Characterization and Applications of On-Wafer Diode Noise Sources

Lawrence P. Dunleavy, *Senior Member, IEEE,* James Randa, *Senior Member, IEEE,*
David K. Walker, Robert Billinger, and John Rice

***Abstract*—A set of wafer-probeable diode noise source transfer standards are characterized using on-wafer noise-temperature methods developed at the National Institute of Standards and Technology (NIST), Boulder, CO. We review the methods for accurate measurement and prediction of on-wafer noise temperature of off-wafer and on-wafer noise source standards. In analogy with the excess noise ratio (ENR) for hot noise temperatures, we introduce a representation for cold noise temperatures called the cold noise ratio (CNR), which is expressed in decibels. The ENR and CNR noise source representations share the property that the difference between off-wafer and on-wafer values may be approximated by the probe loss. We present measurements of the on-wafer ENR and reflection-coefficient information for a preliminary set of on-wafer diode transfer standards at frequencies from 8 to 12 GHz. Such transfer standards could be used in interlaboratory comparisons, as a noise calibration verification tool, as direct calibration artifacts, or as the basis for a new "noise-source probe" conceptualized here.**

***Index Terms*— Noise, noise characterization, noise measurement, noise source, noise temperature, on-wafer noise measurement.**

I. INTRODUCTION

WHEN A microwave noise measurement requires an on-wafer measurement reference plane, the current practice involves translating the excess noise ratio (ENR) from an off-wafer reference plane. This is accomplished using knowledge of the S-parameters, or often just an estimate of the insertion loss, for the wafer probe adapter network. It is important to validate that the equations describing ENR translations are accurate—even when multiple transmission media are involved. Such ENR translation is used as part of the calibration for either a two-port scalar on-wafer noise-figure measurement [1] or a two-port on-wafer noise-parameter measurement [2]. There is currently no good way to independently verify the accuracy of the ENR translation to an on-wafer reference plane.

To address this, the National Institute of Standards and Technology (NIST), Boulder, CO, has developed the capability to accurately measure one-port noise temperature on a wafer or on a substrate (in this paper, the term "on-wafer" refers to either case) [3], [4]. An example of a one-port noise temperature measurement would be that used to calibrate the ENR of a coaxial diode noise source. We applied this one-port on-wafer noise measurement capability to characterize a preliminary set of on-wafer diode sources as presented at a recent conference [5]. This paper expands on this work, detailing the system characterization, as well as the relevant formulations for prediction of on-wafer noise properties associated with known off-wafer sources.

There are many possible applications for on-wafer noise diode transfer standards. Such standards can be used as the basis for interlaboratory comparisons of one-port noise measurement capabilities. A one-port noise measurement verification would represent a partial check for two-port on-wafer noise measurement calibrations. This type of check would supplement other techniques that have been suggested to improve confidence in on-wafer noise-parameter measurements with passive verification devices [6], [7]. They may also be useful as calibration artifacts, replacing off-wafer coaxial sources for some one-port, as well as two-port, test configurations. Since an on-wafer noise diode cannot be easily connected to the input of a two-port on-wafer device-under-test (DUT), a new noise-source probe is suggested that would facilitate their use in direct calibration of scalar on-wafer noise-figure measurements.

II. MEASUREMENT CONFIGURATIONS AND SYSTEM CHARACTERIZATION

A. Measurement Configurations

Fig. 1 contains a block diagram of our experimental setup for the measurement of on-wafer noise temperatures, with relevant reference planes numbered. The radiometer used in the measurements also contained an isolator, thus, there are isolators immediately to the left and right of plane 0. The radiometer is similar in design to that used in previous tests [3], [4], but is a developmental unit that has not been fully qualified for calibrations. The configuration of Fig. 2 is used to measure the on-wafer diode sources. The bias for the on-wafer diode is supplied through Probe 2 from an off-wafer current source. The cryogenic and ambient standards are used to calibrate the radiometer. The radiometer is switched between the ambient standard noise source (plane 1), the cryogenic standard noise source (plane 2), and the on-wafer device (plane 7), as the delivered power from each is measured and recorded. A previously measured high-temperature coaxial diode noise

---

Manuscript received March 1998; revised September 1998. This work was supported in part by the NIST/Industrial MMIC Consortium.

L. P. Dunleavy is with the Department of Electrical Engineering, University of South Florida, Tampa, FL 33620 USA.

J. Randa, D. K. Walker, and R. Billinger are with the National Institute of Standards and Technology (NIST), Boulder, CO 80303 USA.

J. Rice was with the National Institute of Standards and Technology (NIST), Boulder, CO 80303 USA. He is now with the National Weather Service, Marquette, MI 49866 USA.

Publisher Item Identifier S 0018-9480(98)09267-9.

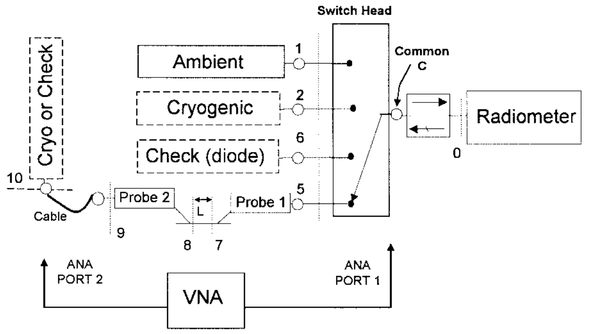


Fig. 1. Configuration used for VNA characterization of the test system and for measurement of off-wafer cryogenic and diode "check" standards through probe networks. For on-wafer measurement of off-wafer standards, the probes are connected either to an on-wafer line (L) or thru (T) CPW standard. For the case of the thru, planes 7 and 8 are coincident.

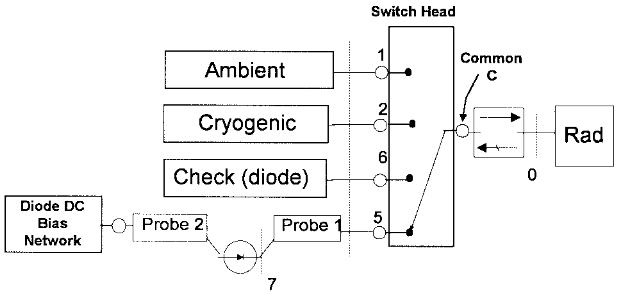


Fig. 2. Configuration for characterization of on-wafer diode noise sources. Bias is applied through Probe 2.

source, or check standard, is connected at plane 6. Its noise temperature is also measured to confirm the proper operation of the radiometer.

