Wide-Band Millimeter Wave Characterization of Sub-0.2 Micrometer Gate-Length AlInAs/GaInAs HEMT's

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Abstract—**The S parameters of an AlInAs/GaInAs high electron mobility transistor (HEMT) were measured using a picosecond optoelectronic system over a bandwidth of 100 GHz. These picosecond optoelectronic measurements were validated by comparing low frequency measurements to those obtained using on wafer RF probes/vector network analyzer, and *W*-band results to measurements done using a waveguide-to-microstrip transition/vector network analyzer frequency extender. This is the widest bandwidth of measured S parameters reported on a single transistor.**

I. Introduction

HIGH electron mobility transistors (HEMT's) are increasingly replacing GaAs MESFET's in microwave and millimeter wave circuits [1, 2]. Their higher cutoff frequencies combined with lower noise make them more attractive in applications such as millimeter wave low-noise amplifiers [3] and mixers [4]. In particular $Al_{0.48}In_{0.52}As/Ga_{0.47}In_{0.53}As$ HEMT's have demonstrated superior performance over HEMTs made from other material systems [5, 6]. However, these transistors have cutoff frequencies well beyond the bandwidth that can be measured conveniently using conventional network analyzers. As a result only a small amount of data exists describing the performance of HEMT's in the W band. By using external mixers the present bandwidth of network analyzers has been extended to about 100 GHz. But several difficulties arise in characterization of devices in the millimeter wave region. At high frequencies the transistors have to be mounted in test fixtures with waveguide-to-microstrip transitions. It is difficult to design wide bandwidth waveguide-to-microstrip transitions that have low insertion and return loss. The actual S parameters of the transistor have to be de-embedded from the test fixture and using transitions having a high insertion/return loss can cause erroneous results.

In order to improve and optimize performance of millimeter wave transistors it is important to have a simple technique for direct characterization of devices at very high frequencies. Using picosecond optoelectronic techniques ultrafast electrical pulses can be generated and sampled [7]–[9]. These electrical pulses can be used to test the response of high speed semiconductor devices [10] and integrated circuits [11] over a wide bandwidth. Using photoconductive switches, picosecond electrical pulses can be generated and sampled at a very short distance from a device. Therefore, the high frequency signals do not have to travel through long sections of transmission lines and waveguide transitions, making this technique superior to conventional network analyzers. In this study S parameters of $Al_{0.48}In_{0.52}As/Ga_{0.47}In_{0.53}As$ HEMTs were measured using picosecond optoelectronic techniques over a 100-GHz bandwidth. To validate the optoelectronic measurements the S parameters were also measured using on wafer RF probes/network analyzer (over the frequency range of 1-26 GHz) and a network analyzer frequency extender (over the frequency range of 75–100 GHz).

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II. Measurements

The cross section of the $Al_{0.48}In_{0.52}As/Ga_{0.47}In_{0.53}As$ HEMT is shown in Fig. 1. The gate-length of the transistor is less than 0.2 μm with a gate-width of 50 μm. The maximum transconductance of the device is greater than 1000 ms/mm. For the optoelectronic measurements the AlInAs/GaInAs HEMT was mounted in a test fixture as shown in Fig. 2. The microstrip lines were fabricated using Cr/Au on silicon-on-sapphire (SOS) substrates. The sapphire substrates were about 125 μm thick and the microstrip lines were designed to have a 50 Ω impedance. The silicon epi-layer was about 0.5 μm thick and was heavily implanted with silicon ions to shorten the carrier lifetime.

On each side of the HEMT there are two photoconductive switches that consist of 25 μm gaps in the side microstrip lines. By applying a DC bias to a photoconductive switch and focusing a picosecond laser beam on the gap, fast electrical pulses are generated that propagate on the center transmission line. A second photoconductive switch is used for sampling of the electrical pulses. The details of the measurements are described elsewhere [12].

Depending on which one of the four optical switches is used as the generator and which one as the sampler the HEMT can be characterized completely in the time-domain. By taking the Fourier transform of the reflected and transmitted signals and normalizing it to the Fourier transform of the appropriate input signal the S parameters of the device can be determined [10].

