INTERLABORATORY COMPARISON OF NOISE-PARAMETER MEASUREMENTS ON CMOS DEVICES WITH 0.12 μm GATE LENGTH*

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Abstract—We present results of an interlaboratory comparison of S-parameter and noise-parameter measurements performed on 0.12 μm gate-length CMOS transistors. Copies of the same device were measured at three different laboratories (IBM, NIST, RFMD), and the results were compared. Each of the laboratories used a different measurement method, although two used similar commercial systems. Effects of different calibration reference planes are shown. The devices measured have large values of $|S_{11}|$, $|S_{22}|$, and $|\Gamma_{opt}|$, and have very low minimum noise figures (below 0.2 dB) over some of the frequency range. For the most part, the measurements at the different laboratories are in reasonable agreement, though there are discrepancies. It is also evident that the noise performance of the devices is better than our ability to measure it.

***Index Terms*—CMOS transistors, noise, noise parameters, on-wafer measurement**

I. Introduction

APPLICATIONS of CMOS transistor technology have expanded greatly over the past few years. The 1 – 10 GHz frequency range is now very important, and applications are moving to still higher frequencies as well. The 1 – 10 GHz range poses a major challenge for noise-parameter measurements because the devices tend to be very poorly matched at those frequencies. Exacerbating the measurement problem is the fact that the noise performance of the devices is excellent, with noise figures often significantly below 0.5 dB, which would pose a challenge by itself.

Groups within IBM, RF Micro Devices (RFMD), and the National Institute of Standards and Technology (NIST) have formed a collaboration (the "Kelvin" Collaboration) whose goals include improved understanding of, and better measurement methods for, the thermal noise properties of CMOS devices, especially above about 1 GHz. This paper is the first report of results from that collaboration.

An initial step toward improving measurement methods for low-noise, poorly matched devices is to assess the accuracy of present-day measurements. Even if improved methods are not developed, it would be useful to know how accurately the noise parameters can be measured, since the results of such measurements are used to determine parameters in models that are then used to design new devices.

Since most of the electronics industry uses commercial noise-parameter measurement systems, for which a complete uncertainty analysis may not be available, it would be useful to at least compare measurements made by different laboratories. Some time ago, interlaboratory comparisons were performed on GaAs devices [1,2]. The present paper reports results of a comparison of noise-parameter and S-parameter measurements on NMOS transistors with 0.12 μm gate length, fabricated in CMOS process technology at the IBM foundry and measured at the IBM, RFMD, and NIST laboratories. Significant effort was devoted to designing devices for low noise characteristics. Each participating laboratory was sent a die containing the same transistors and calibration structures, with all three dies coming from the same wafer. The different laboratories measured different frequencies in the 0.5 – 26 GHz range, according to the capabilities of their measurement systems. The ranges were 0.5 – 6 GHz for RFMD, 2 – 12 GHz for NIST, and 2 – 26 GHz for IBM. Several different experiments or series of measurements on different structures are in progress or planned. This paper reports the first results on a comparison of measurements on the same transistor design, at the same bias conditions, at the three laboratories.

II. Measurement Methods

IBM and RFMD use commercial on-wafer noise-parameter measurement systems. Though not identical, the two systems are quite similar. Both use one hot and many ambient-temperature input states [3,4,5] and fit an equation for the output power in terms of the noise parameters. In both systems, the different ambient-temperature input states are generated by an electronic tuner. The noise parameters of the measurement system's receiver are determined first, and then the noise parameters of the device under test (DUT) plus the receiver are measured. The noise parameters of the DUT are then extracted. The results are given in terms of the IEEE form for the noise figure,

$$F(dB) = 10\log\left(\frac{T_0 + T_e}{T_0}\right),$$

$$T_e = T_{e,\min} + \frac{4R_n T_0}{Z_0}\frac{\left|\Gamma_i - \Gamma_{opt}\right|^2}{\left(1-\left|\Gamma_i\right|^2\right)\left|1+\Gamma_{opt}\right|^2},$$

where Γ_i is the reflection coefficient of the input termination, the reference impedance Z_0 is taken to be 50 Ω, and T_0 = 290 K. The noise parameters to be determined are the minimum noise figure F_{min}, corresponding to $T_e = T_{e,min}$, the noise resistance R_n, and the complex Γ_{opt}, which is the value of the input reflection coefficient that yields the minimum value for the noise figure (or T_e). Fig. 1 shows the location of the relevant on-wafer reference planes (in a highly distorted representation). The reference planes are shown only on the left side in Fig. 1, but obviously they occur in symmetric pairs (except M). The initial calibration at both IBM and RFMD is normally performed at the probe tips, plane P in Fig. 1, through an off-wafer calibration [6], LRRM (line-reflect-reflect-match) in the case of RFMD and SOLT (short-open-line-thru) for IBM. A de-embedding process is used to extract the S-parameters and the noise parameters at the transistor reference planes (plane T) from the probe-tip results [7]. The de-embedding relies on measurements of an auxiliary structure on the die, an open located at the transistor reference planes. For comparison purposes, IBM and RFMD also calibrated and measured at the D reference plane used by NIST (below).

