MESFET LINEARITY IMPROVEMENT BY CHANNEL DOPING CONTROL

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Abstract

The present work is intended to evaluate the linearity that can be provided by general purpose MESFETs.

By a simple physics-based analysis, and a practical amplifier design, it will be proved that educated device and bias point selection, can approximate IMD performance of normal channel doping profiles, to the one that expected from a MESFET device with a specially tailored doping profile.

I. Introduction

Many are the telecommunications systems that require amplifiers capable of providing large carrier to in-band intermodulation distortion ratios, C/I. It is widely known that in those amplifiers nonlinear distortion products of third order dominate the circuit's in-band intermodulation distortion performance, IMD. To maintain 3rd order IMD at reasonably low levels, their active devices are always biased for class-A operation, and the signal excursions kept small compared to the transistor's maximum allowed clipping free signal range. This form of distortion, which in most cases manifests itself as a kind of soft clipping, is imposed by the active device's strong nonlinearities (hard knees of the I/V curves). In linear operation, however, the residual, or mild nonlinearities of the drain-source current, Ids, which in conjunction with the mild nonlinearities of the gate-source capacitance, Cgs, are the true responsibles for IMD performance, can be described by a Taylor Series expansion around the bias point:

$$\begin{aligned} Ids(vgs,vds) = {} & Ids_{DC} + Gm.vgs + Gds.vds + \\ & + Gm2.vgs^2 + Gmd.vgs.vds + Gd2.vds^2 + \\ & + Gm3.vgs^3 + Gm2d.vgs^2.vds + \\ & + Gmd2.vgs.vds^2 + Gd3.vds^3 + \dots \qquad (1) \end{aligned}$$

It has been many times observed that in a well designed class-A amplifier Gm2 and Gm3 are the dominant coefficients. That is the reason why a great effort was paid to reduce them by proper bias point selection, or, in the foundry field, by an appropriate device's channel doping control.

Nevertheless, some very good results of IMD performance observed in amplifiers based on general purpose MESFET's, have recently been published[1,2]. The first aim of this communication is to provide a theoretical justification for these encouraging experiments, and the necessary analysis for the control of their physical origins.

II. Theoretical Background

Assuming the depletion region model, it can be shown that, in a MESFET, the depletion zone width, d(V), is related to the drain-source current, and applied gate-channel voltage, V, by:

$$V = V_{bi} - \frac{q}{\varepsilon} \cdot \int_0^{d(V)} y.N(y).dy \qquad (2)$$

$$Ids = q.vs.W. \int_{d(V)}^{A} N(y).dy \qquad (3)$$

Therefore, Gm, Gm2 and Gm3, can be calculated by successive differentiation of Ids in order to V, which gives:

$$Gm = \frac{vs.W.\varepsilon}{d(V)} \qquad (4)$$

$$Gm2 = \frac{vs.W.\varepsilon^2}{2.q} \cdot \frac{1}{d(V)^3} \cdot \frac{1}{N[d(V)]} \quad ; \qquad (5)$$

and

$$Gm3 = \frac{vs.W.\varepsilon^3}{6.q^2} \cdot \frac{1}{d(V)^5} \cdot \frac{1}{N[d(V)]^3} \cdot$$

$$\cdot \left[3.N[d(V)] + d(V).N'[d(V)] \right] \qquad (6)$$

From an expression equivalent to this last one, Pucel[3] derived two doping profiles that minimize the device's in-band nonlinearity, i. e., low Gm3: $y^3.N(y) \to \infty$ or $y^3.N(y)$ constant. The first condition, which can not be precisely realized, and thus has been approximated by the spike doping[3,4], reduces Gm2 and so its derivative, Gm3. It can be seen from the relation of V and d(V) that this doping profile makes depletion region's width almost constant for a fairly wide range of gate biases. Therefore it would be able to produce a truly linear FET, i. e., one presenting a transconductance independent of bias.

Even if this condition is not met, it is still possible to minimize 3rd order nonlinear distortion. This is done with a linear dependence of Gm on bias, or in other words, a constant Gm2. This is exactly what is meant by the second condition, $y^3.N(y)$=constant or $N(y) \propto y^{-3}$. It is easy to conclude that this condition constitutes the solution of the differential equation obtained for a vanishing Gm3:

$$3.N(y) + y \cdot \frac{d\,N(y)}{d\,y} = 0 \qquad (7)$$

From the device physics point of view, it should be clear that neither of the above conditions can be exactly obeyed for the whole range of gate biases. For example, as the FET approaches pinch-off it can not present there (or in any other bias point) discontinuities in Ids or in any of its derivatives. It is known that Ids bellow the threshold region presents a constant value of zero, and then softly increases for higher values of Vgs. Therefore, it seams to be obvious that to guarantee the continuity of the function and all its derivatives, Gm3 must take some positive non null value, at least in that zone.

