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MICROWAVE PERFORMANCE OF AN OPTICALLY CONTROLLED AlGaAs/GaAs HIGH ELECTRON MOBILITY TRANSISTOR AND GaAs MESFET

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Abstract

Direct current and also the microwave characteristics of optically illuminated AlGaAs/GaAs HEMT are experimentally measured for the first time and compared with that of GaAs MESFET. The results showed that the average increase in the gain is 2.8 dB under 1.7 mW/cm^2 optical intensity at 0.83 μm. Further, the effect of illumination on S-parameters is more pronounced when the devices are biased close to pinch-off. Novel applications of optically illuminated HEMT as a variable gain amplifier, high-speed high-frequency photo detector, and mixer are demonstrated.

Introduction

Use of direct optical control of microwave semiconductor devices for optical injection locking, phase shifting, and signal distribution has the potential to enhance the performance of future space borne phased array antenna systems.[1,2] Previously, several authors have experimentally investigated the effect of light on the dc as well as the microwave characteristics of IMPATT diodes and GaAs MESFETs.[3-6] Their investigations show that these changes in the characteristics are due to photoconductivity and photovoltaic effects. Further, an analytical study, by the authors taking into consideration material properties of hetrostructures showed that the hetrostructures have a higher sensitivity to optical illumination. When this investigation was extended to microwave device structures, it was observed that the dc characteristics of an AlGaAs/GaAs High Electron Mobility Transistor (HEMT), when compared to that of a GaAs MESFET, are more sensitive to optical illumination greater than the semiconductor band gap.[7]

In this paper, we present for the first time extensive experimental results which show the sensitivity to optical illumination, that is, the light induced voltage and as a consequence the changes in the drain to source current, the intrinsic transconductance, the scattering parameters, and the gain of an AlGaAs/GaAs HEMT. Further, fromthe de-embedded HEMT scattering parameters, the changes in the equivalent circuit element values due to optical illumination are also computed. In order, to compare and contrast the performance of a HEMT with a MESFET, experiments are also carried out on two different GaAs MESFETs and these results are also presented here. Finally, three novel applications of optically illuminated HEMT as a variable gain amplifier, high-speed high-frequency photo detector, and mixer are demonstrated.

Experimental Setup

A low noise AlGaAs/GaAs High Electron Mobility Transistor (MPD-H503, Gould Inc.) with recessed Pi-gate of length 0.5 μm and width 280 μm,[8] a low noise, low power GaAs MESFET (DXL 0503A, Gould Inc.) with recessed Pi-gate of length 0.3 μm and width 280 μm, and a medium power GaAs MESFET (RPX 2322, Raytheon Co.) with T-gate of length of 0.5 μm and width 500 μm are used for investigation. For optical illumination an AlGaAs/GaAs Laser diode (SL-620 S, Ortel Corp.) with a fiber pigtail, which operates at a wavelength of 0.83 μm and has a direct modulation bandwidth of 6 GHz is used. The optical power emitted from the 50 μm multimode graded index optical fiber pigtail as measured using a calibrated digital power meter and a photosensor (815, Newport Corp.) is 1.7 mW/cm^2. The tip of the fiber is held at a distance of 1 mm from the device.

These devices are mounted on a 0.375 by 0.375 in., 25 mil thick alumina carrier. The alumina carrier also accommodates a pair of 50 Ω coplanar waveguides (CPW) which serve as the signal input and also output ports. The device gate and drain pads and the source pad are wire bonded to the CPW center strip conductors and the ground plane respectively. The carrier is then mounted in a test fixture (Design Techniques, Inc.) which has two 3.5 mm coaxial connectors for external connection. The test fixture also has provision for ensuring repeatable pressure contact between the terminals of the CPWs on the carrier and the two 3.5 mm coaxial connectors on the fixture. A CPW calibration kit consisting of a 50 Ω through, two short circuits, and an open circuit on similar alumina carriers are used for calibrating the HP8510 automatic network analyzer and de-embedding

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the device S-parameters. A block schematic of the entire experimental setup is shown in Fig. 1.

dc Device Characteristics Under Illumination

Light Induced Voltage

The light generated voltage V_{lit} is obtained by plotting the measured gate current I_g as a function of the reverse biased gate to source voltage V_{gs}, and extrapolating the graph till it intersects the X-axis. The intersection point is read as the light generated voltage, which from Fig. 2(a) and (b) for a AlGaAs/GaAs HEMT and a GaAs MESFET are 0.57 and 0.24 V respectively.

Drain to Source Current, Transconductance, and Gain

The measured drain to source current I_{ds} as a function of the drain to source voltage V_{ds} with and without optical illumination for an AlGaAs/GaAs HEMT and a GaAs MESFET are presented in Fig. 3(a) and (b) respectively.