NIST has recently developed the capability to perform noise-parameter measurements on wafer. The method will be described in detail elsewhere; here we summarize it briefly. The NIST measurements begin with an on-wafer multiline TRL (thru-reflect-line) calibration [8,9] at a reference plane corresponding to the center of the Thru of the on-wafer multiline TRL calibration set included on each die (plane M in Fig. 1). The reference plane is then translated back 12 μm, to the location of the center of the vias going down to the transistor (plane D in Fig. 1). This translation is possible because the multiline TRL calibration determines the propagation constant of the transmission line, in addition to the S-parameters of the probe. The noise measurements are similar to those done for a packaged amplifier, using the NIST coaxial radiometer to measure the output noise temperature for a number of different known inputs. A succession of terminations (one hot, eight at ambient temperature) is connected to the input, and the resulting on-wafer reflection coefficients are measured. The output noise temperature at plane D is measured for each input termination. Besides these forward measurements, a reverse measurement is made, of the noise temperature at the input of the device when the output is terminated in a matched load at ambient temperature (T_{rev}). The noise parameters (and gain) are obtained by fitting the expression for output noise temperature as a function of the noise parameters, gain, and the known characteristics (reflection coefficients and noise temperatures) of the terminations.

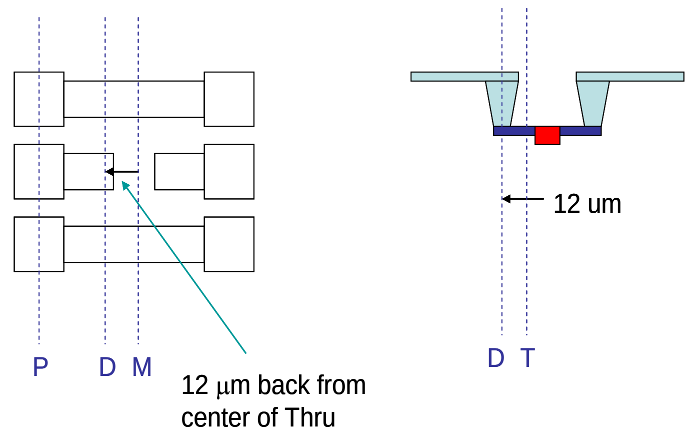

Fig. 1 On-wafer reference planes for measurements.

The uncertainties in the NIST measurements are evaluated in a manner similar to that used in amplifier noise-parameter measurements [10,11]. 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 not for the IEEE parameters, but rather for the X parameters of [11], 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 [11]. The original amplifier applications were restricted to relatively small values of $|\Gamma_{opt}|$ (less than about 0.4), which would be of little use in the present case, so the program was modified and extended to allow its application to values of $|\Gamma_{opt}|$ up to one.

III. Measurement Results and Comparison

The transistor for which results are presented is a 128×3×0.12 NMOS device in which there are 128 fingers of polysilicon over a 3 μm wide active channel, with a transistor gate length of 0.12 μm processed in 0.13 μm CMOS process technology. It was biased with a drain voltage V_{ds} = 1.2 V and J = 25 μA/μm. This transistor with this set of bias conditions is referred to as R2 in the figures.

All three laboratories measured the noise parameters using an on-wafer TRL calibration. NIST and IBM translated the reference plane from M to D, whereas RFMD left the reference plane at M. This 12 μm difference in the reference plane location should have little effect, since even at 10 GHz it corresponds to 4×10^{-5} of a (free-space) wavelength. Since measurement of S-parameters underpins any noise-parameter measurement, results for the S-parameters at plane D were also compared. Results for S_{11} of the device at plane D are graphed in Fig. 2, which shows good agreement among the three laboratories. It also shows that $|S_{11}|$ is quite large, very near 1 at low frequency. The agreement for S_{22} (not shown) is also good, but its magnitude is about 0.5 or less.