Fig. 1 also depicts the configuration used to verify the on-wafer noise-temperature measurements using known off-wafer standards. This verification is accomplished by connecting either a diode check standard or cryogenic standard to reference plane 10 and measuring the noise temperature at reference plane 7 with both probes connected to an on-wafer transmission line. The noise temperature at plane 7 can also be predicted from the known off-wafer noise temperature and the measured properties of the cable and Probe 2. Measurement and prediction are compared to partially verify the methods. When the cryogenic standard is measured in this way, the check standard is used as the nonambient standard in the calibration of the radiometer.

B. System Characterization Using Vector Network Analyzer (VNA) Measurements

Reflection coefficients and S-parameters of various parts of the system needed for computing the desired on-wafer noise temperatures are measured using a VNA in conjunction with NIST's MultiCal thru-reflect-line (TRL) calibration and deembedding software [8], [9]. A "first-tier" calibration is established by measuring coaxial TRL standards at the ends of the VNA test cables, providing reference planes at VNA Port 1 and VNA Port 2 of Fig. 1. The reflection coefficients of the cryogenic and check standards are measured using one of these test ports. Next, measurements are made of the switch path two-port S-parameters S(2-0), S(5-0), S(6-0). The ambient standard and the associated switch path do not need to be measured since the switch path is held at the same ambient temperature T_a and the available noise power produced at plane 0 is known (kT_aB, where k is Boltzmann's constant and B is the receiver bandwidth). Finally, a "second tier" calibration is performed by connecting the VNA cables to planes 10 and 5 and then measuring a set of on-wafer coplanar waveguide (CPW) TRL standards connected between the probes. Using the measured data from the coaxial (first-tier) and on-wafer (second-tier) TRL standards, MultiCal determines the S-parameters, $SP1$ and $SP2$, of the two probe networks. The orientation of these results is as follows: $SP1$ represents the two-port S-parameters from plane 5 to plane 7 (located in the middle of the on-wafer thru standard) in Fig. 1. $SP2$ represents the two-port S-parameters from plane 8 (coincident with 7 when the probes contact a CPW thru) to plane 10.

A few additional measurement sets are needed to facilitate the on-wafer noise-temperature measurements. The S-parameters from 7 to 0 are determined by cascading $SP1$ (with input and output ports interchanged), and S(5-0). The reflection coefficients for all of the on-wafer one-port DUT's (e.g., the on-wafer diode noise sources to be described below) are measured at reference plane 7 using two-tier deembedding within MultiCal. For determination of on-wafer noise-temperature due to an off-wafer standard, the combination of the off-wafer standard, cable, Probe 2, and line (or thru) standard connected between planes 10 and 7 is treated as a one-port device. The on-wafer diode reflection coefficients are measured at plane 7 in Fig. 2. For reasons that will be explained later, this reference plane differs from plane 7 in Fig. 1 in that it has been transformed from the middle of the thru calibration standard to the probe tip using MultiCal.

One of the steps involved in the measurement is the determination of the complex characteristic impedance Z_0 of the line standards [10] used in each TRL calibration set and using transformations facilitated in MultiCal to reference all reflection coefficients and S-parameters to a 50-Ω real reference impedance. Thus, the system is completely characterized through the use of S-parameters and reflection coefficients defined in terms of pseudo-waves [11].

III. FORMULATION FOR ON-WAFER NOISE-TEMPERATURE MEASUREMENT

A. Determination of On-Wafer Noise Temperature

We first define our notation. Available powers will be denoted by a capital P and delivered powers by lowercase p. The subscript on an available power generally indicates the device, except in the case of P_a, where it indicates the ambient. The dual subscripts on the powers and mismatch factors will indicate the reference plane and the switch setting. The DUT will be labeled by x, and the cryogenic standard is denoted by the subscript S. Thus, $p_{5,x}$ refers to the delivered power at plane 5 when the radiometer is switched to the DUT.

For a linear total-power radiometer, with perfect isolators assumed, the noise temperature T_x of the unknown one-port device at on-wafer reference plane 7 of Fig. 2 is described by the following radiometer equation [3], [4]:

$$T_x = T_a + (T_S - T_a)\,\frac{M_{0,S}\alpha_{02}}{M_{0,x}\alpha_{07}}\,\frac{(Y_x - 1)}{(Y_S - 1)} \tag{1}$$

where $Y_x \equiv p_x/p_a$, and $Y_S \equiv p_S/p_a$. p_x is the delivered noise power measured by the radiometer with the switch connected to plane 7. Similarly, p_s is the delivered power measured with the switch connected to plane 2, and p_a is that measured with the switch connected to plane 1. T_S is the known noise temperature of the cryogenic standard, and T_a is the ambient standard temperature. $M_{0,x}$ is the mismatch factor at plane 0 when the radiometer is switched to plane 5 in Fig. 1, and $M_{0,S}$ is the mismatch factor at plane 0 when the radiometer is switched to plane 2. Finally, α_{ij} denotes the available-power ratio from plane j to plane i. These are defined formally by

$$M_{0,x} = \frac{p_{0,x}}{P_{0,x}} = \frac{\text{Delivered power at 0 with switch to 5}}{\text{Available power at 0 with switch to 5}}$$

$$M_{0,S} = \frac{p_{0,S}}{P_{0,S}} = \frac{\text{Delivered power at 0 with switch to 2}}{\text{Available power at 0 with switch to 2}}$$

$$\alpha_{ij} = \frac{P_i}{P_j} = \frac{\text{Available power at } i}{\text{Available power at } j}.$$

Equation (1) is the usual form of the radiometer equation for an isolated total-power radiometer [12]. The measurement complications associated with the on-wafer environment show up in generalized expressions for the mismatch factors and available-power ratios [3], [4]. This is due to the more complicated form of the power equation for transmission lines with significant loss [11], [13]. In terms of traveling-wave amplitudes, complex characteristic impedance, and reflection coefficients, the expressions are rather involved [3], [4], but they can be transformed into simpler forms by the use of pseudo-waves [11]. In the radiometer equation, the ratio of mismatch factors and available-power ratios becomes

$$\frac{M_{0,S}\alpha_{02}}{M_{0,x}\alpha_{0.7}} = \frac{|S_{21}^{(50)}(2-0)|^2}{|S_{21}^{(50)}(7-0)|^2} * \frac{|1-\Gamma_x^{(50)}\Gamma_{7,r}^{(50)}|^2(1-|\Gamma_{2,S}^{(50)}|^2)}{|1-\Gamma_S^{(50)}\Gamma_{2,r}^{(50)}|^2(1-|\Gamma_x^{(50)}|^2)} \tag{2}$$

where the superscript "(50)" indicates that the reflection coefficient or S-parameter is referenced to a 50-Ω impedance. The various Γ's denote the reflection coefficients looking both ways from reference planes 2 and 7.

