Modeling on Statistical Distribution of Noise Parameters in Pulse-doped GaAs MESFETs

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ABSTRACT

Process-related variation of noise parameters in pulse-doped GaAs MESFETs is discussed in this paper. Fluctuation in gate length of the proposed devices is shown to be a dominant source of variation in noise parameters. The statistical distribution of the minimum noise figure (Fmin) is modeled and the probability density function is described. Comparison between the calculated result of the derived equation and the measured distribution of Fmin is also shown.

INTRODUCTION

Monolithic microwave integrated circuits (MMIC's) have been developed principally for non-commercial application such as electronic warfare systems. Recently, attention has been focussed on the R&D of MMIC's to replace hybrid devices used in consumer application such as direct broadcast satellite (DBS) receivers, owing to recent advances in GaAs materials and process maturity [1][2]. MMIC's allow miniaturization, reduction of the assembling cost in large volumes and improvement of reliability. For high volume consumer application, cost is the most important problem. The ability to fabricate devices consistently with uniform characteristics is a key factor in manufacturing cost-effective MMIC's.

Pulse-doped GaAs MESFET's were designed for MMIC use from this point of view [3]. In previous works, high performance with excellent uniformity was reported [4], and electronic properties were investigated as well [5]. The FET configuration is shown in Fig. 1. They have a very narrow, high carrier concentration (pulse-doped) active region and combine noise performance equaling that of AlGaAs/GaAs high electron mobility transistors (HEMT's), with the reproducibility of the MESFET structure. Furthermore, relatively high throughput is achieved by the use of organometallic vapour phase epitaxy (OMVPE). The X-band amplifier and an MMIC family for a DBS down-converter based on the proposed devices with 0.5μm gate exhibited excellent low noise performance and a high yield [6][7]. Thus, the potential of the proposed device has been demonstrated.

On the other hand, yield enhancement by the design technique of the circuit should be studied for MMIC affordability as well as improvement of the uniformity by device technology. For this purpose, it is important to estimate the variation of their performance while designing them before fabrication: a great deal of emphasis is now being placed on yield modeling and yield prediction [8]-[10]. The mathematical representation of the statistical distributions in FET parameters greatly help to simulate the variation of the designed circuit's

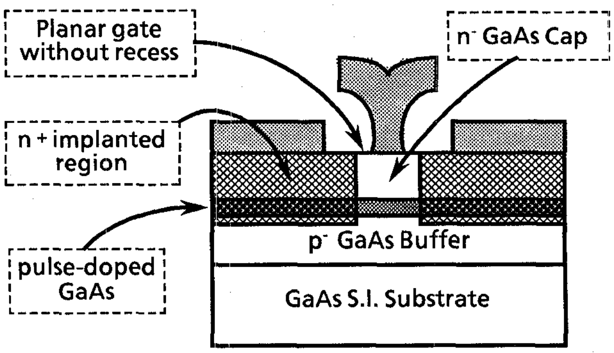


Fig.1 : Structure of pulse-doped GaAs MESFET

P- GaAs buffer layer *(1μm)*
Si doped GaAs active layer (4$\times 10^{18}$/cm^3,100Å)
Undoped n- layer *(300Å)*

performance. In the case of the design of a low noise amplifier, a minimum noise figure (Fmin) in the FET's is one of the most important parameters. However, the statistical distributions in noise parameters and the source of the variation have hardly been reported on.

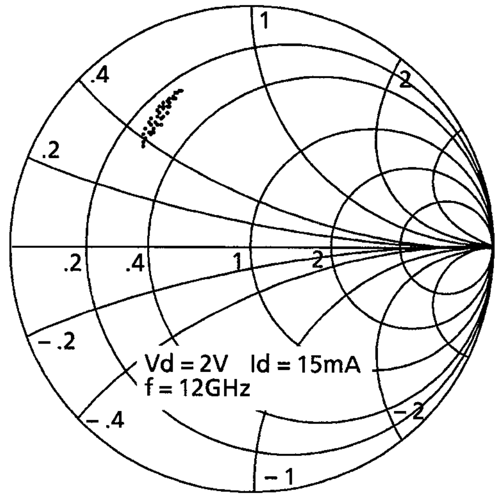
The objective of this work is to model the statistics of Fmin in the pulse-doped GaAs MESFET's. In this paper, measured distributions of noise parameters of pulse-doped GaAs MESFET's are presented. Process-related variation in gate length (*Lg*) is shown to be a large source of variation in Fmin and optimum source reflection coefficient (Γopt) in the experimental results. The probability density function of Fmin is derived from the statistical distribution of *Lg* for the first time. Finally, the calculated result of the derived probability density function is compared with the measured distribution of Fmin, demonstrating a good correlation between both.