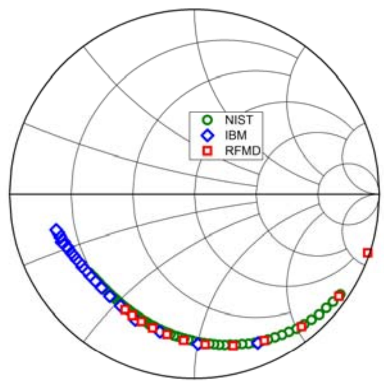

Fig. 2 Measured values for S_{11} at reference plane D.

The results for the noise parameters at plane D are shown in Fig. 3(a) – (d). Error bars on the NIST results correspond to the standard uncertainty (one-sigma) of [12]. For the minimum noise figure in dB (F_{min}), graphed in Fig. 3(a), there is a considerable spread among the measured values, with differences of around 0.5 dB at the low frequencies. The NIST uncertainties and the differences among the measurements at the different laboratories indicate that F_{min} is smaller than the collective resolution at low frequencies. For R_n in Fig. 3(b), there is good agreement at the higher frequencies, but there appears to be a systematic divergence of one or two ohms at the lowest frequencies. The situation for $|\Gamma_{opt}|$, Fig. 3(c), is rather muddled at the lowest frequencies, where it is very difficult to measure due to its large value (0.9 or above). At the higher frequencies, the NIST and IBM results differ by about 0.1 or a little more. Fig. 3(d) shows that the measurements of ϕ_{opt}, the phase of Γ_{opt}, at all three laboratories are in very good agreement, except for one point.

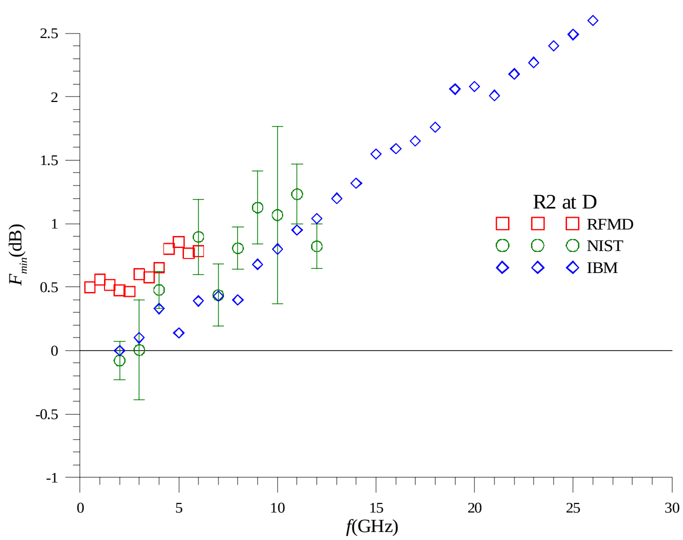

Fig. 3(a) Measurement results for F_{min}(dB) at plane D.

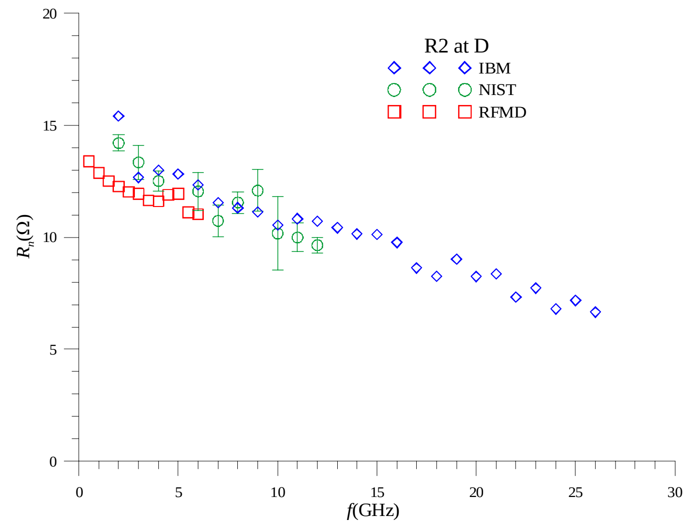

Fig. 3(b) Measurement results for R_n at plane D.