B. Prediction of On-Wafer Temperature Due to Off-Wafer Standards

The relationship

$$T_{\text{on-wafer}} = \alpha_{\text{probe}} T_{\text{off-wafer}} + [1 - \alpha_{\text{probe}}]T_a \tag{3}$$

relates the noise temperature associated with the available power at the output of a passive wafer probe network $T_{\text{on-wafer}}$ to a known off-wafer noise temperature $T_{\text{off-wafer}}$ [3], [4]. In (3), α_{probe} is the ratio of the available power on the on-wafer side of the probe to that on the off-wafer side, which can be calculated rigorously according to

$$\alpha_{\text{probe}} = \frac{|S_{21}^{(50)}|^2(1-|\Gamma_{s,\text{off-wafer}}^{(50)}|^2)}{|1-\Gamma_{s,\text{off-wafer}}^{(50)}S_{11}^{(50)}|^2[1-|\Gamma_{s,\text{on-wafer}}^{(50)}|^2]} \tag{4}$$

where $S_{21}^{(50)}$ and $S_{11}^{(50)}$ are pseudo-wave S-parameters associated with the probe and any interconnecting cables required, e.g., between planes 10 and 7 in Fig. 1. $\Gamma_{s,\text{off-wafer}}^{(50)}$ is the reflection coefficient of the off-wafer noise standard, e.g., looking toward the standard from plane 10. $\Gamma_{s,\text{on-wafer}}^{(50)}$ is the reflection coefficient looking toward the standard from the on-wafer reference plane, e.g., looking to the left at plane 7 in Fig. 1.

Equation (3) shows that the effect of translating an off-wafer hot noise temperature to an on-wafer reference plane will reduce the hot temperature, while translating an off-wafer cold noise source to an on-wafer reference plane will increase the cold temperature. In either case, the limiting value for a very lossy probe or high valued attenuator is the ambient temperature T_a.

C. ENR and Associated Temperatures

Commercial diode noise sources and gas-discharge tubes are usually specified in terms of an ENR at a coaxial or waveguide reference plane. The ENR is defined by

$$\text{ENR} = 10\,\log_{10}\left(\frac{(T_h - T_0)}{T_0}\right) \quad \text{(decibels)} \tag{5}$$

where $T_o = 290$ K. In general, the hot temperature T_h can either be the available noise temperature T_h^{av} or the effective noise temperature T_h^e associated with the power delivered to a matched load. The two noise temperatures are related by

$$T_h^e = T_h^{\text{av}}(1 - |\Gamma_s|^2) \tag{6}$$

where Γ_s is the reflection coefficient of the source. We use the notation ENR^{av} or ENR^e according to which noise temperature is used in the ENR calculation. Calibration of diode noise sources usually is specified in terms of ENR^e; however, for well-matched commercial sources, the difference between ENR^e and ENR^{av} is on the order of 0.01 dB.

To calculate the on-wafer ENR^e due to a known off-wafer ENR^e, a modified version of (3) is required, which may be expressed as [1]

$$T_{\text{on-wafer}}^e = \left[\frac{\alpha_{\text{probe}} T_{\text{off-wafer}}^e}{(1-|\Gamma_{s,\text{off-wafer}}^{(50)}|^2)} + [1-\alpha_{\text{probe}}]T_a\right] \cdot (1-|\Gamma_{s,\text{on-wafer}}^{(50)}|^2). \tag{7}$$

Once the on-wafer effective temperature is calculated according to (7), it can be used in (5) to obtain the on-wafer ENR^e in a rigorous way. The difference between on-wafer ENR^e and ENR^{av} will typically be larger than off-wafer due to the degradation in source match introduced by the probe. Which ENR is more useful depends on the application. The more important distinction is whether available or effective temperature is known at a given reference plane.

One useful feature of the ENR representation is that if we assume that the ambient temperature $T_a = T_0 = 290$ K, then the simple approximation

$$\mathrm{ENR}^{\mathrm{av}}_{\text{on-wafer}} \approx \mathrm{ENR}^{\mathrm{av}}_{\text{off-wafer}} + 10\ \log\left(\alpha_{\mathrm{probe}}\right) \quad (\mathrm{dB}) \tag{8}$$

relates the on-wafer and off-wafer ENR's with negligible error for noise temperatures above 1000 K. Since the available power ratio is less than 1 for a passive network, the effect of the probe will always be to reduce the ENR value. If we further assume that $\Gamma^{(50)}_{s,\text{off wafer}}$ is negligible, then the power ratio reduces to the familiar form

$$\alpha_{\mathrm{probe}} \approx \frac{|S^{(50)}_{21}|^2}{[1 - |S^{(50)}_{22}|^2]} \tag{9}$$

which further reduces to $|S^{(50)}_{21}|^2$ for a well-matched probe. Like (3), (7)–(9) apply to any passive two-port network connected to a noise source.

D. The Cold Noise Ratio (CNR)—A New Decibel Representation for Cold Temperatures

The usefulness of (8) is that it provides an intuitively simple approximation for how ENR is changed in transforming through a lossy passive network. It is clear from (5) that ENR is only defined for hot temperatures above 290 K. A simple extension of the ENR concept allows us to define an analogous noise ratio for cold noise temperatures. Its utility is that it also can be used to develop a similar intuitive approximation for transforming through lossy networks. We define the CNR as

$$\mathrm{CNR} \equiv 10\, log_{10}\left(\frac{(T_0 - T_c)}{T_0}\right) \quad (\mathrm{dB}) \tag{10}$$

where T_e is either the effective or available cold noise temperature. To keep the analogy with our ENR definitions complete, we will use the terms CNR^e and $\mathrm{CNR}^{\mathrm{av}}$ according to which temperature is used.

