THE BELL SYSTEM TECHNICAL JOURNAL
Vol. 60, No. 6, July–August 1981
Printed in U.S.A.

Noise Caused by GaAs MESFETs in Optical Receivers

By K. OGAWA

(Manuscript received January 8, 1981)

In the application of GaAs metal-semiconductor field effect transistors (MESFETS) in ultra low-noise lightwave receivers, the channel noise is often the dominant effect in determining sensitivity. This paper analyzes for the first time the excess channel-noise factor Γ for GaAs by considering the effect of circuit capacitance, as well as gate-to-source capacitance on the correlation of gate and channel fluctuations, and derives a useful and analytic expression for Γ. For example, we find that Γ for practical GaAs MESFET amplifiers can be much larger than 1.1 as is usually assumed. The multiplication factor, Γ is approximately 1.75 for the practical GaAs MESFET with 1-μm gate length, which explains the discrepancy between the optical sensitivity from the noise calculation and experiments.

I. INTRODUCTION

The GaAs metal-semiconductor field effect transistor (MESFET) originally designed for microwave applications has become an important component of lightwave receivers used in communication applications. Unlike most microwave applications, the lightwave-receiver application requires a consideration of induced gate noise and correlation with the channel noise. Van der Ziel's original evaluation of the noise contribution from this component[1–3] was later extended by Baechthold to include effects present in MESFETs with short gate length, as well as the intervalley scattering in GaAs.[4,5] The following computation extends this earlier work to determine the noise factor Γ.

This factor relates the input noise current i_{nt} resulting from all noise sources of the FET to the FET transconductance g_m such that

$$\langle i_{nt}^2 \rangle = 4kT\Gamma(\omega C_T)^2 \Delta f / g_m, \tag{1}$$

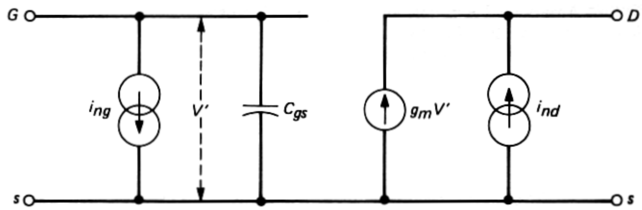


Fig. 1—Equivalent circuit of the intrinsic field-effect transistor with channel noise current i_{nd} and induced gate noise current, i_{ng}.

where C_T is the total input capacitance, k is Boltzman's constant, and T is absolute temperature.

Figure 1 shows an equivalent circuit of the intrinsic field-effect transistor with two noise sources, the channel thermal noise and the induced gate noise sources. We neglect other well-known noise sources, such as the gate leakage current noise and the flicker noise, because our main purpose is to evaluate the noise factor Γ.

The channel noise is described in the equivalent circuit by the noise current i_{nd} having the mean square

$$\langle i_{nd}^2 \rangle = 4kT \cdot P \cdot g_m \cdot \Delta f, \tag{2}$$

where P is a factor depending on various FET parameters and the gate bias.[4]

As explained in Ref. 2, every disturbance in the channel potential introduces a gate voltage disturbance and, in turn, a channel current fluctuation. The mean square of the induced gate noise current is

$$\langle i_{ng}^2 \rangle = 4kT \cdot R \cdot \frac{(\omega C_{gs})^2}{g_m} \cdot \Delta f, \tag{3}$$

where C_{gs} is the gate source capacitance and R is a factor depending on various FET parameters and the gate bias.[4] Since these two noise sources have the same origin, a correlation exists. It can be expressed in the form

$$\langle i_{ng}^* i_{nd} \rangle = j4kT \cdot Q \cdot (\omega C_{gs}) \cdot \Delta f, \tag{4}$$

where Q is a factor depending on various FET parameters and the gate bias.[4]

Figure 2 shows P, Q, and R for GaAs MESFETS of various gate lengths parameters and gate bias parameters.[5]