This discussion is really centered in the dependence of Gm3 on Vgs bias, which, in the model of (1), is represented by the magnitude of the higher order coefficients, Gm4, Gm5, ... Bearing in mind the Volterra Series Techniques for nonlinear circuit analysis, it is easy to conclude that those higher order effects do not contribute to the 3rd order IMD products, which are the responsibles for the device's low level IMD performance. In conclusion, as long as high C/I ratios or other related nonlinear parameters as IP_3 are concerned, it is not possible, nor it is strictly necessary, to have the above conditions verified for all ranges of gate biases, but at least one for a given quiescent point. It will be shown next that this situation is verified for some channel-doping profiles commonly encountered in commercially available general purpose GaAs MESFETs, which rend them obvious advantages over the specially designed devices already proposed[4].

We started the analysis with some expressions commonly used to approximate the doping profiles encountered in the great majority of devices.

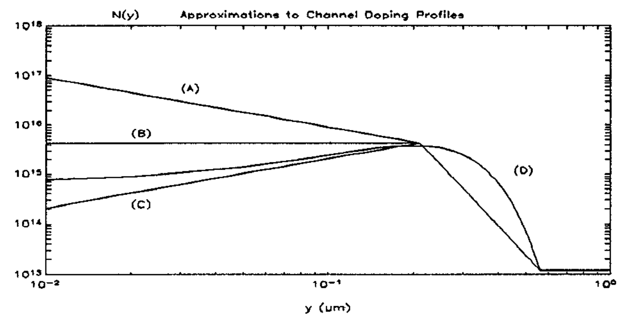

Fig. 1 - Examples of channel doping profiles approximations using piece-wise n'th power doping (A,B and C), and gaussian doping (D).

The first group of doping profiles considered, describes the n'th power doping:

$$N(y) = No.(y-y_o)^n \quad , \quad y>0 \text{ and } y>y_o \qquad (8)$$

Allowing y_o to get positive or negative values, this expression really shows great flexibility to model decaying (n<0), uniform (n=0) and retrograde (n>0) profiles. Also, it can be combined in a piece-wise manner to produce more complicated patterns, as is shown in Fig. 1. If y_o is positive, (8) will only give points of null Gm3 (i. e., will verify (7) for some y_c value) for $(y_c = \frac{3}{2} \cdot y_o)$ when n=-1, and for $(y_c=3.y_o)$ when n=-2. If y_o=0, then (8) will be zero for all y when n=-3 (Pucel's 2nd condition). Finally, if y_o is negative, (8) will present null values for $y_c = \frac{3.y_o}{3+n}$ when n<-3.

The second group of profiles considered is the gaussian doping, often used to describe ion implant devices:

$$N(y) = No.e^{-\left(\frac{y-y_o}{\sigma}\right)^2} \qquad (9)$$

If $y_o \geq 0$, the gaussian profile produces null Gm3 for

$$y_c = \frac{1}{2} \cdot \left[y_o + \sqrt{y_o^2 + \frac{3}{2} \cdot \sigma^2}\,\right],$$

while if $y_o<0$, $y_c = -\frac{1}{2} \cdot \left[y_o - \sqrt{y_o^2 + \frac{3}{2} \cdot \sigma^2}\,\right]$, provided that $y_c>0$.

The above discussion shows that there are certain parameters for these expressions, capable of generating very good IMD regions that can be observed for gate voltages (given by (2)) such that $d(V)=y_c$.

This is a remarkable result since it leads to the conclusion that one may expect very good IMD performance even from devices with doping profiles for which previous theories would not predict linear behavior.

Let us now focus our attention to the real doping profiles encountered in practice. Although they may be conceived to match the ideal uniform, retrograde, gaussian patterns, etc., they always end in soft transitions between different doping regions. This is what happens, e. g., is the channel to the intrinsic substrate or buffer layer interface. Also, it should be noted that the effects of these soft doping transitions will be, in fact, even more pronounced due to the non abrupt depletion region to neutral channel interface. Therefore, the equivalent doping profiles that must be used in the present analysis (based in the depletion region approximation), will present a greater complexity than the simple ideal starting forms. An interesting and useful consequence of this is that we may find Vgs bias points of null Gm3 in thin channel general purpose MESFET's, which rend them 3rd order IMD performance comparable with the one that is obtained with devices designed with specially tailored doping profiles.

