MEASUREMENT CIRCUITS AND DATA PROCESSING FOR TRANSISTOR 1/F NOISE PARAMETER EXTRACTION

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Introduction

Despite enormous developments in semiconductor technology low frequency noise is still a problem. It is an important factor determining C/N ratio of modern communication equipment (phase noise in oscillators, noise in direct conversion receivers, etc.). Its value can not be theoretically predicted with the needed accuracy. At the same time low frequency noise reflects internal processes of semiconductor devices. Targeted noise measurement can be used to determine some specific semiconductor technology features [1,2] that could lead to technology improvements. Therefore, experimental determination of noise parameters during the manufacturing process is of utmost importance. These parameters are also used in SPICE and other simulation software models instead of the default simplified 1/f noise model [3,4].

In this paper features of three widely used noise measurement circuit configurations are analysed and application options discussed. Methodology of measurement data processing and extraction of 1/f noise parameters is proposed. As an example analysis of FET noise measurement and parameter extraction is given.

Measurement circuit and measurement conditions

Different low frequency noise measurement set-ups are used in practice, but some common features can be found in all cases. Measurement circuit (MC) consists of elements maintaining:

- Appropriate bias conditions for device under test (DUT),
- Low-noise current or voltage amplifier with feedback circuit and/or calibration opportunity,
- Careful shielding and filtering ensured to avoid influence of external interference.

Noise measurement set-ups range from simple ones used to obtain experimental evidence in noise modelling [3] to very sophisticated complex measurement systems from Agilent Technologies for industry applications containing 1/f noise measurement opportunity [4,5]. In this paper we are concentrating on optimisation of noise measurement circuit to minimise errors and improve measurement efficiency. It must be stressed that special elements and circuit configuration could be chosen to ensure dominance of the target noise source in the output noise. For example, large signal source resistance in the base circuit must be used to provide measurement of the BJT base current noise parameters.

The most widespread MC configurations used in noise measurement are the following:

- Measurement circuit without a common feedback;
- Measurement circuit with a current amplifier;
- Measurement circuit with a common feedback.

Measurement circuit without a common feedback (Fig.1) is widely used in practice. The main advantage of this circuit configuration is that both signal source resistance R_G and load resistance R_L values could be chosen in large range without fear of self - oscillations starting in the circuit, being a typical problem in MC with feedback.

Disadvantage of this MC is that output noise level is dependant on parameters of DUT, as well as on values of R_G and R_L. Calibration of the circuit must be provided for each transistor separately. The same applies to DC bias that must be adjusted for each transistor. There is no stabilisation of DC bias and it could create problems in long running experiments. It is very difficult to evaluate the contribution of load resistance noise and noise from DC bias source in the output noise signal of this MC. The last is very important in FET noise measurement as will be discussed later. This MC is not suitable for noise measurement of large batch of transistors in large variety of bias conditions.

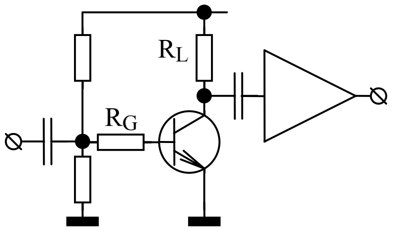

Fig.1. Measurement circuit without common feedback.

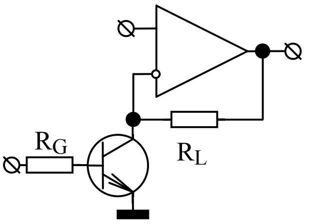

Fig.2 Measurement circuit with current amplifier.

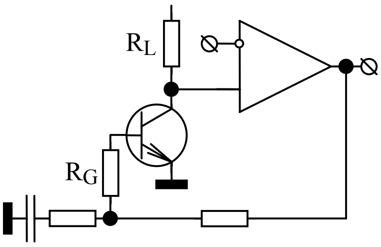

Fig.3 Measurement circuit with common feedback.

Measurement circuit with current amplifier (Fig.2) is used for example in [5]. The output noise signal directly represents current noise in corresponding circuit and variations of transistor parameters has a negligible impact on output signal. This feature of MC is valuable in current noise source measurement.

