The Compressive Nature of Optical Detection in GaAs MESFETs and Possible Application as an RF Logarithmic Amplifier

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***Abstract*— The photodetection mechanisms in GaAs MESFETs have been investigated by several researchers. Recently the authors have published an in-depth study of the MESFET as an optical detector under constant illumination involving both experimental and theoretical modelling. In this paper we discuss the compressive nature of that photodetection process. Experimental results involving constant illumination, modulated light and pulsed illumination verify the theoretical conclusions. Finally we present a suggested structure of an RF logarithmic amplifier based on the above phenomenon.**

I. Introduction

The properties of the MESFET under illumination have been investigated by several researchers during the last decade [1]–[6]. An experimental and theoretical MESFET characterization was carried out by DeSalles [1], [2]. Darling [3] developed a perturbation analysis that accounts for the photoconductive effect under low level illumination. Madjar *et al.* [4] have identified photoavalanche effects in MESFETs, which can be utilized to increase the optical response. Mizuno [5] conducted an experimental study on DC optical response and microwave scattering parameters of the MESFET as function of the biasing conditions and light intensity. Gautier *et al.* [6] measured the effect of optical illumination on the MESFET both at dc and at microwave frequencies for several biasing conditions. They explain their results by the optically induced bias change (gate photovoltaic effect).

Recently we performed an in-depth systematic investigation of the MESFET's optical response to constant illumination and presented an analytical model [7]. Both the theory and the experimental results suggest that the MESFET acts as a compressive photodetector, namely, the output current is approximately a logarithmic function of the incident optical power. We further verified this property experimentally for the case of pulsed illumination and small signal sinusoidally modulated light. These new results are presented in Section II. The new suggested structure of the RF logarithmic amplifier is presented in Section III.

II. The Compressive Nature of MESFET Photoresponse

The new illuminated MESFET model published recently ([7]) includes all the photodetection mechanisms in the device. Our investigatin shows that for constant illumination the response is dominated by photovoltaic effects. The photoconductive effect in the channel is much smaller, and is usually negligible compared to the photovoltaic effect. Two photovoltaic effects are identified: 1) the external gate p. v. effect due to optically induced current in the gate. 2) the internal p. v. effect due to optically induced change in the barrier layer between the substrate and the epitaxial layer. The details are presented in [7], including an equivalent circuit for the illuminated MESFET. To utilize the external effect a large resistor (several hundred kohm) should be connected to the gate circuit. The internal effect exists under all conditions and is not related to the external loading of the device.

The photoconductive effect is linearly dependant on the incident optical power as shown by Eq. 1 in [7], however this is a negligible effect (several orders of magnitude smaller than the photovoltaic effects). On the other hand, both photovoltaic effects depend on the optical power in a nonlinear compressive fashion. For the internal p. v. effect the drain current response is proportional to the optically induced photovoltage across the epi/substrate barrier, V_{ph}. The solution for V_{ph} is derived from Eq. 12 in [7], and can be written:

$$V_{ph} = k_1 \log\left[1 + k_2 P_{opt}(1 - V_{ph}/V_{bar})^{1/2}\right] \qquad (1)$$

where k_1, k_2 depend on device geometry, physical parameters, optical wavelength, etc. and V_{bar} is the built-in potential in the epi/substrate barrier. P_{opt} is the incident optical power. V_{ph} ranges from zero for no illumination to V_{bar} for very large illumination, thus, the response has an upper limit. Except for very large illumination levels for which V_{ph} approaches V_{bar}, the square root term in Eq. 1 is very close to 1, and the response has a pure log dependance on the incident optical power. For very large illumination levels the square root term decreases, which increases the degree of compression, and makes V_{ph} approach V_{bar}.

For the external p. v. effect the response is proportional to the photovoltage induced in the gate. If the illumination level is low and the gate diode is negatively biased, the response is a linear function of P_{opt} (Eq. 28 in [7]). However, when the gate diode is positively biased (high level illumination and/or gate bias close to zero) the response is a logarithmic function of P_{opt} (Eq. 29 in [7]):

$$V_{phx} = c_1 \log[1 + c_2 P_{opt}] \qquad (2)$$

where V_{phx} is the gate photovoltage and c_1, c_2 depend on the device parameters and optical wavelength.

