

General Considerations of Noise in Microphone Preamplifiers

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Abstract

In this paper a study of the noise performance of electret microphone systems as a part of hearing aids is presented. The signal-to-noise ratio of the microphone-preamplifier combination, containing a field-effect transistor (FET) and a high value resistive bias element in a hybrid configuration, is mainly determined by the noise generated in the preamplifier circuit.

A theoretical analysis of the noise sources in a source follower is given. The dominating noise sources are the channel noise of the FET, the thermal noise of the gate bias element, and finally the noise due to the gate leakage current of the FET and its package. It is shown that for the systems investigated, the noise performance does not depend on the choice of the amplifying device (JFET or MOSFET) itself, but only on its packages. Besides this, it is found that it is necessary to keep the parasitic capacitances as small as possible and to make the resistance of the bias element as large as possible.

1. Introduction

Recently, growing attention has been paid to the noise performance of electret microphone systems as part of hearing aids. The signal-to-noise ratio of the microphone-preamplifier combination is mainly determined by the noise generated in the preamplifier circuit. Until now only JFETs with a high input impedance have been used as the active part of the microphone preamplifier in a hybrid configuration, resulting in an *A*-weighted equivalent input noise of

about 13 μV typically and 19 μV maximally [1]. Because it is possible that the preamplifier will be integrated with a silicon-based microphone [2] in the future, a CMOS preamplifier, which will have a very high input impedance, seems to be another possibility. Therefore the noise performance of microphone preamplifiers with JFETs has to be compared with that of preamplifiers with MOSFETs.

In this paper only the noise contribution of the FET and the bias element are considered. The noise caused by other components, like the impedance between source and ground or between drain and supply, will be neglected because of their minor influence.

As a starting point, in Section 2 a general model of the source follower with the capacitive microphone will be considered. In Section 3 some experimental results will be presented, and the noise-to-signal ratios of source followers with JFETs and MOSFETs will be compared and discussed.

1. A General Model of the Microphone with the Source Follower

In conventional hearing aids, a first-stage amplifier is used to transform the high capacitive output impedance of the electret microphone into a low impedance. Usually a source follower is applied. In an ideal situation, this has a unity voltage gain; in practice, however, an attenuation can be expected due to parasitic capacitances. In Fig. 1(a) a source follower with an enhancement-type p-channel MOSFET is drawn together with the capacitive microphone, which can be considered as a sound-pressure-sensitive voltage

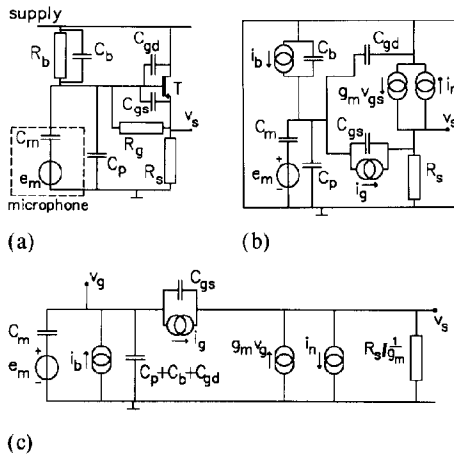


Fig. 1. (a) Capacitive microphone with a source follower with a FET T and its capacitances, a resistive bias element R_b and leakage resistance R_g due to packaging. (b) Small-signal presentation of this circuit. (c) Simplified small-signal circuit.

source e_m with an output capacitance C_m . A bias element having a resistance R_b and a (parasitic) capacitance C_b is used to provide the gate with a well defined d.c. voltage. The FET is assumed to consist of an ideal transistor T without any capacitances, a gate-to-source capacitance C_{gs} , a gate-to-drain capacitance C_{gd} and a gate-to-source leakage resistance R_g . The source resistor R_s is chosen in such a way that its noise contribution can be neglected. Finally, a parasitic capacitance C_p due to wiring is shown in the Figure. If a JFET is used, the same drawing can be used, although in that case the bias element should be connected to ground.