We evaluate the total input noise by transferring i_{nd} to the input as shown in the circuit of Fig. 3. In this circuit, the input admittance Y is defined by

$$Y_{in} = G + j\omega C_T, \tag{5}$$

capacitance C_T consists of the gate capacitance C_{gs} and a capacitance C_s comprising the photodiode capacitance of the circuit stray capacitance. The mean square of the total input noise current becomes

$$\begin{aligned}\langle i_{nt}^2 \rangle &= \langle (i_{ng} + i_{nd} Y_{in}/g_m)(i_{ng}^* + i_{nd}^* Y_{in}^*/g_m) \rangle \\ &= 4kT \left[P - 2Q \left(\frac{C_{gs}}{C_T} \right) + R \left(\frac{C_{gs}}{C_T} \right)^2 \right] \frac{(\omega C_T)^2}{g_m} \Delta f \\ &\quad + 4kTP \frac{G^2}{g_m} \Delta f. \end{aligned} \tag{6}$$

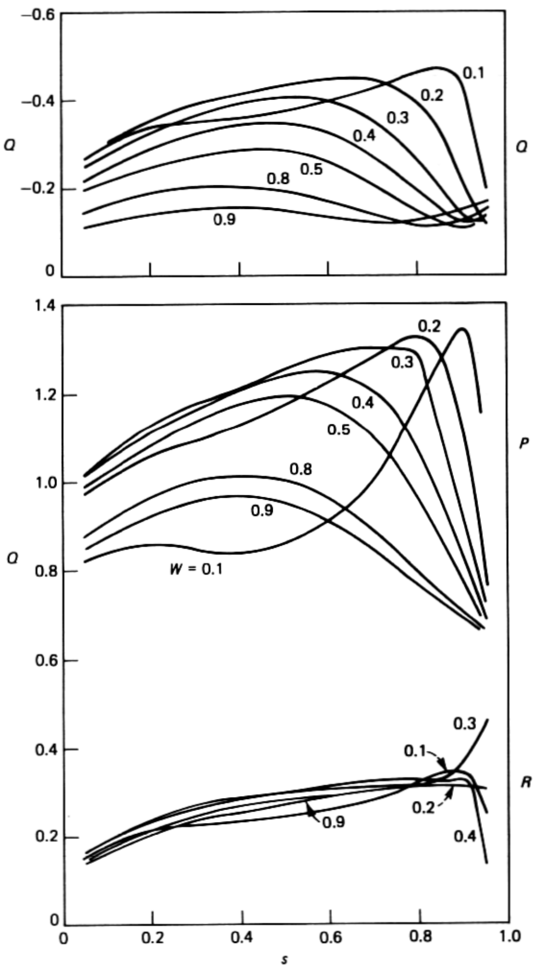
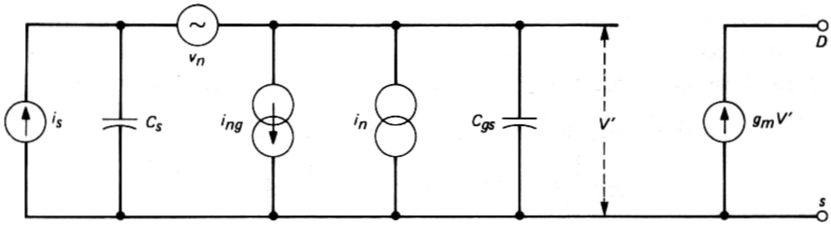


Fig. 2—The dependence of P, R, and Q on normalized gate voltage $s = [(0.8\text{-}V_g)/W_0]^{1/2}$. The normalized gate length $W = E_s L/W_0$ is the parameter used. W_0 is the pinch-off voltage, E_s is the saturation field (4kV/cm), and L is the gate length.[5]



$$\langle v_n^2 \rangle = \langle i_{nd}^2 \rangle / g_m^2$$

$$\langle i_n^2 \rangle = \langle i_{nd}^2 \rangle (\omega C_{gs})^2 / g_m^2$$

Fig. 3—Equivalent circuit as in Fig. 1 but with channel noise i_{nd} transformed into input current and voltage noise sources.