This compressive type of behavior is depicted by the experimental results in Fig. 1. The curve shown is the drain current response of the device as a function of the incident optical power. The device is FSX51X made by Fujitsu. It has a gate length of about 1 micron, total gate width of 300 microns (two fingers of 150 microns each), a pinchoff voltage of 1.5 V, Idss of 50 mA, maximum transconductance of 45 mmho and is specified to operate up to 18 GHz. The measurements were performed with the device biased at $V_{ds} = 3$ V and $V_{gs} = -0.8$ V. The light source is a semiconductor laser at an optical wavelength of 850 nm. The incident optical power levels range over more than 30 db. The laser light was routed via an optical fiber to the MESFET by bringing the fiber end to a close proximity to the device's surface such that the light spot covers the entire active area. An optical attenuator was used to change the power of the incident light. The optical power scale is logarithmic and the near-logarithmic behavior is evident from the graph.

When the MESFET is illuminated by light, which is amplitude modulated at different RF frequencies, it is necessary to take into account the time constants associated with each one of the photodetection compoonents. As is well-known, photovoltaic effects are usually associated with large time constants. The external p. v. effect is related to the RC time constant of the gate, which is typically larger than 0.1 microsecond due to the large gate resistor. Thus, the external p. v. effect is greatly reduced at modulation frequencies larger than 10 MHz, and therefore this effect becomes negligible at RF frequencies.

Manuscript received February 6, 1992; revised May 4, 1992.
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IEEE Log Number 9204010.

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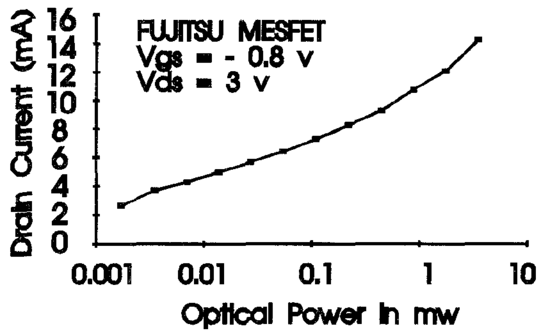

Fig. 1. Drain current response of Fujitsu MESFET versus incident optical power.

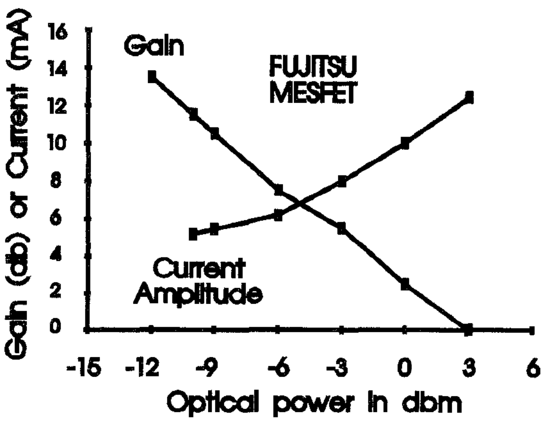

Fig. 2. Relative small signal gain and drain current pulse amplitude versus incident optical power.

The time constant associated with the internal p. v. effect is typically much smaller compared to those of the external effect. This arises due to the greatly reduced resistance of the barrier junction, which is forward biased. Thus, the time constant is dominated by the low barrier junction resistance, and the substrate resistance, which is usually very large, has no effect (except for very low illumination level when V_{ph} is very small and the junction resistance is high). Typically, the 3 db cutoff frequency of this effect runs in the range of 100 MHz to several hundred MHz. Thus, it is expected that the logarithmic behavior of MESFET's optical detection exists at RF frequencies. This assumption was tested by us by performing two sets of experiments, as outlined below.

The first experiment involves pulsed illumination. The laser light was pulse modulated by pulsing its current. The pulse length was several microseconds to ensure steady state operation and a complete decay of the transient response. The incident optical power was controlled by an optical attenuator. For each power level the induced drain current pulse amplitude at the MESFET was recorded. The MESFET was biased at $V_{ds} = 3$ volt and $V_{gs} = -1.5$ V (at the pinchoff). The rise and fall times depend on the optical power level. The rise time is typically around 0.1 microsecond, while the fall time is around 2–3 microsecond. Fig. 2 depicts the drain current pulse amplitude versus the incident optical power. The optical power scale is in dbm (logarithmic), and it is seen that the drain current pulse amplitude is very close to a logarithmic function of the optical power.