Collector current of DUT is flowing through feedback resistance R_L of current amplifier. Therefore R_L can be chosen from a limited range of values and not as large as one may wish. This is a reason why output signal level obtained with this MC could be comparably low.

In [4] modification of this MC is used. Collector current is provided from a separate current source connected to virtual ground input. As a consequence, value of R_L (and accordingly gain as well) could be increased. But in this case noise of the current source must be taken into account. An additional circuit must be introduced to maintain stability of DC bias conditions possibly cancelling all advantages of this MC.

Measurement circuit with common feedback is presented in Fig. 3. Output signal of this MC is strongly proportional to input voltage or current (at large R_G values) noise source. Common feedback for DC is to maintain stabilisation of DC bias conditions in this MC even if parameters of DUT are very diverse. This circuit is therefore the best choice for noise tests of large batches of transistors in fixed bias conditions. Disadvantage of this MC is that due to feedback self-oscillations could be observed in some regimes if bias and source resistance values are varied in a large range.

Processing of noise measurement data

The processing of measured raw data is an important stage in dermining noise parameters. Some other specific procedures must be introduced besides the application of Fast Furrier Transformation with averaging and windowing. The aim of these procedures is extraction of measurement target noise source (for example, 1/f noise) parameters from the measured signal. Data processing must include:

- The filtering of measured noise power spectral density to avoid such interfering components as 50 Hz with harmonics [6] and other.

- Subtraction of unwanted noise spectra components (for example, thermal and shot noise, G-R noise, RTS noise).
- Determination of the specific parameters in the noise model, such as KF, AF and γ for 1/f noise.

All these procedures introduce some error. Neglecting data processing accuracy can lead to the false interpretation of results. Initial measurement errors related to the estimation of low frequency noise parameters as the parameters of the stochastic process have been analysed elsewhere [7]. Here we will provide analysis of possible data processing and noise modelling errors that appear due to incomplete information.

The output noise signal of MC can be presented as a contribution of many noise sources. Power spectral density (PSD) of output signal could be expressed by the formula:

$$S_{\mathrm{EX}} = \sum S_{\mathrm{i}} K_{\mathrm{i}}^2, \tag{1}$$

where S_{i} is PSD of particular noise source and K_{i} is the corresponding voltage or the current gain factor. Most of these PSD and gain factors are unknown and only about few of them information could be obtained by theoretical calculation or measurement. The same applies to gain factors. It is even difficult to determine the number of terms in the formula. Nevertheless, this approach could be fruitfully applied in the noise modelling. It is possible to simulate noise measurement/extraction for different measurement circuits and different complexity of the transistor model[8]. By this we can evaluate and compare possible errors.

Based on common small signal and noise models one can interpret S_{EX} as:

$$S_{\mathrm{EX}} \approx S_{\mathrm{T}} K_{\mathrm{T}}^2 + \sum S_{\mathrm{K}} K_{\mathrm{K}}^2 \tag{2}$$

where S_{T} - measurement target PSD true value,
S_{K} - other known noise source PSD,
K_{T}, K_{K} - appropriate gain factors.

As a noise sources with known PSD, we will treat those that could be measured (for example, measurement system amplifier noise voltage and current source parameters) or could be calculated (for example, thermal noise of resistance). From the interpretation (2) PSD of the target noise source PSD can be calculated:

$$S_{\mathrm{TI}} = \frac{S_{\mathrm{EX}} - \sum S_{\mathrm{K}} K_{\mathrm{K}}^2}{K_{\mathrm{TI}}^2} \tag{3}$$

The value of S_{TI} obtained from (3) is a result with some relative error:

$$\frac{\Delta S_{\mathrm{T}}}{S_{\mathrm{T}}} = \frac{S_{\mathrm{TI}} - S_{\mathrm{T}}}{S_{\mathrm{T}}} = \left(\frac{K_{\mathrm{TR}}^2}{K_{\mathrm{TI}}^2} - 1\right) + \sum \frac{S_{\mathrm{K}}}{S_{\mathrm{T}}} \cdot \frac{K_{\mathrm{KR}}^2 - K_{\mathrm{KI}}^2}{K_{\mathrm{TI}}^2} + \sum \frac{S_{\mathrm{U}} K_{\mathrm{UR}}^2}{S_{\mathrm{T}} K_{\mathrm{TI}}^2} \tag{4}$$

where S_{U} - PSD of unknown noise source,
K_{TR}, K_{KR}, K_{UR} - true values of corresponding gain factors,
K_{TI}, K_{KI}, K_{UI} - approximate values of corresponding gain factors.