Since the noise temperature equations, (3) and (7), apply for any off-wafer temperature, hot or cold, in analogy with (8), the $T_a = T_0$ approximation yields the relationship

$$\mathrm{CNR}^{\mathrm{av}}_{\text{on-wafer}} \approx \mathrm{CNR}^{\mathrm{av}}_{\text{off-wafer}} + 10\ \log(\alpha_{\mathrm{probe}}) \tag{11}$$

between on- and off-wafer CNR. Like (8), (11) provides a simple estimate of the effect of translating through a lossy network. The on-wafer CNR or ENR is approximately equal to the off-wafer value reduced by the probe loss in decibels. The symmetrical form of the CNR and ENR functions in the vicinity of 290 K is shown in Fig. 3.

IV. SYSTEM VERIFICATION USING OFF-WAFER STANDARDS

A. System Checks at Coaxial Reference Plane

The first check of the system was a direct off-wafer (coaxial) measurement of a commercial diode noise source whose noise temperature is well known from past measurements. The noise temperature was measured at 8–12 GHz. This off-wafer check-standard test was repeated several times during the diode measurements made using the configuration of Fig. 2. The results agreed with past measurements within 1% in almost all cases (worst case was 1.25%). Although better agreement is desired for calibration service measurements, this was considered sufficient for this exploratory research.

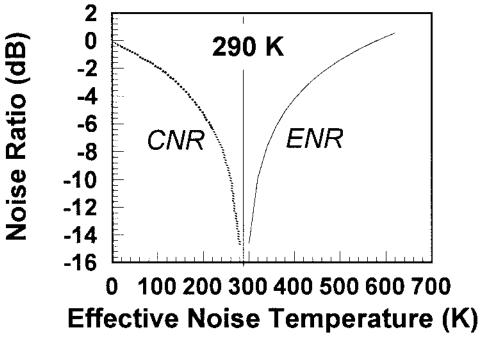


Fig. 3. Functional behavior of CNR and ENR in the neighborhood of 290 K.

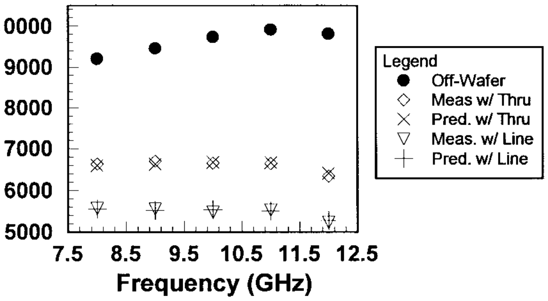


Fig. 4. Comparison of measured and predicted on-wafer temperature (at plane 7 of Fig. 1) presented by a coaxial diode noise source connected to Probe 2. Measurements were made with both a short (thru) and long (line) CPW line connected between the probes.

B. On-Wafer Measurement of Off-Wafer Hot Diode Standard

As another verification, known off-wafer standards were connected to the probe station (see Fig. 1). By measuring and correcting for the S-parameters of Probe 2 and the cable connected between reference planes 10 and 9, we used (3) to predict the noise temperature at on-wafer reference plane 7. This predicted temperature was then compared to the measured on-wafer noise temperature at this reference plane determined using (1) and (2), and noise measurements observed through Probe 1.

The results of Figs. 4 and 5 show the available off- and on-wafer noise temperature and $\mathrm{ENR}^{\mathrm{av}}$ for a diode check standard. The off-wafer noise temperature is about 9200 K at 8 GHz, which corresponds to $\mathrm{ENR}^{\mathrm{av}} = 14.87$ dB. Results are shown with the probes contacting both a thru (short CPW line) and a line (longer CPW line) on the substrate. At 8 GHz, the 6500-K on-wafer temperature, or $\mathrm{ENR}^{\mathrm{av}} = 13.3$ dB, at plane 7 of Fig. 1 for the thru line case is consistent with the 1.5-dB available power ratio (loss) determined for Probe 2 at 8 GHz, based on the measured S-parameters $SP2$ in the approximation $\alpha_{\mathrm{probe}} \approx 10\ \log_{10}(|S^{(50)}_{21}|^2)$. There is more loss between planes 10 and 7 when the line is used, which is consistent with the lower on-wafer temperatures observed for this case. In fact, from the ENR differences, we can conclude

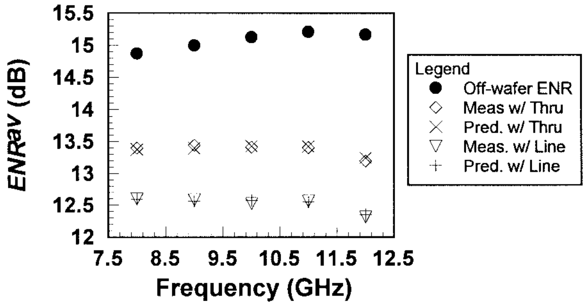


Fig. 5. Comparison of measured and predicted on-wafer (available) ENR (at plane 7 of Fig. 1) presented by a coaxial diode noise source connected to Probe 2. Measurements were made with both a short (thru) and long (line) CPW line connected between the probes.

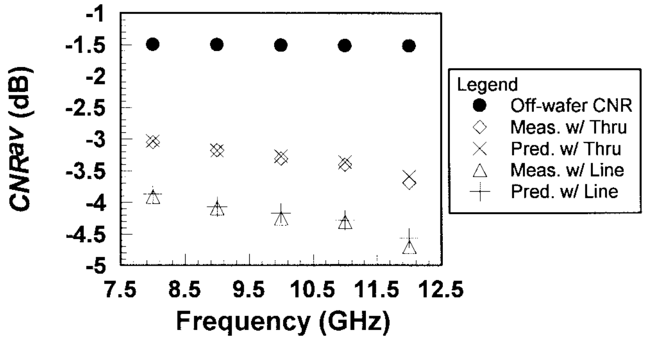


Fig. 7. Comparison of on-wafer CNR's associated with available on-wafer temperatures due to an off-wafer cryogenic standard.