EXPERIMENT AND DISCUSSION

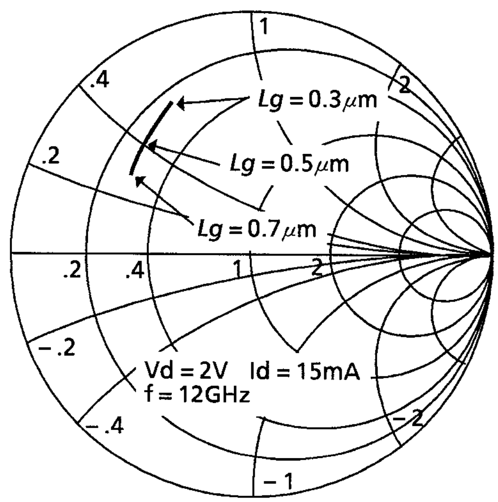
To determine the exact mathematical representation of the statistical distributions in Fmin, all contributors of process-related variation should be taken into consideration. Generally, the epitaxial layer structure and/or the fabrication process are complicated in low noise devices. The proposed device, however, can simplify this problem due to the simple layer structure and its easy process. It could probably be assumed that the dominant factor will be variation in *Lg*, due to the following features [4].

(1) The planar gate structure without the gate-recessed structure might be a strong factor of process-related variation in FET parameters
(2) A quite uniform epi-layer obtained by specially designed OMVPE systems, providing less than 3% fluctuation in the uniformity of thickness and carrier concentration across a wafer 2 inches in diameter
(3) Unavoidable *Lg*-variation in the submicron gate as defined by the conventional photolithography

To demonstrate this assumption, wafers were fabricated for measurement of Fmin, Γopt, and *Lg*, with *Lg* designed to be from 0.3μm to 0.7μm. Figure 2(a) shows the measured distribution of Γopt on a Smith chart in the FET's designed to be 0.4μm *Lg* in a wafer 2 inches in diameter typically processed: the measurement was performed at the bias condition for the lowest Fmin at 12GHz. Variation in ∠Γopt is demonstrated to be considerably larger in contrast to



(a) Measured distribution of Γopt in the FET's designed to be 0.4μm *Lg*



(b) Locus described by measured Γopt in some FET's having known *Lg* by precise SEM-measurement

Fig. 2 : Comparison between the measured distribution of Γopt in the FET's designed to be 0.4μm *Lg* and a locus described by measured Γopt in some FET's having known *Lg* (measurement was performed at the bias condition for the lowest Fmin at 12GHz)

negligible fluctuation in |Γopt|.

On the other hand, the solid line shown in Fig. 2(b) describes in the same way the little changing |Γopt|. The part ranging in Lg from 0.3μm to 0.5μm on the solid line corresponds well with the measured distribution of Γopt. This solid line illustrates a locus of Γopt in some FET's having different Lg in the same site: each Lg was precisely measured by a scanning electron microscope (SEM). Thus, process-related variation in Lg was found to be a strong source of this in Γopt. In Fig. 2(a), the slight breadth of the point swarm in the direction of the radius is thought to result from other process-related fluctuation.

Figure 3 shows the measured distribution of Lg designed to be 0.4μm in the same wafer. This distribution can be approximated by the gaussian as shown in this figure, and Lg is the gaussian random variable having the probability density function:

$$p_{Lg}(Lg)=\frac{1}{\sqrt{2\pi}\,\sigma_{Lg}}\exp\left[-\frac{(Lg-\overline{Lg})^2}{2\sigma_{Lg}^{\ 2}}\right] \quad (1)$$

$\sigma_{Lg}^{\ 2}$: variance of Lg, $\overline{Lg}$: mean of Lg

On the other hand, Fmin is expressed as the function of the random variable Lg as suggested in Cappy's equation[11]:

$$\mathrm{Fmin}(Lg)=1+2\omega Lg\sqrt{(\alpha \mathrm{Wg}+\beta \mathrm{Id})(\mathrm{Rs}+\mathrm{Rg})/v_{\mathrm{ave}}} \quad (2)$$

ω : angular frequency α, β : Cappy's constants
Wg : gate width Id : drain current
Rs : source resistance Rg : gate resistance
v_{ave} : average carrier velocity

Figure 4 shows the measured Fmin at 12GHz versus Lg in some FET's whose Lg is precisely measured and the calculated result of Cappy's equation. A small difference is found between the theoretical and measured slopes in Fig. 4. This may be because v_{ave} is assumed to be constant with gate length. As the gate length was shown to have a standard deviation, 10% of the mean gate length value, Cappy's equation is understood to be useful.

