CAD-oriented modeling of the optically-controlled GaAs MESFET

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Abstract

A CAD-oriented circuit model for the optically-controlled GaAs MESFET was developed on the basis of a dedicated characterization method. By exploiting separation of direct and indirect photo-induced effects, a simple but accurate modeling of both the static and microwave characteristics of the illuminated transistor was achieved. As demonstrated by the test circuits implemented, good agreement between measured and simulated performances can thus be obtained with limited device parameter identification effort.

Device characterization

It is well known that when the active region of a GaAs MESFET is illuminated by a photon beam with quantum energy greater than the semiconductor bandgap, both the DC and microwave characteristics of the transistor change, because of the combined influence of photo-voltaic and photo-conductive effects.

In order to perform a meaningful characterization and to achieve a good phenomenological insight, it is convenient to avoid unnecessary interactions to occur between different photo-induced effects. As a first step along this line, all the measurements should be performed with reference to the internal voltages $E_{X,Y}$, i.e., by removing the influence of access parasitics resistances $R'_g$, $R'_s$, and $R'_d$ (see Fig. 1). This can be conveniently done by measuring them beforehand, and then adopting a computer-controlled bias system with a software feedback loop. In this regard, it can be pointed out that, although in theory such resistances should be treated as light-intensity dependent and nonlinear, in practice they can be often considered constant and linear, their variation being of the order of a few percents under normal (electrical and optical) operating conditions.

The photo-generated excess electron-hole pairs and the modification of the potential barriers at the gate-to-channel and channel-to-substrate (or buffer-layer) interfaces cause variations both in the gate and in the drain currents, as illustrated by the shift in the relevant DC characteristics reported in Fig. 2. Such variations, occurring at fixed internal voltages ($E_{gb}, E_{ds} = const.$), are a direct (DC) effect of illumination, and normally interact through the parasitic resistor $R_g$. This means that the functional dependence of $I_g$ and $I_d$ on the external voltages ($V_{gs}, V_{ds}$), usually considered in the DC characterization of an illuminated transistor, would be more difficult to model and to relate to the device physics. As an example of this fact, it can be analyzed the measured dependence of the gate and

![EXTRINSIC DEVICE PARASITICS](image)

Fig. 1. General scheme of the optically-controlled MESFET.
drain photocurrent on the beam intensity (Fig. 3). For the
gate photocurrent, a nearly perfectly linear dependence from
the injected optical power ($W_o$) is observed, independently
of the bias point selected. This experimental result is in
agreement with the theoretical expectations, and would
have not been analogously evident from the measurements
of $I_g(V_{gs},V_{ds},W_o)$, especially at highest current levels. As
to the drain current dependence on $W_o$, it can be noticed
that it is instead highly nonlinear, with a logarithmic-type
shape. This result too is in good qualitative agreement with
physics-based considerations, although the quantitative
aspects of its functional dependence on DC bias are more
complicated than calculable from simplified theories.

Passing to the microwave characterization, it can be noticed
that, since a variation of the light intensity after the bias
point and therefore the AC response of the transistor,
without appropriate methods to counterbalance this DC
shift, what is obtained from a conventional VANA
measuring system is a combination of the (direct)
light-induced effects and of the (indirect) bias-shift related ones.
Therefore, a smart (computer-assisted) biasing technique is
required for the microwave characterization too.
In particular, for this research, the same hardware and software
used for the DC measurements have been integrated into a
hp8510B network analyzer and its external controlling
computer, respectively.

The S-parameters measurements executed by this approach
(i.e., by fixing internal voltages, but letting gate and drain
current to vary), exhibited some peculiar features. In
particular, all the samples of the GaAs MESFET tested
(the MGF1801 by Mitsubishi) have shown a rather limited
variation of the small signal device parameters throughout
the whole 20GHz frequency range investigated (see Fig. 4).
Moreover, such variations - once related to an equivalent
circuit model - are attributable for the most part to changes
in the resistive elements and not to the reactive ones. Both
results are not in agreement with previous observations
made by other authors. In this regard, it can be pointed out
that a conventional biasing scheme would have provided
different results for the same devices, exhibiting fictitious
variations of the device intrinsic capacitances. That might
explain above mentioned discrepancy, as well as the
difficulties encountered in correlating theoretical predictions
and previous experimental results of the literature. Indeed,
although a variation of intrinsic capacitances for the direct
effect of illumination is within the theory, quantitatively
high numbers are not expected to occur in practice, because
of the low optical coupling efficiency achieved in
irradiating the device through the gate-source and gate-drain
metallizations openings. Obviously, this situation could
change in case of purposely designed OPTOFET devices
(e.g., the buried-gate or the bottom-fed structures suggested
in [2]) or if unusually high-power laser sources are adopted.