In the formula (4) three clearly distinguishable relative error components are present:

1. The first term represents error due to difference between true and approximate value of the gain factor for target noise source.
2. The second term represents error due to difference between true and approximate value of gain factor for known noise sources.
3. The third term represents error due to the contribution of unknown noise sources.

This formula is a very useful tool for the evaluation of accuracy of obtained results. Small signal analysis and evaluation of possible error must be provided before choice of most appropriate measurement configuration.

FET noise measurement

As an example, this approach is applied in the analysis of FET drain current I_D noise source measurement. MC with current amplifier based on OP-AMP AD743 is chosen as the most appropriate. Drain current is flowing through feedback resistance R_L. Let us assume that changing I_D value of R_L is changed accordingly to maintain constant voltage drop 10V ($R_L=10/I_D$). DC current from bias voltage sources U_{GS} and U_{DS} is negligible (few μA) and therefore their noise component could be easy to remove even with an RC filter.

Modelling of noise sources in MC provides result for output noise PSD (solid line) and its components (dotted lines) presented in Fig. 5. Output noise voltage is negligible and must be amplified. It is evident that noise source of I_D is dominant. Other noise sources could be easy calculated and subtracted.

Providing noise measurement at several I_D values and subsequent data processing procedure set of S_{EX}(f) graphs is obtained. Next step is extraction of S_{ID}. Let us evaluate possible extraction error for two cases:

- values of FET parameters are unknown,
- values of main FET parameters are determined.

In the first case FET small signal parameters are unknown and for S_{ID} extraction a simplified approach is used:

$$S_{ID} = \frac{S_{EX} - 4kTR_1 - S_{EOP}}{R_1^2} - S_{IOP}, \qquad (5)$$

where S_{EOP}, S_{IOP} – power spectral density of OP-AMPs input noise voltage and current.

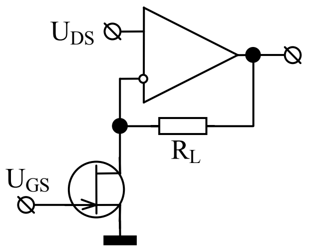

Fig.4. Measurement circuit for FET drain current noise.

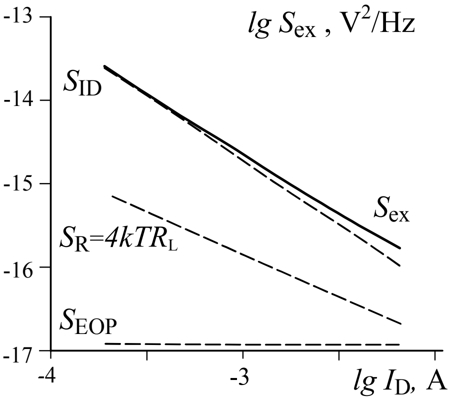

Fig.5. Noise PSD at the output of MC for $f = 1$ kHz .

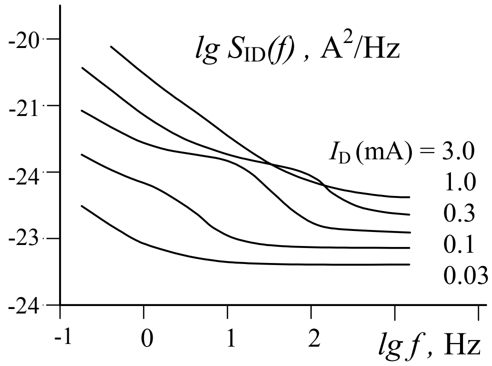

Fig.6. FET drain current noise source PSD at several I_D values. Presence of G-R noise is evident.

Analysis shows that relative error $\Delta S_T/S_T$ in determination of S_{ID} could be unacceptably high (even over 20%).