Three noise generators will be considered: the noise current density i_b of the bias element parallel with the bias resistor, the FET noise current density i_n between drain and source, and the noise current density i_g due to the gate leakage resistance of the FET between gate and source. In Fig. 1(b) the small-signal circuit is shown, also containing the three noise generators. To describe the small-signal behaviour of the circuit, the resistors R_g and R_b can be omitted, because their impedance is much larger than the impedance of the capacitances parallel with these resistors in the audio range of frequencies, as

required to get a frequency-independent microphone signal transfer.

The FET is considered as a current source $g_m v_{gs}$, with v_{gs} the small-signal gate-to-source voltage and g_m the channel transconductance ($\partial I_d / \partial V_{gs}$) of the FET. The channel output conductance ($\partial I_d / \partial V_{ds}$) of the FET can be neglected in the source follower configuration [3].

Analysing Fig. 1(c), which gives the simplified small-signal circuit, it is possible to calculate the contribution of the three noise sources and the signal source, and thus the noise-to-signal ratio, at the source. It can be found that the squared noise-to-signal ratio density can be expressed as [4]

$$\frac{v_s(n)^2}{v_s(e_m)^2} = \frac{(i_b^2 + i_g^2)(1/\omega)^2}{C_m^2 e_m^2} + \frac{(C_m + C_p + C_b + C_{gd} + C_{gs})^2 (i_n/g_m)^2}{C_m^2 e_m^2} \quad (1)$$

The equivalent input noise density N_i can be considered as a noise voltage source in series with the signal source e_m . N_i^2 , which can be derived from eqn. (1) by multiplying the right-hand part with e_m^2 , can be expressed as:

$$N_i^2 = \frac{(C_m + C_p + C_b + C_{gd} + C_{gs})^2}{C_m^2} \frac{i_n^2}{g_m^2} + \frac{i_b^2 + i_g^2}{\omega^2 C_m^2} \quad (2)$$

The channel noise density of a FET can be expressed as [3]

$$i_n^2 = g_m^2 \left(\frac{K}{f} + \alpha \frac{4kT}{g_m} \right) \quad (3)$$

with K a device- and bias-dependent parameter, α equal to 0.67 for JFETs and $\alpha \geq 0.67$ for MOSFETs, depending on the gate length [5].

The noise density due to the gate leakage current can be expressed as

$$i_g^2 = \frac{4kT}{R_g} + 2qI_g \quad (4)$$

In this expression R_g is the gate leakage resistance, mainly caused by packaging of the bias element and the FET. The second part of eqn. (4) with I_g , the gate current, describes the shot noise, which occurs only in JFETs because $I_g = 0$ for MOSFETs. Finally the

thermal noise density of the bias element is considered:

$$i_b^2 = 4kT/R_b \quad (5)$$

Combining eqns. (2) to (5), the total equivalent input noise density of a JFET is

$$N_{ij}^2 = \frac{(C_m + C_p + C_b + C_{gd} + C_{gs})^2}{C_m^2} \times \left(\frac{K}{f} + 0.67 \frac{4kT}{g_m} \right) + \left(\frac{1}{R_b} + \frac{1}{R_g} \right) \frac{4kT}{\omega^2 C_m^2} + \frac{2qI_g}{\omega^2 C_m^2} \quad (6)$$

and of a MOSFET

$$N_{iM}^2 = \frac{(C_m + C_p + C_b + C_{gd} + C_{gs})^2}{C_m^2} \times \left(\frac{K}{f} + \alpha \frac{4kT}{g_m} \right) + \left(\frac{1}{R_b} + \frac{1}{R_g} \right) \frac{4kT}{\omega^2 C_m^2} \quad (7)$$

It is desirable to analyse eqns. (6) and (7) for audio frequencies. Because they are frequency dependent, a simple comparison is not always possible. In order to analyse the total noise performance of the circuit in a hearing aid application, eqns. (6) and (7) have to be filtered by the so-called *A*-weighting function [6], which represents the frequency-dependent sensitivity of the human ear:

$$N_i(A)^2 = \int_{f_1}^{f_2} N_i^2 A_w^2 df \quad (8)$$

with $f_1 = 1$ Hz, $f_2 = 100$ kHz

By using eqn. (8) for source followers with JFETs and MOSFETs, in combination with eqns. (6) and (7) respectively, both configurations can be compared.