Illuminated FET modeling

A general circuit model for the optically driven GaAs
MESFET is shown in Fig. 1. The fourport embedding the
intrinsic transistor represents the parasitic elements of the
chip device (including bond wires and the package, if
applicable) and is thus assumed to be linear and light-

In this case, it can be identified by
conventional techniques and will not be considered further.
On the other hand, all the elements modeling of the
intrinsic device are in theory both nonlinear and
illumination-dependent. However, on the basis of the
experimental results reported in the previous section, a
number of simplifications can be done in order to derive
a first-approximation, but phenomenologically valid model
of the optically controlled transistor. In particular, the DC
characterization results justify the following assumptions:
- to use linear and constant resistors for $R_g, R_d$ and $R_d'$;
- to adopt, for the controlled current generators $I_{gs}$ and $I_{gd}$,
a functional dependence of the form

$$I_{dx}(E_s, E_s', W_o) = I_{dx}(E_s, E_s') + K_{dx} \cdot E_s \cdot W_o$$

where $I_{dx}(*, *, 0)$ is the nonlinear relationship modeling
the gate-source or gate-drain current under dark operating
conditions, $K_{dx}$ and $E_{dx}$ are parameters characterizing
the gate photo-current, and $W_o$ is the optical power.

- to employ, for the controlled generator $I_{ds}$, a functional
dependence of the form

$$I_{ds}(E_s, E_s', W_o) = I_{ds}(E_s, E_s') + K_{ds} \cdot E_s \cdot (W_o - T_{ch}) \cdot E_s'$$

where $I_{ds}(*, *, 0)$ is the nonlinear relationship modeling
the static characteristics of the unilluminated transistor,
and $E_{ds}(W_o - T_{ch})$ is an equivalent voltage which account
for the drain photo-current. Its dependence on optical
power and channel temperature can be approximated by

$$E_{ds}(W_o - T_{ch}) = E_{ds}(1 - K_{ds} \cdot T_{ch}) \cdot \ln(1 + K_{ds} \cdot W_o)$$

Notice that above formulas are explainable either on an
experimental basis, e.g., by considering the similarity
existing among the $(I_{dx}(*, *, W_o) - I_{dx}(*, *, 0))$ curves and
the device transconductance, or by theoretical considerations
on the barrier lowering effect caused by the illumination.
Since the observed variation of the device S-parameter with
illumination is already accounted for by the change in the
resistive nonlinear elements (and the consequent bias shift),
no additional optical-drive related parameters are introduced
for simulating the AC characteristics of the FET.

Summing up, according to the proposed method, only the
above cited seven parameters are required for the modeling
of all photo-induced effects. Such number can be further
reduced in case of devices with structural symmetry or if
thermal effects are disregarded. In any case, their computer-
assisted identification is straightforward, and can be done on
the basis of the sole DC characterization data acquired.

Experimental verification

To test the validity of the proposed modeling approach,
several experiments have been performed using a medium
power GaAs MESFET by Mitsubishi (MGF1801). Since
this device is a packaged one, its metallic top cover lids
have been removed, and a hole was drilled in the transistor
holding insert of test fixture (hp85041), to allow for
the optical injection. In particular, unguided propagation of
the (He-Ne) laser beam was employed for the characterization at
633nm, while a cleaved optic fiber was micro-positioned through the hole in the nearby of the chip surface, for the experiments using the (Laser Diode) source at 850nm.

For each sample device tested, the following modeling procedure has been applied. After aligning of the optical bench (using the gate photo-current as indicator), a full characterization of the DUT was first made under dark condition. The relevant DC and AC bias-dependent model was then derived using a custom extraction software (MES-FIT), which employs a combination of direct identification and optimization techniques for the fitting. This step generates the look-up tables for the bias-dependent dark model parameters. Thereafter, the characterization was repeated for seven different levels of illumination (optical attenuation values of 0, 1, 2, 3, 5, 7 and 10 dB). From the DC data, the additional parameters involved in the illuminated device model (five, exploiting the DUT structural symmetry) have been identified by least square criterion curve fitting.