Figure 4 presents the measured dc transconductance g_m for a GaAs MESFET. The g_m is considered almost insensitive to optical illumination since the maximum change observed is less than 2 mmhos.

The measured gain with and without optical illumination as a function of V_{gs} for an AlGaAs/GaAs HEMT and a GaAs MESFET are presented in Fig. 5(a) and (b) respectively. As an example, for the case of a AlGaAs/GaAs HEMT, the gain increases by 2.5 dB at $V_{gs} = -0.95$ V and frequency equal to 26.5 GHz when the illumination is 1.7 mW/cm^2.

Microwave Characteristics Under Illumination

The S-parameters, namely S_{11}, S_{22}, and S_{12} are measured as a function of the frequency and illumination (1.7 mW/cm^2) with the devices biased close to saturation and also pinch-off. These bias points or operating points are labeled as points A and B respectively in Fig. 5(a) for the AlGaAs/GaAs HEMT and Fig. 5(b) for the GaAs MESFET.

The measured S_{11} over the frequency range 0.045 to 26.5 GHz for AlGaAs/GaAs HEMT in pinch-off ($V_{gs} = -0.95$ V) condition is illustrated on a Smith Chart plot in Fig. 6(a). Similarly, S_{22} is illustrated in Fig. 6(b). Figure 6(c) illustrates S_{12} on a linear magnitude polar plot. In these figures L and D denotes that the measurements are carried out with or without illumination. A similar set of measurements have also been carried out for GaAs MESFET.

Thus from Fig. 6 it is observed that illumination does affect S_{11}, S_{22}, and S_{12}. Besides, this effect is more pronounced when the devices are biased close to pinch-off.

Using the CPW calibration kit and the through, short, delay (TSD) technique the influence of the small length of coplanar waveguide on either sides of the chip devices and the test fixture coaxial connectors are effectively removed. The small signal device equivalent circuit element values are next obtained from the de-embeddded device S-parameters using the models in Refs. 9 and 10. As an example, Fig. 7 shows an increase in the gate and the source capacitances and a decrease in the gate to drain feedback capacitance, with optical illumination. In addition, the model also shows that the gate charging resistance R_1 and the channel resistance R_0 both decrease with optical illumination. The effect of these on the f_t, f_{max}, and noise figure are being further investigated.

Optically Controlled HEMT as a Variable Gain Amplifier

The feasibility of using an AlGaAs/GaAs HEMT as an optically controlled variable gain amplifier is clearly evident from the measured S_{21} magnitude and phase characteristics shown in Figs. 8(a) to (d). Figure 8(a) and (b) when compared, show that the gain increases with illumination. Further it is interesting to observe that the phase of S_{21} is insensitive to optical illumination as evident from Figs. 8(c) and (d).

High Frequency HEMT Photodetector

An experiment was conducted by illuminating the HEMT device with an optical signal which had been modulated with a 6 GHz RF signal and observing the output on a spectrum analyzer, which is shown in Fig. 9(a).

HEMT Oscillator and HEMT Mixer with Optically Coupled LO

The capacitance variation of HEMT with illumination is shown in Fig. 7. This can be successfully exploited in the design of an injection locked oscillator.

Preliminary experiments with a HEMT as a mixer show that it is possible to optically couple the local oscillator signal. This is achieved by directly modulating a laser diode at the local oscillator frequency (6 GHz). The laser diode output is then made to illuminate the gate region of the HEMT. The RF signal (9 GHz) is electrically coupled to the gate terminal. The resulting IF signal (3 GHz) as seen on a spectrum analyzer is shown in Fig. 9(b).

Conclusions

The paper presents for the first time extensive experimental results which show the sensitivity to optical illumination. The light induced voltage and as a consequence the changes in, the drain to source current, the intrinsic transconductance, the scattering parameters, and the gain of an AlGaAs/GaAs HEMT have been measured. The light induced voltage for a HEMT is observed to be 0.57 V and 0.24 V for MESFET at 0.83 μm wavelength. The higher V_{lit} for HEMT is attributed to the higher increase in hole concentration Δp mainly due to the absorption thickness d, (see Eq. 1).[7] Further, from the de-embeddded HEMT scattering parameters the changes in the equivalent circuit element values due to optical illumination are also computed. These computations show an increase in the gate and also the drain capacitances and a decrease in the gate charging and also the channel resistances. The effect of these changes on the f_t, f_{max} and the noise figure is being further investigated. In addition to the above, experimental results or GaAs MESFETs have also been presented for comparison.