3. Experimental

In order to compare eqns. (6) and (7), a few device parameters have to be measured. For the measurements, n-channel JFETs were used, which were fabricated especially for electret microphone preamplifiers. The p-channel MOSFETs used for these experiments were fabricated at the CMOS production facility at the University of

Twente. For the noise measurements a capacitor of 2 pF was used instead of a capacitive microphone.

3.1. Channel Noise i_n of JFETs and MOSFETs

In order to determine the FET noise i_n^2 , the noise of source followers is measured with a set-up as shown in Fig. 2 ($R_b = 0$). In this circuit the output noise density can be expressed as [4]

$$N_o^2 = \left(\frac{R_s}{1 + g_m R_s} \right)^2 i_n^2 = \frac{H_A^2 i_n^2}{g_m^2} \quad (9)$$

Figure 3 shows the measured output noise density spectrum of a JFET (curve a) and a MOSFET (curve b) source follower. As can be seen in these plots, there is no significant difference in flicker noise as well as in thermal noise between JFETs and p-channel MOSFETs.

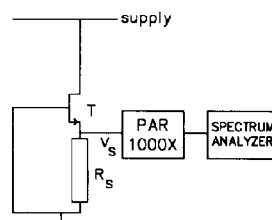


Fig. 2. Measurement set-up for the channel noise of a FET.

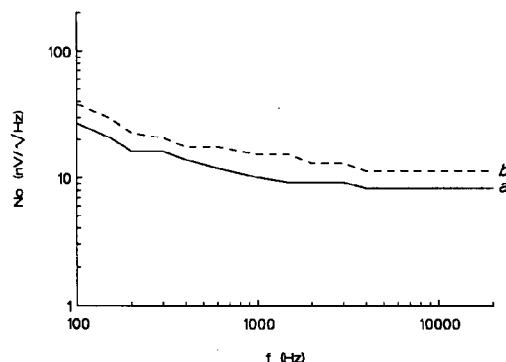


Fig. 3. Measured channel noise density as a function of frequency of (a) a JFET and (b) a MOSFET with a gate oxide thickness t_{ox} of 25 nm, a gate L of 5 μ m and a gate W of 440 μ m. Drain current $I_d = 30$ μ A.

3.2. Noise i_b of the Bias Element

In a hybrid configuration with a JFET, a thick-film resistor of several $\text{G}\Omega$ is commonly used as the bias element. If the resistor exhibits only thermal noise, its noise can be expressed according to eqn. (5). However, if the preamplifier is realized in a CMOS process, the bias element can be realized in the same process. In that case it is not desirable to use a resistor as a bias element, because it will consume too much space on the chip. A zero-biased diode or a switched-off MOSFET will be a good alternative. The shot-noise current density of a zero-biased diode can be described by

$$i_D^2 = \frac{4kT}{r_D} \quad (10)$$

and can be considered to be the thermal noise of a resistor with a small-signal resistance r_D . Using a parameter analyser, an average value of about $100 \text{ G}\Omega$ for r_D has been measured for diodes fabricated at the University of Twente. The thick-film resistor as used by Microtel [1] in their hearing aid microphones had a value of about $6 \text{ G}\Omega$.

Using these results, it can be concluded that the noise contribution of the bias element will be much larger when a thick-film resistor is used than when a diode is used. Unfortunately, it is not possible to measure the noise of the bias elements separately.

3.3. Noise i_g Caused by the Gate Leakage Current

Measuring the d.c. gate leakage current I_g of the JFET with a parameter analyser for several devices, an average value of 0.5 pA was observed.

Using a General Radio 1621 impedance measurement system, the frequency dependence of the resistive and the capacitive part of the JFET gate admittance and the admittance of the bias resistor were measured. The same measurement was done for MOSFETs with a bias diode. The capacitances were found to be 5.5 pF for JFETs and 7 pF for MOSFETs and were frequency independent.

