mHEMT with shorted source and drain with 12.5 µm gate width, and a design with 1.25 µm² square shape diodes at zero bias.

Fig. 10 shows the broadband response of the detector circuit covering the complete D-band from 110 to 170 GHz. Again mHEMT and square layout of the Schottky diodes are compared, demonstrating the advantage of the square layout with a sensitivity of 1000 V/W at zero bias.

Using 100 nm mHEMT technology we demonstrate an active, sub harmonic down-conversion mixer operating beyond 200 GHz. Besides a lower conversion loss, the advantages of active FET mixers over conventional diode mixers include a potentially lower noise figure, lower local oscillator (LO) power requirements, and most important, the on-chip integration with other circuit components like LNAs to form multi-functional single-chip receivers. Fig. 11 shows the chip photograph of the realized G-band dual-gate FET mixer MMIC. Its total chip size is 1 × 1.5 mm². Details of the mixer are published by Kallfass et al. [9]. The mixer's conversion gain characteristic was evaluated on-wafer.

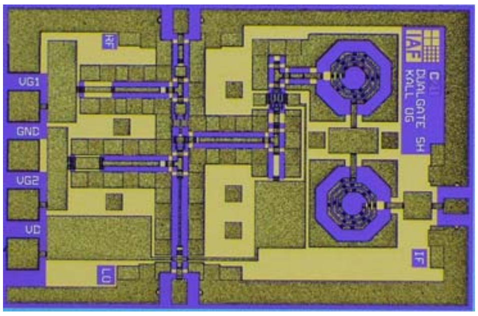

Fig. 11. Chip photograph of the sub harmonic dual-gate FET mixer. The chip size is 1.0 × 1.5 mm².

Fig. 12 shows the measured and simulated conversion gain performance of the subharmonic dual-gate mixer MMIC. The mixer was driven with 10 dBm LO power and the IF was measured at 400 MHz. The mixer MMIC achieved a maximum conversion gain of -4.7 dB at 214 GHz. Over the full measured bandwidth of 165 to 220 GHz, the conversion gain stayed above –10 dB. In-house nonlinear FET models were employed to predict the frequency translating effect.

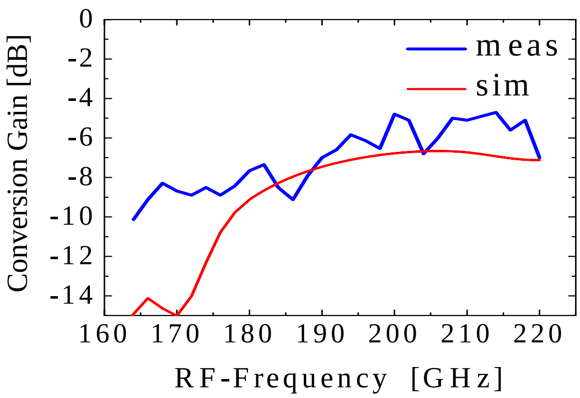

Fig. 12. Measured and simulated conversion gain versus RF frequency of the subharmonic dual-gate FET mixer MMIC at 10 dBm LO-power.

Fig. 13 shows the chip photograph of a sixtupler MMIC in 100 nm mHEMT technology. An active single-ended-to-differential-converter stage is followed by a balanced tripler and a doubler stage. With the balanced multiplier concept, broadband six-fold frequency multiplication from Ku-band into W-band could be demonstrated, overcoming the bandwidth limitations of conventional single-ended multiplier chains. The circuit employs an innovative cascode topology in its doubler stage. The realized sixtupler MMIC shows more than 7 dBm output power and over 6 dB conversion gain within a bandwidth of 78 to 104 GHz. This design enables broadband system designs and provides monolithic integration for broadband power measurement setups at W-band. Fig. 14 shows the output power versus frequency of the sixtupler. Details of the sixtupler are published by Kallfass et al. [10].

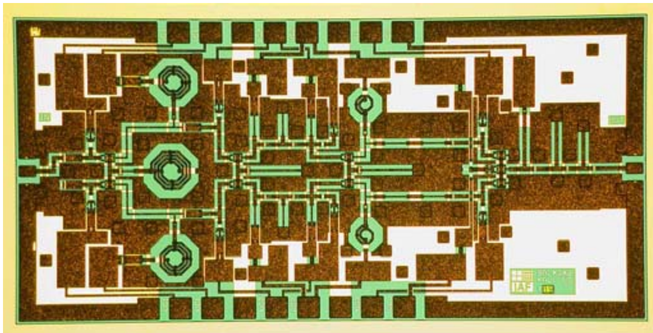

Fig. 13. Chip photograph of the sixtupler MMIC realized in metamorphic HEMT technology with a chip size of 3 x 1.5 mm².