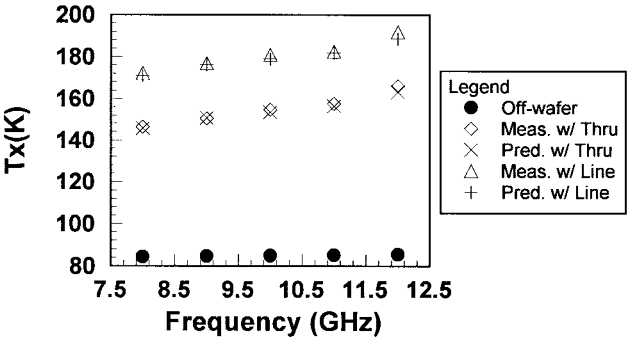


Fig. 6. Comparison of measured and predicted on-wafer temperature (at reference plane 7 of Fig. 1) presented by a cryogenic primary standard connected to Probe 2. Measurements were made with both a short (thru) and long (line) CPW line connected between the probes.

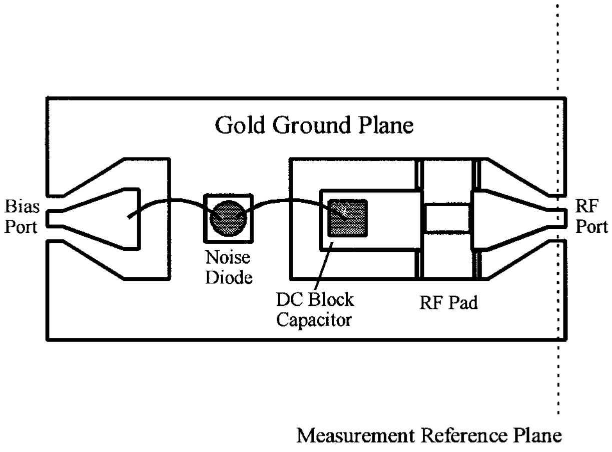


Fig. 8. Layout for wafer probeable diode noise source used in this paper. Diodes with three different attenuator (pad) values were used, labeled Diode A, Diode B, and Diode C.

that the line adds about 0.8 dB of insertion loss, which again is consistent with the approximate difference in the MultiCal determined Probe loss for the two cases (thru and line).

C. On-Wafer Results for Off-Wafer Cryogenic Primary Standard

We also measured a cryogenic off-wafer standard using the configuration of Fig. 1. The noise temperature and CNR results for this set of measurements are shown in Figs. 6 and 7. The off-wafer temperature at 8 GHz is 84.3 K, corresponding to $\mathrm{CNR}^{\mathrm{av}} = -1.49$ dB, compared to an on-wafer temperature (thru line case) of 146 K, corresponding to $\mathrm{CNR}^{\mathrm{av}} = -3.05$ dB. The 1.5-dB difference between on- and off-wafer CNR values at 8 GHz (see Fig. 7) is in agreement with expectations from the 1.5-dB approximate probe loss and (11). For the cold off-wafer source, Fig. 6 shows that the increased loss for the line case produces a higher on-wafer temperature at plane 7. The corresponding CNR difference between the thru and line case values at 8 GHz (see Fig. 7) is 0.8 dB, the same as the ENR differences from Fig. 5.

The agreement between measured and predicted values, based on rigorous theory, for the on-wafer noise temperature for both the diode and cryogenic off-wafer standards is within 2% in all cases, which is consistent with expanded (2σ) uncertainty estimates of about 2% determined previously [3], [4]. Although these tests do not check all aspects of the measurements, they nevertheless provide confidence in the general technique and in the current set of measurements.

One measurement aspect not specifically included in this measurement set was whether or not the unshielded on-wafer noise measurements could be affected by external spurious signals. This was tested for in previous work [3], [4] by measuring off-wafer ambient noise sources (matched terminations) in addition to cryogenic and diode off-wafer noise sources through on-wafer transmission lines of varying lengths in a configuration similar to Fig. 1. Since the measured result did not deviate significantly from ambient room temperature, it is unlikely that spurious external noise is a problem for our on-wafer noise measurements.

V. ON-WAFER DIODE NOISE SOURCES

A. Design of Preliminary Set of On-Wafer Diode Noise Sources

The on-wafer noise source is depicted in Fig. 8. It consists of a noise diode bonded to a section of coplanar waveguide with an integrated attenuator between the diode and output. The noise diode is a GaAs Schottky diode that is either reverse-biased or unbiased. Three different on-wafer sources (labeled A, B, and C) were built and tested, with three different attenuations of nominally 10 dB (A), 15 dB (B) and 20 dB (C). The bias current for the diode is supplied from an off-wafer constant-current biasing circuit (see Fig. 2) through a probe contacting the pads at the left of Fig. 8. For the present measurements, no special attention was paid to the termination of the bias port. We are, therefore, dependent on the bias circuit and probe presenting some "reasonable" impedance at the plane of the diode. Since no major problems arose, we infer that this was indeed the case. The (off-wafer) bias circuit is identical to that used in a commercially available coaxial diode noise source and provides a 10-mA constant dc current with an estimated reverse voltage of 8.5 V across the diode. A blocking capacitor isolates the attenuator and the RF section of the on-wafer diode source from the dc bias. The reference plane for the noise-temperature measurements, plane 7 of Fig. 2, is at the RF port on the right-hand side in Fig. 8.

The output section leading to the RF port does not include a section of coplanar waveguide identical to half the thru line used in the on-wafer calibration kit; this introduces a complication not present in our earlier measurements [3], [4]. In the on-wafer TRL calibration [8], [9], the probe is defined to extend to the middle of the calibration thru line. It thus includes a short (0.25 mm) section of coplanar waveguide, which is not present when the probe is set down on the pads on the right of Fig. 8. We must, therefore, translate the probe calibration to the probe tip to reduce the errors incurred by the lack of an appropriate access line.

This procedure neglects the effect of evanescent modes, or transition fields, in the vicinity of the probe tip. These effects could introduce errors into noise measurements; however, these concerns are ignored for the present set of exploratory measurements. Designs of future on-wafer noise sources will include a section of coplanar waveguide identical to that used in the set of on-wafer TRL calibration standards. Ideally, the TRL calibration set and noise sources will reside on the same wafer or substrate.