III. Experimental Validation

Those theoretical results induced the study of real world effective doping profiles, found in general purpose GaAs MESFETs, like the one of Fig. 2.

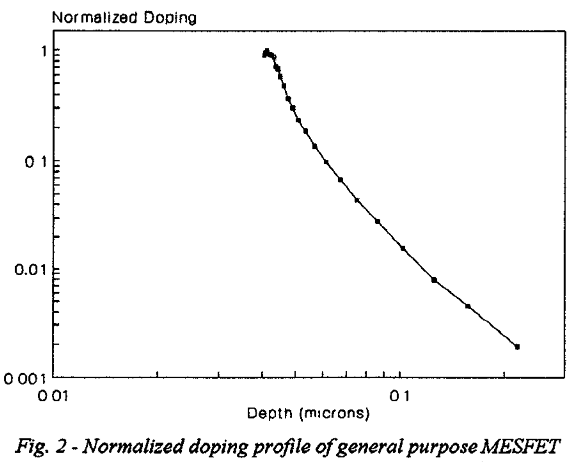

Fig. 2 - Normalized doping profile of general purpose MESFET NE70083, obtained from the measured ratio of $Gm^3/Gm2$.

Using the approximation of this pattern by a piece-wise combination of appropriate n'th power doping profiles like the ones given in (8), two different depletion depth values, corresponding to null Gm3 were predicted. As each of these depths has a V_{GS} bias voltage counterpart, it was anticipated that this device should present two distinct bias points of very good IMD performance. That was really confirmed by the direct laboratorial extraction of Gm and Gm3, from S parameters and harmonic measurements[5].

Fig. 3 shows the nonlinear characterization results thus obtained. It presents the ratio of Gm/Gm3 (which is a figure of merit of the device's linearity) for the whole range of negative gate bias. The observation of this figure leads to the conclusion that this MESFET really shows two points of high Gm/Gm3, corresponding to two V_{GS} values of null Gm3. The first Gm3 null is located at V_{GS}=-1.05V, near the FET's threshold voltage, where Gm is very small. Therefore, this is a point of little practical interest for linear power amplification, because of its low associated gain. However, the second Gm3 null stands for V_{GS}=-0.25V, i. e., in a zone of high transconductance. So, contrary to the former, this Gm3 null constitutes a quiescent point of great importance as it may be used to build low IMD amplifiers.

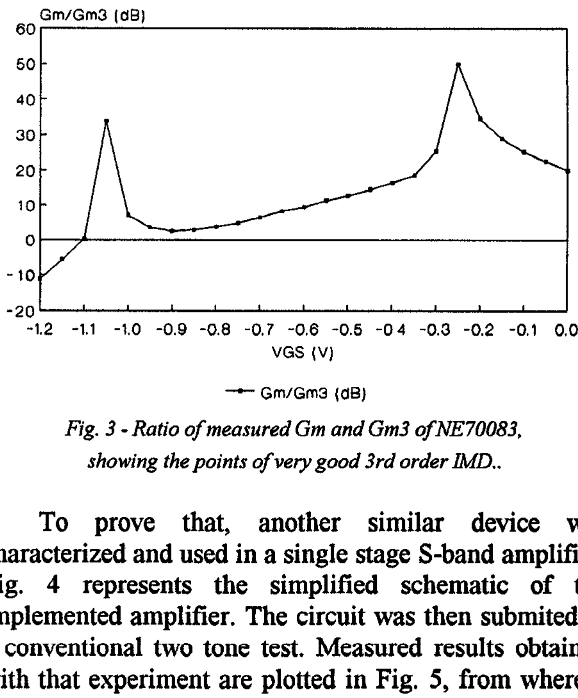

Fig. 3 - Ratio of measured Gm and Gm3 of NE70083, showing the points of very good 3rd order IMD..