The average values of the resistive part of

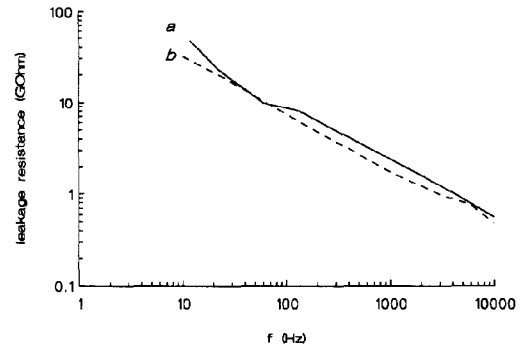


Fig. 4. Measured leakage resistance as a function of frequency of (a) a JFET with thick-film bias resistor, (b) a MOSFET ($t_{\text{ox}} = 25 \text{ nm}$, $L = 5 \mu\text{m}$, $W = 440 \mu\text{m}$) with bias diode.

the gate impedance for JFETs as well as MOSFETs have also been measured. For the JFET, this resistance is considered to consist of an ideal, frequency-independent resistor R_b of $6 \text{ G}\Omega$ parallel with a frequency-dependent resistance R_g , of which the experimental results are plotted in Fig. 4 (curve a). Note that for frequencies higher than approximately 100 Hz , the leakage resistance R_g is smaller than the $6 \text{ G}\Omega$ bias resistor R_b . Curve b shows the measured frequency-dependent leakage resistance of the circuit with a MOSFET. If these resistances exhibit thermal noise, their contribution to the equivalent input noise voltage density can also be calculated for both source followers, as shown in Fig. 5, curves a and b respectively. In Fig. 5 (curve c) the contribution of the shot noise to the equivalent input noise density of the source follower with a JFET is shown, as calculated with eqn (6). According to this Figure, the contribution of the shot noise of the JFET can be neglected in comparison with the contribution of the thermal noise due to the gate leakage resistance of the source follower.

3.4. The Equivalent Input Noise Density of Source Followers with JFETs and MOSFETs

Considering the results presented in Figs. 3 and 5 and eqns. (6) and (7), it is possible to

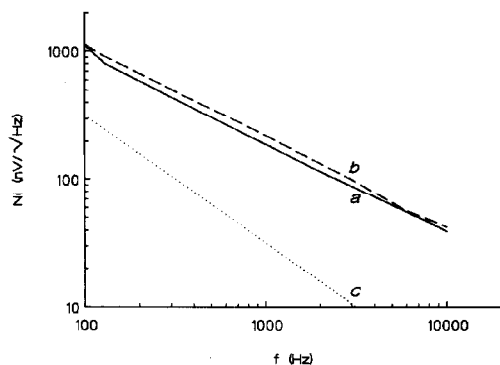


Fig. 5. Calculated thermal noise density as a function of frequency of (a) a JFET with thick-film resistor and (b) a MOSFET ($t_{ox} = 25$ nm, $L = 5$ μ m, $W = 440$ μ m) with bias diode, and calculated shot noise of the JFET ($I_g = 0.5$ pF).

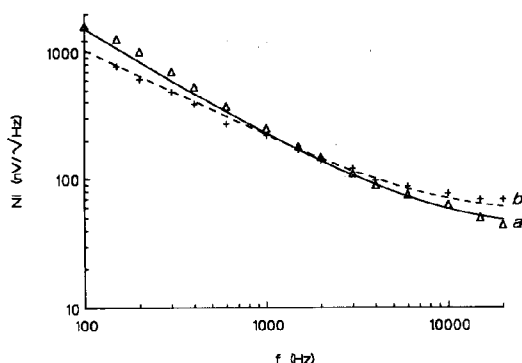


Fig. 6. Equivalent input noise density as a function of frequency of a capacitive signal source with a source follower ($I_d = 30$ μ A). (a) Calculated, with a JFET and a thick-film bias resistor of 6 G Ω , based on the experimental results of Figs. 3 (curve a) and 4 (curve a). (b) Calculated, with a MOSFET and a bias diode, based on the experimental results of Figs. 3 (curve b) and 4 (curve b). (+) Measured with a JFET and a thick-film resistor of 6 G Ω . (Δ) Measured with a MOSFET ($t_{ox} = 25$ nm, $L = 5$ μ m, $W = 440$ μ m) and a bias diode.