B. Measurement Results

Using the configuration of Fig. 2 and calculations enabled by (1) and (2), we characterized the noise temperatures for the three on-wafer diode sources across the 8–12-GHz frequency range. The noise temperature for each of the three sources (shown plotted in [5]) is approximately constant across the frequency range measured with values of about 1200, 3400, and 10 000 K. The corresponding equivalent values of $\mathrm{ENR}^{\mathrm{av}}$, shown in Fig. 9, are approximately constant at about 5, 10, and 15 dB for the three sources. The 5-dB drop in ENR observed in moving from noise source A to B and from B to C (see Fig. 9) is consistent with that expected from the 5-dB successive increase in pad attenuation values for sources A (10 dB), B (15 dB), and C (20 dB), in accordance with (8). We may also infer that the ENR of the bare noise diodes used in the noise sources studied here is approximately 25 dB. On-wafer noise-temperature measurements of the unbiased on-wafer diodes as well as that of an on-wafer load resistor were all confirmed to lie within ±0.25 K of 297.5 K across the 8–12-GHz measurement frequency range, in correspondence with the ambient room temperature.

The magnitudes of the reflection coefficients of the three dc-biased diode noise sources are plotted in Fig. 10. The values range from about 0.04 to 0.12. As expected, the source with the highest attenuation (source C) exhibits the least variation with frequency, remaining almost constant at 0.06, and the source with the least attenuation (source A) exhibits the most frequency dependence in its reflection coefficient. The difference between the coefficients in the bias-on state and the bias-off state is shown in Fig. 11. Again, the results are as expected, with the highest attenuation resulting in the smallest difference between the reflection coefficient in the two states, less than 0.005 for source C.

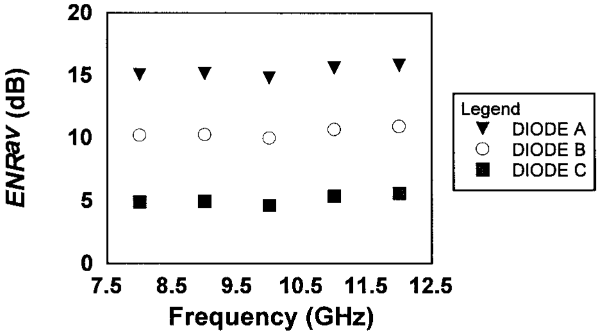


Fig. 9. ENR corresponding to measured temperature of the three on-wafer diode noise sources.

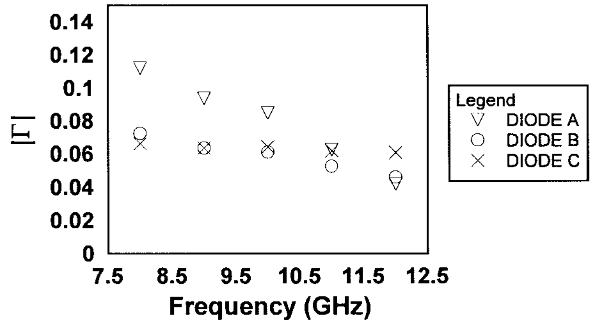


Fig. 10. Reflection-coefficient magnitudes for the three on-wafer diode noise sources with dc bias on.

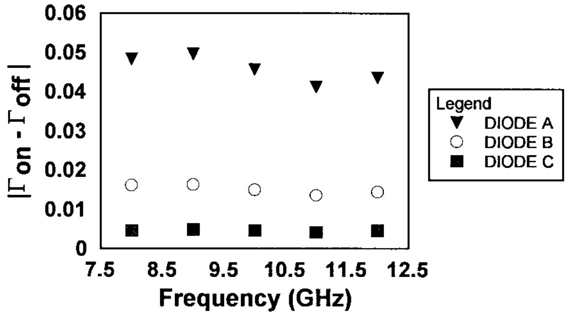


Fig. 11. Magnitude of vector difference between reflection coefficients of bias-on and bias-off diodes.

VI. APPLICATIONS AND EXTENSIONS OF ON-WAFER DIODE NOISE SOURCES

A. Applications of Theory

The specific measurement configurations of Figs. 1 and 2 are related to the radiometric approach to on-wafer noise-temperature measurement used by NIST. With appropriate modifications, MultiCal enabled system characterization, (1) and (2) could be used to produce fully corrected on-wafer one-port noise-temperature measurements with a conventional noise-figure meter and a coaxial diode noise source. Though beyond this paper's scope, such application may be useful to future interlaboratory comparisons of on-wafer noise sources.

The applications of (3)–(9) are more obvious. Today's practice for on-wafer two-port noise-figure measurements follows one of two approaches. The first is to perform "scalar" 50-Ω noise-figure measurements using a conventional noise-figure meter and an off-wafer diode noise source, more or less in the arrangement discussed in [1]. Equations (3) and (7) can be used along with MultiCal or alternative probe S-parameter determinations to obtain the effective on-wafer noise temperatures and corresponding ENR's using (5). The resulting on-wafer ENR can be used directly for on-wafer scalar noise-figure calibration. The second approach to on-wafer two-port measurements is on-wafer noise-parameter measurements [2]. Properly performed, the noise-parameter approach is the most accurate commercially available way to measure on-wafer two-port devices (e.g., monolithic amplifiers).

A common trait of commercial noise-parameter and scalar noise-figure measurement systems is that an off-wafer diode noise source is generally used as part of the calibration. Equations (3), (4), and (7) rigorously address this part of on-wafer noise-parameter or on-wafer scalar noise-figure test systems calibration.

B. Interlaboratory Comparisons Using On-Wafer Diode Noise Sources

One possible use of on-wafer diode noise sources is for interlaboratory comparisons. The second generation of on-wafer diode sources, currently under development at NIST, are to be embedded in CPW and fabricated along with CPW TRL standards on a substrate we will call a noise-verification substrate. The layout of the noise diode sources and the TRL standards on the noise-verification substrate would facilitate measurement of on-wafer ENR for on-wafer diode sources at a reference plane in a uniform CPW transmission line. The on-wafer noise sources under development will likely contain a bias filter network that will set the microwave-frequency reflection coefficient looking to the left of the diode in Fig. 8.

The diode sources on the noise-verification substrate would be first characterized by NIST and then circulated to other laboratories for characterization on their test systems and comparison to NIST results. Since most industrial laboratories generally measure two-port devices, detailed procedures for partial verification of their two-port measurement systems and calibrations against the one-port on-wafer noise transfer standards would need to be established.

