# ON-WAFER NOISE-PARAMETER MEASUREMENTS AT NIST[*]

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## Abstract

NIST has developed the capability to measure noise parameters on a wafer in the 1 – 12.4 GHz range. We briefly describe the measurement method and the uncertainty analysis and present results of measurements on a very poorly matched transistor.

## Introduction

At least two National Measurement Institutes can perform noise-parameter measurements on packaged amplifiers [1-3], but there is no corresponding capability for transistors on a wafer. Noise-parameter measurements of bare transistors on a wafer pose several challenges absent from measurements of packaged amplifiers. There are difficulties associated with performing the measurements on a wafer—transmission-line losses, corrections for the probes, probe restrictions on the range of input reflection coefficients achievable, and the need for on-wafer calibration. There are also difficulties due to the properties of the transistors themselves—very low noise temperatures and often a very poor match to a nominal 50 Ω transmission line.

Though difficult, measurements of the noise parameters of bare transistors on a wafer are of enormous practical importance and are performed extensively in industry. The noise parameters of transistors must be known in order to design amplifiers and other circuits with optimal noise performance, which is of paramount importance in mobile communications, for example. There are commercial systems available for such measurements, but the noise properties of modern transistors challenge the capabilities of those commercial measurement systems at the same time that accurate knowledge of those properties becomes more important in some of the most common applications. Also, because of the increasingly small noise figures or noise temperatures to be measured, it becomes increasingly important to have a good uncertainty analysis, which is not always available in commercial systems. There is a definite need for better measurement methods, improved uncertainty analysis, and traceability, or at least an independent point of reference.

NIST has now developed the capability to measure noise parameters of a transistor on a wafer in the 1 – 12.4 GHz range. This work was done as part of the "Kelvin Project," a collaboration of groups at IBM, RF Micro Devices, and NIST, whose aim is to improve the understanding of, and the measurement methods for, the thermal noise properties of CMOS devices. Initial results can be found in [4]. Here we outline the measurement method and uncertainty analysis and present some results.

## Measurement Method

The measurement method is similar to the method used recently at NIST for amplifier noise-parameter measurements [3], modified to accommodate the on-wafer environment. Fig. 1 shows the measurement setup. An on-wafer multiline TRL calibration is performed [5] at planes 1 and 2 on the wafer, defined by the center of the through of the calibration set. The reflection coefficients at plane 1, $\Gamma_{1,i}$ are measured for a series of different terminations connected at the coaxial port of probe 1 (plane 1′). At least one of these terminations is not at ambient temperature, and for this termination the noise temperature is measured at plane 1. The probes are placed down on the device pads, and each input termination is connected, in turn, at plane 1′. For each input termination $i$, the output reflection coefficient $\Gamma_{2,i}$ and the noise temperature $T_{2',i}$ at plane 2′ are measured. Probe 2 is treated as an adapter, and its available power ratio $\alpha_{2'2}$ is computed from its S-parameters (measured in the on-wafer calibration process) and $\Gamma_{2,i}$. (For simplicity, we suppress the subscript $i$ on $\alpha_{2'2}$.) Knowing $\alpha_{2'2}$, we can compute the output noise temperature at plane 2 in terms of $T_{2',i}$ in the usual manner, from $T_{2'} = \alpha_{2'2}T_2 + (1 - \alpha_{2'2})T_a$, where $T_a$ is the temperature of the probe, assumed to be ambient. In addition to the forward measurements, one reverse measurement is made, with $T_1$ measured when port 2 is terminated with a

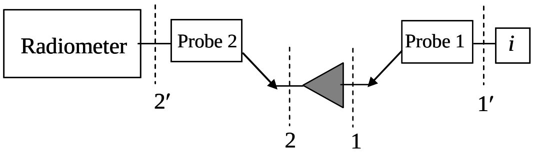

Fig. 1 Configuration for forward measurements.

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(nearly) matched load at ambient temperature. A simultaneous fit is then performed to all the measurements, using equations from [6] for $T_{2,i}$ (and $T_1$ for the reverse configuration) in terms of the real parameters $X_1$, $X_2$, and the complex $X_{12}$. (Note that (6) of [6] incorrectly used $X_{12}$ rather than $X_{12}^*$.) The fitting parameters are the $X$ parameters and $G_0 \equiv |S_{21}|^2$. The $X$ parameters are directly related to the elements of the noise matrix in the wave representation [7]. The more familiar IEEE noise parameters are related to the $X$'s by algebraic expressions involving the S-parameters.

## Uncertainty Analysis

The uncertainties are evaluated in a manner similar to that used in amplifier noise-parameter measurements [6]. The type-A uncertainties are the square roots of the diagonal elements of the covariance matrix, obtained from the fitting routine. Because the fit is done for the $X$ parameters, the type-A uncertainties obtained are those for the $X$ parameters. To obtain the type-A uncertainties in the IEEE parameters, the covariance matrix obtained in the fit must be converted to a covariance matrix for the IEEE parameters through use of the Jacobian matrix for the transformation between $X$ parameters and IEEE parameters. The type-B uncertainties are evaluated with the Monte Carlo method previously developed for amplifier measurements [6]. This program evaluates the type-B uncertainties for both $X$ parameters and IEEE parameters. The original amplifier applications were restricted to relatively small values of $|\Gamma_{opt}|$ (less than about 0.4), which are often exceeded by bare transistors, so the program was modified and extended to allow its application to values of $|\Gamma_{opt}|$ up to one.

## Results

Measurements were made on an NMOS transistor with 0.12 μm gate length, designed by RF Micro Devices and fabricated by IBM as part of the Kelvin Project. Details of the device are contained in [4]. The results for the minimum effective input noise temperature $T_{min}$ are shown in Fig. 2. The error bars correspond to the standard combined uncertainty $u_c$. At low frequencies, the measured noise temperature is smaller than our uncertainty, demonstrating the need for improved measurement methods for these transistors. The anomalously large uncertainty at 10 GHz is due to a particularly poor set of input states, which was not obvious in advance. We intend to screen for such problems in the future. Further results are in [4] and a forthcoming full paper.

## Discussion and Conclusions

The results for $T_{min}$ in the 1 – 5 GHz range indicate a need for smaller uncertainties. Common commercial systems do not provide uncertainties for their results, but inter-laboratory comparisons [4] show that they, too, need improvements to properly measure existing transistors. We expect to reduce our uncertainties by improving our selection of input states. We also will investigate the effect of using a below-ambient input state, either instead of, or in addition to, the hot source. Even with our present uncertainties, this capability provides a very useful reference for a very large, important industry sector.

## References

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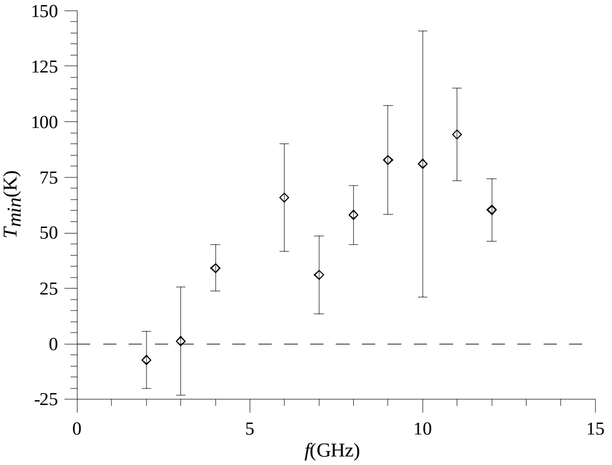

Fig. 2 Measurement results for $T_{min}$.

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