III. Results

Using the picosecond optoelectronic system the time-domain response of the HEMT was measured and the S parameters of the HEMT were determined over a bandwidth of 100 GHz. This is the widest bandwidth of S parameters measured on a single transistor. To validate these measurements the S parameters of similar HEMTs were measured using a wafer RF probe and a conventional network analyzer (HP8510) over the frequency of

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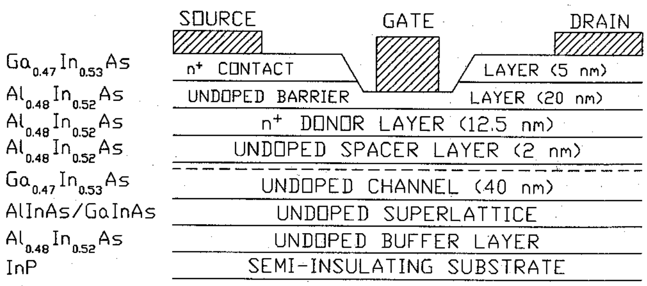


Fig. 1. Cross section of $Al_{0.48}In_{0.52}As/Ga_{0.47}In_{0.53}As$ HEMT.

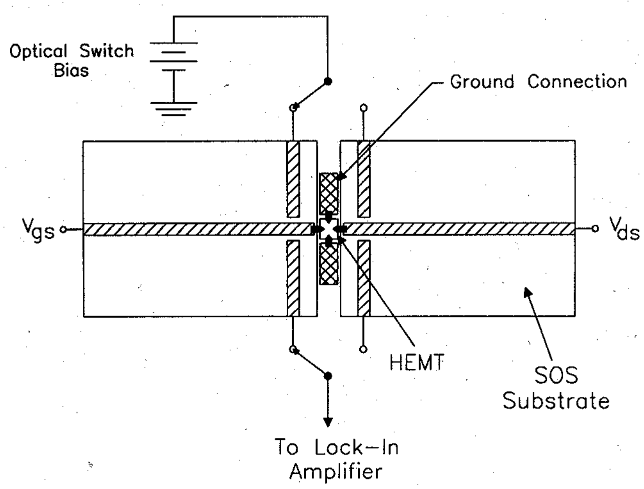


Fig. 2. Picosecond optoelectronic test fixture with HEMT wire-bonded to center microstrip lines.

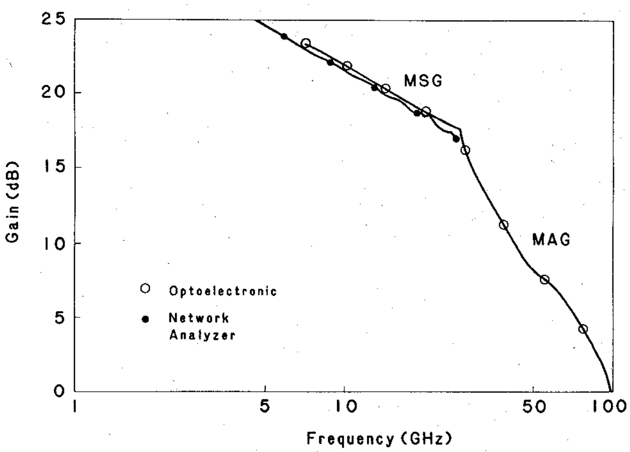
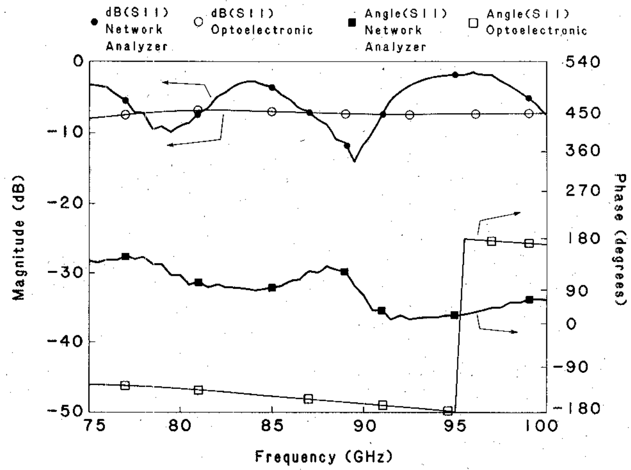


