NOISE MODELS FOR FET TRANSISTOR

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ABSTRACT

Statistical fluctuation of electric charge exists in all conductors, producing random variation of potential between the ends of the conductor. The electric charges in a conductor are found to be in a state of thermal agitation, in thermodynamic equilibrium with the heat motion of the atoms of the conductor. The manifestation of the phenomenon is a fluctuation of potential difference between the terminals of the conductor. The term spontaneous fluctuations, although, perhaps, theoretically the most appropriate, is not commonly used in practice; usually it is simply called noise. This paper presents electrical noise types, which is a significant problem for electrical engineers designing sensitive circuit. The limit to the sensitivity of an electrical circuit is set by the point at which the signal-to-noise ratio drops below acceptable limits.

1 INTRODUCTION

Noise behavior is an important characteristic of analog circuits, as it usually determines the fundamental limit of the performance of analog circuits. Noise is a signal with random amplitude versus time. It is generated by all passive and active devices. Its average value over a certain period of time is zero and therefore its power is measured by the noise voltage v_N squared to v_N^2 and averaged over that time period.

The frequency spectrum of noise extends from nearly zero to frequencies up to 10^{14} Hz. In some cases, more noise is generated at low frequencies. At these low frequencies, the power decreases linearly with the frequency and is called 1/ f (or pink) noise. At higher frequencies, all frequencies are equally present and it is called white noise. In order to be able to take into account frequency spectra with variable amplitude, an elementary small frequency band *df* is taken. The noise power in this band is then denoted by $\overline{dv_N^2}$. The total noise in a given bandwidth from frequency f_1 to f_2 is given by

$$\overline{v_{12}} = \sqrt{\int_{f_1}^{f_2} \overline{dv_N^2} df} \quad (1)$$

In electrical circuits there are 5 common noise sources:

- Thermal or Johnson noise
- Shot noise
- Flicker or 1/f noise
- Burst or popcorn noise
- Avalanche noise

2 FET NOISE MODELS

Noise signals are small and can thus be added in the FETs small-signal model. This is shown in Fig. 1a for a FET in saturation. Two noise sources are included: thermal noise in the channel and gate leakage noise. Channel resistance R_{ch} generates thermal noise $\overline{di_{DS}^2}$, shown in Fig. 1b. It is given by

$$\overline{di_{DS}^2} = \frac{4kT}{R_{ch}} df \quad (2)$$

Resistor R_{ch} is actually the drain-source resistance in the linear region, given by R_{DS}. However, the drain-source resistance R_{DS} in the linear region approximately equals the inverse transconductance 1/gm in the saturation region. Because of field effects in the channel, the noise is reduced by a factor of 0.6 to 0.7, or about 2/3. The resistive channel noise $\overline{di_{DS}^2}$ can thus be described by

$$\overline{di_{DS}^2} = \frac{8kT}{3} g_m df \quad (3)$$

This is a truly important expression and definitely worth memorizing. In order to be able to compare the noise generated by the FET to the input signal applied, the noise is referred to the input. It is then called the equivalent input noise voltage and is represented by $\overline{dv_{ieq}^2}$. Its value is obtained by division of $\overline{di_{DS}^2}$ of Eq. (2) by g_m^2 and is given by

$$\overline{dv_{ieq}^2} = \frac{8kT}{3} \frac{1}{g_m} df \quad (4)$$

It occurs in series with the gate (see Fig. 1b). To this thermal noise source, a 1/ f noise source is added. The current dependence disappears after division by g_m^2 and given by