In these experiments the HEMT is optically illuminated by an AlGaAs/GaAs laser diode. This feature further enhances the attractiveness of the above experiments, since it leads to the possibility of integrating a HEMT and a laser diode on a single MMIC chip to perform multiple circuit functions optically, such as, switching, amplifier gain control, phase shifting, and mixing. Such an integration, when fully accomplished not only promises improved MMIC circuit performance, but also vastly simplifies the signal distribution and beam steering in future phased array antenna.

Finally, three novel applications of an optically illuminated HEMT as a variable gain amplifier, high frequency photo detector, and mixer are demonstrated.

Acknowledgment

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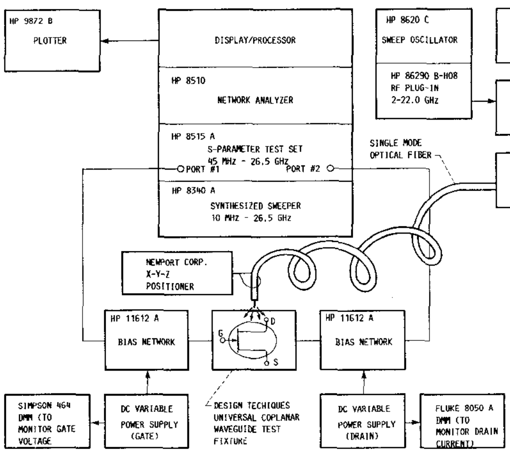

FIGURE 1. - BLOCK SCHEMATIC OF THE EXPERIMENTAL SETUP.

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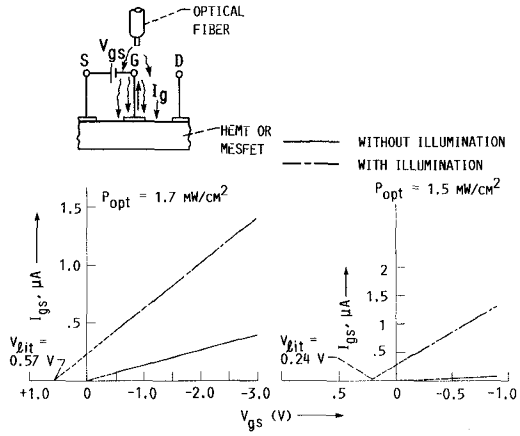


(A) DEVICE ALGAAS/GAAS HEMT (MODEL NO. MPD-H503); V_{ds} = 0 V.

(B) DEVICE GAAS MESFET (MODEL NO. RPX 2322); V_{ds} = 0 V.

FIGURE 2. - MEASURED I_g VERSUS V_{ds} FROM WHICH $V_{\ell it}$ IS OBTAINED. DISTANCE BETWEEN END OF FIBER AND DEVICE, 1 MM; λ = 0.83 μM; P_{opt} = 1.5 MW/CM^2.

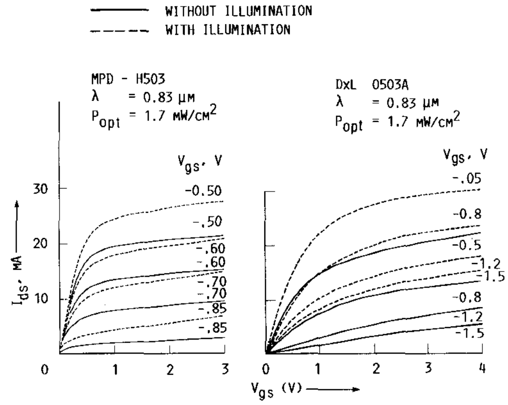


FIGURE 3. - MEASURED I_{ds} VERSUS V_{ds} WITH AND WITHOUT OPTICAL ILLUMINATION.

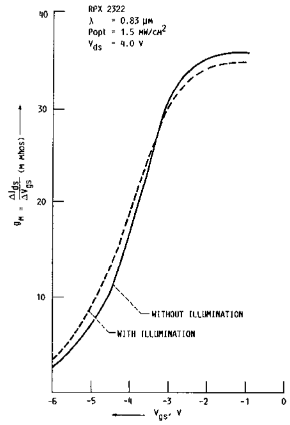


FIGURE 4. - MEASURED g_m VERSUS V_{gs} FOR GaAs MESFET WITH AND WITHOUT OPTICAL ILLUMINATION.