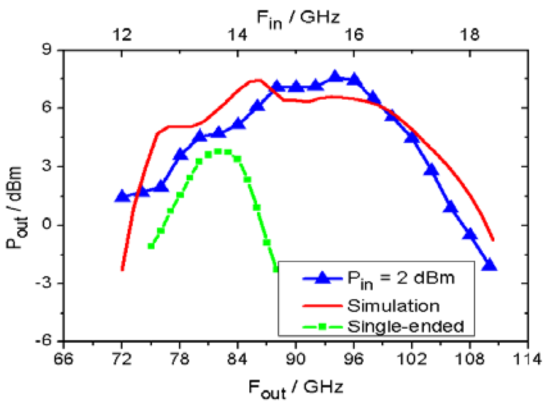

Fig. 14. Output power versus frequency of the sixtupler MMIC.

Using 100 nm mHEMT technology, a PLL-based stabilization technique for monolithic integrated W-band voltage controlled oscillators (VCOs) was demonstrated. A 92 GHz push-push oscillator in coplanar waveguide technology and a frequency divider-by-eight were developed and integrated on a single MMIC. Fig. 15 shows the chip photograph of the push-push VCO with divider.

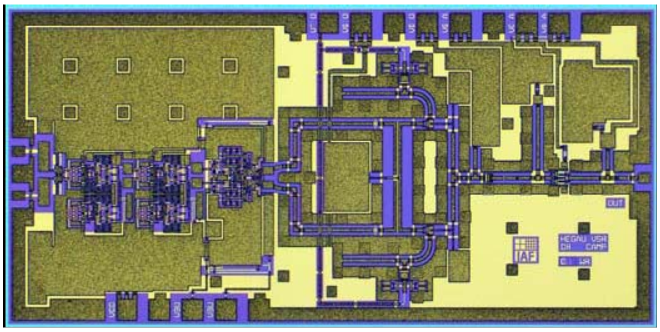

Fig. 15. Chip photograph of the VCO MMIC (chip size: 3.0 x 1.5 mm²).

The oscillator achieves a tuning range of 3.4 GHz around the center frequency of 92 GHz and an output power of more than 5.5 dBm. By applying this concept, the VCO was synchronized to a low frequency reference signal at 180 MHz using a commercially available PLL circuit. Compared to the free running oscillator, the phase-noise was improved by 24 dB to -77 dBc/Hz at 100 kHz offset from the carrier. Fig. 16 shows the measurement results. Details of the oscillator are published by Weber et al. [11].

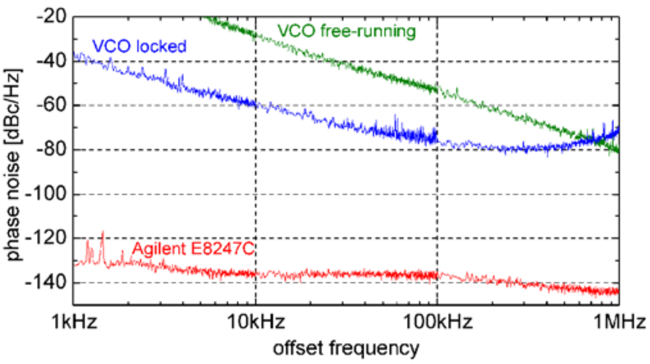

Fig. 16. Measured phase noise of the free-running and locked VCO at 92.16 GHz and the reference signal at 180 MHz.

IV. Conclusion

Metamorphic HEMT technology has been demonstrated to be highly suitable for the development of advanced millimeter-wave and sub-millimeter wave circuits for space applications. Sub-millimeter and millimeter wave amplifier circuits have been demonstrated with mHEMT devices of 35 nm and 50 nm gate length. Devices with 100 nm gate length were used for a mixer, a sixtupler and a PLL based VCO design operating at W-, D-, and G-band. The possible monolithic integration of special Schottky diode detectors with this technology was also presented.

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