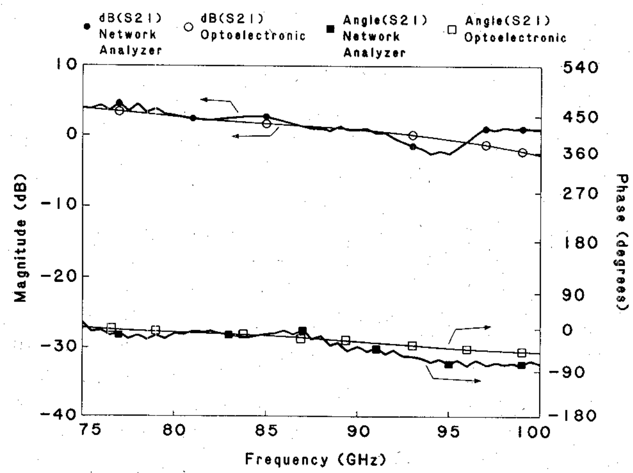
Fig. 3. Maximum available gain (MAG)/maximum stable gain (MSG) versus frequency of AlInAs/GaInAs HEMT calculated from measured S parameters by optoelectronic system (○), and from network analyzer measurements using on wafer RF probes (●).

1–26 GHz. From the measured S parameters the maximum available gain (MAG) of the device was calculated. The plot of MAG versus frequency (maximum stable gain (MSG) for conditionally stable case) for both the optoelectronic measurements and network analyzer measurements are shown in Fig. 3. Very good agreement can be seen between both techniques over the range of frequency overlap.

It is also important to find the accuracy of the optoelectronic measurements at millimeter wave frequencies. For this purpose an AlInAs/GaInAs HEMT was tested using a W-band (75–100 GHz) network analyzer frequency extender. The device was



(a)



(b)

Fig. 4. Magnitude and phase versus frequency over frequency range of 75–100 GHz for optically measured S parameters and measurements by network analyzer frequency extender (a) S_{11}, (b) S_{21}.

mounted in a W-band ridged waveguide-to-microstrip transition which consists of a Chebyshev stepped impedance transformer between the WR-10 waveguide and the 50 Ω microstrip transmission line [13]. This type of transition was chosen for its broadband characteristics with a center frequency of 90 GHz and a passband from 70–110 GHz. The microstrip transmission lines were fabricated on 0.005 in. fused silica. The return loss of the fixture was measured to be more than 5 dB and the insertion was less than 5 dB across the band. The measured data was de-embedded from the fixture response using a two tiered technique [13].

Figs. 4(a) and 4(b) show comparison between S_{11} and S_{21} measured by the optoelectronic system and network analyzer frequency extender over the range of 75–100 GHz. Measurement of the W band test fixture revealed a distinct resonant waveguide mode propagating from input to output in addition to the microstrip transmission line. This resonance has a tendency to mask the performance of the device under test to some degree. Measurements of S_{11} and S_{22} are affected most by the resonance; S_{21} and S_{12} are impacted to a lesser degree. The effect of this resonance on the transistor data may be seen as a distinct ripple in the magnitudes of S parameters. From Fig. 4(b) the agreement between S_{21} measurements using the two techniques is quite good. Due to the ripples in network analyzer measurements S_{11} results have discrepancies. Both the network analyzer and the picosecond optoelectronic measurements show the effects of source inductance due to the bond wires. This will be discussed in connection with the equivalent circuit model and high frequency performance elsewhere [14].

IV. Conclusion

S parameters of an AlInAs/GaInAs HEMT was measured using picosecond optoelectronic techniques over a bandwidth of 100 GHz. The results show good qualitative agreement with measurements of a similar HEMT using on-wafer RF probes and a conventional vector network analyzer over the bandwidth of the network analyzer (26 GHz). Comparison with measurements by a W-band network analyzer showed excellent agreement for S_{21} and S_{12} but there were limited by de-embedding in the case of S_{11} and S_{22}. This study demonstrates the advantages of wide bandwidth characterization of high frequency transistors using picosecond optoelectronic techniques.

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