$$\overline{dv_{ieqf}^2} = \frac{KF_F}{WLC_{OX}^2} \frac{df}{f} \quad (5)$$

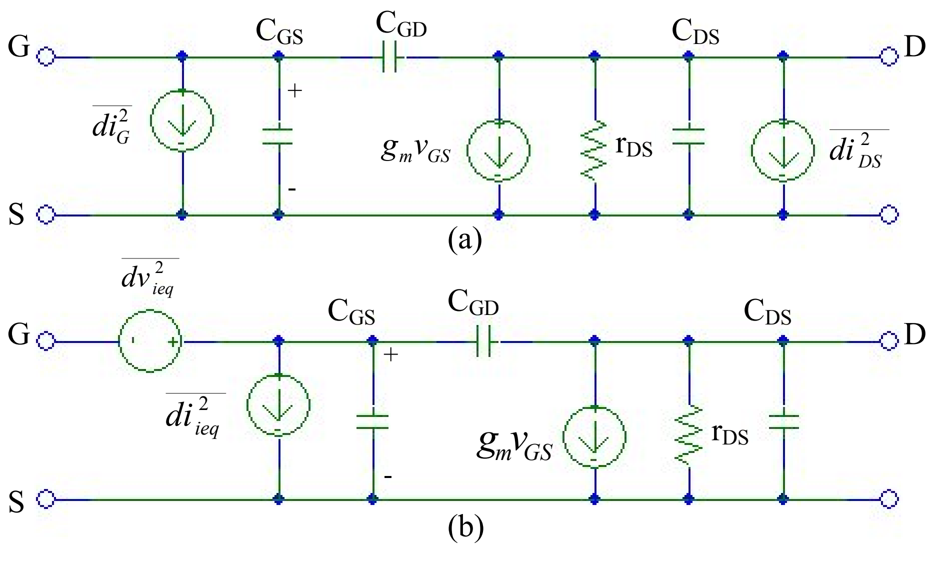

Fig. 1: *Noise sources in a FET.*

in which W and L are in cm, and C_{ox} is in F/cm^2. Constant KF_F depends on the FET used. Empirical values are:

pJFET	$KF_F \approx 10^{-33} C^2/cm^2$ (and $C_{GS} = C_{OX}$)
pMOST	$KF_F \approx 10^{-32} C^2/cm^2$
nMOST	$KF_F \approx 4x10^{-31} C^2/cm^2$

These are obviously approximate values. Depending on the actual technology they can easily differ by more than a factor of two. Note that a JFET is about ten times higher in noise power (a factor of $\sqrt{10}$ in equivalent input voltage) than a pMOST of the same size. Also note that an nMOST is considerably worse than a pMOST.

The capacitances in the small-signal circuit cause an equivalent input noise current to flow. It cause by the thermal channel noise and so it can be derived from Eq.(4) and is given by

$$\overline{di_{ieq}^2} = \frac{8kT}{3}\frac{1}{g_m}(wC_{GS})^2\,df \qquad (6)$$

It is heavily frequency dependent, and thus it become important at high frequencies, in applications of receivers or detectors, etc.

The gate leakage noise or the second noise source in the small-signal circuit of Fig. (1a) is $\overline{di_G^2}$. It is shot noise caused by the gate leakage current. For MOSTs, this current is quite small and its corresponding noise is negligible. If a protection network is added, however, the protection diode leakage current causes noise. This is also the case for a JFET in which the input gate diode leakage current causes noise.

3 NOISE PERFORMANCE OF SINGLE TRANSISTOR AMPLIFIER

The noise behaviour of the single transistor amplifier with resistive load and biasing resistor is analysed by use of the noise sources mentioned in previous subsections. These are included in the small-signal equivalent circuit at low frequencies of Fig.2, shown in Fig.3.

The transistor itself is represented by its equivalent input noise voltage $\overline{dv_{ie}^2}$. The noise voltage of the source resistor R_S is given by $\overline{dv_s^2}$. The noise current of the load resistor R_L is denoted by $\overline{di_L^2}$, and the noise current biasing resistors R_{12} is denoted by $\overline{di_{12}^2}$. All noise sources, except that of R_S, now can be lumped into one, total equivalent, input noise voltage source $\overline{dv_{it}^2}$ at the input, in series with $\overline{dv_s^2}$, (as shown in Fig. 3b). Its value can be found by equation of the total output noise of the circuit in Fig. 3a, with all the noise sources to the total output noise of the circuit in Fig. 3b, with the total equivalent input noise source $\overline{dv_{it}^2}$. This yields (assuming that $R_S << R_{12}$):

$$\overline{dv_{it}^2} = \overline{dv_{ie}^2} + R_S^2\,\overline{di_{12}^2} + \frac{\overline{di_L^2}}{g_m^2} \tag{7}$$