calculate the equivalent input noise spectrum of source followers with JFETs as well as with MOSFETs, as shown in Fig. 6 curves a and b respectively. With a spectrum analyser the equivalent input noise spectra of source followers with JFETs and MOSFETs have also been measured, as denoted in Fig. 6 by Δ and + respectively. Comparing the measured and the calculated plots, it can be concluded

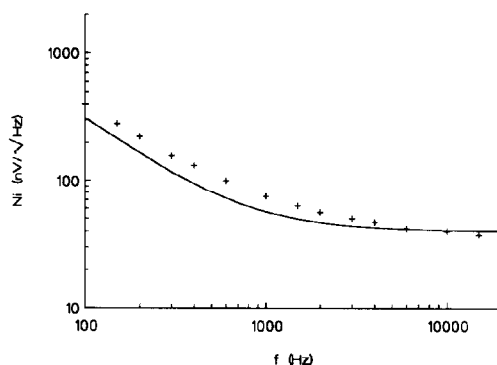


Fig. 7. (+) Measured equivalent input noise density of a completely integrated capacitive signal source with a source follower with a MOSFET ($t_{ox} = 25$ nm, $L = 10$ μ m, $W = 1000$ μ m) and a bias diode. Solid curve: calculated equivalent input noise density of a capacitive signal source with a source follower with a MOSFET ($t_{ox} = 25$ nm, $L = 10$ μ m, $W = 1000$ μ m) and a bias resistor with $R_b = 100$ G Ω , $C_b + C_p + C_{gs} + C_{gd} = 1.75$ pF, $I_d = 30$ μ A. The flicker noise of the MOSFET is based on the results in Fig. 3.

that the previous considerations concerning the three noise sources in source followers seem to be in good agreement with the experimental results. On the other hand, there is no significant difference in noise behaviour between source followers with JFETs and source followers with MOSFETs.

Finally, by comparing Figs. 5 and 6 it can be concluded that the dominant noise source is the frequency-dependent leakage resistance R_g for both types of source followers. In order to find the origin of this leakage resistance, special chips were made containing the circuit of Fig. 1 completely integrated. Because in this case the gate is not connected to a terminal of the package, the leakage resistance R_g should be infinite if it is a package resistance and still have a finite value if it is the resistance of the FET or the bias element itself. This measurement was only done with CMOS circuits, fabricated at the University of Twente. In Fig. 7 the measured equivalent input noise of this circuit is shown as a function of frequency (curve marked with +), together with the equivalent input noise calculated with eqn. (7) with $R_g = \infty$ and $R_b = 100$ G Ω (solid curve). Note that the

difference between the experimental and calculated results in Fig. 7 can be explained by the actual value of R_b , which could be smaller than $100\text{ G}\Omega$ in the completely integrated devices. For the A -weighted equivalent input noise voltage, a value of about $5\text{ }\mu\text{V}$ r.m.s. was measured. Comparing Fig. 7 with Fig. 6 (curve b), it appears that the equivalent input noise is reduced significantly due to the absence of the gate leakage resistance, which is apparently caused by the package of the MOSFET and the bias diode.

4. Discussion and Conclusions

It can be concluded that there is no significant difference in noise performance between a source follower with a JFET and one with a p-channel MOSFET, as long as the circuit is applied in a hybrid configuration. The thermal noise due to the frequency-dependent leakage resistance of the package is dominant in both types of circuits. However, if the circuit can be completely integrated with the microphone, this important noise source will be eliminated, resulting in an A -weighted equivalent input noise of about $5\text{ }\mu\text{V}$ for MOSFETs, being a significant improvement as compared with the specifications of Microtel of $13\text{ }\mu\text{V}$ [1]. In this case the noise produced by the bias element will dominate and therefore its resistance should be chosen to be as large as possible to reduce its noise contribution. However, there will

be an upper restriction for its value when a JFET is used, because the leakage current I_g of the JFET will cause a voltage drop across the bias element, resulting in a bias of the JFET which depends strongly on I_g . In the case when a MOSFET is used, which has a zero leakage current, a much larger bias resistor can be used, while the voltage drop across the bias element still can be neglected. Therefore the use of MOSFETs in a microphone preamplifier may offer a significant advantage, compared to the use of JFETs.

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