The second experiment involves measurement of the small signal sinusoidal response of the MESFET. The laser modulation port was excited by a 0 dbm RF signal from a network analyzer. The MESFET's output at the drain was fed back into the network analyzer,

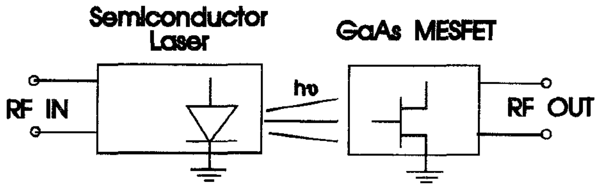

Fig. 3. Suggested structure of an RF logarithmic amplifier.

and thus the total RF gain of the system containing the laser and the MESFET was measured. The RF signal level at the laser input was kept at 0 dbm during the entire measurement, however, the incident optical power on the MESFET was controlled by an optical attenuator between the laser and the MESFET. Thus the modulation index of the laser was kept constant, while the optical power incident on the MESFET could be changed. The RF to RF measured power gain was compensated for the attenuation in the optical domain by subtracting from the input power level twice the optical attenuation in db. The relative small signal gain vs. the incident optical power level on the MESFET is depicted in Fig. 2. Clearly the gain is a decreasing function of the optical power, which demonstrates the compressive nature of the MESFET. The gain function depicted in Fig. 2 corresponds to low frequencies below the 3 db cutoff frequency. For the measured device the cutoff frequency depends on the optical power, and ranges from around 20 MHz for the low power end to over 100 MHz for the upper power end.

III. Suggested Compressive Amplifier

The compressive nature of the MESFET's optical response as demonstrated above can be used for a new type of compressive (logarithmic) amplifier. The suggested structure is depicted in Fig. 3. The amplifier consists of a semiconductor laser and a MESFET. The input of the amplifier is at the modulation port of the laser. The modulated light illuminates the MESFET, and the output of the amplifier is at the MESFET's drain. The coupling of the light from the laser to the MESFET can be performed in many ways: direct illumination by close proximity of the two devices, use of an optical fiber, etc. In the future, as MMIC technology and integrated optics become compatible, the light coupling can be achieved by an integral optical waveguide on the chip.

The advantages of this amplifier are:

1) Potentially Large Dynamic Range: Eq. (1) of this article shows that the deviation from logarithmic response occurs only for high optical power levels as the barrier photovoltage approaches the built-in potential. If a deviation from log response is permitted the dynamic range can be very large—from the noise level to the maximum laser power. In principle, the dynamic range may be limited by the photoconductive effect, which depends linearly on the optical power, and may exceed the p. v. effects for very large optical power. However, due to its extremely small size for typical optical power levels this does ot occur for practical optical power levels.

2) Low Cost: For relatively low frequencies (tens or even hundreds of MHz) it is possible to use a simple low cost laser or even an LED. Also, small signal MESFETs well into the microwave range are available at very low cost.

3) Small Size: Using chip devices and hybrid technology such an amplifier can be very small. In the future-using ICs containing both microwave and optical devices this amplifier can be made as a small single chip (perhaps 1×1 mm).

The main limitation of the suggested structure may be the bandwidth. As mentioned above, the 3 db cutoff frequency of the MESFET depends quite strongly on the optical power. In fact, the bandwidth increases with the optical power, so for wideband amplifiers it is necessary to use lasers with higher power (50–100 mw), which reduces the gain (Fig. 2). Even for these power levels it is expected that the bandwidth will be not more than 200–300 MHz. The optimum performance and cost seem to apply for bandwidths around 100 MHz or lower, since then low cost lasers and MESFETs can be used.

The proposed amplifier may be relatively noisy due to the noise inducing deep level traps in the epi/substrate barrier. The situation may be somewhat better for ion-implanted devices. However, the noise performance is not very important for logarithmic amplifiers, since usually they are not used in RF front ends, but rather in the IF section.

IV. Conclusions

In this paper we have shown both theoretically and experimentally that the MESFETs photodetection mechanism is of a compressive nature. Based on the above a new structure for a compressive (logarithmic) amplifier is suggested. The new structure has some potential advantages, and seems to be a low cost alternative to conventional log amps. More work is necessary to fully evaluate the new amplifier.

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