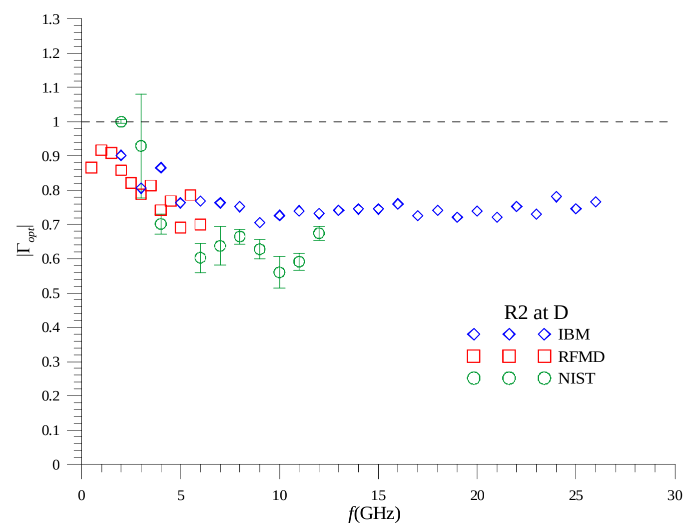

Fig. 3(c) Measurement results for $|\Gamma_{opt}|$ at plane D.

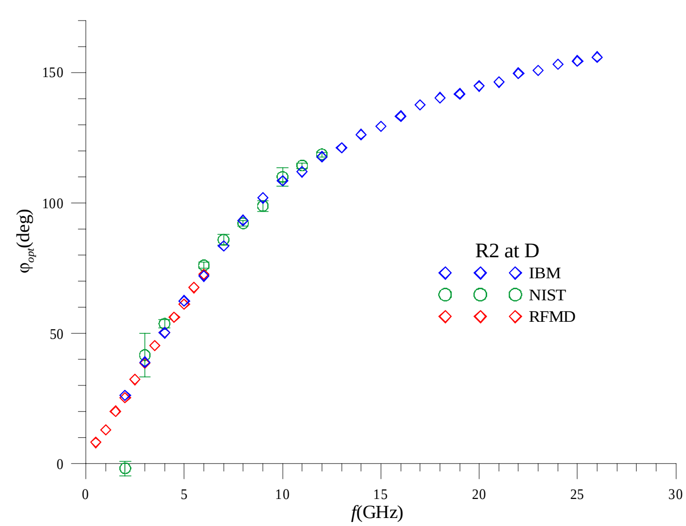

Fig. 3(d) Measurement results for ϕ_{opt} at plane D.

IBM and RFMD also performed probe-tip calibrations to measure the noise parameters at the probe tip, and used "open de-embedding" [7] to obtain the noise parameters at the transistor, plane T. Fig. 4(a) – (d) show the RFMD and IBM results at the probe tip. There is very good agreement for ϕ_{opt}, Fig. 4(d), but for the other three parameters there is a systematic difference at low frequencies. The two sets of results appear to converge as the frequency increases. The results at reference plane T are qualitatively similar, but the de-embedding process can introduce some erratic behavior at a few points.

IV. Conclusion

There are two basic conclusions from the measurement comparison. One is that the noise performance of the devices is very good at low frequencies, although the matching is poor. The other conclusion is that the present measurement methods are inadequate to measure just how good the noise performance is at the lower frequencies.

Given what we know about the uncertainties, the agreement is not so bad, but neither is it good. If the RFMD and IBM results are assigned uncertainties comparable to those of the NIST measurements, then for the most part, the results at the different laboratories are in agreement. However, it is evident that the uncertainties need to be considerably smaller to measure these devices at frequencies below about 6 GHz.

There are several possible improvements that could be explored. The calibrations of the hot noise sources used in the measurements could be checked or updated, since a discrepancy in the noise-source calibrations would induce corresponding discrepancies in the noise parameters. Analysis of the NIST results indicates that inclusion of a measurement of the noise temperature from the device input (T_{rev}) could reduce the uncertainties in $|\Gamma_{opt}|$ in the RFMD and IBM measurements. The NIST measurements could be improved by the inclusion of more input states, or perhaps by a better distribution of input states. Finally, the measurements at all three laboratories could benefit from the inclusion of a cold

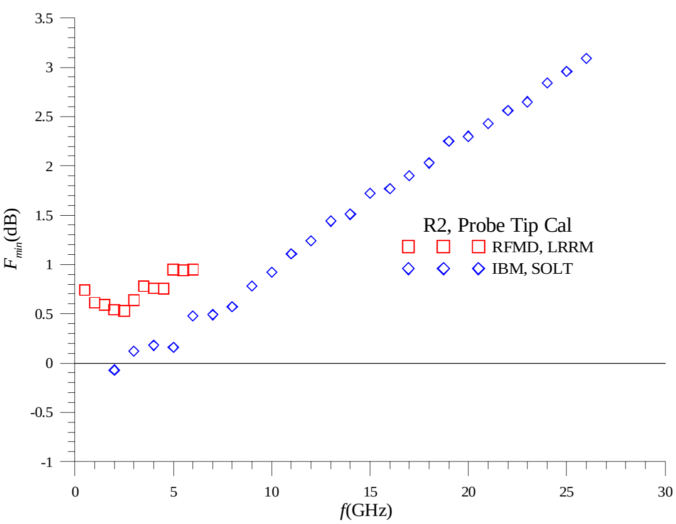

Fig. 4(a) Measurement results for F_{min}(dB) at plane P.