On this basis, the S-parameter of the illuminated MESFET have been simulated, and compared to the measured ones. In general, quite satisfactory agreement was obtained, thus discouraging the idea of resorting to a “tuning” of the look-up tables of the incremental model parameters, which would have certainly improved the simulation accuracy, but would have also implied dealing with a more involved (both bias- and light-dependent) AC model, which was not the goal of this work.

To better evaluate the simulation capabilities of the extracted model, by testing it under operating conditions different from those of the initial characterization, and more similar to those occurring in a practical circuit, additional measurements have been performed.

First, a simple optically-controlled variable-gain amplifier was implemented, directly on the network analyzer. In particular, a fixed supply/resistor circuit was used for biasing gate (V_{GG}, R_{GG}=270kΩ) and drain (V_{DD}, R_{DD}=3Ω) of the device under test. At difference with previous measurement conditions, in this case there is a strong interaction between direct and indirect photo-effects (and therefore between DC and microwave response). Thus, it is a valid test of the global quality of the model under CW optical drive operation. The measured and predicted dependence of drain current on the optical beam intensity (for fixed V_{DD} and stepped V_{GG}) are compared in Fig. 5, while the frequency dependence of amplifier insertion gain (for fixed V_{GG} and V_{DD} and three different optical drive levels) is reported Fig. 6. It can be seen that quite good agreement was achieved in either case.

As a final test, a GaAs MESFET photodetector circuit was realized, by 50Ω terminating its input and output, and by optically driving it with a low-frequency amplitude-modulated LD source (at 850nm). Although the model here presented is not intended for use under short-pulse or microwave-frequency AM optical drive (since dynamics of photo-effects was not characterized nor accounted for), it is expected that if the beam modulation period is much less than the involved optical time-constants, the model should maintain its validity. In fact, as demonstrated by Figs. 7-8, at 1kHz modulation the detector output is quite accurately simulated, over a more than 10dB of optical-signal dynamic range. Notice that the strongly nonlinear response shown by the two photos of Fig. 7, constitute also an independent validation of the logarithmic-type dependence of E_{0} on W_{0} identified under stationary DC operation. In this regard, it is authors' opinion that, by properly exploiting such type of measurements, it can be derived a frequency dispersive functional dependence for E_{0}, thus improving the model and extending its applicability to high-speed optical drive.

Conclusions

Starting from an appropriate experimental characterization aimed at separating direct and indirect light-induced effects, a first-approximation CAD-oriented circuit model of the optically-controlled GaAs MESFET was derived. Once the (DC nonlinear, AC bias-dependent) unilluminated transistor model is obtained through conventional identification methods, the additional parameters characterizing the photo-effects can be extracted from a simple procedure based on DC measurements only. The selected model structure allows its straightforward integration into most commercial circuit simulators with custom or behavioural modeling capability. Notwithstanding its simplicity, the developed model inherits from its phenomenological basis accurate simulation capabilities, as demonstrated by the good agreement between measured and predicted performances of the verification circuits realized.

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References

Fig. 2. Measured variation of gate (left) and drain (right) current for fixed $E_{gs}$, $E_{ds}$ values at full-to-zero optical power step.

Fig. 3. Measured dependence of gate (left) and drain (right) current on optical power, for fixed $E_{gs}$ and $E_{ds}$ values.

Fig. 4. Measured variation of S-parameters for $E_{gs}=2$, $E_{ds}=1$ and full-to-zero optical power step.

Fig. 5. Measured (left) and simulated (right) drain current of the optically-controlled test amplifier versus $W_1/W_{\text{max}}$ and $V_{gg}$, for $V_{dd}=1\text{V}$.

Fig. 6. Measured (left) and simulated (right) insertion gain of the optically-controlled test amplifier for $V_{gg}=-2.5$, $V_{dd}=1\text{V}$, $W_1/W_{\text{max}}=0$ (A), .5 (B), 1 (C).

Fig. 7. Measured response (top trace) of the photodetector circuit, for a scaled optical power $W_1/W_{\text{max}}=1$ (left) and 0.1 (right) and 1 Vpp modulation signal (bottom trace).

Fig. 8. Simulated response (top trace) of the photodetector circuit, for a scaled optical power $W_1/W_{\text{max}}=1$ (left) and 0.1 (right) and 1 Vpp modulation signal (bottom trace).