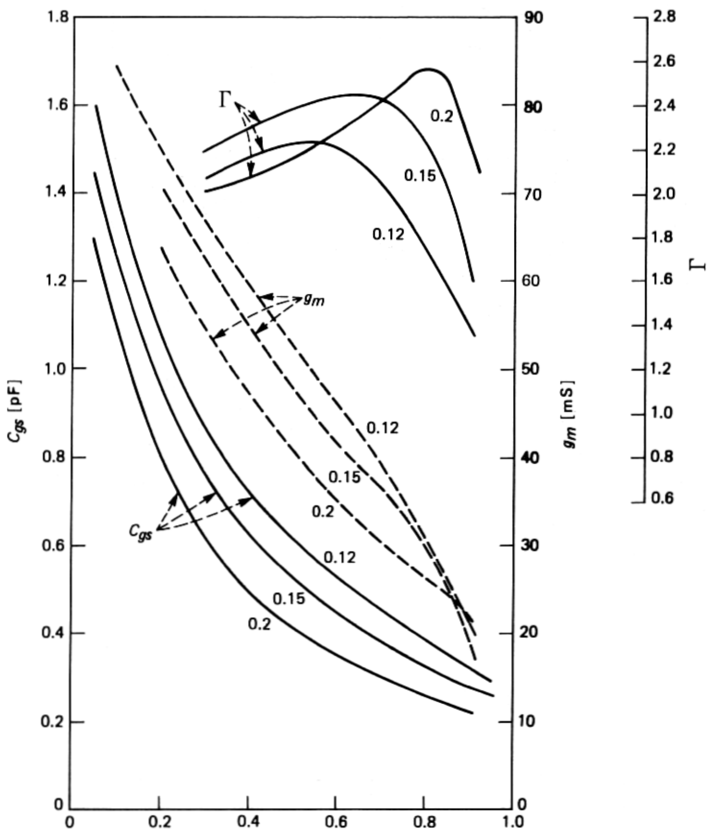


Fig. 4—Transconductance g_m, capacitance C_{gs} and Γ as functions of the normalized gate bias voltage s for $C_{gs} = C_T$. The channel depth in μm is the parameter.

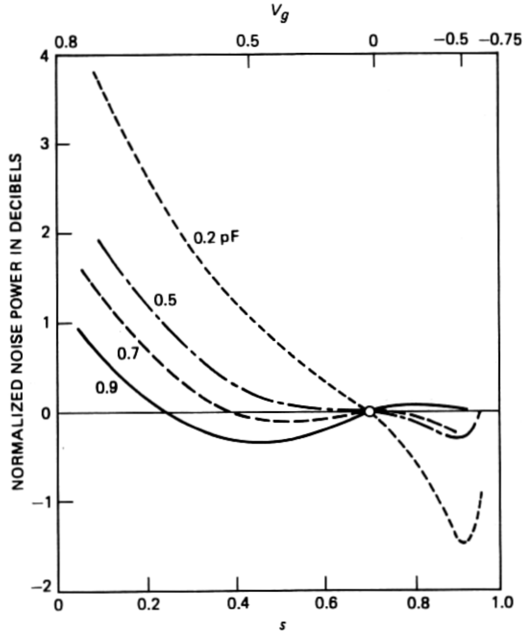


Fig. 5—FET noise power normalized with respect to noise power at zero bias voltage as a function of the normalized bias voltage s. The additional input capacitance C_s in pF is the parameter.

Since commonly $G \ll g_m$ in optical receiver design, the comparison of (1) and (6) yields

$$\Gamma = P - 2Q\left(\frac{C_{gs}}{C_T}\right) + R\left(\frac{C_{gs}}{C_T}\right)^2. \quad (7)$$

As shown in Figs. 2 and 4, P, R, Q, g_m, and C_{gs} are functions of the bias voltage and the FET gate length. However, as Fig. 5 shows, the noise

Table I—Noise factor Γ for 1-μm gate length and various C_s (C_{gs} = 0.5 pF)

C_s (pF)	Γ
0.1	2.164
0.2	2.009
0.3	1.897
0.4	1.814
0.5	1.749
0.6	1.697
0.7	1.655
0.8	1.619
0.9	1.589

$\langle i_{nt}^2 \rangle$ changes little in the bias voltage range between −0.5 V and + 0.5 V as long as C_s is between 0.5 pF and 0.9 pF in spite of the voltage dependency of P, Q, and R.

As a good approximation, one can use the noise parameters determined at zero gate bias voltage for the entire operating range of the transistor. Table I shows Γ at zero bias voltage for various capacitance values C_s, in the case of an FET gate length of 1 μm, a gate width of 400 μm which have the following parameters: $P = 1.24348$, $Q = -0.42384$, and $R = 0.30329$.

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