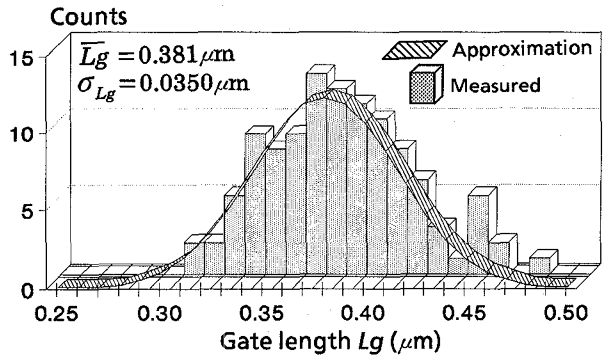


Fig. 3 : Measured distribution of Lg designed to be 0.4μm and fitting curve by gaussian approximation

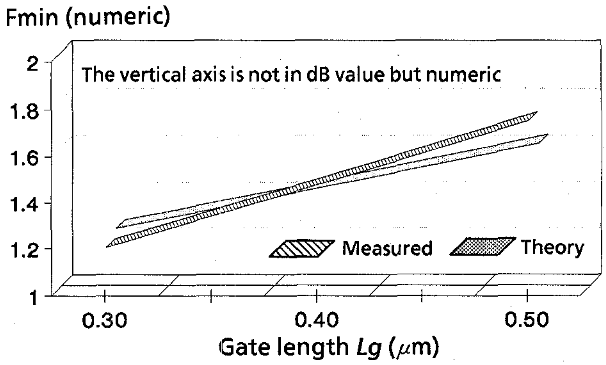


Fig. 4 : Measured Fmin at 12GHz versus Lg in some FETs whose Lg is precisely measured and the calculated result of Cappy's equation

The probability density function of the new random variable Fmin can be derived by variable transformation in Eq. (1) using Eq. (2); hence, we find as follows [12].

$$p_{\mathrm{Fmin}}(\mathrm{Fmin})=\frac{1}{\sqrt{2\pi}\,C\sigma_{Lg}}\exp\left[-\frac{(\mathrm{Fmin}-1-C\overline{\mathrm{Lg}})^2}{2C^2\sigma_{Lg}^{\ 2}}\right]$$

$$C=2\omega\sqrt{(\alpha \mathrm{Wg}+\beta \mathrm{Id})(\mathrm{Rs}+\mathrm{Rg})/v_{\mathrm{ave}}} \quad (3)$$

Figure 5 shows the measured distribution of Fmin in FET's designed to be 0.4μm and the calculation result by the Eq. (3), demonstrating a good correlation between both. Process-related variation in Lg, therefore, is also shown to be a dominant source of fluctuation in Fmin. As a result, the statistical distribution of Fmin can be calculated by this probability density function.

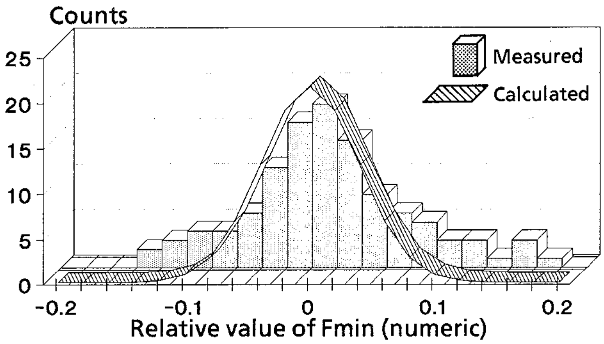


Fig. 5 : Measured distribution of Fmin in FETs designed to be 0.4μm and the calculated result of the Eq. (3)
The line is calculated by $N\Delta_{Fmin}p_{Fmin}(Lg)$, where N is the total number, and Δ_{Fmin} of 0.02 is a step value of Fmin in this histogram.

CONCLUSION

Process-related fluctuations in gate length between devices are found to be an apparent dominant source of the variation in Γopt and Fmin. Therefore, the probability density function of Fmin can be derived from the statistics of Lg-distribution, if a mathematical representation of Fmin expressed as a function of Lg, which has good consistency with experimental results, are known. Cappy's modification of Fukui's classic equation was shown to be useful.

At a shorter gate length, which promise higher performance, the relative variation would be likely to increase. The obtained equation can be used if only the mean value and the standard deviation of Lg are known, helping to estimate the yield of MMIC's using pulse-doped MESFET's. Further study is required to determine the probability density function of Γopt, because Γopt is also a key parameter in the design of low noise amplifiers.

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