To prove that, another similar device was characterized and used in a single stage S-band amplifier. Fig. 4 represents the simplified schematic of the implemented amplifier. The circuit was then submited to a conventional two tone test. Measured results obtained with that experiment are plotted in Fig. 5, from where a 1dB compression point of 12dBm and an extrapolated IP_3 of 36dBm can be observed. These are thought to be remarkable results for a general purpose MESFET biased with V_{DS}=3.0V and I_{DS}=40mA. In fact, they correspond to figures of merit, FOM's, of IP_3/P_{DC}=33 and IP_3/P_{1dB}=24dB, which compare to the IP_3/P_{DC}=3.7 and IP_3/P_{1dB}=14dB published for a conventional power

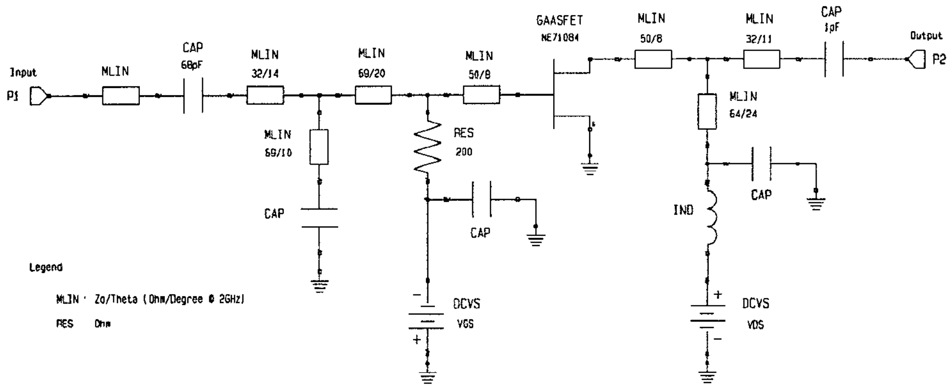

Fig. 4 - Simplified schematic diagram of the implemented S-band amplifier.

MESFET amplifier, and to FOM's of IP_3/P_{DC}=50 and IP_3/P_{1dB}=24dB obtained with a MESFET device with a spike-doped channel[4].

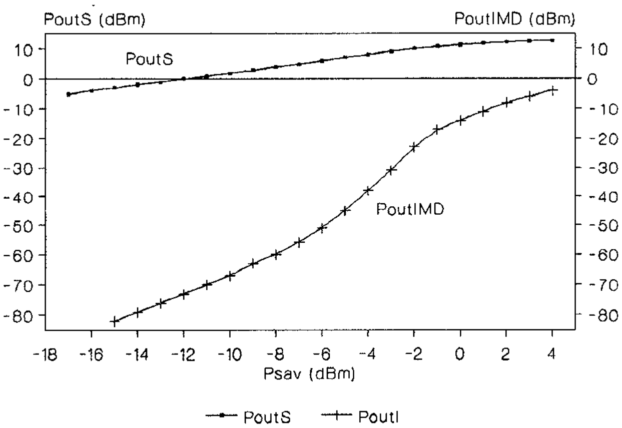

Fig. 5 - Measured results of output power at the fundamental and 3rd order IMD from the implemented amplifier.

IV. Conclusion

A different point of view on the MESFET linearity dependence on doping profile was presented. It led to the interesting conclusion that good IMD performance may be expected from a MESFET with no specialized doping profile, if its channel doping pattern is carefully studied and the V_{GS} bias point criteriousely selected.

Two tone test results maid on a practical amplifier proved that the present procedure indeed produces linearity FOM's that are much better than obtained with conventional power FET's, and can even approximate the FOM's of specially tailored devices.

Acknowledgement

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References

[1] - J.C. Pedro and J.Perez, "Design Techniques for Low Intermodulation Distortion Amplifiers", Microwave Journal, vol. 37, nº 5, May 1994.

[2] - J.C. Pedro and J. Perez, " On the Bias Point Selection for Improved Performance in Low Intermodulation Distortion Amplifiers", Proceedings of the European GAAS Symposium, pp.353-355, Torino, April 1994.

[3] - R. Pucel, "Profile Design for Distortion Reduction in Microwave Field Effect Transistors", Electronics Letters, vol. 14, nº 6, pp.204-206, Mar. 1978.

[4] - S. Chu, J. Huang, W. Struble, G. Jackson, N. Pan, M. J. Schindler and Y. Tajima, "A Highly Linear MESFET", 1991 IEEE Int. Microwave Theory and Tech. Symposium Digest, pp.725-728, Boston, Jun. 1991.

[5] - J. Pedro and J. Perez, "Accurate Simulation of GaAs MESFET's Intermodulation Distortion Using a New Drain-Source Current Model", IEEE Trans. on Microwave Theory and Tech., vol. 42, noº 1, pp.25-33, Jan. 1994.