C. Direct Use of On-Wafer Diode Noise Sources as Calibration Artifacts

The calibrated on-wafer diode transfer standards could be used to calibrate directly a radiometer or a noise-figure meter for one-port on-wafer noise measurements. One-port on-wafer test systems, so calibrated, could be used as part of interlaboratory noise comparisons, or they may have direct applications to device modeling. For example, with knowledge of a small-signal model and suitable approximations [14], the measured one-port output noise temperature could be used to specify the noise parameters for a two-port field-effect transistor (FET).

On-wafer diode noise sources could be used directly in noise-parameter measurements that use a single measurement of hot diode power and multiple measurements under varying ambient temperature source reflection coefficients [15]. In this case, it would be possible to use the on-wafer noise diode only as part of the receiver noise-parameter calibration sequence. By measuring the two-port DUT S-parameters with an VNA, the DUT noise parameters could be determined from subsequent output noise power measurements made with various ambient temperature loads connected on the source side of the device, e.g., by connecting the input probe to a variable impedance tuner.

The use of on-wafer diode transfer standards could simplify user calibrations of such noise-parameter measurements by eliminating the steps required to characterize the input probe network S-parameters. On-wafer diode noise sources should also reduce errors associated with user determination of the probe S-parameters and place the burden for minimizing these errors instead on the laboratory responsible for ENR calibration of the on-wafer diodes.

D. Proposed Noise-Source Wafer Probe

There are still a large number of users who want to avoid the complications and expense of on-wafer noise-parameter measurements and prefer to make scalar noise-figure measurements in a nominally 50-Ω environment. These users may be well served by the development of a noise-source wafer probe based on the concept shown in Fig. 12. The illustrated noise-source probe incorporates a diode noise source of the type shown in Fig. 8 into a wafer probe. This probe would be an extension of current RF wafer probes, which generally affix coplanar probe tips (ground-signal or ground-signal-ground) to the ends of a miniature coaxial transmission line or to the ends of a CPW transmission line on a substrate attached to the probe. As illustrated in Fig. 12, accommodation could be made to allow for the noise-source probe to be used for both S-parameter and noise figure. The on-wafer ENR of the noise-source probe could be characterized along with a chosen TRL calibration substrate using the methods described in this paper. The calibration temperatures (or ENR's) would be specified by the calibrating laboratory at an on-wafer reference plane, e.g., in the middle of the thru calibration standard.

There are several advantages to the proposed noise-source wafer probe. It could be used directly for scalar noise-figure measurements as the diode noise source contained in the probe could be connected to the input of a two-port on-wafer device. The use of a calibrated noise-source probe would remove the requirement for the user to characterize probe S-parameters. Also, as shown in Figs. 10 and 11, the presence of the noise source attenuator close to the DUT interface provides low

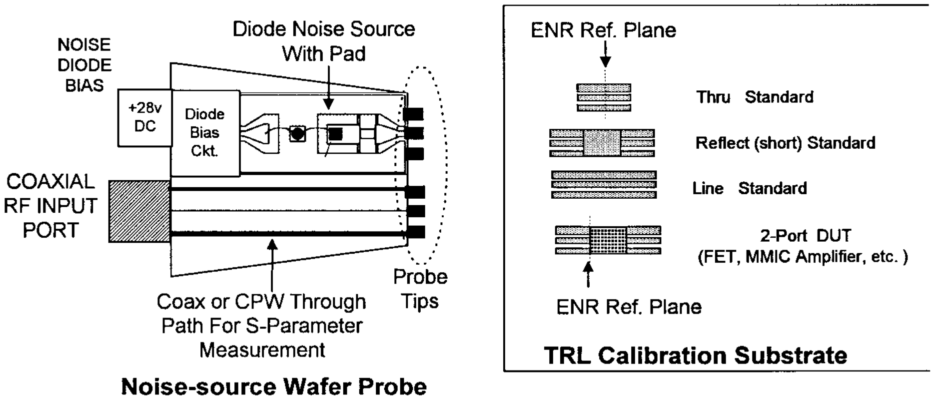


Fig. 12. Conceptual design for "noise probe," which would incorporate a noise diode and integrated attenuator into a wafer probe. The noise probe would be calibrated along with a chosen TRL calibration substrate as a transfer standard with calibrated temperatures or ENR's specified at the middle of the calibration thru.

source reflection coefficients so that measured scalar noise-figure results could correspond closely to the true 50-Ω noise figure for the DUT. Scalar 50-Ω noise-figure measurements made over a frequency range can be combined with a small-signal model to specify the two-port noise performance of an FET [16].

The noise-source probe could also simplify calibrations made for one-port noise temperature measurement and two-port noise-parameter measurements analogously to that discussed above for on-wafer diode noise sources. Incorporation of a tuner into the S-parameter path of the noise-source probe would allow the input hardware for a noise-parameter measurement to be contained entirely in the probe.

VII. SUMMARY

We have reviewed the theory and methods related to NIST's on-wafer noise-temperature measurements and have outlined applications of the theory to the prediction and measurement of the on-wafer temperature due to an off-wafer noise source. The CNR is suggested as a decibel representation for cold-temperature noise sources, analogous to the ENR for hot sources. It shares the property that the on-wafer value can be estimated by subtracting the probe loss in decibels from the off-wafer value. A set of three on-wafer diode noise source transfer standards was described. We detailed the characterization from 8 to 12 GHz of on-wafer noise temperature, ENR, and reflection coefficients for these sources. The sources have noise temperatures ranging from about 1000 to about 10 000 K, corresponding to ENR's from about 5 to 15 dB, that are only weakly dependent on frequency. Their reflection coefficients in the biased state range from about 0.04 to 0.11.

Applications of on-wafer diode transfer standards were discussed in some detail. One possibility is to develop an inter-laboratory comparison program involving a second generation of such devices. On-wafer diode noise sources have applications to on-wafer noise calibrations, potentially replacing coaxial diode standards in some circumstances. A concept for a noise-source probe was also presented as a practical extension of on-wafer diode noise sources that could provide for more efficient and accurate noise calibrations.

ACKNOWLEDGMENT

The authors are grateful to E. Strid and L. Hayden, Cascade Microtech, for providing the basic on-wafer diode mounting structures, and to K. Kerwin, Hewlett-Packard, for providing the biasing circuit and the noise diodes.