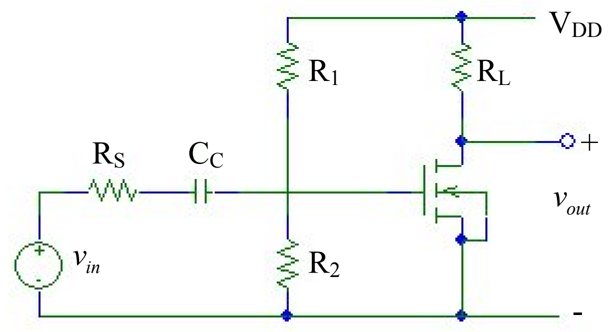

Fig. 2: *Single transistor amplifier with resistive load and biasing resistor.*

The ratio of the equivalent input noise $\overline{dv_{it}^2}$ to that of the input transistor $\overline{dv_{ie}^2}$ can be introduced by an excess noise factor y. It is obtained by substitution of $\overline{dv_{ie}^2}$ by $4kT/1.5g_m$ and of $\overline{di_{12}^2}$ by 4kT/R, which yields:

$$y = \frac{\overline{dv_{it}^2}}{\overline{dv_{ie}^2}} \approx 1 + 1.5 g_m R_S \left(\frac{R_S}{R_{12}}\right) + \frac{1.5}{g_m R_L} \tag{8}$$

It can be concluded that the equivalent input noise of the amplifier depends mainly on the noise of the transistor itself. Only large input source resistances could add some noise. For low noise applications, the transistor transconductance must be made large.

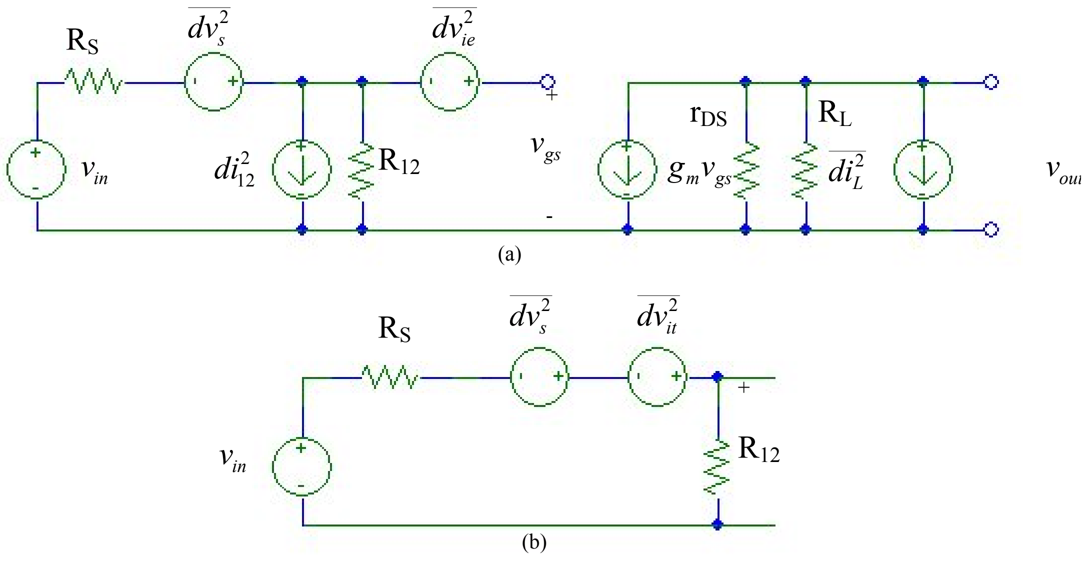

Fig. 3: *Small-signal equivalent circuit of signal-transistor amplifier at low frequencies with noise source*

4 ACKNOWLEDGMENTS

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