In the second case let us assume that FETs small signal parameters (transconductance g_m, source resistance R_S and channel resistance R_{DS}) are known. Then we can use an accurate formula for S_{ID} extraction:

$$S_{ID} = \frac{S_{EX} - S_{IOP}R_1^2 - 4kTR_1 - S_{EOP}\left(1 + \dfrac{R_1}{R_{DS} + R_S\left(1 + g_m R_{DS}\right)^2}\right)^2}{\left(\dfrac{R_1}{1 + g_m R_S}\right)^2} \qquad (6)$$

Error analysis with formula (4) shows, that now relative error $\Delta S_T/S_T$ is less than 2% in drain current range 0,1…10mA which is a good result. Graphs of power spectral density of FET drain current calculated with formula (6) at different I_D values are presented in Fig.6.

Conclusions

Extraction of 1/f noise parameters from measurement data is a complex task because other noise sources contribute to the output noise of the device being tested, such as thermal noise, shot noise, G-R noise and RTS noise. Contribution of hese other (unwanted) noise sources must be subtracted. There are also noise sources outside DUT, such as DC bias noise and load noise that also contribute to the measured value.

The most appropriate configuration of measurement circuit and bias conditions must be chosen to enhance contribution of target noise source and minimise contribution of internal and external noise sources in measured value.

Measurement circuit with common feedback is the most appropriate for automation of 1/f noise test on the production line.

In particular cases noise parameter extraction error could be very big (over 20%) as presented on example of FET noise measurement. Error can be decreased to less than 2% if small signal parameters of FET are determined and used in the extraction process.

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Zeltiņš M., Slaidiņš I. Mērīšanas shēma un rezultātu apstrāde tranzistoru 1/f trokšņa parametru izdalīšanai

Tranzistoru 1/f trokšņu parametru noteikšanas precizitātes uzlabošanai ieteikts novērtēt mērīšanas shēmu un mērījumu apstrādes algoritmu metodiskās kļūdas. Šīs kļūdas izraisa nepietiekami precīza maza signāla modeļa izmantošana, kā arī citu mērīšanas shēmas un paša tranzistora trokšņu avotu ietekme. Analizētas biežāk lietotās mērīšanas shēmas. Secināts, ka bipolāro tranzistoru trokšņu mērījumiem izdevīgākas ir shēmas ar kopējo atgriezenisko saiti. Lauktranzistoriem izdevīgāka ir mērīšanas shēma ar pārveidotāju strāva-spriegums. Piemērā ir parādīts, ka pilnīgāka lauktranzistora mērīšanas shēmas maza signāla modeļa izmantošana ļauj samazināt metodisko kļūdu no 20% uz 2%.

Zeltins M., Slaidins I. Measurement circuits and data processing for transistor 1/f noise parameter extraction

For improvement of accuracy of 1/f noise parameter extraction it is recommended to provide evaluation of errors introduced by measurement circuit and measurement data processing methodology. These errors appear because of approximate small signal model used, as well as due to influence of noise sources in measurement circuit and transistor itself. Often used noise measurement circuits are analysed. It is concluded that the most appropriate circuit for BJT noise measurement is one with common feedback. For FETs the most appropriate is a measurement circuit with current –voltage converter. It is demonstrated on example of FET that application of more precise small signal model for measurement circuit provides decrease of data processing error from 20 % to 2 %.

Зелтиньш М., Слайдиньш И. Измерительная схема и обработка результатов для определения параметров 1/f шума транзисторов

Для повышения точности определения параметров 1/f шума транзисторов рекомендовано оценить методические погрешности измерительной схемы и алгоритма обработки результатов измерений. Рассмотреные погрешности вызываны пользованием недостаточно точной малосигнальной модели транзистора, а также влиянием других источников шума как в транзисторе, так и в измерительной схеме. Анализ используемых измерительных схем позволяет утверждать, что для измерений шумов биполярного транзистора оптимальна схема с общей отрицательной обратной связъю, а для полевого транзистора – с преобразователем ток-напряжение. На примере измерения параметров шума полевого транзистора показано, как использование более полной малосигнальной модели позволяет снизить методическую ошибку с 20 до 2%.