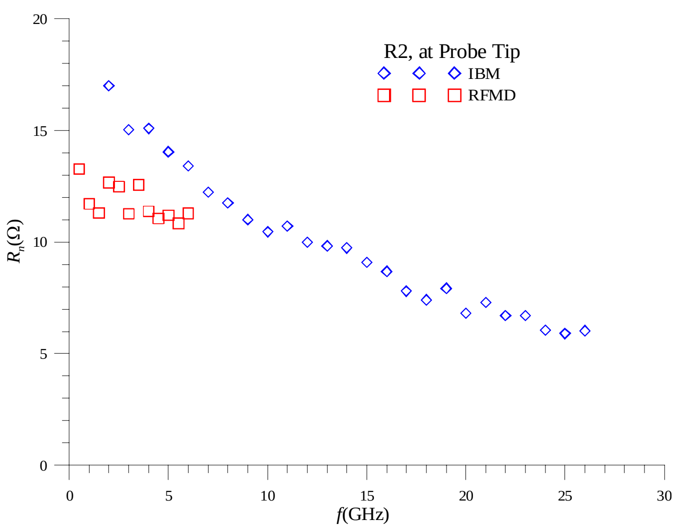

Fig. 4(b) Measurement results for R_n at plane P.

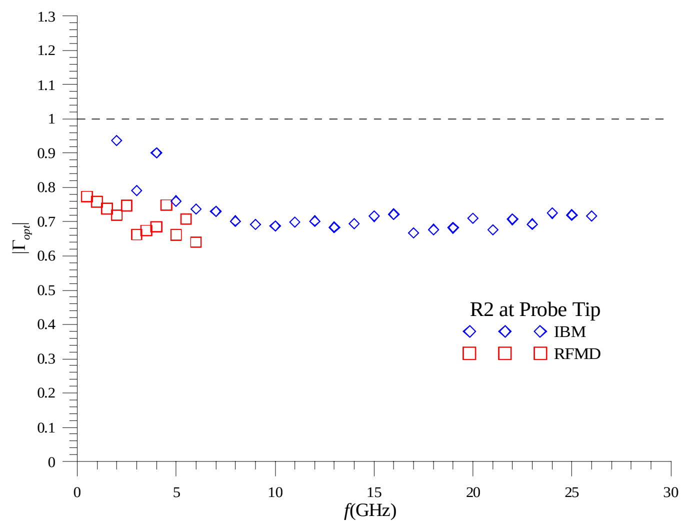

Fig. 4(c) Measurement results for $|\Gamma_{opt}|$ at plane P.

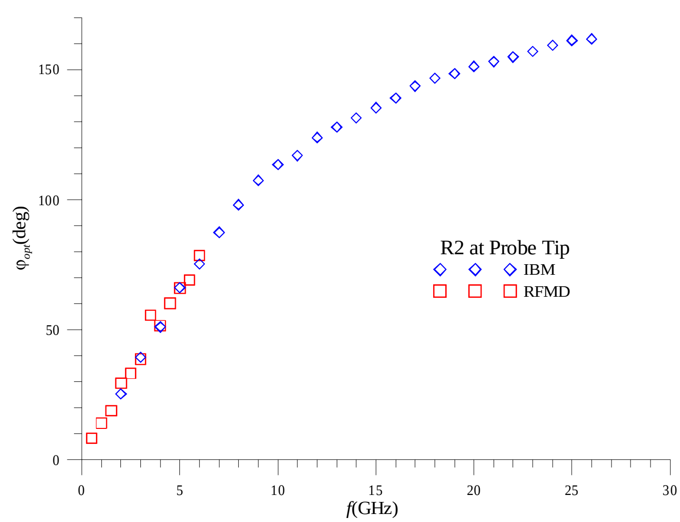

Fig. 4(d) Measurement results for ϕ_{opt} at plane P.

(i.e., well below ambient temperature) noise source as one of the input states. Simulations indicate that using a cold noise source improves the uncertainties in measurements on low-noise amplifiers [11], and it is likely that the same would be true for the present case as well. We hope to try some or all of these improvements as the Kelvin Collaboration continues.

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