REFERENCES

[1] L. Dunleavy, "A Ka-band on-wafer s-parameter and noise figure measurement system," in *34th ARFTG Conf. Dig.*, Ft. Lauderdale, FL, Dec. 1989, 127–137.
[2] C. E. Woodin, D. L. Wandrei, and V. Adamian, "Accuracy improvements to on-wafer amplifier noise figure measurements," in *38th ARFTG Conf. Dig.*, Dec. 1991.
[3] J. Randa, "Noise temperature measurements on wafer," Nat. Inst. Stand. Technol. Tech. Note 1390, Mar. 1997.
[4] J. Randa, R. L. Billinger, and J. L. Rice, "On-wafer measurements of noise temperature," *IEEE Trans. Instrum. Meas.*, submitted for publication.
[5] J. Randa, D. Walker, L. Dunleavy, R. Billinger, and J. Rice, "Characterization of on-wafer diode noise sources," in *51st ARFTG Conf.*, Baltimore MD, June 1998.
[6] A. Boudiaf, C. Dubon-Chevallier, and D. Pasquet, "Verification of on-wafer noise parameter measurements," *IEEE Trans. Instrum. Meas.*, vol. 44, pp. 332–335, Apr. 1995.
[7] L. Escotte, R. Plana, J. Rayssac, O. Llopis, and J. Graffeuil, "Using cold FET to check accuracy of microwave noise parameter test set," *Electron. Lett.*, May 1991, pp. 832–835.
[8] R. Marks and D. Williams, *NIST/Industrial MMIC Consortium Software Manuals*, Feb. 1992.
[9] R. Marks, "A multiline method of network analyzer calibration," *IEEE Trans. Microwave Theory Tech.*, vol. 39, pp. 1205–1215, July 1991.
[10] R. Marks and D. Williams, "Characteristic impedance determination using propagation constant measurement," *IEEE Microwave Guided Wave Lett.*, vol. 1, pp. 141–143, June 1991.
[11] ——, "A general waveguide circuit theory," *J. Res. Nat. Inst. Stand. Technol.*, vol. 97, pp. 533–562, Sept./Oct. 1992.
[12] W. C. Daywitt, "Radiometer equation and analysis of systematic errors for the NIST automated radiometers," Nat. Inst. Stand. Technol. Tech. Note 1327, Mar. 1989.
[13] N. Marcuvitz, *Waveguide Handbook*. New York: McGraw-Hill, NY, 1951.
[14] M. S. Gupta, O. Pitzalis, S. E. Rosenbaum, and P. T. Greiling, "Microwave noise characterization of GaAs MESFET's: Evaluation by on-wafer low-frequency output of noise current measurement," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-35, pp. 1208–1218, Dec. 1987.
[15] V. Adamian and A. Uhlir, Jr. "A novel procedure for receiver noise characterization," *IEEE IEEE Trans. Instrum. Meas.*, pp. 181–182, June 1973.
[16] L. Dunleavy, S. Lardizabal, and R. Webster, "A new millimeter-wave noise modeling method for field effect transistors," presented at the Int. Device Res. Symp., Charlottesville, VA, 1991.

Lawrence P. Dunleavy (S'80–M'82–SM'96) received the B.S.E.E. degree from Michigan Technological University, Houghton, in 1982, and the M.S.E.E. and Ph.D. degrees from the University of Michigan at Ann Arbor, in 1984 and 1988, respectively.

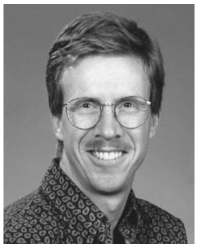
From 1982 to 1983, he was with E-Systems, Inc. From 1984 to 1990, he was with Hughes Aircraft Company, which included three years as a Howard Hughes Doctoral Fellow. In 1990, he joined the Electrical Engineering Department, University of South Florida, Tampa, where he is currently an Associate Professor. From August 1997 to August 1998, he was on a sabbatical research leave with the Microwave Metrology Group, NIST, Boulder, CO.

Dr. Dunleavy serves on several IEEE MTT-S Committees, as well as on the Executive Committee for ARFTG.

James Randa (M'84–SM'91) received the Ph.D. degree in physics from the University of Illinois, Urbana, in 1974.

He then successively held post-doctoral or faculty positions at Texas A&M University, University of Manchester (U.K.), and the University of Colorado at Boulder. During this time, he performed research on the phenomenology of elementary particles and on theories of fundamental interactions. Since 1983, he has been with the Electromagnetic Fields Division, NIST, Boulder, CO. From 1983 until early 1994, he was in the Fields and Interference Metrology Group, where he was involved with characterization of electromagnetic environments, probe development, and other topics in electromagnetic interference (EMI) metrology. He is currently with the Microwave Metrology Group, NIST, where he works in the area of thermal noise.

Dr. Randa chaired the EMC Society's TC-3 (1991–1994).



David K. Walker received the B.A. degree in physics from Hastings College, Hastings, NE, in 1980, and the B.S.E.E. and M.S.E.E. degrees from Washington University, St. Louis, MO, in 1982 and 1983.

From 1983 to 1985, he was with the Central Microwave Division, Alpha Industries. From 1985 to 1991, he managed the Semiconductor Facility, Millitech Corporation. In 1991, he joined the Microwave Metrology Group (now called the RF Electronics Group), NIST, Boulder, Colorado.

Robert Billinger received the associates degree in electronics technology from Wichita Technical Institute, Wichita, KS, in 1979.

From 1979 to 1984, he was with PureCycle Corporation, where he became Manager of electronic production and testing. Since 1985, he has been with the Electromagnetic Fields Division, Microwave Metrology Group, NIST, Boulder, CO, where he is involved in the area of thermal noise.

John Rice served as an Electronic Technician in the U.S. Navy from 1976 to 1982. He then spent 5 years as a Contractor in the Naval Calibration Laboratory, Rota, Spain, followed by three years as an Electronic Technician at the Naval Air Test Center, Patuxent River, MD. In 1990, he joined the Noise Project in the Electromagnetic Fields Division, NIST, Boulder, CO. Since early 1998 he has been an Electronic Systems Analyst with the National Weather Service, Marquette, MI.