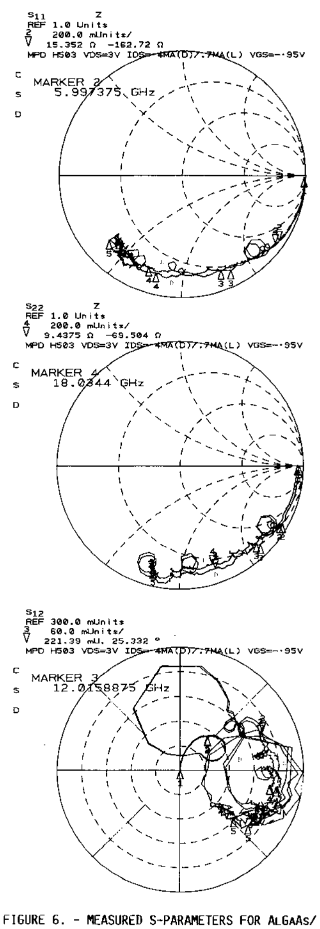
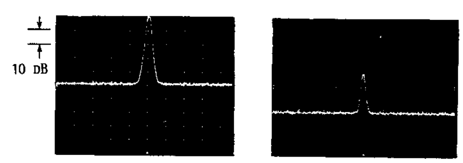


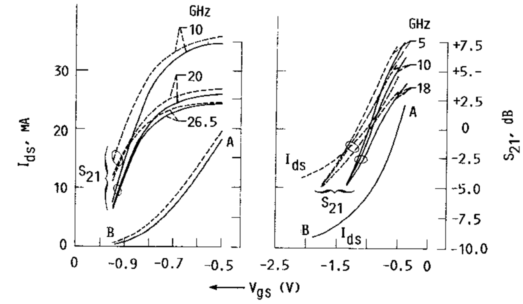
FIGURE 6. - MEASURED S-PARAMETERS FOR AlGaAs/GaAs HEMT WITH AND WITHOUT ILLUMINATION WHEN BIASED CLOSE TO PINCH-OFF. START 0.045 GHz, STOP 26.5 GHz.



CENTER 6.000 GHz
SPAN 10.0 MHz
(A) DETECTED 6 GHz SIGNAL.

CENTER 3.000 GHz
SPAN 10 MHz
(B) 3 GHz IF SIGNAL.

FIGURE 9.



(A) DEVICE AlGaAs/GaAs HEMT (MODEL NO. MPD-H503); V_{ds} = 3.0 V.

(B) DEVICE, GaAs MESFET (MODEL NO. NO. DxL 0503 A); V_{ds} = 3.5 V.

FIGURE 5. - MEASURED GAIN VERSUS V_{gs} WITH AND WITHOUT ILLUMINATION. DISTANCE BETWEEN END OF FIBER AND DEVICE, 1 mm; λ = 0.83 μm; P_{opt} = 1.7 mW/cm^2.

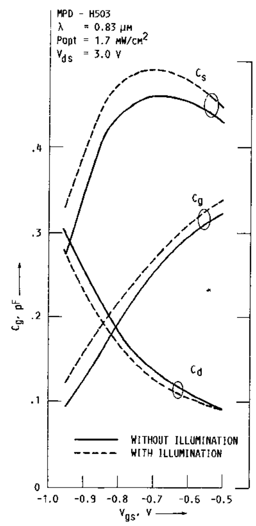
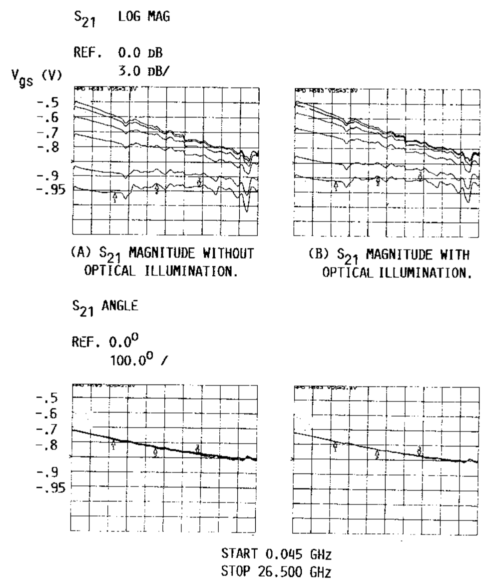


FIGURE 7. - DE-EMBEDED GATE, SOURCE, AND GATE TO DRAIN CAPACITANCES FROM THE MEASURED S-PARAMETES WITH AND WITHOUT OPTICAL ILLUMINATION FOR AlGaAs/GaAs HEMT.



START 0.045 GHz
STOP 26.500 GHz

(C) S_{21} PHASE WITHOUT OPTICAL ILLUMINATION.

(D) S_{21} PHASE WITH OPTICAL ILLUMINATION.

FIGURE 8. - MEASURED S_{21} FOR AlGaAs/GaAs HEMT.